CLIMATE

A TREATISE
ON THE PRINCIPLES OF WEATHER AND CLIMATE

By

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OXFORD
AT THE CLARENDON PRESS
1930

CLIMATE

The Matterhorn with its Banner Cloud

OXFORD UNIVERSITY PRESS
AMEN HOUSE, E.C. 4
LONDON EDINBURGH GLASGOW
LEIPZIG NEW YORK TORONTO
MELBOURNE CAPETOWN BOMBAY
CALCUTTA MADRAS SHANGHAI
HUMPHREY MILFORD
PUBLISHER TO THE
UNIVERSITY

PRINTED IN GREAT BRITAIN

PREFACE

This treatise is written primarily for the general reader who wishes to know something of the principles of weather and climate, ever intrusive elements in his surroundings, and for those workers who find a knowledge of climatology desirable for the furtherance of their main subject of study.

It is non-technical so far as that is possible, and no great knowledge of physics should be found necessary for its understanding. The essential fundamental bases of the phenomena of the atmosphere, those great factors whose control is literally world-wide, such as insolation and the major pressure and wind systems of the globe, are kept prominent throughout. But it is hoped that enough of the minor influences, sunshine, humidity, the effects of shelter and exposure and the like, which though secondary or local are often very significant from the biological point of view, have been indicated to give a foundation for more detailed work, and to make the treatment of real practical application rather than of merely theoretical and meteorological interest; for climatology sets before itself the practical purpose of describing and explaining the actual atmospheric conditions that are so prominent in the environment of Life. The book considers climatology mostly from the geographical side, which seems the natural approach to the subject, and treats the principles of climate largely from a distributional stand-point.

My cordial thanks are offered to many friends who have helped me in many ways, and in particular to Mr. J. N. L. Baker, University Lecturer in Geography, Oxford, to Mr. J. Kendrew, for preparing the Index, to Dr. H. Knox-Shaw, Radcliffe Observer at Oxford, for valuable help and for providing the records of his Observatory of which much use is made in these pages, and to Captain T. R.

Mowat, whose wide experience of the days of sail has been specially useful in describing marine conditions.

It is a pleasure also to acknowledge the frequent use made of the work of those scientists and others whose observations and results are the foundation of a book of this character as will be obvious from every chapter. Many acknowledgements by name are made in the text and on page xi, but probably there are very many omissions for which apology is due.

W. G. K.

OXFORD,
July 1930.

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PART I. INTRODUCTION

CHAPTER I

THE SCOPE OF CLIMATOLOGY

MODERN civilized life has become so highly artificial that our relations with and dependence on basal natural conditions are to a large extent masked. In primitive societies these relations are obvious; only the man who can adapt himself to his surroundings survives; the community which is most richly endowed by nature, and is able to take full advantage of its endowment, makes headway and secures pre-eminence over its neighbours. We can see the romance of evolution played out still more clearly in the realms of animals and plants.

Climate is in general the most fundamental and far-reaching of the natural elements which control our destiny. The vegetation of the earth is closely dependent on it, and there are numerous obvious adaptations of animal life to it; of climatic types in mankind we will mention only the Eskimo on the frozen margins of the Arctic, the fair-skinned races of the westerlies, the Arabs of the arid trade-wind deserts, and the Negroes of the equatorial zone. The adaptation to climate is both direct and indirect. It is only when men of any race are moved to a new climatic environment that their specialized adaptation to their home climate, and their lack of adaptations to their new conditions, become clearly manifest. In spite of all his command of the resources of civilization, and his advances in scientific knowledge, the individual white man is unable to flourish for many consecutive years in the heat and moisture, the 'hot-house' atmosphere, of the Guinea coast, and certainly the White race is as yet unable to establish itself there as colonists, reproducing its species. The human organism appears to be debilitated by the direct influence of the new climate, and so falls a ready prey to sundry germ-diseases such as malaria and yellow-fever, which haunt the region. This is an extreme case, but by no means an isolated one. Some changes of climate appear to be stimulating when the change is not of great magnitude, but if a race is permanently subjected to such new conditions it is probable that the type changes gradually, possibly by a process of elimination.

In this work some of the important features of climate will be described, and some indication given of the physical principles underlying them. The geographical distribution of climate will be kept prominently in view, since the influence of climate on the distribution and characteristics of the plant and animal inhabitants of the earth is probably the most interesting, and it is certainly the most important, aspect of the study of applied climatology. It is altogether outside the scope of this book to treat of applied climatology, but the attempt is made to provide an outline of the pure climatology necessary for the more extensive and valuable study.

'Climate' and 'Weather'

'Climate' is a composite idea, a generalization of the manifold weather conditions from day to day throughout the year. There are regions, especially on the equator, where the weather is so little changeable that 'weather' and 'climate' are almost synonymous. Any one day is a fair sample of the climate. The farther we go from the equator the greater becomes the variation, at any rate in the seasons, for astronomical as well as meteorological causes; and between the tropics and the poles the weather is so variable—especially in the region of the Westerlies—that it is difficult to form any simple idea of the climate unless it be the idea of something very changeable. Certainly no picture of climate is at all true unless it is painted in all the colours of the constant variation of weather and the changes of season which are the really prominent features. And we must guard against contenting ourselves with the mean conditions of any element of climate. The variations from the mean are always much more frequent than the mean values themselves, and they deserve full description. To do full justice to this requirement demands a long treatment, so long perhaps as to be incapable of being grasped and used. The best course lies midway between extreme generalization and excessive detail; in most parts of the world meteorological records are so few that there is no temptation to indulge in over-detailed description.

In the study of climatology we are primarily interested in the facts and phenomena of the climates of the earth in themselves, and as elements in the natural environment of life. The investigation of the physical causes underlying the facts is an important as well as an interesting side of our study, but it is to be regarded as subordinate. Climatology thus differs from meteorology which is a physical science primarily concerned with the physical processes which go on in the atmosphere, from the surface of the earth up to the highest strata which are concerned in weather.

PART II

INSOLATION AND TEMPERATURE

CHAPTER II

TEMPERATURE DIFFERENCES

TEMPERATURE is a very important element of climate, indeed from many points of view the most important, as for example, in controlling the distribution of life on the earth; and in any treatment of the subject it must come first since most of the other elements—winds, rainfall, cloudiness—are dependent on it directly or indirectly.

Temperature may be considered from many points of view. Comparison with other places is implied, even if not expressed in words, in most climatic descriptions, and comparisons of temperature are most easily made by means of isotherms, lines drawn on a map through places which have the same temperature for any period, as the whole year, a season, or a month.

The position and run of the isotherms are determined by such wide influences as latitude, prevailing winds, and distribution of land and sea. But many places have peculiarities in their climate which are due to their own topography. Among mountains even neighbouring valleys often show great differences which are by no means constant but vary with the time of day, the season of year, the type of weather, and are due to the influence of the mountain barrier on the air movements. Again, districts lying near a hot desert may be liable to hot dusty winds; and continental interiors sometimes pour floods of cold air in winter over regions which usually enjoy warmth.

The analysis of the temperature of a place is somewhat complicated. The source of our heat is the sun (the internal heat of the earth may be ignored as having a uniform influence everywhere, except for occasional and very limited local heating by volcanic eruptions) and it is necessary to trace out first the relative amounts of solar heat received at different latitudes, then the effect of the atmosphere on its passage, and thirdly, a very important consideration, the nature of the surface on which the heat is received, for the temperature of the air depends very largely on the temperature of the surface on which the air rests. If the atmosphere were still we should then be almost at the end of our inquiry. But a new train of effects is set in action by the temperature differences themselves, in that they give rise to the winds which tend to carry with them the temperature of their place of origin, modified always by the conditions of the land or water over which they blow. Thus every place is subject not only to the direct effect of its own insolation, but to diverse influences carried by the winds. And finally, there are often local topographical effects to be allowed for.

We now proceed to study the first factor, the amount of heat received from the sun.

CHAPTER III

THE DISTRIBUTION OF INSOLATION

THE sun is constantly radiating into space the complex of energy which is called insolation. The sun's diameter is about 864,000 miles, and its volume 1 million times that of the earth. So hot is it that our human imagination is unable to form any conception of the conditions. The temperature of the surface is estimated at about 10,000° F., of the centre at 50,000,000° F. The whole mass consists of gases, and the intense activity of the blazing ball is perhaps made most strikingly visible to us in the prominences which we see shooting forth through its corona during a total solar eclipse. These gigantic tongues of brilliance have sometimes been observed to attain a height estimated at about half a million miles, and they dart forth at a speed of some 250 miles a second. From the fiery surface, in comparison with which our hottest furnaces are cold, radiant energy is poured forth into space in all directions. The earth revolves round the sun at a distance of 92 million miles in the field of insolation, and intercepts a minute fraction (about 1/2,000,000,000) of it, but minute as it is all the life on our planet depends on it.

The amount of solar energy that reaches the outer surface of our atmosphere is called the 'solar constant', and its value has been determined at about 135 millewatts per sq. centimetre of surface at right angles to the rays, or 1·94 calories per minute; but in spite of the name the solar constant is found to be liable to appreciable variations. However, the important consideration for most of our present study will be not the absolute amount of energy received, but the relative amounts of heat on different parts of the earth, or rather, as a first element in our analysis, on different parts of the outer surface of our atmosphere at different times.

The Intensity of Insolation at the Surface of the Atmosphere

This is a matter of mathematical calculation, the variables being the angle of incidence of the solar rays, and the length of the day, or in other words the latitude and, owing to the earth being tilted at a constant angle of 66½° to the plane of its orbit, the season; an additional seasonal effect is produced by the fact that the orbit of the earth is not a true circle, the earth approaching nearest to the sun (91,300,000 miles) on December 20 and being most distant (94,500,000 miles) on June 21.

The following table, computed by Angot, gives the amounts of insolation received in 24 hours at the equinoxes and the solstices, expressed in kilowatt-hours per sq. dekametre with the solar constant assumed to be 135 kilowatts per sq. dekametre.

	Equator.	20°	40°	60°	90° N.	90° S.
Mar. 22	1,038	980	805	532	30	0
June 21	915	1,085	1,150	1,135	1,249	0
Sept. 20	1,023	972	805	541	20	0
Dec. 20	977	702	371	58	0	1,331

The facts are shown graphically in Fig. 1. It will be noted that the seasonal change in insolation is least on the equator. The noon sun swings from 23½° N. of the zenith in June to 23½° S. in December, and is overhead at the equinoxes. The day is 12 hours long throughout the year. The insolation is greatest at the equinoxes, and is at a maximum at the spring equinox, when the distance from the sun is somewhat less than at the autumn equinox. At the solstices the insolation is less owing to the lower altitude of the sun, the day being still 12 hours long.

Everywhere in the zone between $23\frac{1}{2}°$ N. and $23\frac{1}{2}°$ S. the sun's rays are vertical on either one or two days each year. The greater the distance from the equator the longer are the summer days. Hence the insolation is considerably greater at the tropic on midsummer day than at the equator in March when the sun is overhead there.

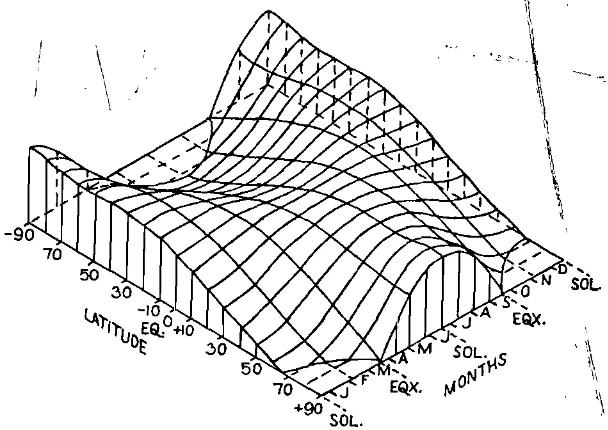


FIG. 1. Distribution of Insolation on the Earth (W. M. Davis)

The length of the summer day continues to increase as far as the Polar circles. But on the other hand the angle of incidence of the sun's rays becomes less—on the polar circles the midsummer sun is 47° above the horizon at midday, and just skirts the horizon at midnight (we ignore the effect of refraction which increases the altitude slightly). Between the polar circles and the poles the midsummer sun is above the horizon all the 24 hours, but its noon elevation becomes less, till at the poles it is only $23\frac{1}{2}°$. But what the sun loses in noon altitude it gains during the 'night' hours, the elevation remaining the same throughout the 24 hours at the pole. The net result of these factors is that on their midsummer days the Poles receive more insolation than any other part of the earth in any 24 hours. The south pole is the more favoured since the earth is nearer the sun on December 21 than on June 21.

Let us now consider the conditions of insolation on June 21, starting from the South Pole. Until we reach the Antarctic circle the sun does not appear above the horizon, and the insolation is nil. From the Antarctic circle northwards the length of the day and the elevation of the sun both increase as far as lat. $23\frac{1}{2}°$ N. and the insolation increases rapidly. Beyond $23\frac{1}{2}°$ N. the sun's altitude decreases but the length of the day continues to increase, the result being that a maximum of insolation is received about lat. 44° N. Still further north the diminishing altitude of the sun more than neutralizes the increasing length of the day nearly as far as the Arctic circle. From here to the Pole the day lasts for the whole 24 hours, and the nearer the Pole we go the greater is the altitude of the sun during the 'night', though not during the day. At the Pole itself we have the maximum insolation for the whole globe.

The statistics we have given are the result of mathematical calculation, and they are certainly interesting and striking. The Polar figures are especially noticeable; the frozen Arctic Ocean, and the snow-covered Antarctic plateau, where the mean monthly temperature never exceeds 32° and the highest temperature does not rise much above freezing-point, receive considerably more insolation at mid-summer than even the hottest lands inside the tropics such as the Sahara where the sand is often too hot to touch. It is evident that the influences to which the insolation is submitted before it reaches the surface of the earth must be of very great importance—greater importance for the study of climate than the mathematical factors we have been considering.

CHAPTER IV

THE EFFECT OF THE ATMOSPHERE ON INSOLATION

WHEN the solar energy reaches the atmosphere part of it is reflected back into space and is lost to the earth, part is absorbed during its passage through the atmosphere, part reaches the earth. It is this last part that is by far the most effective in controlling the air temperature. Though it seems paradoxical we may perhaps regard the part that is directly absorbed by the atmosphere rather as a loss from the store that is available for raising our air temperature. The important factor is the intensity of the insolation that actually reaches the earth's surface.

The absorption of insolation by the atmosphere depends on (i) the length of the passage, or, in other words, the angle of incidence of the rays; and (ii) the transparency of the atmosphere. The first is a factor capable of mathematical

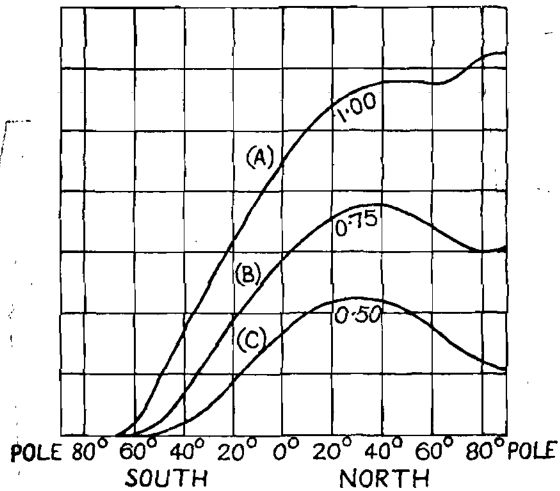


FIG. 2. Reduction of the Insolation by the passage of the Atmosphere (Angot)

calculation. Its importance is shown by the fact that if the length of the path is doubled the amount of heat is reduced to one-fourth, for the latter decreases in geometrical ratio while the length of the path increases in arithmetical ratio. The long oblique path in the polar regions is one obvious cause of the discrepancy between the high insolation value and the low air temperature. The second factor is very variable according to time and place. We cannot calculate the coefficient of transparency, and therefore the proportion of the total insolation that will reach the surface of the earth, without a detailed knowledge of the conditions of the air through which the insolation has to pass—and this knowledge is never available.

Fig. 2 shows the relative amounts of insolation that would reach the earth's surface at the summer solstice (A) if the atmosphere were quite transparent, (B) if the transparency were such that three-quarters of the insolation succeeded in passing through, and (C) if one-half passed through. The influence of the increasing obliquity of the rays and the longer path through the atmosphere poleward of the tropic is evident. The actual transparency of the air varies constantly; it is only very exceptionally that as much as three-quarters of the insolation reaches the earth's surface.

The rays are impeded chiefly by particles of water, and by particles of dust. The more oblique the rays, the longer becomes their path especially in the lower strata where the impurities are most numerous. The water particles are the more effective obstacle. They are usually visible as cloud, and no instruments are necessary to tell us that clouds intercept the sun's heat. Even the finest film of cirrus cloud which is hardly visible has great effect, and often the sky is covered with masses of cloud which have a thickness of several miles. The passage of every cloud across the sun, especially on a bright summer day, causes a sensible fall in the air temperature.

Water-vapour, even when not condensed into drops of water or particles of ice, is also a serious obstacle. At Montpellier, South France, 71 per cent. of the insolation penetrates to the earth in December, and only 48 per cent. in the summer months; the less vapour in the air (i. e. the less absolute, not relative, humidity) in winter more than balances the lower altitude of the sun and the consequent longer path of the insolation through the atmosphere.

Dust particles are most numerous close to the surface of the earth. The dust is mostly of terrestrial origin, being blown up from the dry surface of the earth, or thrown into the air by volcanoes. Salt from dried sea-spray is also an appreciable element; a dense haze on the Norfolk coast in September 1926 was found by microscopic examination to consist almost entirely of crystalline salts. Generally speaking the coarser particles of dust float at the lowest levels. The amount is naturally greatest over the arid lands, especially the trade-wind deserts. A shower of rain removes most of the dust from the air it falls through. But the finer particles may float above the level of clouds. This has been noted after great volcanic eruptions. The terrific eruption of Krakatoa in the Strait of Sunda in 1883 threw dust high into the atmosphere—so thick that it was dark at midday for hundreds of miles round about. But the finer particles were carried by the winds of the upper atmosphere right round the globe, and made themselves evident by brilliant sunset colours for some three years after the eruption. These particles were high above the clouds, and therefore were not washed down by rain. Such volcanic dust may envelop the earth after great eruptions, and impede the solar radiation so seriously that the temperature of the air is appreciably reduced for some years, and this may be a not inconsiderable factor in the production of unusually cold or wet seasons. The dust from the eruption of Mount Katmai (Alaska) on June 6 and 7, 1912, seems to have produced a haze all round the globe. Observations on Mount Wilson, California, and at Bassour, Algeria, indicate that the insolation was reduced by some 20 per cent., and the summer of 1912 was abnormally cold in Europe. Some thinkers incline to attribute glacial epochs to this same cause working on a large scale.

Another important source of solid impurities is smoke, especially over great cities, and over certain extensive tracts of grass-land such as the Sudan when the dead grass is fired in the dry season. The smoke may remain at low-levels in the atmosphere, and collect till the sun is hidden. But without attaining such density the obstacle is almost always present over great cities in sufficient volume to be of serious significance from the aesthetic and medical standpoints, and smoke trails may be carried for a hundred miles from large cities by the wind.

Generally speaking the atmosphere is clearest over the tropical deserts, the belt where the trade winds blow all the year. It is so dry that clouds are few and thin, and rain is very rare. On the other hand a necessary consequence of the aridity is dust, and the winds, generally strong, may sometimes sweep up clouds of it, forming dust-storms, but it is confined to the lowest layers of the atmosphere. Over the oceans there is little or no dust, save what is carried by the wind from the land, but there is more moisture, and there are often light cumulus clouds even in the deep blue sky of the trades. At the summer solstice the sun is overhead in these latitudes, and in view of the long days and clear air it is not surprising that the trade-wind deserts are then the hottest regions of the globe.

The equatorial region has much moisture and abundant cloud, especially during the hottest hours of the day, and consequently the insolation does not reach the surface of the earth with the intensity found in the belt of the trade winds.

On the poleward sides of the trade-wind belts the surface air is almost saturated with moisture, since it blows over comparatively warm seas, and frequent cyclonic disturbances produce abundant cloud. Insolation is much weakened, and in winter the air temperature is more strongly controlled by other influences than by the direct rays of the sun. In the far interiors of the continents the air is drier.

Inside the Arctic circle there is an expanse of water partly open but mostly frozen. The air is vapour-laden, and probably there is much mist and cloud. This, together with the long path of the oblique rays through the atmosphere, goes some way to explain the difference between the high value of the insolation which reaches the Polar atmosphere at the summer solstice and the low temperature of the air at the surface of the earth. The Antarctic land mass has less cloudy skies. Moreover the plateau, being some 7,000–10,000 feet above the sea, is raised above the denser and more humid strata, and the insolation is more intense than at lower levels.

The importance of altitude in this connexion is shown by the fact that on the average one-half of the total vapour is contained in the lowest 8,000 feet, and very much more than half of the solid particles; one-half of the whole mass of the atmosphere is below 17,500 feet; and above 6 miles there are no clouds. Therefore, in general, the greater the altitude the more intense is the insolation.

CHAPTER V

THE HEATING AND COOLING OF THE SURFACE OF THE EARTH

THERE is still another stage to consider before we arrive at the temperature of the surface air.

The air is heated and cooled not nearly so much by the direct passage through it of the sun's rays as by transference of heat through conduction and convection from the surface of the earth on which it rests, and by the radiation of dark heat rays from that surface.

Heating of the earth by insolation

The surface of the earth heats very differently under any given insolation which reaches it, according as it is land, water, ice, or snow. Land has a much lower specific heat than water, that is to say it heats and cools more rapidly, and therefore it will become hotter than water if both are exposed for the same time to the same insolation. Other influences also are at work. More of the incident light and heat rays are reflected from water than from land. Water evaporates and is cooled in the process; the evaporation on a dry spring day in England may easily cool a water surface some 15°. Water is transparent to heat as well as to light; the heat that falls on its surface is not restricted to the surface layer as in the case of land, but penetrates to a considerable depth, so that a volume several fathoms deep is slightly warmed instead of the surface layer alone being heated more intensely.

The mobility of water, both vertically in waves and horizontally in currents, also has its effect, mixing the warmer surface layers with the cooler water below, and transporting the warm water to cooler regions hundreds of miles away. The total amount of heat may be unaltered, but its distribution is very different on sea and land, the surface water which receives the insolation being kept cooler, the lower layers and distant seas warmer. The surface waters of the oceans over which the trade winds blow are of high specific gravity owing to the great evaporation. The heavy water sinks, carrying its high temperature down with it to the depths of the ocean. In the sub-tropical belt of the North Atlantic the water even at 500 fathoms is about 10° warmer than the normal (Fig. 3), and there is a similar, but smaller, excess in corresponding latitudes in the other oceans. The high salinity of the Mediterranean causes a strong current to set out into the Atlantic over the sill of the Strait of Gibraltar, and the high temperature of this water is very perceptible in the Atlantic outside the Strait from 500 down to 1,000 fathoms. We find a similar outflow from the Red Sea into the Indian Ocean. There is thus a constant removal of the heated surface water, which is distributed to great depths.

The difference in temperature from day to night is perceptible down to a depth of perhaps 3 fathoms, and that from summer to winter to about 30 fathoms in the Black Sea and the Baltic Sea, 120 fathoms off the Algerian coast and 250 fathoms in the Red Sea.

The diurnal range is about 1° on the surface in equatorial waters, and only about $\frac{1}{4}$° in the Atlantic north of the British Isles—figures strikingly different from those for land, for even in Europe the surface of the soil is often 50° warmer in the day than in the night, and in the Sahara the difference often exceeds 120°.

On land the change of temperature from day to night ceases to be perceptible about 3 feet below the surface, and the annual variation is annihilated at a depth of about 3 feet near the equator, 50 to 60 feet in middle latitudes, and about 80 feet in high latitudes.

For many reasons then water tends to be conservative, heating slowly and cooling slowly. Dry earth is at the other extreme. Wet soil is more conservative than dry, and wet forest land is still more so, for the wet leaves intercept the heat, much of which is either reflected or rendered latent in the process of evaporation.

Special considerations are involved in the case of snow or ice. In the first place such a surface is a very good reflector, and a large proportion of the solar rays is returned to space. Another important point is that a great deal of energy is required to convert ice at 32° to water at 32°, just as the change from water at 32° to ice at 32° liberates much energy.

It can be observed every winter that ponds that have been frozen during a spell of frost retain their ice long after the air temperature has risen above the freezing-point. The thaw is a long process unless the air temperature rises very high. In countries which have deep snow in winter the spring is delayed in this way, for even a warm sun cannot raise the temperature of the ground above 32° until the snow is melted. Weeks of slush and flood and cold air come

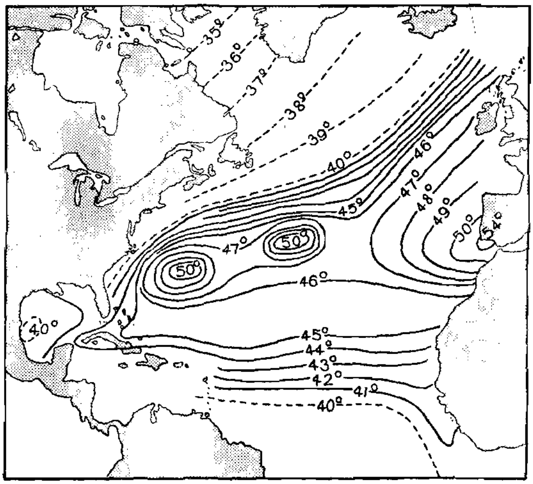


FIG. 3. Temperature of the sea at 500 fathoms

to an end in a few days when the last of the snow is gone, for then the land is rapidly heated by the sun, the air temperature rises fast and spring comes on with a rush. In the Polar regions the ice is so thick that it never melts completely; the sun's heat is used up in melting it throughout the summer, and the surface remains at, or little above, 32°. This is the chief reason for the discrepancy we have noted between the very liberal insolation at the Poles during the summer and the inhospitable air temperature. Just as ice is slow to melt, so water is slow to freeze. At night the air temperature may fall considerably below freezing-point, and yet ponds have little if any ice in the morning. Even when the water has cooled to 32°, itself a slow process, there is a long pause before it becomes a block of ice, since in freezing much heat is liberated and this counteracts the fall in temperature due to the loss of heat by radiation or conduction.

Radiation of heat from the earth

The earth is constantly receiving heat from the sun, yet it does not become progressively hotter, for the reason that it is always radiating its own heat into space, and the temperature at any time may be regarded as the balance between the heat received from the sun, and that lost by radiation into space. During the day the former is in excess and the temperature rises, during the night the latter and the temperature falls.

The rate at which heat is radiated depends upon the nature of the radiating substance. Clear air radiates its heat extremely slowly, but the rate is greatly increased if the air contains particles of dust or water in suspension. A land surface loses its heat more rapidly than water, and a snow surface more rapidly than a land surface. But it must be noted that other factors come into play as well as the rate of radiation in determining the temperature of any surface. Thus in the case of water, as soon as the surface-water is cooled it sinks owing to its increased density, and is replaced by warmer water from below, so that the change of temperature at the surface itself is very slow indeed, the effect of the radiation being spread through the whole volume. Land is exempt from this convection effect. But land surfaces themselves vary very much—a water-logged land acts almost like a water surface, but a dry sandy expanse cools rapidly. The presence or absence of vegetation, and even the colour of the surface are also controlling factors.

It is hardly necessary to point out that the loss of heat from a body can be checked by surrounding it with suitable substances which are poor conductors of heat. The earth is blanketed by the atmosphere, not a very effective blanket when the air is clear, for clear air allows the passage into space of a good deal of the heat radiated from the earth, but more effective when it contains dust or smoke particles, and still more so when water-vapour and clouds are present. The denser the air the more resistance it offers. On high mountains the rarefied atmosphere is a less effective blanket than the denser air near sea-level; consequently we are scorched by the powerful sunshine by day and frozen by the sudden and rapid cooling as soon as the sun sets.

The conditions under which there is heavy dew at night may be readily observed, and since the formation of dew is caused by the nocturnal cooling of the surface of the earth by radiation of its heat the amount of dew depends, other conditions being the same, on the rate of radiation. Dew is heavy on a night when the sky is clear, but there is little or none in cloudy weather. Cloudy nights are warmer than clear ones, especially in winter. If the temperature of the radiating surface is below freezing-point the vapour in the air condenses in ice-particles, forming the deposit we call hoar frost; there is hoar frost not infrequently when the air temperature 4 feet above the ground is above freezing-point.

In the orchards of California frosts sometimes occur on spring nights when other circumstances are favourable, owing to a very clear sky permitting such a rapid loss of heat that the ground is cooled considerably below freezing-point, and in turn cools the surface layers of air to a point low enough to ruin the fruit blossom. As a preventive stoves have been installed on many orchards to produce great volumes of smoke. They are lit when frost threatens, and in most cases the smoke-screen blankets the region sufficiently to ward off disaster.

The atmosphere may be likened in this connexion to the glass roof and sides of a hothouse. The glass allows the light rays of the sun to enter, but it obstructs the outward passage of the dark heat, into which the light rays are converted, from the inside that has been warmed by the sunshine. The glass acts as a valve, not a very efficient one, and the inside of the house becomes warmer and warmer. Similarly the atmosphere is much more transparent to the light heat rays coming direct from the sun, than to the dark heat radiated from the earth.

CHAPTER VI

THE MEASUREMENT OF TEMPERATURE; MEANS AND EXTREMES. ISOTHERMS

As the succeeding chapters on temperature will deal chiefly with air temperature, it is desirable at this point to explain how the temperature of the air is taken.

In order that the records may be strictly comparable it is essential that thermometers be of standard pattern, and exposed under standard conditions; otherwise discrepancies are introduced which are merely adventitious, and without general climatic interest. In most countries the thermometers are enclosed in a 'Stevenson Screen', a wooden box with a double top, and double-louvred sides, the whole painted white. The air can circulate freely, but the direct rays of the sun do not reach the instruments. The screen is set on a stand so that the bulbs of the thermometers are 4 feet above the ground, and it should be placed in a fully open position, away from trees and buildings; the ground below should be turf-covered. Unfortunately the standard screen is not used universally even in Europe. In the tropics other forms are commonly used, consisting of a large thatched shelter under which the instruments are hung, freely exposed to the air but well protected from the rays of the sun; in India, however, the Stevenson screen is replacing the thatched shelter. In Egypt so intense is the sunshine that extra ventilation has to be provided in the sides of the screen to prevent excessive heating. The screen should contain at least four thermometers. Two are standard mercury thermometers of identical pattern, one of which has its bulb covered with thin muslin kept wet by a wick dipping in a small vessel of water. The dry bulb instrument gives the air temperature, and the difference between the readings of the dry bulb and the wet bulb enables the humidity of the air to be determined by means of tables. The other two thermometers are self-recording, maximum and minimum. All the instruments should have certificates showing the correction, if any, which must be applied to the readings.

The dry and wet bulb thermometers should be read at least twice daily if it is desired to establish the climate of the station. 9 a.m. and 9 p.m. are the hours adopted for Normal Climatological Stations in the British Isles. Three observations daily, at 7 a.m., 1 p.m., and 9 p.m. are preferable.

The maximum and minimum thermometers record automatically the highest and the lowest temperatures that have occurred since they were last set. They are read and set each morning. They are very useful instruments not only because the highest and lowest temperatures are in themselves important, but also because they enable the mean temperature of the day to be readily calculated, for the sum of the maximum and minimum readings divided by 2 gives a good approximation to the mean temperature for the day.

If possible the screen should contain a thermograph, a self-registering thermometer, which, by means of a pen resting on a chart, gives a continuous record of the temperature by day and by night (e.g. Fig. 15). The ordinary forms of the instrument are not so accurate as mercury thermometers, but they give most valuable information about rises and falls of temperature which would escape our notice if we were limited to the usual two or three eye-readings of the mercury thermometers each day, and for many purposes it is more interesting to know when the temperature changed and by how much than to have the exact readings at stated hours.

A grass minimum thermometer is a useful addition to the equipment. It is an ordinary minimum thermometer without any back or frame, and it is set on the ground with the bulb just clear of the grass, in a fully exposed position. Its readings compared with those of the screen thermometers give interesting information about the rate of the radiation of heat from the surface of the ground.

In climatic descriptions quantitative statements of the elements are essential. The mean values must be given, and since weather is very variable a long series of records is necessary to establish the mean, 35 years being generally considered desirable since there appears to be a fairly definite weather cycle of that length. The arithmetical mean of the 35 yearly values is the annual mean for the period.

Similarly monthly and seasonal means are obtained. Means for shorter periods, weeks for example, are not usually given as the gain is outweighed by the practical difficulties of such numerous statistics.

Account must be taken of extremes as well as of means. We should know at any rate the highest and the lowest temperatures that are likely to occur each day in a given month (called the mean daily maximum and mean daily minimum temperatures), and the highest and lowest temperatures likely to occur in the whole month (called the mean maximum and mean minimum monthly temperatures). The former are obtained by taking the means of the maxima and minima respectively for each day in the month for the period of observation, the latter by taking the means of the one highest and one lowest reading in the month for the period. It is evident that the actual readings may depart considerably from the means. Perhaps a more useful statement would be the number of times that maximum readings between 70° and 75°, 75° and 80°, 80° and 85°, &c., have occurred at the station in the month during the period of observation, and similarly with the minima and the diurnal means. But the calculation is laborious and the resulting tables are rather too voluminous for practical convenience.

The highest and the lowest readings ever recorded in each month for the period of observation should be included in the statistics. They are called the absolute maximum and the absolute minimum, and they are useful provided that the observations have been carried on long enough; the longer the period the higher the absolute maximum and the lower the absolute minimum will turn out. A period of 10 years is too short to give comparable extremes.

The range of temperature is the difference between the highest and lowest readings in the period. The range for any day is got by subtracting the minimum reading for that day from the maximum. The mean range is the difference between the mean maximum and the mean minimum. Thus the mean daily range for a given month is the difference between the mean daily maximum and the mean daily minimum for that month. The mean annual range is the difference between the mean temperatures of the warmest and the coldest months. Similarly the extreme ranges may be obtained. The absolute (extreme) annual range at Kew is 91° since the absolute maximum reading recorded is 100°, the absolute minimum 9°.

The following table gives these statistics for Oxford:

RADCLIFFE OBSERVATORY, OXFORD, Alt. 212 ft.

TEMPERATURE

	Period.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year.*
Mean	66 years	38·7	39·7	41·7	46·9	52·7	58·5	61·4	60·7	56·4	49·5	43·0	39·9	49·1
Mean max.	66 years	52·6	53·7	59·2	66·6	73·6	78·8	81·3	79·2	73·5	65·2	57·4	54·2	66·3
Mean min.	”	21·7	23·3	25·0	29·5	33·7	41·2	45·3	44·1	38·1	31·5	26·2	22·0	31·8
Mean daily max.	70 years	43·5	45·2	48·9	55·5	61·8	67·6	70·7	69·6	64·7	56·4	48·4	44·5	56·4
Mean daily min.	”	34·4	34·7	35·5	39·1	44·1	50·0	53·3	52·9	48·9	43·5	37·8	35·2	42·4
Absolute max.	1852–1927	56·9	61·0	66·7	77·8	85·6	90·0	93·1	92·6	89·2	80·9	63·9	59·0	93·1
Absolute min.	”	5·8	7·5	13·0	23·7	27·7	35·9	36·3	32·4	32·4	21·7	15·7	0·0	0·0
Mean daily range	70 years	9·1	10·5	13·4	16·4	17·7	17·6	17·4	16·7	15·8	12·9	10·6	9·3	14·0
Absolute range	1852–1927	51·1	53·5	53·7	54·1	57·9	54·1	56·8	60·2	56·8	59·2	48·2	59·0	93·1

Even 35 years' observations are not available for all stations. Records for shorter periods diminish in value in proportion to their length, and the variability of the climate, but very often 20 years' records have to be accepted. Means for even 5 years are approximately correct for the monotonous equatorial region, but are liable to considerable error in the variable temperate latitudes. It is possible to obtain a close approximation to the true means for a station with, say, only 10 years' records by comparing its records with those of another station with records for 35 years which include the 10 years of the first station's records, if the second station is in the same meteorological region and not very far away from the first. The records for the 10 years that are common to the two series are compared and the difference established for the year and the several months; it may be assumed that the difference for the whole 35 years is the same as for the 10 years, and thus the 35 years' means can be obtained for the first station. This procedure is justified by the examination of many simultaneous long-period records. But if the two stations are in different meteorological regions the method fails, for there is no necessary parallelism between the records.

Isotherms—their Uses and Limitations. Kind of Heat

The distribution of temperature is most conveniently shown by isotherms (Figs. 4 and 5). An isotherm is a line drawn through places which have the same temperature, just as the contour lines of our topographical maps are lines drawn through places of the same altitude. The isotherms may show the temperature at any given moment, or for any given period, a day, a week, a month, or they may show the mean temperature for any period; mean monthly and mean annual itotherms are frequently used. Again, isotherms may show actual temperatures as observed, or temperatures 'reduced to sea-level'. The changes of temperature with altitude are explained in Chapter XXXIX; it is found that on the average an elevation of about 300 feet lowers the mean temperature 1° F. This control by altitude is stronger than any other, and unless it is eliminated the isotherms follow almost exactly the contour lines, so for many purposes it is convenient to eliminate it by adding to the observed reading 1° F. for each 300 feet. The corrected figures are used for drawing the isotherms which then show the effect of the other factors which are masked by altitude, and such isotherms are especially instructive in theoretical investigations. But we must not forget that except in lowlands they give little useful indication of the climate since the all-important effect of altitude is ignored. Over great areas of plateau, for example in Asia and Africa, the actual mean temperature is at least 10° lower than the sea-level isotherms show.

Maps of isotherms are so graphic that they sometimes give erroneous impressions in other ways also, and a warning is necessary as to the limitations of what is expressed by mean isotherms. Two stations which are on the same mean monthly isotherm certainly have the same mean temperature

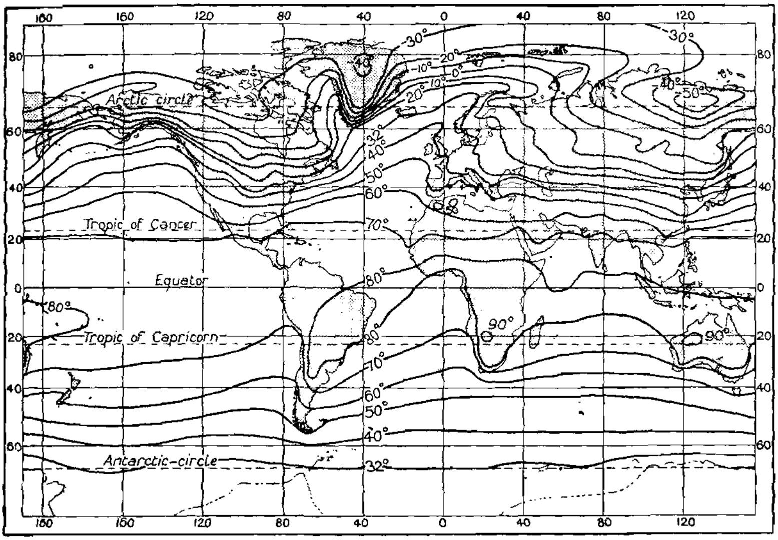


FIG. 4. Mean Temperature, January

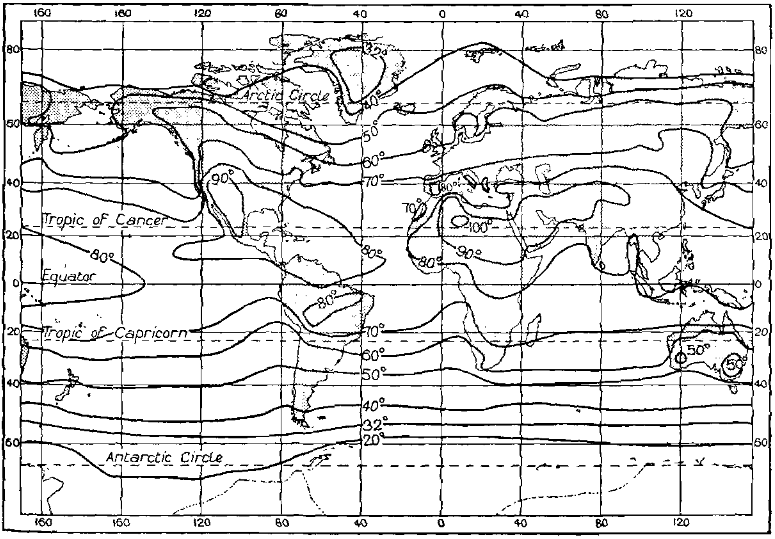


FIG. 5. Mean Temperature, July

for the month, when allowance is made for any difference in altitude. But the actual sensible temperatures at the two places as experienced from day to day may have more points of difference than of resemblance. The Orkney Islands and the north of the Aegean Sea have the same mean temperature, 40°, in January. But there the resemblance ends. The Orkney Islands have an abnormally high mean because of the strong and almost constant south-west winds which sweep over them after a long passage over an ocean which is remarkably warm for the latitude. The sky is very cloudy, and the sunshine scanty. There is little gain of heat in the daytime through sunshine, little loss at night through radiation. The duller the sky and the stormier and damper the weather, the warmer it is. The heat is essentially imported from tropical regions by both air and ocean currents. There are no great extremes of either heat or cold. But in the Aegean a day without sunshine is rare and the warmth is largely due to the sun's rays, both direct and reflected from the sea. The nights are correspondingly cold since heat is lost rapidly by radiation in that region of clear sky and dry air. Thus the typical weather is much warmer by day (and warmer with the bright and exhilarating rays of the sun), and colder at night than in the Orkneys. Also greater variations from the mean may occur. Sometimes cold waves sweep down from the steppes of Hungary and snow and frost are prominent but unwelcome visitors on the sunny coasts of the Aegean. Or again, the 'sirocco' wind, originating far south in the Sahara and charged with moisture during its passage of the Mediterranean, may bring muggy weather, unpleasantly damp and warm. To say nothing of the other elements of the climate, the differences in the temperature conditions are really more important than the one similarity that the mathematical mean of the readings for 30 Januaries is the same at the two places.

This same isotherm of 40° for January is responsible for misleading ideas on the climate of the British Isles. The fact that it crosses the north of Scotland and the Isle of Wight does not imply that the actual temperatures from day to day in the two districts are the same.

Again we must not think that in months for which the mean temperature is 80° in the Congo Basin and in the Sahara these places have even approximately the same conditions.

CHAPTER VII

AIR TEMPERATURE

THE air is heated and cooled only to a slight extent by the direct passage of the sun's rays, and by the radiation of heat from itself. Its temperature depends chiefly on conduction from the surface on which it is resting.

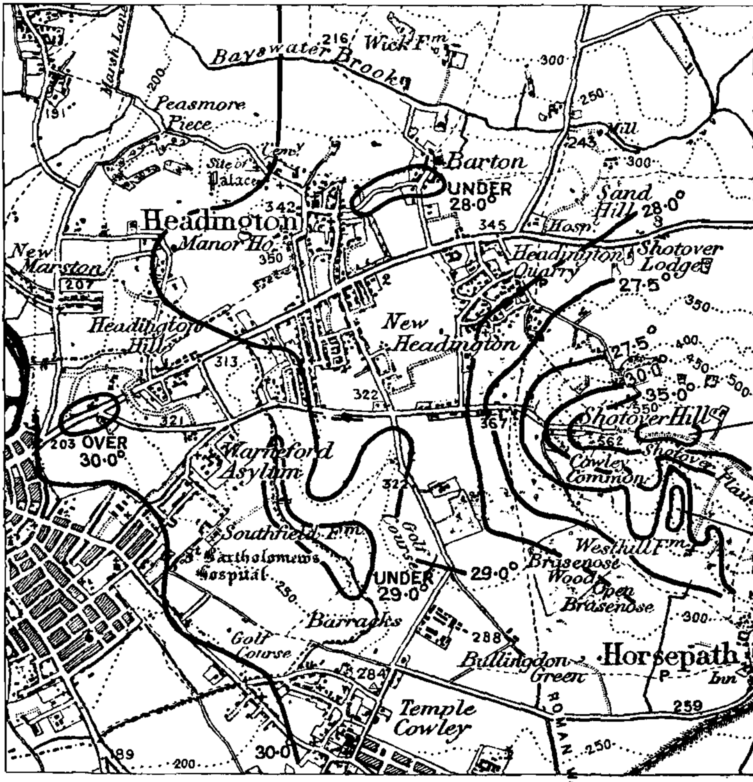
The air is warmest not at noon but during the afternoon, for the earth still continues to heat when the sun is already sinking. On land the warmest hour of the day is 2 p.m., but on the sea about 3 p.m. For a similar reason the warmest month of the year in the northern hemisphere, outside the tropics, is July on land but August on the sea. The coolest time of day is just before sunrise, when radiation without compensating insolation has had its longest effect; and the coolest month is January on land, February on the sea. On individual days and in individual years there may be considerable irregularities owing to the passing weather conditions. In temperate latitudes it is not uncommon in winter for the night to be warmer than the day, and other peculiar diurnal temperature curves are mentioned later.

Topographical Control of Air Temperature

As the air is heated and cooled chiefly by contact with the earth, evidently its temperature changes will tend to be greatest when the surface of contact is greatest, that is to say in basins and valleys; and the changes will be least over a convex surface, and at a minimum over a sharp mountain summit. The bottoms of mountain valleys thus tend to have extremes of heat and cold, as do extensive land masses; but on mountain peaks the small range of air temperature (this must not be confused with the temperature of solid objects exposed to the sun's rays) is suggestive of oceanic conditions. In the free atmosphere a mile above the earth there is no appreciable change of temperature with day and night.

Temperature Inversion

An interesting condition is 'temperature inversion'. The air that is chilled by resting on a surface which is losing heat through nocturnal radiation tends, in the absence of disturbance by wind, to sink to the lowest level possible. Thus in calm weather there is a steady drainage of the coldest air into the valley bottoms and other depressions.



Oxford University Press]

FIG. 6. Air Temperature, Feb. 13, 1913, 6 a.m. (Based upon the Ordnance Survey Map with the sanction of the Controller of H. M. Stationery Office.)

This occurs especially among mountains, since the higher valley sides and the mountain summits are but thinly blanketed by the rarefied atmosphere, and the steep slopes provide ready drainage for the cold air. The valleys become filled with lakes of cold and damp air, while the upper slopes are much warmer, since the chilled air drains away and is constantly being replaced by warmer air from the atmosphere above. Obviously any concave land form will tend to collect cold air at night. And it does not require any great altitude to produce this effect. It can be observed on almost any clear calm night wherever there is a difference of a hundred feet between adjacent tracts of land. As we come down from the higher levels where it is still warm and dry we seem to be entering a bath of cold damp air below. The effect is most marked in the long winter nights, when the lower levels may often be filled with a cold fog, so thick that it is not dispersed even by day. This is perhaps the most important of the differences in climate between the low plains and valley bottoms and the uplands in regions of small relief such as the south-east of England. Unfortunately most towns lie on the lowest ground, and are often enshrouded in cold damp or foggy air during the nights while the neighbouring heights, even if only two or three hundred feet higher, are comparatively warm and dry. The smoke from the chimneys of the towns is another drawback, for it discolours the fog, and in large towns it may help to form black fogs, the well-known fogs of London being the best example. In many districts the average night temperature in winter is lower at the low levels than on the slopes or plateaux which lie higher but are so placed that the chilled air drains away. This is the case especially in calm regions normally dominated by anticyclones, such as central Europe. The mean temperature in January is 34·4° at Lugano, situated 902 feet above the sea on the southern slopes of the Alps overlooking the Plains of Lombardy, but only 32·4° at Milan 482 feet above the sea but lying on the Plain. Generally the temperature inversion during the nights is much more marked than the mean figures for the month indicate. It is most striking during spells of still anticyclonic conditions in winter. Mountain summits may then be enjoying cloudless skies, with intense sunshine by day, and dry warm air with bright stars at night, while the valleys thousands of feet below are shrouded in a thick stagnant fog, unrelieved by a beam of sunshine, at a temperature far below freezing-point. The following figures are for the summit of the Puy-de-Dôme, an isolated volcanic cone 4,823 feet above the sea, and Clermont Ferrand, a town in the bottom of the Allier Valley, only 10 miles from the mountain and 1,280 feet above the sea. The weather was controlled by a large anticyclone, with fog on the lowlands.

Dec. 20–8, 1879. 6 a.m.

	Temp. °F.	*Rel. Humidity.*
Puy-de-Dôme	38·9	38%
Clermont	8·2	91%

Even lesser heights may produce similar effects, as was shown by observations made in the Oxford district, in February, 1913. An extensive anticyclone covered England and the neighbouring parts of the Continent, and by February 12 Oxford and the surrounding plain was enveloped in a thick fog, the air being quite calm. The temperature in Oxford at 6 a.m. was 30°. But Shotover Hill, an upland some 350 feet above the city and 3 miles east of it, was high enough to project above the lake of fog; the air was clear and comparatively warm, the grass sparkled with hoar-frost and the stars twinkled brightly in the sky; the temperature was 40° (Fig. 6). In the bottom of a combe in the south side of the hill, only 180 feet below the summit and not half a mile distant, the temperature was as low as 26°, and there was a thick fog.

To illustrate further the conditions in the scarplands of the south of England, a region of weak relief, there are observations available from Oxford, 208 feet above the sea, lying in the midst of the wide expanses of flood-plain in the middle Thames valley, and Leafield, 612 feet, situated on an open limestone plateau of the eastern Cotswolds, 15 miles north-west of Oxford. The mean monthly temperatures are always higher at the former station, but the excess in the mean daily minimum is much less in winter (0·9° in December) than in summer (2·5° in August); during the cold winter nights there is sometimes an inversion of temperature, Leafield being warmer than Oxford as, to take an extreme case, on February 17, 1924, when the screen minimum was 30° at Leafield, 21° at Oxford. The day maxima are almost always higher at Oxford, and the mean excess is about 2·5° all the year; Leafield very rarely, if ever, has a higher

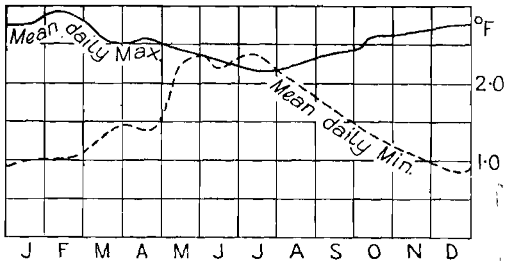


FIG. 7. Temperature difference, Oxford–Leafield; 6 years means, smoothed curves

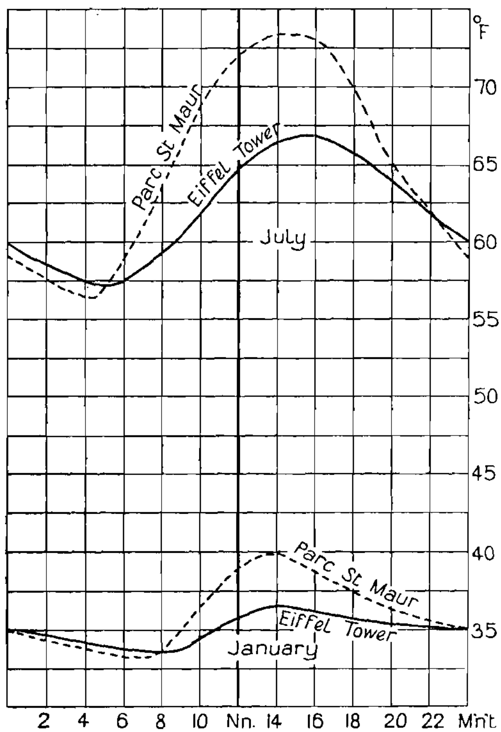


FIG. 8. Mean diurnal temperature curves for Parc St. Maur, Paris, and the top of the Eiffel Tower

maximum than Oxford. Fig. 7 shows the mean difference between the stations in the maximum temperatures and the minimum temperatures. The difference in the maximum remains nearly the same throughout the year, but the difference in the minimum is only half as great in winter as in summer.

Observations on the top of the Eiffel Tower, Paris are available for comparison with those in Paris itself (Fig. 8). The top of the Eiffel Tower gives the conditions of the free atmosphere 1,000 feet above the city except for the slight influence of the ironwork of the structure itself. In the first place it is clear that the mean range of temperature from day to night is much greater on the surface of the earth than aloft, both in summer and winter. Secondly, the higher station is warmer during the night than the lower, in July between 10 p.m. and 4 a.m. and in January between 1 a.m. and 8 a.m., even when the mean temperatures are considered; in favourable conditions the difference in favour of the higher station is much greater, but on the other hand the lower station is warmer in windy and cloudy weather. Thirdly, we notice that in summer the warmest hour on the Eiffel is 4 p.m., but in Paris 2 p.m.

The chilling of the ground at night is very striking in low latitudes, especially in elevated positions. At Simla, 7,232 feet, the hill station in the Himalayas, ice fit for skating is available in December, though the standard air temperature has never been known to fall below 40°. At Baguio, 4,800 feet, lat. 16½° N., in the Philippine Islands, ground frost is not infrequent in winter in the hollows, and ice forms on still water, even when the standard air temperature on the flat plateau is as high as 45°.

Snow is the best radiating surface, and the lowest temperatures known are generally due to radiation from a snow-covered land during long clear winter nights. The surface becomes very cold, for the underlying body of snow is a poor conductor, owing to the presence of a large volume of air in its interstices. Consequently though the surface of the snow, and the atmosphere resting on it, may be very cold the ground on which the snow is lying is protected by it, and may be little below freezing-point. Even a thin blanket of snow is effective. On February 5, 1917, at 9.30 a.m., the ground at Oxford was covered with 2½ inches of dry snow, and the temperature of its surface was as low as 15°, for the sky was very clear, and heat was still being lost rapidly though the sun had risen. On the ground under the snow the temperature was 29°, and on bare ground from which the snow had been swept some time earlier the reading was 20°. These effects are much more marked in the interior of a continent in high latitudes, for the snow covering is deeper and more continuous and the nights are longer. The lowest temperatures recorded on the earth are at Verkhoyansk in Eastern Siberia, a village situated almost on the Polar circle in the bottom of a steep-sided valley incised in the plateau. The air sinks into the valleys when it is chilled by contact with the snow, which loses heat extremely rapidly by radiation owing to the clear and dry atmosphere and almost cloudless sky, the loss continuing through the long Polar night. The remarkably low readings for which Verkhoyansk is known are thus largely 'inversion' effects and are typical only of the valley-bottoms.

In general, then, the lowest temperatures are likely to occur during long winter nights in valley-bottoms when the ground is snow-covered so that heat is rapidly radiated, the atmosphere clear so that the heat rays can pass out, and the air calm so that the coldest layer remains on the ground. Temperature inversion is of great practical importance in agriculture. Frosty nights in spring after vegetation has got well started are one of the farmer's greatest dangers. In some of the coffee-growing districts in São Paulo, Brazil, the bottoms are often avoided and the higher slopes of the valley sides used for the plantations.

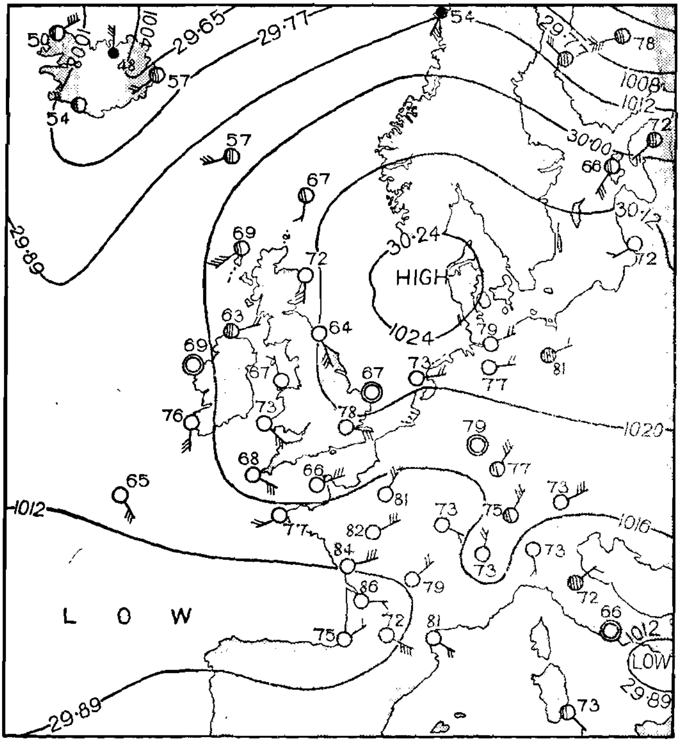
Quite a different type of temperature inversion occurs in the fogs of the Grand Banks and similar tracts (p. 216).

Convection over a heated surface

As the air is heated by contact with hot ground it rises—the shimmering of the distant landscape on a hot day is the effect of the rising currents—and cooler air from above takes its place, to be warmed in turn. Hence under ordinary conditions a considerable depth of air will be warmed to a moderate degree, and the surface layer will not become unduly hot. The rate of convection will depend not only on the temperature of the air which is warmed by the earth, but also on the temperature of the overlying strata. If the latter are unduly cold convection will be more active and the surface air will not remain long enough in contact with the earth to be much heated. These conditions are often found in the rear of a cyclone. The sky may be cloudless and the insolation powerful. Yet the air temperature remains low, since the higher strata of the atmosphere are colder than usual, and vigorous convection currents are set up. The strong wind that will probably be blowing also helps to mix the air and diffuse the heating through a large volume. The rapid convection becomes visible in the formation of cumulus clouds which may give passing showers. Thus the higher the temperature on the surface of the earth becomes, the more it tends to bring about its own annihilation, both by convection, and also by the inflow of cooler air from round about which is a result of the ascending convection currents. Cold, on the other hand, tends to persist and be intensified, since it causes stable equilibrium, and also because it favours high-pressure conditions, with clear air and cloudless skies which favour loss of heat by radiation; but in this case, too, the process provides its own check in that the high pressures give rise to outflowing currents which remove the cold air.

The opposite conditions are sometimes experienced, the higher strata being unusually warm. Convection is then less rapid, the heated surface air is not so rapidly removed and becomes abnormally warm. The warm upper strata may be regarded as a ceiling, which hinders the vertical movement. We have an example of this in July 1926. On July 11 maxima of 81° and 82° were recorded in the south of England; on the 12th it was warmer, and on the 13th still warmer, the sky being almost cloudless, and many parts of the country having more than 12 hours of sunshine. Next day, July 14, was again remarkably cloudless, and even longer sunshine records were obtained; the temperature in the south of England was the highest during the spell. An anticyclone had spread north-eastward from the Azores, and covered France and much of Central Europe, becoming centred over north Germany and the North Sea on the 12th, 13th, and 14th. The wind over England was light from the south-east (Fig. 9), bringing warm air from the Continent.

But an additional cause of the great heat was the abnormal warmth of the upper air. On July 12 the air between 7,000 and 16,000 feet over the south of England was warmer



BAROMETER.—Isobars are drawn for intervals of four millibars.
TEMPERATURE.—Given in degrees Fahrenheit.
WIND.—Direction is shown by arrows flying with the wind. Force, on the scale 0 to 12 by number of feathers. Calm ◯
WEATHER SYMBOLS.—◯ clear sky; sky ¼ clouded; sky ½ clouded; sky ¾ clouded; overcast sky; ● rain falling; ✳ snow; ▲ hail; ≡ fog; ≡˙ mist; T thunder; thunderstorm;

FIG. 9. A day of very high temperature in north-western Europe, July 13, 1926, 6 p.m.

than ever before observed, and next day it was warmer still, the temperature being 47° at an altitude of 12,500 feet above Lympne, this being 25° over the mean for the month. The result was that convection was almost, or entirely, stopped, and the superheated surface air was not removed. Moreover, none of the usual convection clouds of summer formed, and therefore the sun shone powerfully all day, intensifying the already high surface temperature.

Thus the surface air temperature is controlled not only by the transparency of the upper strata of the atmosphere but also by their temperature thousands of feet above the earth.

CHAPTER VIII

'IMPORTED' TEMPERATURE

So far we have considered how the air temperature is controlled on the spot by the balance between the local insolation and radiation, and the resulting vertical currents.

But the temperature is largely 'imported' from the surrounding regions. The wind may arrive hot or cold, for the moving air retains the temperature of its place of origin, modified by the influences to which it has been submitted during its journey. This is especially important in winter in temperate latitudes when the local control by insolation is weak, the wind strong, and there are normally great differences of temperature within short distances.

Let us consider an actual case. On December 12, 1924, an anticyclone had been lying over Europe for some days; radiation had been favoured by the clear skies, the calm air had become cold, and finally a thick fog covered a wide area of West and Central Europe and south-east England, with temperatures below freezing-point in the daytime as well as at night. But by 6 p.m. on December 12 (Fig. 10) a deep depression had appeared near Iceland, and the barometric gradient was steepening over the British Isles for southerly winds. In the south-east of England it was still cold, 39° at London, 34° in Norfolk, but in the west the temperature had risen to 51° at Pembroke, 54° at Valencia, 53° at Stornoway. In the former region the air was being drawn from the frost-bound continent, while in the west the wind had travelled thousands of miles over the warm ocean, having come originally from the south-west before its course changed to north. Furthermore, the wind here was strong, about 20 m.p.h. at Valencia; but in south-east England there was only a light breeze, and the surface air, chilled by radiation from the ground, was less mixed with the warmer air above.

Fig. 108, p. 287, is another good example. The south-east of England is in the grip of icy winds, reaching gale force in places, blowing from Central Europe which had been

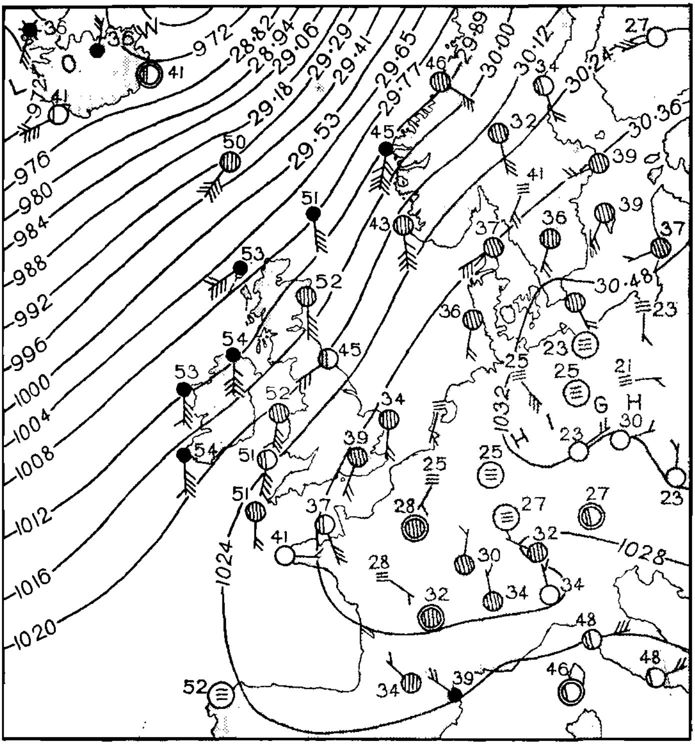


FIG. 10. December 12, 1924, 6 p.m. For meaning of symbols see Fig. 9, page 33

experiencing a spell of intense cold for several days previously; these winds were south and south-east. The south-west of the British Isles is more than 20° warmer, with northerly winds derived from the comparatively warm North Atlantic.

A light breeze is usually as effective a transporter of cold as a strong wind. The cold air is a shallow surface layer, and if the wind is strong it is churned up with the warmer strata above, and so becomes warmer. On the other hand a light breeze is more susceptible to the conditions of the regions it crosses in its passage, owing to the longer contact.

Trajectories of Air Currents

The wind frequently changes its direction during its journey, and indeed it rarely travels far in a straight line. The place of origin can seldom be found by simply tracing a straight line backwards into the wind direction at any station. Fig. 11 gives some actual courses traced back for several days. A low-pressure system is east of Newfoundland, and an anticyclone south-west of Spain. The trajectory lettered A shows how air started as a north wind among the ice-floes off Greenland, but performed a large circuit, and appeared as a south wind off Ireland after a journey of some 5,000 miles. In Fig. 12 trajectory B starts in the same region as A, but it continues south, and brings Arctic air beyond the Cape Verde Islands. Trajectory C carries warm air far north into Davis Strait. Between these two wind currents there is a large anticyclone.

Quite different temperatures and humidities may therefore be brought by winds which have the same direction at the place of observation. In the British Isles in winter a south wind is sometimes cold and dry, sometimes abnormally warm and moist. It is cold and dry if it originates in an anticyclone in Central or Eastern Europe, where the ground is snow-covered, and the air temperature very low; the air in this case starts its journey as an east or south-east wind, and becomes a south wind later, in obedience to the barometric gradients. The warm and moist south wind on the other hand may originate over the warm Atlantic Ocean, a thousand miles or more to the south-west of the British Isles. The mere direction of the wind at any station cannot tell us much about its qualities, which are determined by its past history.

In winter the continent of Europe is usually cold, often very cold, but in summer it is warm or hot. Hence a wind blowing from it will be cold in winter, warm in summer. The north-east of the Atlantic Ocean is very warm for its latitude in winter, and a wind that has blown far over it will be warm. In summer, however, the ocean is relatively cool for its

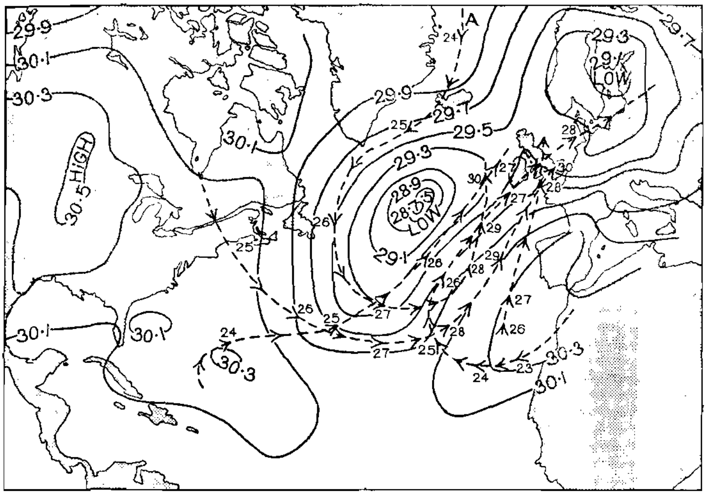


FIG. 11. The isobars are those for noon (GMT), December 26, 1882. The arrowheads on the trajectories (broken lines) with figures against them indicate the position of the air at noon on the dates (in Dec. 1882) indicated by the figures. The intervening arrowheads indicate the position at midnight (Shaw)

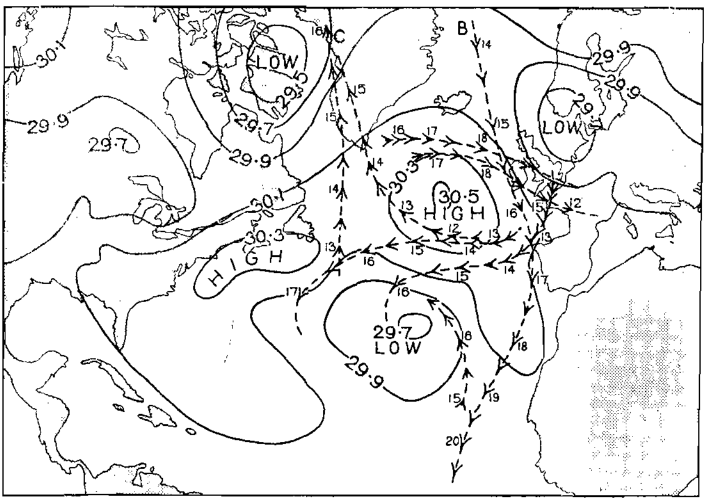


FIG. 12. The isobars are those for noon (GMT), June 16, 1883. The arrowheads on the trajectories (broken lines) with figures against them indicate the position of the air at noon on the dates (in June 1883) indicated by the figures. The intervening arrowheads indicate the position at midnight (Shaw)

latitude. The North Sea is cooler in all seasons than the Atlantic Ocean.

We may here conveniently sum up the conditions for an abnormally hot day in England. The sky must be clear and cloudless, allowing the full force of the summer sun's rays to pour down to the earth. The ground should be dry, and already warmed by previous hot days. The atmosphere should be calm so that the same air remains in contact with the heated ground, or at most let there be a slight drift from the south. And the upper atmosphere must be warmer than normal, so that the super-heated surface air may not be removed and dissipated by convection. All these conditions are not very often realized simultaneously.

The direct influence of a neighbouring cool or warm surface, land or water, is important only when the prevailing winds blow over it. The temperature of Western Europe is controlled very largely by the Atlantic Ocean since the prevailing winds are from the west. China has very cold and dry winters for its latitude because its prevailing winter winds blow from the bitterly cold plateaux of North and Central Asia; the warm waters of the Kuro Siwo bathe its coasts, but have little effect on the temperature since the winds are off-shore. But on the other side of the Pacific the westerlies arrive warm and damp from the ocean, and give remarkably mild winters to the North American coast. The great lakes of North America have an appreciable effect on the temperature of their leeward, eastern, shores. Thus the mean date of the first killing frost in autumn in the interior of the peninsula of Michigan is September 21, but along the east shore of Lake Michigan it is after October 11.

Generally speaking the influence of a warm ocean extends further inland than that of cold water; the reason being that the cold water is usually only a narrow strip along the coast, and the on-shore winds which carry its chilling influence do not penetrate far inland. The coast of South-west Africa affords an example. The Benguela current which washes it is a very cold current for the latitude, but the cold damp air derived from its surface does not make its way more than some 50 miles inland, usually not so far, for the on-shore winds are of the nature of a sea-breeze. On the other hand the warming influence of the North Atlantic Ocean, carried inland by the prevailing westerlies, is strongly felt over most of Europe and can be traced in Western Asia.

The well-known 'cold waves' of the American winter illustrate excellently the importation of thermal conditions. These winds may originate on the High Plains which lie on the east of the Canadian Rockies, where the air has been lying stagnant for days, becoming colder and colder under the clear skies of an anticyclone in the interior of the Continent, and the temperature may have fallen to -20° F. or lower. A cyclone now appears over the United States, and the air is drawn south, the cold flood sweeping forward sometimes as far as the Gulf of Mexico. The air will not be as cold after its journey as when it started, for the local conditions encountered on its passage, and the churning of the lower and higher strata of the atmosphere will have warmed it; but still the cold wave well deserves its name; zero temperatures have occurred only a few miles from the coast of the Gulf of Mexico. An interesting local effect may be mentioned. Sometimes these cold waves pass over the Great Lakes; even in the depth of winter most of the surface away from the shores is open water and the winds are so much warmed by their passage that the south shore sometimes has a temperature 20° higher than the north shore.

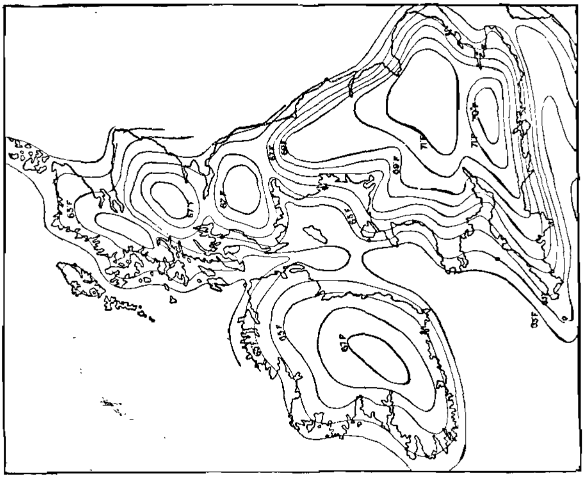
Extreme Heat and Cold

The highest temperatures on the earth are recorded in summer in the trade wind deserts, and the lowest readings occur in winter in the interior of the great land masses in high latitudes. The latter fall considerably more below the mean for the station than the former rise above it.

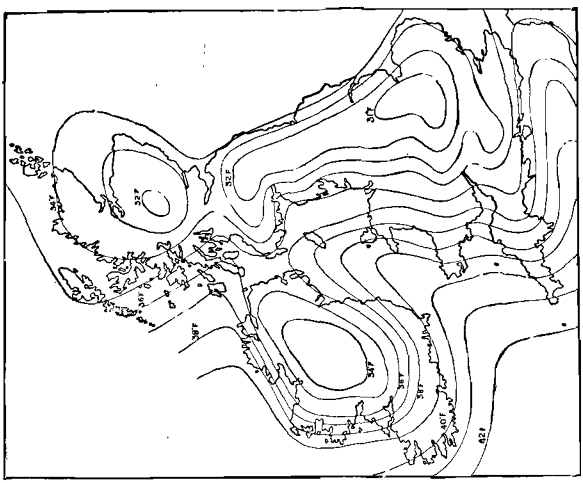
There are two main reasons for this. Firstly, inside the Polar circles there is at least one day of the year on which the sun does not appear above the horizon, and the loss of heat continues throughout the 24 hours. Compare with this long period of cooling the heating process in low latitudes. However fierce the burning rays of the summer sun may be they are interrupted by the on-coming of night, and the clear sky that gave passage to the sun's heat by day is at night equally favourable to the loss of heat by radiation from the earth. Secondly, cold air is in stable equilibrium; the greater the cold the greater the density, and the air remains stagnant in the lowest levels unless it is displaced by still colder air draining down the surrounding slopes. Only a strong wind in the higher atmosphere can succeed in extending by eddy action down into the dense cold surface air so as to mix it with the warmer air above. These lakes of cold and almost stagnant surface air thus often become colder and colder for weeks, and extraordinarily low temperatures are attained in north-east Siberia, north Canada, Greenland, and Antarctica. Let us now compare the conditions in the hottest parts of the earth. As the air heats its density becomes less, equilibrium becomes unstable and convection currents begin to carry the superheated surface air upwards, to be replaced by the air of the higher atmosphere which is at a normal temperature. The hotter the surface air becomes under the rays of the sun, the more vigorously does it bring about its own removal by convection. The heat instead of being confined to and intensified in a shallow surface stratum, as is the cold in the Polar winter, is diffused through a thickness of some thousands of feet of the atmosphere, and carried off by the strong winds. Hence in spite of the powerful rays of the overhead midday sun the air temperature rises much less above the mean than the Polar winter minima fall below the mean for the latitude.

To illustrate these facts we may take Verkhoyansk just inside the Arctic circle in north-east Siberia, the station with the lowest temperatures recorded, and Insalah, an oasis in the Algerian Sahara, one of the hottest parts of the earth in summer. At Verkhoyansk the mean temperature for the year is 3°, the mean for January −59°, and the lowest record −83°. At Insalah the mean for the year is 77°, the mean for July 98°, and the highest record 129°. While at Verkhoiansk the mean temperature of the coldest month is 62° below the mean for the year, and the absolute minimum 86° below, at Insalah the mean temperature of the warmest month is only 21° above the mean for the year, and the absolute maximum temperature only 52° above.

PLATE 2



b. Mean daily maximum temperature in July



a. Mean daily minimum temperature in January

Continentality and Temperature

To show the effect of increasing distance from the windward ocean in a land mass we give in Fig. 13 curves of mean temperature for a series of stations, all in approximately the same latitude, in North America. Eureka has the warm winters and small range to be expected on a windward western seaboard; its cool summers are due largely to the

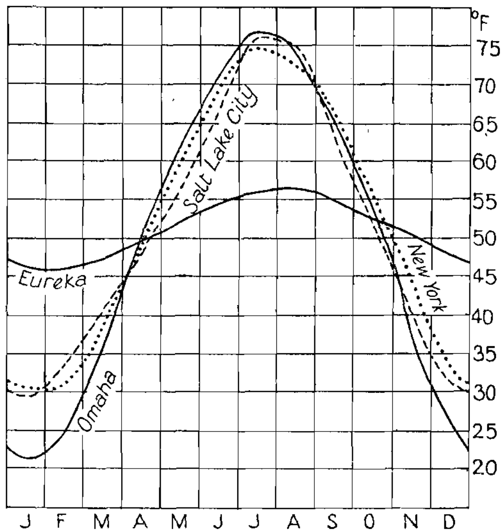


FIG. 13. Mean Temperature

frequent fogs of that fog-bound coast washed by the cool California current. Salt Lake City is 4,366 feet above the sea, but it is as warm in summer as Omaha (1,103 feet, in the middle of the continent) owing to the clear dry air and strong sunshine, and in winter it is considerably warmer, partly owing to being nearer the Pacific, partly owing to the influence of the Lake. New York on the east coast and Salt Lake City have very similar curves.

Plate 2 shows strikingly the effect of continentality in the British Isles, the interior having appreciably warmer days and cooler nights than the coasts.

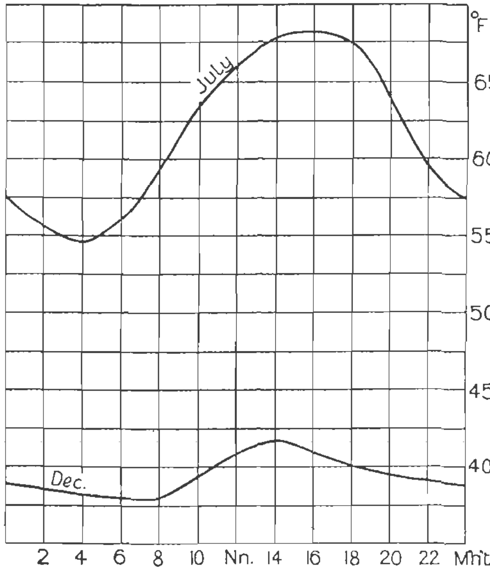


FIG. 14. Mean hourly temperature at Oxford in December (month with least diurnal range) and July (month with greatest diurnal range)

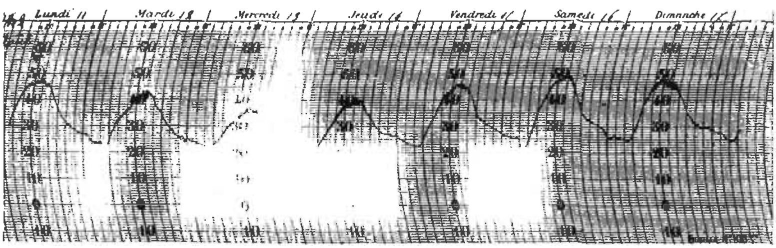


FIG. 15. Temperature (°C) at Touggourt, Algerian Sahara, August 11–18, 1912

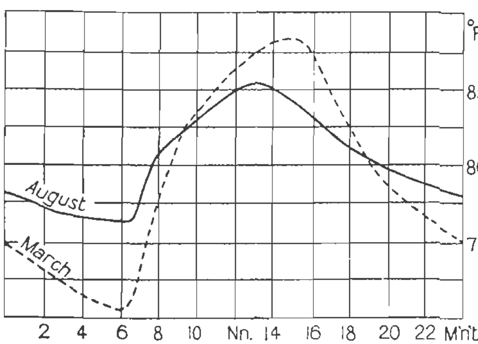


FIG. 16. Mean hourly temperature at Manila in March (dry season) and August (rains)

CHAPTER IX

THE DIURNAL CURVE OF TEMPERATURE

Everywhere outside the Polar circles it is warmer by day than night in ordinary weather, but the form and amplitude of the temperature curve vary greatly. The difference between land and sea in this respect has been pointed out; the range of temperature is much greater on land, the nights being colder, the days warmer; the maximum temperature is at about 2 p.m. on land, 3 p.m. on the sea. The form of curve depends on the season and on the weather. In temperate latitudes the mean amplitude of the curve, or the range of temperature, is very much greater in summer than in winter (Fig. 14). This is due partly to the finer weather and clearer skies, since a clear sky favours hot days and cold nights, but chiefly to the stronger solar control of temperature in summer. It is very rare in summer that a night is warmer than the preceding or following days. But it is not rare in winter, when the weather control may be stronger than the solar control, that is to say, the general weather conditions, especially the amount of cloud and the direction and force of the wind, are more effective than the direct rays of the sun in determining the temperature. Thus on Nov. 15, 1929 (Fig. 98c, p. 269) the temperature remained low during the day, and the maximum occurred in the night owing to a change of wind. Cold gloomy days are only too frequent in temperate latitudes, especially near the oceans; east winds and overcast skies may continue day after day, and the sun is obscured and has little or no direct effect on the temperature, which is hardly higher by day than by night. On the other hand the curve in Fig. 15 from the Sahara reflects the intensity of the direct insolation, the weather remaining constant and the solar control being strongly marked in the trade-wind desert.

The temperature may rise in the night in winter owing to clouds forming, which check the loss of heat by radiation, or owing to the wind rising after a calm and churning up the chilled surface air with the main body of the atmosphere which is warmer, or to the wind blowing up from a warm quarter. And the temperature may fall during the day though the sun's altitude is still increasing, owing to a change in the wind or the state of the sky. Such inversions are not very frequent, but they are frequent enough to cause the mean diurnal range of temperature to be notably less in winter than in summer.

In monsoon countries the diurnal range is least during the cloudy and rainy months of the wet monsoon, and greatest in the dry season, especially during the hottest months (Fig. 16).

In temperate latitudes there is often an interesting relation between changes of temperature and barometric pressure, especially in winter. A falling barometer, indicating an approaching depression, gives cloudy skies and southerly winds, and the weather becomes warmer. As the depression passes away and the barometer rises the sky clears, the wind comes in from a polar quarter and the temperature falls. Thus the trace of the thermograph tends to rise while the barogram falls and vice versa (Fig. 98, p. 269, 1 a.m. Nov. 12, and noon, Nov. 15).

The effects we have been describing are noticeable whereever the weather is under a strong cyclonic control, that is to say, speaking generally, on the poleward sides of lat. 30°. In many districts topographical peculiarities intensify the effects, as we shall see later in considering föhn winds, the mistral and the sirocco, and cold waves. We may mention here two types of diurnal curve which are characteristic of large areas. On the coasts of the warmer parts of the world, roughly between the Equator and lat. 40°—Britain is not warm enough, but the south of Europe is included—the wind alternates from the land-breeze at night to the seabreeze by day (p. 303). The sun's rays are powerful, and the heat increases rapidly after sunrise. But the rapid heating of the land leads to its own undoing, for about 10 o'clock the sea-breeze sets in, bringing cool air from the sea, and the rising temperature curve is checked and often reversed, the maximum for the day occurring as early as 10 or 11 o'clock (Fig. 17). The practical importance of this is that the highest portion of the diurnal curve is, as it were, cut off, and the coasts enjoy a great advantage over the interior, where the curve goes on rising till the early afternoon when the heat becomes overpowering.

Even in the interior the rising temperature is often checked to some extent. The convection currents that are set up give rise to heavy cumulus clouds in humid regions,

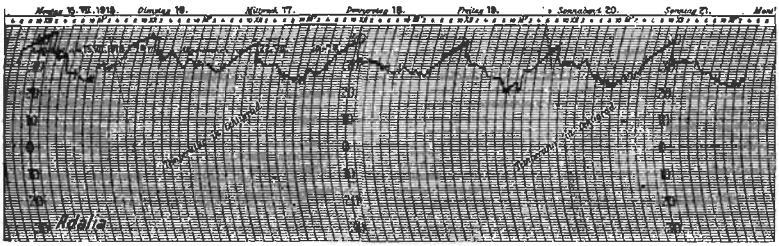


FIG 17. Temperature at Adalia, south coast of Asia Minor, July 15–22, 1918

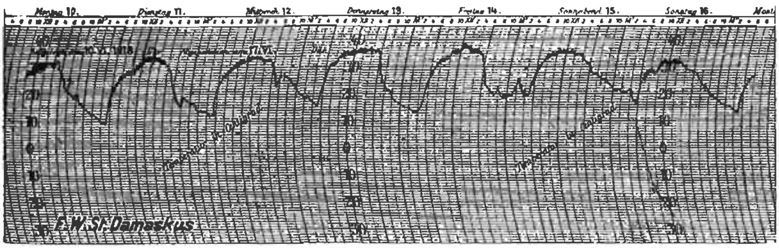


FIG. 18. Temperature at Damascus, Syria, June 10–17, 1918. The thickening of the trace in the midday hours is due to the rapid oscillations in temperature associated with convection currents

and the clouds screen the earth. Arid districts do not enjoy this alleviation, but even here the convectional mixing of the scorching surface air with the cooler winds aloft has some effect (Fig. 18). These are further instances showing that very high temperatures on the earth's surface tend to be prevented by the air movements to which the heat itself gives rise. The contrast with the occurrence of excessive cold has been already pointed out (p. 39).

An interesting, though not common, temperature curve (Fig. 19) shows the effect of an eclipse of the sun. In this case the eclipse was not quite total, a maximum of 0·65 of the sun's disk being covered; the sky was cloudless.

In the Polar regions the 24 hours' day in summer and 24 hours' night in winter introduce a variation. At the Poles themselves it would seem probable, though records are

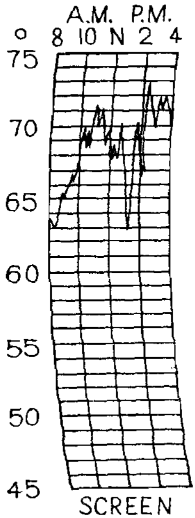


FIG. 19. Air temperature at Warlingham, Surrey, during a partial eclipse of the sun, noon—2 p.m., August 21, 1914

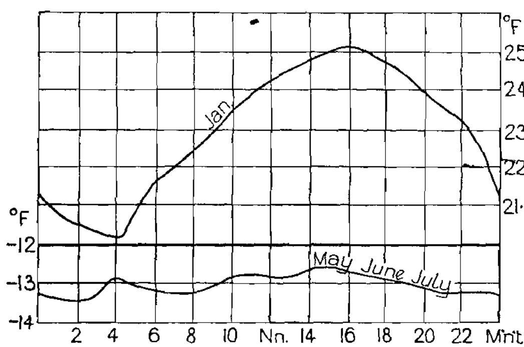


FIG. 20. Mean diurnal temperature curves for McMurdo Sound in Antarctica

lacking, that the mean diurnal temperature curve for those days is a straight line. For lower latitudes inside the Polar circles several records are available, the longest for McMurdo Sound in Antarctica (Fig. 20), but even these are far too short to establish the true mean values. The range in summer seems at first surprisingly high, seeing that the sun is above the horizon continuously; but the great difference between the noon and midnight altitudes explains the large range. The winter curve has two striking features—in the first place the rise between 9 a.m. and 7 p.m., and the fall to a minimum at 2 a.m., although the sun never appears above the horizon, and secondly, the slight, but apparently real, secondary maximum at 4 a.m.[1]

CHAPTER X

THE EFFECT OF SHELTER

A NORTH wind sometimes blows so strong and cold in spring that even the unclouded sun hardly tempers the piercing blast. But under the lee of a high wall or a screen of trees the conditions are quite different, for there is shelter from the wind and at the same time an intensification of the heat of the sun by reflection. The old gardeners understood this when they made the walled gardens that are so prolific. On a larger scale in nature a range of hills or mountains takes the place of the wall, and may modify the climate in an appreciable degree. The Mediterranean region provides many important instances. In several respects the Mediterranean is suited for invalids and holiday makers in the cooler half of the year, but a serious disadvantage of the northern coasts is the liability to strong cold winds from the interior of Europe, for the prevailing winds are between north-west and north-east. Fortunately the Mediterranean Sea is almost everywhere ringed round by mountain ranges and where they rise steeply from the sea on its northern side they give the necessary protection from the wind, while the direct rays of the sun, together with the reflected heat from the background of white limestone mountain and from the azure waters of the sea, make these favoured littorals veritable sun-traps. The French and Italian Rivieras, the Dalmatian coast, and the Italian lakes are well-known winter resorts which owe their climatic advantages largely to the mountain shelter; the cold winds which are turned aside pour down with the greater rigour to the coast where there is no pro-

[1] Simpson, *British Antarctic Expedition*, vol. I, ch. 2.

tection (p. 294). All the popular Mediterranean resorts are on the sheltered coasts except those on the southern shores such as Algiers. But in summer the mountain background so intensifies the powerful sunshine that all who can do so retreat to cooler places. The north-east shore of the Lake of Geneva owes to its mountain shelter and southward exposure the climatic advantages that attract a large health- and pleasure-seeking population.

The Himalayas are a much mightier screen which shields the plains of India from cold winds that would blow out in winter from the icy deserts of the interior—such winds as are a scourge in China. The south of the United States lies in the same latitudes as the north of India, but it has no shelter on the north so that cold waves often sweep down in winter from Canada.

In the heat of summer a strong wind is welcome since it promotes evaporation and tempers the 'physiological' temperature. The furnace heat of the Sahara and similar deserts would be not only unpleasant but impossible for human life were it not for the strong and dry wind that usually blows during the hottest hours.

CHAPTER XI

TEMPERATURE, GEOGRAPHICAL DISTRIBUTION

For many of the points considered in this chapter reference should be made to the isotherms for January and July (Figs. 4 and 5). The mean range of temperature (that is the difference between the mean temperatures of the extreme months) is given in Fig. 21.

The Equatorial Belt

A most important point to remember in considering world meteorology is the vast area subject to the equatorial climate. It covers degree after degree round the globe where degrees are most spacious. Any variation from the normal conditions here is likely by reason of the area alone to have more influence on the rest of the atmosphere than a similar variation in say the Polar regions.

In spite of the latitude this belt (roughly between lats. 5° N.

and S.) is by no means the hottest part of the earth. In no month has it the highest mean monthly temperature, nor yet can it show any very striking records of great heat on individual days; higher readings have often been registered even within the Arctic circle in Canada and Siberia; but such high readings are rare in high latitudes, and confined to the warmest months, while on the Equator the temperature reaches nearly 90° on every day of every year. On the other

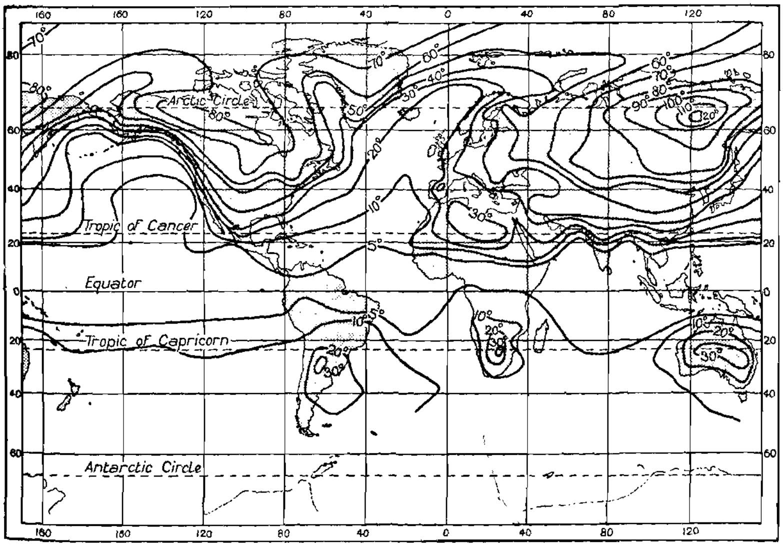


FIG. 21. The mean annual range of Temperature (Connolly)

hand if we consider the mean annual temperature the Equatorial zone is the warmest, and in particular it has the warmest nights. The explanation of these facts is partly astronomical, partly geographical. The altitude of the sun, taking the mean for the whole year, is greatest at the Equator, where it is overhead twice a year, but the length of the day is always 12 hours. Between the Equator and the tropics the sun is overhead twice a year, and in the summer the days are considerably more than 12 hours long. For this reason the summers tend to be hotter towards the tropics. The geographical influences are the nature of the surface of the land—dry bare rock or sand in the neighbourhood of the tropics, but near the Equator a constantly wet soil, thick vegetation consisting largely of dense moist forests, much water in rivers, lakes, and swamps. The atmosphere is clear and dry and cloudless near the tropics, damp and cloudy along the Equator.

The outstanding feature of the Equatorial belt is the monotony of the temperature from day to day, and from month to month throughout the year. The mean for each month remains between 75° and 85°. The temperature is most uniform on the oceans and small oceanic islands. At Nauru, Gilbert Islands, lat. 0° 26′ N. the mean annual range is only 1°, at Jaluit, Marshall Islands, 5° 55′ N., as little as 0·7°; the absolute range of temperature from the lowest to the highest ever recorded in these islands does not exceed 25°. Not only on the oceans but in much of the land areas the twelve monthly means do not vary by more than 1°. Wallace in his essay on Tropical Nature mentions the interesting fact that in June the sun's altitude is 60° at Batavia, lat. 6° S., and 62° at London, and yet London is colder than Batavia, and this in spite of the advantage London gains from its longer days. It proves that the mean temperature even at low latitudes is not directly dependent only on the altitude of the sun. The winds that reach the Equator from both sides blow over hundreds of miles of sea where the surface temperature is almost uniform; cold Polar influences are unable to cross these defences. And furthermore the abundant water on the Equatorial lands exercises its conservative influence. The constant length of day and night also tends to uniformity of temperature. There is practically no seasonal change in this belt, even in the interior of continents. The change from day to night is about average for the earth, amounting to some 15°; it is often stated to be very great, and indeed the nights seem cold, but that is chiefly a physiological effect, due to the weakening of the physique by the monotonous climate. The diurnal range is certainly high by comparison with the annual.

The records from Singapore illustrate the conditions; we give the actual records for one year as being more instructive than mean values.

KANDANG KERBAN, SINGAPORE

Alt. 33 ft. Lat. 1° 18′.

TEMPERATURE

1925.	*Mean.*	*Highest maximum.*	*Lowest minimum.*	*Mean diurnal range.*	*Highest wet bulb.*
Jan.	78·8	89·0	70·0	12·7	81·0
Feb.	78·2	88·0	70·0	12·0	80·0
Mar.	79·7	89·5	70·0	13·4	81·0
Apr.	81·3	90·5	72·5	13·2	82·0
May	82·1	92·2	72·8	13·3	82·5
June	82·6	91·0	73·5	10·9	82·0
July	81·9	91·0	71·0	12·4	82·0
Aug.	81·6	90·4	71·0	12·8	82·0
Sept.	81·2	91·5	72·0	12·3	82·0
Oct.	80·6	89·8	72·2	13·1	82·0
Nov.	80·3	90·8	72·0	13·0	82·0
Dec.	78·8	88·0	71·8	10·8	80·5
Year	80·6			12·5	82·5
Range	4·4	22·2		—	—

The warmest month was June, the coolest February, but the temperature difference was only 4·4°. The highest maximum, 92·2°, was recorded in May, but in no month did the thermometer fail to reach 88°, and in no month did it fall below 70°. The mean diurnal range varied between 10·8° in December and 13·4° in March.

The records for the whole zone are similar. The monotony is what makes the climate so injurious to the health of the white man, and so unfavourable to high intellectual development in the black. There are many hotter regions, and they may be rainier and damper for part of the year, but they enjoy the great advantage of having a cool and dry season. In the hothouse monotony of the Equatorial climate white men lose both mental and physical vigour, and a change to a bracing climate is desirable each year and essential after a few years.

The Tropical Belts (between the Equatorial Belt and the Tropics)

As we leave the Equator the mean temperature for the year becomes lower, the summers become hotter, and the winters cooler; the seasonal change makes itself felt more and more. We may illustrate this from the islands of the Pacific which are far removed from the disturbing influence of land-masses; all the stations are by the sea:

	Lat.	Mean Temperature. Warmest month.	Coolest month.	Range.
Nauru (Gilbert Is.)	0° 26′ N.	82·3	81·3	1·0
Apiang (Gilbert Is.)	2° 50′ N.	83·5	81·3	2·2
Guam	13° 36′ N.	82·2	77·7	4·5
Apia (Samoa Is.)	13° 49′ S.	79·5	76·9	2·6
Levuka (Fiji Is.)	17° 41′ S.	80·0	74·8	5·2
Oahu (Hawaii Is.)	21° 18′ N.	77·5	70·2	7·3

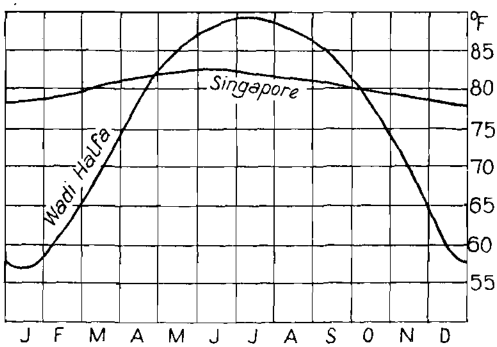


FIG. 22. Mean Temperature at Singapore (lat. 2° N.) and Wadi Halfa (lat. 22° N.)

In summer the sun is overhead, and the days are more than 12 hours long, but in winter its altitude on the tropics is only 43°, and the nights are longer than the days. The mean monthly temperature is above 70° in every month (except in the neighbourhood of the tropics themselves where there is one month with a mean a few degrees below).

The range of temperature, both annual and diurnal, is greatest in the trade-wind deserts. The heat in summer is intense; the mean temperature in July exceeds 90° in much of the Sahara. Day after day the thermometer rises to over 120°, and the rocks and sand, and still more the mud houses and walls, are so heated that even at night there is little relief; for though the air temperature falls as much as 40° it is still terribly hot. The dryness of the air, the brisk wind, and the cool winter, however, make the climate not unhealthy, and provided he has abundance of water man finds life tolerable even in summer. But words fail to portray the horrors of the desert for the traveller who is without water in the heat of summer—the furnace heat and the pitiless glare of the unclouded overhead sun, the sand too hot to touch, the air often full of fine dust. Over a considerable area of the deserts in the north centre of Australia the temperature has been known to exceed 100° on 64 consecutive days. At Azizia, 25 miles south of Tripoli, 136·4°, the highest reading ever taken under standard conditions, was recorded in September 1922, and readings above 110° are to be expected in every month from May to September. Death Valley, in the desert of California, is another famous furnace, and has recorded 134°; the valley is below sea-level, and this intensifies the usual high summer temperatures in the trade-wind deserts. We illustrate the conditions further from the Sahara; Wadi Halfa is in the tract that has the hottest summers of the whole earth:

WADI HALFA. EGYPT

Alt. 421 ft. Lat. 21° 55′ N.

TEMPERATURE °F. (19 years records)

	Mean.	*Absolute maximum.*	*Absolute minimum.*	*Mean diurnal range.*
Jan.	57·9	99	32	29
Feb.	61·0	106	34	32
Mar.	68·5	116	38	34
Apr.	78·1	126	46	35
May	84·6	117	55	33
June	88·2	118	56	32
July	88·5	120	63	32
Aug.	87·4	116	57	31
Sept.	84·6	117	56	30
Oct.	79·5	117	42	31
Nov.	70·0	115	39	30
Dec.	60·1	102	28	29
Annual	75·7			32
Range	30·6	94		—

For comparison the curves of mean temperature here and at Singapore are given on one diagram (Fig. 22). The absolute range of temperature is 94° at Wadi Halfa, 22° at Singapore. The further we go from the Equator the more strongly differentiated are the seasons. As far as about lat. 15° the chief difference is in the rainfall; beyond that are the rainless deserts, and the seasons are marked by temperature differences. Frost may occur in winter even inside the tropics and ground frost is not rare, but the summers are the hottest on the earth. The thermometer may rise to 100° even in the winter months, and in summer it exceeds 110° every day for weeks. But as the air is very dry, and the wind usually fresh, the high temperatures are reduced 30° or 40° by evaporation, and the summer conditions, though trying, are not so enervating as the high thermometer readings might indicate. The powerful rays of the unclouded overhead sun heat the naked rocks and sand till they are too hot to touch. Night brings some relief, for the dry air permits rapid loss of heat by radiation, and the ground becomes cool.

Bombay (Fig. 23) is typical of wide areas in the tropics where the rainy season begins in the middle of summer with overcast skies, thick clouds, and heavy downpours. So effective are the cloud screen and the deluges of rain in cooling the air that there are two maxima in the temperature curve, one just before, the other just after, the rains, and the year is divided into three seasons, the cool season, the hot season, and the rains. Such are the conditions especially in the monsoon lands (but only inside the tropics) and in lands with the Sudan type of climate, that is to say, where the equatorial rain belt has migrated almost to its extreme north and south positions, as at Khartoum and Timbuktu. The diurnal range of temperature is much less during the rains than in the rest of the year owing to the overcast skies and damp air.

The Temperate Belts (i, the Sub-Tropics)

On the poleward side of the tropics as far as about lat. 45° (i. e. in the 'sub-tropics') the winters become colder, and frost and snow occur in most winters. The summers, however, though not rivalling the furnace heats of the central Sahara are yet hardly less warm than on the Equator; at Toulouse, France, the temperature rose to 110° on August 9, 1923. The range of temperature is therefore much greater than on the Equator, but hardly as great as in the Sahara, for the sub-tropical winter is not cold enough to balance the Saharan summer heat. The seasonal contrast is strongly marked both in respect of temperature and rainfall. There are at least 4 months with a mean temperature above 70°, and at least 1 month, but not more than 8, with a mean below 70°.

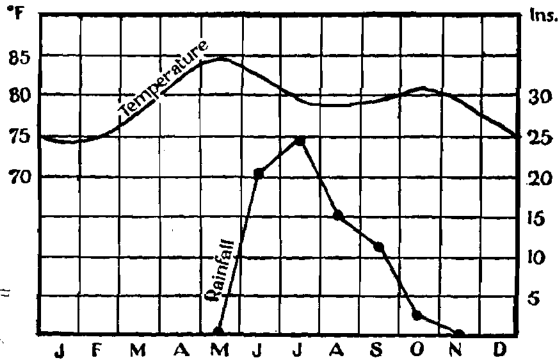


FIG. 23. Mean Temperature and Rainfall at Bombay

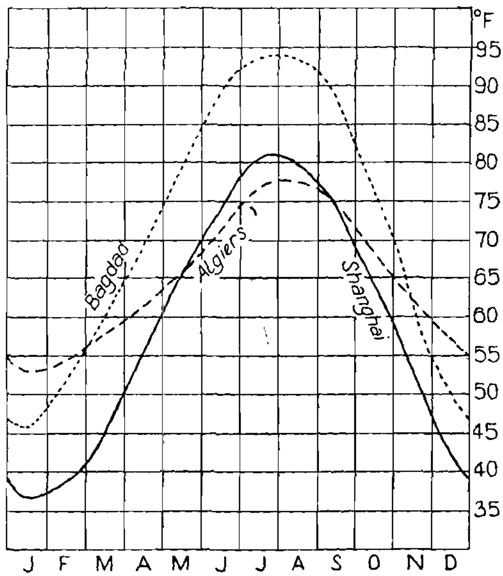


FIG. 24. Mean Temperature in the Sub-Tropics

Fig. 24 shows the mean temperature at three stations in the same latitude—Algiers, a 'Mediterranean' station, that is to say a station on the west coast of a land mass, Shanghai on the east coast, and Bagdad in the arid interior. The winter is warmest on the west coast, for the Mediterranean region has westerly winds and cyclonic weather in that season. It is much colder at Shanghai, where the winter monsoon blows from the very cold and dry steppes and deserts of Mongolia. In summer Bagdad is distinguished by its great heat, which it shares with the trade-wind deserts. There are no clouds to cut off the sunshine which beats down with fierce intensity on the arid plains. Even at night in July the temperature does not usually fall below 80°, and by day the mean maximum is 94°, and 123° has been recorded. Underground chambers are a refuge, not very effective, from the heat of the day, and at night the housetop which catches the breeze is the coolest place for sleeping.

In the sub-tropics the winters are coldest on the east sides of the land masses, the summers are hottest in the arid interiors. Land and sea influences are prominent, even in such small land areas as Spain or Italy; the mean annual range at Lisbon is 21°, at Madrid 36°. The daily weather control also becomes a serious element of the climate since the pressure irregularities of the Westerlies invade the region. The Mediterranean lands often suffer severely from cold winds from the north, and the temperature falls well below freezing-point except in the islands and on the south shores. Snow is not uncommon, and it has fallen even in the north of the Sahara. In spring and autumn it is the south wind in front of cyclones which is a serious visitation owing to its heat (Chapter XLVIII). The southern United States are invaded by cold waves which may bring freezing temperatures to the shores of the Gulf of Mexico.

In the sub-tropics—and still more in the higher temperate latitudes—the annual range of temperature is so great that the transition seasons, spring and autumn, are important divisions of the year.

The Temperate Belts (ii, lat. 45°—66½°)

This belt can be called temperate only in the sense that in respect of the mean annual temperature it is between the equatorial and the polar zones. In other respects the name is unsuitable, for the temperature ranges from high to the lowest recorded, and larger and more sudden fluctuations occur than anywhere else; it may fall 20° or more in a few hours even in the mild oceanic division of the belt, and there are equally sudden rises. The oscillations are sometimes of long duration. Whole seasons may be abnormally cold or abnormally warm. The belt lies between the cold polar regions and the warm tropics, and is liable to be invaded by winds from both sides. These fluctuations are almost all due ultimately to the influence of the pressure irregularities of the westerlies—the zone we are considering is essentially the zone of the westerlies—and the winds to which they give rise. Moreover the mean monthly temperature has a high range from summer to winter; a statement of the mean annual temperature conveys little useful information since the temperatures of the twelve months from which the mean is formed are so different. Valencia in south-west Ireland has almost the same mean annual temperature as Peking, but the mean annual range is only 15° at the former, 55° at the latter.

The effect of position in relation to land and sea is so great that no one station can be regarded as typical. We must examine at least three, one in the ocean or on the east coast of an ocean, one in the interior of a land mass, and one on the east coast of a land mass, with land winds in winter and sea winds in summer. In the northern hemisphere there is no lack of regions in all three categories, but most of the zone in the southern hemisphere consists of unbroken ocean, save for the narrow southern extremity of South America.

To represent the oceanic type we take Valencia, Co. Kerry:

Lat. 52° N. Alt. 30 ft. TEMPERATURE °F.

	Mean.	*Mean daily maximum.*	*Mean daily minimum.*	*Mean daily range.*
Jan. . .	44·4	48·8	40·0	8·8
Feb. . .	44·3	49·1	39·9	9·2
Mar. . .	45·0	50·4	39·8	10·6
Apr. . .	48·0	53·4	42·5	10·9
May . .	52·2	57·6	46·0	11·6
June . .	56·7	62·2	51·0	11·2
July . .	58·8	63·9	53·7	10·2
Aug. . .	58·9	64·2	53·9	10·3
Sept. . .	56·6	61·8	51·3	10·5
Oct. . .	51·5	56·5	46·5	10·0
Nov. . .	47·5	52·2	42·7	9·5
Dec. . .	45·5	49·9	40·8	9·1
Year . .	50·8	55·8	45·7	10·1

In view of the high latitude and consequent great difference between summer and winter in the sun's altitude and in the length of the day, the very striking features are the remarkably warm winters (no month has a mean temperature below 32°), the cool summers, and the small range of temperature. The warmest month is August, the coldest February, the long 'lag' behind the sun being typical of an oceanic climate. Spring is much cooler than autumn, the mean for March being 45·0°, for September 56·6°. The mean diurnal range, always small, is least in winter (only 8·8° in Jan.), but even in May, the month which has most variation nearly everywhere in this belt, it is only 11·6°; extreme cold and heat are unknown. Frost is rare—rarer than on the north shores of the Mediterranean Sea—and the temperature has not been known to fall below 20°. Many sub-tropical plants flourish, such as the strawberry tree, fuchsia, and laurel. The mean range of temperature from day to night in winter is less than 9°.

The long transition seasons in temperate oceanic climates are noteworthy. Spring is said to begin with March, but in some years there are signs of its approach in February, and the season continues, in a succession of bursts of warmth and returns to cold, till June—the cold being more prominent than the warmth in most years. North-east winds may blow for weeks, and it is rare for spring to pass without a lengthy spell of them. Except on the actual coast there may be frequent snowstorms (16 inches of snow fell at Oxford on April 25, 1908) and severe frost. But the sun is steadily rising in the sky, and the intensity of the insolation as well as the length of the day increases rapidly in these latitudes. On the Peace River, Alberta, lat. 58° 30′ N., the snow is melted by the beginning of April, and wheat is sown sometimes by the middle of the month, and ripens within 90 days. The absolute range of temperature is greater in May than in any other month.

It is impossible to choose one station which shall be 'typical' of the continental interiors, since the climate changes rapidly with distance from the western ocean. The winters rapidly become colder and longer as we go eastward into the great land masses. Semipalatinsk (Fig. 25), Western Siberia, in the same latitude as Valencia, has a decidedly continental climate, though one by no means so continental as the east of Siberia. There are 5 months (November—March) with a mean temperature below 32°, the mean for January, the coldest month, being 0°; during the 5 months the ground is snow-covered and the rivers ice-bound. The summers are warm for the latitude, with

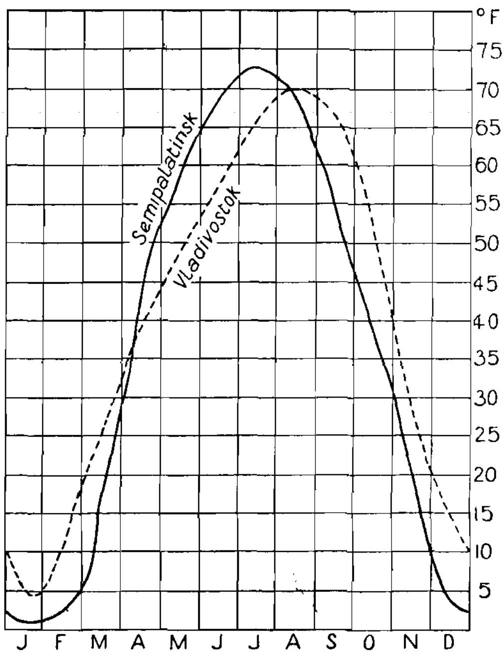


FIG. 25. Mean Temperature

a mean temperature well over 60° in 3 months (72° in July). This is 10° warmer than we have in the British Isles. The annual range of temperature is 71°. The change from week to week in the transition seasons is strikingly rapid—the mean temperature is 19° higher in May than in April, and the drop in autumn is equally rapid. In the beginning of September it is still summer, but the rigours of winter set in by the end of October.

The steppe-lands of Siberia, Russia, and America are included in this region. The effect of the rapid rise of temperature in spring is graphically described by Brehm—

'Even before the last patches of snow have vanished the bulbous plants, and others which live through the winter, put forth their leaves and raise their flower-stalks to the sun. Among the sere yellow grass and the dry grey stems of all herbs which were not snapped by the autumnal storms, the first green shimmers. From the apparently sterile earth herbaceous and bulbous growths shoot up; buds are unpacked, flowers unfold, and the steppe arrays itself in indescribable splendour. Boundless tracks are resplendent with tulips, yellow, dark red, white, white and red. It is true that they rise singly or in twos or threes, but they are spread over the whole steppe-land, and flower at the same time, so that one sees them everywhere. Immediately after the tulips come the lilies, and even more charming colours appear wherever these lovely children of the steppes find the fit conditions for growth; they completely dominate wide stretches of country.'

Vladivostok (Fig. 25), on the east coast of Siberia, represents 'east-coast' conditions; this town, however, is some 10° of latitude farther south than Valencia. Since the Pacific Ocean lies to leeward in winter it has little ameliorating effect. The winters are brought from the steppes of the interior by the north-west winds of the winter monsoon. The cold is intense for the latitude. The rivers are frozen for over 15 weeks, and the harbours on the coast closed to navigation from mid-December till the beginning of April unless kept open by ice-breakers. The coldest spots are where valleys open on the coast, for the bitter blasts from the interior sweep down them. The land is snow-covered, sledges are the usual means of transport, and heavy fur garments are worn. The thermometer may fall to 30° below zero.

Summer is much warmer than at Valencia owing partly to the more southerly latitude, partly to the southerly winds of the summer monsoon, blowing from the warm waters of the Pacific. But it is not so warm as at Semipalatinsk which is in the far interior. This is the rainy season, damp and cloudy, and the summer heat, though not excessive, is enervating, and the range of temperature from day to night is small. The mean annual range of temperature is 65°. Autumn is warmer than spring, the excess of October over April being 9°; but the transition seasons are short—summer passes rapidly into winter, for September is as warm as the English July, November much colder than the English January. Spring is really shortened to the one month of May; April is still winter, June already summer.

The Tundra Lands

These lie for the most part just inside the Arctic circle. The corresponding latitudes in the southern hemisphere are either ocean or everlasting snow and ice.

It is a cold region. In winter there is no effective sunshine for several months, and the cold is intense both by day and night, though not so intense as further inland, for there the continental influence more than balances the slightly lower latitude. The mean monthly temperature is below zero from November to April and minima of $-60°$ are frequent. In many parts snow and ice remain unmelted even in summer, and everywhere there is permanently frozen soil below the surface; the coasts are ice-bound much of the year. The winters may be termed polar; but the summers distinguish the tundra from the polar regions, since the mean temperature for at least 1 month is between 40° and 50°. In July and August it may be pleasantly warm or even hot at midday, when the temperature often rises above 80° at a distance from the sea; 100° has been recorded at Fort Yukon. In spite of these high temperatures the ground a foot below the surface may be frozen solid. On sunward slopes the snow melts, the water drains away, and the ground is warmed enough to produce a xerophytic and hardy vegetation, with over 100 species of flowering plants. Slope is all-important owing to the low sun; where it is poleward there is little warmth; much of the flat ground remains sodden and marshy.

The tundra is distinguished from the Polar region by its advantage in having some summer—short and cool, but enough to make vegetation possible. On the other hand it is the shortness and coolness of the summer, no month having a mean temperature much above 50°, together with the permanently frozen subsoil, the water-logged surface, and above all the strong winds, that preclude the forest growth which characterizes the lands on the south of the tundra, and condemns even the most favoured slopes to produce only a stunted shrubby or grassy growth, and large expanses to remain for ever wastes of snow, mud, and marsh, frozen hard for half the year.

The Polar Regions

Antarctica, a lofty snow-covered plateau, naturally has very cold winters. The snow is an excellent radiator, and being dry and powdery it insulates the surface from the warmer land underneath. The sky is clear and the air dry. Probably the central part of the plateau is one of the coldest tracts on the earth, where the temperature falls to $-80°$ or lower, but no one has paid a winter visit to obtain records. The loss of heat during the 6 month's night must produce intense cold, even without the aid of temperature inversion which is a factor in the cold Siberian winters. There can be little, if any, change in temperature from day to night, since the sun never appears above the horizon. And it is unlikely that there are any great fluctuations of temperature from day to day. In September the sun rises, and it climbs higher each day till the solstice, when its altitude is $23\frac{1}{2}°$. But in spite of the perpetual day the air temperature does not rise very high since the snow is never melted. In the 4 days, January 16–20, 1912, when Scott's party was at the South Pole or within 30 miles of it, the highest reading was $-19{\cdot}1°$, the lowest $-26{\cdot}7°$. The altitude, some 10,000 feet, is in itself a cause of the great cold, but even when the usual correction to sea-level is applied the mean for January is probably not above 15°. As the readings just given indicate, the daily range of temperature is presumably small. The annual range on the other hand is very great, though probably much less than in Siberia and northern Canada, where the summers are much warmer.

Even at sea-level on the shores of Antarctica the summers are remarkably cold, no month having a mean temperature above 32°. On the south coast of the Ross Sea the January mean is probably about 20°, and on the shores of the open Southern Ocean about 30°. A result, and at the same time a cause, of the low temperature is that there is no ground bare of snow; there are no animals (except birds) or flowering plants. The sun is above the horizon the whole of the 24 hours at midsummer, but its altitude ranges (at lat. 70°) from 43½° at noon to 3½° at midnight, and the diurnal range of temperature is about 10° in summer. The highest temperature recorded in 4 years on Ross Island was 42°. On most summer nights the minimum is below 20°. The warmest month is December, the month with the highest sun, so that there is no 'lag' in air temperature behind the curve of insolation. The reason is that the dry and loose snow which covers the ground is a good insulator; the surface warms rapidly, and there is not the usual delay of a month or more while the ground is warming. The winters, with little if any sunshine, are cold. The mean temperature in August, the coldest month, is about −15° on Ross Island, and probably much lower on the Great Barrier where it is estimated at below −35°. The lowest reading actually recorded in Antarctica was −76°, taken on the Barrier near Ross Island on July 6, 1911. On the open coasts of the Southern Ocean the mean for August is about −10°.

The temperature falls rapidly after the summer solstice and in McMurdo Sound the monthly mean remains about −12° from April to September, when the even more rapid rise to the summer maximum starts.

The daily range in temperature is considerable in McMurdo Sound, being least in summer, about 10°, and increasing to 17° in winter. The rises and falls of temperature are almost without relation to the time of day, and depend on the direction and force of the wind and on the state of the sky.

The Arctic region is a great expanse of ocean, probably completely ice-covered in winter for thousands of miles round the Pole, and indeed over its whole area except where the Gulf Stream Drift enters. In summer there is a good deal of open water. The winters are much less cold than in Antarctica; the mean January temperature in the neighbourhood of the North Pole is estimated by Mohn at about −40°, and in most of the Arctic Basin at between −20° and −40°, but it becomes rapidly warmer on the side of Spitzbergen (0°) and Norway owing to the North Atlantic Drift. These are far higher temperatures than prevail in the north of Siberia and Canada, and the interior of Greenland. The mean July temperature is about 32° round the Pole and 40° on the outskirts of the basin. The mean annual range is thus about 60° or 70°—a remarkably high figure for an ocean, but readily understood when we remember the alternation of months of continuous day and months of continuous night. The summers are the bleakest and coldest known at sea-level in the northern hemisphere, but they are not so cold as those of Antarctica.

CHAPTER XII

OCEAN CURRENTS

Ocean temperatures are so much controlled by currents that a knowledge of them is required for the understanding of climatology. Water is easily set in motion by the wind, and the great wind systems cause permanent ocean currents to set more or less in their own directions. Differences in the density of the ocean also help to cause movement in the body of the water. The circulation is best understood by starting on the east sides of the Pacific and Atlantic Oceans, where between lats. 30° and 10° N. and S. cool water is blown forward by the trade winds towards the Equator. Currents moving towards the Equator are cool, since the water is always reaching warmer latitudes, and it lags in temperature behind its new surroundings. In the case of these trade-wind currents there is another reason for the low temperature; the prevailing winds blow obliquely off-shore, wafting the surface water with them, and its removal is compensated by a steady upwelling of water from the depths of the ocean along the coast. As the depths are everywhere, and especially in tropical latitudes, cooler than the surface, this upwelling water appears cold, and as will be seen later its presence has important climatic effects.

The cool trade-wind currents from the two hemispheres converge near the Equator, and a great equatorial current sets towards the west; there are really two equatorial currents in the Atlantic and Pacific Ocean, separated in the east of the ocean by a counter current setting to the east. The equatorial currents are cool for the latitude in the east like the currents which feed them, but they become warmer on their passage, and in the west of the oceans they have the normal temperature. From here they diverge to north and south, and as they are then moving towards higher latitudes they are warmer than their surroundings, and they appear as great streams of water carrying the heat of the tropics into temperate and Polar latitudes. After skirting the east coasts of the continents as far as about lat. 45° N. and S., they strike more eastward under the influence of the prevailing westerly winds of those regions and cross the oceans, to be caught in the trade-wind currents again. But in the North Atlantic the movement is more complicated owing to the shape of the basin, the main drift continuing north-east from Newfoundland between Iceland and the British Isles, past the North Cape of Norway and the North Russian coast into the Arctic Ocean. The remarkably mild winters of North-west Europe are due to this northward extension of the warm water. In addition to this, the Gulf Stream itself is of great volume; it originates in the equatorial currents, and owing to the position and shape of Cape S. Roque, Brazil, not only the north equatorial current but also a considerable part of the south equatorial is turned into the North Atlantic.

Of the many minor currents, mention must be made of the Labrador current. The wide drift of warm water into the Arctic Ocean causes a compensating current to set out from that ocean on the other side as a cold current through Denmark Strait, round the south end of Greenland through Davis Strait and along the Labrador coast as far as the Grand Banks of Newfoundland. Not only is this water cold, with a temperature little above freezing-point, but it carries with it great quantities of pack-ice and massive icebergs.

Owing to the thermal conservatism of water warm currents are especially important in winter in temperate and high latitudes, when they provide abnormal warmth and moisture for the winds that blow over them, and cold currents are most important in summer, chilling the air and often causing the vapour it contains to be condensed into thick fog. On-shore winds carry these conditions over the lands, in some cases, as in Europe, to great distances, in others not far beyond the littoral.

PART III

PRESSURE AND WINDS

CHAPTER XIII

THE MEASUREMENT OF ATMOSPHERIC PRESSURE

Two forms of barometer are in common use. For accurate measurements the mercury barometer must be employed. In it a column of mercury adjusts its length automatically so that it balances the weight of a column of the atmosphere

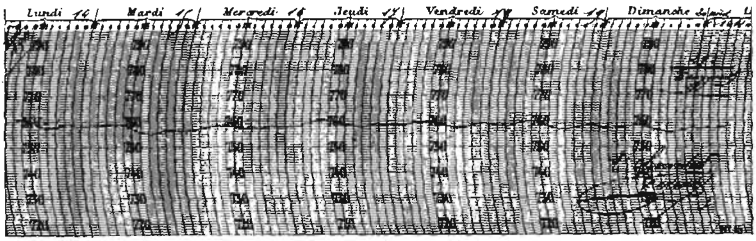


Fig. 26. Barometric pressure, August 14–21, 1911, at Touggourt, Algerian Sahara

of equal section. The instrument gives readings of great precision, and is usually read to 1/500 of an inch, or 1/10 of a millibar.

A more portable and convenient, but less accurate, barometer is the aneroid, the essential element of which is a spring which is compressed more or less as the pressure of the atmosphere changes. The spring is contained in an air-tight chamber which is almost exhausted of air. The upper lid of the chamber rests on the spring and is free to move as the pressure of the atmosphere resting on it changes; if the inside were not air-tight the changing atmospheric pressure would *not* produce any movement in the lid, since both sides of it would be equally affected.

Continuous self-registered records of barometric pressure are most valuable and instructive in the study of the atmosphere. Both the mercury and the aneroid barometer can be arranged to give such records. The instrument in commonest use is the barograph in which the reading of an aneroid is registered continuously by a pen on a revolving drum. When a good instrument of this pattern is kept in good working order its records are accurate enough for most purposes of climatology, and such an instrument is one of the most useful and instructive a climatological observatory possesses. Barometers are graduated to show pressure either in terms of the height of the column of mercury which balances the weight of the atmosphere, or in terms of units of pressure, viz. millibars (1000 millibars are equivalent to 29·53 inches of mercury at 32° F. and Latitude 45°, or 1 millibar = ·03 inches).

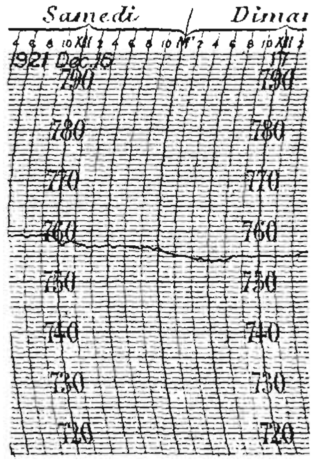


FIG. 27.

The traces of a barograph show that there are several distinct types of pressure change in the atmosphere. In temperate latitudes the most obvious and frequent is a fairly steady rise or fall which may last for only a few hours or for as long as several days (Fig. 106, p. 285); such changes are closely associated with the weather. Then there is a fluctuation which has no connexion with weather changes but depends on the time of day; the pressure increases to a maximum about 10 a.m., falls away to a minimum at 4 p.m., increases again to a second maximum at 10 p.m., and decreases to a second minimum at 4 a.m. (Fig. 26). This oscillation is greatest at the Equator and becomes less with increasing latitude, till outside the tropics it is hardly noticeable except during settled anticyclonic weather, being quite masked at other times by the weather irregularities. At the Equator it is so prominent and regular that Humboldt remarked that we can tell the time there by the barometer; the total amplitude, however, does not exceed 1/10 of an inch.

Another definite type of pressure change is seen in the jerks, usually upward, in the trace, showing a sudden

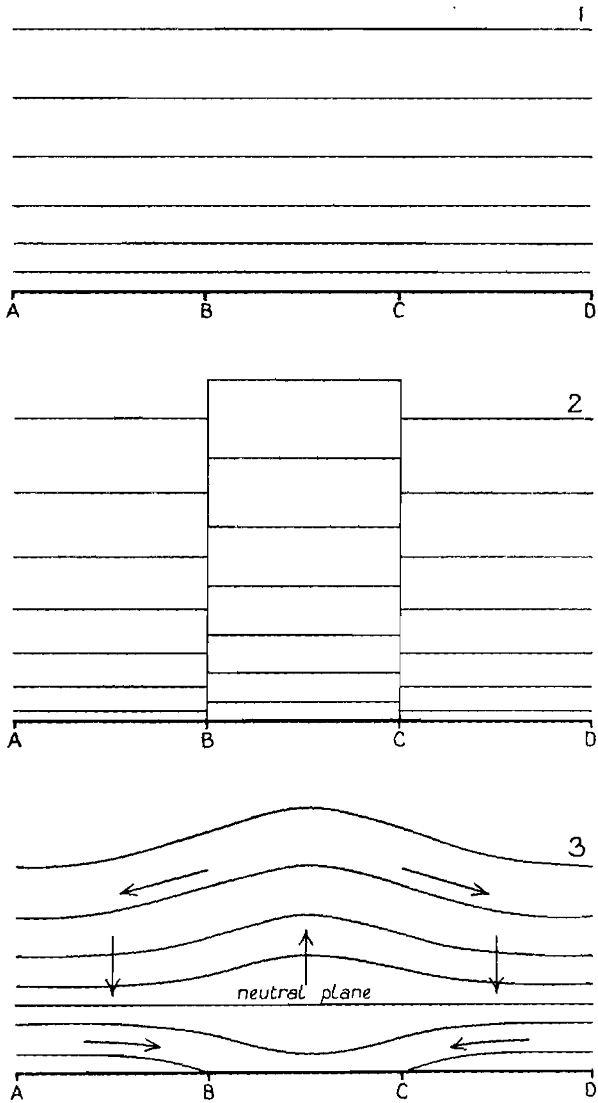


Fig. 28.

pressure change of as much as 1/10 of an inch (Fig. 97b, p. 267). They are often associated with violent phenomena, squalls of wind, heavy showers of rain, thunder and lightning.

Sometimes a generally level trace has oscillations of very small amplitude and a period of 1 or 2 hours, continuing perhaps for 6 or 9 hours (Fig. 27). They often seem to have no connexion with weather changes.

In spite of these irregularities the mean pressure is constant for any given place and season. It is low, about 29·8 inches at sea-level, in the equatorial belt, and gradually rises poleward to a maximum in the 'horse latitudes' about 30° S. and 35° N. of the Equator, where it exceeds 30·1 inches in some regions. Then there is a fall to a minimum of about 29·7 inches in the neighbourhood of lat. 60° N. and S., and beyond this a slight rise again to the Poles.

In temperate latitudes the irregularities vary from about 2 inches below to 1 inch above the mean. In the British Isles the mean is 29·9 inches, and readings below 27·4 inches, and above 31 inches have been recorded. The variations become less and less towards the Equator where the range is less than half an inch.

Pressure differences caused by Differential Heating

Fig. 28 (1) represents a section of the atmosphere; the temperature is everywhere the same along horizontal planes, and the air is at rest. Let the column of air above BC be separated by air-tight walls from the surrounding air, and the base of the column be warmed. The air expands and being unable to move sideways rises, the new position being shown in Fig. 28 (2); in spite of the heating there can be no change in the pressure of the column on BC since all the air that was in the column before it was heated is still present.

Next let the enclosing walls be removed; the air on the top of the column above BC will at once flow sideways, and a difference in pressure between BC and AB is set up since the air-flow removes air from above BC and adds air outside BC.

As soon as that happens the air near the ground will flow from AB and CD towards BC (Fig. 28 (3)). Thus the outflowing currents aloft bring about a decrease of pressure at ground level above BC and an increase on each side; the wind blows inward at the lower levels towards the heated, low-pressure area, and there are rising currents above BC to feed the outflow above, and descending currents above AB and CD to feed the surface winds. It is clear from the diagram that the upper and lower systems of winds are separated by a 'neutral plane' where there is no horizontal movement. If the heating of BC is continued the wind systems will be maintained.

On the earth we find such a system realized where a land mass is surrounded by an ocean at a different temperature, on an island, for instance, which is warmer than the ocean by day, cooler by night, giving rise to land and sea-breezes, or a continent such as Asia where the rhythm is a seasonal one with monsoon winds. And the general circulation of the atmosphere as a whole depends on the greater heating of the equatorial zone. But many of the features of the circulation are evidently not due to differential heating, and in particular most of the temporary irregularities call for some other explanation.

CHAPTER XIV

PHYSIOLOGICAL EFFECTS OF CHANGES OF PRESSURE; MOUNTAIN SICKNESS

THE human body is not sensible to such changes of pressure as are referred to in the last chapter. Changes of far greater magnitude are experienced as we ascend a mountain, or rise in an aeroplane. The lower layers of the atmosphere are the densest owing to the pressure of the layers resting on them, and therefore there is a greater fall of pressure in any given vertical distance near sea-level than at greater altitudes. The barometric pressure (approximate) when the pressure at sea-level is 29·9 inches and the mean temperature of the air 32°, is

Sea-level	29·9 in.	5,000 ft.	24·7 in.	10,000 ft.	20·4 in.
1,000 ft.	28·8 „	6,000 „	23·8 „	15,000 „	16·9 „
2,000 „	27·7 „	7,000 „	22·9 „	20,000 „	13·9 „
3,000 „	26·7 „	8,000 „	22·0 „	25,000 „	11·4 „
4,000 „	25·7 „	9,000 „	21·2 „	30,000 „	9·3 „

At 17,500 feet the pressure is only half that at sea-level.

If we ascend to considerable altitudes the change in pressure may cause 'mountain sickness'. Persons who travel from the west coast of South America to the plateau of the Andes frequently suffer from it. At first the respiration becomes faster and the skin gets blue; the mental powers begin to fail, and if the pressure becomes very low paralysis of the limbs and finally death may occur. More usually prolonged exposure to a moderate decrease of pressure as on a mountain top may lead to headaches, sleeplessness, and sickness. Mountain sickness appears to be caused by the decrease in the oxygen pressure in the lungs. If the change in altitude is effected slowly the body may be able to acclimatize itself so as to suffer no ill effects. Thus the party of the Duke of the Abbruzzi reached 24,600 feet in the Himalayas with such complete immunity from discomfort that they concluded that mountain sickness must really be due to causes other than mere change of pressure, probably fatigue. But these persons had become acclimatized by their slow ascent through the Himalayas. The trials of the British Everest expedition in 1924 show the effects on men who have recently arrived. After a climb of 50 feet, a member of the expedition writes, 'you fall exhausted on the bed. It seems touch and go whether by rapid panting you will ever catch up the deficit of oxygen in the lungs the exertion has caused. . . . Above 27,000 feet (during a climb) you may aim at doing 20 consecutive paces before you pause, arm on bent knee, to pant and rest. You sit down for some minutes at least every 100 feet'. When the change of pressure is rapid the results may be fatal. This was the case in the balloon ascent of Crocé-Spinelli, Sirel, and Tissandier in 1875. They reached 24,600 feet in some 2 hours without serious discomfort. Ballast was then thrown out and the balloon rapidly rose higher, the altimeter registering a maximum height of 28,600 feet. Soon all three occupants were paralysed and unconscious. Tissandier alone recovered consciousness when the balloon fell to 20,000 feet; his two companions were dead. It is a remarkable fact that they were all provided with oxygen apparatus, but apparently they succumbed so suddenly to the effects of the altitude that they had no time to adjust it before they lost their faculties. Evidently muscular exertion is not an essential factor in mountain sickness, but it may hasten it. Men in good physical training are less subject to it than others. The preventive is the artificial provision of oxygen, and apparatus for this purpose is regularly used by the crews of aircraft at great altitudes. As long as the normal oxygen pressure is maintained there seems no reason why man's respiration should be affected. Above about 30,000 feet pure oxygen would have to be breathed.

CHAPTER XV

BAROMETRIC GRADIENT AND AIR MOVEMENT

THE most important effect of pressure in relation to climate is its control of the winds. The air tends to move from a region of higher pressure towards one of lower, its speed depending on the steepness of the pressure gradient, that is to say on the rate at which the pressure changes. The distribution of pressure is most readily shown by means of isobars drawn on a map; they are lines through places with the same barometric pressure, and are comparable with the contour lines of altitude on a topographical map. To draw them the barometer readings at all the available stations are plotted on a map after being 'corrected to sea-level'; such a correction is necessary because the pressure differences due to altitude are far larger than those due to meteorological causes, and unless they are eliminated our map of pressure distribution will convey little information beyond the altitudes of the country. The amount of the correction depends on the altitude and on the temperature of the air. The pressure gradient is steep where the isobars are close, just as the gradient of the land is steep where the contour lines on the topographical map are close. So we may naturally expect that the wind will be strong where the isobars are close, and weak where they are wide apart.

But the air does not simply move down the gradient. Owing to the rotation of the earth all moving bodies are deflected towards the right in the north hemisphere, and towards the left in the south; there is no rotational deflection at the Equator itself; the magnitude of the angle of deflection increases from that line to a maximum at the Poles.

In Fig. 29 the arrow XY, drawn normal to the isobars and pointing from the high to the lower pressure, shows the direction of the gradient. The gradient is steeper at B than at A, and consequently the force urging the air forward is greater at B. For purposes of comparison the barometric gradient is often expressed as the difference in barometric pressure in 15 nautical miles. The following table of values which were found by Whipple and Baker to apply to Kew gives an idea of the relationship between gradient and wind velocity, but such figures can only be approximate. The velocity of the wind for any gradient becomes much greater towards the Equator.

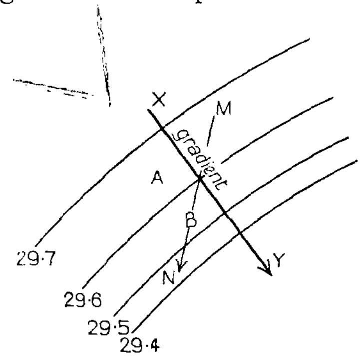


FIG. 29.

Difference in pressure per 15 nautical miles.	*Corresponding wind velocity.*
inches.	m.p.h.
0·002	5·0
0·005	7·0
0·01	9·2
0·015	12·6
0·02	16·5
0·03	25·2

In the northern hemisphere the moving air is deflected towards the right, and the resultant direction is somewhat as shown by the arrow MN in Fig. 29. On and near the surface of the earth the wind is subject to much friction, the effect of which is both to decrease its speed and to diminish the angle of rotational deflection; its velocity among the houses of a town may be less than half that in the open country. Friction is least over the sea, greater over bare flat land, and still greater over mountainous and heavily forested regions. It becomes rapidly less as we rise above the earth, and in temperate latitudes at an altitude of less than half a mile the wind blows along the isobars at a speed which is almost exactly that appropriate to the gradient in the absence of friction. This is the explanation of the fact that the lower clouds may almost invariably be observed to be moving from a direction several degrees to the right hand of the surface wind; the higher clouds are frequently floating in a stratum of the atmosphere where the gradient is not the same as near the surface, and therefore their movements are not comparable. It is useful to remember that the general air movement in the lower atmosphere of temperate and high latitudes is along the isobars.

The wind is proverbially unstable in direction and speed. Even at times when the average remains constant it really blows in a series of gusts (e.g. Fig. 109, p. 293); the degree of gustiness depends on both the atmospheric conditions and the nature of the surface over which the wind is blowing. The direction also is constantly varying slightly about the mean. The irregularity manifests itself in the vertical as well as the horizontal plane. There is almost always an eddying movement which carries the surface air upwards, and the higher air downwards, thus mixing the whole mass. This churning causes the surface conditions of temperature and humidity to be communicated to the higher layers, the thickness of the layer affected becoming greater with the speed of the wind and the distance the air travels. An interesting example is recorded by Taylor in his observations from the ice-patrol vessel s.s. *Scotia* in the neighbourhood of the Grand Banks of Newfoundland in July 1913. A warm current of air had reached the cold waters of the Labrador current and was cooled as it blew over it. By means of soundings with kites the upward propagation of the air that was cooled by contact with the cold current could be traced. It was found that after a 6 days' journey of about 1,000 miles over a surface that became colder with distance the air had been cooled up to 2,300 feet. The eddy motion or turbulence had thus caused a fall in temperature to extend upwards from the cold surface where it originated, in spite of the normal stability in still air of the arrangement of cold below and warmth above. Some interesting eddy effects among mountains are mentioned in Chapter XXVIII.

We have already explained in Chapter *VIII* how the winds may control the air temperature; the movement of the air is also in itself of great importance physiologically. The effect of the air temperature is intensified when the air in contact with the body is constantly being renewed and this is especially noticeable when the air is cold or dry (see Chapter XXX).

CHAPTER XVI

KATABATIC WINDS

THE wind has been described in the previous pages as due to differences in the general atmospheric pressure as shown by barometers on the surface of the earth. Most winds are of that class. But there are local winds caused by the action of gravity on steep slopes, which may be strong and even violent, and are due to conditions existing in the immediate neighbourhood of the surface of the earth; there is no appreciable difference of barometric pressure associated with them. The term 'Katabatic winds' has been applied to them. The two chief cases are the winds that blow down mountain sides and valleys at night (to be replaced by the valley breeze up the valleys by day), and (possibly) the winds that blow down the ice-slopes of ice-caps, especially the ice-domes of Antarctica and Greenland. These downward currents are quite shallow, and are due to their own density. Owing to the rapid loss of heat by radiation the mountain, or the ice-cap, becomes cold, and the air resting on it is chilled. Being on a slope the chilled and denser air move downward under the action of gravity without any gener disturbance of the atmosphere. On the Polar ice-caps t ill area concerned is so large and the cooling so continu ght that a permanent system of outblowing winds is establis ay and where the topography is favourable they may reach d y force. But many meteorologists insist that the process f that much greater magnitude in this case, and that pern ise he anticyclones—systems with air-pressure appreciably act than the normal—are formed, with definite inflow cy cator io here

CHAPTER XVII

WIND VELOCITY AND TIME OF DAY

THERE is usually much less wind at night than in the day; calm nights are not uncommon, but a perfectly calm day is rare; the fact that sound carries better and minute noises can be heard with startling clearness by night is in part due to the absence of wind noises. In the tropics the nights are almost invariably calm. After a calm night the wind begins to blow a couple of hours after sunrise, strengthens to a maximum in the early afternoon, and dies away again in the evening; marked fluctuations, however, are liable to occur about sunset; these times suggest a connexion with the diurnal curve of temperature. At several thousand feet above the earth the wind force is independent of the time of day. At night a layer of dense air is often formed on the surface of the earth owing to rapid loss of heat, and the density may be such that the air remains still, unaffected by the movement of the wind aloft. After sunrise heating begins, and in an hour or two the surface becomes so warm that convection currents are set up, effecting an interchange between the still air below and the rapidly moving air above, and the calm of the night gives place to a breeze. The wind blows stronger as long as the heating continues, and dies away again as the cool of evening comes on; in the interior of the British Isles it is usually more than twice as strong in the afternoon as in the night hours; thus at Kew the mean velocity for July 1926 was 5 miles an hour from 1–5 a.m., and 10 miles an hour from 1–5 p.m. On the coasts the increase during the hot hours is less, and in thnter it is slight. But even on the coast of Greenland there coi, slight tendency to an afternoon increase during the of amer. At Athens the mean velocity in winter ranges dista 7 miles per hour at 4 a.m. to 11 miles per hour at 4 moticand in summer from 3 miles per hour at 4 a.m. to 15 to extoer hour at 4 p.m. At Helwan, near Cairo, the range in spitcity from day to night is twice as great in summer of cold inter; it is least in December, when the wind is effects at at 3 p.m. (mean 7·7 miles per hour) and weakest at 8 a.m. (mean 2·7 miles per hour), and greatest in June, when the wind is strongest at 8 p.m. (mean 16·1 miles per hour) and weakest at 6 a.m. (mean 5·3 miles per hour); the lateness of the time of maximum here is due to local causes.

The increase in the wind velocity by day in the lower atmosphere must have its complement in a decrease in the higher strata, and vice versa at night. Paris provides an excellent example. Fig. 30 shows how the wind increases

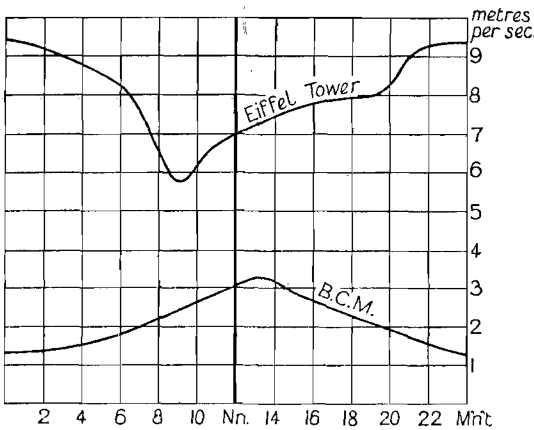


FIG. 30. The mean velocity of the wind in July on the top of the Eiffel Tower, Paris, and at the Bureau Central Météorologique, near the foot of the Tower

with the heat of the day in Paris itself; but on the top of the Eiffel Tower, 1,000 feet above, there is a pronounced decrease from night to day. The curves are similar throughout the year, but the amplitude is much greater in summer. These curves also show that the wind is very much stronger at all hours at the higher station.

A consideration of the simple underlying causes will explain most variations. At sea the surface heating is slight and there is little change in the wind from night to day; in some regions the wind is stronger at night. On land a screen of cloud may prevent any change in the force of the wind by checking loss of heat and consequent increase in the density at night and superheating with consequent active convection by day. Sometimes in autumn a clear frosty night is followed by a cloudless hot day, and yet no phere

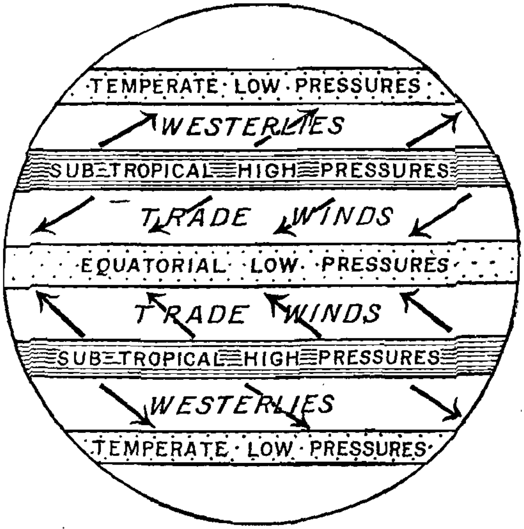

TEMPERATE LOW PRESSURES
WESTERLIES
SUB-TROPICAL HIGH PRESSURES
TRADE WINDS
EQUATORIAL LOW PRESSURES
TRADE WINDS
SUB-TROPICAL HIGH PRESSURES
WESTERLIES
TEMPERATE LOW PRESSURES

FIG. 31.

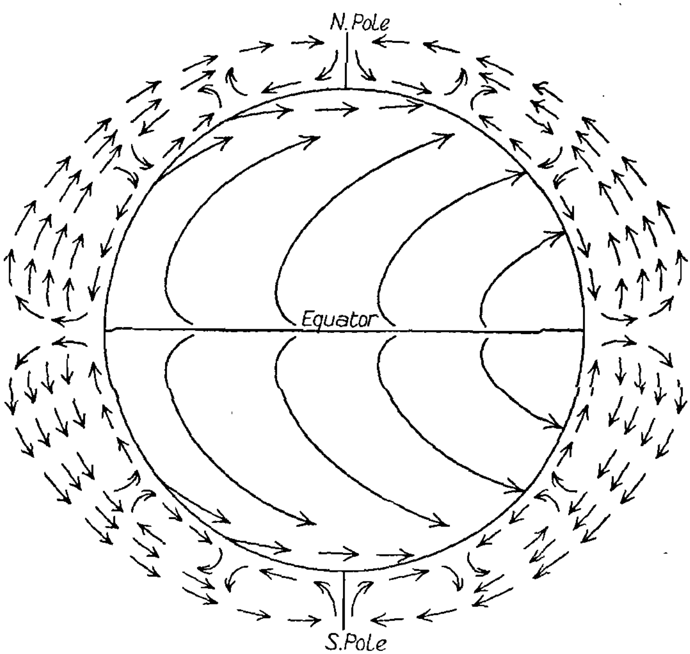

N. Pole
Equator
S. Pole

FIG. 32.

springs up; the explanation is generally found in the existence of very calm anticyclonic conditions, so that the convectional interchange merely replaces the heated calm surface air by calm air from aloft. Conversely, on a cold clear night there may be a strong wind; in this case the wind aloft is so strong that it breaks up the denser layer that tends to form on the surface and mixes it with the main mass of the atmosphere.

The dense surface layer at night is often made visible by the surface mist which is condensed and fills the depressions, to appear as a white sea when the morning light falls on it. And the convectional ascent during the heat of the day is shown by the cumulus clouds to which it gives rise.

CHAPTER XVIII

THE WIND SYSTEMS OF THE GLOBE

THE great wind systems directly control most of the climates of the globe. They are themselves controlled by the great pressure systems, whose differences they are always striving to equalize. Hence an understanding of the pressure distribution, the fundamental element in the geography of the atmosphere, is an essential basis of the study of climate.

Fig. 31 is a diagrammatic sketch of the arrangement that would probably be found on the globe if the surface were homogeneous, all land or all water, and this arrangement is recognizable in the actual distribution of pressure in April or October, in which months the disturbing effects of land and water on temperature are least prominent.

The pressure belts owe their existence primarily to the differential heating of the globe by the sun. The equatorial belt of low pressure is thus explained; but obviously this explanation fails us outside the equatorial belt, for actually the lowest mean pressures are found in high latitudes, about 60° N. and S., and there are belts of high pressure in the sub-tropics.

The air that is warmed and expanded over the Equator rises, and flows away in the higher strata of the atmosphere towards higher latitudes, where the cold causes contraction, descent and an inflow aloft (Fig. 32). Thus there is set up a general movement from the Equator towards the Poles in the higher atmosphere, and it is probable that the air pressure at heights above 12,500 feet decreases steadily from Equator to Poles. But all moving bodies come under the influence of the rotation of the earth, the magnitude of the rotational force increasing rapidly with the latitude. Hence in their poleward journey these air currents become deflected more and more towards the east, until in high latitudes a gigantic circumpolar whirl is set up. Another influence now makes itself felt, for centrifugal force is developed in a rotating mass of this kind, and the air, instead of reaching its Polar goal, tends to be thrown back towards the Equator, since its speed is much greater than that of the earth below. The upper winds are therefore moving eastward and poleward in low latitudes, eastward with a slight equatorward component in high latitudes. The result is a piling up of air between the thermal outflow over the Equator and the dynamical, centrifugal, movement in high latitudes, giving high atmospheric pressure in the sub-tropics.

Poleward of these high-pressure belts pressure becomes less towards the poles, the centres of the circumpolar whirls. The lowest pressures might be expected at the poles themselves, and in fact it was long thought that the pressures there were extremely low; but it is now known that in Antarctica at any rate the thermal influence is so strong as to assert itself over the dynamical force of the circumpolar whirl, and produce an increase of pressure, slight but quite sufficient to effect a change in the wind direction from westerly to easterly. The matter is more fully discussed on p. 109.

These pressure belts swing some 5° to 10° towards the north in the northern summer, and some 5° to 10° south in the southern summer, following the seasonal temperature changes.

The winds we have been considering so far have been those in the higher atmosphere, not those on the earth's surface. The surface winds are caused by the differences of pressure which are themselves, in part, the effect of the upper winds. Fig. 31 shows the 'planetary' winds on our imaginary globe, which must result from the distribution of pressure that has been described. The air is rising at the Equator, this movement being, perhaps, the most fundamental in the whole circulation. It is not possible to measure the volume and velocity of vertical currents in the atmosphere, but the ascent in this belt is proved by the dense cumulus clouds, and the heavy rain that falls almost every afternoon. It seems surprising, in view of the velocity and extent of the trade winds which are always blowing towards

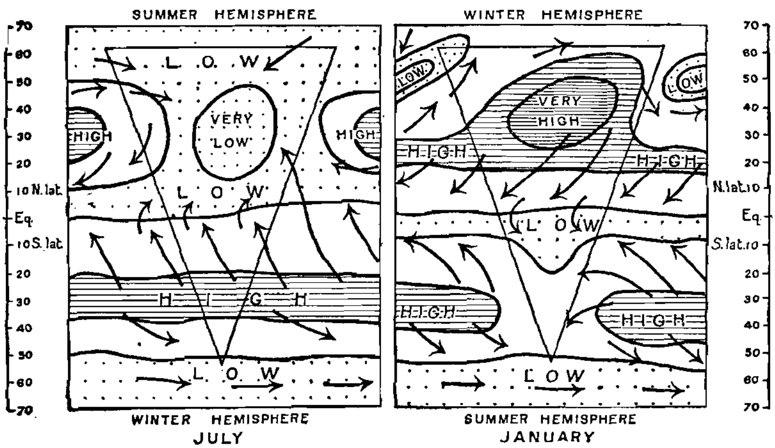


FIG. 33.

the Equator, that the ascent of air where they meet is not more prominent than it is. But two facts must be remembered in this connexion: the trades are shallow systems, with an average depth of 5,000–8,000 feet; and the equatorial belt being a great circle of the earth has a greater diameter than the latitudes of the trades, and the vertical movement is correspondingly diminished.

In the Horse latitudes the air is descending, but again the vertical movement is probably very slow; it is estimated by Shaw at about 300 feet in the day.

It must be admitted that the general circulation of the atmosphere is by no means fully understood, and other representations of some of its features than the scheme of Fig. 32 have been given by meteorologists.

It is necessary now to consider the complications that actually exist. Over the lands pressure tends to be low in summer, high in winter, while the oceans in the higher latitudes are relatively cool in summer, and so favour high pressures, very warm in winter and favourable then to low pressures.

These local thermal influences are superposed on the diagrammatic scheme of Fig. 31, and the result may be represented, again diagrammatically, as in Fig. 33, based on Hettner, *Die Klimate der Erde*. The triangular shape of the land mass is chosen as representing roughly the actual land masses of the earth. In the July diagram the equatorial low-pressure belt lies somewhat north of the Equator; but the most notable feature is the break in the sub-tropical high-pressure belt over the land in the summer hemisphere; the land is hot enough to develop a low-pressure system in spite of the planetary tendency to high pressure. The air that is displaced from the hot continent tends to accumulate over the sub-tropical oceans, where large detached anticyclones are formed. The planetary belts of the southern hemisphere are hardly disturbed. The winds of the northern hemisphere are profoundly modified. In particular the north-east trades no longer form a belt round the globe in the summer hemisphere, but blow only on the east and south sides of the sub-tropical anticyclones over the oceans, their direction being north, north-east, and east; on the south and south-east of the summer continent they are replaced by 'monsoonal' winds drawn in from the south; they are in most cases a continuation of the south-east trade winds of the southern hemisphere which have crossed the Equator. It will be noticed that these monsoonal winds blow in some parts in the opposite direction to the trades they replace, and we may add also that in their conditions of temperature and humidity also they are the opposite of the trades.

In January (right-hand diagram of Fig. 33) the severe cold in the northern continent intensifies the sub-tropical high pressures which are extended far north so as to cover the land mass, and even form a detached anticyclone with very high pressures. Owing to this accumulation of the air

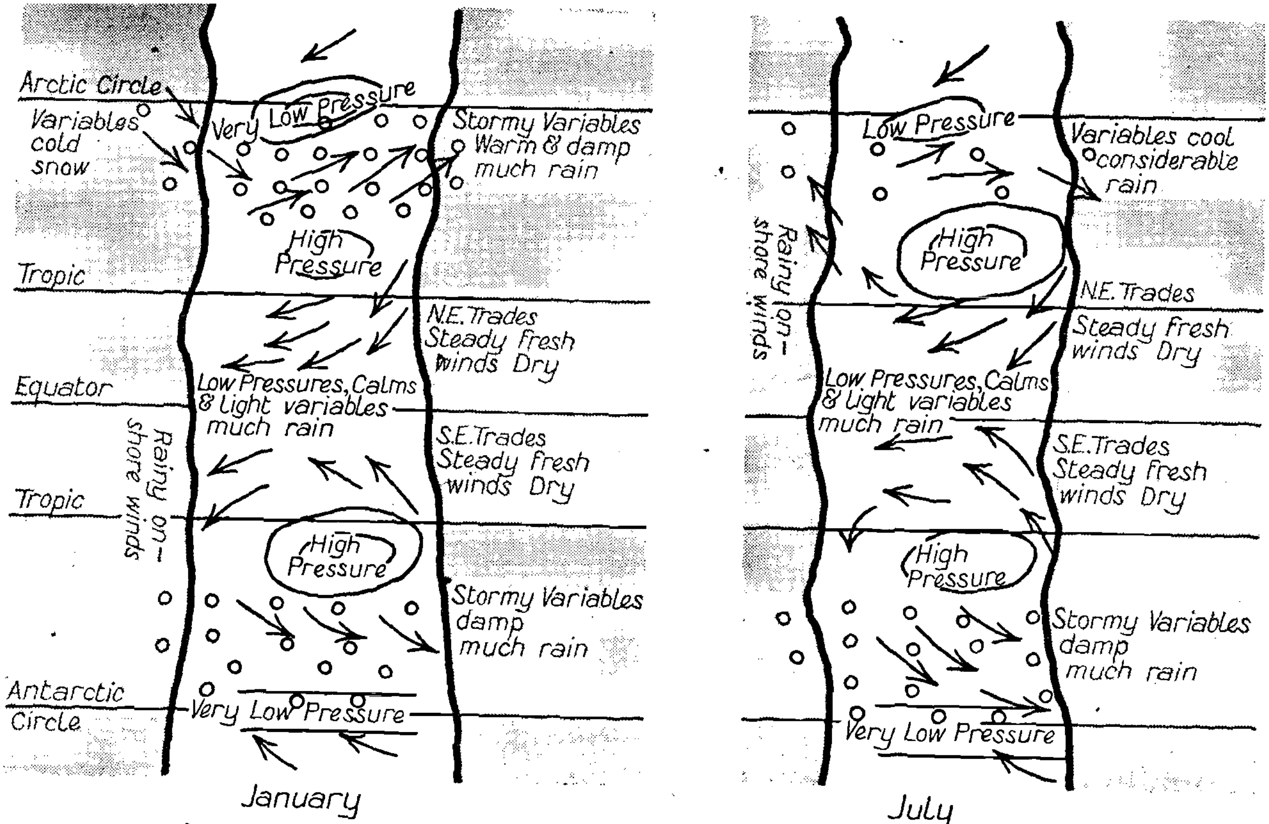


FIG. 34. Pressure and winds (generalized) over an ocean. The small circles indicate cyclonic activity

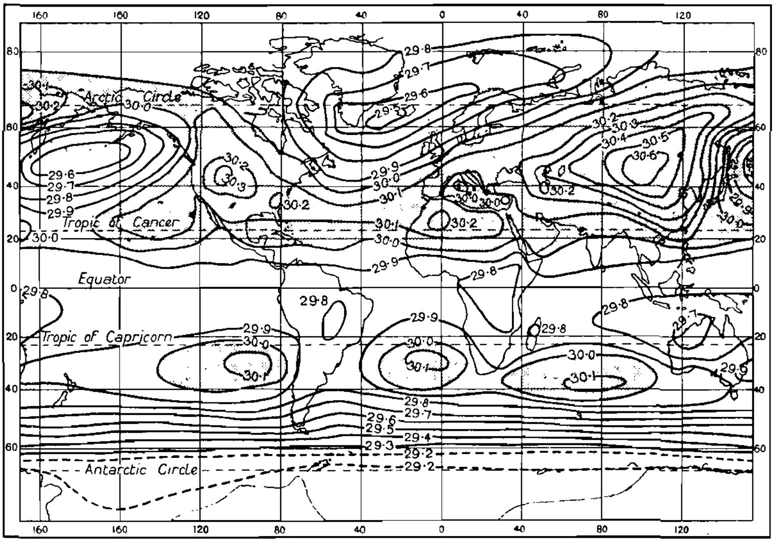


FIG. 35. Mean Isobars for January

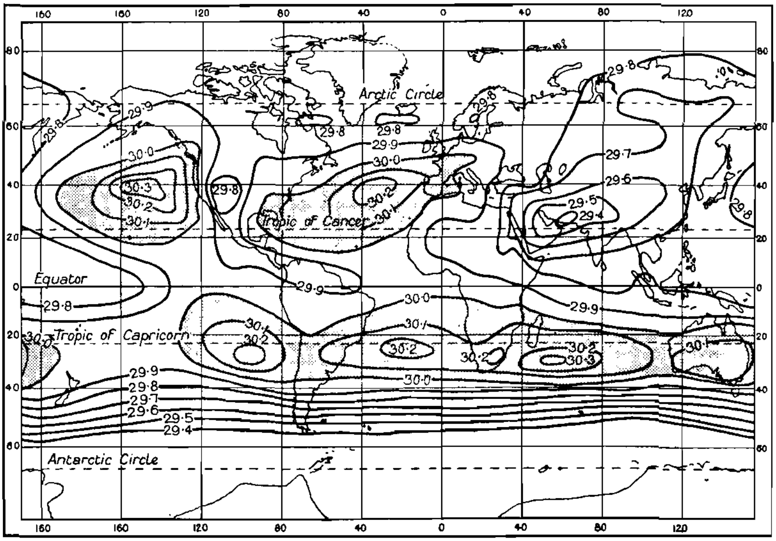


FIG. 36. Mean Isobars for July

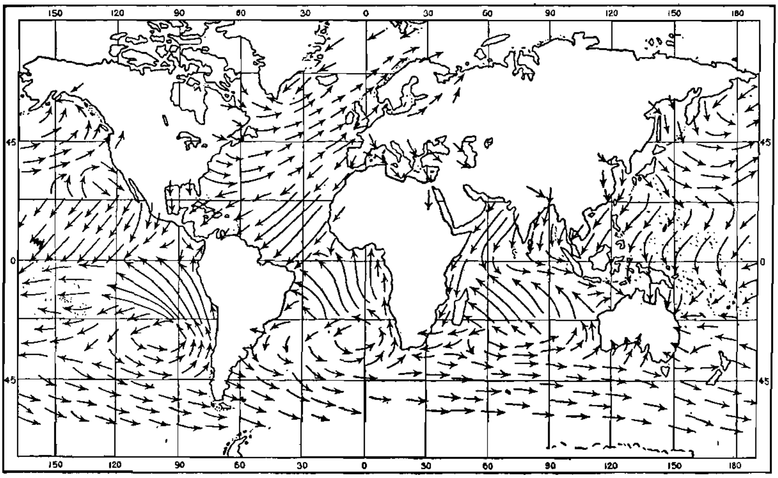


FIG. 37. Winds in January

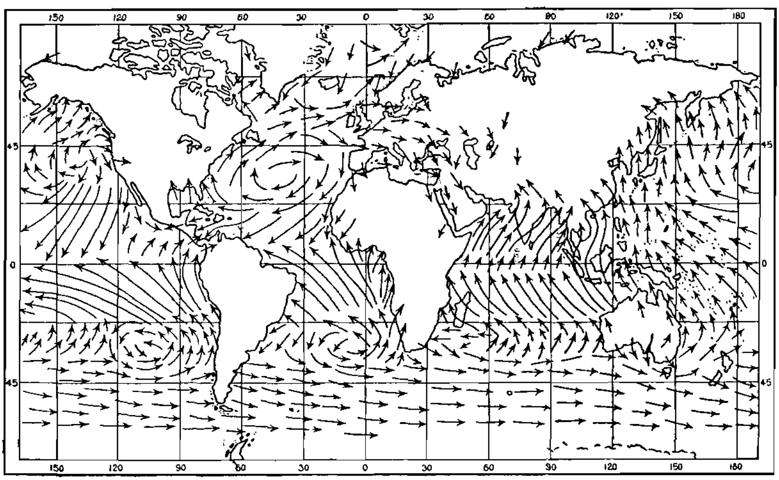


FIG. 38. Winds in July

over the land the oceans have less, and the sub-tropical high pressures over the oceans are little more than connecting strips joining the continental anticyclones. The temperate low-pressure systems over the oceans have much lower pressures than in summer, and are regions of very vigorous cyclonic activity, the scene of the storms of the westerlies. The southern hemisphere is now enjoying its summer, and the land becomes hot enough to draw the equatorial low-pressure belt, which normally lies at this season a few degrees south of the Equator, still further south, and to develop a definite but shallow low-pressure system, which breaks the continuity of the sub-tropical high-pressure belt. The north-east trades blow strongly in an almost unbroken belt in the northern hemisphere, and their strength is much increased by the continental anticyclone. On the east side of the anticyclone there are strong north-west winds, the winter monsoon of China and to a less degree of Labrador, where in summer there was an indraught from the south-east. The westerlies are shown passing round the north of the anticyclone.

In the southern hemisphere we see the same modifications (though less prominently developed) as in the northern hemisphere in July; the trades are replaced by monsoonal winds on the east coast, and light winds are drawn in to the equatorial low pressures across the Equator, the 'deflected trades'.

Fig. 34 shows the general conditions over an ocean and its east and west coasts more clearly, and Figs. 35–38 give the actual distribution of pressure, and the prevailing wind systems in winter and summer. The close resemblance to the theoretical schemes that have been described will be evident.

CHAPTER XIX

THE MAJOR REGIONS OF PRESSURE AND WINDS

The Equatorial Belt

AROUND the Equator the barometric pressure is low, and uniform in place and time, the most striking variation being the semi-diurnal pressure wave (Fig. 26). The great irregularities which are so prominent in temperate latitudes are unknown, one reason being that should a localized system of lower pressure develop it would very soon be filled up by the direct radial inflow of air from all sides, for there is no rotational deflection to divert the air from the gradient direction.

The winds are normally sluggish, but there are exceptions. On the coasts the sea-breeze is important (see p. 303). Occasionally tornadoes vary the monotony. These are thunder-squalls, often very violent, but lasting only for a short time, sometimes only a quarter of an hour. As a rule there is a very heavy downpour of rain, accompanied by violent thunder and lightning. But in general the region is one of calms and light airs, and the absence of a brisk wind intensifies the enervating effect on Europeans of the hot vapour-laden air.

This belt extends between about 5° N. and 5° S. latitude. But there are many regions within it which do not conform. Thus the east of Africa and the whole East Indies region are influenced by the monsoonal winds of the Indian Ocean. Moreover, there are few areas which remain under true equatorial conditions the whole year. Owing to the seasonal swing of the pressure belts the trade winds of the north or the south hemisphere, or both alternately, blow over the Equator for part of the year, and bring with them the usual trade-wind characteristics, causing a pronounced seasonal change. Throughout the year the coasts of the equatorial belt are beaten by the heavy surf which swings across from the windy belts on each side.

The equatorial calms are the 'Doldrums' of the sailors, where sailing ships may sometimes be becalmed for days.

In the days of sail it was a matter of importance and frequent discussion in what longitude the passage of the Doldrums should be made in the course of a voyage between the North and South Atlantic, or the North and South Pacific, ship-masters being willing to take a longer course if by so doing they could cross the Doldrums at their narrowest. But calculations were often upset, and days might be lost in the baffling airs and sultry weather of this tract. The duration of long voyages depended considerably on the ship's luck in this part of the voyage.

The Trades

Between the sub-tropical high pressures (the Horse Latitudes) and the equatorial low pressures the trade winds blow, from north-east in the northern hemisphere, and south-east in the southern; they sweep over a great area of the earth's surface. The isobars for January show that in the northern hemisphere the sub-tropics are covered by a continuous belt of high pressure reinforced by the cooling of the land masses in the northern winter; indeed the 'belt' consists rather of great high-pressure systems over Asia and North America, joined by bridges over the oceans, where the pressure is considerably lower, though still appreciably higher than on the north and south.

The anticyclone over Asia is especially prominent, the central region being enclosed by the isobar of 30·7 inches. It must be remembered, however, that most of this area consists of plateau some 4,000 feet or more above the sea, so that a large correction for altitude has been added to the actual barometer readings. The topography is partly responsible for the very high pressure. The interior of the continent becomes very cold, and the cold air collects in the great basins which are to a large extent enclosed by the mountain ranges. The cold layer therefore becomes deeper, and gives higher barometric pressure. The North American anticyclone is much less intense, chiefly owing to the open passage for air movements on the north and south.

The equatorial low-pressure belt is somewhat south of the Equator, and over the three southern continents the heat of the summer reduces the pressure still more, the result being that the equatorial belt has southward bulges in which the pressure is lowest some 10° to 20° of latitude south of the Equator.

The north-east trades blow from the sub-tropical high pressures of the northern hemisphere to the equatorial low pressure. They are strongest and steadiest between the tropic of Cancer and 5° N. lat. They are very weak on the Equator, and when they cross the Equator in their journey to the low pressures in the southern hemisphere they undergo rotational deflection towards the left, and become light and variable north-west winds.

The sub-tropical high-pressure belt of the southern hemisphere is much less extensive than that of the north, and its continuity is interrupted by the continents because of the summer heat over the land, which is conducive to low pressures. Hence we find as the most prominent feature detached high-pressure systems over the eastern Pacific, Atlantic, and Indian Oceans, with an anti-clockwise air circulation. The north and east sectors of this circulation form the south-east trades, which are particularly strong and steady owing to the great expanse of ocean over which they blow; but on the west of the high pressures the winds blow from the north, and are very different in character.

In July it is winter in the southern hemisphere and the high-pressure belt is continuous; the equatorial low pressures are well north of the Equator, and consequently the trades cross the line, becoming south-west winds owing to the change of rotational deflection. In the northern hemisphere the heating of the land masses breaks the continuity of the sub-tropical high-pressure belt so that it is hardly recognizable as such. The arrangement really is a great low-pressure system covering most of Asia, a similar but much less marked system over North America, and prominent anti-cyclones over the North Atlantic and North Pacific Oceans. The north-east trades are completely interrupted on the west sides of these anti-cyclones, the prevailing winds on the south-east coasts of North America and Asia being southerly.

The trade winds are notable for their steadiness, especially at sea; over the oceans they are the steadiest winds on the earth. Indeed, in the heart of the trade-wind regions the wind is almost constant in direction and force, day and night throughout the year, and cyclonic disturbances are practically unknown (Fig. 39). The mean wind direction (percentage frequency) in St. Helena, which lies in the centre of the south-east trades of the South Atlantic, is:

	N.	*NE.*	*E.*	*SE.*	*S.*	*SW.*	*Calm.*
Jan.	—	—	5	76	19	—	—
July	1	2	9	62	20	1	5

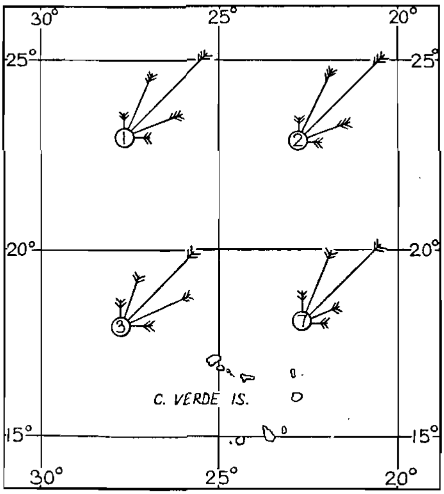


FIG. 39. Mean Wind Frequencies in July. The figures in the centres of the wind-roses indicate the numbers of calms

The importance of the trades for navigation is indicated in Chapter XX.

'For four days we steamed south and east before the fresh trade breeze. The ocean was piled on end about us in white-crested ridges, flashing green on their sides, violet in the hollows. The sky was one unbroken sweep of crystalline ether, fading into neutral on the sea rim, while a glorious rush of pure keen air awoke weird music from every tight-strung shroud, and filled each cranny of the ship with life and freshness. And this is the weather the N.E. trades, blowing all the way from Cadiz Bay to Cape de Verde, bring with them. Now and then we crossed the course of a great four-masted clipper, storming down wind for Australia round the Cape under wide breadths of straining sail-cloth, with the ocean roaring apart beneath her swinging bows, and spouting high about the quarters as she tore through it at eleven knots.' (Bindloss.)

In the interior of a continent the trades are less steady than on the oceans, but they show their main characteristics especially over the hot deserts. The strong heating of the land by day, and the cooling at night cause the diurnal variation in wind strength to be well marked. The nights

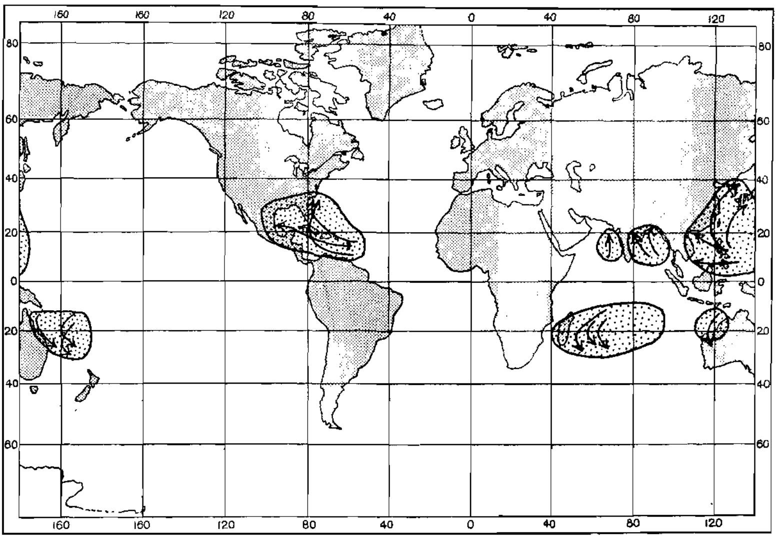


FIG. 40. The chief regions subject to tropical cyclones are stippled. The arrows show some of the usual storm tracks

are often calm, but at sunrise the wind begins to blow, lightly at first, to reach a maximum in the hottest hours and die away again towards sunset. The topography may give rise to considerable local variations in the direction.

There are irregularities even in the generally uniform trades. Along the coasts the greater heating of the land causes the winds to be drawn in, so that in some regions there is an almost constant on-shore deflection. This is the case on the coast of south-west Africa. A few hundred miles out at sea the south-east trades are notably steady, but on the coast the prevailing winds are south-west throughout the year, strongest and most persistent during the hottest hours in summer. They are cool and damp, and in many places almost perpetually fog-laden, in complete contrast to the trades with their bright skies and dry bracing air.

Another exception, and a very important one, to the steadiness of the trades, is found in the west equatorial sector of the oceans over which they blow. One such area includes the West Indies, another lies round the Philippine Islands (Fig. 40). These regions are liable to be visited by terrible storms of wind and rain, known as hurricanes, typhoons, or cyclones. The winds are among the most violent on the earth and they work extraordinary havoc both on land and sea. The storms are essentially maritime and seldom penetrate far inland, but the islands in the seas frequented by them, and sometimes the continental coasts, have to bear all their fury, and they often suffer severely. Even high-powered steamers are in serious danger unless they can escape in time from the area of disturbance.

The cyclones originate in definite regions, where the trades are dying out and merging into the equatorial calms over the hottest parts of the oceans. The local heat and moisture of the Doldrums are predisposing causes. These conditions are present in even greater degree sometimes when the Doldrums lie on the Equator itself, but on the Equator there is not the necessary rotational deflection to set up the whirl which itself tends to increase the violence of the storm by the centrifugal force it generates. Cyclones are likely to originate in late summer and autumn when the Doldrums lie at their greatest distance from the Equator, in latitudes where the rotational deflection is considerable and the temperature of the ocean still high. The meeting of the north-east and the south-east trades (deflected north of the Equator into westerly winds) possibly tends to set up a revolving movement, and may thus assist the formation of the cyclones; probably a marked discontinuity in respect of temperature and especially humidity is always present. Abnormally cold air in the higher atmosphere above the cyclone is probably another necessary condition. The South Atlantic is the only tropical ocean in which cyclones do not occur, and it is noteworthy that the Doldrums never swing south of the Equator here, nor yet do the north-east trades cross the line.

FREQUENCY OF TROPICAL CYCLONES

Percentage monthly frequency.

	Average number per year.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
W. Indies . .	6	0	0	0	0	0	7	7	16	32	31	6	1
China Seas . .	22	4	2	2	3	5	6	15	16	19	15	9	5
Arabian Sea .	2	4	0	0	5	11	25	7	0	4	22	18	4
Bay of Bengal .	10	0	0	0	2	5	11	18	15	19	15	10	5
S. Indian Ocean (Mauritius region) . .	6	21	29	20	9	3	0	0	0	0	1	4	13
S. Pacific (Fiji Is., Queensland) .	2	23	18	22	9	4	6	5	0	3	2	1	7

The storms develop in the midst of an extensive area where the barometer is falling, and the winds are weak and irregular and the weather sultry. At some spot the fall of the barometer becomes more rapid, and the wind blows in from all sides. The area of rapidly falling barometer is not extensive, and the winds, influenced by rotational deflection, soon form a rapidly rotating whirl round it, anti-clockwise in the northern hemisphere, clockwise in the southern. The weather conditions are almost uniform in all directions from the centre (Fig. 41). The centre itself, the core of the storm, is a small region perhaps 20 miles in diameter, where the pressure is very low, and the winds light and irregular, but the waves are particularly high and dangerous owing to the violent cross seas produced by the winds round about. Sometimes the air is quite calm and the sky clear in the 'eye of the storm' as the core is called. Outside the core the winds are revolving with hurricane force, the transition from calm to shrieking hurricane being often extraordinarily sudden, and many a ship has been taken aback. The sky is covered with dense black clouds, and a torrential downpour of rain, often with violent thunder and lightning, completes the tempest. With increasing distance from the centre the violence becomes less, and finally there is a rapid but not sudden transition to light winds. The total diameter of the whirl may be from 100 to 200 miles.

A ship which is so unfortunate as to find herself exactly on the track of an advancing hurricane may experience the change from a moderate breeze and fair weather to the full

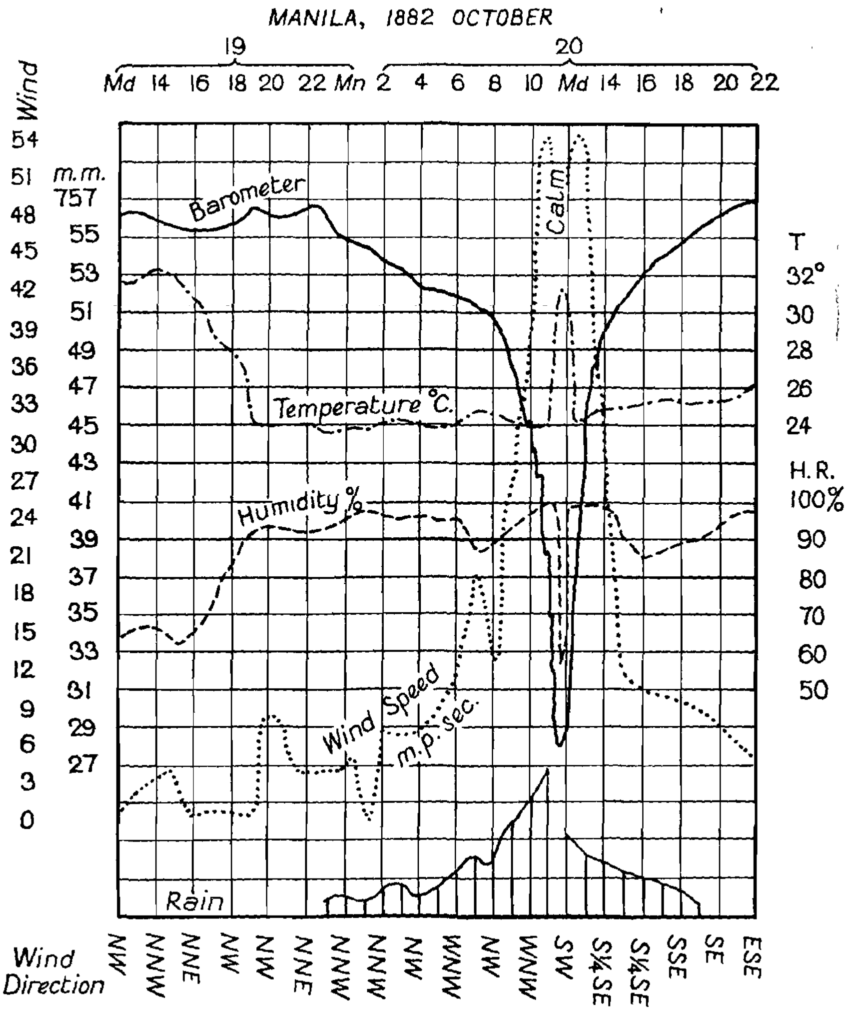


FIG. 41. Meteorological conditions at Manila, Philippine Islands, during Typhoon. The centre of the storm passed over the station about noon on October 20

violence of the hurricane within a few hours. Reaching the eye of the storm she is in calm air for a short time, but quite suddenly finds herself again in the hurricane blowing from the opposite direction on the other side.

The cyclones move along more or less precise tracks at a speed which is very variable but averages about 12 m.p.h. Shipping losses are of course much less frequent in these days of steam. But the damage done on land tends rather to increase with the advancing standard of life and the building of more elaborate settlements. In the West Indies and on the south-east coasts of the United States the havoc is frequently very extensive. Trees are uprooted, crops washed away or

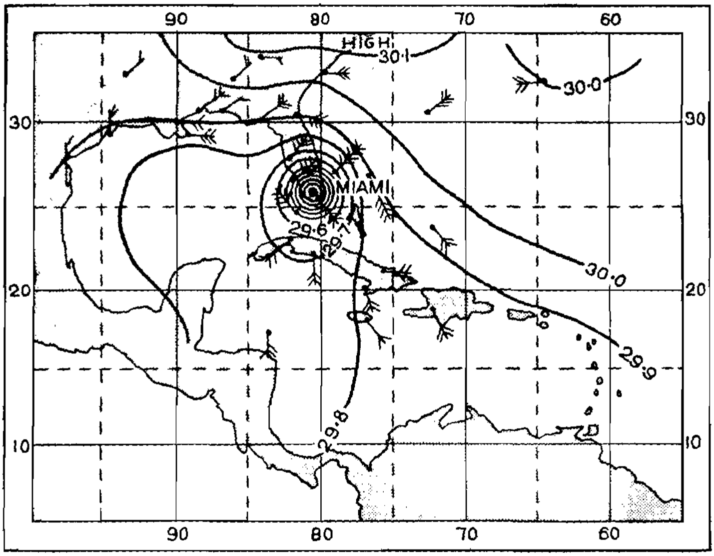


FIG. 42. Synoptic Chart, September 18, 1926, 8 a.m.

buried, buildings and factories destroyed, roads, railways and embankments carried away, while additional destruction is often wrought by the huge waves that sweep in from the sea. Thousands of persons may be killed or injured, and the after effects of the storm are frequently even more serious, when sanitary works for drainage and water-supply have been destroyed, and typhoid and other diseases break out and spread with great rapidity in the stricken community.

A violent hurricane (Figs. 42 and 43) struck the coast of Florida on September 18, 1926, and devastated Miami—

'At noon it was realised that the centre of the storm was moving towards Miami. . . . In the evening the wind freshened, and by midnight it was blowing a full gale. Thereafter it steadily increased in violence until daylight, blowing in this first phase from the north and north-east. Estimates of a force of 110 to 120 miles an hour were made. Mere figures can convey no picture of the physical suffering and mental distress caused by the furious onslaught of the elements, wind and driving rain, wave and thunderbolt, amid the crashing of palms and firs, sputtering of telephones and vivid flashes from high-tension wires. Sign-boards and roof-tiles hurtled through the air, roofs were ripped off and wooden houses crumpled up like matchwood. . . .

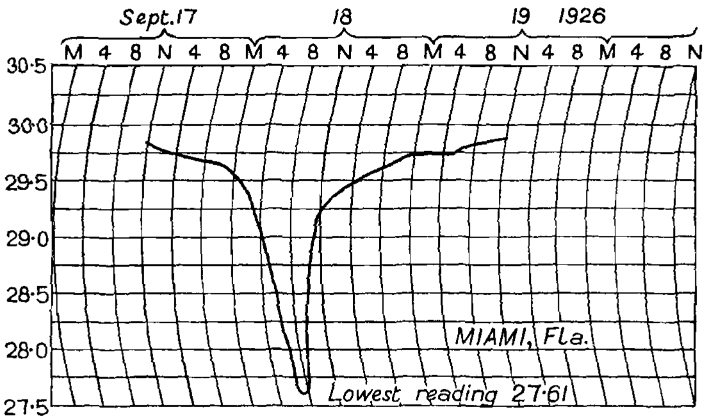


FIG. 43. Barogram recorded during the hurricane at Miami

During the lull, which came as the centre of the storm moved over the coast-line, many women and children were moved to safer dwellings and some injured were brought to the hospitals. As most people did not realise that a second phase was coming, the lull was not fully utilized and many were caught wandering about the streets looking at the damage. About 8 a.m. the wind came again with increased fury, blowing now from the south and south-east, lashing into mountainous seas the high tides of the equinoctial full-moon. Within the bay behind the islands the wind drove the tide northwards to encounter the flood-waters pouring down from the Everglades into the inlets of Miami and Fort Lauderdale. Banked up in these inlets the waters spread out through the city and suburbs, loosening foundations of houses and roots of trees and palms. It was during this phase of the storm that most of the casualties occurred. About half of those who met their death were drowned. The remainder were caught in the collapse of houses, or hit by flying debris as they ran to other shelter.' [*The Times*.]

At least 114 lives were lost in the Miami district, and the damage to buildings (exclusive of furnishings) was estimated at £15,000,000.

Monsoons

This word, derived from an Arabic word for season, is applied to those wind systems in which the prevailing direction is reversed or almost reversed from summer to winter. They are especially prominent within the tropics on the east side of the great land masses, but they occur also outside the tropics, as in East Asia as far north as about 60° N. lat. The following statistics show the degree of completeness of the wind reversal.

North China. Percentage Wind Frequency.

	N.	*NE.*	*E.*	*SE.*	*S.*	*SW.*	*W.*	*NW.*
Winter .	17	8	5	6	6	8	18	**32**
Summer .	10	9	12	**26**	16	10	7	10

In winter the outblowing continental winds are notably strong and regular in north and central China, which receives the full sweep of the cataract of cold air that pours over the eastern rim of the interior plateaux; and owing to the proximity of the deserts the winds are very dry and dusty as well as cold. Their prevailing direction is north-west in north China, north in central China, and they work round to north-east in the south of India; these directions will be readily understood on reference to the position of the high-pressure system which controls them. The very bold feature lines of the south of the Continent introduce important modifications. In particular the plains of the north of India are cut off from the interior of Asia by the great barrier of the Himalayas and associated ranges, and by the plateau of Tibet, and are thus sheltered from the winds which blow out from the interior of the Continent. Instead there is merely a gentle drift, generally from the north-west, down the river valleys; these local currents merge into the normal monsoon current in the south of India. The winds are much lighter in the Indian region than in China. The winter monsoon finds its goal in the equatorial low pressures which lie just south of the Equator in the Indian Ocean, and over the hot interior of Australia.

Though the winds of this monsoon may be considered steady by comparison with many of the other great wind systems, yet they are liable to much interruption by cyclonic disturbances. The interruptions are least in evidence in the north of China, but the occasional snowstorms there, and the not infrequent dust-laden gales, are clearly caused by

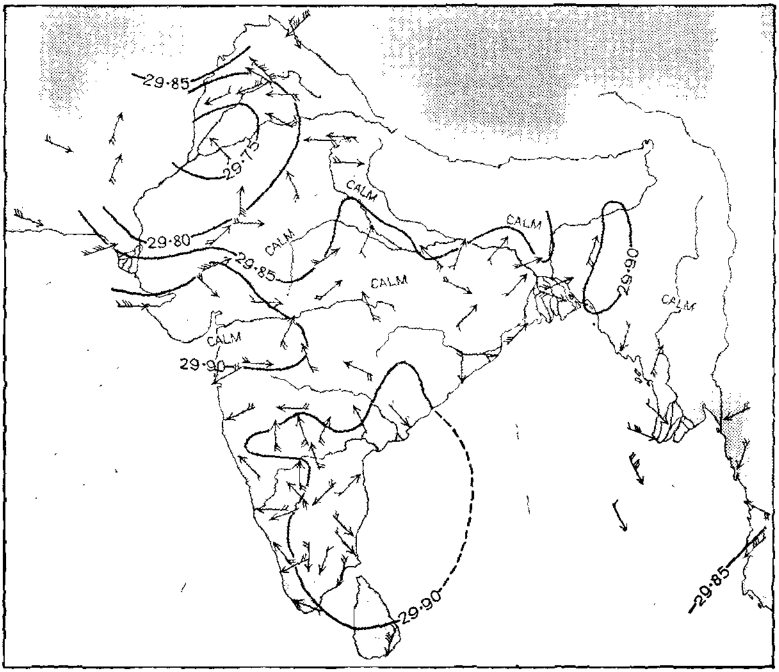


FIG. 44. A cold-weather cyclone in north-west India, 1921, February 27, 8 a.m. The Beaufort scale of wind force is indicated by the number of barbs on the wind arrows

passing irregularities of pressure. The lower Yangtze Valley has frequent cyclones, shallow systems which move east from the interior, and cause southerly winds to blow on their front; these winds, coming from the sea, are rainy and warm by comparison with the usual north wind of the monsoon. Disturbances of apparently the same type are well known in the north-west of India. They appear frequently on the daily synoptic charts (Fig. 44) which show that they come from Persia and Afghanistan and travel slowly towards Bengal. Though they are of no great intensity, and cause only light winds, they are important as giving an appreciable rainfall (from $\frac{1}{2}$ to 2 inches in January) to a considerable area, and making possible the cultivation of wheat. Their passage causes a marked change in wind and weather from the usual fine conditions and light breezes of the cold weather season.

The winter monsoon lasts from October till March. By April there is a low-pressure system over Asia, and it deepens with the increasing heat of summer. Until June the doldrums of the Indian Ocean still persist, but in the early part of that month the pressure over Asia has become so low, and the sub-tropical anticyclone of the South Indian Ocean so much intensified, that a continuous gradient is established right across the South and North Indian Oceans and India, and the south-east trades, no longer finding a low-pressure trough to act as a barrier at the Equator, continue to India as a strong and steady south-westery current, saturated with moisture owing to its long passage over the ocean. The strong winds and heavy seas, overcast skies, and frequent downpours of rain form a striking contrast to the winter conditions. The relief of the land in the Indian region exerts a marked control over the summer monsoon as over that of winter. The monsoon surges forward with a definite 'front', and reaches given points at approximately the same date each year, e.g.

Bombay . . .	June 5
Bengal . . .	June 15
Punjab . . .	July 1.

The direction and speed of the monsoon are influenced by the Himalayas especially, and three main currents may be distinguished. One of these meets the western Ghats at right angles, another advances from the south up the Bay of Bengal, and the third comes from the south-east and blows up the Ganges Valley (Fig. 45). The centre of lowest pressure is over Sind and Baluchistan, and hence the last current is easily understood. The Himalayas constrict it, and prevent its northward extension, and so, indirectly, limit the northward extension of the main south-west current of the Arabian Sea; an important result of this is that the main monsoon current does not blow up the Indus Valley. Another effect of the Himalayan barrier is the cutting off of any inflow from the north to the low-pressure centre, and a consequent strengthening of the currents on the south and east. The monsoon continues till the middle of September over all India, and then retreats, the north-west being the first part of the country to lose it. It ceases in Bengal towards the end of October, and in the south-east of the Deccan at the end of December.

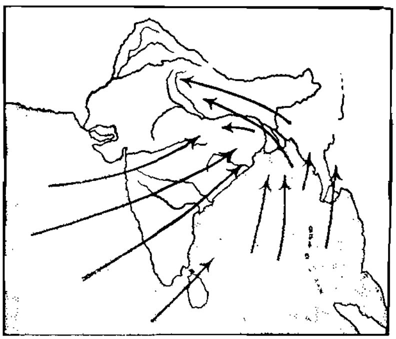


FIG. 45. The main currents of the south-west monsoon

The south-west monsoon is by no means uniform in wind force or direction. Violent tropical cyclones not only occur in its van and rear, but occasionally also during the height of the monsoon. More frequently the disturbances are shallow cyclones with weak gradients and light winds, which often advance from the head of the Bay up the Ganges Valley; much of the heaviest rainfall is associated with them (Fig. 46).

The summer monsoon of China appears to be a simpler system than that of India, though the apparent simplicity may possibly be due largely to our lack of adequate observations. The winds blow from the south-east, and are light in force, very much lighter than the winter winds. In India, on the other hand, the winter winds are much lighter than the summer monsoon. The south-east winds set in gradually in May and continue till September, blowing in from the warm ocean to the heated interior of the Continent. They are laden with moisture, and the weather is hot, sultry, rainy, and unhealthy. The heaviest rain is associated with shallow depressions, a few of which come from the land, but most from the south-east. Over the China Sea and its islands, and on the south coasts of China tropical cyclones, here called 'typhoons', are a terrible visitation; they are

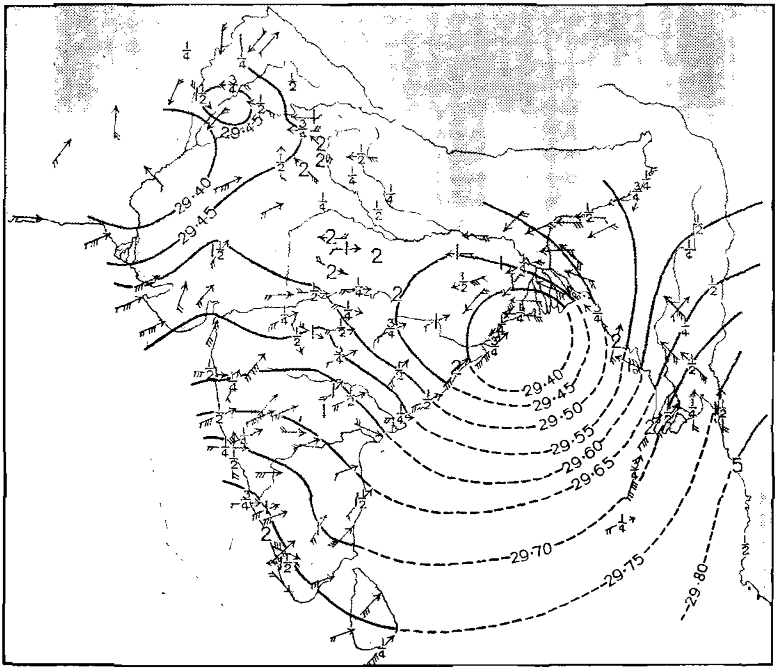


FIG. 46. A cyclone advancing up the Ganges valley during the south-west monsoon, 1921, August 8, 8 a.m. The Beaufort scale of wind force is indicated by the number of barbs on the wind arrows. The figures show the approximate rainfall in inches during the past twenty-four hours

liable to occur especially in the late summer as in the West Indies region.

No other region has such strongly developed monsoons as south-east Asia. In the south-east of the United States of America there is a distinct monsoonal tendency, though not a complete reversal of the wind. At Charleston the prevailing direction is north-west in January, south in July, at New Orleans north in January, south-east in July; the wind direction day by day is more variable than in east Asia. In the southern continents there are moist inblowing winds on the east coasts in summer, but the area of the land outside the tropics is insufficient to develop winter anticyclones comparable with that of Asia, and there is no very pronounced system of outblowing winds.

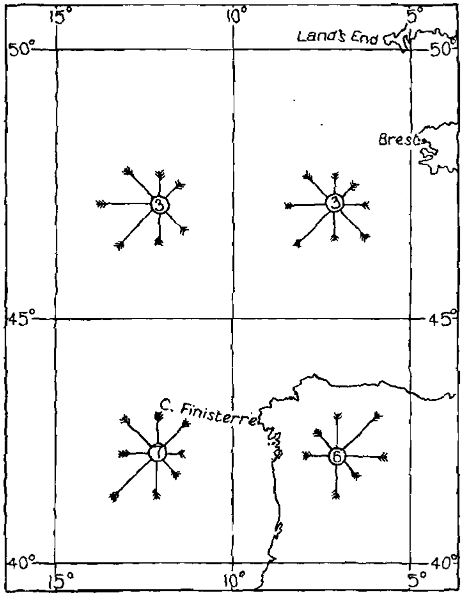


Fig. 47. Mean wind frequencies in January. The figures in the centres of the wind-roses indicate the number of calms

The Westerlies

On the poleward side of the sub-tropical high pressures lies the wild region of the westerlies. The limits are so variable that they cannot be laid down definitely. The central parts of the sub-tropical high-pressure systems over the oceans, the 'horse latitudes', normally enjoy fine weather, clear skies, and light winds, but even in summer stormy interludes occur, and in winter the westerlies frequently extend over much of the area, so that it has the Mediterranean type of rainfall and weather. Such are the conditions in the Azores and the Canaries (but the Canaries lie well within the north-east trades in summer). Similarly in the North Pacific the Hawaian Islands have almost unbroken trade winds in summer, but a considerable proportion of westerlies in winter, and as a result there is more than twice as much rain in winter as in summer; in the months June to September the trade blows day after day almost without interruption, but in December, January, and February only on one day in two.

Between about lat. 40° N. and 35° S. and the Polar circles—which we take as a convenient though only very approximate general boundary—the westerlies prevail all the year.

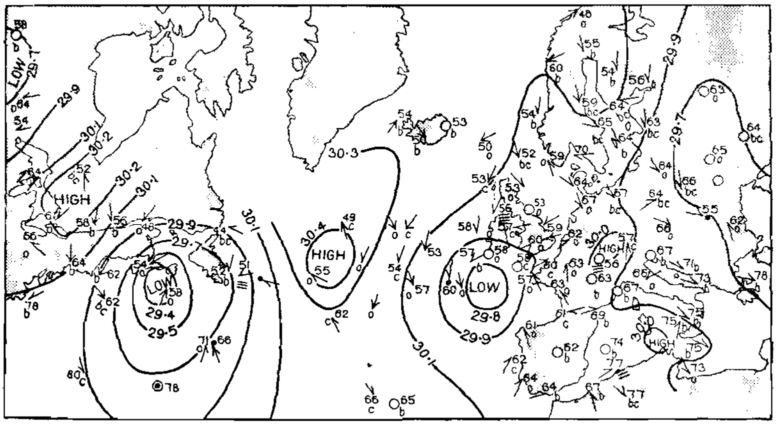


FIG. 48. 1912, July 23; for meaning of symbols see Fig. 9; b denotes cloudless sky, c detached clouds, o overcast sky

They deserve attention both for their great meteorological interest, and from the fact that they embrace those parts of the earth where the highest civilizations have developed, including the most advanced parts of Europe and North America. They are named from the prevailing winds, the mean direction being south-west in the northern hemisphere, north-west in the southern hemisphere. Unlike the constant trades the winds are very variable both in force and direction, and sometimes for weeks together the prevailing direction may be easterly (Fig. 47). The mean wind direction (percentage frequency) at Scilly is:

N	5	E	7	S	6	W	11
NNE	5	ESE	5	SSW	5	WNW	10
NE	5	SE	4	SW	6	NW	9
ENE	4	SSE	4	WSW	7	NNW	4

Calm 3

The belt is really the scene of an almost constant procession of high- and low-pressure systems (generally low), moving from west to east (Fig. 48), and the sequence of winds and weather depends on the position of the station in relation to them; their peculiarities are described in Part VIII. The westerlies of the southern hemisphere cover a belt of almost uniform width between lats. 35° and 60° S., the 'Roaring Forties' as the sailors have significantly named it; it consists of the almost unbroken southern ocean. In winter it is a wild tract; gale follows gale with little interruption, the wind veering and backing as cyclones approach and pass on. The skies are overcast with thick and rapidly-drifting clouds, the air is damp and raw, and much rain and snow falls; to add to the inclemency of the weather the temperature is low, owing to the cold water that spreads from Antarctica; icebergs come far north, the ice not seldom reaching lat. 40° in the South Atlantic, and it has approached within sight of Cape Agulhas. Even large steamers do not face the westerlies of the Roaring Forties if they can avoid it. A westward passage round Cape Horn is a wild experience, buffeted by mountainous seas, and delayed by head winds. Antarctic expeditions often find the voyage from New Zealand to the Ross Sea no bad preparation for the hardships that await them when they land. The Roaring Forties are stormy all the year round; there is little difference between summer and winter, and owing to the great expanse of ocean there are but minor variations from place to place.

The westerlies of the northern hemisphere are a much more complex system owing to the alternation of oceans and continents, the latter containing high mountain ranges and vast plateaux. The oceans themselves add variety since they contain the warmest and the coldest currents (relatively to the surrounding temperatures) of the globe. The seasonal change in wind and weather is also prominent. In winter the storminess, of the North Atlantic especially, equals, and probably exceeds, that of any other part of the globe in any season, but in summer the weather is much less violent than in the Roaring Forties. So great is the seasonal change that ships have a special load-line on their Plimsoll mark for winter voyages in the North Atlantic, more freeboard being insisted upon.

Having crossed the Pacific the westerlies reach the American coast. The western mountains rise range behind range as if to defend the interior, but the westerlies surmount the obstacle and continue right across the Continent. Owing to the intense cold of the continental winter the pressure is higher than over the ocean, but in spite of this the cyclones maintain themselves and have the same essential characteristics, though the absolute pressure is higher, as they have on the ocean. Anticyclones frequently form in the west of the Continent and join in the procession to the east. The alternation of cyclones and anticyclones is the cause of the great floods of cold air, 'cold waves', which advance from the frozen north-west to the Gulf of Mexico, and also of warm waves from the south. The cyclone tracks from the west of the Continent tend to converge in the neighbourhood of the Great Lakes and the St. Lawrence, and the track from the south appears to be guided largely by the Gulf Stream; thus the conditions of temperature and humidity on the surface of the earth have considerable influence on the movements of the atmosphere. The result is that the south-east of Canada and the north-east of the United States have as much precipitation, most of it in the form of snow, in the winter, when cyclonic activity is at a maximum, as in summer, when on-shore winds are frequent owing to the heating of the land mass. The interior of the Continent is too far from the ocean, and the air is too cold, for more than an occasional snowfall; the maximum precipitation is in summer. The windward slopes of the western mountain ranges have very heavy rain and snow, but the deep valleys that lie between get very little.

It should be noted that although our maps of mean isobars for the winter months show a large anticyclone in the interior of North America, in which the pressure is certainly higher than it is on the oceans, yet the region is the scene of great cyclonic activity, and the daily synoptic charts usually show one or more cyclones crossing the Continent. The pressure in them is higher than when they are over the ocean, but it is not the absolute pressure, but the barometric gradient that determines the weather conditions. The absolute pressure is increased owing to the cold of the continental winter, and we have the paradox that a region which appears on our maps of mean isobars in winter as definitely anticyclonic, is really subject to constant cyclonic disturbances.

On the Atlantic the westerlies, dominated by the Icelandic low-pressure system, become more stormy, especially near the meeting of the warm Gulf Stream and the cold Labrador current, and round the south of Greenland. In winter cyclone follows cyclone, rarely separated by the calms of an anticyclone, and even the great liners that work the ferry between England and America are sometimes compelled to reduce speed for days together, especially on their westward voyages, and suffer much damage. Smaller vessels are often battered by the gales till they become unmanageable, and even when help arrives it calls for the ablest seamanship to effect a rescue in the wild seas.

Western Europe lies fully exposed towards the west; it has no mountain barrier, and moreover the Mediterranean Sea, the Black Sea, and the Caspian on the south, the Baltic and the White Sea on the north, provide marine conditions inviting the westerlies far into the land mass of Eurasia. The winter storms and rains of the Mediterranean lands are caused partly by depressions that enter the region from the Atlantic, partly by cyclones that originate over the warm sea itself.

The North Atlantic narrows towards the north-east, but offers a fairly wide channel between Norway and Greenland into the Arctic Ocean. The Gulf Stream, after sweeping northward off the United States coast, sends vast volumes of surface drift water across the ocean towards Europe; much of it passes between Norway and Iceland, continues east round the north of Norway and has an appreciable warming influence even as far as Novaya Zemlya and the south of Spitzbergen. The warm water provides a favourable path for cyclones, most of which, instead of entering Eurasia, skirt the north of the land mass; the coasts of western and northern Europe, however, come under the influence of their mild rainy sectors. But though the centres of primary cyclones tend to avoid the land, secondary disturbances not infrequently cross the British Isles and all western and central Europe (Fig. 88, p. 255). Central and northern Asia and eastern Europe are dominated by the winter anticyclone, which feeds a constant system of outblowing winds—the north-west monsoon of China, the north-east monsoon of the North Indian Ocean, the bitter north-east winds of the steppes of the Caspian Lands and Asia Minor, and the north-west winds of Mesopotamia. Although this high-pressure system is very stable it is invaded at times by disturbances which probably belong to the westerlies. Unfortunately adequate daily records of the weather are lacking from vast areas in the heart of Asia.

Probably the main sweep of the westerlies is deflected to the north of Eurasia and follows the warm waters of the North Atlantic drift. There is no such warm sea passage round the north of Canada, the way being blocked by the westward extension of Alaska, and this may be an important factor in causing the westerlies to cross North America itself; certainly the interior of that continent is subject to more frequent and intense cyclonic activity than the interior of Eurasia. But, in the east of Asia at any rate, cyclones are frequent, moving eastward from Siberia or Central Asia across China, and they cause strong winds, with most unpleasant dust storms, and a little snow in winter. Their intensity increases as they reach the Pacific, and over the ocean they develop into the ordinary stormy cyclones of the westerlies which we have mentioned already.

The 'Mediterranean' Regions

These regions are between the westerlies and the trade winds; owing to the seasonal swing of the pressure belts of the globe they are dominated by the former in winter, the latter in summer. And this involves not merely a change in wind direction but also in the whole face of the weather, owing to the great differences between those wind systems. The topography of the Mediterranean basin itself gives it many peculiarities. In summer the region as a whole has north-westerly winds blowing between the North Atlantic anticyclone and the great low-pressure system of south Asia. In winter the winds are variable, and on that ground the region may then be classed with the westerlies, but it is rather to be considered as a separate zone in view of its many local features. Broadly speaking the sea, owing to the heat and humidity, is covered by a low-pressure system, bounded on

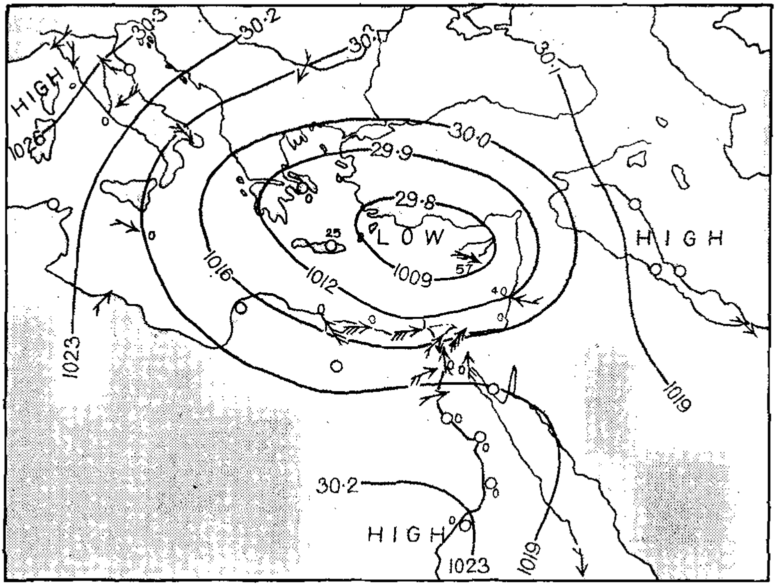


FIG. 49. January 10, 1926, 8 a.m.; a depression over the eastern Mediterranean. The small figures give the rainfall in mm. during the 24 hours January 10–11, 8 a.m.

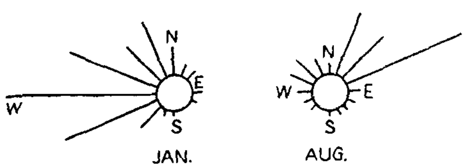


FIG. 50. Frequency of wind directions at Algiers in January 1927 and August 1927; the lengths of the rays are proportional to the number of times the directions were observed

the north by the high pressures of Central Europe, on the south by those of the north of Africa. The air circulation is anti-clockwise, with prevailing south-west and westerly winds on the south coasts, north and north-easterly on the north coasts. But, as in the true westerlies, the winds are very variable in speed and direction, being controlled by the cyclones and other pressure irregularities which move along the axis of the sea from west to east (Fig. 49). The wind-roses given in Fig. 50 show both the change in the mean direction of the wind from summer to winter, and also the contrast between the steady summer and the variable winter winds. Additional information is given in Chapter LII.

The Polar Zones

Antarctica. The poleward fall in pressure from the sub-tropical high-pressure belt continues steeply and steadily through the Roaring Forties nearly as far as the Antarctic circle, in the neighbourhood of which the trough of lowest pressure encircles the globe. It was formerly thought that the pressure continued to decrease all the way to the South Pole owing to the influence of the great circumpolar whirl in the higher atmosphere (p. 80), but recent exploration has corrected this view. Antarctica consists of a vast plateau, nearly twice the area of Australia, much of it more than 8,000 feet above sea-level, and the whole covered by a thick ice-cap. It is intensely cold in winter, and even at mid-summer the snow and ice prevent the temperature rising above the freezing-point. The local thermal influence out-weighs the dynamical forces exerted by the general circulation of the atmosphere, and an anticyclone is formed over the Continent; it is probably a shallow system in the surface layers of the atmosphere which are chilled by the ice, with a depth of not more than a few thousand feet, but it is enough to reverse the barometric gradient of the westerlies, and to feed a system of winds blowing outward; all expeditions have reported south and south-east winds as soon as the belt of lowest pressure near the Polar circle has been passed, and on his last journey to the South Pole Scott recorded S., SSE., or SSW. winds for 73 per cent. of his observations. The anticyclonic outflow is strengthened, and locally intensified to violent gales, by the tendency of the cold air to flow down the slopes of the ice-cap under the action of gravity as a 'katabatic' wind. Such was probably the cause of the extraordinarily violent and continuous gales which Mawson experienced in 1913 in Adelie Land, an inhospitable waste which he has christened the 'Home of the Blizzard'. The mean wind speed during his stay was 50 miles an hour.

Above the surface anticyclone there is presumably the centre of the general circumpolar low pressures, and a slight inward movement of the air from the WNW. This movement would seem to be shown by the direction of the smoke-drift of Mount Erebus, a volcano 13,000 feet high on Ross Island, which acts as a useful wind vane for the air at that level; the direction is the opposite of that of the surface winds at Cape Evans which is at the foot of the mountain (Fig. 51). The inflowing winds of the upper strata feed the descending currents over the ice-sheet. Fig. 51 also shows the winds in the South Orkneys which are in the westerlies.

The southerly winds on the surface are, of course, liable to interruption. Blizzards are only too well-known to explorers, and during the stay of the British Antarctic Expedition at Cape Evans, Ross Island, blizzards were raging for almost a quarter of the time. A blizzard is a strong wind, which may rise to gale force, with furious gusts of over 50 miles an hour. The air is so thick with whirling eddies of snow that not only is it impossible to see a few yards ahead, but the wayfarer's faculties are bewildered, and he sometimes perishes of cold though shelter is close at hand. Part of the snow falls from the clouds, but a considerable portion is swept up from the ground—which can easily happen because of its loose, dry, powdery character. Blizzards are clearly due to a steepening of the barometric gradient, but probably not to cyclones of the ordinary type. Such cyclones are frequent enough in the westerlies, and sometimes their poleward sectors sweep the coasts of Antarctica. But Dr. Simpson, who was meteorologist on Scott's expedition, fails to find evidence that their influence extends any distance inland, or that the blizzards are connected with them. According to him there are 'surges' of pressure, moving apparently radially outwards from the Pole, and where the topography is suitable steep barometric gradients may be set up, giving strong winds. Now owing to the intense cold of the snow the surface air becomes so much chilled, and therefore so dense, that where the land is flat it forms a stagnant layer of supercooled air; there is a strong temperature inversion. This surface layer remains inert, and the winds set up by the barometric gradient usually blow over it. But if the wind becomes strong enough under the influence of the pressure surges it may churn up the underlying strata, the calm that has prevailed on the

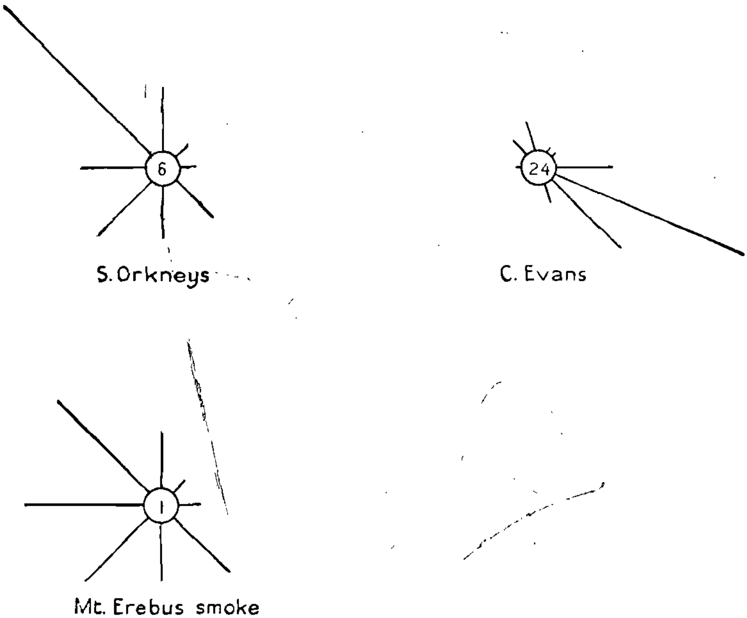


FIG. 51. Mean annual wind directions. The lines, read towards the centre, are proportional to the frequencies. The figures at the centres show the percentage of calm and variable winds

surface comes to an abrupt end with sudden gusts, and the full force of the storm is developed sometimes within an hour or two. The blizzard continues to moan and shriek for it may be a few hours or a few days. The snowfall is largely due to the ascent of the air currents which are forced over the denser surface strata. This theory would explain the sudden and often large rise in temperature which is noticed immediately the blizzard starts, the supercooled surface air being replaced by air at the normal temperature. It is often thought that the temperature falls decidedly when blizzards start, but instrumental records prove this to be wrong; the apparent fall is a physiological effect of the rapid movement of the air past the body.

There are difficulties in applying this theory to all blizzards, though it seems to explain excellently the facts observed on and near the Great Ice Barrier. In other regions there may well be other causes in operation, and possibly in most regions the blizzard is a locally intensified katabatic wind. It is a striking fact, supporting Simpson's theory of blizzards, that in the Ross Sea quadrant there is usually either a calm or a high wind, light winds being rare.

The North Polar Region. The Arctic is a more complex region than the Antarctic. The Polar basin itself is a deep ocean, entirely ice-covered in winter, and with but little open water even in summer. It is nearly surrounded by the land masses of the Old World and Canada, the large, closely-set archipelago on the north-east of Canada, and the great ice-covered plateau of Greenland, itself as large as India. The only wide entry into the basin is between Greenland and Scandinavia. Perhaps we may regard the island groups of Spitzbergen, Franz Josef Land, and Novaya Zemlya as marking the boundary of the Arctic basin on this side. The Arctic circle itself passes through the north of Siberia and Canada and the south of Greenland, enclosing large areas of land within the astronomical Polar zone.

In winter the coldest parts of the earth are the north-east of Siberia, the north of Canada, and the interior of Greenland, where extensive anticyclones are built up. The ice-covered Arctic basin is certainly cold during the winter, though considerably less cold than the surrounding lands, and the available data indicate that a belt of high pressure crosses the basin on the Bering Strait side of the Pole, and connects the Asiatic and American anticyclones; the pressure is not so high in this belt as over the continents, but very much higher than in the Icelandic and Aleutian low-pressure systems on the oceans on either side of it. The belt of high pressure has been well termed the 'Arctic wind-divide' in relation to these last systems, into which it feeds north-east winds. The sea-ice is drifted slowly by wind and current from west to east. Trusting to this movement Nansen allowed the *Fram* to be frozen in on the north-west of the

New Siberian Islands, and for a period of 3 years the ship was carried on a generally direct course, in spite of many temporary digressions and even reversals, towards the north of Greenland, finally reaching open water north of Spitzbergen; the westward drift was far more rapid in winter than summer. The centre of the Arctic is probably a fairly calm region in winter, with very clear skies, rarely troubled by storms or high winds; the ice favours the formation of a surface stratum of cold, dense, still air as in the Antarctic, and there are no disturbances caused by katabatic winds. But on the outskirts, over against the warm waters and the low pressures of the Icelandic and Aleutian regions, the winds are strong and often boisterous, being under the control of the westerlies; but the prevailing direction is northeast.

In summer the pressure over the whole zone appears to be fairly uniform. The anticyclones of the adjacent continents have disappeared, and the Polar basin probably has slightly higher mean pressure than both the lands and the oceans which bound it, with a weak gradient for outflowing winds. The partial break-up of the sea-ice allows the mean temperature in July to rise to about the freezing-point, and this is not cold enough to form a very prominent cap of high pressure. The drift of the ice from east to west is much slower than in winter, and indeed is often reversed.

The meteorology of the Poles is not of any very great direct human importance, seeing that there are few inhabitants or travellers in the northern, and none at all in the southern Polar zone. But the Arctic region is crossed by the shortest routes from Europe and Asia to North America, and it is possible that it may be followed by airship services in the future, in which case detailed meteorological observations and investigations will be imperative. At present the human importance of the meteorology of these zones is chiefly indirect. From them currents of cold air blow southward into the low-pressure systems of the temperate latitudes, and there meet the warm and moist southerly winds from an equatorial direction. Many meteorologists see in the interaction of the cold 'polar' and the warm 'tropical' air currents the fundamental cause of the cyclones and anti-cyclones for which the westerlies are notorious. Whether in this or in other ways, it seems probable that the Polar conditions do influence the daily and seasonal weather of the temperate zones, and much help in its study and more success in forecasting our weather might be derived from the establishment of an adequate number of Polar telegraphic reporting stations. The atmospheric pressure in the Polar zones is the most important element, and it seems to be controlled largely by the amount of sea-ice present, the ice tending to maintain high pressure, open water lower pressure; a knowledge of the state of the ice-covering in different parts is very desirable, not only by reason of its immediate effects, but also because a large field of ice can only melt slowly, since it surrounds itself on melting with cold fresh water which floats on the more saline water of the sea. A detailed knowledge of the surface drifts would enable us to forecast the arrival of the ice and cold water in other areas weeks or months in advance, and hence we might gain an indication of the probable nature of the seasons, as likely to be warmer or colder than the normal. It is not impossible that some control of the seasonal weather within the temperate zone is exerted in more indirect ways also by the varying ice-covering of the Polar seas.

CHAPTER XX

SAILING-SHIP COURSES

MODERN high-powered steamers usually ignore the winds in determining their courses, choosing the shortest possible passage from point to point, but it is very different with sailing-ships. Fig. 52 shows some of the sailing tracks followed, the object being to profit by the prevailing winds even at the cost of an increase in the length of the voyage.

Ships bound from the United Kingdom to Australia usually sight Madeira and Cape de Verde Islands and endeavour to cross the line in about 25°–28° W. long., where the doldrums are narrowest, and so pick up the south-east trades as soon as possible after leaving the north-east trades. If, as is frequently the case, the south-east trades have more southing in them than easting, vessels may sight the Brazilian coast about Pernambuco. The trade wind is usually lost near the small island of Trinidad, where light variable winds principally from the north-west prevail, which enable ships to get to the southward and eastward,

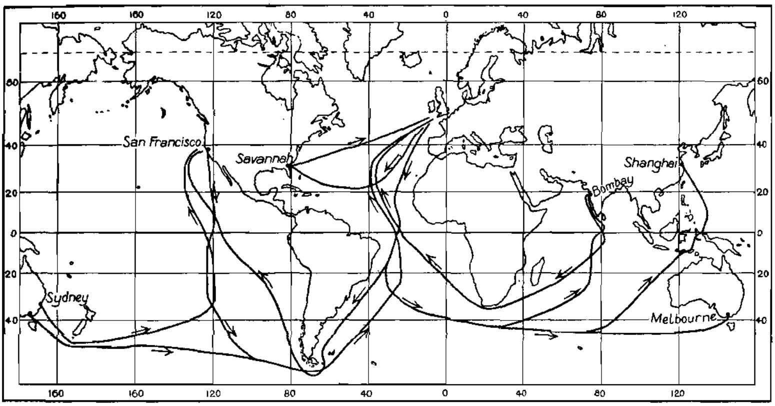


FIG. 52. Recommended Sailing Courses, Dec.–Feb.

and by the time Tristan da Cunha is reached they are well in the westerlies, and make their easting in lat. 40° to 48° S.; farther south than that ice is likely to be encountered.

On the homeward passage they pass south of the Snares Rocks, New Zealand, and carry the prevailing westerly winds up to the Horn. In that stretch of water gales of westerly winds are almost continuous, and sometimes blow with terrific force, raising a tremendous sea which cannot be equalled in any other part of the ocean. In fact Captain—afterwards Admiral—Fitzroy, when Darwin was with him in H.M.S. *Beagle*, estimated the height of the seas near Cape Horn at 70 feet from crest to trough. After rounding the Horn vessels pass inside the Falklands; they never, if possible, go to the eastward of them, on account of a north-east current which brings up ice from the Antarctic. The weather after passing the Falklands is generally moderate, but in the neighbourhood of the River Plate 'pamperos' are not infrequent. After passing through the south-east trades the north-east trades are generally entered a little to the north of St. Paul's Rocks. This wind forces the ship into a NNW. or NW. by N. course, and on account of the equatorial

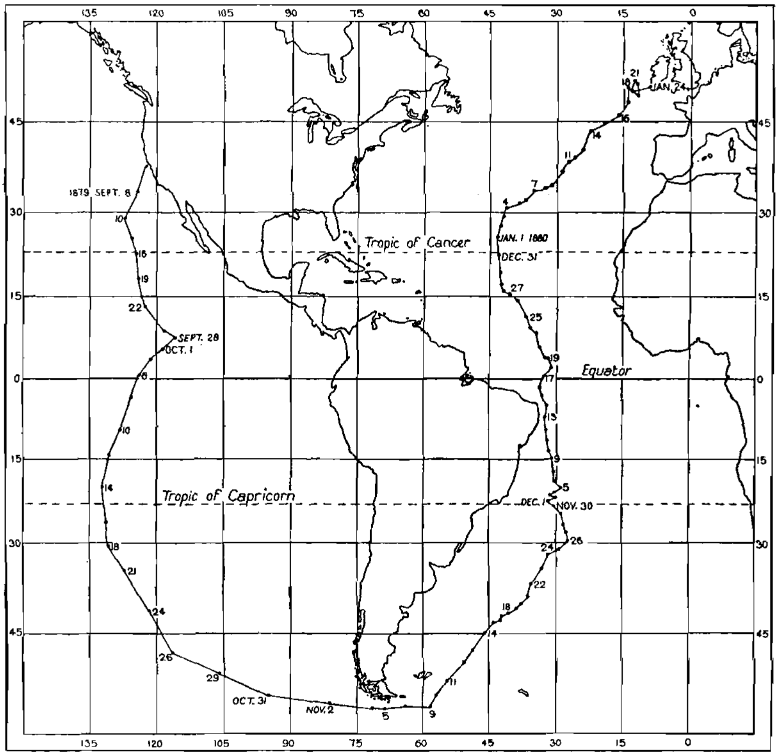


FIG. 53. Track of the barque 'Scottish Hero' (Capt. T. R. Mowat) from San Francisco to the United Kingdom

current the vessel is set well to the westward, frequently passing through the Saragossa Sea. North of this westerly winds are again found, and carry her to the channel.

In going, however, from the North Atlantic to ports on the west coast of South or North America, vessels must make the westward passage round Cape Horn, and have to contend with strong head winds; they encounter very severe weather and frequently sustain much damage. Their efforts to get to the westward are assisted by the frequent changes of wind from north-west to south-west, which, if the wind is moderate, enable them to sail on the tack which would give them the most westing. Vessels bound to China from the United Kingdom proceed along the same route as those going to Australia until they reach the meridian of about 80° E. when they stand to the north-east to catch the south-east trades; during the south-west monsoon they would proceed by the Straits of Sunda direct up the China Sea, but during the north-east monsoon they would go through the Ombay and Gillolo Passages into the Pacific, and work to the eastward in the variable winds before standing to the northward.

The outward and homeward tracks from the United Kingdom to Savannah show well the advantage that can be derived from the prevailing winds of the North Atlantic.

The tracks referred to are those for the northern winter. There are considerable differences in the other seasons, especially in monsoon regions.

Fig. 53 shows an actual voyage as pricked off from day to day.

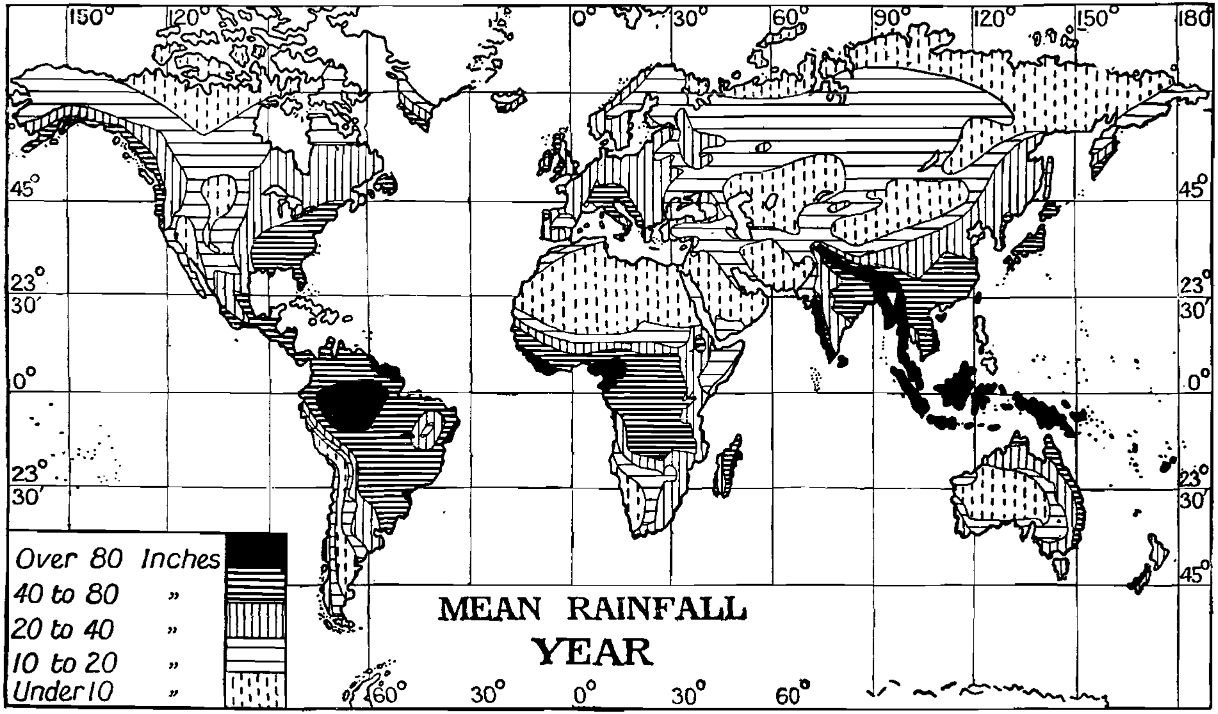

MEAN RAINFALL
YEAR
Over 80 Inches
40 to 80 „
20 to 40 „
10 to 20 „
Under 10 „
150°
120°
0°
30°
60°
90°
120°
150°
180
45°
23° 30′
0°
23° 30′
45°
60°
30°
0°
30°
60°

FIG. 54

PART IV

HUMIDITY, RAINFALL, EVAPORATION, CLOUDS, THUNDERSTORMS

CHAPTER XXI

THE IMPORTANCE OF RAINFALL
THE MEASUREMENT OF RAIN

It is unnecessary to state in detail how our daily life, our work and our pleasures, are controlled by the weather, and especially by the rain. We depend on rain for our water-supply, and even in England, which is not a dry land, a few weeks of drought brings the fact clearly to our notice, for springs and wells fail, and the land dries out. Not only our drink but our food also is at its mercy; crops can grow only if the rainfall is adequate, or if artificial irrigation can be supplied, that is to say if the rainfall of distant areas can be directed to the dry lands that need it. In the 3 years 1926–8 it is estimated that 10,000,000 sheep died in Queensland owing to a protracted drought; a deficiency in the rainfall is especially destructive in semi-arid lands, which have barely enough rain in good years for the stock which optimistic farmers put on them, and for the crops that they expect. Terrible famines are liable to occur in India and China. On the other hand an excess of rain works even greater havoc over restricted areas, which are flooded by rivers breaking their embankments. The floods of China are notorious; during the summer monsoon the Yangtze may rise 100 feet above its lowest winter level. The Hwang Ho is specially dangerous because it has built up its lower course well above the level of the plain, through which it flows as on an embankment; in September 1925 it burst its banks and over 2,500 persons were drowned; the survivors were in perhaps a worse case, since the river spread débris over their cultivated lands and ruined the crops; death by famine awaited them after their escape from the flood. Not only must the amount be adequate, but the rain

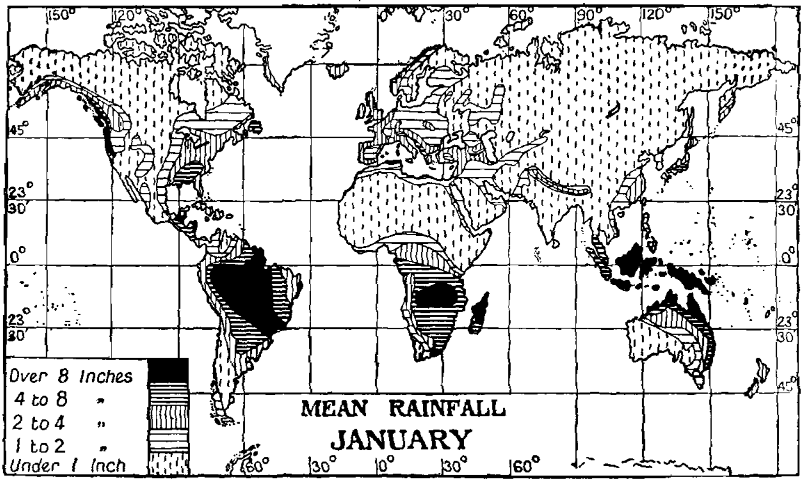

Over 8 Inches
4 to 8 "
2 to 4 "
1 to 2 "
Under 1 Inch
MEAN RAINFALL
JANUARY

FIG. 55

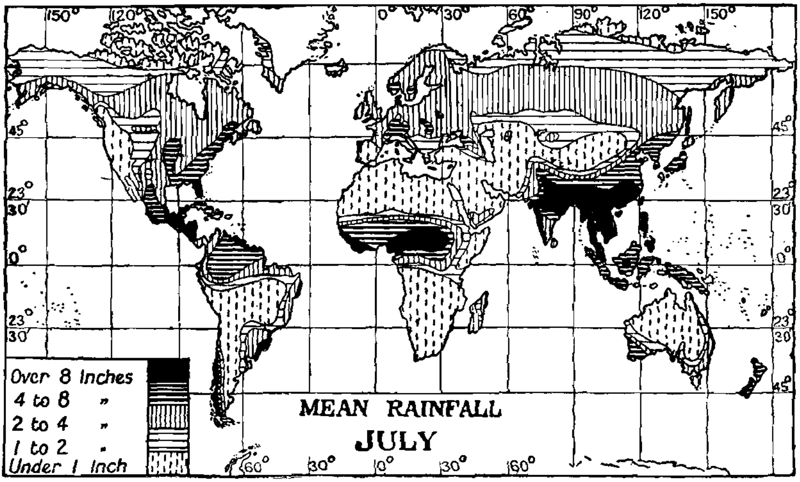

Over 8 Inches
4 to 8 "
2 to 4 "
1 to 2 "
Under 1 Inch
MEAN RAINFALL
JULY

FIG. 56

must fall in the right season for the crop. In some regions all the rain falls in the hot season, and the combination of heat and moisture is conducive to a vigorous growth of vegetation. If there are high temperatures and heavy rains all the year round growth will be especially luxuriant, as seen in the exuberance of the rain forests of the equatorial belt. In some lands the rain falls during the cool season, and the hot summer is rainless. For plant life, and also in other respects, 20 inches of rain with the temperature at 70° has very different effects from the same amount with the temperature at 40°.

The kind of the rain should also be taken into account. There may be violent downpours, often thunderstorms, or the rate of fall may be moderate as in the British Isles; in some places a light rain, or drizzle, is common. The number of rainy days is important; a 'rainy day' is a day on which 0·01 inch, or in some countries 0·1 mm., or more, of rain is received.

Inside the tropics most of the rain falls during the hot hours, in other regions there is not much connexion with the time of day.

The rainfall may be fairly regular from year to year, or it may be liable to great variations, some years being almost or quite rainless. And again we must distinguish between rain which falls sporadically in small areas, the intervening country enjoying fine weather (see for an example, Fig. 72, p. 183), and 'general' rain which affects a wide area, either at the same time, or consecutively as a rain-belt moves over it. The former is usually a heavy rain of short duration, often falling in thunderstorms, the latter may be called the cyclonic type, since its immediate cause is cyclonic activity.

The Measurement of Rain

When we say that 1 inch of rain has fallen in a certain time we mean that if all the rain during that time had remained on a flat surface where it fell, suffering no loss by evaporation or percolation, it would form a layer of water 1 inch deep. The rain gauge aims at indicating this theoretical depth by collecting the rain in a suitable receptacle and storing it till the amount can be measured (this is usually done once a day). The rim of the rain gauge is 1 foot above the surface of the ground at British stations, and the instrument is placed in an open situation well away from the shelter of trees or other objects. Unfortunately in some countries the standard height of the gauge above the ground is not 1 foot, and more or less serious discrepancies may result. Figs. 54–56 show the mean rainfall for the year, for January and for July over the globe. In much of the low midlands of England about 30 inches is the mean annual rainfall, and it falls on about 175 days. The mean rainfall on a rainy day—or the mean intensity of rainfall—is therefore about 0·17 inch. This statement gives useful information about the rainfall of any place. Thus at Nice the mean intensity is 0·46 inches—almost three times that of the English midlands.

CHAPTER XXII

THE VAPOUR IN THE ATMOSPHERE; ABSOLUTE AND RELATIVE HUMIDITY; DEW-POINT

THE atmosphere contains many gaseous constituents; the nitrogen, oxygen, carbon dioxide, and other gases, the proportions of which remain almost constant, are individually of no special meteorological significance; but the water-vapour, which is very variable in amount, is of great importance since the rainfall depends on it, and to a slight extent the atmospheric pressure also. The amount decreases rapidly from the surface of the earth upwards, partly because the ultimate source is the water on the earth's surface, partly because the amount varies with the air temperature. Half the vapour in the atmosphere is in the lowest 8,000 feet.

Air at a given temperature and pressure can contain water-vapour in an invisible form up to a certain fixed amount; the air is 'saturated' if it contains all the vapour possible. A cubic foot of air will hold

1·9 grains	of water-vapour	when	the	temperature	is	30°
2·9	,,	,,	,,	,,	,,	40°
4·1	,,	,,	,,	,,	,,	50°
5·7	,,	,,	,,	,,	,,	60°
8·0	,,	,,	,,	,,	,,	70°
10·9	,,	,,	,,	,,	,,	80°
14·7	,,	,,	,,	,,	,,	90°
19·7	,,	,,	,,	,,	,,	100°

By 'absolute humidity' is meant the actual amount of vapour present in the air. This may be expressed as the weight of vapour in a cubic foot of air. Or the same information may be conveyed in terms of the 'vapour pressure' (or 'vapour tension'), for the pressure of the atmosphere measured by the barometer is made up of the pressure of the separate components, and the pressure of the water-vapour may be expressed in inches or millimetres of mercury or in millibars of pressure. In England on a summer afternoon the vapour-pressure is about 0·45 inches, on a winter night about 0·15 inches. At Calcutta the mean is about 1 inch in July during the hot moist monsoon, and about 0·45 inches in January. The lowest records have been obtained in the Polar regions in winter; during the drift of the *Fram* in the Arctic the pressure in January was about 0·007 inches throughout the 24 hours. At Helwan near Cairo, which is representative of the Sahara, the mean monthly vapour-pressure varies from 0·25 inches in February to 0·5 inches in August. The pressure is usually highest when the temperature is highest, since the air is always tending towards saturation, and warm air can contain more vapour than cool. But one of the lowest readings at Helwan, 0·7 mm., was taken on May 8, 1918, at 2 p.m. when the wind was south and the atmosphere abnormally dry though hot. At Athens the mean pressure is lowest, 0·2 inches, in January, highest, 0·5 inches, in July.

The absolute humidity of the air is not changed unless vapour is added or subtracted. A change of temperature does not affect the absolute humidity unless the air is cooled below the dew-point and some of the moisture is deposited. It is quite different with the 'relative humidity' which de-spring water is placed in the hot air on a summer afternoon the outside soon becomes coated with a film of droplets; in favourable conditions the condensation is so copious that drops of water trickle down the glass. We see the same process sometimes in winter when a spell of cold gives way to moist warm weather; the walls of our houses are still cold, and when the warm air blows against them so much moisture may be condensed as to be a source of great discomfort.

More water is derived from the cooling of saturated warm air than cool. Saturated air at 80° contains 10·9 gr. per cubic foot, at 60° 5·7 gr., so that a cooling from 80° to 60° gives a condensation of 5·2 gr. But a further cooling of 20° gives only 2·8 gr., since saturated air at 40° contains 2·9 gr.

Pure air may be cooled far below its dew-point without condensation of the vapour it contains; some kind of nuclei must be present about which the minute droplets of water may form. Dust and smoke particles serve this purpose and the abundance of the latter in the air of large towns explains in part the poor visibility and frequent mists and fogs. But ions also, especially negative ions, act as nuclei, and since the ionization of the atmosphere is largely due to the passage of ultra-violet rays we have the interesting fact that bright sunshine, as well as the smoke from our chimneys, may be responsible for the formation of cloud.

CHAPTER XXIII

THE CAUSES OF RAIN

THE study of the causes of rain resolves itself into a study of the processes whereby air may be cooled below its saturation-point. The important ones are:

(*a*) Direct radiation from the air itself. The cooling that results is very slow, but it is accelerated by the presence of dust or water particles, which are more efficient radiators than pure air. This process rarely if ever condenses enough moisture to give rain, though stratus clouds may be formed.

(*b*) A land surface rapidly loses its heat by radiation, and the air resting on it may be cooled to dew-point by conduction. Dew or hoar frost is thus formed on clear calm nights, and in autumn and winter the process may be active enough to produce the ground mists which are often seen forming over open fields and low-lying meadows after warm days. But much of the condensed vapour is derived from the ground and the vegetation in these cases.

(*c*) When warm saturated air blows over a cold surface such as a cold current at sea or an ice-field, the cooling may produce dense fog. This is the cause of the well-known fogs over the Grand Banks of Newfoundland, where the warm Gulf Stream meets the cold Labrador current; also of the fogs of the coast of South-west Africa and other cold-water coasts. But again this condensation is rarely if ever sufficient to produce rain, since the chilling of the air takes place only at the surface, not throughout the air mass. Sometimes the fog is so shallow that the tops of the masts of ships project into the clear air above.

(*d*) Air is cooled if it moves from warm to colder latitudes, as in the case of the westerlies, which therefore tend to be damp; but this cooling is so gradual that it can rarely continue long enough to lead to rainfall. It is, however, one cause of the humid air of the westerlies. On the other hand, movement from cool to warmer latitudes partly explains the dryness of the trade winds.

(*e*) A large mass of air is cooled most rapidly by ascent. Suppose that a given volume of air rises from the surface of the earth where the atmospheric pressure is 30 inches. As it rises the surrounding pressure becomes less, an ascent of some 17,000 feet from sea-level bringing about a reduction of the pressure by a half, and the air expands, its volume being doubled when the pressure is halved; the energy required to effect the movement of the air molecules whereby the double volume is occupied is obtained at the expense of heat, and hence the temperature falls; this is known as adiabatic cooling. Since the pressure falls most rapidly in the densest, that is the lowest, strata of the atmosphere, the cooling by ascent will be most rapid there. Unsaturated air cools about 1·6° for each 300 feet of ascent, the exact figure depending on the initial pressure. Conversely, descending air is adiabatically warmed by compression, and in the absence of other influences it becomes drier. When the air cools to saturation-point a new factor is introduced which we must now consider.

The 'Liberation of Latent Heat'

If water is heated to 212° F. (at ordinary atmospheric pressure) it is not at once converted into vapour. Water at 212° and vapour at 212° are not identical thermally, and to convert the former into the latter the expenditure of much energy in the form of heat is required; the term 'latent heat of evaporation' has been applied to the heat which is used to effect the transformation. Similarly, to change ice into water, heat must be expended, and it becomes 'latent' in the water formed. When the reverse processes take place, vapour being turned into water, or water into ice, the same amount of energy is liberated in the form of heat as was previously expended. These processes are extremely important in the atmosphere. Rising air expands, as we have seen, and is cooled adiabatically. After dew-point is reached continued elevation leads to further cooling, which causes the condensation of the water-vapour contained in the air. But this liberates latent heat which goes far to counteract the cooling due to expansion, and the rate of cooling of ascending air after saturation is only about 0·8° for 300 feet in the lower atmosphere, instead of 1·6° for 300 feet for unsaturated air. A result is that damp air which starts to rise owing to its being warmer than the surrounding air can continue to rise higher than dry air. For ascent causes cooling, and thus after no very great ascent dry air must become as cool as the surrounding air, and further ascent is stopped. But the liberation of latent heat in rising damp air tends to maintain its temperature and so leads to greater ascent and the condensation of more vapour. This is a very important factor in the production of heavy rain.

Part of the energy of insolation is used in evaporating water and becomes 'latent', to be liberated again when the vapour is condensed. Solar energy is transported in this form from one region of the earth to another, especially to the belt of the westerlies.

The Ascent of Air

Air may be caused to ascend in various ways.

(*a*) One process is often in evidence on sunny days. The land, heated by the sunshine, heats the air resting on it, which expands and rises, the movement manifesting itself by a shimmering appearance. In favourable conditions the convection currents are so active that the air may rise many thousands of feet and be cooled far below its dew-point. This is the origin of the cumulus clouds which are a well-known feature of fine summer afternoons; they begin to appear about 10 or 11 in the morning, grow higher and larger till afternoon, when the sky may be almost overcast, and dissolve again in the cool of the evening. They may become so massive as to give rain, but this does not generally happen unless there are other conditions present to increase the instability, such as abnormal cold in the higher strata, or unusual heat and humidity below, when the convectional overturning may be so violent that cumulus clouds some miles in height build up and give violent thunderstorms.

This may be called the convection type of rainfall. It is usually due to the lower strata being abnormally hot, and hence it is associated especially with hot lands, and the hottest hours of the day; heavy cumulus clouds are rare in the Polar regions, and are nowhere so common over the sea as over the land. A distant coastline may sometimes be recognized from the sea by the line of cumulus clouds over it, when the land itself is below the horizon. Within the tropics most of the rain is convectional, and the hot air gives very heavy downpours, generally associated with violent thunderstorms. Similar, but less heavy, rainfall is received in the interiors of the continents even in temperate latitudes. Rain of this type falls in small scattered localities.

The lighter cumulus clouds that appear in the deep blue sky behind a cyclone of temperate latitudes are due rather to abnormally cold air in the higher strata of the northerly winds than to any great heat below; the surface air may even feel cold, but the higher strata are so much colder that there is convectional overturning and cloud formation.

The necessary conditions are often present in the south-east sector of a shallow cyclone in summer. The light southerly winds are abnormally hot and moisture-laden, and the air movement being sluggish they are still more heated by contact with the sun-baked ground. At such times heavy cumulus clouds form, and there is always a tendency to local thunderstorms, especially if the higher atmosphere is abnormally cool.

(*b*) Vortical ascent in revolving storms such as tropical cyclones and tornadoes may be very active, and produce an extensive area of thick cloud and heavy rain, the high temperature and humidity of the air conducing to the intensity of the condensation. There must be ascent in the low-pressure systems of the westerlies also, but it is usually not of a vortical nature (see Chapter XLV). The descending currents in anticyclones are warmed and dried.

(*c*) Forced ascent to surmount a barrier gives the heavy 'orographic' rainfall and dense clouds which are associated with mountains, and is the cause of the heaviest rainfalls of the earth. The Western Ghats of India, standing full in the course of the south-west monsoon, provide a good example. The monsoonal winds after sweeping over thousands of miles of tropical seas and becoming saturated with moisture have to rise to over 4,000 feet. The rainfall during the 4 months, June–September, when the monsoon is at its height is 71 inches at Bombay, and more than 200 inches on the top of the Ghats. After depositing this moisture, the winds descend to the plateau of the Deccan and become dried, giving a rainfall of not more than 15 inches in many parts. In July some stations on the west slopes of the Ghats have more than 50 inches of rain, while only half an inch is received on the east.

On the windward slopes the rainfall is far in excess of what agriculture requires, but the east suffers from serious drought. An irrigation system in the south of India is based on these facts. It collects its water-supply on the wet western slopes of the Cardamom Hills, and conveys it through a tunnel 1¼ miles long to the arid plains on the east. The River Periyar which is tapped rises on the upper western slopes of the Ghats, and formerly carried its over-abundant waters unutilized to the Arabian Sea. A dam constructed across its valley at an altitude of 3,000 feet forms a large reservoir, and the tunnel leads the water to the arid east of the watershed where it is so much needed. The excessive rainfall on the west was itself the cause of almost insuperable difficulties in the construction of the works. The first embankments were more than once carried away—which is not to be wondered at, seeing that as much as 3 inches of rain sometimes fell in a few hours, and the flooded river swept all before it. Malaria and other diseases fostered by the moist climate were rampant, and the maintenance of an adequate supply of labour was a hardly less formidable task than the engineering of the works to harness the refractory river. But determination triumphed, and the undertaking was completed in 1895. The water-supply irrigates 176,000 acres in southern Madras, which were formerly liable to frequent famine, and the scheme is very successful financially.

The heavy rainfall of the west coast of Scotland is caused by the westerly winds having to rise over the steep west-facing edge of the Highlands. There are other subsidiary factors also. The westerlies are warm winds and have travelled far over the warm water of the North Atlantic Drift, so that their vapour-content is high. Moreover, they are subject to frequent irregularities of pressure, low-pressure systems, which are in themselves a fruitful source of rain. But we see that the mountain influence is the most important from the fact that the mean annual rainfall is over 170 inches on the windward slopes of the Highlands, but sinks to less than 25 inches on the leeward lowlands round the Moray Firth. Similar conditions exist in Scandinavia and British Columbia, in the south of South America, and in New Zealand, and in nearly all cases the mountains stand out almost as clearly on the rainfall as on the relief map. Even the massifs of the Ahaggar, Aïr, and Tibesti, in the midst of the arid wastes of the Sahara have enough rain to maintain perennial streams and nourish vegetation. The Chiltern Hills in south-east England have about 5 inches more rain annually than the plains around, though they rise only about 500 feet above them. Where the rain is due to the forced ascent of strong winds the heaviest rain is not on the actual mountain ridge but at some little distance to leeward. In Snowdonia, North Wales, the highest records come from round Llyn Lydau, a mile eastward of the top of Snowdon. In the Lake District of Cumberland there is considerably more rain on Styehead Pass (1,070 feet) than on the surrounding summits of about 3,000 feet.[1] It is especially wind-borne, cyclonic, rain which shows this pronounced increase with elevation. Thunderstorm rain is usually heavier on the plains than on the hills. In the British Isles the heaviest rainfalls recorded in one day, or in shorter periods, are often considerably greater in the plains than in the mountains, since very heavy instability rain is not common in the mountains, which lie in the cooler west and north; but excessive totals for a week or a month are more frequent in the mountains (e. g. Snowdon, 57 inches in October 1909).

The area of low rainfall on the lee side of a mountain range is sometimes called the rain shadow. Thus Alberta is in the rain shadow of the Rockies, Sweden in that of Norway. The rainfall in the shadow is chiefly cyclonic or convectional. Fig. 57 shows the close relationship between the relief of the land and the rainfall in the Alpine region.

(*d*) Mountains form an obvious and visible barrier. An interesting feature of the atmosphere is the existence of invisible barriers consisting of denser air lying across the path of less dense currents. They are frequent in the low-pressure systems of the westerlies, since the inward movement towards the lower pressures brings currents of diverse origin, some warm and damp and therefore relatively light, others cold and dry and therefore dense, into juxtaposition. Let us consider the conditions in North-west Europe. On the north-east of the low-pressure centre we often find an east wind which has originated over the Continent, and is cold, dry, and dense, especially in winter. Such a current may be at a temperature of 40°, and have a relative humidity of 60 per cent. On the south-east of the low-pressure centre the wind blows from south or south-west; it comes from the

[1] Salter, *The Rainfall of the British Isles.*

ocean, saturated with vapour, at a temperature of perhaps 55°. This current meets the easterly current at right angles, and rises over it by reason of its less density (Fig. 95, p. 263). The ascent causes cooling and condensation of moisture above the east wind barrier, and the rain falls through the east wind to the earth. Such is the cause of much of the rain which accompanies an east wind. It often falls steadily for many hours, and it is especially unpleasant by reason of

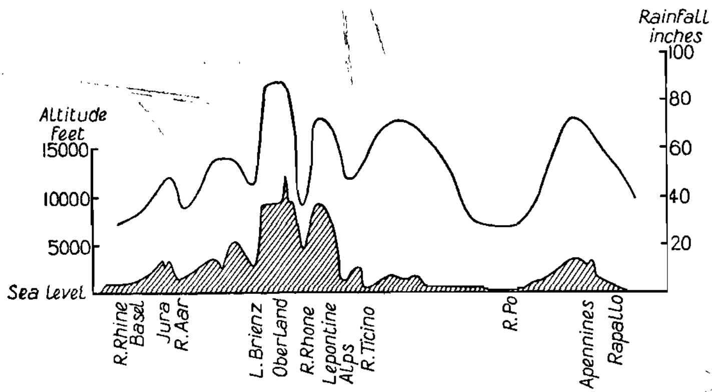


FIG. 57. The control of rainfall by topography. The upper curve shows the mean annual rainfall along the section of the Alpine Region from the Gulf of Genoa to Basel. The proximity of the Mediterranean gives the Apennines a heavy rainfall for the altitude. The Upper Rhone Valley (2,500 ft.) has almost as little as the Po Plains (250 ft.) owing to the high surrounding ranges

the low temperature. Some of our worst weather is of this type. The rain is not brought by the east wind but is condensed from the south wind in the path of which the east wind forms a barrier comparable with a mountain range. This is one of the usual forms of what may be called 'cyclonic rain'. But much of the rain that falls in cyclones is due to other causes, as will be explained in Chapter XLV, which deals with 'weather'. Unlike convectional rainfall, cyclonic rain is independent of the time of day and of the surface temperature at the place where the rain falls; nor does the rain fall in violent storms of short duration, but in a steady downpour of no very great intensity, which may continue over a large area for even 48 hours or more without intermission. The total amount derived from the passage of a single cyclone does not generally exceed 1 inch in flat country, and it is usually much less. Its occurrence is due simply to the air movements in the cyclones, and the amount varies with their frequency and intensity, which are highest in autumn and winter.

Most of the rain of the lowlands of west coastal regions in the belt of the Westerlies is cyclonic, as in the Midlands of England. Weather phenomena, however, can seldom be separated into sharply marked categories. Convectional influences may be present with cyclonic, and both are associated with orographic in mountain regions.

(*e*) The wind is impeded by friction with the surface over which it blows. The friction is least over water and greatest over a forested land. Hence the lower strata of on-shore winds are slowed down when they reach the land, and there is formed, as it were, a 'block' in the circulation which the air that continues to press on from the sea has to overrun. For this, as well as other reasons, on-shore winds tend to give cloud and rain. The very heavy rainfall, nearly 150 inches a year, of the densely forested Niger delta is partly due to it.

Aridity

The converse process of descent dries the air and leads to a scanty rainfall as we have already pointed out. Instances of the rain shadow in the lee of a range of mountains are the east of Scotland, the semi-arid plateau on the east of the Rocky Mountains, and the desert of Patagonia in lee of the southern Andes.

Anticyclones give, speaking generally, descending currents and consequently dry air, in contrast to the rainfall which is associated with cyclones. The aridity of the centre and west of Australia is to be ascribed partly to the fact that the region is almost always dominated by anticyclones moving from west to east.

Since cold air can contain little vapour there tends to be a less amount of precipitation, though not necessarily a shorter duration of rainfall, in cold than in hot lands. The low precipitation of the tundra and of the 'cold-water coasts' (Chap. XXXV) illustrates this.

Variability of Rainfall

The amount of rain in any place is liable to be very variable from year to year. The average variability may be expressed numerically as a percentage of the normal value; to obtain it the excess above or deficit below the normal is found for as many years as possible and the arithmetical average (ignoring signs) is taken. As instances we may quote the following values for the mean variability in the annual rainfall:

	%
British Isles (as a whole)	11
Central and Western Europe	13
California	26
India, Assam and E. Bengal	5
Punjab Plains	13
N.W. Provinces	23
Sind	37

As a rule the most arid climates are subject to the greatest variability of rainfall. The shorter the period considered the greater is the variability; it is greater for a season than for the year, for a month than for a season. It is useful to know not only the mean but the absolute highest and absolute lowest rainfalls that have been recorded, provided that the records extend over an adequate period, not less than 30 years. The following tables give these figures for each month for Oxford for the period 1890–1927:

Heaviest rainfall (in inches) recorded.

Jan. 4·39	Apr. 4·31	July 4·75	Oct. 6·68
Feb. 4·25	May 4·59	Aug. 5·13	Nov. 4·96
Mar. 5·18	June 5·82	Sept. 6·01	Dec. 5·82

Year 37·71

Lowest rainfall recorded.

Jan. 0·47	Apr. 0·02	July 0·28	Oct. 0·50
Feb. 0·17	May 0·18	Aug. 0·80	Nov. 0·58
Mar. 0·29	June 0·07	Sept. 0·41	Dec. 0·45

Year 14·94

Mean rainfall for the same station—

Jan. 2·10	Apr. 1·72	July 2·58	Oct. 2·87
Feb. 1·62	May 1·97	Aug. 2·42	Nov. 2·18
Mar. 1·75	June 2·37	Sept. 2·18	Dec. 2·24

Year 26·02

Extreme annual rainfalls for other zones are

	Lat.	*Mean Annual Rainfall (inches)*	*Largest Rainfall recorded in a year.*	*Lowest Rainfall recorded in a year.*
Singapore	1° N	93	159	33
Malden Islands (1890–1909) .	4° S	21	63	4
Manila (1865–1919) . .	15° N	77	153	36
Brisbane (1842–1924) . .	27° S	45	88	16
Athens (1857–1907) . .	38° N	15	33	5
Paris (1851–1900) . .	49° N	20	26	14
New York (1826–1909) .	41° N	42	60	29
Victoria, B.C. (1881–1910) .	48° N	31	44	22
Winnipeg (1885–1914) .	50° N	20	27	14

The variability for shorter periods is much greater. The lowlands of the south of England are probably liable to receive as much as 10 inches in 24 hours; among the highest records are 9·56 inches at Bruton, Somerset, on June 28, 1917, and 9·40 inches near Cannington, Somerset, on August 19, 1924. These high totals are generally—though not always—due to sudden downpours in thunderstorms, and only a small area is affected by any one storm (Fig. 72). The highest records in the mountains are due to strong on-shore winds during the passage of cyclones, and the area affected is larger. In the hot lands heavier falls are to be expected. Fifteen inches in the day is not uncommon in tropical mountains, and over 40 inches has ... The heaviest rainfall recorded

CHAPTER XXIV

THE CHIEF RÉGIMES AND REGIONS OF RAINFALL

BEFORE describing the rainfall types it will be convenient to state the main 'régimes' of rainfall on the earth. The word régime denotes the seasonal distribution at any place; the régime can be well expressed graphically by the curve of the amount of rain month by month through the year (as in Fig. 59, p. 142). The régime is the same over wide areas though the amount of rain may vary greatly, and the boundary between different régimes is often capable of sharp delimitation.

The Chief Régimes

(*a*) Equatorial. The rain is due primarily to convection, and is heaviest at and just after the equinoxes. Between these two maxima there is less rain, and some months have very little, but there is no dry season so long or pronounced as to be of very serious biological importance.

(*b*) Tropical. This prevails between the equatorial belt and the trade-wind deserts. The rain is of the same type as in (*a*), but the farther we go from the Equator the closer are the two rainfall maxima in the summer half-year of the hemisphere; and on the outskirts they coalesce into a single maximum in high summer. Of the two relatively dry seasons of (*a*) one becomes shorter, the other longer, and most of this tropical belt there is one long season of such period of equatorial rain, and the longer the dry season when the conditions are those of the trade-wind deserts (Fig. 58).

(*c*) Monsoonal. The rain curve has a pronounced maximum in summer; the contrast between the very wet summer months and the long dry winter is even more marked than in (*b*). We separate this type from (*b*) primarily because its

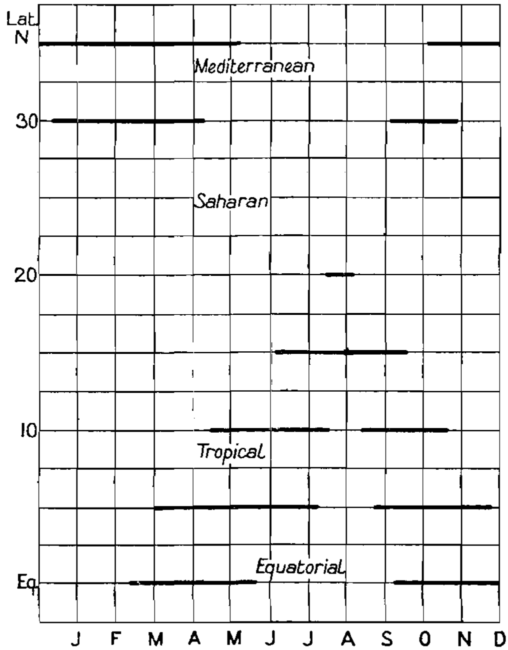


FIG. 58. The rainy seasons are shown by the dark lines

seasons are controlled by the prominent seasonal change of winds. It occurs both inside and outside the tropics, especially on the east coasts of continents.

(*d*) The oceanic régime of the westerlies, with rain all the year round, but a maximum in autumn or winter and a minimum in spring.

(*e*) The continental régime of the westerlies, with most rain in summer. We may subdivide the steppe type, in which the maximum is in spring and early summer.

(*f*) The Mediterranean régime. This is found on the west of the land-masses, between the westerlies and the trade-wind deserts. The rainy season is winter, and summer is almost or quite rainless. The winter rain is due to the influence of the westerlies spreading equatorwards with the swing of the pressure belts towards the summer hemisphere. In the case of the Old World Mediterranean region the local geographical conditions intensify this factor, and also introduce considerable modifications into the régime. In the northern half of the area there are two maxima in the rainfall curve, in autumn and spring. The dry and sunny summer is everywhere characteristic, and on the south-east coasts rain is all but unknown from May to September inclusive. At Alexandria in the years 1888–1922 no rain whatever fell in July; it rained on only one occasion in June, twice in August, five times in September.

The Chief Rainfall Regions of the Globe

The equatorial belt. The equatorial belt, the 'Doldrums' of sailors, is a region of hot and damp air. The heat is not nearly so great by day as in the trade-wind deserts on the north and south, and the highest temperature does not usually exceed 90°; but at night there is not that welcome coolness that compensates for the intense heat of the day in the desert lands, and—worst feature of all for the white settler—the heat continues monotonously high throughout the year, there is no cool season. Moreover, the air is always nearly or quite saturated with vapour, and consequently there is little evaporation of perspiration from the skin, the process by which in drier climates the 'physiological' temperature is reduced so as to be safe and even pleasant. The equatorial low-pressure belt is the goal of the north-east and south-east trade winds, which in spite of their low relative humidity yet contain abundant moisture ready to condense with any drop in temperature; they are impelled towards the Equator by the pressure gradients, and being forced to rise they cool and condense their vapour in heavy clouds (whence the term 'Pot au noir' applied to the region by French sailors). Hence the rainfall is heavy—heavier (if we take the belt as a whole) than in any other of the rainfall belts. The mean annual total exceeds 60 inches over vast areas, lowlands as well as mountains.

For a large part of its course the Equator lies over the ocean. Where it crosses land the ground is generally wet, and much of it is swamp or dense forest, the foliage of which pours vapour into the air. The air is thus laden with additional moisture, and especially in the neighbourhood of forests the atmosphere may well be compared with that of a hot-house, being hot, moist, calm, and enervating. But it requires the aid of the convection currents of the hot hours of the day to bring about the ascent necessary to give rain.

At night the ground cools, and mist or fog may form. The rising sun dissipates it, and in the early morning the air is clear and the sky unclouded. The heat increases rapidly until, near the coast, a sea-breeze may set in, which lowers the temperature but increases the humidity. Towards midday convection becomes active, the rising air is soon cooled below its dew-point, and huge masses of cumulus cloud form, inky black when seen from underneath, but when viewed from the side a magnificent spectacle of dazzling white as they swell upwards in the blue sky. The copious condensation is accompanied by high electrical tension, and soon after noon the storm bursts, with torrents of rain, frequently thunder and lightning, and sometimes violent gusts of wind. The rain cools the air and weakens the convection process. By sunset the cloud masses dissolve, and the stars shine brightly from a clear sky.

Bates[1] gives us the following description of the weather on the Equator in Brazil:

'The heat increased rapidly towards 2 o'clock (92° and 93° F.), by which time every voice of bird or mammal was hushed; only in the trees was heard at intervals the harsh whir of a cicada. The leaves, which were so moist and fresh in early morning now became lax and drooping, the flowers shed their petals. . . . On most days in June and July a heavy shower would fall sometime in the afternoon; producing a most welcome coolness. The approach of the rain-clouds was after a uniform fashion very interesting to observe. First, the cool sea-breeze, which commenced to blow about 10 o'clock, and which had increased in force with the increasing power of the sun, would flag and finally die away. The heat and electric tension of the atmosphere

[1] Bates, *The Naturalist on the River Amazon*, chap. II.

would then become almost insupportable. Languor and uneasiness would seize on every one; even the denizens of the forest betraying it by their motions. White clouds would appear in the east and gather into cumuli, with an increasing blackness along their lower portions. The whole eastern horizon would become almost suddenly black, and this would spread upwards, the sun at length becoming obscured. Then the rush of a mighty wind is heard in the forest, swaying the treetops; a vivid flash of lightning bursts forth, then a crash of thunder, and down streams the deluging rain. Such storms soon cease, leaving bluish-black motionless clouds until night. Meantime all nature is refreshed; but heaps of flower petals and leaves are seen under the trees. Towards evening life revives again, and the ringing uproar is resumed from bush and tree. The following morning the sun again rises in a cloudless sky, and so the cycle is completed; spring, summer, and autumn, as it were, in one tropical day. . . . With the day and night always of equal length, the atmospheric disturbances of each day neutralizing themselves before each succeeding morn; with the sun in its course proceeding midway across the sky, and the daily temperature the same within two or three degrees throughout the year—how grand in its perfect equilibrium and simplicity is the march of Nature under the equator!'

Such is a usual cycle of daily weather; the weather control is diurnal, depending on the sun. The irregular cyclonic control which governs the weather in temperate latitudes is lacking.

The station Half Assinie, on the Guinea coast, West Africa, illustrates the intensity of equatorial rain. In June the mean total is 25·8 inches, falling on 15 days, so that the average is 1·7 inches per rainy day.

Mountains modify, and to a certain degree intensify, the usual equatorial weather. During the day valley breezes blow up the valleys, and by their ascent an orographical effect is added to the convectional. Dense clouds hide the mountain tops and the thunderstorms are more violent than in the plains. At night the valley-bottoms are filled with mist as the result of the drainage of cooled air from the higher slopes.

This equatorial type of rainfall is associated with the meeting of the north-east and south-east trade winds under or near the overhead sun. Thus it is rather a seasonal than a local type, few if any regions being subject to it throughout the whole year. The belt of equatorial climate swings from the north hemisphere in the northern summer to the south hemisphere in the southern summer. On the Equator itself we should expect on theoretical grounds two rainy seasons in the year, one in March and April and the other in September and October.

Even on the Equator the weather conditions are not uniform nor is the rainfall always of this convectional type.

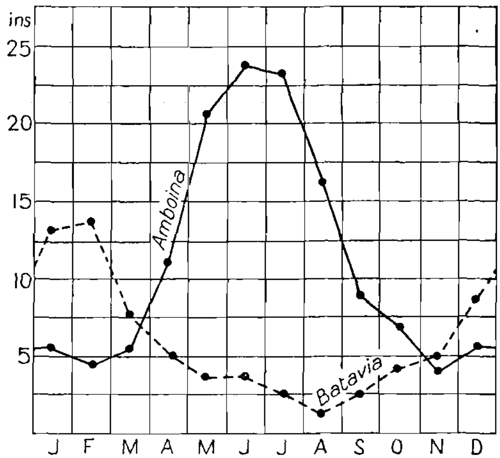


FIG. 59. Mean Rainfall

At certain times, especially at the beginning of the rainy seasons, there are violent storms of wind known in Africa as tornadoes which may do great damage on land and sea as they sweep along from east to west, generally accompanied by a torrential downpour with terrific thunder and lightning. They may occur by day or by night, and seem to be without any strong diurnal control. They do not last long, often only a quarter of an hour. The rainfall is subject to as much variability from year to year as in most other parts of the world—an important difference from the temperature, which is notably uniform.

So far we have described some of the general features common to equatorial lands. But there are important regional differences in the three great regions of land included in this belt, South America, Africa, and the East

Indies. The total annual rainfall is by no means the same, and the régime is rarely of the simple type we have described. The rainfall is heaviest on the slopes of mountains which face strong and constant winds, and to a less degree on windward coasts generally. The highest total recorded is 412 inches on the south-west side of Kamerun Peak, where a south-west wind blows on shore for the greater part of the year; the heaviest rains are received from

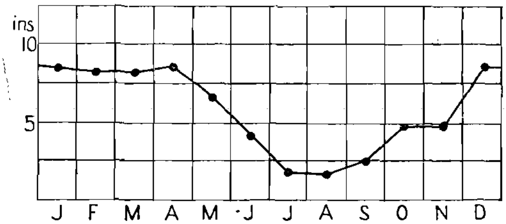


FIG. 60. Mean Rainfall, Manaos

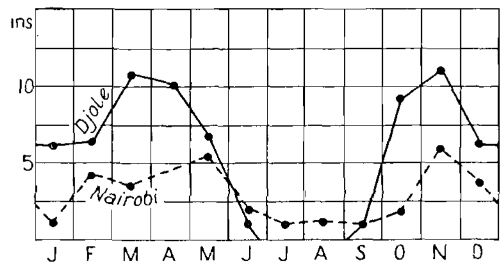


FIG. 61. Mean Rainfall

June to October, the months when the monsoonal indraft is strongest. Kamerun is situated about 5° N. lat., and this too tends to give it its wettest season in the northern summer. There are stations outside the Equatorial belt which have a larger rainfall.

The East Indies have a very heavy rainfall, and here again the cause is the prevalence of winds blowing over a very warm sea, for the Archipelago lies between Australia and Asia in the path of both the summer and winter monsoons. Totals exceeding 100 inches are common. The season of maximum rain varies according to the position in relation to the monsoon wind currents. Thus Batavia on the north coast of Java has a strong maximum in January and February, when the north-west winds are at their height; but Amboina, in the same latitude but on the south coast of the island of Ceram, is comparatively dry at that time, and receives a very pronounced maximum in June and July, the season of south-east winds (Fig. 59). The effect of onshore winds is well marked in South America where the coastal belt between (and including) the estuaries of the

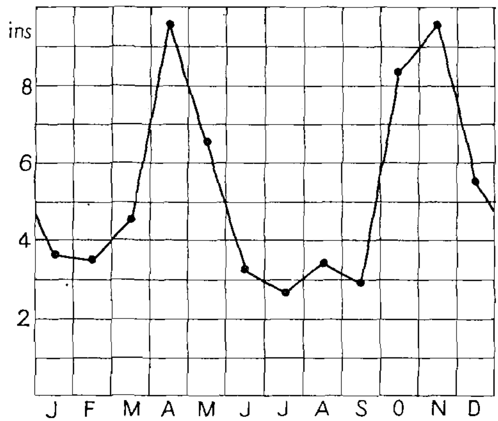


FIG. 62. Bogota mean Rainfall

Amazon and the Orinoco receives from 80 to over 100 inches a year from the almost constant north-east trades. In the west of the Amazon basin the influence of the Andes gives an ascending tendency to the east winds and a heavy rainfall results; the lower Amazon has considerably less rain than these two very rainy regions on each side, but even here the total is from 60 to 80 inches. Along the Amazon the heaviest rains are in the southern summer, but the two maxima do not synchronize with the overhead sun (Fig. 60). We may compare with these very wet regions the Congo basin which has not much more than 60 inches a year, owing doubtless chiefly to the fact that it is bounded on the eastern, windward, side by the plateau of East Africa. But the rain is more uniformly distributed over the year, and at many stations in Central Africa the two maxima seem to be directly controlled by the passage of the overhead sun (Djole, Fig. 61).

The East African plateau itself has a surprisingly low rainfall, generally between 40 and 50 inches, and the low coastal strip has so little as to be almost desert. But the régime is more normal, for the double maximum is well developed, occurring in April and November at most stations (Fig. 61). There is another plateau on the Equator in South America, and in spite of the great altitude of over 9,000 feet the rainfall is remarkably low, owing to the fact that the

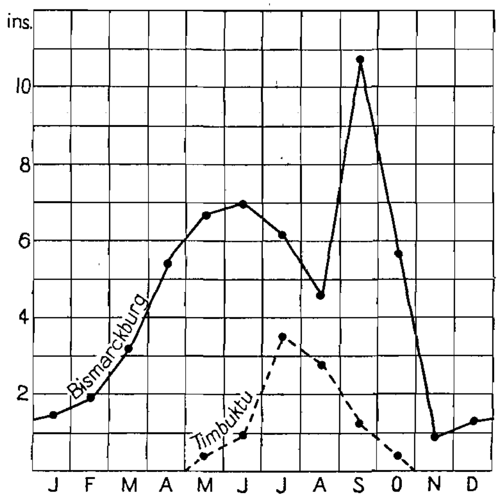


FIG. 63. Inter-tropical rainfall curves, W. Africa; Bismarckburg, 8° N. lat., has 2 maxima, Timbuktu, 18° N. lat., 1 maximum

ranges of the Andes tower up in a continuous wall on each side. Quito receives only 42 inches a year, the rainiest months being April and November. Bogota, alt. 8,730 feet, on the eastern Cordillera of the Andes has a well-marked equatorial régime although it is 5° N. of the Equator (Fig. 62).

In the many little islands near the Equator in the Pacific Ocean the rainfall varies greatly in season and amount. Jaluit (Marshall Islands, 5° 55′ N.) has the high totals of 163 inches of rain and 265 rainy days; the rainiest months are May, June, and July, each with over 16 inches, the driest February with 9 inches. Nauru, lying almost on the Equator, has 75 inches, well distributed over the year; December has most, 10 inches, March least, 4 inches.

The tropical belt. The equatorial rain belt moves northward in the northern summer, southward in the southern summer, returning to the Equator at the equinoxes. The type of rain is the same everywhere, and we need refer here only to the régime. Fig. 63 illustrates the two régimes, described on p. 137. The total annual rainfall decreases with the length of the rainy season. During the long dry season the landscape is brown and arid, but the advent of the rains soon calls forth a luxuriance of green.

The trade-wind belt. The trades are dry winds. They originate in the horse latitudes, in the belts of high pressure situated about 35° north and south of the Equator, where the air is very slowly descending to the surface of the earth—too slowly probably to have much appreciable direct effect on its temperature and humidity, for the rate is of the order of only 300 feet in the day according to Shaw.

In their passage towards the Equator the winds are reaching warmer latitudes, and this tends to keep them dry. They are remarkably free from such irregularities of pressure and weather as are responsible for most of the rainfall of the westerlies, being among the steadiest winds on the globe. Over the oceans the trade-wind regions are almost rainless, except in the hurricane areas (p. 92) where a single storm may give 10 inches of rain. Most of the hot deserts are due to the fact that the dry trades blow over them; the Sahara is the most prominent example, being under the sway of the north-east trades throughout the year. The desert coast of South-west Africa, the Kalahari, and the Atacama desert in Chile are in the zone of the south-east trades, and are the more arid because of the mountain barrier to windward. The delightful weather of the Trades out at sea is famous. The air is fresh and pure, and feels cool and invigorating owing to its rapid movement. The sun shines brilliantly from a deep blue sky brightened by a few light white roll-cumulus clouds, and white-crested rollers sweep across the transparent ultramarine ocean. The relative humidity of the air between the Canaries and Cape Verde is about 60 per cent., and the evaporation is so active that the sea surface is more saline than the normal.

But the fact that the trades are not saturated makes them ready to absorb moisture whenever possible, as in their passage over the sea or over a land covered with vegetation. Although the humidity remains below saturation point the absolute vapour content becomes high, and if the air is cooled by ascent there may be very heavy rain. The simplest case is where high mountains rise in their course after they have passed over a wide ocean. The north-east trades of the Pacific Ocean meet such a barrier in the Sandwich Islands, where the volcanic mountains rise steeply from the ocean to 13,000 feet; on Mount Waielale (5,080 feet) in the island of Kauai a high cliff facing north-east forces the trade winds to rise almost vertically, and the rainfall is both heavy and continuous. The records are slightly uncertain owing to the difficulties involved in reaching this remote and elevated spot in order to read the rain guages, but it seems that the mean daily rainfall is over 1 inch, and the mean annual over 400 inches. This is among the highest figures recorded on the earth; but on the south-west side of West Maui, in the same group, the annual total is only about 8 inches. On most of the 'high' islands of the South Seas there is a similar remarkable difference between the rainy windward and the much drier, in places almost arid, lee sides. Apia, Samoa Islands, 13° 49′ S. lat., has 114 inches of rain, falling on 218 days, and Utumapu in the same group 131 inches, falling on 193 days (giving a mean rainfall of 0·7 inches per rainy day). The peaks of all these South Seas islands hardly ever put off their cowl of cloud. Even in the middle of the Sahara the mountains receive considerable precipitation, being snow-capped in winter and having perennial streams. Naturally the precipitation is less in the midst of the desert than on the boundless expanse of ocean.

In general elevated east coasts within the tropics have a heavy rainfall, since the prevailing winds are the on-shore trades. The rain is heaviest in the hot season, since convection is then most active, and also the heating of the land masses tends to develop lower pressures so that a monsoonal effect is produced. West coasts have much less rain, and in many parts are arid, because the trades reach them after their passage of the land mass. The east coast of Africa south of the Equator has more than 40 inches a year, but most of the west coast has less than 10 inches, and some hundreds of miles in South-west Africa are barren desert, with practically no rain at all. South America and Australia show similar striking differences between east and west coasts.

In the hot deserts over which the trades blow the instability caused by the excessive heating of the sand, or by the arrival of an unusually cold upper current, sometimes produces extremely heavy rainfall, usually of short duration. At Helwan, 12 miles south of Cairo in the Egyptian Sahara, the mean annual rainfall is 1·5 inches. But this mean value gives an inadequate idea of the conditions. 'A mean annual rainfall of 37 mm. seems almost negligible, but the yearly fall results from only a few storms which are often severe. Thus from 1904 to 1924 the total rainfall was 780 mm., nearly a quarter of which fell in 7 single storms.'[1] In one severe storm on April 19–21, 1909, 1·8 inches were registered; torrents swept down the wadis, and much damage was done to buildings and crops. This storm was cyclonic and travelled up from the south, making its way to Syria. Hogarth records similar visitations in the desert of Arabia: 'I myself have been witness of such a flood. It lasted about 4 hours, and the result was to lay silt 5 feet deep over the whole plain on which I was living, and completely to alter the physical geography of the valley.' At Doorbaji in the desert of Sind where the mean annual rainfall is 5 inches, on one occasion as much as 34 inches of rain fell in 2 days.

Owing to their uncertainty and violence these rains cannot be turned to account by the natives, and most of the water runs away rapidly; but a certain amount sinks and helps to maintain the underground supplies, which are brought to the surface here and there by artesian and other wells. In regions where roads, railways, bridges, irrigation systems, and other public works have been made the floods may do much damage in their short life. The wadis, generally quite dry, are filled with a rushing torrent of muddy water in a very short time, and it may travel to a great distance from the place where the storm burst. In the French

[1] Sutton, *The Climate of Helwan.*

Sahara army regulations forbid troops to camp overnight in the bottoms of dry wadis, a tempting site owing to the shelter of the high and steep banks, for in the past camps have been washed away by floods which swept down suddenly in consequence of sudden deluges in distant parts of the basin.

Dust, together with flies, is one of the great discomforts of all arid lands. Except on still nights the air is full of fine particles which percolate through the finest chinks into

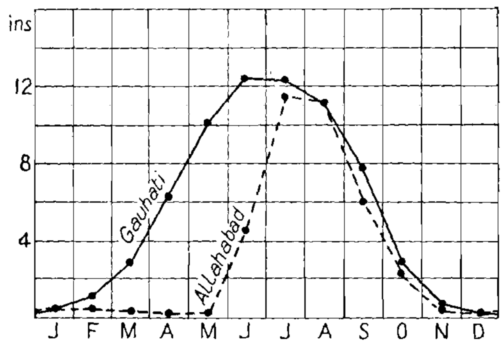


FIG. 64. Mean Rainfall in Assam (Gauhati); compare the normal monsoon curve for Allahabad

houses and even closed boxes. Dust lies thick on every shelf, covers furniture, settles on food, and is inhaled with the air we breathe; many Arabs cover their mouths and nostrils with mufflers. There are all degrees of intensity of dust, according to the nature of the ground and the strength of the wind. Sometimes the dust is merely blown in light clouds along the surface, at other times it is whirled up in 'dust devils'. Worst of all it may be carried up to great heights, and be thick enough to darken the sky, forming real dust-storms. These may be 5,000 feet high, or more, as in Mesopotamia and the Plains of India in April and May. They are known as 'Habub' in the Sudan (Plate 3).

Monsoons. The rainfall is in general heavy, and it must be remembered that nearly all the rain falls in 4 or 5 months; consequently the downpours during the rainy season are much heavier than even the high annual totals might indicate. The winter months are almost or quite dry (Fig. 64, Allahabad). The seasonal contrast in the rainfall in monsoon lands is quite as striking and important for plant and animal life as the contrast between winter and summer temperatures in high latitudes. Bombay has a mean rainfall of 75·7 inches in the four months June to September, and only 0·2 inches in the four December–March. The whole life of the monsoon lands, which are essentially agricultural, is based on the seasonal rhythm, and any serious departure from the normal weather may lead to great distress and even widespread famine. Unfortunately there are large variations in both the duration and the amount of the rain, especially in India and China. In some years the crops fail through drought, and in others the rain is so excessive that the rivers burst their banks, and the floods destroy crops and drown the people by thousands, especially in China.

The association of heavy rain with the full heat of summer causes the vegetation to grow with riotous luxuriance; rice is the characteristic and very prolific crop and supports a very dense population. The monsoon lands are by far the most densely populated regions of the earth outside the industrial countries of Europe and North America.

The summer winds contain very rich stores of vapour owing to their long passage over warm oceans—a passage of several thousand miles in the case of the monsoons of South-east Asia and West Africa. The condensation of the vapour gives the heavy rain, but in many cases it is not quite clear to what process the condensation is due. Many different processes probably act in combination in most regions. The high temperature over the land causes ascending air currents—the initial cause of the monsoon—and the rising air cools adiabatically; hence it is to be expected that dew-point may be reached, and rain result. But we see that this process alone is inadequate from the fact that the centres of lowest pressure and greatest heat are by no means the rainiest areas; the deserts of Sind and Mongolia are in the heart of the lowest pressures of Asia in summer, and the deserts of Arizona are similarly situated in North America. Surface friction on the land (p. 134) must be one factor in causing the heavy rain, by obstructing the great volume of air that surges in from the ocean. Another

PLATE 3

A dust-storm sweeping over Khartoum and the Nile factor of very considerable importance is the existence of cyclonic irregularities in the monsoon current (Fig. 46, p. 101). But probably the most effective cause of the heavy general rain is ascent caused by the slope of the land, and especially that due to mountains. Special stress has been laid on this in the case of India by Dr. G. C. Simpson.[1] The north of India may be regarded as a compartment bounded by practically continuous mountain ranges of at least 6,000 feet on the north, the west, and the east; but on the south it lies open to the sea, and receives the great current that has crossed the south and north Indian Oceans. Evidently none of this air can leave the area without rising at least 6,000 feet, and the ascent is the primary cause of the rainfall. In addition there is the local effect of mountain ranges—which stand out so unmistakably on the rainfall map that it is unnecessary to refer to them in detail (Fig. 56, p. 120). The natural complement of the heavy rains of the mountains is the deficient rainfall of the rain shadow in their lee; while the coastal strip on the windward side of the Western Ghats receives more than 100 inches of rain a year, there is less than 20 inches on the east side. The most striking orographical effect is seen in the Khasi Hills in Burma, a range of an altitude of about 5,000 feet which extends westward from the Arakan Range. The plain narrows in from the south-west to the junction of the Khasi Hills and the Arakan Range, and thus is a funnel-shaped area widely open to the south-west monsoon. The narrowing of the funnel by the mountain ranges causes rapid ascent, and the rainfall that results is the heavier owing to the floods of warm water which cover the lowlands and pour vapour into the winds that blow over it. Cherrapunji, situated 4,455 feet above the sea on the south slopes of the Khasi Hills, receives during the monsoon months June to September a mean rainfall of no less than 318 inches, and 41 inches has been recorded in a single day. Shillong, on the same range and at a rather greater altitude, but on the northward leeward slope gets only 55 inches during the same months.

In China, too, the influence of the relief must be considerable, for the winds from the sea are confronted by the

[1] 'The South-West Monsoon', *Quarterly Jour. R. Meteorological Soc.*, July 1921.

eastern edge of the interior plateau, and the ranges that buttress it. The winds, however, are not so strong as in India, nor is there any 'compartment' effect. The rainfall is heaviest in the east near the sea, and especially in the south-east where the temperature is highest. Similarly in the north of Australia the monsoon rain is heaviest near the coast, especially on the mountains of the north-east of Queensland, and it decreases rapidly towards the arid interior. There is a similar distribution in the Guinea lands of West Africa, but here the lower latitude introduces other factors. In North America the south-east of the United States has the heaviest rain of the region. The rain may be described, though with reservations, as monsoonal, and the air is notably humid owing to the warm waters of the Gulf of Mexico and the Gulf Stream which wash its windward coasts.

It has already been pointed out that the monsoon rain falls in the warm season. The periodicity is very pronounced, in the Asiatic monsoon region especially; in India about 85 per cent. of the whole falls during the summer monsoon. In north China as much as 90 per cent. is received in the 5 months May to September. The monsoon brings about a wonderfully sudden transformation of the face of nature. During the previous months the land has lain dry and hard as a paved road, parched and dusty, with hardly a green blade of grass or a green leaf to be seen; and for many weary weeks before the rains begin the air has been extremely dry, the heat intense, and the sky cloudless, though grey with heat and dust rather than blue. The rivers, except those which are fed by melting snow and glaciers, are mere trickles of water, meandering through wide banks of sand on the floor of a channel which seems altogether disproportionate to the volume of the stream. But once the rains start all is changed. The land is not only saturated but large areas are flooded by the torrential rains. Vegetation springs into life and the landscape is clothed in green. The air is as unpleasantly moist as it had previously been uncomfortably dry; wood swells and doors and windows jam, leather becomes mouldy, and paper is damp and limp. Thick black clouds often cover the sky, and the river-beds, which in the dry season looked like survivals from some past epoch, justify their great width, which indeed proves all too small to contain the swollen volumes of rushing muddy water. Tree trunks, débris of all kinds, light and heavy, is carried down, and bridges have to be built to resist not only the terrific force of the rushing river but also the impacts of the floating projectiles with which it assails them. The greatest floods are in the middle and end of the monsoon, for the heavy rains at the beginning are largely absorbed by the empty channels and reservoirs, the thirsty land, and the riot of vegetation.

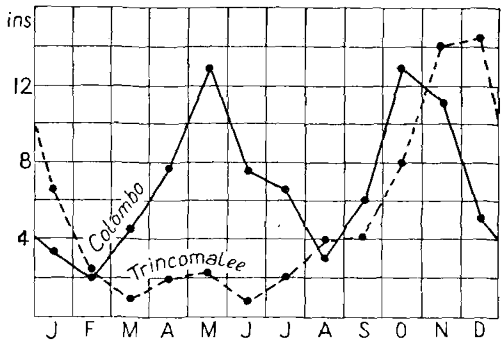


FIG. 65. Mean Rainfall in Ceylon

We shall now consider the rainfall régimes in more detail. In the Indian region Ceylon (Fig. 65) has the peculiarity of receiving rain not only from the south-west monsoon but also from the north-east, for the mountainous island is exposed to the north-east winds that have crossed the Bay of Bengal. The east side of Ceylon of course gets more rain from the north-east monsoon than the leeward west of the island, and much of it has the heaviest rain of the year in January and February. But even in the west, where the south-west monsoon meets the mountains and there is a very strong maximum in the summer, there is appreciable rain in winter also. The coast of Annam, the west coast of Hondo (Japan), and the eastern islands of the Philippine group are like eastern Ceylon in receiving their heaviest rain from the winter monsoon.

Assam (Fig. 64), a humid, mountain-girt land, receives considerable rain from local thunderstorms in April, May, and June, and the arrival of the monsoon causes merely an intensification of the rains. The early rains are important in lengthening the season of growth for the tea plants. The north-west of India (Fig. 66) has two maxima in its rainfall curve. That of the summer monsoon is by far the more prominent, but the secondary maximum in January is of interest both theoretically and practically (see p. 99).

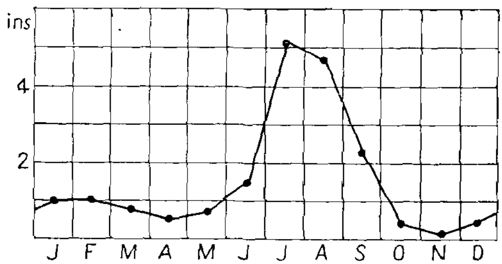


FIG. 66. Lahore, Mean Rainfall

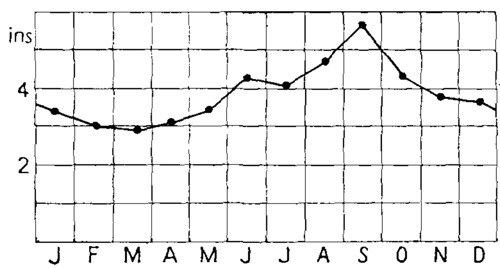


FIG. 67. Galveston U.S.A., Mean Rainfall

In China the rains last from May till October with a maximum in July, but there is the peculiarity in the south of China that the maximum is in June, before the monsoon is at its height, and a secondary maximum comes in August and September, caused by the heavy rains associated with typhoons. The June maximum occurs in the south of Japan also. It is one of several features of the monsoons which have not been satisfactorily explained. The lower Yangtze valley has its rainfall more evenly distributed over the year owing to the occurrence of appreciable rain in the winter.

North America has only a very much modified type of monsoon. This is true of the rainfall as well as of the winds. In the south-east of the United States August and July are the rainiest months, but there is abundant rain throughout the year (Fig. 67). The warm waters of the Gulf of Mexico and the Gulf Stream which bathe the shores on the south and east favour cyclonic activity in winter even more than in summer and consequently the winter rainfall is heavy in spite of the low air temperature. The hurricanes of late summer add to the rainfall totals. Space does not admit of a reference to many other peculiarities which are to be found in these and other monsoon regions.

The Westerlies. Poleward of the dry trade-wind belts are the zones of the westerlies—rainy zones, the windward coasts of which are among the rainiest parts of the globe. The mountainous western sea-boards of North America, North-west Europe, the south of Chile, and the south island of New Zealand have in many places mean annual rainfalls exceeding 100 inches.

The westerlies always tend to be saturated with vapour owing to the fact that they blow from warmer to colder latitudes. Their passage over wide oceans which are abnormally warm for their latitude provides them with abundant moisture. If they blew as a steady current we might expect them to bring warm damp air, overcast skies, and constant light rain, the exact opposite of the conditions which prevail in the trades. But the westerlies are not a steady current; on the contrary they consist rather of a very turbulent eastward procession of irregularities of pressure, usually cyclones and other low-pressure systems, but sometimes anticyclones, giving rise to winds which are very variable in force and direction, and weather which is notoriously changeable. Instead of a constant light rainfall we have fairly heavy rains alternating with finer and drier weather. The rainfall is cyclonic and on the oceans is heaviest when cyclonic disturbances are most numerous and active, that is in autumn and winter. An advancing cyclone carries its weather system with it, modified continually by changes in the form and intensity of the system itself, and especially by the changes in the nature of the associated air currents, whose origin, and therefore temperature and humidity, are necessarily different in the different parts of the system's course. The structure of cyclones is treated in Chapter XLV. The rain falls, speaking generally, in the front half of a cyclone, being condensed from the warm air that blows in from the equatorial side; its intensity and duration are very variable. A rainfall of a quarter of an inch in the course of 6 or 8 hours may be taken as an average value for an active cyclone in the British Isles region. As the cyclone travels on, its rear sectors dominate the weather, and the winds coming from a polar quarter are cool and comparatively dry. The sky may be clear, but in the daytime the convection set up between the heated surface air and the cold Polar air above often causes the formation of cumulus clouds which may even give showers of rain.

Average values are of little significance when the conditions are so variable that no two depressions are alike. There may be no rain at all, or there may be a heavy downpour; we leave out of account both thunderstorm rains and mountain rainfall, most of which is intimately associated with depressions, but can best be considered separately. The rain may be of short duration, or it may continue with few breaks for several days owing to an unusually slow or erratic movement of the system, or owing to the presence of secondary disturbances, which are frequently a cause of continuous bad weather. Spells of 30 consecutive days with rain are not unknown.

Although cyclonic activity is greatest in the winter the total rainfall is greater in the summer half-year over all the land masses in the belts of the westerlies except on the western coastal strips, since at even a short distance away from the oceans the higher temperature, and therefore greater vapour content of the air, in the warmer months, together with the instability caused by the strong surface heating, more than compensates for the lesser cyclonic activity. Moreover the higher temperature is conducive to lower air-pressure, and therefore facilitates the entry of depressions into the continents. It was in summer (June 1903) that one of the heaviest and most persistent cyclonic rains within living memory occurred in south England (Fig. 101, p. 277). August 1912 was another summer month which gave one of the heaviest rainfall totals on record over much of England. On both these occasions the rain was of a definitely cyclonic type, with few thunderstorms.

To represent the régime of the rainfall associated with the cyclones of the westerlies, unaffected by land influences, we may take the records from Sumburgh Head, Shetland Islands, lying between Scotland and Iceland, and full in the stormiest tract of the westerlies.

SUMBURGH HEAD (Alt. 112 ft.)

	Mean Rainfall (inches).	Mean number of rainy days.		Mean Rainfall (inches).	Mean number of rainy days.
January	3·9	27	August	3·1	20
February	3·0	22	September	3·2	20
March	2·9	25	October	4·1	25
April	2·0	19	November	4·0	24
May	1·9	18	December	**4·4**	**27**
June	*1·7*	*15*	Year	36·7	260
July	2·3	18			

The strict oceanic régime is only found on the open ocean and over a narrow strip of the windward coasts. Even in the east of England continental influences begin to appear:

LONDON, CAMDEN SQUARE (Altitude 110 feet)

	Mean Rainfall (inches).	Mean number of rainy days.		Mean Rainfall (inches).	Mean number of rainy days.
January	1·9	15	August	2·2	14
February	1·7	14	September	1·8	12
March	1·8	13	October	**2·6**	15
April	*1·5*	13	November	2·4	14
May	1·8	13	December	2·4	**16**
June	2·0	*12*	Year	24·5	164
July	2·4	13			

The rainiest month here is October, and the rainiest seasons summer and autumn. Spring has least rain, as in the oceanic régime, but winter has almost as little. The summer half-year has more rain than the winter half-year. An interesting feature is the heavy rain in July, almost as heavy as in October. In the interior of Europe these continental features are intensified; at Munich June and July are the rainiest months, February the driest; summer is the rainiest season, and the summer half-year has more than twice as much rain as the winter half; Munich is within the influence of the westerlies, but the continental cold reduces the winter precipitation, and the heavy instability rains and frequent thunderstorms of hot summer days swell the summer records. In Hungary the proportion of the rain that falls on days with thunderstorms is:

43% in May	51% in July
51% in June	49% in Aug.

At Oxford, England, 28 per cent. of the rain in June, 32 per cent. in July, falls on days on which thunder is heard. The summer maximum of rainfall is due to the heaviness of the showers rather than to the number of rainy days. Thus at Moscow there are 18 rainy days in December, only 13 each in May, June, and July. But the rainfall of July is 2·8 inches, of December only 1·5 inches.

The continental variety of the westerlies rainfall régime covers most of the interior of Europe except the Mediterranean lands, most of Siberia, the greater portion of Canada, and much of the United States. Its extent in the southern hemisphere is very small.

To sum up the main features of this continental régime, there is precipitation all the year round, mainly cyclonic in origin, but in summer associated largely with thunderstorms due to local convectional overturnings. The summer rainfall is heavier (but of shorter duration) than the winter, but the oceanic control is seen in the secondary maximum that often appears in the curve in autumn. No season can be described as dry, and though winter may have the least amount of precipitation, the number of days on which rain falls may be as great as in summer; and owing to the low temperature and damp air the conditions in many regions situated not far from the coasts are considerably more humid then than in summer, and it is difficult to believe the records of the rain-gauge. In England February is sometimes named 'fill-dyke', though the actual mean precipitation of the month is in some places less than in any other month. But in view of the chilly damp air and the water-logged condition of the land, the name is not inapt. Even in abnormally wet summers, with a rainfall twice as great as the average, evaporation is far more rapid than in winter. Thus in England in 1927 the summer was notably cloudy and rainy, and after the heaviest spells of rain the rivers ran in high flood. Yet it was noticeable that the floods were of much shorter duration than those of winter, and the land soon recovered from its water-logged condition. In spite of this, however, the summer was so wet as to be ruinous for farmers. The only season that can be said to be noticeably less rainy than the others is spring, when the less rainfall is associated with strong drying winds and bright skies. But in the continental interiors of North America and Asia the winter cold is intense, the air fairly dry, and the sky often clear. Almost all the precipitation falls as snow. The clear dry air makes the keen frost much more pleasant than the dampness near the coasts, where the temperature may be above 32°.

Mediterranean Region. In the Mediterranean region, including both the Mediterranean Sea and the surrounding lands, and especially the peninsulas and islands, the rainy season is the winter half-year (Fig. 115, p. 316), and a similar régime prevails in corresponding regions on the west coasts of continents in sub-tropical latitudes in other parts of the world—California, Central Chile, the south-west of the Cape Province of South Africa, and the south-west of West Australia. The rainfall is similar to that of West Europe, being cyclonic in type. The amount depends closely on the relief of the land. But the duration of the rain is less than in the westerlies, the sky is less cloudy, and the sunshine much more abundant, although the amount of rain associated with any one cyclone is often greater. Thus while the mean rainfall in October at Oxford is 2·8 inches, falling on 16 days, at San Remo, on the Italian Riviera, the mean for the same month is 6 inches, falling on only 7 days, and at Alassio 5·2 inches, falling on 5 days. Most of the Mediterranean region has only about 90 rainy days a year, while North-West Europe has about 180. At Athens the mean duration of rain per rainy day is only 1·9 hours, at Paris 3·9 hours.

Very heavy downpours are a feature especially of the mountains, which are so characteristic of the Mediterranean coasts, but they are not uncommon on the lower ground. Perpignan has had more than 4 inches in a day 10 times in 50 years; in October 1876 14 inches fell within 63 hours.

At such times the water-courses, which in summer are wide expanses of gravel and sand lying dry and white in the dazzling sunshine, save where dotted with dark oleander bushes, rapidly become filled with roaring torrents of muddy water, which flood the country and may do great damage. The conditions in Greece are similar; Athens, with a mean annual rainfall of 15 inches, had 4·5 inches on November 10, 1912, and similar, though rather less intense, downpours are not uncommon, light steady rain being rare. Recently much damage has been done in Western Algeria by similar torrential rain; in the 6 days November 24–9, 1927, even

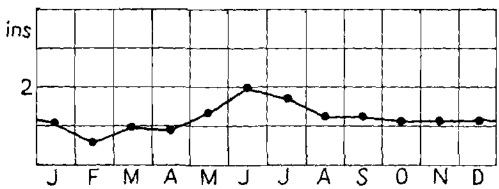


FIG. 68. Orenburg Mean Rainfall

the low plain of the Sig received about 14 inches of rain, and 17 inches and more fell in the neighbouring mountains, this being about 80 per cent. of the mean total for the year. The rain was cyclonic. Crops were ruined, houses destroyed, and many persons drowned. Such storms are largely responsible for sweeping the limestone mountains bare of soil, and leaving them white and dazzling in the bright sunshine.

Thus the winter rains of the Mediterranean lands are distinguished from those of the westerlies by the heaviness of the showers and by the quick return of clear skies. The main cause of this would seem to be the close juxtaposition of the moist air over the sea and the cold dry air over the continent. As soon as the cyclone passes on eastward a flood of clear dry air sweeps down in rear of it, and the weather is fine again.

Further information on the Mediterranean will be found in Chapter LII.

The Steppes. A modification of the usual continental type prevails in the steppe lands, such as the interior of south-east Russia, Turan, Asia Minor, the Meseta of Spain, and the plateau of the Shotts. The peculiarity is that most rain falls in spring and early summer; late summer is drier

(Fig. 68). The prevailing winds in south-east Russia, Turan and Asia Minor are north and north-east, and as they blow from the arid interior of Asia the rainfall is necessarily scanty. The most favourable circumstances for precipitation occur in spring when the insolation is rapidly increasing and warming the ground, but the higher atmosphere is still cold. Convection becomes active during the hot hours of the day and heavy rain may fall. In high summer the ground is still hotter, but so also is the higher atmosphere, and convection is less active. Moreover there is then a definite air movement, controlled by the low-pressure system of South Asia, and local temperature differences and minor irregularities of pressure which give the heavy convectional showers of the earlier months have less chance to develop. The spring rain is contributed to by occasional cyclonic disturbances from the Mediterranean region.

The early summer rain is one of the main causes of the prevailing vegetation of grass, which requires moisture especially in the early part of the growing season. The rainfall of high summer is less valuable for plant life than the actual amount might indicate owing to the heat, for the surface of the hot ground is baked so hard that much of the rain is lost by rapid run-off or by evaporation. In winter much of the scanty precipitation is snow, and the fierce north-east winds that sweep across the bleak open plains blow most of it away. As the cold dry winds are in themselves also highly hostile to tree growth the conditions are in every way suited to grass.

The steppe type of rainfall prevails over much of the centre of North America, including the great wheat lands of the south of Canada and the north of the United States. It is less extended in the southern hemisphere, owing to the absence of large land masses in middle temperate latitudes.

The Polar zones. The conditions are simpler in the south hemisphere than the north, for almost the whole area inside the polar circle is occupied by Antarctica, an ice- and snow-covered plateau. It is intensely cold in winter, and even in the warmest month the mean temperature is below freezing-point on the coasts; it is very much colder on the high snow fields of the interior. Rain practically never falls; all the precipitation is snow, and owing to the low temperature the snow consists of hard fine sharp spicules of ice. But it is not easy to see why there should be precipitation of any kind since the continent is covered by an anticyclone which seems to be notably constant in position. However, the facts that great glaciers move outwards from the interior and that icebergs are constantly being calved from the edges of the ice-sheet show that the precipitation must be considerable, and much in excess of the very appreciable loss by evaporation. Various theories have been advanced to account for the precipitation. Professor Hobbs points out that the intense cold is the result of the rapid radiation from the snow surface; the air is constantly descending in the anticyclone, and when it reaches the surface contact with the cold snow causes its moisture to be condensed in fine ice particles, or as hoar frost. This process is almost always going on, and therefore though the rate of deposit is slow the total amount is considerable. It would certainly seem likely that some addition to the ice-cap is due to this cause, but it is difficult to believe that it accounts for the total precipitation. Many of the cases of surface mists and drifts of ice spicules which have been observed are capable of other explanations, and the process seems altogether incapable of explaining the thick snow of blizzards. Moreover, the centre of an anticyclone is a region of calms; but if this process can provide much deposit of snow it can only be by rapid renewal of the air in contact with the surface—that is to say, strong winds rather than calms would be needed. On the other hand, the condensation would be most rapid in the winter, for the snow surface is then intensely cold, while the air currents feeding the anticyclone from above are not very much colder than in summer. But no expedition has spent much time even on the outskirts of ice-caps in the depth of winter, and hence we are without the records which may lend support to this theory.

Dr. Simpson advances a different theory, explaining the precipitation by the forced ascent in blizzards of air currents which advance over the more slowly moving or stationary surface layers in front of them. Though in its descent in the polar anticyclone the air is warmed and dried, yet on reaching the surface it loses so much heat by contact with the very cold snow that the additional cooling brought about by an ascent of 1 or 2 km. would suffice to bring it below its dew-point. Such an ascent can easily occur in blizzards, and condenses the thick snow that fills the air. If this is the complete explanation of the precipitation in Antarctica, we must assume that blizzards are frequent in the interior, a point on which there is not much evidence; they are certainly frequent near the coasts.

The North Polar zone is a more complex region geographically. The central tract is unbroken ocean, but the peripheral zone includes considerable areas of America and Eurasia, and most of Greenland. Greenland resembles Antarctica; but although the ice-cap is probably covered normally by a shallow anticyclone it is frequently invaded, or at any rate influenced, by cyclones from the regions of very disturbed atmospheric conditions on the west, south, and east, and probably much of its precipitation is of the cyclonic type, almost all of it falling as snow except on the coasts, especially the comparatively mild west coast. Professor Hobbs, however, maintains that the anticyclone is intense enough to keep all cyclones at bay, and he is convinced that the whole of the precipitation in the interior is due to the surface cooling of the air with consequent condensation of its vapour, as explained above for Antarctica.

Arctic Canada and Eurasia, including all the barren lands of the tundra and some of the forest belt, receive most of their precipitation in the summer and autumn, when the temperature is considerably above freezing-point; it is mostly rain with occasional wet snow. There is a little fine dry powdery snow in winter, but the ground is not usually deeply covered, owing to the strong winds. The total precipitation is not much more than 10 inches, if as much. Records from the middle of the Arctic basin are few, but it is probable that winter is a season of almost cloudless skies; such little precipitation as occurs is in fine dry spicules of snow. In summer there is much fog, the air is often damp and cheerless, the sky often cloudy, and the precipitation is more abundant than in winter, consisting chiefly of rain or fog, with some snow.

CHAPTER XXV

SNOW

'Precipitation' in the meteorological sense includes all forms of condensed vapour which collect on the surface of the earth—rain, dew, fog, snow, hail, hoar frost. Snow will now be considered.

Snow is of far-reaching importance both in the processes of nature and in the life of man. A sudden heavy snowstorm in a part of the world where such visitations are rare brings home to us very effectively and quickly how much our land communications are at its mercy, and in modern communities most activities of life are dependent on rapid and easy communications. In February 1929 the Simplon-Orient express was snowed up for about a fortnight in Turkey by a snowstorm which formed drifts as high as the coaches. When a high wind accompanies the snow we have the dreaded blizzard, in which the bewildered wayfarer may easily lose his way and perish from exposure. On the other hand, a deep snow-covering is a very effective 'blanket' for the earth below, and its absence from the steppe lands is one factor in bringing about their treelessness; the coniferous forests that adjoin the steppes have a considerable depth of snow throughout the winter, and the soil keeps warmer.

The melting of the snow in spring may cause disastrous floods when it takes place unduly rapidly. There are serious floods in Russia every spring owing to the rapid melting of the snow. Thus in 1926

> 'the Volga broke its banks, spreading destruction for miles on each side of its normal bed along the whole of its course of 2,000 odd miles, from the Valdai Hills to the Caspian Sea. For a month the floods continued, and town after town was inundated. Some 10,000 villages were swamped, even the roofs of houses being in many cases submerged. . . . Nizhny-Novgorod was under water, the level of the Volga had risen to 46 ft. above the normal, and the width of the stream was over 20 miles.' (*The Times*.)

All rivers that drain snow-covered mountains increase in volume when the snow begins to melt, e.g. the Tigris; the rivers of the Alps have a similar rise in late spring, but owing to the many glaciers the high level of the rivers is maintained throughout the hot season (Fig. 69); many irrigation systems are fed from such glacier rivers. Snow is of great advantage for agriculture in that when it melts the water sinks slowly into the earth, which becomes saturated to a great depth, so that there is little fear of drought in the hot dry summer weather.

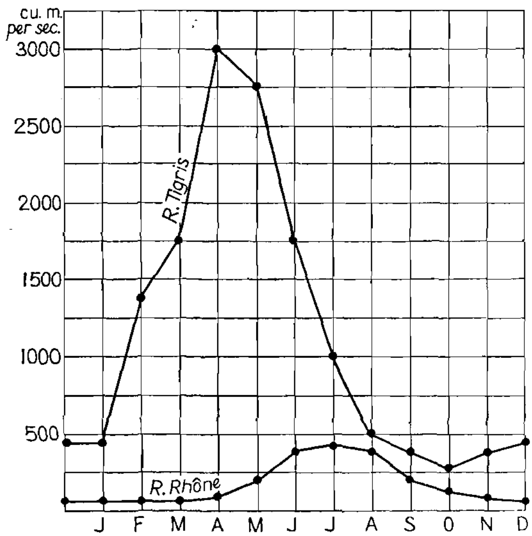


FIG. 69. Mean discharge of the River Tigris at Bagdad (Willcocks); and of the River Rhône at Porte-du-Sex, Valais (Pardé and de Martonne)

Snow is formed when vapour condenses at a temperature well below 32°. The minute crystals of ice unite into beautiful flakes of snow as large as an inch across. The atmosphere through which the snow descends to the earth must be at a temperature below, or at any rate little above, freezing-point, or the flakes will melt. Twelve inches of snow, if melted without loss by evaporation, gives approximately 1 inch of water, but there is considerable variation according to the nature of the snow. If it is very dry, light and powdery, as when freshly fallen in Antarctica, 30 inches might be required to form 1 inch of water. At the other extreme snow merges into sleet, wet and compact, so that perhaps 4 inches suffice. In general the older the snow the more compact it is; the transparent ice of glaciers shows the result of long-continued compression and the percolation of water. It will be gathered that the usual expressions of snowfall in terms of the rain equivalent are merely approximate. It is not easy to measure the real depth of the snow itself, for even when the land surface is flat the depth is liable to vary owing to drifting, and it is almost impossible to recognize where deepening has taken place in an expanse of smooth snow. However, a good approximation may be obtained if the mean of the depths at several different places is taken. It is useful to indicate also the depth in the drifts, for they are of very great practical importance, but they depend of course chiefly on the interaction of the wind and the details of the topography.

Snow—even perpetually lying snow—occurs in all latitudes from Equator to Pole, but at sea-level it is very rare inside the tropics, and its usual equatorward limit is about 30° N. and S. It is by no means infrequent in winter on the north and especially the north-east Mediterranean coasts; Jerusalem is not immune in spite of its low latitude, since it is on a plateau at some distance from the sea. The plateau of the Shotts in Algeria and the Meseta of Spain are also subject to severe snowstorms and bitterly cold winds in winter—a striking contrast to the furnace heat of summer

in Algeria and Tunis,

extraordinarily heavy snowfalls on their windward western slopes; the necessary moisture is brought by the ocean winds from the Pacific. On all the higher ranges there is a snowfall of 16 feet a year, and on many there is far more —over 40 feet in the Sierra Nevada and the Cascades. Much of the Rockies has over 20 feet. On the Pacific coast the temperature is too high for much snow. Mountains which rise in the heart of Asia are equally lofty, and even colder, but have far less snow owing to their remoteness from damp sea winds.

Lowlands in temperate latitudes have less snow than might be expected. In continental interiors the winters are certainly cold enough, but the air contains little vapour; in summer there is abundant vapour, but the temperature is too high. On western seaboards there is no lack of moisture, but the winter temperature is not low enough; however, it not infrequently happens in winter that heavy falls occur, associated especially with east winds on the front of a cyclone following a path south of the station—in the case of the British Isles over the south of England or the English Channel (see p. 275). In a country with a climate of the British type where the winter temperature is a little above freezing-point, the snowfall increases very rapidly with altitude, since the temperature is reduced to, or below, freezing-point, and there is the usual increase of precipitation with altitude. The mountainous parts of the British Isles ... frequent snow every winter; in the Highlands of Scot-
[illegible] kinds throughout

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Heavy snowfall is possible only where there is abundant vapour and at the same time a low enough temperature, and this is most frequent on mountains. On the high Alps it snows all the year round, and on the Säntis (8,202 feet) only in July and August is rain more frequent than snow. In the lower Swiss valleys (e.g. Altdorf) snow is as frequent as rain in December, January, and February; from the beginning of May till the end of September it never snows. The higher Alpine valleys often have a depth of 25 feet of snow in winter, and the passes are closed to traffic for about 6 months.

The western mountains of North America also receive extraordinarily heavy snowfalls on their windward western slopes; the necessary moisture is brought by the ocean winds from the Pacific. On all the higher ranges there is a snowfall of 16 feet a year, and on many there is far more—over 40 feet in the Sierra Nevada and the Cascades. Much of the Rockies has over 20 feet. On the Pacific coast the temperature is too high for much snow. Mountains which rise in the heart of Asia are equally lofty, and even colder, but have far less snow owing to their remoteness from damp sea winds.

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Let us consider now the coastal regions on the east sides of the land masses outside the tropics. In the case of Asia there is little snow owing to the constancy of the north-west winds of the winter monsoon. In South America Patagonia is so closely sheltered by the Andes that it receives little precipitation at any time. But the east coast of North America is very different. The St. Lawrence region is one of the snowiest lowlands outside the polar regions. The precipitation in winter is heavy owing to vigorous cyclonic activity (in parts heavier than in summer), and the winds that blow from the Atlantic are vapour-laden and at a suitable temperature to give snow. Even in Saskatchewan, in the far interior of the continent, the mean snowfall is from 2 to 4 feet a year, and it is probably more than 4 feet everywhere east of Winnipeg. On the east of the Great Lakes the on-shore winds give as much as 17 feet of snow, and the shores of the Gulf of St. Lawrence have more than 8 feet a year in most parts; Montreal has 10 feet, and the precipitation in January falls as snow on 18 days, as rain on only 4 days. In Newfoundland snow usually begins in October and continues till well into May; there are about 30 days with snowfall in the east of the island, and 90 in the west. In the north of Canada, the region of coniferous forests and the Barren Lands, the snowfall is less heavy owing to the lower temperature, but the snowy season is longer. On the other hand, in Asia there is considerably more snow in the taiga and tundra than in the deserts of the interior where mountain shelter and distance from the sea conspire with high atmospheric pressure to keep the winter precipitation extremely low. The steppe lands are liable to frequent snowstorms and blizzards, but the amount of snow is not

[1] Many of the above details for the British Isles are taken from an article in *British Rainfall*, 1927, by L. C. W. Bonacina.

great, and each fall is soon swept away or evaporated by the strong dry winds.

The snowfall of the Polar zones has been described on pp. 161–3. Further details on snow in mountain regions are given in Chapter XL.

CHAPTER XXVI

GLAZED FROST

IT occasionally happens in winter in temperate latitudes that a coating of clear hard ice forms over roads, walls, branches, telegraph wires, and other similar objects. The layer may be ¼-inch thick or more, and is as smooth as if it had been laid on like enamel. The cause is well shown by an instance in England and much of Western Europe on December 21, 1927. There had been a keen frost for several previous days, and the ground was at a temperature far below freezing-point. Suddenly a westerly breeze set in, bringing moist air and some light showers of rain. As soon as the drops touched the ground they froze, and there was soon a coating of ice on everything. Road traffic was almost completely suspended:

'The rain coated roadways and pavements with a thin sheet of slippery ice. Progress on the treacherous surface, alike for pedestrians and vehicles, was extremely precarious. Hospital staffs could not recall in any previous year conditions which had produced such a number of accidents. The total of broken arms and legs, injured shoulders, head injuries, and concussions made a formidable list. . . . Lorries with produce from the country arrived very late, and drivers told of hours occupied in crawling over ice-bound roads.' (*The Times*, Dec. 22, 1927.)

Sometimes very serious damage is done, branches and telegraph wires breaking under the weight of their ice. Glazed frosts are most common in the eastern states of America, when a moist south wind from the sea blows over a frozen land. But even there they are rare.

For the formation of glazed frost the object of deposit must be at a temperature below freezing-point, the air above freezing-point. The moisture is deposited in liquid form, and then freezes. For hoar frost and rime both the air and the object of deposit are below freezing-point, and the vapour is deposited in ice particles.

CHAPTER XXVII
EVAPORATION

EXCEPT when the air is saturated water surfaces evaporate, and the rate of evaporation is hardly less important climatically than the amount of rainfall. Unfortunately there are not very many records of evaporation, and those that are made are not all comparable, since different forms of instrument give somewhat different results. In some evaporimeters water contained in a vessel is left fully exposed to the weather, and the drop in the level of the water-surface gives a measure of the evaporation, allowance being made for any rain that may have entered the vessel; the result is largely affected by the form of the vessel, by its exposure to sun and wind, and by the temperature of the water. In the Piche evaporimeter water contained in a tube is allowed to evaporate from a piece of porous paper, and the loss in a given time can be readily measured on a scale graduated on the tube.

The evaporation might be thought to vary inversely with rainfall; but there are such important exceptions that the relationship is of little value. The 'cold water coasts' (Chap. XXXV) are rainless, but the air is almost always highly charged with vapour. Again, in the interior of the continents in temperate latitudes summer is the rainiest season, but it is also the season with highest evaporation. The rate of evaporation increases rapidly with the temperature and the air movement. The highest records of evaporation come from the trade-wind deserts, as is to be expected from the appearance of the land—thousands of miles of dust and sand-dune and sun-baked rock.

The Sahara and the Sudan provide the following records, all taken with a Piche evaporimeter except that for Helwan where a Wild type was used:

	Mean daily evaporation (inches) Highest month.	Lowest month.	Mean annual evaporation (inches).
Helwan . .	0·42 (June)	0·11 (Dec.)	94
Wadi Halfa .	0·87 (June)	0·35 (Dec.)	233
Atbara . .	0·81 (May)	0·53 (Dec.)	246
Khartoum .	0·77 (Apr.)	0·50 (Dec.)	213
Mongalla .	0·45 (Jan.)	0·11 (Aug.)	89

These excessive evaporation records are curiously similar to the records of excessive rainfall from the rainiest mountains.

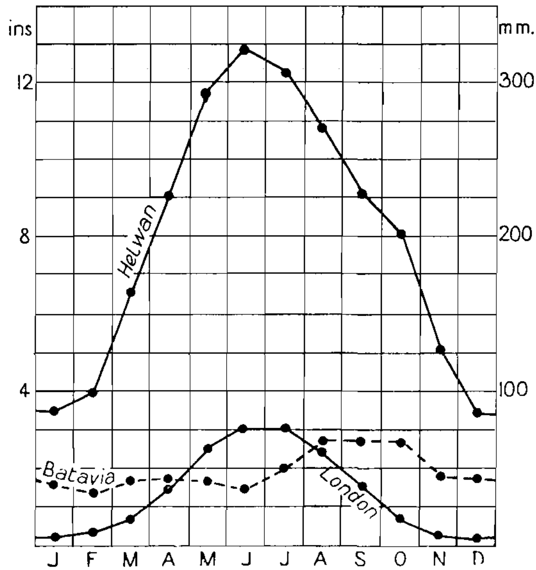


FIG. 70. Mean Evaporation. The total for the year is 13·1 ins. at London, 23·5 ins. at Batavia, 93·8 ins. at Helwan

In the trade-wind regions on the oceans the evaporation is between 40 and 50 inches a year, three or four times as much as the rainfall. In the deserts of Australia the mean annual evaporation is over 100 inches; at Perth it is 66 inches, at Sydney 38 inches. In the semi-arid lands on the east and south-east of the deserts it is often almost as dry in summer as in the deserts themselves, and bush-fires are a most serious danger. 'Every summer the predisposing conditions arise which may lead to an outbreak, and the utmost vigilance is needed. The vast stretches of unsettled country, the hard unwatered earth, the dry heat of the

Australian summer, the abundance of oils in leaves and plants—all these combine to make the bush country an unrivalled carrier of fire. Dry overland winds from the north or from the west may come to fan any casual spark into a flame and to drive along the flames in extending lines so that enormous areas of hundreds of miles are quickly covered.' (*The Times.*)

The evaporation increases rapidly with altitude; at Bulawayo, South Rhodesia, 4,470 feet, it is about 105 inches, and the same on the plateau of Palestine. It is very rapid on high mountains during fine weather when the wind is strong.

In the equatorial zone evaporation is low—20 to 30 inches a year. The westerlies also have low evaporation—15 inches a year at London and about 25 inches in the interiors of the continents.

The variation of the evaporation with the season is shown in Fig. 70.

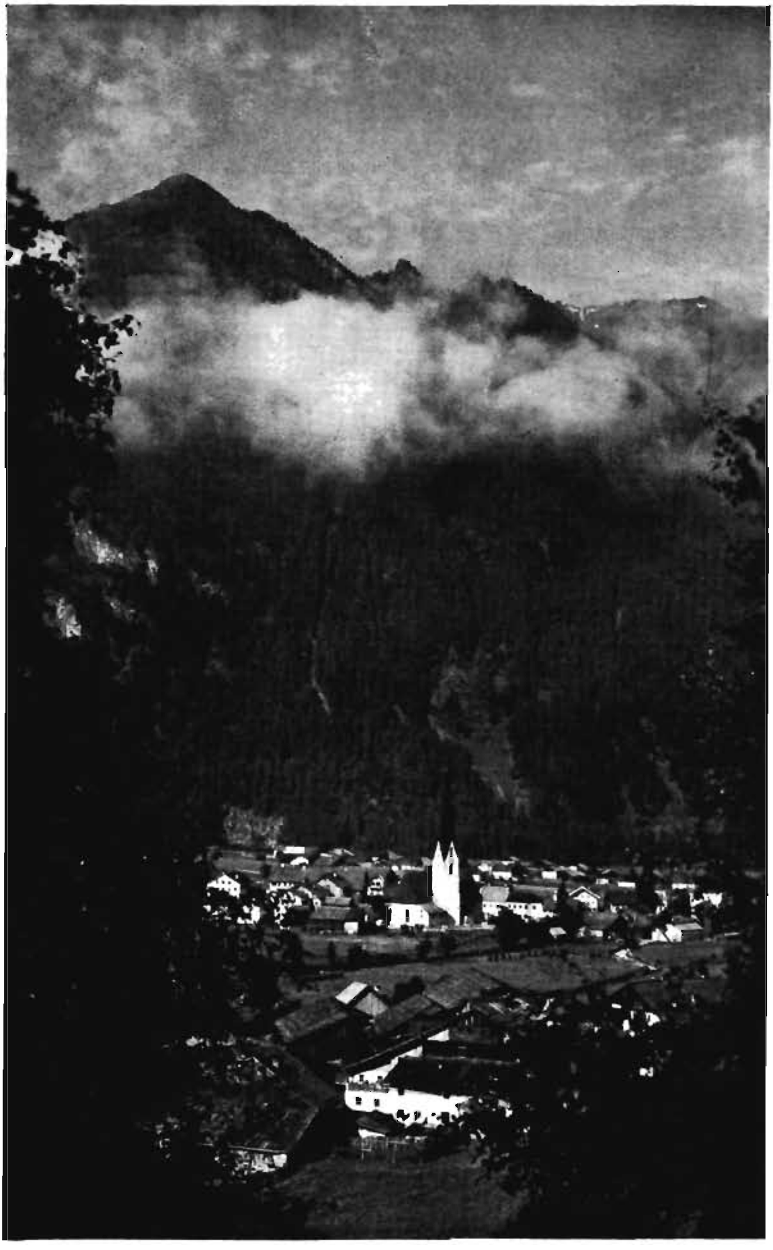
CHAPTER XXVIII

CLOUDS

THE water-vapour in the air is condensed by cooling into droplets of water, the droplets form clouds, and if the process continues vigorously enough rain falls; all this has been already described (Chapter XXIII). Apart from the rain which they produce, clouds are important and interesting in themselves, and often very beautiful. Their form and extent are determined by geographical position, season of the year, time of day, and weather conditions.

The forms of clouds are infinite in number, and are always changing. Moreover, the separate globules of water that compose any cloud are constantly being changed, new ones being added to replace those which are evaporated or fall as rain. A beautiful illustration of this is the 'banner-cloud' that trails to leeward of a lofty mountain summit in an otherwise clear sky, remaining apparently stationary and attached to the mountain like a flag to its flagstaff in spite of the wind which rushes past (Plate 1, Frontispiece). The eddy which is formed in the wind by the mountain obstacle causes a rising current on the lee side, and the vapour is condensed and becomes visible as the banner-cloud; the droplets are

PLATE 4



Eddy cloud in an Alpine valley; Umhausen, Ötztal soon evaporated and disappear in the main current, but new ones take their place as long as the wind and the eddy persist.

A more familiar effect of eddy movements in mountain valleys is seen in the bands of cloud that often hang perhaps half-way up the mountain side in bad weather (Plate 4). Air currents are necessarily much deflected both vertically and horizontally, as they pass over mountain ranges and through deep mountain valleys. The wind direction in a deep valley is almost always either up or down the valley, but there are eddies, often of considerable size, around, and especially in lee of, obstructions and irregularities in the valley sides. Vertical movements are set up in many places, and if the air is vapour-laden the ascent causes the formation of bands of cloud along the top of the eddy. Such clouds are usually to be seen here and there, close to the valley sides, when the weather is unsettled. They are quite local and remain fixed in position; they have no connexion with the main mass of cloud which is high above.

In spite of their variety three definite fundamental cloud-forms can easily be recognized, and most clouds referred to them, viz. cirrus, cumulus and stratus.

Cirrus

Cirrus (Plate 5), though sometimes the forerunner of bad weather, is in itself a fine-weather cloud, associated with blue skies, and never giving rain. It is usually fibrous in structure, as if drawn out, and indeed that is probably how it is formed at the surface of contact of two air currents of different humidities and temperatures and moving at different speeds. Beautiful wave-like forms are often seen; sometimes curls of hair are suggested (hence the name cirrus), and sometimes there is a pattern of lines or bands. These clouds are the loftiest known, being at an average height of 5 or 6 miles, which is the level of the tops of our highest mountains. They are as high as 7 miles near the Equator and as low as 4 miles near the Poles; most cloud-forms are considerably higher in low latitudes. Necessarily in the rarefied air in which they float they are extremely light, indeed almost transparent. Their colour is pure white, for they are never thick enough to have any shadows. They consist of minute particles of ice in which halos of the sun and the moon may be formed.

Cumulus

These are the massive rounded cloud-heads, cauliflower-like in shape, which are so frequent a feature of the summer afternoon skyscape (Plate 5). They are usually formed by the condensation of the vapour in hot and damp air which ascends rapidly by convection in localized masses, either when it is abnormally warm below or abnormally cold above, so that the normal lapse rate of temperature is exceeded. Thus when the ground becomes strongly heated by the sun on a summer day the layer of air near the surface is super-heated. Over it is the air which is still at its normal temperature. The convectional exchange cannot take place at once over the whole layer, but the rising currents are localized and arranged somewhat like the cells of a honeycomb, the cool air descending between the cells. Thus separate cumulus clouds are formed, with blue sky between them. They are associated generally with hot weather, and are a feature of the hot zones and of the summer season in the temperate zones. In the latter three times of occurrence may be specially distinguished, summer afternoons in fine weather, the hours when the influence of an advancing cyclone is making itself felt, and the period after the cyclone has passed. As a cyclone approaches warm and damp light southerly winds set in, and their abnormal warmth causes instability and rising currents in which the abundant vapour condenses into massive cumulus; in rear of the depression it is the arrival of abnormally cool polar air in the higher atmosphere that causes the instability, but the clouds in this case are less massive since the rising air is less moist.

The flat bases of the clouds are at some 5,000 feet above the earth; especially when seen from a considerable altitude the uniform level of the bases is often a striking feature. The clouds often extend upwards for half a mile or more. We have the most impressive form of cumulus in thunder-clouds—often a most ominous sight with the gigantic round white heads visibly seething and swelling upwards from their inky black bases, shadows of all intensities from

PLATE 5

a. Light cumulus clouds, with alto-cumulus above

b. Cirrus

delicate grey to deep black marking the inmost recesses, and the whole suffused sometimes with a coppery glow, while thunder rumbles in the distance. When the storm breaks the rain or hail is usually very heavy indeed, but before this happens the tops of the clouds lose their sharp outline and spread sideways in a cirrus-like plume, or often in an anvil form. Cumulo-nimbus is the name given to the cloud from which rain is falling ('nimbus' added to the name of any cloud merely implies that rain is falling from it). Most of the heaviest showers of rain are provided by cumulus clouds.

But cumulus clouds are often much less massive than we have described. The ordinary summer afternoon cumulus clouds of fine weather in temperate latitudes are comparatively light, and usually give no rain. And we must distinguish 'alto-cumulus' a much lighter cloud, with only slight shadows, but of a pronounced globular form, which is formed at a height of about 12,000 feet (Plate 5); and higher still, at about 20,000 feet, floats 'cirro-cumulus', really a form of cirrus, and one of the most beautiful cloud-forms, consisting of delicate white globular cloudlets in the deep blue sky, too light to have any shadows, and often arranged in long billowy lines.

Neither alto- nor cirro-cumulus are formed by air ascending from the surface of the earth; they are due to convection between air strata in the higher atmosphere where the air, being at a low temperature, is unable to contain enough vapour to form massive clouds.

Special mention must be made of 'roll-cumulus' or 'strato-cumulus' (Plate 6), which is very common in temperate latitudes. It is a combination of stratus, to be described later, and cumulus, and is often produced by convectional ascent in a sheet of stratus, and probably also as a wave formation between two currents of air moving with different velocities. It may also occur in the layer between a warm upper stratum and cooler surface air. In summer in most parts of the earth it is rare that the lower clouds are devoid of cumulus form.

Stratus

Cumulus clouds are always interesting, usually very beautiful, and sometimes extremely impressive. The last of our three fundamental forms is stratus, which is much less spectacular, and the least distinctive of the three. Its essential feature is its layer arrangement—it has considerable extent, but usually no great thickness, and its thickness tends to be uniform. It often appears amorphous from below, with little variation in its dull shades of grey perhaps covering the sky from horizon to horizon and leaving not a patch of blue. It may be formed by the mixing of air masses at the plane of contact of two strata of different temperatures and humidities; or by a gentle ascent of air, as when a southerly wind meets an easterly in front of a cyclone (p. 263); or eddy motion may be responsible, or again the cooling of the surface air by radiation at night, especially in still anticyclonic weather. Stratus may be at any height up to 5 or 6 miles; a fog is often a stratus cloud resting on the earth; ordinary stratus is usually about 2,500 feet above us. Stratus at about 10,000 feet is called alto-stratus; it is thinner and the sun or moon can sometimes be seen dimly through it as through ground glass. Still higher we have cirro-stratus, some 5 miles up, which looks like a pale mist, giving a milky sky, through which the sun or moon are clearly seen, surrounded by a halo. Cirro-stratus with its halos is often the first visible sign of an approaching cyclone, followed by alto-stratus with its 'watery' sun or moon (Plate 6).

Stratus is the common cloud of temperate latitudes in winter. It forms those monotonous and depressing palls of dull grey which sometimes cover the whole sky for several days. But if we rise in an aeroplane, or on a mountain side, we find that even the dullest stratus has a silver lining, and the clear blue sky and brilliant sunshine above are rendered the more glorious and exhilarating by reflection from the upper surface of the sea of clouds that fills the valley-bottoms and covers the lowlands.

It will have been gathered that stratus clouds accompany many different types of weather. In the British Isles we are familiar with spells of easterly winds especially in spring which are unpleasantly dry as well as cold; a sky completely overcast with stratus often adds a strong note of drab gloom. A large proportion of the ordinary cyclonic rain of temperate latitudes, and almost all the rain and snow of winter fall from stratus and alto-stratus clouds.

PLATE 6

a. Strato-cumulus clouds

b. Alto-stratus clouds

Diurnal Variation in Cloudiness

In most parts of the world the afternoon is the cloudiest, the night and early morning the least cloudy time, and the variation is often well marked inside the tropics. Thus at Trichinopoly, south India, the mean cloudiness in January is:

Midnight	2 tenths	Noon	4 tenths
2 a.m.	2 ,,	2 p.m.	5 ,,
4 ,,	2 ,,	4 ,,	5 ,,
6 ,,	3 ,,	6 ,,	4 ,,
8 ,,	3 ,,	8 ,,	2 ,,
10 ,,	4 ,,	10 ,,	2 ,,

The other months show a similar but less pronounced variation. The same periodicity occurs in summer in temperate lands, but not over the oceans; the cumulus clouds floating high in the sky are often the first indication to the sailor that he is approaching land, and sometimes the shoreline is almost as clearly defined in the sky as on the earth.

The mean cloudiness at Potsdam in July is:

Midnight	5 tenths	Noon	7 tenths
2 a.m.	6 ,,	2 p.m.	7 ,,
4 ,,	7 ,,	4 ,,	7 ,,
6 ,,	7 ,,	6 ,,	6 ,,
8 ,,	7 ,,	8 ,,	6 ,,
10 ,,	7 ,,	10 ,,	5 ,,

The night is less cloudy than the day with the minimum at 11 p.m. But the cloudiest hours are just after sunrise, and the mean for the day occurs at 2 p.m.

In fine weather the mornings may be quite cloudless, but as the day grows hotter cumulus clouds gradually collect and by afternoon the sky is almost overcast. But such clouds do not usually give much, if any, rain, and they dissolve again in the evening. In bad weather the diurnal control is masked by the general weather conditions, and consequently in the means for any given month this feature is not prominent, though it is very noticeable on suitable days. An absolutely cloudless afternoon is very rare except in the trade-wind deserts. Elsewhere, and especially in the neighbourhood of the sea where the air contains much vapour, clouds appear towards midday. If they do not the reason may be (1) exceptional cold on the surface of the earth, causing unusual stability so that convection does not occur; or (2) such unusual dryness of the air that the rising currents are not cooled to their dew-point; this may sometimes occur for instance in an anticyclone, or during the passage of a 'wedge' of high pressure; or (3) the state of the upper air, for if it is abnormally dry or warm the stability of the atmosphere may be such that convection does not take place at all, or not actively enough to carry the rising surface air to a height where it would be cooled to dew-point. This last case is referred to more fully on p. 32.

In calm anticyclonic weather the surface air loses heat by radiation at night, and stratus cloud—or sometimes surface fog—may form, to dissolve when the sun becomes powerful. In some deserts the early morning is the cloudiest part of the day for this reason, as at Helwan, near Cairo, where in summer stratus and strato-cumulus is sometimes abundant in the early morning hours; but in winter the afternoons are cloudier than the mornings. At Kew, near London, 7–9 a.m. is usually the cloudiest part of the day in winter.

For the regional distribution of cloudiness see Chapter XXXIII.

CHAPTER XXIX

THUNDERSTORMS, HAIL

Let us consider first the immediate cause of the state of high electrical tension which produces those discharges through the atmosphere which we call lightning. The matter has been most recently and satisfactorily investigated by Dr. G. C. Simpson[1] who concludes that the source of the high charge in clouds is the breaking up of raindrops. Raindrops may be minutely small, but experiment shows that there is an upward limit they cannot exceed, viz. a diameter of $\frac{1}{4}$ inch; a drop of larger size must soon break up. Simpson also shows that raindrops cannot fall through still air at a greater speed than 24 feet a second, and that an upward current of 24 feet a second prevents their descent.

The formation of the drops of rain is the same in a thunder-

[1] London, *Proc. R. Soc.* 114(A), 1927.

storm as in other storms. An ascending current of damp air cools adiabatically, and its vapour is condensed. If the ascending current exceeds a speed of 24 feet a second the drops that are condensed cannot descend through it, but grow larger and larger. But as soon as they exceed the limiting diameter of $\frac{1}{4}$ inch they break up. Thus in the upper part of such an updraft there accumulates a great deal of water, and the drops are continually growing and splitting up. Each time a drop breaks it becomes charged with positive electricity, the negative charge being carried away in the updraft of air into the rest of the cloud, and in a short time the cloud is highly charged, and a flash of lightning passes from it to the earth, or to another cloud. A lull in the updraft allows the accumulation of water to fall to the earth in a massive shower, which is sometimes called a cloud-burst. This theory explains the fact that heavy rain is almost always associated with a thunderstorm, and that it is very rare for thunder to accompany a light shower. The rising air must start with a high temperature and humidity or there would not be sufficient water condensed, and it must be in very rapid vertical movement, a result which will be attained if it is itself abnormally warm, or if the higher atmosphere is abnormally cold, giving rise to vigorous convectional overturning. These conditions are usually present in the equatorial belt of hot moist air. In the trade-wind deserts the air is too dry; but violent thunder and lightning usually accompany the downpours of rain in the tropical hurricanes of trade-wind oceans. In temperate latitudes there is often sufficient heat and moisture in summer, but cyclonic activity is required to give the necessary updraft. In the Polar zones there is rarely enough heat or vapour in the air to give the necessary condensation.

Frequency of Thunderstorms

The region of equatorial rain is the outstanding thundery area, especially over continents and islands. Thunder is recorded on more than 75 days in the year in the East Indies, Central and West Africa, and much of the plateau of South Africa, the Amazon Basin, Central America, and Mexico. Java seems to be the most thundery region on the globe with over 200 days; the perpetually warm and very moist air, and the influence of the mountains are very favourable to copious condensation. Outside the tropics the south-east of the United States is most thundery, with about 50 days a year; here the moist warm air from the Gulf Stream is favourable.

The trade-wind deserts are too dry, and have less than 5 days a year with thunder. For a wet tropical land India is remarkably free from thunder, with only about 25 days.

In the temperate belt there is a marked excess of thunder on the land as compared with the sea. Over much of the North Atlantic and North Pacific there are less than 5 days a year with thunder, but over Central Europe and much of the United States the total exceeds 25.

In the equatorial and tropical belts the thunder is naturally associated entirely with the rainy season, and for the most part occurs during the afternoons, the time of heaviest convectional rain. In temperate latitudes there is a strong seasonal control, thunder being almost unknown in winter in the interiors of the land masses. But on the coasts of North-west Europe and British Columbia there are almost as many—in some places more—thunderstorms in winter as in summer. This is indicated by the monthly frequency at Brest and Paris.

Mean monthly frequency of thunder (per cent. of total for year).[1]

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May.*	*June.*	*July.*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Total for year.*
Brest	8	7	6	5	9	16	10	10	13	6	5	5	7
Paris	0	1	3	8	15	21	21	17	10	3	1	0	27

The low temperature explains the rarity of thunder in the continental winter; we shall consider the winter thunder on the coasts later.

Over the lands there is generally a strong maximum of thunderstorms during the hottest hours—

Diurnal Frequency (%) of Thunderstorms[1]

	midnight–6 a.m.	6 a.m.–*noon*	*noon*–6 p.m.	6 p.m.–*midnight*.
Batavia . .	18	6	50	26
Edinburgh .	5	21	58	16

[1] *The Distribution of Thunderstorms over the Globe.*—Brooks

At sea the frequency is reversed, with a decided maximum at night.

Thunderstorms in Temperate Latitudes

Most thunderstorms are closely connected with cyclones.

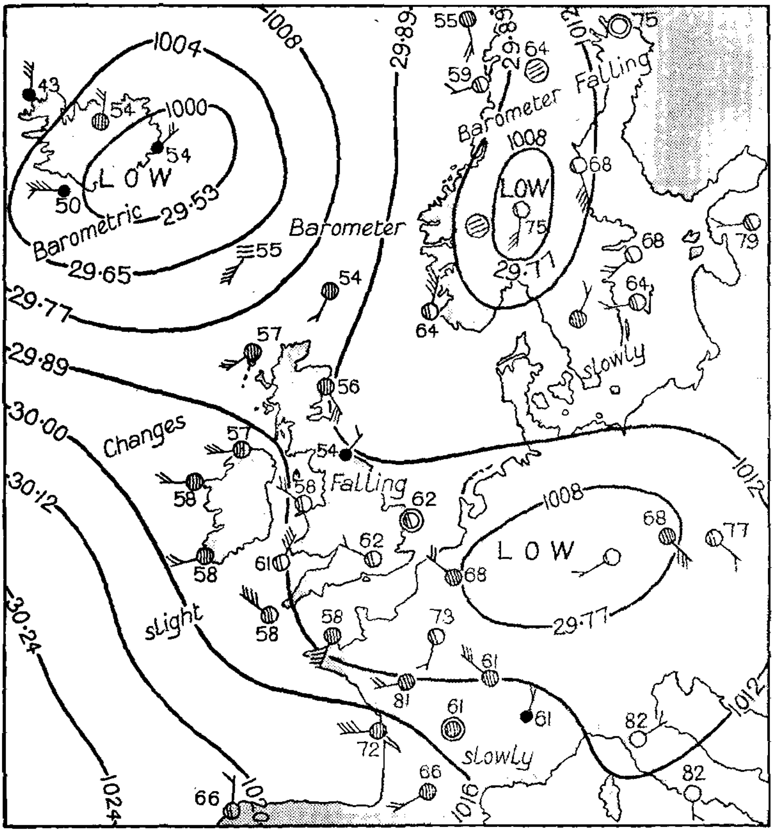


FIG. 71. July 22, 1924, 6 p.m. For meaning of the symbols see Fig. 9, p. 33.

There are two sectors in which they are likely to occur in summer. Firstly, the whole of the south-east sector provides favourable conditions when the barometric gradient is slight. The air is drawn in slowly from the south-east, and is hot and moist; the sky is often clear, and the strong sunshine adds more heat and moisture to the stagnant air. Local convection may then be vigorous enough to produce not only cumulus clouds but heavy sporadic thunderstorms. These conditions may persist for a couple of days, or they may be quickly removed by the advance of the depression. The other scene of thunderstorms is the trough-line, thunder and lightning frequently accompanying the line-squall which sweeps across the country. In this case the necessary condensation is produced by the forcing upwards of the flank of the warm and moist southerly winds of the cyclone by the advancing cold front (p. 266). The ascent of the air is so vigorous that there may be a few peals of thunder even in the cold months.

It is during the passage of line-squalls that the winter thunderstorms of the coasts of North-west Europe occur. These storms are especially a feature of the steep scarped coastal belt of Scandinavia, North-west Scotland, the Färoe Islands, and Iceland, where the normal heavy condensation of the squall-line is intensified by the forced ascent of the steep coast. They are frequent in winter owing to the cyclonic activity being then at a maximum. Such a thunderstorm forms a striking scene on a winter night in the Färoe Islands. The flashes of lightning flicker over the steep west-facing cliffs of the islands, and the thunderstorm remains fixed there as long as it lasts, while on the sea round about there is merely a gale of wind with rain—or snow—of no very marked intensity.

Another frequent scene of thunderstorms is a shallow irregular secondary in summer. Fig. 71 shows such a system in which there were great differences of temperature. The air in the south of England had come from Central Europe which was experiencing a very hot spell, and the temperature was high (74° in London before the storm broke), but the north-west of England was much cooler. Vertically also there was a steep temperature gradient, for the upper air was cooler than usual, and the convectional overturning caused the moist warm surface air to rise to extraordinary heights; cumulus clouds were found by measurement to have their bases 4,000 feet and their tops 23,000 feet above the earth. The temperature at South Kensington dropped 18° when the storm broke. The rain was extremely heavy

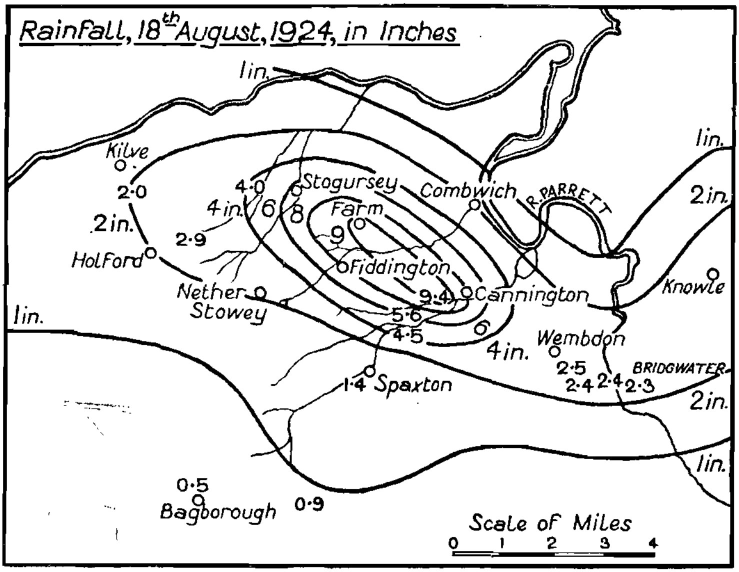


Fig. 72. Heavy Local Rain. From *British Rainfall*, 1924

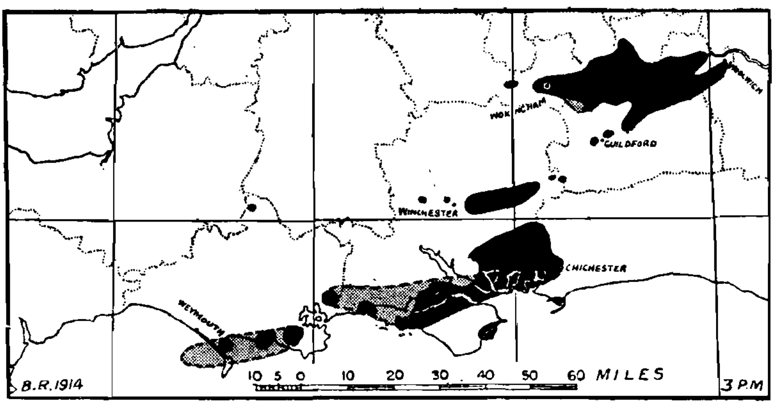


Fig. 73. Rainfields, 3 p.m., June 14, 1914. The areas where rain is known to have been falling are shown in black, those where rain was probably falling are stippled. (Fairgrieve, in *British Rainfall*, 1914.)

locally, half an inch falling in 5 minutes; hailstones of over half an inch in diameter fell in London. London had the worst of the storm, but there were thunderstorms of less intensity over most of the south of England.

Thunderstorms are of comparatively small extent, and they often break out sporadically on days when the general conditions are favourable. A small area may have a torrential downpour, while the surrounding country enjoys almost cloudless skies (Fig. 72). Sometimes there is a distinct tendency for thunderstorms in the British Isles to occur in parallel bands (Fig. 73), the bands extending, diminishing, and moving across the country.[1] In the interior of continents there is often a long belt, associated with a shallow trough of low pressure, along all or part of which thunderstorms are raging, and the whole system sweeps across the country.

Hail

Hail usually falls during thunderstorms; but many thunderstorms occur without hail. It consists of pellets of ice of characteristic structure, layers of clear hard ice alternating with layers which are white and opaque owing to the presence of minute bubbles of air; stones with as many as 20 concentric layers have been recorded. The pellets are formed by the freezing of drops of water in the upper part of lofty cumulus clouds. The frozen drops fall through the cloud, collecting water on their surface, which afterwards freezes. Then they are apparently carried upwards again by a vigorous updraft in a different part of the cloud, receiving another coat of water, and fall again, the falling and rising being repeated several times. The opaque layers of ice result from very rapid freezing, as when the stone is passing through drops of water in a state of superfusion at a temperature well below freezing point; the transparent ice is formed by the slow freezing of a coat of water. The necessary conditions for the ascent of large hailstones seem to be provided only by the very rapid uprush of air currents in parts of thunder clouds, and the structure of the hail itself provides a strong presumption for the existence of such currents in thunder clouds.

[1] J. Fairgrieve, in *British Rainfall*, 1914.

Most hailstones do not exceed half an inch in diameter. Some are spherical and many of the other common forms are probably produced by the breaking up of spheres; others may result from the cohesion of several small stones. Half-inch stones can do serious damage to trees, which may be entirely stripped of foliage and fruit, and to crops, which are sometimes destroyed by a hailstorm coming at a critical period of growth. Glass roofs and shades, such as those used in market gardens, are broken, and tiles riddled; in India men and animals are often killed. Such damage is so common in many countries that hail-insurance is usual. Fortunately the hail is generally restricted to a narrow belt less than half a mile wide, a belt much narrower than that of the thunderstorm in which it falls. Stones much larger than half an inch are frequently reported; a diameter of 4 inches and a weight of 2 lbs. are well authenticated and not uncommon. But it is difficult to credit the reports of stones of a foot or more in diameter.

Like thunderstorms hail is very rare in the Polar regions. In the equatorial belt also hail is rare, though thunderstorms are frequent; the hail is absent probably because it melts before it can reach the ground. Between the Polar and the Equatorial belts hail is well known except in the deserts, and it can be very destructive, as in India. It is specially common on plateaux; the plateau of South Africa is very subject to destructive hailstorms during the summer, the latitude as well as the topography being favourable. In India hail occurs chiefly with the thunderstorms of the hot-weather season from March to May, and the stones are often of great size. Hail may fall in the tornadoes of the United States and Central Europe and other regions in temperate latitudes. The season of occurrence of hail coincides generally with that of thunderstorms.

CHAPTER XXX

HUMIDITY AND TEMPERATURE IN RELATION TO THE HUMAN BODY

PART of the heat of the body is used up in evaporating moisture from the lungs and the skin. Even if the air temperature is well above 98° the temperature of the blood remains approximately at 98° as long as the perspiration machine is working well, and the necessary supply of liquid to provide perspiration is imbibed. But if this cooling process is hindered or stopped by either internal causes—fatigue or injury of the perspiring mechanism, or lack of liquid to evaporate—or by external conditions, viz. the fact that the air, at a temperature of 98° or above, in contact with the body is saturated with vapour, or is almost saturated and remains stationary so that evaporation from the body soon brings the air actually in contact with it to saturation point, the body is unable to cool itself, and heat-stroke results, often with fatal results. Unacclimatized persons very soon suffer in hot damp weather, as during the 'heat waves' of summer in the east of the United States.

Wind necessarily intensifies the physiological effect of low temperatures by constantly renewing the air in contact with the body. When the wind is dry the rapid evaporation reduces the temperature still more. When it is damp and foggy—'a raw day'—our clothes become damp, and their insulating power is lessened, and moreover much of the heat of the body is used up in evaporating the droplets of water which the air contains. The body is especially sensitive to changes in the humidity of the air when the temperature is either above or below the normal; at normal temperatures considerable changes in the humidity are hardly noticed. The strong north-east winds which are frequent in western Europe in spring are notoriously trying, being both cold and dry. The damp winds which blow in winter at a temperature of about 40° are also very unpleasant, and they feel colder than the still air in the interiors of continents where the temperature is 50° lower.

Cooling by evaporation is a normal function of the body, and it is necessary to continued health and vigour. It should not be excessive, but the healthy body can stand a great strain. The dark pigmentation of the skin of negroes probably serves to intensify its heating by the sun, and excite the more perspiration. The air comes into contact with the body partly in the lungs, where it is raised to a temperature of about 90°, and partly on the exterior skin where it is heated to a temperature of from 70° to 90° according to the rapidity of the air movement and the conditions of clothing. The cooling will be greatest when the air is cold and dry and in rapid movement, and least when it is hot and moist and still. The former is found in the interiors of continents in temperate latitudes in winter; the climate is bracing if there is a considerable degree of cooling, but in the interior of Canada and Siberia the winter cold is too intense, especially if there is much wind, and such heavy clothing is commonly worn that many of the advantages of a bracing climate are neutralized; fortunately calms and light winds are usual. At the other extreme is the equatorial belt, where the temperature is little below that of the body; the sluggish air is almost saturated with vapour during most of the year, and even the nights do not bring much relief. Europeans soon become enervated, and fall ready victims to various tropical diseases which may be directly due to micro-organisms but would be resisted if the body retained its tone. Similar conditions prevail during the rainy season in the tropical belts between the Equator and the trade-wind deserts, including the Sudan, India, much of China, the north of Australia, Brazil, Central America, and the south-east of the United States of America, but here the cooler and drier winters provide a welcome respite. The hot waves of New York and neighbouring cities claim many victims to heat-stroke every summer, though they last only for some days. The unhealthy 'hot-house' conditions are familiar nearer home in crowded and unventilated rooms where the temperature and humidity are abnormally high owing to the number of persons present.

In the hot deserts the temperature on summer days is usually above body heat, and even 120° is not uncommon. Contact with the body cools the air in this case, and increases its relative humidity. But the air is so dry that this small increase is not important, for if the initial temperature is 115° and relative humidity 20 per cent.—not uncommon figures—the relative humidity after the air is cooled to 98° is only 32 per cent.; fortunately there is usually a strong breeze in the hottest hours. These lands are much more healthy than the Guinea coast, the 'White Man's Grave', where the air is some 20° cooler but saturated with moisture. Similarly the dry and windy plateaux in the south-west of the United States are much less debilitating in summer, in spite of their higher air temperature, than the moist and sultry lowlands of the lower Mississippi and the Gulf coast.

The winter climate of high Alpine valleys is very favourable to health and vigour, for the air is bracing without being excessively cold, and it is fairly dry. The breathing is deeper, and evaporation is vigorous in the rarefied air. Additional advantages are the calm air and the exhilarating sunshine, while the snow-cover prevents dust and forms a bright and cheerful scene.

For many purposes the wet-bulb thermometer readings give a more useful indication of the temperature conditions as affecting the health and comfort of man than the ordinary dry bulb, since the evaporation from the skin tends to make the body experience the wet-bulb temperature. The dry-bulb temperatures during the Australian summer are extremely high, but owing to the dry air the physiological temperature is much reduced, the maximum wet-bulb readings on summer days in the hottest parts being as much as 35° below the dry-bulb readings. In Victoria it is rare for the wet-bulb thermometer to record 80° even on the hottest days. For the same reason the trade-wind deserts, which are the hottest regions of the earth in summer, are by no means unhealthy, though the days are unpleasantly hot. The high summer temperatures of Mediterranean lands are very appreciably tempered, and the wet-bulb usually does not rise above 70°. The highest recorded temperature at Athens was 106°, but the wet-bulb maximum was only 73°. In the damp British climate the wet-bulb does not usually read more than 2° or 3° below the dry in winter, and sometimes the two readings do not differ at all for days together;

on fine spring and summer days the difference may be 10° or 15°.

The wet-bulb thermometer, however, is not a perfect indicator of the physiological conditions of the air, for the body, the human wet-bulb, is maintained at a temperature of 98°, not at the air temperature. The point of most importance is the difference between the amount of vapour actually present in the air (i.e. the absolute humidity) and the amount that saturated air at body-temperature contains (viz. about 45 gm. per cubic m.). This difference is called the physiological saturation deficit. On a typical winter day in North-west Europe or on the Pacific coast of Canada the air temperature may be 40°, and the relative humidity 80 per cent., so that the amount of vapour contained in the air is 5·4 gm. per cubic m. ($\frac{80}{100}$ of 6·8 = 5·4); the physiological saturation deficit is 39·6 gm. (45–5·4). On a summer afternoon with air temperature 70° and relative humidity 60 per cent. the physiological saturation deficit is 34·6; and in the Sahara, with temperature 115° and relative humidity 20 per cent., it is 28·2. The higher the physiological saturation deficit the more vigorous is the evaporation and consequently the greater the cooling of the body.

An important consideration from the physiological point of view is the cooling power of the air, depending on its temperature and rate of movement. An instrument called the kata-thermometer has been designed by Dr. L. Hill to measure this. It is a large alcohol thermometer, graduated from 100° to 95° F., and before use the bulb is placed in warm water till the reading is above 100°; it is then exposed in the air which is to be examined, and the time taken for the reading to fall from 100° to 95° is measured in seconds. The number of seconds clearly varies inversely with the cooling power of the air, and the actual cooling power in calories may be obtained by dividing the number of seconds into a given factor which depends on the instrument. The range from 100° to 95° is a near approach to that through which the temperature of the air in contact with the body changes. The conditions of a perspiring body may be imitated by surrounding the bulb of the kata-thermometer with wet muslin.

PART V
SUNSHINE AND CLOUD

CHAPTER XXXI

THE INTENSITY OF SUNSHINE AND ITS COMPONENT RAYS

It is only in recent years that the full importance of sunshine for plant and animal life has been realized. Many researches have engaged the attentions of scientists working on the human effects both psychological and physiological. The methods used are largely comparative, the effects, for instance, at a high Alpine station where the sunshine is strong and abundant being compared with those in the cheerless slums of a great city, surrounded closely by drab brick walls instead of distant snow mountains, and rarely illuminated by even the pale disk of the sun shining hazily through the smoky atmosphere.

The duration of sunshine is usually measured by means of a Campbell-Stokes recorder, which consists essentially of a clear 'crown-glass' sphere 4 inches in diameter, that focuses the rays on a prepared card graduated to show hours. When the sun is shining brightly a burn is made on the card, and the length of the burnt track is readily measured. A fairly bright sun is required to burn the card; there is rarely any record registered by the sun when near the horizon, shining through light clouds though still visible. This selectivity is perhaps an advantage, for a weak sun is by no means comparable in its biological effects with the sun at full strength. Hence the ordinary sunshine recorder gives a record of the duration of sunshine of more than a certain heat intensity. Another form of recorder, the 'Jordan' pattern, registers in a similar way the path of the light of the sun focused on sensitized paper; the record, depending on the actinic rays, is not always of exactly the same duration as that of a Campbell-Stokes recorder. It is often useful to get a rough estimate of the intensity of the sunshine at any moment, and a simple method is recommended by Dr. L. Hill. A piece of black fur is exposed perpendicularly to the sun's rays, and a slender thermometer bulb is embedded as far as possible in it. The black fur is a very efficient absorber of the heat rays, and the difference between the readings of the thermometer in the fur, and of one in the open air (shade temperature) gives a measure of the intensity of the insolation. Examples quoted by Dr. Hill are—at an Alpine station in mid-winter the air temperature was 41°, the black fur temperature 120° to 140°; on a calm sunny July day in England the air temperature was 72°, the black fur 130°. These records indicate the great intensity of the Alpine sun in winter; for various medical purposes the coldness of the air is an advantage. Another striking case occurs under the overhead sun in the clear air of the trade winds, where very powerful insolation and intense light are accompanied by high air temperature.

Insolation consists of a complex of energy-waves of different lengths. Following Sir Napier Shaw we may divide it into:

ultra-violet rays, wave-length from 0·1 to 0·4 thousandths of a mm., making 12% of the whole,
visible rays, wave-length from 0·4 to 0·8 thousandths of a mm. making 37% of the whole,
dark heat rays, wave-length from 0·8 to 6·7 thousandths of a mm. making 51% of the whole.

Gamma, Millikan, and X-rays consist of vibrations of shorter wave-length than the ultra-violet, and at the other end are Hertzian waves as much as several miles in length; Daventry broadcasts on a wave-length of 1,554 metres.

The generally accepted theory maintains that the differences we perceive or postulate between light, heat, and the electric waves by which music and pictures are broadcast, or between, for example, red, blue, and green light, are due simply to the difference in the lengths of the waves in the ether that reach us. All the waves advance at precisely the same rate, 186,000 miles a second; thus the light complex that we call white, which consists of all the colours of the spectrum combined, remains white however many millions of miles it may have travelled, since all the waves, of lengths between 0·4 and 0·8 thousandths of a mm., travel at the same rate, and the complex remains unseparated.

But separation begins through diffusion when the insolation enters the atmosphere of the earth. The rays are diffused, according to Rayleigh's law, in inverse proportion to the fourth power of their wave-length, by the fine particles (molecules) of air, and by the very minute particles of dust, vapour, &c. Thus all the shortest ultra-violet rays are abstracted from the direct rays of the sun before they reach us on the surface of the earth, and a large proportion of the violet and blue is diffused, giving the blue colour to the sky. The blue of the sky is formed chiefly in the atmosphere between about 2 and 10 miles above the earth; the highest mountains penetrate through much of the belt, and seen from their summits the sky appears a very deep blue-violet; the effect is still more noticeable in very high balloon and aeroplane ascents. If we could rise some miles higher the sky would presumably be colourless, black; even near sea-level in the clear dry air of the trade-wind deserts the sky is of a specially deep blue, and the moon and bright stars are often clearly visible while the sun is still high in the sky.

The longer waves, yellow, orange, and red, are scattered especially by the coarser particles of the lower atmosphere; our brilliant warm sunset glows are formed in the lowest few miles of the atmosphere, and often the sun's rays have suffered such loss by diffusion of first the ultra-violets, then the violets, blues, and greens, and lastly the yellows and oranges and reds, that only the deeper reds reach the earth and the sun itself appears as a dull red ball, very different both in colour and intensity of light from the noon-day sun in a clear sky.

CHAPTER XXXII

ULTRA-VIOLET RAYS

Ultra-violet rays are quite invisible, and have little heating power, but they exert a powerful chemical action; it was the reduction of silver chloride by some then unknown form of radiation outside the violet end of the visible spectrum that first drew attention to them in 1801. The group embraces wave-lengths from 0·1 to 0·4 thousandths of a mm.—almost as wide a range as all the visible rays of the spectrum—and the different wave-lengths have different properties. The shortest of them, of less than 0·2 thousandths of a mm., do not penetrate the atmosphere at all and even those between 0·29 and 0·33 thousandths of a mm. can reach sea-level only under favourable conditions of transparency; they are stopped by the smoky air of large cities, and they are unable to penetrate ordinary soda glass, or the thinnest of skin. Only the longest wave-lengths reach the earth in most circumstances. This selection of the rays is due to the fact that the rays of shortest wave-length are most scattered by the finest particles, which are relatively most abundant in the highest atmosphere. All the ultra-violets are so much scattered in their passage of the atmosphere that those that do reach the earth come in greater quantity from the blue sky than from the direct rays of the sun even when the sun is overhead; the proportion of diffused to direct is far greater when the sun is near the horizon.

Many doctors are enthusiastic believers in the value and even the necessity of ultra-violet rays for our health, and in their high efficacy in the treatment of numerous maladies. In view of the powerful insolation at great altitudes (see Chapter XXXVIII) a sojourn in the high Alps, at Davos or Montana for example, is recommended, or if that is impossible at least let us enjoy irradiation from some artificial source of ultra-violet rays, such as the mercury-vapour lamp. Tuberculosis and rickets are stated to be especially amenable to the treatment. In the case of rickets both in human beings and in animals there does seem to be a clear effect directly attributable to the rays, though, as Dr. Campbell Macfie points out, it is difficult to believe that such short waves can penetrate through the hair of a goat or the feathers of a fowl, or to any appreciable depth of skin. As for the other diseases which are specified for light treatment there is no agreement as to what is the exact effect of the rays, whether they act by killing the bacilli directly—this would seem impossible at any depth under the skin—or by forming on the surface of the skin exposed to the rays irradiated compounds which circulate throughout the body, or by a general tonic stimulation. Some experimenters think that the whole of the spectrum, and not merely the ultra-violet rays, is the effective agent, while others incline to attribute the therapeutic benefits chiefly to the other elements of the high Alpine environment, pure bracing air with a low temperature and low humidity, exciting scenery, regular life and exercise, and suitable clothing.

It is for rays of wave-length between 0·28 and 0·32 thousandths of a mm. that the highest therapeutic value is claimed, and as already stated these are just the rays that are so liable to be cut off from the surface of the earth at sea-level; hence the advantage of mountain stations. Though they are unable to penetrate ordinary soda glass, quartz is pervious, and this is the reason that the medical authorities who think that we are suffering in health in temperate latitudes from a deficiency of sunshine urge that quartz glass should replace the usual window glass of our houses, seeing that so large a proportion of civilized life is passed indoors.

Ultra-violet rays ionize gases, and have many organic effects, such as coagulating protoplasm and killing living cells. Living tissues, or perhaps rather the salts contained in them, absorb the rays, and the screen provided by the skin of our bodies is a necessary protection for the cells below. It is the ultra-violet rays which cause sunburn, and at high altitudes very serious injury, both local and general, may result. Consequently sun-bathing and other light treatment, whether under the rays of the sun or an artificial source, should be in expert control, especially until the subject is acclimatized.

The insolation is much more intense in low than in high latitudes; indeed the intensity of the insolation is one of the most prominent features of tropical climates. But in spite of its practical importance few useful records are available from low latitudes. There appear to be considerable differences in regions situated in similar latitudes, for in some countries the risk of sunstroke is notably greater than in others. Thus in Java and in South America the risk is comparatively small, and Europeans do not need very much protection against the sun's rays, but in India sunstroke is frequent, and careful precautions are enjoined.

The Measurement of Ultra-violet Rays

Many measurements of the intensity of the ultra-violet rays have now been made. The method in use in Britain is to expose to the full light of sun and sky a tube of quartz glass containing a solution of acetone and methylene blue of standard strength. The rays bleach this solution, and their intensity is measured by comparing the colour of the solution after exposure with standards which have been graduated according to a more or less arbitrary scale. Fig. 74 illustrates the results; the murkiest station is the Strand, in the heart of London; Hampstead on a hill, 450 feet above sea-level, on the nothern outskirts of the city, is usually considerably brighter than the smoky city below, but is by no means free from the city's smoke; Greenwich (Royal Observatory) is 5 miles south-east of the heart of the city. The other two stations are away from the metropolis, Peppard on a dry chalk plateau 370 feet above the sea, in the Chilterns, and Frodsham near sea-level on the estuary of the Mersey. The figures show the total number of 'degrees' of ultra-violet rays received day by day during a sunny week in July and during a misty week in December; the advantage of Peppard is obvious. The graphs show the usual relationship. London and other large cities even in the south of England are often entirely deprived of ultra-violet rays by their screen of fog and smoke, while stations not many miles away, but clear of smoke, and set on a hill which rises clear of the cold damp inversion layer in the valley-bottoms, are well irradiated. In the high Alps daily totals of 40 or 50 degrees are not uncommon; the advantage is especially great in winter (Chap. XXXVIII). In general the ultra-violet radiation depends on the length of the day, the altitude of the sun, the amount of cloud in the sky, and of vapour, water and dust particles in the air. In part these are the same factors as control the duration of sunshine, but the ultra-violet rays are much more intercepted by vapour and dust than are the visible rays. Dr. L. Hill makes the general estimate for England that the open country receives in the

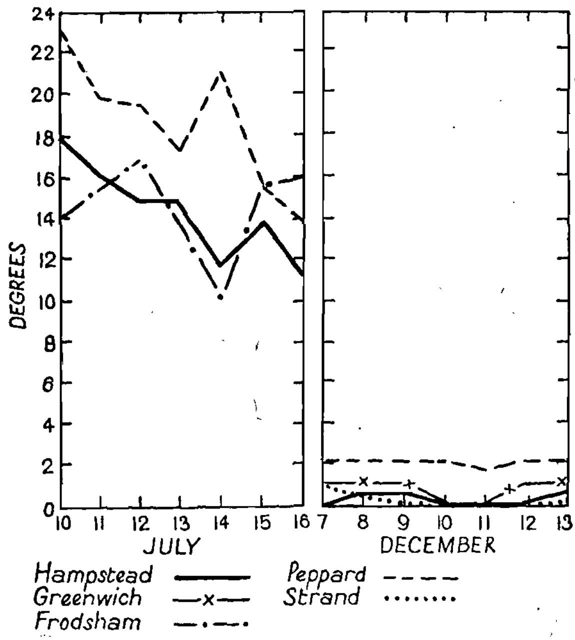


FIG. 74.

year about three times as much ultra-violet radiation as smoky cities; Didsbury, a suburb of Manchester, receives about twice the ultra-violet radiation of the heart of the city, 4 miles distant. At the seaside we get less cloud and clearer (though often damper) air than inland; the sunshine is both stronger and of longer duration (e. g. Marlborough 1,399 hours a year, Worthing 1,773 hours) and we are soon bronzed; but the ultra-violet rays are much less strong than at high altitudes. At the seaside the sunshine is associated with cool air, usually in rapid movement, which is physiologically beneficial; but high altitudes have here also an advantage in that the air is usually dry as well as in rapid movement.

In many cases the beneficial effect of light on animal organisms lies in the visible rays and the shorter of the infra-red rays. Objects exposed to the light rays from the sun or to an electric arc lamp become heated far above the temperature of the surrounding air. It is easy to heat the fur of a rabbit up to 150° in this way. But in a space heated to say 70° by a source of dark heat such as hot-water pipes, objects are not heated above that temperature. Not only is the exposed surface raised to a high temperature under the former conditions, but it is observed that the visible and the shortest of the infra-red rays are able to penetrate to a considerable depth through the outer skin and reach the underlying tissues. This is much more beneficial physiologically and psychologically than the dull dark heat of warm air.

The Solid Impurities of the Atmosphere

The amount of the solid impurities deposited from the atmosphere is now regularly observed at several stations. As indicating their order of magnitude we give the following figures for the year ending March 31, 1927, the last available:

Tons of solids deposited per sq. mile, Apr. 1, 1926—Mar. 31, 1927

London, Golden Lane	474
Kensington (Meteorological Office)	313
Kingston-on-Thames	130
Newcastle-on-Tyne, City Road	1,063
Town Moor	247
St. Helens	583
Southport	126

There is a very great increase in the centre of large cities or manufacturing areas.

The records show that the murkiness in cities is largely caused by the smoke from domestic fires before they are heated to redness, and it reaches its maximum in the early morning shortly after most fires are lighted; in recent years coal-fires have been largely replaced by gas, especially in London, and the sunshine records for the city show a notable rise. On the other hand, in the open country natural causes alone are in operation. Thus a dense haze on the Norfolk coast in September 1926 was found on microscopic examination to consist practically entirely of crystalline salts.

The visible rays of the spectrum, that is to say what we commonly call light, pass almost without loss through air, ordinary clear glass, water, and many other substances. The dark heat rays, as invisible as the ultra-violet rays, but immediately perceptible by our skin as heat (the heat, for instance, emitted by hot-water radiators consists of dark heat rays) are intercepted by water, and also by water-vapour in the air; glass offers great resistance to them. It must be remembered that a large proportion of the visible rays are heat rays, and they also are absorbed by water and water-vapour. When the visible rays fall on a solid body such as the surface of the earth they are converted in large part into longer, dark heat, waves, which are then radiated back towards space. But while the visible rays pass almost unimpaired through the atmosphere on their way to the earth (when clouds do not obstruct) the outward passage of the dark heat rays is impeded by the vapour, and still more by any water particles, in the atmosphere. The atmosphere thus acts like the glass of a greenhouse, or like a valve—not a very efficient one—which allows the visible rays to reach the earth, but resists the return passage of the dark heat rays. Clouds are especially effective in this latter process, and hence a cloud layer acts as an excellent blanket for the earth at night. The conversion of the short visible waves into longer dark heat rays is not an isolated phenomenon; when a beam of ultra-violet rays, which are quite invisible, strike certain minerals they are turned into longer waves, which appear as light of various beautiful colours; fluor spar usually shows this 'fluorescence' well.

A considerable proportion of our light is 'diffused' light derived from the clear sky and reflected from the clouds and from the earth itself, especially from water and snow surfaces. With a bright noonday sun and a clear sky perhaps a quarter of the total light near sea-level is diffused. At high altitudes the proportion is very much less. The diffused light is of the highest importance in the visible world, for without it there would be no gradations between bright sunshine and black darkness; all the infinite gradations of shade which have such great practical and aesthetic significance would be lost.

CHAPTER XXXIII

THE DURATION OF SUNSHINE AND THE AMOUNT OF CLOUD

We may treat these two elements together since the one varies in most cases inversely with the other (only, however, if we include fog as cloud). On the other hand, neither the sunshine nor the cloudiness have necessarily a very close relation to the amount of rainfall, for some of the most arid regions show a very poor sunshine record.

The method of registering sunshine is described on p. 190. There are still far fewer records available than the biological importance of sunshine demands. Cloudiness is estimated by eye, the number of tenths of the whole sky covered with cloud at the time of observation being stated. Such estimates can be rapidly made in daylight, and are then reliable, but it is a very different matter at night and probably few night records are trustworthy. Fig. 75 shows the mean distribution of cloudiness. The amount varies in most latitudes with the season; but the variation is much less on the sea, where indeed it is hardly perceptible, than on the land.

The Trade-wind Deserts.

To begin with the sunniest parts of the earth the first place must certainly be given to the trade-wind deserts in every month of the year. These are perhaps the only lands where by common consent there is too much sun. Over wide areas the average cloud covering is less than $\frac{2}{10}$ of the whole sky, in parts less than $\frac{1}{10}$, in each month. The records for Helwan Observatory, a few miles south of Cairo, illustrate the Saharan conditions. The total mean sunshine for the year is 3,668 hours, 82 per cent. of the total time the sun is above the horizon. June to September is the sunniest period, with more than 90 per cent. of the possible; it is

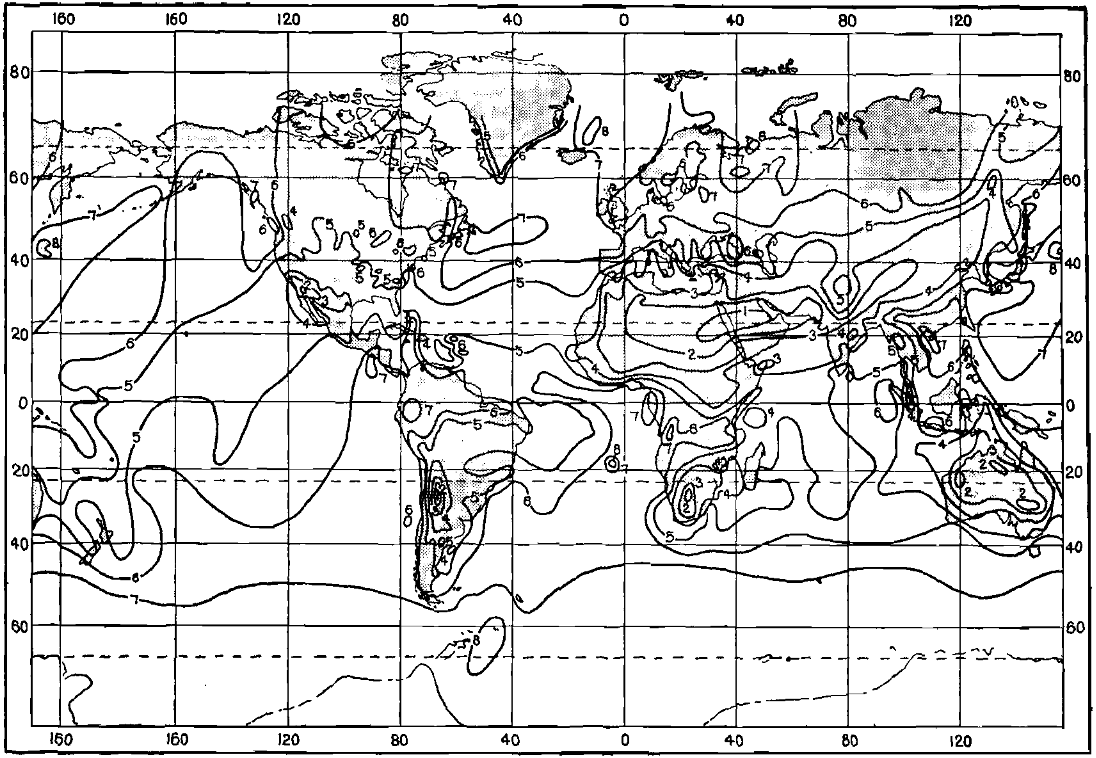


FIG. 75. Mean annual cloudiness (tenths of sky covered). (After Shaw, *Manual of Meteorology*.)

a little cloudier in winter owing to the influence of Mediterranean depressions and the occasional formation of stratus cloud by surface radiation of heat, but even January, the cloudiest month, receives 70 per cent. of the possible. In the 15 Januaries of 1906–20 there were only 11 days on which the sun did not appear at all. In the same years there was not a single day in the months May to October inclusive without any sunshine, and a day with less than 12 hours is very rare in summer; Heliopolis, near Cairo, was well chosen by the ancients as the centre for the worship of the sun. The most usual forms of cloud are cirrus and light cumulus. Farther from the Mediterranean the Sahara is still sunnier. At Asyût the cloudiest months, December and January, have only $\frac{1}{10}$ cloudiness, and from June to October there is less than $\frac{1}{30}$ cloudiness; August has almost an absolutely cloudless sky. In such a climate we long to escape from the harsh and pitiless glare of the midday sun if only in the shade of a group of palms, and still more welcome is a darkened chamber behind thick walls or under the ground. Especially in summer the cool peace of sunset with its gloriously painted skies comes as a welcome relief from the exciting and wearing brilliance of the day. And yet so essential to the desert landscape is the bright light of the sun that there is something depressing and ominous in a day when the sky is overcast and curtains of rain sweep over the bare drab expanses. Most of the trade-wind deserts are sunny like the Sahara; the south-west of the United States has over 85 per cent. of the possible annual sunshine.

The trade-wind regions on the oceans are considerably cloudier, especially in winter; the typical sky is a deep blue flecked with light alto-cumulus and roll-cumulus clouds over about half its expanse. Where the trades meet a mountainous coast there is heavy cloud as well as rain.

The equatorial belt

With a mean for the year of $\frac{6}{10}$ or more, this region is much cloudier than the last, and the sky is often quite overcast with massive black-shadowed cumulo-nimbus clouds in the afternoon, the time of thunderstorms. But in the mornings the sunshine is intense, and a helmet or other good head protection is essential for Europeans. The natives are apparently protected adequately by the dark pigmentation of their skin. Owing to the abundant verdure and deep shade of the equatorial vegetation, escape from the sun's glare is easier than in the deserts, and moreover the day never exceeds about 12 hours. Owing to the humidity of the atmosphere the insolation of short wave-length is less intense.

There are considerable differences in place and season in this as in other elements of the equatorial climate. At Manaos, in the heart of the selvas of the Amazon, the mean cloudiness is between $\frac{6}{10}$ and $\frac{7}{10}$ in each month, the driest season being almost as cloudy as the rainiest. But at Para it ranges from $\frac{4}{10}$ in the driest season to $\frac{8}{10}$ in the rains. There are considerable differences too in the daily curve of cloud-amount. Thus though in general the night is much less cloudy than the hottest part of the day, at Batavia there is little difference during the rains, for the cloudiness is $\frac{7}{10}$ at night and $\frac{8}{10}$ in the day; in August, the driest month, there is a greater range, from $\frac{4}{10}$ at 4 a.m. to $\frac{6}{10}$ at noon.

The westerlies

A decidedly cloudy as well as rainy tract—'coelum crebris imbribus ac nebulis foedum' is the description of the British climate given by Tacitus, and it truly indicates the outstanding drawback of the climate of almost the whole of the belts of the westerlies. Except in the far interiors of land masses there is much more cloud than clear sky, the mean cloudiness being more than $\frac{7}{10}$ over wide areas. In summer the afternoons are cloudiest, for cumulus clouds are formed in the damp atmosphere after midday; but in winter the afternoons are usually sunnier than the mornings, for the sky often becomes overcast with radiation stratus cloud in the night, and this is not dissipated till the middle of the day; in the lowlands in calm weather the inversion fogs of night time persist far into the day. The type of cloud is controlled largely by the weather—that all-powerful influence outside the tropics—but there is also a noticeable seasonal control. In summer, especially during the hot hours, we have cumulus forms, often alto- or roll-cumulus, and sometimes battalions of towering cumulo-nimbus, rivalling those of the equatorial belt, give heavy thunderstorms. But in winter cumulus is rare, and stratus is the prevailing form; sometimes it is an uninteresting and gloomy dull grey pall spread motionless over the whole sky; sometimes the same type of cloud in rapid movement, driven along in the gales, forms an exhilarating scene. The appearance in late winter of bright cumulus clouds reflecting the low sunshine is a welcome sign that spring is at hand.

On the oceanic seaboards in the westerlies autumn and winter are the rainiest seasons, and also the seasons of most cloud and least sunshine; short days and overcast skies, astronomy and meteorology, conspire, and Valencia, south-west Ireland, (Fig. 76) has a mean of only 1⅓ hours of sunshine a day, 17 per cent. of the possible total, in December. Stornoway in the Hebrides, being in a higher latitude and nearer the most frequented cyclone tracks, has only ⅔ of an hour, 12 per cent. of the possible. The weather becomes sunnier with the New Year till May, which is the sunniest month with 6⅔ hours a day, 43 per cent. of the possible, at Valencia, and 6 hours a day, 37 per cent. of the possible, at Stornoway; in spite of its longer days Stornoway is still unable to equal Valencia. June and July have rather less sun than May, but the curve shows a slight rise in August and September before the rapid falling off to the December minimum. The figures for the Pacific coast of North America are similar, the cloudiness increasing to a maximum of $\frac{8}{10}$ in December but falling to a minimum of under $\frac{5}{10}$ in July and August; the summers are considerably more sunny than in the British Isles.

Much of this western seaboard is mountainous, and has not only excessive rainfall but also very cloudy skies. The slightest cyclonic disturbance caps the summits with clouds, which may spread and often enshroud the mountains for weeks together, and the valleys are sunless and cheerless under their low ceiling of cloud even if no rain is falling. We may refer in particular to the Lake District of Cumberland, the Western Highlands of Scotland, and the Fiords of Norway and British Columbia.

In general the rainfall and cloud curves rise and fall together in the oceanic variety of the climates of the westerlies. The relationship is quite different in the interior of the land masses. Nor does the cloudiness diminish nearly as much as the rainfall with distance from the sea, for it is only in the most remote interiors that it sinks as low as $\frac{5}{10}$. The striking feature is that the sunniest and least cloudy months are those with most rain. At Potsdam (Fig. 77) there is most rain in summer, least in winter, but winter is considerably more cloudy than summer. The same is true of most of Central Europe and Russia, the mean cloudiness in Russia being about $\frac{6}{10}$ in summer, $\frac{8}{10}$ in winter. In Siberia, on the other hand, summer, with $\frac{7}{10}$, is rather cloudier than winter, $\frac{6}{10}$. Even in the deserts of Central Asia the sky is far from clear, the mean cloudiness being $\frac{5}{10}$ in both summer and winter in the Tarim Basin; Gobi is less cloudy in winter but equally cloudy in summer, when the influence of the Chinese monsoon is felt. In the neighbourhood of Verkhoyansk, the winter 'cold pole' of the earth, the winter sky is notably clear for the latitude, for the cloudiness is less than $\frac{3}{10}$; the rains of summer bring up the cloudiness to almost $\frac{7}{10}$ in August. Thus this eastern part of Siberia has a monsoonal curve of cloudiness.

The interior of North America is cloudier in winter than in summer; generally speaking there is appreciably less cloud than in the Old World. The New England States have almost uniform cloudiness, between $\frac{5}{10}$ and $\frac{6}{10}$, throughout the year. The annual mean is between $\frac{4}{10}$ and $\frac{6}{10}$ over the whole continent, except the Pacific coast and adjoining region and the St. Lawrence Basin. California, Arizona, and New Mexico have between $\frac{2}{10}$ and $\frac{4}{10}$.

The explanation of the discrepancy between the curves of rainfall and cloudiness is that the summer rain usually falls in heavy showers of not great duration, and the rest of the day may be clear, but in winter the smaller total amount of rain is spread over long periods of cloudy weather, and in addition there is much low stratus cloud in winter as a result of the cooling of the surface of the earth, and also frequent ground fog. The winter days are often cloudy without being rainy, and the long gloomy spells are one of the drawbacks to life in the Prairies and other steppe lands.

The duration of sunshine in the westerlies, and indeed everywhere outside the tropics, is so much under the control of the seasonal variation in the length of the day that the record of cloudiness is no index to it, since the change in

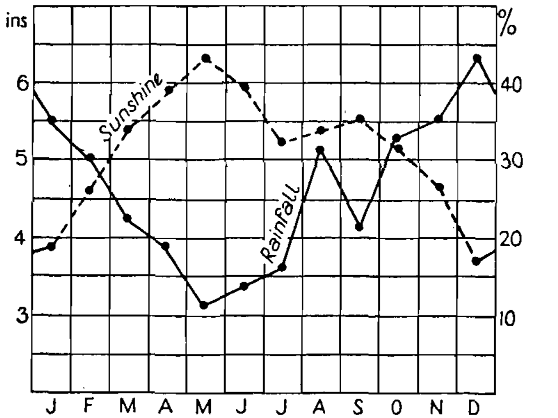


FIG. 76. Valencia (SW. Ireland) mean sunshine (percentage of possible) and rainfall

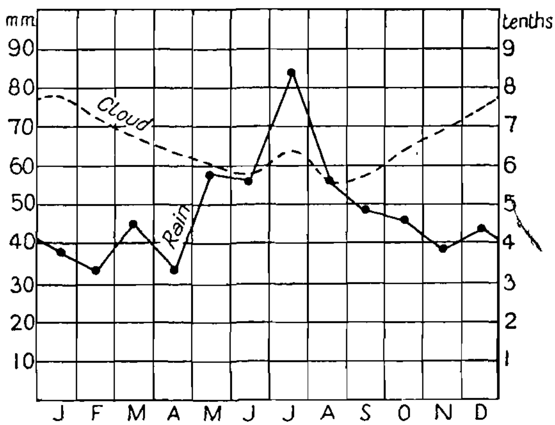


FIG. 77. Mean cloudiness and rainfall, Potsdam

the possible duration may easily override the effect of the degree of cloudiness. Especially in the higher latitudes of the westerlies, in the centre of Canada for instance, the 20 hours of daylight may go far to compensate plant life for the shortness of the summer season. Even in the north of Scotland there is hardly any real night at midsummer, for when the sun does set it skirts so close below the horizon that the glow remains. The following table gives the lengths of the day and night in lat. 40° (New York, Denver, Rome, Peking, Melbourne), lat. 50° (Winnipeg, London, Semipalatinsk), and lat. 60° (Great Slave Lake, Orkney Islands, Petrograd, Tobolsk):

Latitude.	*Number of hours a day sun is above horizon.*	
	Midwinter.	*Midsummer.*
40°	9	15
50°	$7\frac{1}{2}$	$16\frac{1}{2}$
60°	$5\frac{1}{2}$	19

The dark cloudy winters are the most unpleasant feature of the climate of the westerlies. In 1927 there were as many as 78 days on which the sun did not appear at all at Rothamstead, south England, a station in the open country, and in spite of a slight exaggeration, for 1927 was an unusually bad year, this record illustrates an important feature, the palls of cloud that may remain unbroken for a week. Greenwich, London, had 74 days without any sunshine even in the good year, May 1928—March 1929. Summer, too, is sometimes cloudy enough, but two consecutive days without any sunshine are rare.

The tundra lands are within the westerlies, but the high latitude and the low rainfall, less than 10 inches, claim special mention for them. Being for the most part within the Polar circles the range of possible duration of daylight is 24 hours; though the rainfall is low there is not much sun even in summer, owing to the frequent fogs and palls of stratus cloud. At Archangel November is the cloudiest month ($\frac{9}{10}$) and July the clearest ($\frac{6}{10}$).

The Sudan and Monsoon Regions

We now consider two climates which are compounds of the previous types. The Sudan is Saharan in winter, equatorial in summer. At Roseires on the Blue Nile, a Sudan station, the cloudiest (and rainiest) months are June to September, with a maximum cloudiness in August ($\frac{6}{10}$). In winter the sky is almost cloudless, the cloudiness being less than $\frac{1}{10}$ from December to March. Thus the curves of cloudiness and rainfall are in agreement. The summer rain falls for the most part in the afternoon, leaving the mornings clear. The winter sky though almost cloudless is by no means always blue, for the dust haze and frequent smoke from bush fires give it a whitish leaden colour, and the sun is seen as a pale disk. The South African plateau is notably sunny both in summer and winter; Kimberley has 85 per cent. of the possible sunshine in June, 70 per cent.

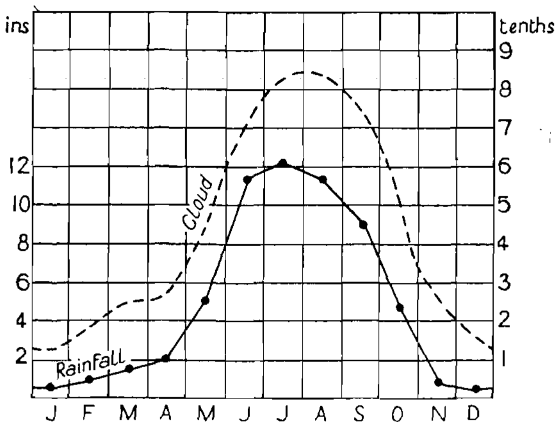


FIG. 78. Mean cloudiness and rainfall, Calcutta

in February, the mean for the year being 9·4 hours a day. Along the middle course of the Orange the mean cloudiness for the year is only $\frac{2}{10}$. The summer clouds are mostly of the thunderstorm cumulus type everywhere on the plateau.

Monsoon lands resemble the Sudan, but the sky is generally clearer and the sun brighter and more cheerful in the dry season. North India is almost as sunny as the Sahara from October to March, but in April the heat and dust haze becomes prominent and dims the sun, though there is little real cloud and no rain, and the dry heat grows more and more suffocating every day. Then when the monsoon breaks in June the sudden rise in the curve of cloudiness is as pronounced as in that of rainfall, for almost overcast skies become the rule; Fig. 78 shows the agreement of the two curves. The various local peculiarities in the rainfall régimes in India are reflected in the amount of cloud.

The conditions in China are similar. Peking is least cloudy in December ($\frac{2}{10}$) and most cloudy in July ($\frac{6}{10}$). The south and centre of China is cloudier as well as rainier than the north. But it is not always the case that the rainiest parts of monsoon lands are the cloudiest. Some of the mountains of India that have excessive rainfall have good sunshine records. This is partly owing to the strong periodicity of the rain and cloud, the winters being dry and sunny, and

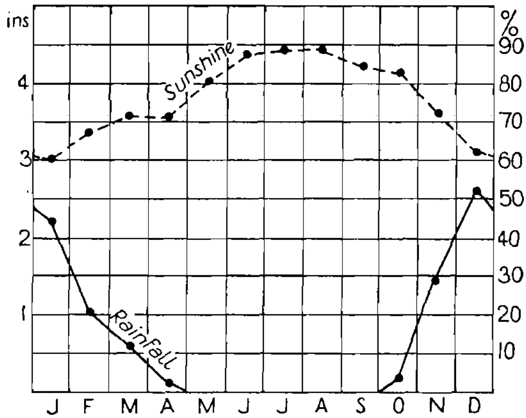


FIG. 79. Mean sunshine (percentage of possible) and rainfall, Alexandria

partly to the intensity of the rain when it is falling; if the sky is overcast and the sun obscured it cannot depress the sunshine record any more, however heavy the rainfall may be. The east of Canada and the United States differs in respect of cloudiness as well as rainfall from the east of Asia in having almost the same amount of cloud in each season, with a slight maximum in winter.

Mediterranean Lands

The regions with a Mediterranean type of climate, i.e. the Mediterranean lands themselves, the Californian coast, central Chile, Cape Town, and the Perth region of Western Australia enjoy almost Saharan skies in summer. The cloudiness is less than $\frac{1}{10}$ in much of the Mediterranean basin, and the south and east is especially sunny, the duration of sunshine much exceeding that in central and northern Europe in spite of the shorter days. Winter is the rainy season, but even in winter a day without sunshine is very rare in the centre and south of the region, and the mean cloudiness does not exceed $\frac{6}{10}$ (Fig. 79). The sunniness is probably the chief attraction of the Mediterranean as a health and pleasure resort for winter. The brightness and exhilaration of air and sky, and the brilliance of the sunlight, both direct and reflected from the white limestone, delight—and dazzle—all newcomers from the gloomy north. The gain in sunshine over even the sunniest parts of Great Britain is shown by the following table—

MEAN DURATION OF SUNSHINE (hours)

	Athens.	*Falmouth.*		*Athens.*	*Falmouth.*
January	112	57	July	**350**	**223**
February	145	84	August	327	211
March	184	139	September	265	161
April	207	181	October	206	113
May	221	229	November	131	73
June	280	221	December	*110*	*53*
			Year	2568	1745

Attention has already been drawn to the fact that considerable, or even heavy, rainfall totals are not inconsistent with abundant sunshine; thus the coasts of Portugal and Montenegro, which have rainfall records among the highest in Europe, have very considerable sunshine even in winter, since the rain is not of very long duration, though of great intensity. The cloud forms are those of North and Central Europe, but there is more cumulus, and the dull grey palls of stratus are much rarer.

The Polar regions

The outstanding feature is the seasonal change in the length of day and night. On the Polar circles the sun does not set at the summer solstice, and does not rise at the winter solstice, so that there are 2 or 3 weeks of continuous day and continuous night at those times; the duration of the midsummer day and the midwinter night increases with latitude to 6 months at the Poles.

Antarctica has anticyclonic conditions, with little cloud. Bright starry skies, brilliant aurorae, and low temperatures in winter are followed by long spells of sunshine in summer. The burn on the card of the sunshine recorder is often unbroken for 24 hours, and Captain Scott's party at Cape Evans secured a continuous record of 66 hours 25 minutes (1911, December 9, 1.5 P.M.—December 12, 7.30 A.M. There was an average of about 14 hours a day in the summer months, and the total for the year was considerably more than we enjoy in England, though the sun was above the horizon on only 246 days. We have no instrumental records from the Polar plateau, but the sky is probably very clear, and explorers report very long sunshine in summer; the eyes must be protected from the dazzling reflection from the snowy wastes throughout the 24 hours. We may imagine the winter landscape—the white snowfields glistening under the bright moon that circles the sky for days together without setting; or the moonless nights lit up by the sparkling stars and the coloured streamers and curtains of the aurora.

The amount and the form of the clouds have been carefully observed, especially in the Ross Sea region. But Dr. Simpson of Scott's last expedition warns us that the records are uncertain owing to the fact that the commonest form of cloud was a very thin stratus, consisting of ice particles, 'a uniform layer of cloud which had no distinguishing features, and the height of which could not be determined . . . the moon and the stars could be seen through it'. Such a sky was entered as overcast, but so thin was the covering that other observers appear to have entered it as clear sky. Thus the estimates of the total cloudiness are not uniform. But there is no doubt that the very cloudy Southern Ocean is bounded on the south by a Polar region of clear skies. The mean cloudiness at Cape Evans, Ross Island, was about $\frac{6}{10}$; but this figure is even more misleading than most mean values, since by far the commonest skies were completely clear or completely overcast, a cloudiness of $\frac{6}{10}$ being rare. It was least cloudy in early summer, most cloudy in February and March and in October. After stratus the commonest forms were alto-stratus, alto-cumulus, cirro-stratus, cirro-cumulus, and cirrus. Ordinary cumulus only appeared in summer, and then extremely rarely, and never over the snowfields. Fog was rare at Cape Evans, but frequent on calm nights and early mornings on the Great Ice Barrier owing to the intense chilling of the snow by radiation of heat through the clear air.

The Arctic is less sunny than the Antarctic. In the summer months there are probably many channels of open water between the icefields, and the consequent differences of temperature and humidity between adjacent areas are conducive to frequent fogs. Even when the sun is visible it is often only dimly seen through the mist. There are no long records to form the basis of an estimate of the number of hours of sunshine. In winter the sky is probably much clearer than in summer but less clear than in Antarctica, owing to the less pronounced anticyclonic conditions, and to the influence of the stormy westerlies which, it would seem, not infrequently penetrate far towards the Pole.

The Cold-Water Coasts

The 'cold-water coasts' on the west side of the trade-wind deserts show a very striking discrepancy between rainfall and cloudiness, for they are among the least rainy and the most cloudy tracts on the globe. The rainlessness has been explained already (p. 134); the cloudiness is for the most part fog. Iquique, on the coast of the Atacama desert, Chile, is practically rainless, the mean annual rainfall being only 0·05 inch, but in the period June to September the cloudiness is $\frac{8}{10}$, a higher record than we find even in the south of Chile, where the rainfall exceeds 80 inches. In summer there is much less fog at Iquique, the 'cloudiness' being $\frac{4}{10}$.

High mountains are usually very cloudy as well as very rainy, and especially so on slopes that have strong winds from the sea. The interesting local peculiarities which are caused by topography, altitude, season, and weather are mentioned on p. 232.

PART VI

FOG

CHAPTER XXXIV. CAUSES

MARINERS have always found fog one of their most serious dangers, and modern inventions in the realm of steam and electricity have not succeeded in removing the peril. Indeed all transport has become even more susceptible to interference from fog as its speed has increased. The dislocation of traffic, the risk of collision, and the expense entailed in working railways during fog are familiar to all. Modern fast road traffic is by no means immune from discomfort, and air transport is practically held up owing to the difficulty of taking off and landing. The effect of fog on health is not very serious in ordinary circumstances, since the total duration of the fog is not great; but in towns the dust, soot and other solid and gaseous particles in the air both darken the fog due to ordinary weather processes, and increase in very great degree the number of hours during which the ultra-violet rays are entirely cut off, with a corresponding injury to the health of the town-dwellers, the most numerous section of many nations. We may also mention the shortening of the daylight and the increased necessity for artificial light; the production of the artificial light reacts through the pollution of the air by the products of combustion.

Fog is so important an element of weather that an exact record of the visibility is now included in the routine work of observatories. The international scale used is as follows:

	Code.	*Range of vision.*
Fog	0	Less than 55 yards.
	1	Exceeding 55 yards, less than 220 yards.
	2	” 220 ” ” 550 ”
Poor visibility	3	” 550 ” ” 1,100 ”
	4	” 1,100 ” ” $1\frac{1}{4}$ miles.
Moderate visibility	5	” $1\frac{1}{4}$ miles, ” $2\frac{1}{2}$ ”
	6	” $2\frac{1}{2}$ ” ” $6\frac{1}{4}$ ”
Good visibility	7	” $6\frac{1}{4}$ ” ” $12\frac{1}{2}$ ”
Very good visibility	8	” $12\frac{1}{2}$ ” ” 31 ”
Excellent visibility	9	” 31 ”

Usually the minute globules of water float in the air, and objects are not wetted by them. But it is otherwise with trees, whether bare or in leaf, for the fog condenses in considerable quantity on them and falls in large drops to the ground. This is especially the case when there is a wind to drive the fog into contact with the tree, and a large amount of water then runs down the trunk or drips direct to the ground. A remarkable instance of this form of condensation is reported from Table Mountain, South Africa. During 8 summer weeks an ordinary rain-gauge collected 5 inches of rain, but a similar gauge close by, in which was placed a bunch of reeds, caught no less than 80 inches; the excess presumably consisted of the water collected from the driving fog or saturated air by the reeds. When the air temperature is below freezing-point the deposit forms rime, which in situations exposed to continuous driving mist or clouds sometimes attains remarkable dimensions, growing out with a sharp edge to windward from the objects on which it is deposited, and dazzlingly white, its weight may break slender poles, telegraph wires, &c. The usual deposit of rime, however, which is fairly frequent in winter in the humid oceanic climate of high latitudes, does not exceed half an inch in thickness. Rime (and hoar-frost) are formed when the temperature of the air as well as that of the surface of deposit is below freezing-point, the vapour being deposited as ice particles. On the other hand, for the formation of glazed frost the air temperature must be above freezing-point, the surface of deposit below.

The usual physical processes which give rise to fog are the cooling of air *in situ* by radiation of heat at night, the cooling of an air current when it reaches a cold land or water surface, and the mixing of masses of air of different temperature. The same processes may produce cloud, but the heaviest clouds, and almost all rain clouds, are formed in ascending currents of air. Ascent never produces fog, which lies on the surface of the earth; fog is not associated with ascending, but sometimes with descending, air currents.

CHAPTER XXXV

COLD WATER COASTS

Fog is very prevalent on the 'fog coasts' of South-west Africa, Chile and Peru, Morocco and California; the circumstances are similar in all, and South-west Africa will serve as an example. The region is dominated by the trade-winds which blow from the land and start on their long ocean journey towards the Equator. The winds are so strong and steady, and cover such a wide area, that they sweep the surface waters along with them (in part forming the Benguela current) and water wells up from the bottom of the ocean along the coast to take their place. This upwelling water, coming from the depths, is much colder than the tropical surface water, and off these coasts it is coldest close along the coast itself (in May the surface of the sea off Swakopmund is 5° colder than the air) and it becomes warmer towards the ocean; the cold is appreciable for 1,000 miles out to sea.

But though the general prevailing winds are the trades blowing off shore, the littoral itself, like most tropical lands, has almost constant sea-breezes by day, intensified here by the cold water of the ocean. Indeed, on the coast of South-west Africa the prevailing wind is south-west, blowing strongest in summer time during the hottest hours of the day. On its journey from the ocean this wind crosses water progressively colder, and being saturated with moisture it soon becomes fog-laden, owing chiefly to the fall in its own temperature and vapour capacity, partly to mixing with the cold and saturated air over the cold water. The foggiest belt is 4 to 6 miles off shore. Thus the sea-breeze is foggy and comparatively cold when it reaches the land. The land is warmer than the sea, and as the air passes over it the fog is gradually dissipated, till at a distance of some 75 miles from the sea fog is rare. The fog, then, is brought by the winds from the sea. When the wind blows from the land—and this is much less frequent—there is a great change of weather, the air being clear and the sun shining brightly. At Swakopmund fog is recorded on 150 days in the year. It usually clears in the afternoons.

PLATE 7

Sea fog pouring through the Golden Gate, California

In spite of the frequent fog and moist air which make the climate unpleasant, disagreeable, and so damp that iron rusts and wood and leather are spoilt by mould, yet the land is a desert, one of the most barren on the earth. A few plants manage to subsist on the fog-moisture, but most of the land is bare. Rain is almost unknown, for despite the sea-breezes of the coastal strip, the climate is under the main control of the trades, which are the drier here in the lee of the South African plateau. A rainstorm is a most unusual occurrence, but the heavy downpours that do occur occasionally as in all arid lands suffice to give a mean annual rainfall of 1 or 2 inches.

A very similar fog-coast is that of central Chile, which is under the general influence of the south-east trades, but has regular sea-breezes near the sea, blowing off the cold Humboldt current. Here again there is an arid desert—even more arid than that of South-west Africa, owing to the lofty Andes on the east and a ridge of hills on the west, which rise immediately from the coast and cut off the Atacama desert from what slight rain might be derived from seaward. The interior may be described as really rainless, though liable to receive a sudden shower at long intervals. It is an unbroken desert of brown earth and nitrates, and in summer the air is hazy with dust and heat. The coast itself is almost equally rainless, but it is subject to very persistent fogs, and at Iquique the mean relative humidity is about 75 per cent.; the climate is very similar to that of Walfish Bay, South-west Africa.

Plate 7 shows the fog at San Francisco, California, where there are on the average 40 days in the year with fog. The fog, together with the direct effect of the cold California current, has a remarkably strong influence on the air temperature along the coast. At San Francisco (Fig. 80) the warmest month is September; the summer months are so foggy that the air temperature rises as the clearer autumn comes on. It is more than 10° warmer in summer on the summit of Mount Tamalpais, a hill 2,375 feet high, which overlooks San Francisco from the opposite side of the Golden Gate, than at San Francisco; the hill-top projects above the surface fog into the clear air and bright sunshine, and is removed from the chilly waters of the sea.

The fogs of the Grand Banks of Newfoundland are famous. They are due to the meeting of the warm Gulf Stream with the cold Labrador current, whose icebergs come south and melt in the warm water. The air is always nearly or quite saturated with vapour, and dense fogs form if warm air from the Gulf Stream blows over the icy Polar water, or if masses of warm and cold air mix. In the Strait of Belle Isle there is fog on 116 days a year, and a wide tract of the seas round Newfoundland is fog-bound for 70 days or more. The foggiest seasons are summer and autumn. The coastal waters east of Greenland are especially subject to fog in summer. The icefloes and bergs reduce the temperature of the air that has come over open water, and dense fogs sometimes persist for days; but their depth is not more than a few hundred feet, and above them the air may be quite clear and the sky cloudless. There is a strong 'inversion of temperature'.

The formation and dissipation of fog was investigated by means of kite ascents on the Grand Banks by Taylor, during the cruises of the ice patrol vessel s.s. *Scotia*, in 1913. We quote the following example from the official Report. 'If the air is originally dry it may cool through quite a large range of temperature before the fog begins, but when it does begin it will be thick owing to a large temperature gradient. . . . In this connexion the ascent of July 29th is particularly interesting. On that occasion the air at a height of 240 metres was very dry, the humidity being only 50 %. It had been cooled through 6° or 7° C. since the sea temperature along its path began to decrease, but it was not yet saturated. At the surface the humidity was 88 % and the temperature 16·3° C. The dew point for air containing this amount of water vapour is 14·2° C. If the quantity of water vapour is not increasing or diminishing one would expect that, if the air explored in the ascent of July 29th were to continue on its course northwards over still colder water, a fog would be produced when the temperature had got down to 14·2° C. Fortunately it was possible to verify this. The *Scotia* proceeded northwards, moving in the same direction as the wind, which remained in the south for about 40 hours. The temperature of the air fell steadily from 16·3° C.

at the time of the ascent, to 13·6° C. at 4 a. m. on July 30th. During this period there was no fog, but between 4 a. m. and 8 a. m. a thick fog came up, and the air temperature fell to 12·6° C. At midnight, when the air temperature had fallen to 10·9° C. the fog was very thick. We see, then, that on July 29th the air had been caught in the act of moving up to a place where fog was bound to be produced. The only things which could have prevented its formation were an

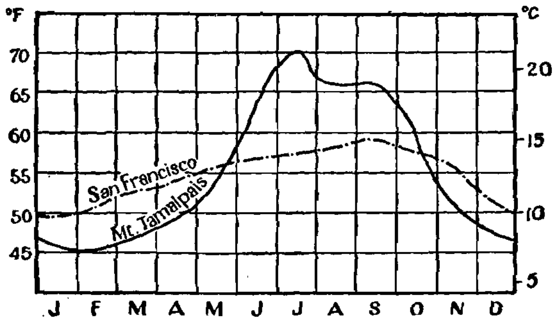


FIG. 80. Mean temperature at San Francisco (207 ft.) and Mount Tamalpais (2,375 ft.)

increase in wind force, which would have the effect of increasing eddy conductivity near the surface and so obliterating the negative temperature gradient, or a change in wind direction of such a kind as to cause the air to blow back again towards the warm water. Some 24 hours after the formation of the fog the wind direction did undergo such a change, and in a few hours the fog vanished.'

CHAPTER XXXVI

SEA FOGS OF TEMPERATE LATITUDES

In temperate latitudes there are two common types of fog, those of spring and early summer over the coasts and the neighbouring sea, and those of autumn and winter which are essentially visitations of the interior, though they may extend over such narrow seas as the Strait of Dover.

The former are common round the coasts of British Columbia and the British Isles. They are caused by the mixing of air masses at different temperatures, or by the cooling of an air current in its passage over colder water, but it is hardly possible to assign any one precise cause that will explain all cases. The season of occurrence suggests that the warm air is derived from the land, and that it becomes chilled on passing over the sea.

When a sea fog of this type is carried back over the land by a sea-breeze it may be seen to dissolve before it is many miles inland; often the coastal strip is shrouded in fog for a whole day while the country behind enjoys the deep blue skies and brilliant sunshine of early summer.

On the other hand, in many cases it is the mixing of cold damp air from the land with the saturated warmer air over the sea that produces the fog, and this cause naturally operates chiefly at night when there is a tendency to land-breezes. It no doubt explains in part the greater prevalence of summer fogs in the early morning than at midday. Thus at Scilly 20 years' observations of fog gave 66 per cent. in summer, 34 per cent. in winter, and of the summer fogs 60 per cent. were in the night and early morning, 40 per cent. by day; in winter night and day were equally foggy. On the east and south-east coasts of Britain there is not the same predominance of summer fogs over winter, and indeed at most stations there is a strong maximum in winter. The reason is partly that the prevailing winds tend to carry the land conditions on to those coasts, partly that the winter fogs which are frequent in the interior of Britain and also over the neighbouring continent may coalesce into one fog-sheet covering the intervening narrow seas. At Dungeness 41 per cent. of the fogs observed in 20 years were in summer, 59 per cent. in winter; there was the same strong predominance of night fogs over day as at Scilly.

The conditions on the coasts of British Columbia are similar. The inner straits have land fogs, with a maximum in autumn and winter; Vancouver has fog on 8 days in October. The outer sounds and the seaward coasts are rarely fog-bound in winter, but navigation is seriously impeded in summer, when there is an average of 10 days a month with fog.

CHAPTER XXXVII

LAND FOGS

LAND fogs are especially a feature of autumn and winter. They are due primarily to the cooling of the land by radiation during a spell of calm anticyclonic weather with clear skies; the air is chilled to dew-point by contact with the ground, and the condensed vapour becomes visible as fog. The process can often be watched on calm evenings, when the cooled air with its white mist flows slowly down the slopes to stagnate in the lowest levels, and there the white sea becomes deeper and deeper as the night advances, till the valleys as seen from above resemble great estuaries of the sea with long branches.

When the condensation continues throughout the long nights of winter the low sun that shines on the upper surface of the fog in the daytime may be unable to warm it enough to dissipate it, and it becomes thicker and thicker night after night, and covers thousands of square miles of land and enclosed waters such as the narrower parts of the English Channel. Probably a slight movement of the air is more favourable than a dead calm, in that it causes mixing of layers of saturated air at different temperatures; it may often be noticed that fog forms, or becomes thicker, just about sunrise, when the surface air temperature begins to rise and slight convection currents are set up.

These fogs are common in autumn and winter in such countries as Britain since the air in a maritime climate is still warm and saturated with vapour, and the land itself is often waterlogged. The long nights give time for the air to cool to a low temperature. They are most frequent and persistent in the valley-bottoms, where the land is moist, the air in less rapid movement, and the basin-shaped topography favourable. Both the prevalence and the unpleasantness of fog are very much greater in the neighbourhood of large cities, where the domestic and factory chimneys pour smoke into the air. The site of even a small town can usually be recognized from afar by the smoke haze that caps it, and in London and other great cities the effect of the smoke, even if there is no fog, can be very impressive. On p. 32 we have shown that some of our warmest and finest summer weather is due to the existence of an abnormally warm upper stratum in the atmosphere. But such an inversion of temperature at times gives rise to less pleasant consequences. On November 23, 1927, Londoners woke to find the city still shrouded in a darkness thicker than that of night, though the air was quite clear. Only in the late afternoon did the daylight break through. Not fog but the accumulation of smoke at probably about 1,500 feet above the city was to blame. The smoke, when not carried away horizontally at once by the wind, usually disperses upwards in convection currents and reaches some layer of horizontally moving air. But on this day there was an increase of temperature above the 2,000 feet level; the smoke rose in the calm air to the base of this inversion layer, but there its ascent was stopped, and the accumulation became so thick after a few hours that the city below was in total darkness.

A similar occurrence on January 23, 1924, is described by the Advisory Committee on Atmospheric Pollution:

'The amount of impurity registered by the automatic filters in Westminster and South Kensington was not unusually large, but a thick bank of cloud overhead, due no doubt to an inversion of the lapse rate, seriously obscured the daylight in most parts of London. . . . In Westminster from 11 a.m. to 1 p.m. the light gradually failed until the whole of the sky visible from the office window in Victoria Street appeared completely black, the darkness appearing to spread from a northerly direction; nevertheless shop window lights could be readily seen in the street approximately ¼ mile away, indicating that surface visibility was still comparatively good.'

The more usual type of 'London fog' consists essentially of a wet and very dense fog of the ordinary valley-bottom kind polluted by smoke. The temperature inversion traps both fog and smoke, and only too frequently every autumn and winter the thick black impenetrable veil dislocates traffic and even makes progress on foot hazardous. The damage to public health is partly positive, since the fog-laden air contains an abnormally large amount of the sulphurous and other noxious products of combustion, and partly negative in that not only the ultra-violet rays, but almost the whole of the sun's radiation is cut off. The lower Thames Valley must necessarily be specially subject to fog owing to its topography, but the persistence of the fog, and its blackness and injurious chemical composition, are due to the emission of smoke from the myriad fires, chiefly domestic fires, of the city.

The same type of fog in a less intense form tends to occur over most great cities in the humid temperate zones. In England the whole of the manufacturing districts of Yorkshire and Lancashire loses a very appreciable fraction of the insolation (see p. 196), and the large towns in the valley-bottoms are subject to fogs little inferior to those of London. In the open country fog is clean and white, but in towns it is discoloured, varying from a greyish-yellow to a deep gloom.

PART VII

MOUNTAIN AND PLATEAU CLIMATE

CHAPTER XXXVIII

INSOLATION

Mountains have very many and somewhat complicated peculiarities of climate. We must examine in the first place the effect of the altitude above sea-level, and then the peculiarities of the various topographical types both in calm and stormy weather; the local winds created by the mountains themselves will also be described.

The Effect of Altitude on Insolation

Most descriptions of mountain climate start by mentioning and explaining the fact that it becomes colder the higher we ascend. We shall begin by considering how it becomes, from one point of view, not colder but hotter as we climb upward —which is as true and hardly less important; and especially we shall consider the intensity of the insolation. It is a striking fact that in the high Alps even in winter visitors become as deeply bronzed as after a stay in bracing sea air in the heat of summer. And perhaps no feature of a high mountain ascent leaves so lasting a memory as the glorious brightness of the sunlight, intensified by the reflection from the virgin snows, and enhanced by the pure dark-blue transparency of the sky. Even in winter the low altitude of the sun is compensated by the extent of the glistening snow-fields, and the brilliance of the heights is the greater by contrast with the gloom of the lower valleys.

The higher we ascend, whether on a mountain slope or in the free atmosphere, the more of the atmospheric 'blanket' is left below; at 8,000 feet above the sea we have left below us about a quarter of the mass of the atmosphere, at 20,000 feet about a half. At eight thousand feet usually we are above about half of the atmospheric vapour, and considerably more than half of the suspended dust.

The liquid and solid impurities decrease rapidly upwards, and at an altitude of 3,000 or 4,000 feet their effect is so much diminished that a further ascent does not make very much difference to the intensity of the insolation (unless there are topographical influences at work, as in the specially important case of temperature inversion with its effect on humidity); 1·55 calories was recorded at 15,000 feet (Mont Blanc), 1·58 at Davos (5,120 feet), 1·64 on Mount Whitney (15,000 feet), and 1·67 calories in a balloon at 23,000 feet. Up to an altitude of 4,000 feet the peculiarities of mountain climate are not prominent, but at 6,000 feet most of them are strongly developed. There is an important difference between the zones below 4,000 feet and above 6,000 feet.

On a cloudless day, therefore, the sun's rays become more intense as we rise to a considerable altitude. Near sea-level the sun's disk is seen surrounded by a hazy white corona separating it from the blue sky, but at high altitudes we see the deep-blue sky reaching right up to the sun. This intensity of the insolation is a most important feature of mountain climate. Though the air temperature may be much lower than at low altitudes, the sun's rays are so powerful that objects exposed to them are strongly heated, and the body may be seriously sunburnt and inflamed if exposed suddenly for even a few hours; invalids who wish to take a sun-cure should acclimatize themselves gradually. It must be remembered that the light reflected from snow is hardly less powerful than the direct rays of the sun.

According to Hill,[1] on clear days some 75 per cent. of the total insolation penetrates to 6,000 feet, and only 50 per cent. to sea-level, but under average conditions the reduction brought about by the passage through the atmosphere is much greater, and in a smoky city near sea-level the intensity of insolation may be less than one-third of that at 6,000 feet. It is one of the accidental advantages of mountains that in most cases there are no large towns to pollute the atmosphere. The total radiant energy from the sun received in a year is 50 per cent. more at Davos than at Potsdam, and in winter the former station receives three times as much as the latter; Davos is in a high valley in the

[1] L. Hill, *Sunshine and Open Air*.

interior of the Alps, some 5,000 feet above the sea, and the figures are the more striking in view of the fact that the surrounding mountains deprive it of 3 hours' possible sunshine a day. Potsdam is near sea-level in the north German Plain—a region of much cloud and damp air.

The intensity of the sun's rays is well observed by letting them fall on a piece of dry black fur, and embedding a small thermometer bulb in it; a reading of 120° to 140° may easily be obtained, though the air temperature is only 70°. It is said that at Leh, 11,500 feet above the sea, in the upper Indus Valley, water has been made to boil (boiling-point 191°) by simply exposing it to the sun in a small bottle blackened on the outside and shielded from the air by a larger vessel of transparent glass.

It is especially the ultra-violet end of the spectrum that is intercepted by the denser atmosphere, smoke, dust and moisture being the chief obstacles. In England Hill estimates the intensity of the ultra-violet rays in a smoky city at one-third that in the open country; the rays are especially strong at high altitudes, the ratio of their intensities at 250 feet, 5,000 feet, and 10,000 feet being, according to Dorns, 40 : 61 : 90.

Reflection from the snow increases the intensity of the light in winter in the high Alps. This, together with the richness of the light in ultra-violet rays is one of the climatic advantages which are sought and obtained at, for instance, Davos, where the coolness and calmness of the air are added attractions.

Slope and Exposure

So far we have been considering the direct rays of the sun; but there is a striking contrast between sunshine and shade. A part of the body exposed to the sun may be seriously burnt while a part in the shade is uncomfortably cold. It should be noticed that the rays pass through the clear air without much heating effect, but solid objects on which they fall become remarkably hot. The more vertical the rays the greater their effect, and hence the direction and angle of slope of the ground are most important factors. In the Alps the altitude of the midday sun is less than 45° for 6 months of the year, and therefore the northern slopes are largely in shadow, while the southern are receiving almost perpendicular rays. This is the cause of the striking differences between the two sides of many mountain ridges and mountain systems. The snow-line tends to be higher on the sunward than on the shady side. But the height depends also, and often to a greater extent, on the amount of snow that falls on the two sides, and this may overcome the former influence. Thus in the Himalayas it is estimated at 16,500 feet on the Indian side in Sikkim, 19,000 feet on the side facing Tibet; in spite of the greater heat the much heavier snowfall on the south keeps the snow-line lower.

The Pyrenees are both warmer and drier on the south side than on the north, and there is no perpetual snow to be seen from Spain, though the highest 2,000 or 3,000 feet, of the northern slope is snow-covered always. In the Alps the snow-line is lower both in the southern and still more the northern ranges than in the central zone, owing to the greater precipitation on the exterior ranges; the mean altitude of the snow-line is about 9,000 feet, but it ranges 1,000 feet on each side of the mean, according to the amount of precipitation, the exposure, the slope, the size and form of the massif. Very steep slopes cannot retain snow, and the snow-line may be much higher than the normal. On the other hand the snow that slides down from the higher slopes collects below, and there the snow-line may be abnormally low. Glaciers, of course, advance far below the snow-line, the Lower Grindelwald glacier descending to 3,800 feet. Near the Equator the snow-line is determined simply by the amount of snowfall, since both north and south slopes receive almost the same amount of insolation; on Kilimanjaro the limit is 17,500 feet on the rainy south slopes, 19,000 on the north. In the south of Norway it is about 5,000 feet, in the north about 3,000 feet, and near the Poles it descends to sea-level.

The more rapid melting of the snow on the sunward slope of any ridge is especially prominent in spring and early summer; we may climb up the sunny slope of an Alpine ridge of 10,000 or 12,000 feet and see no snow except in occasional patches; the bare ground is strongly heated by the almost perpendicular rays of the sun, and it may be as hot at 8,000 feet as at sea-level. But on crossing the ridge we find the shady slope on the other side deep in snow for the upper 3,000 or 4,000 feet. In the Alps the sunny slope is called the Adret or Sonnenseite, the shady the Ubac or Schattenseite; the corresponding names in the Pyrenees are Solanas and Ubagas, and there are other local names elsewhere. The ubac is often left in its natural condition as pine forest, while the opposite slope is rich pasture. Villages and chalets show a strong preference for the sunny slopes. The contrast between Sonnenseite and Schattenseite is very pronounced in the Alps, in the great longitudinal valleys, which have an east-west direction, such as the Engadine, and it is especially striking in spring when the south slope of the valley is still deep in snow, the north side almost or quite clear. In the highest valleys 90 per cent. or more of the population lives on the Sonnenseite.

In the bottoms of deep valleys there is a great diminution of the sunshine owing to the shadow of the surrounding mountains. It is striking how villages and houses avoid, where possible, the most shadowed sites and choose those slopes that get the sun early and keep it late. In some valleys there are permanent settlements perched at great altitudes, where they enjoy specially long sunshine, in some cases 2 or 3 hours longer than the lower villages. The loss of sunshine is especially serious in high latitudes; thus in Norway there are a few villages so unfortunately situated at the north foot of steep mountains as to lose the sun entirely for several weeks in winter.

There is much snow to be melted everywhere, and especially on the higher slopes, before the warmth of spring is really felt. In the higher Alpine pastures the first spring flowers do not appear till the beginning of April. We have to thank this delay in the beginning of the spring for the glorious display of flowers in the higher Alps in late spring and early summer; for plant life starts so late that there is a race against time to accomplish the life-cycle before the snows of autumn draw the veil. All plants must be ready to flower at the earliest opportunity, and by the end of June the meadows about 5,000 or 6,000 feet above the sea are a richly coloured paradise—in remarkable contrast to the snows of winter, and to the slush of brown and decayed vegetation that covers the ground in the end of March when the snow is melting. In April the Alps are still snow-covered down to about 6,000 feet—a figure, however, subject to great local variations depending on amount of precipitation, drifts, exposure, and slope. The main Alpine passes even at 6,000 feet may be completely blocked with 20 or 30 feet of snow well on into May, and the roads over them may be impassable till the middle of June.

The intense insolation is due primarily to the decreased mass of the overlying atmosphere. For some physiological aspects of this element of mountain climate reference should be made to Chap. XXXII.

CHAPTER XXXIX

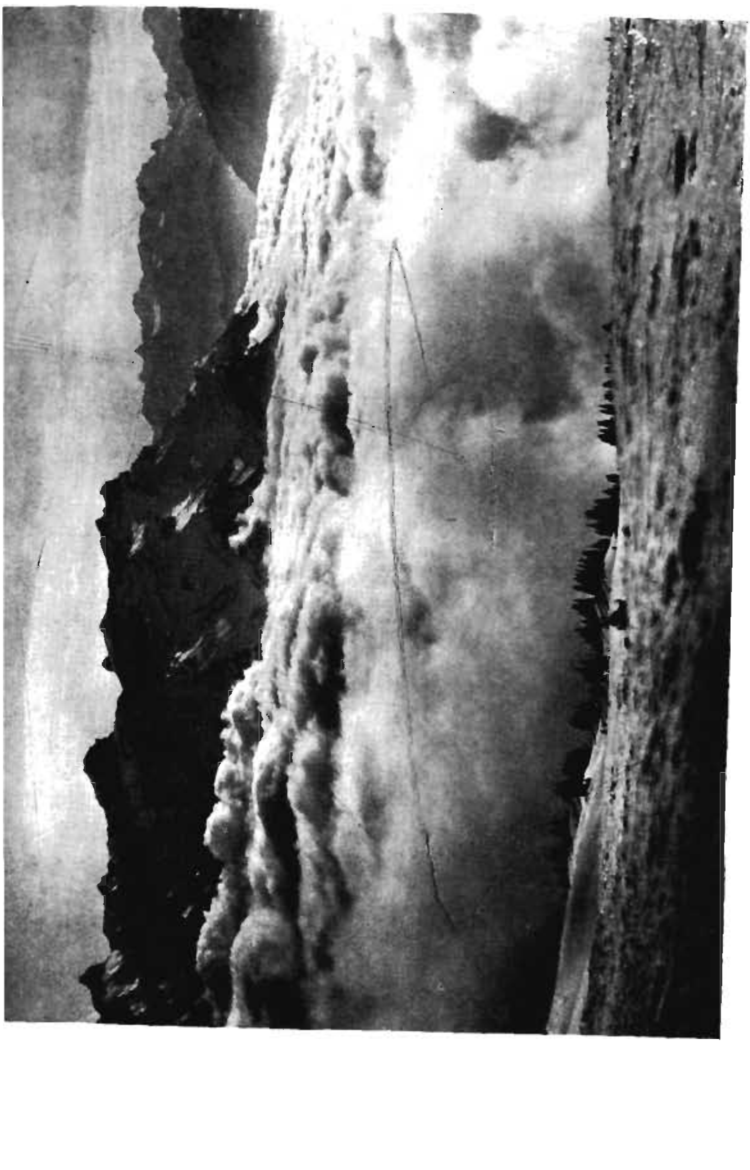
AIR TEMPERATURE, SUNSHINE AND CLOUD, HUMIDITY

THE next point to be considered is the air temperature, as recorded in a Stevenson Screen or otherwise under standard conditions. It must be remembered that pure air is hardly heated at all by the passage of the rays from the sun; in the free atmosphere at 1 km. above the earth there is practically no difference in temperature between day and night. The heating and cooling of the air with which we are familiar on the earth's surface are indirect effects of the insolation. The ground intercepts the insolation and becomes heated, and the air resting on it is heated by conduction, and also by the passage of dark heat rays which are emitted from the warm ground and are in part absorbed. At night there is no insolation to balance the loss of heat by radiation, and the ground cools rapidly, and cools the air in contact with it. Thus in calm weather the range of air temperature depends, *ceteris paribus*, on the extent of the ground in contact with the air. In flat country the extent is fairly constant, but among mountains there are large local differences; at one extreme is the isolated peak projecting high into the ocean of atmosphere, at the other the deep and steep-sided valley where the air is enclosed below and on each side by the ground. We owe to Hann[1] a useful distinction between convex and concave topography—the former exerting little control on the air, the latter much; where the slopes are convex the air temperature tends to be equable, where they are concave, extreme; Hann likens the former to marine, the latter to continental conditions. During the hours of powerful sunshine the rocks even at high altitudes are strongly heated, but (in the case of an isolated peak) the area in contact with the atmosphere is so small that the general air temperature cannot be much affected—the less so since the air at high altitudes is usually in rapid movement and does not remain long in contact with the rocks. In a nook at a high altitude, facing the sun but sheltered from the wind, it feels very warm and the temperature of the still air itself is high; but we find a great difference if we leave the shelter and place ourselves in the current which rushes past outside. At night the rocks become very cold, but again their general effect cannot be very great. Hence the air temperature rises but little in the day, and sinks but little in the night, differing comparatively little from that of the free atmosphere round about.

In the daytime the heat from the warm rocks of the higher mountains is so widely dissipated in the passing air that its effect on the air temperature is negligible, but the cold rocks at night have more influence. When the air is chilled by contact with them its density is increased, and in fairly calm weather there is a creep of cold air down all the slopes, to collect in the deeper and more enclosed valleys in cold damp 'lakes' which begin to be noticeable as soon as the sun sets. The clearer the sky the more rapid is the cooling of the rocks; and the calmer the air the steadier the descent of the cooled air. The effect is most prominent in winter, for in summer the valley-bottoms are so much heated during the day that they keep the air warm far into the short night. On a winter morning it is not unusual to find the bottoms filled with a cold fog, or sometimes roofed over with a low pall of cloud, but on ascending the slopes we come suddenly to a level where we break through the gloom and enter a new

[1] *Handbuch der Klimatologie*, I, Bk. 4

PLATE 8



Sea of clouds in the valley round the Diablerets, Switzerland

and unexpected world bright with the sun shining from a deep blue sky and reflected from the sparkling white mask of snow. Rising still higher we may look down on the upper surface of the lake of mist which enshrouds the bottoms (Plate 8).

'The deep trench of the Lauterbrunnen valley was filled with mists, and snow was falling steadily. As the train toiled up to the Wengeralp, a bright light pierced the hanging cloud, and the next instant we rose out of the mist into a perfect morning. Above, the Jungfrau, the Mönch, and the Eiger swept up into a stainless sky. Below, the silvery surface of the cloud sea stretched over all Northern Switzerland.' (From a report of a winter ascent on the Eiger, January 1929.)

In the Himalayas, Alps, and similar systems there are isolated summits at a less altitude than many of the upper valleys, but in winter they enjoy brighter weather since they usually stand clear above the fog of the surrounding lowlands. The highest summits and ridges are always clear of this type of fog. Many of the higher valleys also, which offer a free outlet for the chilled damp air that drains into them, are exempt, and for this reason among others they are a favoured resort for invalids; the Davos Valley is an example. Ober-Gurgl (Plate 9), the highest village in the Tyrol, is similarly situated, and it too has a reputation as a winter health resort. The elevated shoulder platforms of the larger glaciated valleys are also usually above the fog and are suitable sites for winter cures. Such is Montana, on the south-facing alp overlooking the deep trench of the Upper Rhone.

It must now be evident that there is no constant relationship between temperature and altitude; the usually accepted average of 1° fall of temperature for each 300 feet of elevation is merely a mean value which very rarely occurs. The summits are usually colder than the lowlands, but during bright sunshine the valleys are abnormally warm, and during still nights abnormally cold. Hence the temperature gradient is steeper by day than by night, in summer than in winter. The following table for Alpine stations illustrates this; Lucerne is on the Swiss Foreland, the Rigi is an isolated summit (convex relief), and Bevers is situated in the deep valley-bottom of the Upper Engadine, overlooked by lofty ranges (concave relief); Bevers and the Rigi are at approximately the same height above sea-level, but their topography is in complete contrast.

Mean Temp. °F.

Station.	Alt. feet.	July. Mean daily.	July. 7 a.m.	July. 1 p.m.	January. Mean daily.	January. 7 a.m.	January. 1 p.m.	Range, July–Jan.
Lucerne . .	1,480	65	62	71	30	27	32	35
Rigikulm . .	5,863	50	49	52	24	22	25	26
Bevers . . .	5,610	53	48	62	14	8	22	39
Difference.								
Lucerne–Rigikulm	—	15	13	19	6	5	7	—
Rigikulm–Bevers .	—	−3	1	−10	10	14	3	—

The type of weather also determines the gradient, since it is only under still anticyclonic conditions that inversions of temperature are prominent. This is shown by the following example from Switzerland:

Station.	Alt. feet.	1881. Temp. at 7 a.m. °F. Dec. 25.	Dec. 26.	Dec. 27.
Altdorf . .	1,480	20	19	23
Rigikulm . .	5,863	13	27	35
St. Gothard Pass .	6,877	−2	24	30

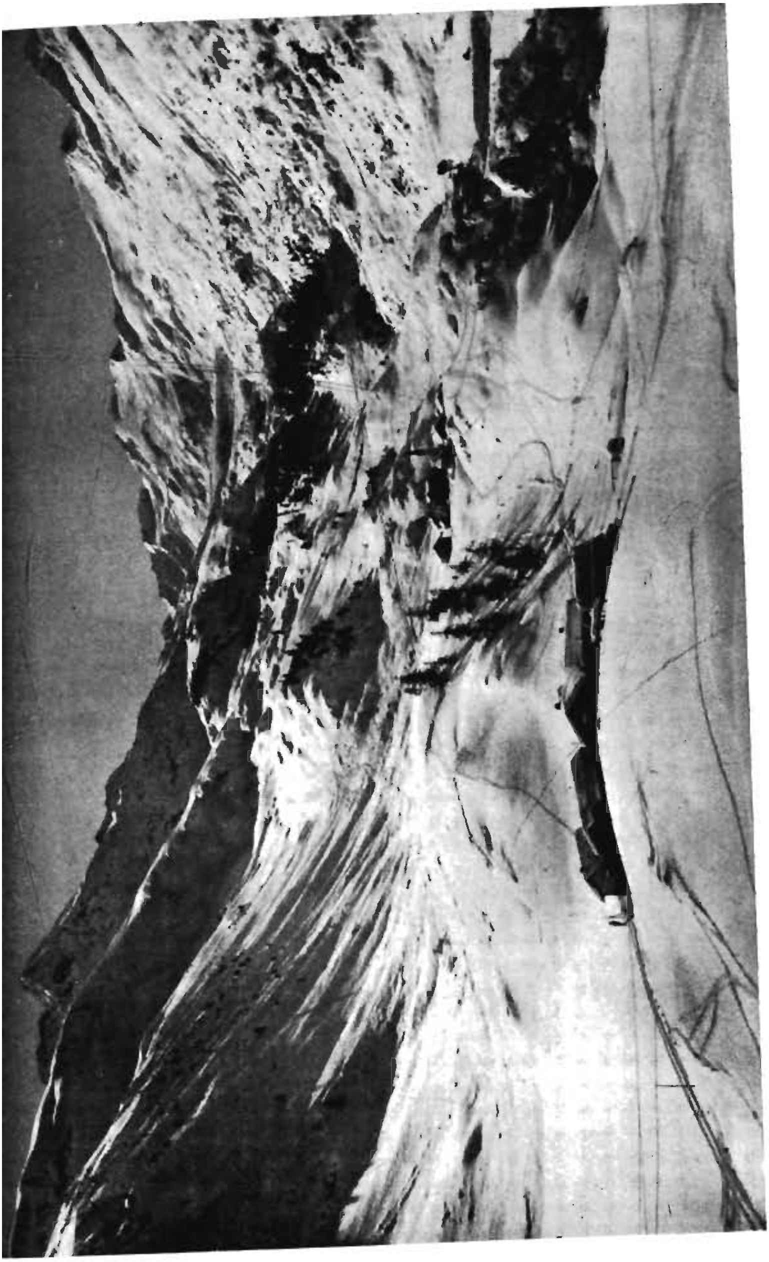
The three stations are not far apart. Altdorf is in a valley bottom, the Rigi is an isolated summit, the St. Gothard Pass a ridge station. On December 25 the weather was cyclonic and the wind strong, so that the temperature decreased with altitude. But the whole situation changed with the arrival of an anticyclone on December 26, a strong inversion of temperature being established; on the 27th at 7 a.m. it was 12° colder at Altdorf than on the Rigi, in spite of the altitude being over 4,000 feet less.

As a contrast to Ober-Gurgl (Plate 9) we give in Plate 10 a view of Zwieselstein, a village some miles lower down the same valley, but deeply enclosed by steep mountain slopes. The cold air collects in the little basin in calm weather, and the winters are very cold.

In a continental climate enclosed upland valleys at great altitudes have remarkable extremes of temperature. Sven Hedin[1] noted this in the Pamirs in Central Asia:

[1] Sven Hedin, *Through Asia*, ch. xiv.

PLATE 9



Gurgl, Tyrol, in winter

'The variations of temperature are enormous, not only in winter but also in summer. At Fort Pamir (12,000 feet) at 7 o'clock in the morning of 11 January, 1894, the thermometer recorded a temperature of $-36°$ F.; one hour after noon it was $53 \cdot 6°$ in the sun—a difference of nearly 90° F. in the course of only 6 hours! The amount of radiation is almost inconceivable. At a time when the temperature of the air was just at the freezing point, the black-bulb insolation thermometer actually registered 133°.'

The rapid changes of temperature between sunshine and shade, wind and calm, are prominent everywhere above about 5,000 feet. Even on snow-covered mountains the heat may be excessive in a sheltered spot in the sunshine, and then within a few minutes, when the sun ceases to shine, and the wind springs up, it is bitterly cold.

The lower slopes of the deep valleys, especially those that face the sun at a steep angle, can become very warm on bright summer days; even at considerable altitudes the sunward slopes are remarkably warm, for in addition to the direct effect of the powerful insolation the valley-breeze blowing over the strongly heated ground in the course of its ascent is as warm some thousands of feet up the valley sides as below. The Upper Rhone Valley in Switzerland is often extremely hot and enervating; the altitude is only about 1,500 feet, and during a spell of summer weather with clear skies and bright sunshine Sion, Sierre, and other similarly placed towns are suggestive of the south of Italy. The resemblance is heightened by the semi-arid type of natural vegetation in the bottom of the valley, which is due partly to the dry hot air, partly to the low rainfall; some tracts are covered with a saline deposit in the heat of summer. The limit of cultivation is remarkably high in this and the tributary valleys—the vine is profitably grown up to 4,000 feet, cereals to 6,500 feet, and trees flourish up to 8,000 feet. For agricultural purposes the low rainfall is remedied by an elaborate and ancient irrigation system fed from the melting snow and ice high above. Ruskin was struck by the heat of Sion—'the air in the morning stagnant also, hot, close, and infected; one side of the valley in almost continual shade, the other (it running east—west) scorched by the southern sun, and sending streams of heat into the air all night long from its torrid limestones'—this only after very hot summer days, for the valley may contain stagnant and very cold air on winter nights, and even on winter days the cold lake is sometimes not dissipated.

We have seen that it is only in calm weather that inversion of temperature can be strongly developed, and it is especially associated with the anticyclonic calms and long nights of winter. The Alps, being dominated by the 'barometric backbone' of Europe, are frequently subject to such conditions.

Sunshine and Cloud

This same phenomenon of the drainage downwards of the cold air explains many features of the sunshine and cloud records. The valleys and lowlands have much cloud (often really fog) and little sunshine in winter as compared with summer, but the high valleys and even the summits are much more favoured in winter:

Station.	*Alt. feet.*	*Cloud, tenths.*		*Sunshine. Hours per day.*	
		Jan.	*July.*	*Jan.*	*July.*
Säntis . .	8,202	5	7	3·9	5·3
Davos . . .	5,121	4	5	3·2	6·7
Chur . . .	2,001	5	5	—	—
Montana . .	5,000	—	—	5	8
Zürich . .	1,542	8	5	1·4	7·7

The high sunshine records in winter, in spite of the short days, at Montana, the Säntis, and Davos are noteworthy. The long duration and the quality of the sunshine both direct and reflected from the snow, are features of great medical importance. Hill[1] points out that Glasgow and Westminster have only a little more than a quarter of the winter sunshine received at Montana.

The high Alps do not enjoy these advantages in windy cyclonic weather. If the air has to cross the mountains it expands as it rises, and cools at the rate of about 1·6° for each 300 feet, so that it usually reaches its dew-point in the course of the ascent. The clouds thus condensed may enshroud the heights for days together and the sun never breaks through. At these times the valleys and lowlands, being

[1] *Sunshine and Open Air*, p. 46.

PLATE 10

Zwieselstein, Tyrol

farther removed from the clouds that shroud the summits, are more favoured. Again, the mountain tops are cloudy during the midday hours in settled weather in summer also, owing to the valley-breezes which set in every day about 9 or 10 a.m. and blow up all the valleys. Wisps of clouds begin to form before noon, and for several hours the highest summits are cloud-capped. The clouds are often thick enough to give thunderstorms. Towards evening the valley-breeze dies away and the clouds disappear. Thus in fine summer weather the mountain tops have their clearest skies during the night and early morning; in high ascents mountaineers aim at reaching their objective and starting down again before the clouds begin to collect. On the Obir (6,693 ft.) in the Tyrol the sunniest hour in summer is 8–9 a.m. and for the whole year 9–10 a.m.; compare Klagenfurt in the bottom of a basin, where the sunniest hour is noon to 1 p.m.

We would emphasize the climatic advantages of the highest altitudes in winter. The high valleys are almost equally favoured with the summits, and they have the advantage of calmer air and a continuous snow-cover, as well as accessibility and other conveniences for human settlement.

It is useful to sum up at this point certain features of the summits and the low valleys. The summits are less cloudy and have drier air in winter than in summer, in the night and early morning than during the afternoons. The low valleys have less cloud, more sunshine, and drier air in summer than in winter, in the middle of the day than in the night and early morning.

Humidity

Very low humidities sometimes occur, and correspondingly rapid evaporation; but sudden and large changes may take place. The rapid evaporation is one of the trials of mountaineers at very high altitudes. A report by a member of the Mount Everest expedition describes the conditions at about 27,000 feet:

'The constantly and rapidly repeated intake of breath and catching at the back of the throat seem to have a curiously drying effect.

Whatever the cause the result is a pronounced desiccation of the whole system. In the great cold the thirst seems not to make itself felt until late in the day, when it becomes intense. There is little doubt that this tremendous desiccation of the body is one of the primary causes of breakdown and failure at great heights.' (Col. Norton in *The Times*.)

The very strong wind which is usually blowing intensifies the physiological dryness of the high altitude climate.

On the other hand, at moderate altitudes of 6,000–12,000 feet the rapid evaporation contributes to the delights of winter sports. We may walk or ski through snow the whole day without our clothes or boots being wet though they are often covered with snow. Probably, too, it is a leading factor in producing that marked feeling of well-being, exhilaration, and energy. The rapidity of the evaporation partly explains the rapid disappearance of the snow and drying of the ground in spring.

CHAPTER XL

RAINFALL

In an earlier chapter some account has been given of the effect of mountains in increasing the rainfall; even low ranges stand out hardly less prominently on the map of rainfall than on the orographical map. In general the windward slopes have most rain, the leeward least, and in a region of dominant winds from one direction the difference is very great. In the larger complex mountain systems each ridge has its rainy windward and drier leeward slope, the totals becoming less and less on corresponding slopes from the windward to the leeward side of the whole system. This is well seen in the Himalayas, the precipitation exceeding 150 inches on the ranges overlooking the plains of India, and diminishing to 3 inches or less in the valleys in the north, as at Leh in the Upper Indus Valley.

The western mountains of North America, and the Andes of South America, are also excellent instances, the ridges, valleys, and intermont basins being outlined prominently by the isohyets. The Alps lie in the direction of the prevailing westerlies, and have their heaviest rain on the exterior ranges, least in the interior, and especially in the enclosed valleys of the interior such as the Upper Rhone (24 inches at Sion), the Upper Adige (16 inches at Glurns), and the Engadine (most of it with less than 30 inches). Fig. 57, p. 133 illustrates the relationship between ranges and rainfall diagramatically.

All types of rainfall may occur—a drizzle when the clouds are forming slowly, a steady cyclonic downpour which may continue for days without intermission, violent thunderstorms on summer afternoons. Even when rain is not falling a very large amount of water is probably deposited on the vegetation from clouds which are constantly swept past by strong winds. On Table Mountain overlooking Cape Town an apparently stationary white cloud is often to be seen before and during bad weather.

Inversion of Rainfall

The amount of precipitation might be expected to increase with the altitude, and up to a certain height that general rule holds good. But the heaviest precipitation will occur where the clouds first begin to deposit rain or snow, since the temperature is highest there, and therefore for any given ascent and cooling the condensation is more abundant than at higher levels, where the temperature is lower. There is the further consideration that in the higher altitudes there are more gaps in the ranges, so that the wind can cross the obstacle without ascending to the highest summits. The zone of maximum precipitation depends on the circumstances of time and place, but in general it is higher in summer than in winter. In such low mountains as those of the British Isles the precipitation continues to increase to the summits, the possible maximum probably being nowhere reached, but in higher systems the increase up to a certain average altitude, and the decrease above, have been proved by rainfall records. On the Pic du Midi in the Pyrenees the maximum zone is about 4,000 feet above the sea in winter, and 6,000 feet in summer. In the Alps the mean altitude is about 6,500 feet, in the Western Ghats

4,500 feet, in the north-west Himalayas 4,000 feet, and in Java as low as 3,000 feet.

The effect of inversion in the Tian Shan of Central Asia has been described by an early traveller; in winter the zone of most cloud and snow is about 9,000 feet, and here there are forests; but above this the precipitation becomes so much less that the pastures are not deeply covered with snow, and the nomads bring up their herds to graze. In summer the maximum rainfall is higher up the mountains, and these same pastures receive the necessary moisture for the growth of grass.

CHAPTER XLI

PLATEAU CLIMATE

Temperature

If we rise from sea-level in an aeroplane, or on a mountain peak, or on a plateau, we leave the densest layers of the atmosphere below, and find above stronger insolation by day, more rapid loss of heat at night, increased evaporation, and stronger winds. A plateau differs from the other elevations in having a large area of ground in contact with the air. The ground heats greatly in the day and cools rapidly at night, and the air resting on it shares the extreme temperatures. This high range of temperature from day to night and from summer to winter is the most obvious feature of the plateau climate to the newcomer. An exception is the uniform mean monthly temperature at the Equator even on lofty plateaux; at Quito, 9,350 feet above the sea, the mean annual range is less than 1°. But even here the contrast from day to night, and the sudden changes from warm to cold are prominent. The plateau of South Africa, between 20° and 30° S. lat., is typical of tropical conditions. The summers are remarkably hot for the altitude, for the mean January temperature at 4,000 feet is almost the same as at sea-level on the east coast. The winters, however, are far colder, and the annual range is greater (Fig. 81); this is partly an effect of continentality, a factor of uncertain amount. The diurnal extremes are much greater on the plateau, especially in the clear rainless weather of the dry season. In the middle of the day the sun may be hot enough to cause sunburn, but as soon as it sets heavy coats must be donned, and there is frost before it rises again. The mean diurnal range at Pretoria in August is 34°. Even on the Rhodesian plateau inside the tropic frost occurs on winter nights.

'No one who has not felt it could believe the rapidity of the change of temperature. So long as there was sunlight it was too hot. In half

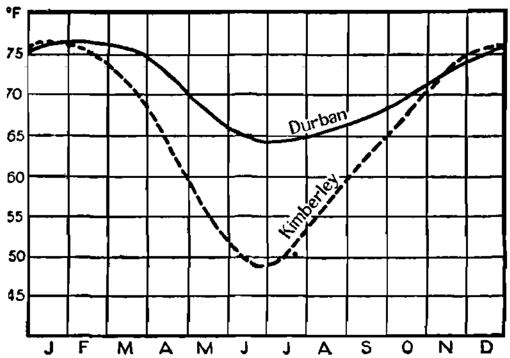


FIG. 81. Mean temperature at Durban (east coast) and Kimberley (interior plateau, altitude 4,042 ft.)

an hour it was bitingly bitterly cold. . . . I don't think I was ever so cold in my life as when we reached home about half-past six. Yet there was not much frost, but one suffered from the reaction after the burning heat of the day.' (BARKER.)

A similar picture is sketched for the higher plateau of Bolivia (altitude about 9,000 feet).

'Early in the morning and late in the evening, when the sun is below the horizon, the cold is liable to be intense even in September and one suffers from almost frozen feet. In the winter, when the winds blow and the frosts are yet more severe, the dry cold is so trying that even the natives cover up their faces in thick woollen masks, and wrap shawls about their heads and ponchos over their bodies. But as soon as the sun is a little way above the horizon, its direct rays scorch the traveller with their great heat, so that he soon begins to pray for the night, as the lesser evil of the two. . . . By day the burning sunshine so envelops all the brown, dry, dusty ground that everything in view seems to vanish in brightness; and the eye, unprotected by dark glass, cannot gaze steadily in any direction. . . . When the sun is hottest little cyclones raise dust whirlwinds which dance along, often by scores at a time.' (SIR MARTIN CONWAY.)

The chilled air drains into the hollows, perhaps more noticeably on plateaux than elsewhere:

'I noticed during the drive (over the Veld) what I have often noticed out here, the layers of cold air. Sometimes the wraps became quite oppressive at the top of a hill or even climbing up it; then in crossing a valley or narrow ravine we seemed to drive into an ice-cold region where we shivered beneath our furs; again in five minutes the air would once more be soft and balmy, crisp indeed and bracing, but many degrees warmer than those narrow Arctic belts.' (BARKER.)

Bolivia provides another good example, the deep valleys incised in the Puna being filled at night with very cold air. But the level tracts are extensive enough to retain a cold layer of air, and are often colder than mountain sides or the free atmosphere at the same altitude.

Asia has plateaux of great altitude (Tibet) and in high latitudes (Mongolia), where the winters are extremely severe. Even the Tarim River is deeply frozen for 3 or 4 months, and water for domestic purposes has to be transported in the form of blocks of ice. Yet in summer the heat is nigh intolerable:

'In the beginning of June summer—the Asiatic summer—was upon us almost before we were aware of it. The sky glowed like a gigantic furnace. The temperature rose to 100° F. in the shade; the black bulb insolation thermometer showed 150°. The queen of the night was powerless to infuse coolness into the superheated atmosphere of east Turkistan. And every afternoon the desert wind blew in across the ancient capital, dry, burning, impregnated with fine dust, filling the streets with a stifling impenetrable haze.' (SVEN HEDIN, describing Kashgar.)

It is true that the Tarim Basin, though in one sense a plateau, 3,000 feet above the sea, is at the same time really a great depression, bounded on three sides by towering ranges, a configuration which intensifies the extremes of temperature.

Tibet, with plateaux of from 14,000 to over 17, 000 feet above the sea, has monthly means below freezing-point most of the year. Iran, on the other hand, with its lesser altitude and lower latitude, is distinguished especially by its blazing heat in summer, but a winter journey over the salt wastes of the interior, in the face of the icy blasts and snow flurries from the north, is no pleasant experience. The plateau of Asia Minor has colder winters, owing to the proximity of the steppes of Russia, and the genial climate of the Mediterranean coasts makes the cold of the interior the more noticeable.

The Plateau of the Shotts in Algeria is in a higher latitude than the Transvaal, and another factor giving it colder winters is its nearness to the land mass of Eurasia. It can be bitterly cold in winter, and severe snowstorms have cost the lives of men caught unprotected. The visitor who is fleeing from the cold of northern Europe must cross not only the Mediterranean Sea but also the plateau before he can be immune in the sheltered oases of the Sahara. As on other plateaux of similar altitude the summers are very hot—hotter than on the coast of the Mediterranean—owing to the fierce sunshine that beats down on the parched plains. The summer days often rival those of the Sahara. The Meseta of Spain has a similar but less extreme climate.

Rainfall

The rainfall on plateaux is usually rather low, partly owing to the fact that most plateaux have an elevated rim which causes a rain shadow. The Shotts have little more than 10 inches a year. The régime of the rainfall depends on the latitude. Quito, being in the equatorial belt, has rain all the year with two maxima. The equatorial plateau of East Africa is similar. The South African plateau has the tropical régime, with most rain in summer and almost rainless winters; the Plateau of the Shotts, the Meseta of Spain, and Asia Minor have the Mediterranean characteristic of dry summers, but there is a strong maximum in spring—another steppe feature. These are brown lands during much of the year, green only when revived by the moisture of the rainy season.

The rain often falls in violent showers, and the thunderstorms and hail of South Africa are well known; at Johannesberg there are on the average 111 days a year with lightning.

'The crops in the citrus orchards over a large area in the Northern Transvaal have been destroyed by hail, and donkeys, pigs, goats, and other animals, including apes and game, have been killed. The damage is estimated at many thousands of pounds. (*The Times*, November 8, 1927.)

The bitterly cold hailstorms of loftier plateaux have been described by many travellers:

'Sept. 22. . . . The weather took a disagreeable turn. The sky darkened in every quarter, and a hailstorm of unparalleled violence burst over the lake. The clouds drove towards us out of the east like a solid black wall, accompanied by fierce hissings and whinings like the sound of steam escaping from the boiler of a locomotive. The surface of the lake turned dark grey. The mountains on the shore became lost in the haze; louder and louder grew the roar of the storm. We could see and we could hear how the drops of water splashed up with a perceptible hiss as the hailstones thrashed the dead smooth surface of the lake. The hail came down in blinding showers, but finally passed over into snow and rain. Then the wind changed, and a terrific gale set in from the west. It blew right in our teeth and nearly froze us to death. The horses literally toiled against it as though they were struggling up a steep hill.' (SVEN HEDIN, on North-eastern Tibet.)

The spring rains, the strong winds, and the rapid evaporation are all steppe characteristics, as the grass vegetation bears witness. But the rainier mountain rims are in some places forested.

PART VIII
THE WEATHER OF TEMPERATE REGIONS

CHAPTER XLII
HIGH-PRESSURE SYSTEMS

In the general account of the westerlies in Chapter XVIII, attention was drawn to the irregularities of pressure which are such a striking feature; the barometer is subject to rises and falls of greater magnitude than in any of the other zones, and their occurrence appears to be quite erratic, and very difficult, if not impossible, to forecast; they are evidently closely connected with the very changeable weather which characterizes the belt (unlike the semidiurnal rise and fall which is the chief movement of the barometer within the tropics, and is independent of the weather). The idea of the 'climate' of any region outside the tropics is a generalization based on such manifold and irregular types of weather that no description of it can be adequate unless it includes some account of the daily weather. There is abundant material available for the study of the westerlies of the north hemisphere, in the detailed synoptic weather charts published officially in many countries within the belt.

The charts show an endless variety of pressure systems; the shapes of the isobars, the movements of the pressure systems, the details of the weather, are never repeated exactly, but we soon learn to recognize certain types. The main distinction is between systems in which there is higher pressure than round about, and those of lower pressure.

High-pressure Systems, 'Anticyclones'

High-pressure systems give us, speaking generally, our fine weather. The ordinary principles of physics would indicate that the air should move outwards from the central region of highest pressure, and that in the central region itself there should be currents of air slowly descending to feed the outflow. Since descending currents suffer compression as they reach the lower strata of the atmosphere

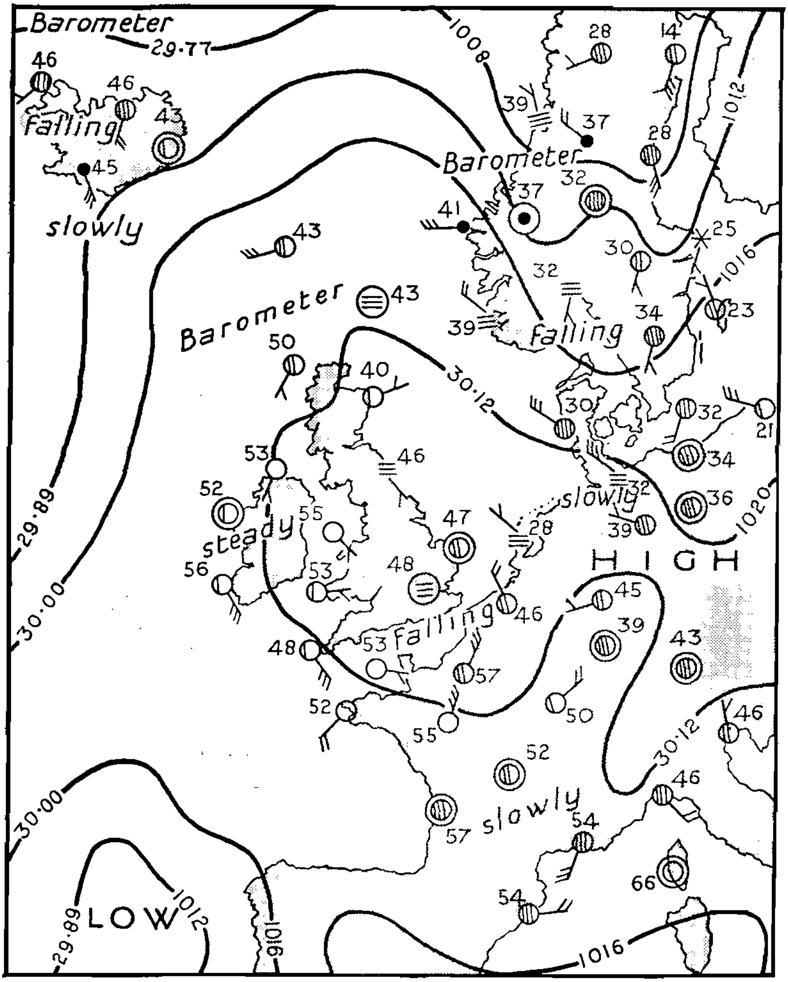


FIG. 82. March 10, 1929, 6 p.m. (For meaning of symbols, see Fig. 9, p. 33)

they become warmer and drier; clear skies, fine weather, and light winds or calms are to be expected. Such conditions do often occur. Fig. 82 shows the anticyclone of March 10, 1929, a day of fine sunny weather over the British Isles—winds light and variable, sky almost cloudless (except locally where there was fog), sunshine about 10 hours almost everywhere; day very warm for the season with maximum temperature over 65° at many stations, the night frosty inland.

Certainly it hardly ever happens that there is heavy rain or a strong wind in an anticyclone, but the weather is very variable; cloudy, overcast, and even very gloomy skies are not infrequent, and sometimes there is a persistent drizzle of fine rain—indeed some of our dullest and least attractive weather. The synoptic chart for Christmas Day 1926 (Fig. 83), shows an extensive anticyclone over the British Isles, with unusually high pressure over Scotland. But the weather was not pleasant; throughout the night and day the sky was overcast with thick and very gloomy stratus cloud, and there was occasional drizzling rain turning to ordinary rain in the evening; a cold wind from the north-east completed the cheerless conditions in the south of England.

It is often impossible to trace outflowing surface winds from the central area of large anticyclones (Shaw and Lempfert, *Life History of Surface Air Currents*, p. 24). Not very much has yet been found out about these systems. It may be suggested that the larger ones are often by no means homogeneous, but are diversified by patches of slightly lower pressure, shallow cyclones, with which the unpleasant weather is associated; such low pressures within the main high-pressure system are sometimes clearly indicated by the surface isobars (Fig. 84). In some cases the gloom is merely a surface phenomenon, above which the sky is cloudless; thus in winter dense fog often forms on land in the still central regions of anticyclones, especially in valley-bottoms. But it is only a surface layer, and a rise of even a few hundred feet may take us out of it into the bright clear air above. The unbroken pall of cloud which often continues for days is sometimes at no great height above the ground, and it is caused by the loss of heat from the ground or from

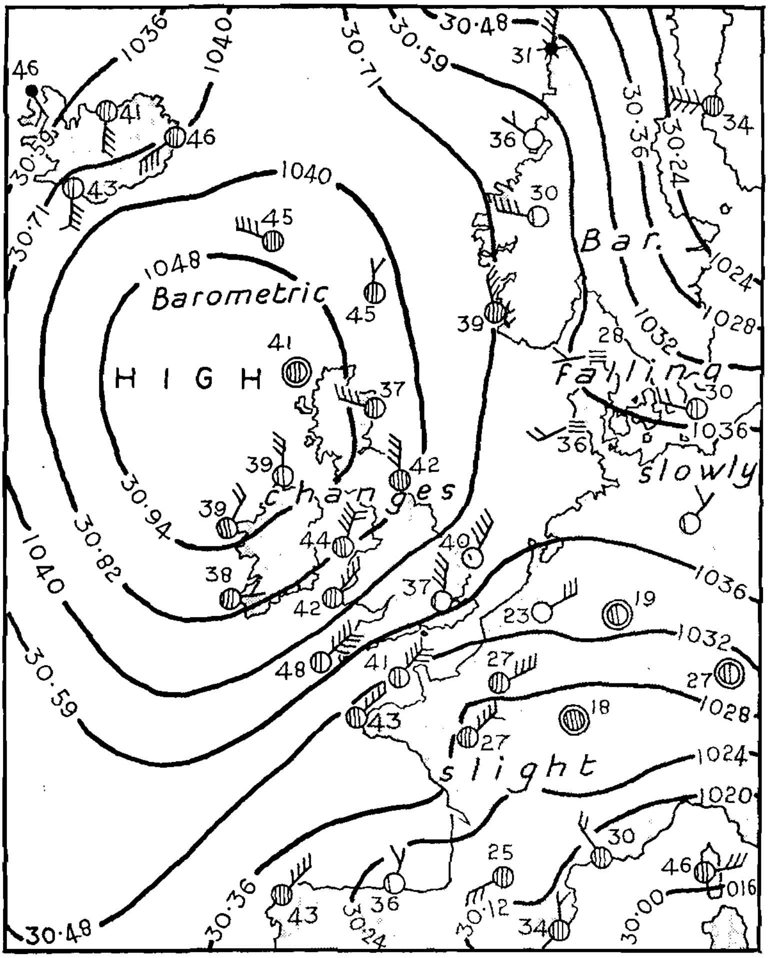


FIG. 83. December 25, 1926, 7 a.m. (For meaning of symbols, see Fig. 9, p. 33)

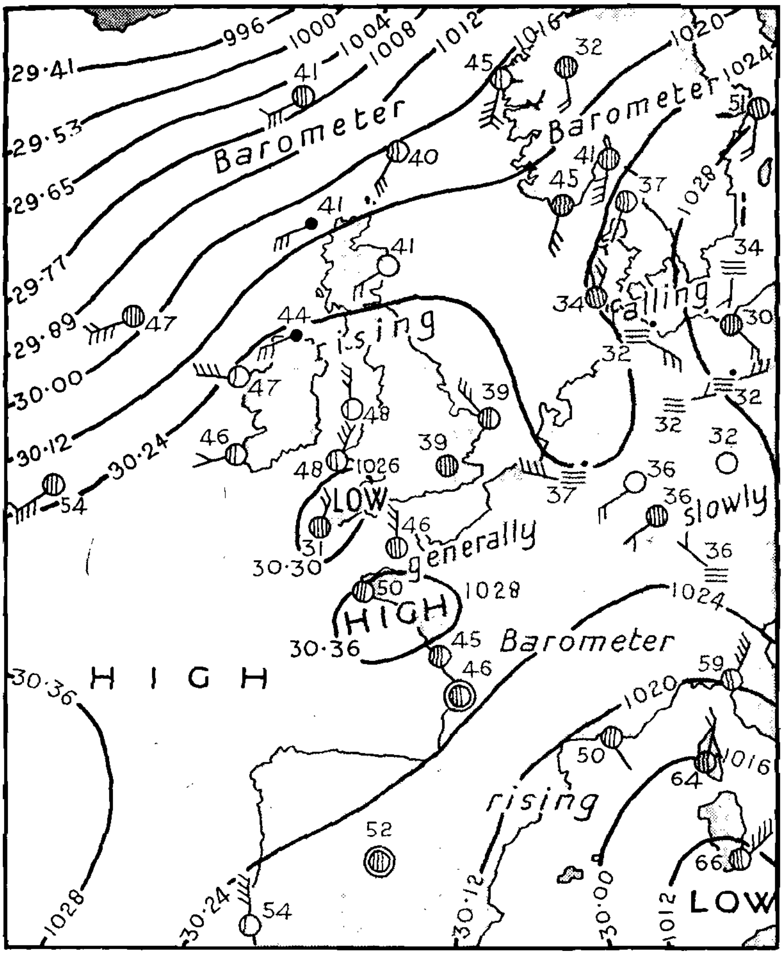


FIG. 84. November 27, 1927, 6 p.m. (For meaning of symbols, see Fig. 9. p. 33)

the cloud layer itself by radiation through the clear still atmosphere above; so that in this case the bright anticyclonic conditions which exist above are hidden on the surface of the earth by their own effects. The warming and drying of the descending air by compression is so slight, owing to the slowness of the movement, that it is often more than neutralized by other influences near the earth. Sir N. Shaw estimates the rate of descent in two anticyclones he investigated at 350 and 450 metres a day.

But it is perhaps incorrect to assume that there is any appreciable descending movement in the central part of many anticyclones. According to Shaw they often seem to consist of a more or less inert mass of air, in which local influences have free play—cooling by radiation, convection due to local heating, and even the local formation of slight rain. Many anticyclones, however, are associated with brilliant cloudless skies of such clearness that it seems necessary to assume descending currents of some velocity, in which the warming by compression is sufficient to override such effects as radiation from the surface of the earth or from strata of the atmosphere near it.

An anticyclone with clear skies favours the ingress of insolation by day, and the loss of heat from the earth by night. Thus in summer the long days are very warm, and the nights are cool. On July 15, 1929, at Renfrew, during a spell of almost cloudless anticyclonic weather over the whole of the British Isles, the temperature on the grass fell to freezing point at night, and the maximum in the screen during the day was as high as 81°. In winter the low sun cannot give much heat, and the rapid radiation through the clear air during the long nights may give very low temperatures. The intense winter cold of the interior of Asia and North America is in part due to the anticyclones which are formed over them; but the anticyclones themselves are originally due to the fact that the land masses are very cold in winter, and thus cause and effect interact. The strong tendency to dense surface fogs over damp land in autumn and winter has already been mentioned.

Anticyclones are usually sluggish and erratic in their movements, in respect both of speed and direction. Sometimes they seem to form barriers round which the main current of the westerlies is deflected. In the North Atlantic region they usually originate in the high-pressure system of the Azores, or in that of Europe, or in the high pressures of Greenland and the polar regions, and stray as rare and welcome visitors into the realm of rain and strong winds. Their uncertain movements and variable weather present serious difficulties to the weather forecaster.

There is another type of high-pressure system, the 'wedge' between two cyclones, which almost always gives very fine bright weather. It will be described in connexion with cyclones.

CHAPTER XLIII

LOW-PRESSURE SYSTEMS

Low-pressure systems are far more common than high-pressure, as is natural in a low-pressure belt; the 'permanent' Icelandic and Aleutian depressions, that are so prominent on charts of mean isobars, are really a composite picture of the numerous individual systems which move over those areas, and the same is true of the low-pressure belt of the Southern Ocean.

We apply the term 'depression' or 'low-pressure system' to a region of the atmosphere in which the pressure is lowest somewhere near the centre, and increases outward; the wind, obeying the gradient, blows inward, but suffers rotational deflection, so that it has an anticlockwise direction in the northern hemisphere, a clockwise in the southern. This, however, is only a much generalized statement, for partly owing to the fact that no cyclone is symmetrical in the direction or the steepness of the barometric gradient, partly owing to the different densities of the winds in different sectors, and for other reasons also, there are important divergences from any symmetrical arrangement of wind direction. And the weather is still less symmetrically arranged as daily experience shows. But as a rule the wind is strong, the sky cloudy, or at any rate not clear for long, and the weather unsettled to bad. In short, depressions bring us our bad weather, anticyclones our good weather, but the statement is only correct in a very general way and frequent exceptions must be expected.

The simplest and most definite form of depression is the cyclone, shown on synoptic charts by a series of nearly circular isobars. The winds blow inwards, but are strongly deflected to the right of the gradient direction in the north hemisphere, to the left in the south; at some thousand feet above the surface the winds blow parallel with the isobars. A single system may be 1,000 miles or more across, and consequently air may travel great distances under its control; polar air may reach the tropics and air from Africa or Central America may penetrate far north to the Arctic circle, the currents bringing with them the temperatures of their place of origin, modified by the surfaces over which they have travelled. In general the wind is south to south-west in the south-east sector of a cyclone in the northern hemisphere, and is warm; east to north-east and cool to cold in the north-east and north-west sectors; north to west in the south-west sector, always fresh and often cold. But the geographical environment must be allowed for; thus in winter in the centre and east of North America the northerly and westerly winds behind a depression are especially cold, for they blow from the frozen continental interior; they constitute the well-known 'cold waves' in extreme cases; in summer the winds in the front of a depression often bring enervating moist heat from the Gulf of Mexico, and are responsible for numerous cases of prostration and heat stroke in New York and other great cities.

Inside a cyclone the diminishing pressure and the convergence of the winds must tend to produce ascending currents, with consequent cooling, condensation of water-vapour, and rainfall; this will be described in more detail in Chapter XLV; for the present a general description must suffice. We are stationed on, or near, the course of the advancing cyclone. Its approach is often indicated by the falling barometer some time before there is any obvious weather change; soon the sky becomes whitish with high cirrus cloud, and often a veil of cirro-stratus gives a halo round the sun or moon. The clouds thicken with alto-

PLATE 11

The Thames in high flood near Weybridge, January 3, 1928; the result of heavy rain and melting snow, patches of which are seen on the right stratus at a lower level, and the sun shines through the grey pall as through ground glass; then still lower and thicker nimbus clouds appear, and rain begins. If the cyclone has been approaching along a path to the north of us the wind during these stages is southerly, warm and damp, but if the path is south of us the wind is easterly, cold and cheerless. In the first case the wind veers to south-west as the storm centre passes along, and at a certain stage there will probably be a sudden change in the sky—a dark threatening roll of cloud blows up, a violent squall of cold wind sweeps out of the west or north-west, and there is a sharp shower of rain, sometimes hail or snow, thunder and lightning. The squall soon passes, and the sky becomes clear; this squall and the associated phenomena occur in the 'squall line' or 'cold front' which will be explained later. If we are observing on the north side of the cyclone's track the wind backs from east to north; there are no specially interesting developments like those of the squall line, but the weather gradually clears. Behind the trough-line the barometer rises, and the hard blue skies contain only high white cumulus clouds which sometimes thicken enough to give passing showers; the air feels cool and bracing.

Such is the ordinary sequence of weather. The intensity of the rainfall and the strength of the wind depend on the intensity of the cyclone. The wind force is directly related to the steepness of the barometric gradient, the closer the isobars the stronger being the wind. The barometer and thermometer move in opposite directions during the passage of a cyclone—the pressure falling and the temperature rising as the cyclone approaches, and rising and falling respectively after its centre has passed.

A single cyclone may cover an enormous area, extending perhaps from the Mediterranean to Greenland, in all of which the weather, though very different in different sectors, and in many parts much modified by the local topography, is closely related; but most cyclones are not so large. The centre of a primary cyclone of this kind does not often cross the British Isles, its trajectory generally lying over the warm waters to the north, though the winds and weather of much of Western Europe may be controlled by it. Most of the disturbances that take a more southerly course and cross the British Isles or the Continent, are 'secondaries', a class which we must now consider. It is often to be noticed that there is a local 'bulge' in the isobars round a large cyclone. The bulge may sometimes be regarded as the resultant of a minor circular depression superposed on the outskirts of a larger system. But the secondary may be larger than this, and sometimes it attains the size and importance of a circular system complete in itself, with all the usual weather characteristics (Fig. 98a, p. 268). Secondaries may develop very rapidly without any warning, or at any rate without there being any indication that has yet been recognized with certainty. They frequently spring up off the west of the British Isles; their speed is variable, and they constitute a serious difficulty in the forecasting of weather. Some of the strongest gales and the worst weather are associated with them.

Low-pressure systems may assume very diverse forms, most of which may be considered as secondaries. Sometimes the secondary forms an elongated trough. An example is given in Fig. 85; in front of the trough, which moved slowly across our islands, there was a warm indraft from the south and very heavy rain, nearly the whole of England receiving 1 inch or more. During the previous week there had been much snow, which still lay deep when the warm winds set in, and the rapid melting of the snow reinforced the heavy rainfall to cause unusually widespread and severe floods (Plate 11).

Sometimes a linear secondary narrows southward in a V-shape, and sweeps along like a scythe; the barometric gradients are often very steep, facing each other across the line of lowest pressure. The winds in front of the advance are generally southerly, those in rear west or north-west and therefore strongly opposed in humidity and temperature, and a great disturbance results from their meeting almost head-on. The northerly wind, 'the cold front', usually advances in a violent squall of cold dry air, which owing to its density forces upward the warm south winds it meets, with the formation of a dense roll of cloud and a heavy shower of rain or snow, accompanied often by thunder and

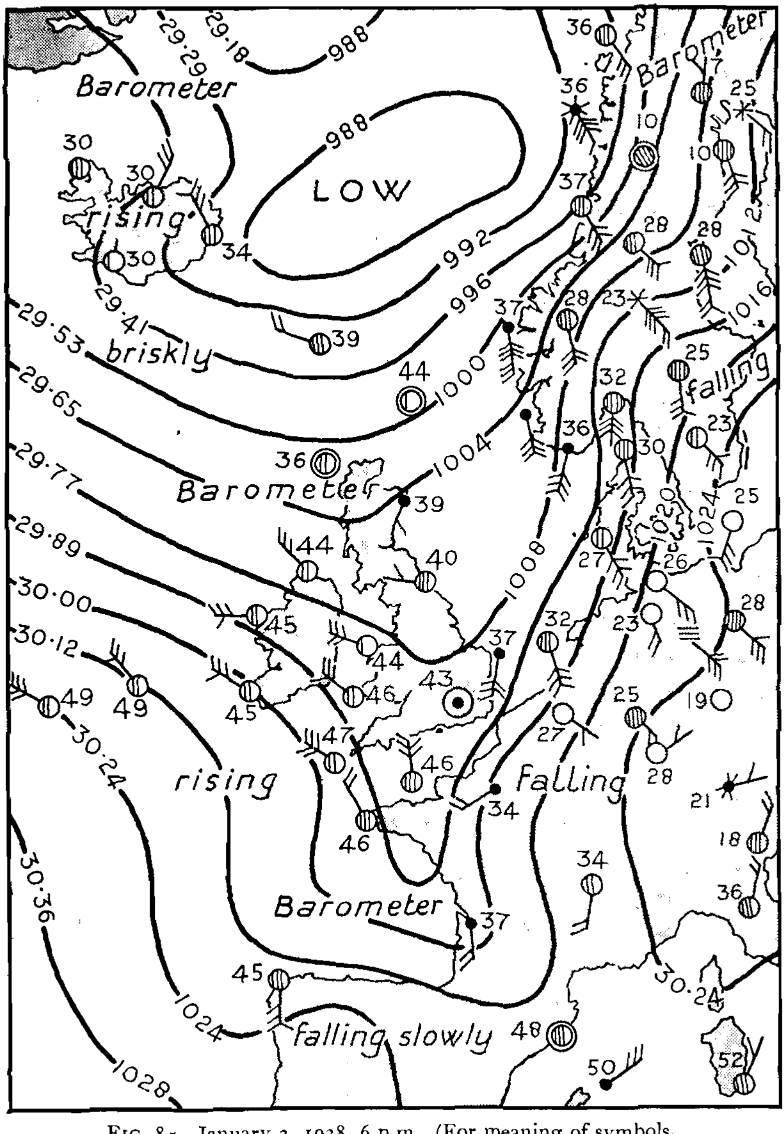


FIG. 85. January 2, 1928, 6 p.m. (For meaning of symbols, see Fig. 9, p. 33)

lightning. The violence of the storm, and the sudden change of weather and wind, is most impressive. Much havoc may be worked on land and sea. The 'Southerly Bursters' of New South Wales (p. 295) are associated with V depressions.

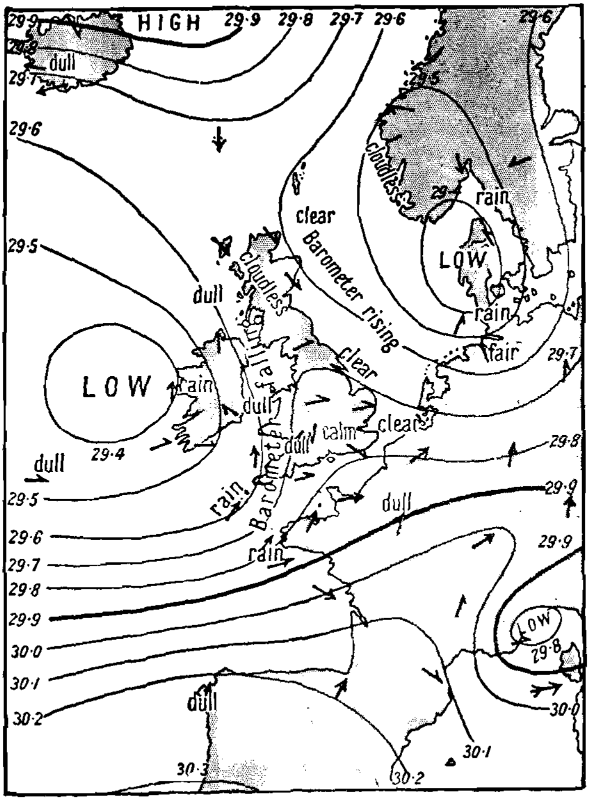


FIG. 86. March 23, 1912, 7 a.m. A wedge of high-pressure is moving across the British Isles, with fine weather and clear sky in front, clouds and rain behind

Cyclones often come up one behind the other in series of three or four or more, all somewhat similar and moving on almost the same course. Between any pair the pressure is relatively high, and sometimes there is a pronounced 'wedge' of high pressure, the point of the wedge being directed to the north (Fig. 86). From such a wedge there is an outflow of air, into the rear of the depression in front, and into the front of the new depression coming up, and therefore the air must be actively descending in the wedge itself to feed these currents. The sky is usually extremely clear, and in the central region of the wedge it is calm. Consequently there may be a sharp frost in winter and spring in such circumstances, the air being already cold owing to the northerly winds that have blown in the rear of the leading cyclone; by day the sun shines brightly and the sky is a clear deep blue. This is one of the most exhilarating types of weather the westerlies provide. But it is transient, for the wedge is essentially a rapidly moving formation, unlike the large sluggish anticyclones described in Chap. XLII.

CHAPTER XLIV

CYCLONE TRACKS

THE weather sequence at any station is closely dependent on the position in relation to the controlling cyclones, so that for the understanding and forecasting of weather it is hardly less important to know the track likely to be followed, than to know the type of weather associated with the system. In the North Atlantic region, there is a distinct tendency for cyclones to remain over the warm waters of the North Atlantic Drift. The region of lowest pressure, and of deepest and most numerous cyclones is almost coincident with the part of the Norwegian Sea where the temperature is abnormally high for the latitude. The warm water seems to be notably propitious for cyclonic growth and activity. The most frequented cyclone paths lie in a belt which lies from south-west to north-east between Britain and Iceland, and continues round the north of Scandinavia, and most of the great primary low-pressure systems follow it. But there are many other favoured tracks, and secondaries especially usually keep farther south, often crossing the British Isles, or following a course over the Channel Entries, and up the English Channel; this course is the more important in view of the weather associated with it in England (p. 264). Again there is a tendency for depressions to move from the north-west over the North Sea into Europe. The entries to the

Baltic Sea and the south part of the Baltic itself are much frequented. Many attempts have been made to map these courses as definite belts. Fig. 87 is based on the tracks plotted by Van Bebber.[1] Such maps have their uses, but a

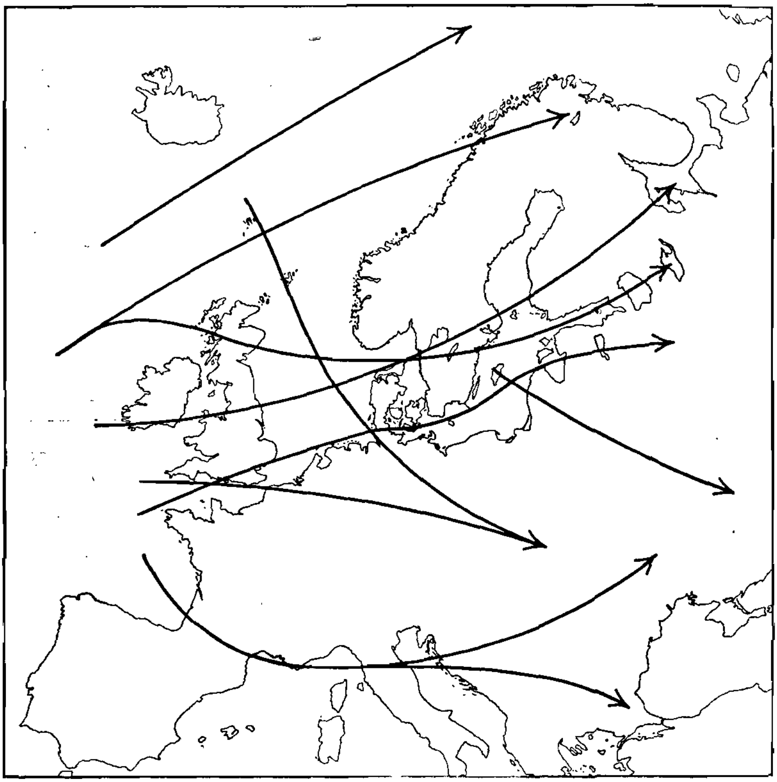


FIG. 87. Some main cyclone tracks of Europe (based on van Bebber)

glance at Fig. 88, which shows the actual courses followed in a single year in the British Isles region, shows that generalization is extremely uncertain, perhaps impossible. Probably the tracks are more erratic in this region than elsewhere. Fig. 89 gives the course of the cyclone which was responsible for the completely overcast skies and heavy rain which disappointed thousands of would-be observers of the total eclipse of the sun in the north of England on June 29, 1927.

[1] *Meteorologische Zeitschrift*, 1891.

The Mediterranean lands owe their winter weather to cyclones, many of which are derived from the North Atlantic. The cyclones are more uniform in their movements than those on the ocean, and the mean tracks shown in Fig. 90

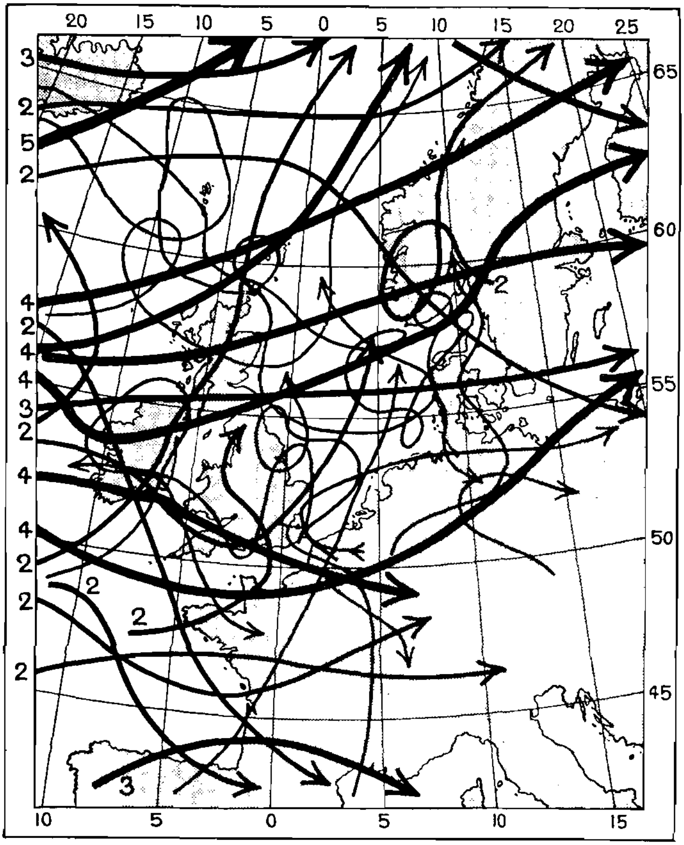


FIG. 88. Courses of depressions, 1926; the figures indicate the number of depressions following each track. (From Monthly Weather Report)

are more reliable than those of Fig. 87 for the North Atlantic. No doubt the strong contrast in temperature and humidity between land and sea is a controlling factor in localizing the depressions.

Fig. 91 gives the tracks for North America. Here also the movements are more uniform than over the North Atlantic region; especially in the east of the continent there seems to be a distinct control exerted by the surface features, the warm waters of the Gulf Stream, and the large inland waters of the Great Lakes and the St. Lawrence. The general

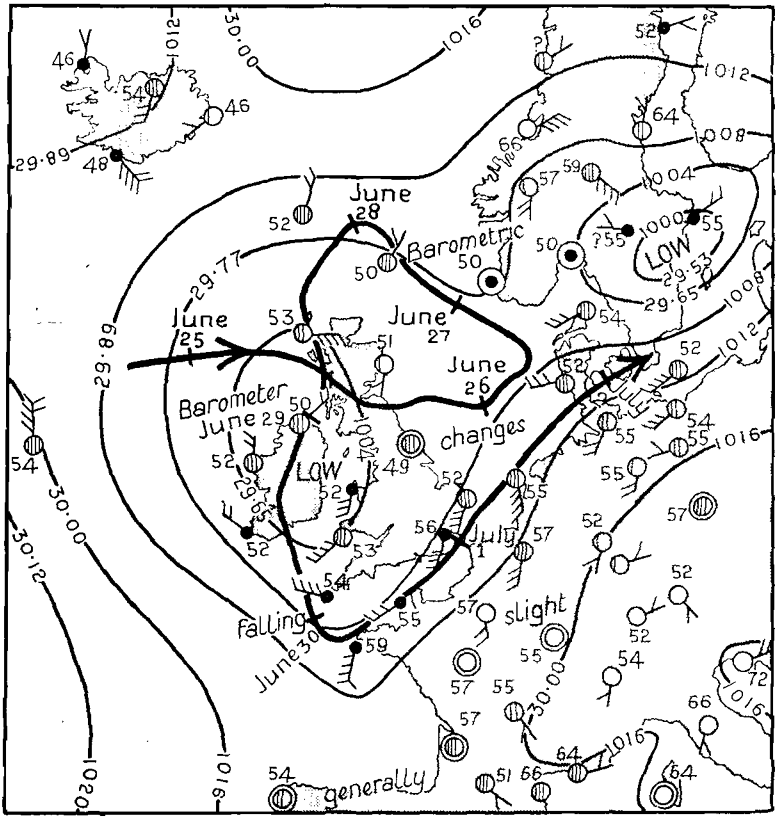


FIG. 89. June 29, 1927, 7 a.m. The heavy line shows the course of the depression, June 25–July 2. (For meaning of symbols see Fig. 9, p. 33)

weather is similar to what has been described for Europe, but the contrast in temperature between front and rear of a cyclone is often greater, since the air currents in front may come from the sultry Gulf of Mexico, and be followed, when the trough has passed, by blizzards or cold waves from the frozen north of Canada. That is the cost in weather which America has to pay for the ease of communication given her by the absence of a transverse mountain barrier.

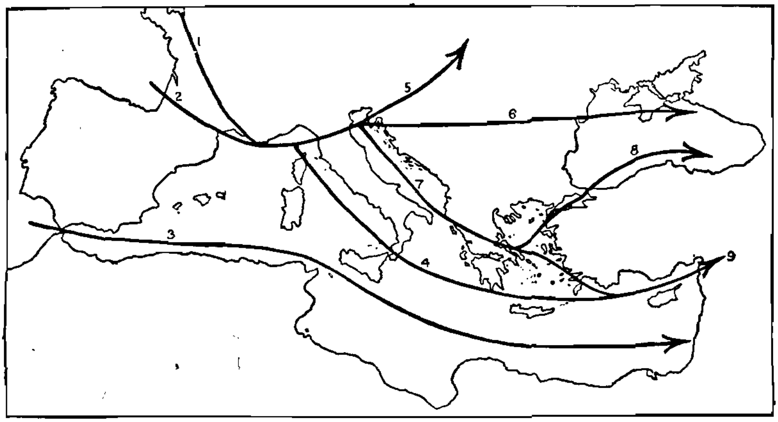


FIG. 90. Cyclone tracks of the Mediterranean region

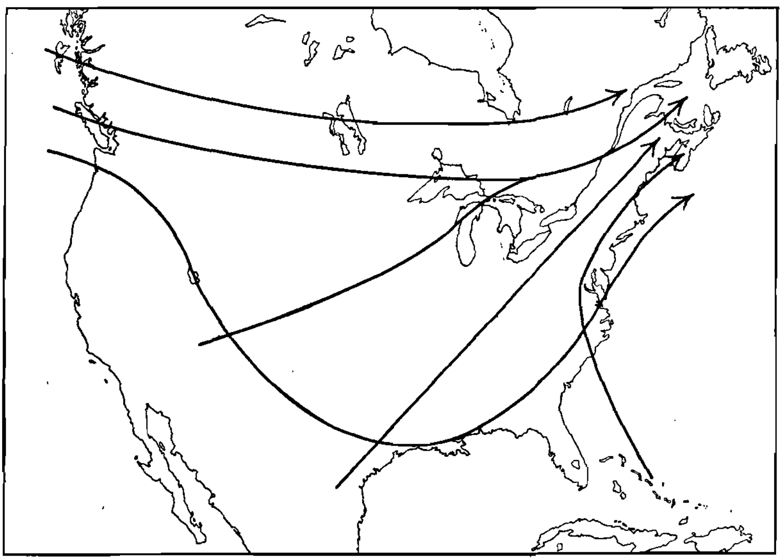


FIG. 91. Some main cyclone tracks of North America

The cold winds are felt even in Central America, the West Indies, and probably on the coast of Venezuela.

Frequently cyclones leaving the American coast can be traced day by day on our synoptic charts as they cross the Atlantic. Sometimes they advance at about the same speed as a Transatlantic liner, and the vessel may remain in the same sector of the depression and experience similar winds and weather for several days, the barometer on board remaining fairly steady. But westward-bound steamers have to plough their way in winter through one cyclone after another in rapid succession, since the speed of the ship is in this case added to that of the cyclones, and the barometer shows a

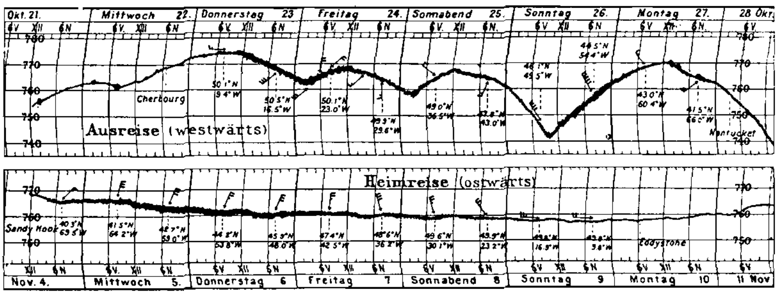


FIG. 92. Barometric pressure and winds experienced between the English Channel and New York by the SS. *Kaiser Wilhelm der Grosse* on an outward (upper diagram) and homeward (lower diagram) trip, October–November, 1902. (Schott)

series of steep rises and falls (Fig. 92). In summer the weather is sometimes fairly settled, but in winter probably the wildest tract on the surface of the globe is the ocean between Newfoundland, Scotland, and Iceland. The largest liners often have to reduce speed, and the mountainous seas may carry away boats and heavy fittings even from the upper decks.

The westerlies of the southern hemisphere are the scene of great cyclonic activity. No material exists for detailed mapping, but in view of the uniformity of the arrangement of land and sea it is likely that the cyclone centres move from west to east in fairly uniform tracks in the belt between 50° S. lat. and the Antarctic circle.

The speed with which cyclones move is very variable, especially in the northern hemisphere; a cyclone may remain stationary, or almost stationary, for several days; some advance fairly uniformly, others change their speed suddenly and erratically. The average speed may be put at from 12 to 20 miles an hour, but speeds up to 60 miles an hour are not unknown.

There is a close relationship between cyclonic activity and season. Angot gives the percentage frequency of cyclones over the North Atlantic as:

Jan. 20	Apr. 5	July 2	Oct. 6
Feb. 17	May 2	Aug. 3	Nov. 13
Mar. 11	June 2	Sept. 2	Dec. 17

But the number of cyclones, like the weather they produce, is liable to depart far from the mean.

CHAPTER XLV

THE AIR CURRENTS IN LOW-PRESSURE SYSTEMS; THE ORIGIN OF CYCLONES; TORNADOES

It is clearly impossible to form a complete conception of the movements of the air in a cyclone without considering the whole depth of the atmosphere which is affected by the disturbance. For the surface currents very many observations are available, but information about the upper strata is much less abundant; it is obtained from the movements of the clouds at different heights, by direct observation in balloons and aeroplanes, and from the self-registered records of instruments sent up with small unmanned balloons or kites. In this chapter some account is given of the surface currents only, which have a direct bearing on climate. The inward gradient round a depression gives rise to a general inward flow of air from the surrounding atmosphere. The movement may be likened to that of a crowd of people forcing their way into a small space, as from a large hall into a narrow exit; in the crowding and jostling the weaker have to give way to the stronger. So in a depression, there is strife and often violent conflict between the air currents which are crowding into the ever narrowing isobars. Compare the very different conditions in an anticyclone, where the streams are diverging and no conflicts arise.

The representation of the winds by arrows on synoptic charts gives merely an 'instantaneous photograph' of the circulation of the air. The air currents may continue for long stretches in an almost straight line (but this is rare) or their course may be sharply curved, especially near the centre of a cyclone. We should try to follow out the history of the moving air from its origin at any rate till it is lost to observation by rising above the surface, that is to say, we should trace 'the life-history of surface air currents', to use the title of a most valuable work by Shaw and Lempfert. It must be noticed that the goal of the inblowing winds is constantly moving, in the case of most cyclones, as the system advances, sometimes slowly sometimes more rapidly than the winds are blowing. The position may be likened to one in which a dog is pursuing a rabbit from some distance to one side of its course; the dog heads straight for the rabbit all the time, but, as the rabbit is itself moving, the dog's actual course is curved, the exact track depending on the relative speeds of dog and rabbit. Fig. 93, taken from the work just mentioned, gives some actual paths followed by the air under the control of a cyclone. Fig. *a* is an instantaneous picture of the cyclone, which moved rapidly, and in Figs. *b*, *c*, and *d* its trajectory across the British Isles is shown, together with the position of the centre at different hours. The lines with arrow-heads in Figs. *b*, *c*, and *d* are the paths of certain masses of air which could be recognized and traced through a series of charts with some certainty; the arrow-heads give the position of the air at the hour entered alongside them, and the position of the centre of the cyclone at the same hour can be obtained from the trajectory. Some of the air currents (A and B) reach the line of the trajectory just as the cyclonic centre arrives, and they disappear—presumably rising above the surface of the earth. Other paths describe loops, and one comes from the north-west in rear of the disturbance. For further information on this very important matter, which, however, concerns meteorology more than climatology, reference should be made to the original work.

The air currents, then, that are drawn in to an extensive depression originate in diverse regions, and differ greatly in temperature and humidity, and therefore in density. These different currents may flow alongside of each other for great distances without mixing and losing their identity, and they have sometimes been traced for thousands of miles. Currents of water behave similarly; the muddy water of a tributary may join a main river the water of which is clear, and the discontinuity between the two streams, one muddy the other clear, remains clearly visible for a considerable distance. The

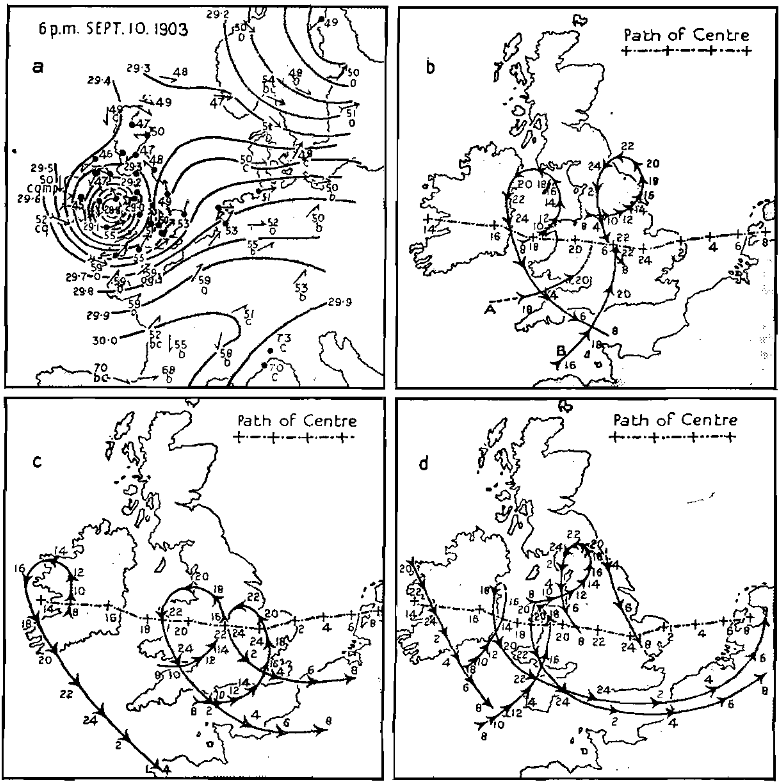


FIG. 93.

significance of such discontinuities in the atmosphere was indicated over 20 years ago by Shaw,[1] and in recent years Messrs. V. and J. Bjerknes[2] have worked out in more detail some of the results in cyclonic systems.

It should be noted that a cyclone, even one which is shown on our synoptic charts by circular isobars, is not fed

[1] e. g. *Forecasting Weather*, 1911, chap. 7.

[2] *Geofysiske Publikationer*, vol. I, No. 2, vol. II, No. 3, vol. III, No. 1, &c.

by air currents moving in on all sides at the same inclination to the isobars; still less must it be regarded as a system of air currents circulating completely round the centre; the term cyclone is misleading in this respect. In the violent cyclones of certain tropical seas, such as the Bay of Bengal, the air movement is probably circular, the air particles circling more than once round the centre in the inner parts of the

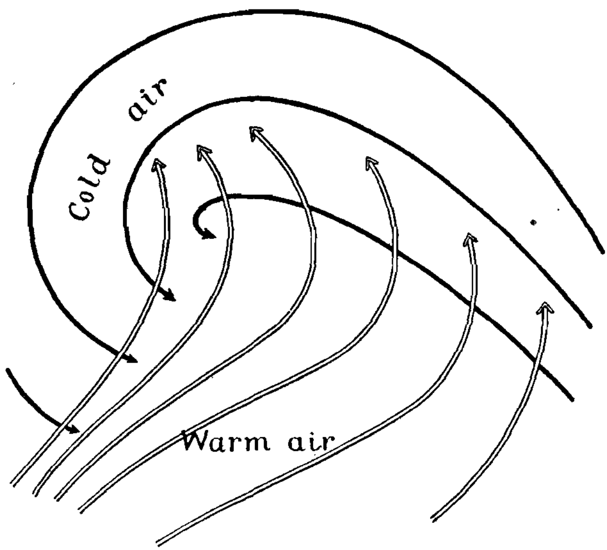


FIG. 94. After Bjerknes

whirl. But it is quite otherwise in the cyclones of temperate latitudes; here, according to Bjerknes, there are two main currents of air, which meet and interact, but maintain their identities and do not circle round the system (Fig. 94). On the north-east and north of the centre of the advancing depression the inflowing air is dense, being comparatively dry, and, in winter, cold; it is derived from the Continent (in the cyclones of the North-west European region) or from high latitudes, and is sometimes called the polar current. The south-eastern sector is occupied by the other current, which comes from the south-west and south, and consists of air which is damp and warm in all seasons, and is therefore of less density than the polar air; it may be called the tropical current. Now the advance of this latter current causes it to meet at right-angles the flank of the cold easterly current, and it has to rise over it. The cold current naturally spreads outward as a wedge under the warm air; and along the junction plane there is a certain amount of mixing through

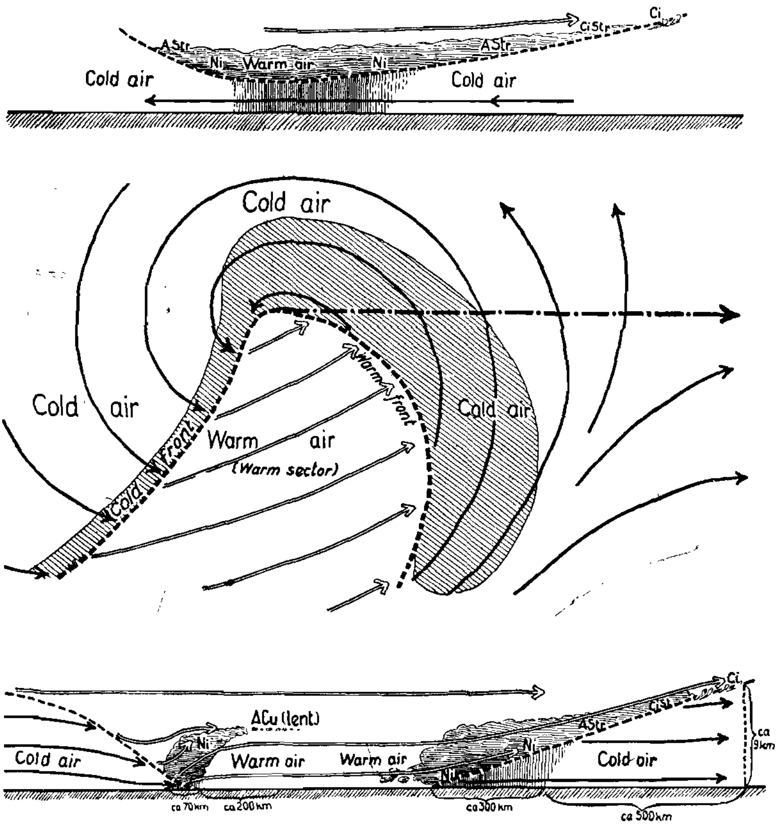


FIG. 95. After Bjerknes

turbulence. As a whole, however, the warm air, retaining its individuality, rises up the slope of the wedge of the cold current—a slope which observations have shown to be of the order of ½°—and is thus lost to the surface. But though the air has gone aloft its surface effects have by no means ceased. Ascent over the east wind barrier causes cooling, condensation of vapour, and therefore rain, which falls through the east wind below to the ground. The weather is particularly unpleasant, since the continuous, though not very heavy, rain is associated with the bleak cold of the east wind, and the sky is covered with a uniform pall of cloud; such weather may continue unchanged for 24 hours or more (Fig. 94). A considerable part of the ordinary 'cyclonic' rain is of this type, falling with an east wind on the left side of the cyclone's path. The east wind itself is often dry; Shaw mentions a striking instance in which there was a spell of rain which lasted with few breaks for some days; the wind remained east or north-east and the relative humidity of the air was about 90 per cent.; but during one of the breaks in the rain the humidity fell to 35 per cent., which shows that the east wind itself was dry, except when rain was falling through it from the southerly current above.

To illustrate the conditions for east-wind rain we take the night of December 27–8, 1928 (Fig. 96), when a shallow secondary passed up the English Channel, with easterly winds in the south of England, and a temperature under 40°; on the south side of the path there were southerly winds with a temperature as high as 50°. There was heavy precipitation with the east winds in the south of England, an inch at some stations, and the day was cold and raw, with gloomy overcast skies; the precipitation fell as rain in and south of the Thames valley, but in the midlands, where the temperature was lower, it was snow.

The discontinuity where the southerly current meets the easterly is known as the warm front. But before the warm air reaches that line it has been undergoing lateral compression in the narrowing space between the westerly winds on its west side and the easterly and south-easterly winds on the east. Hence the air tends to rise, with the formation of cloud and some rain. The gradually diminishing pressure as the air moves inward also conduces to condensation of vapour. These southerly winds in front of cyclones give the damp muggy weather which is commonly associated with the approach of a cyclone, and frequently there is heavy and persistent rain.

The rear of the depression remains to be considered. Any or all of at least three wind currents may be present. There may be a north wind which has come from high latitudes and is therefore justly called a polar current; it will bring low temperatures but generally fine weather. There may be a current which has come from the west, the actual wind direction near the cyclone being north-west; this is a cool

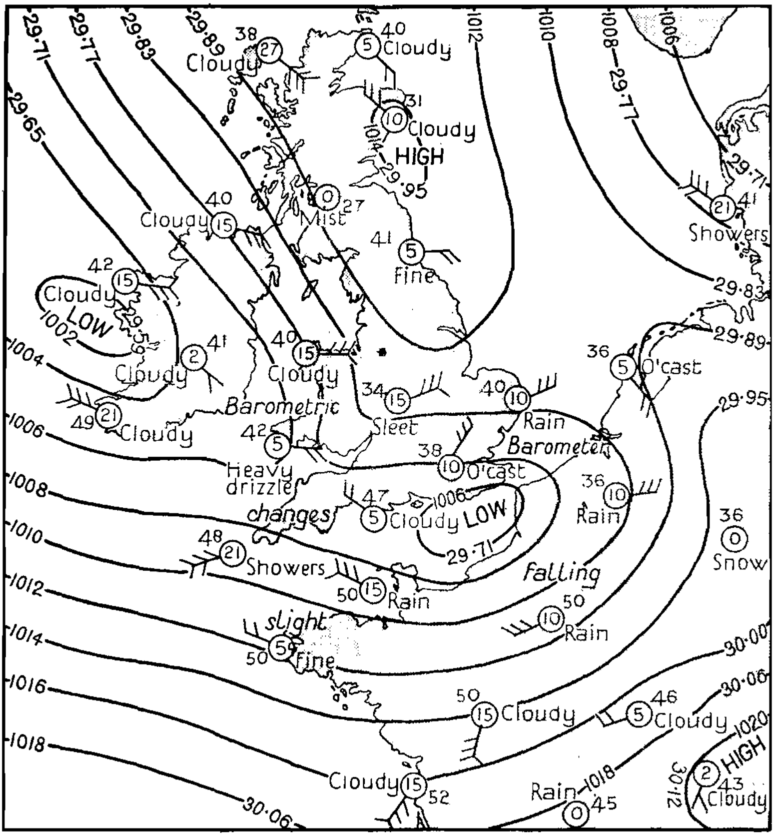


FIG. 96. December 28, 1928, 7 a.m. The numbers inside the circles denote wind velocity in miles per hour, those alongside the circles, the air temperature

wind, but not so cold as the polar current. Or the wind may be a continuation of the east winds of the front, which blow round the north of the cyclone, and then southward in its rear, and sometimes back towards the east on the south side.

The exact course of these winds in the rear, and especially the part played by the easterly current, depends largely on the relative speeds of the disturbance as a whole and the winds themselves. In many cases at any rate the east wind

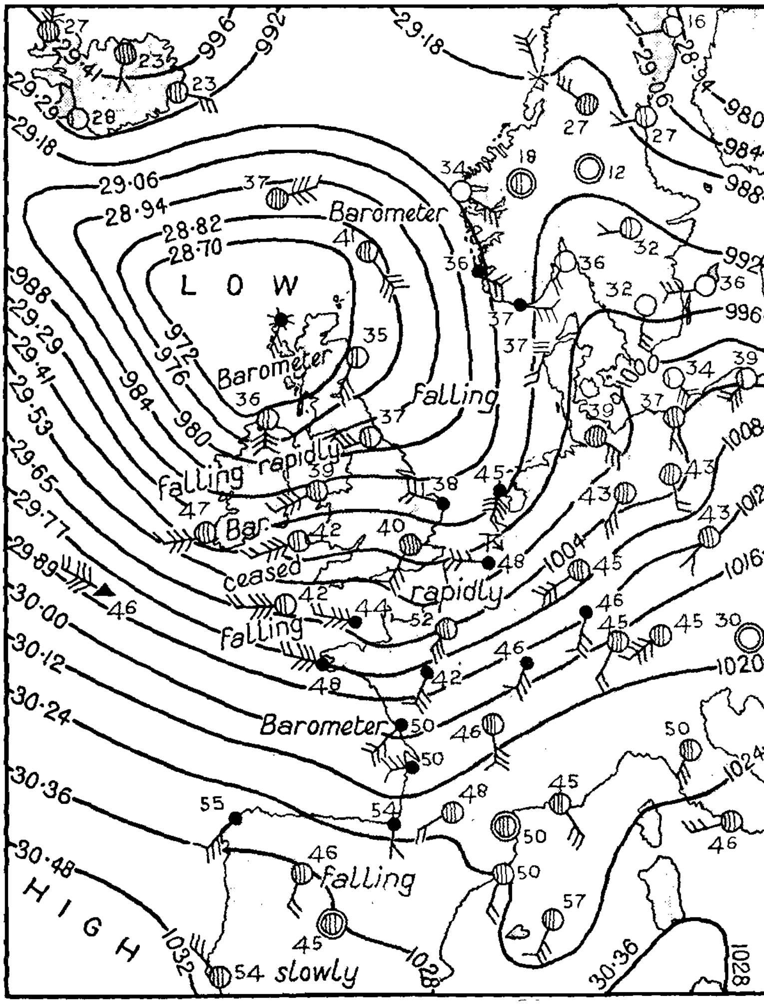


FIG. 97*a*. February 10, 1928, 6 p.m.

curves round in rear of the depression, and overtakes it on its south side as a west wind, a 'cold front', which attacks the south winds of the warm sector in *flank*; the warm damp southerly air is forced upward by the undercutting wedge of west winds (the cold front is advancing more rapidly than the cyclone), and the ascent is often so violent that rolls of dense black cloud are formed, and give smart downpours of rain, often with hail and thunder and lightning; the rain falls in showers, not continuously, and showers tend to occur more or less simultaneously along the line of discontinuity of the cold front, a line which sweeps onward with the cyclone's advance. These are the 'clearing showers', welcome, in spite of their intensity, as indicating the arrival of the dry polar air and clear skies. The surface wind suddenly swings round from south to west or north-west. After a while the cold front sweeps right across the warm sector, the warm air is removed from the surface, its ascent causing steady general rain and the first and most active stage in the cyclone's life is past.

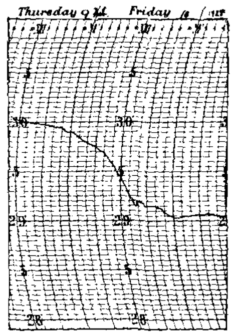


FIG. 97*b*. Barogram.

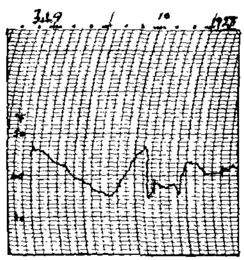


FIG. 97*c*. Thermogram, Radcliffe Observatory, Oxford, February 9–10, 1928,

A good example of a cold front (or line squall) occurred on February 10, 1928, when a large and deep depression crossed the British Isles (Fig. 97). The line squall where the westerly winds behind the depression overtook and undercut the southerly winds in front advanced across the south of England. In the midlands the early afternoon was overcast and mild, wind south-west, with light rain. Suddenly about 3 p.m. a dark cloud appeared on the western horizon, and advanced rapidly. As it approached, a violent squall of cold wind blew up from WNW., a downpour of heavy rain started and the temperature fell decidedly; within a few minutes the rain gave place to snow, forming a mid-winter snow-scene. The barometer showed a sudden rise. Hail and thunder and lightning were reported from many places. The belt in which these violent phenomena occurred lay roughly north-south, and it was easily recognizable as it

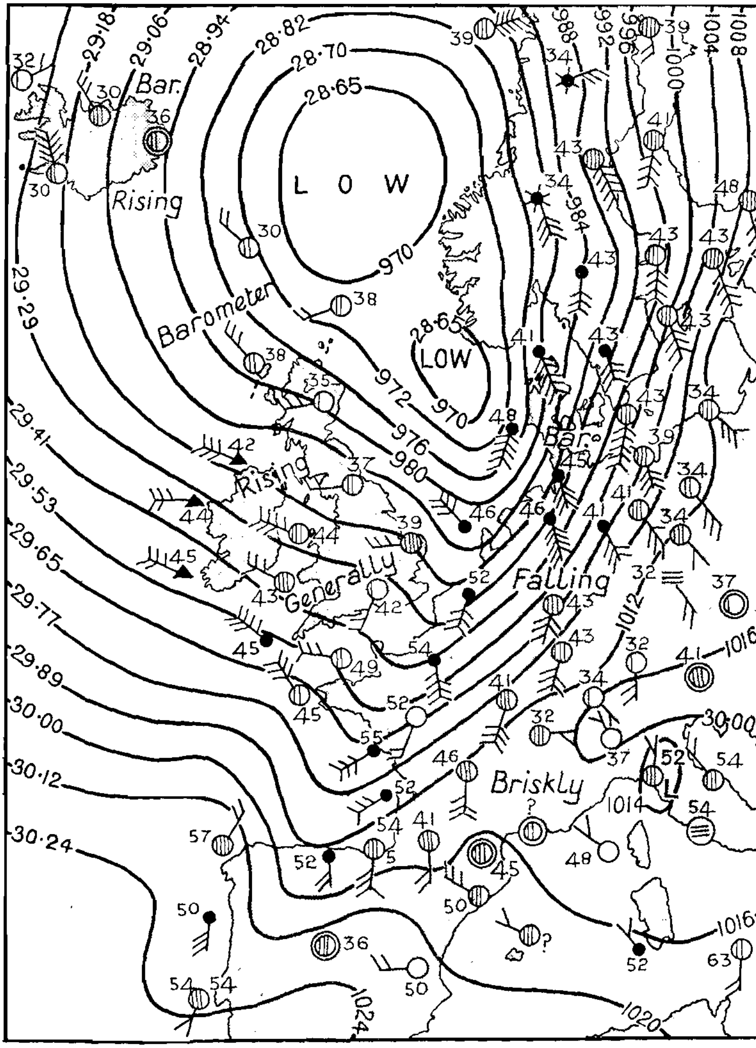


FIG. 98*a*. November 12, 1929, 7 a.m.

swept across from the west to London. At Valencia the wind blew at 83 m.p.h. in gusts, and gale-force was reported all along the south coasts. By 4.30 p.m. the squall reached

London, where the temperature fell 10° in a few minutes. November 12, 1929, 1 a.m. (Fig. 98*a*, *b*, *c* and *d*) is another striking example. With the arrival of the cold front of a vigorous depression the wind veered quite suddenly from SSW. to NNW. and fell from about 40 to 25 m.p.h., and

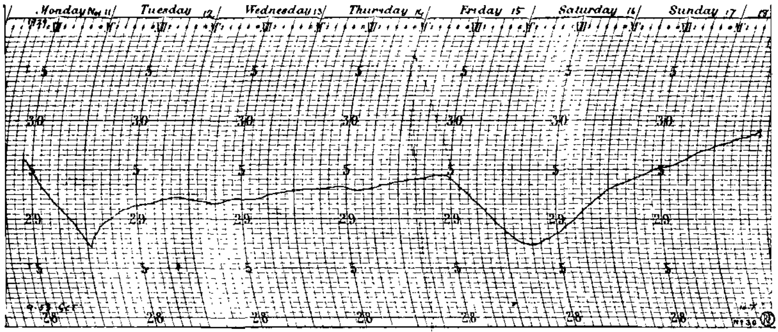


FIG. 98*b*. Barometric Pressure at Radcliffe Observatory, Oxford

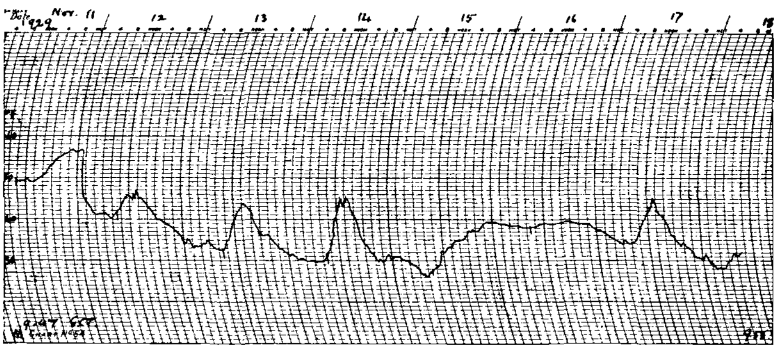


FIG. 98*c*. Temperature at Radcliffe Observatory, Oxford

there was a very heavy shower of rain and hail. The temperature fell 15°, most of the drop being almost instantaneous. The passage of the cold front from west to east was very clearly marked right across the south of the British Isles; it was recorded at Scilly at 10.50 p.m. and at Felixstowe at 3 a.m. The synoptic chart (Fig. 98, a) shows the trough, in which the cold front was developed, over the North Sea and the Bay of Biscay at 7 a.m. on the morning after it had crossed our islands.

It is found that cyclones which have a warm sector move in the direction of the isobars in that sector at the time (a direction which is by no means constant) and at a speed approximately that of the warm current. As long as the warm air remains on the surface of the earth the system moves rapidly, but when it is removed by the spread of the polar air under it, the system slows down and may become stationary.

The important feature in this theory of air movement in cyclones is the stress laid on discontinuities. Along the line of contact of two currents there must be a certain amount of mixing through turbulence, but the change of temperature at the warm front is pronounced and sudden enough to be very noticeable. Still more prominent in the British Isles is the sudden drop in temperature at the cold front, the passage of which is often signalized by a sudden upward jerk in the barograph trace, caused by the increase of air pressure along the line where the cold wedge is forced under the warm air, so that the mass of air is suddenly though temporarily increased. The discontinuities should be visible on synoptic charts in slight but sharp bends in the isobars, but as a rule these do not appear, since the observing stations are too far apart to indicate with precision the local conditions, and also the phenomenon may be entirely missed at the regular observing hours. But a comparison of barograph traces at different stations often shows clearly the passage of a cold front across the country, and personal observation at a single station, interpreted by reference to the daily synoptic charts, soon provides many clear examples proving the reality of discontinuities. The understanding observer may often detect discontinuities, without the aid of instruments, in the long dark and sharply defined edge of a cloud against blue sky or against some other cloud layer. Such cloud edges can often be traced moving right across the sky with little internal change. The dark rolls of cloud in a line squall indicate discontinuities unmistakably.

But it must be admitted that soundings of the upper air are by no means always convincing; the discontinuities being rarely sharply marked. One reason for this is that it is in the early stage, during the growth of a cyclone, that the separate

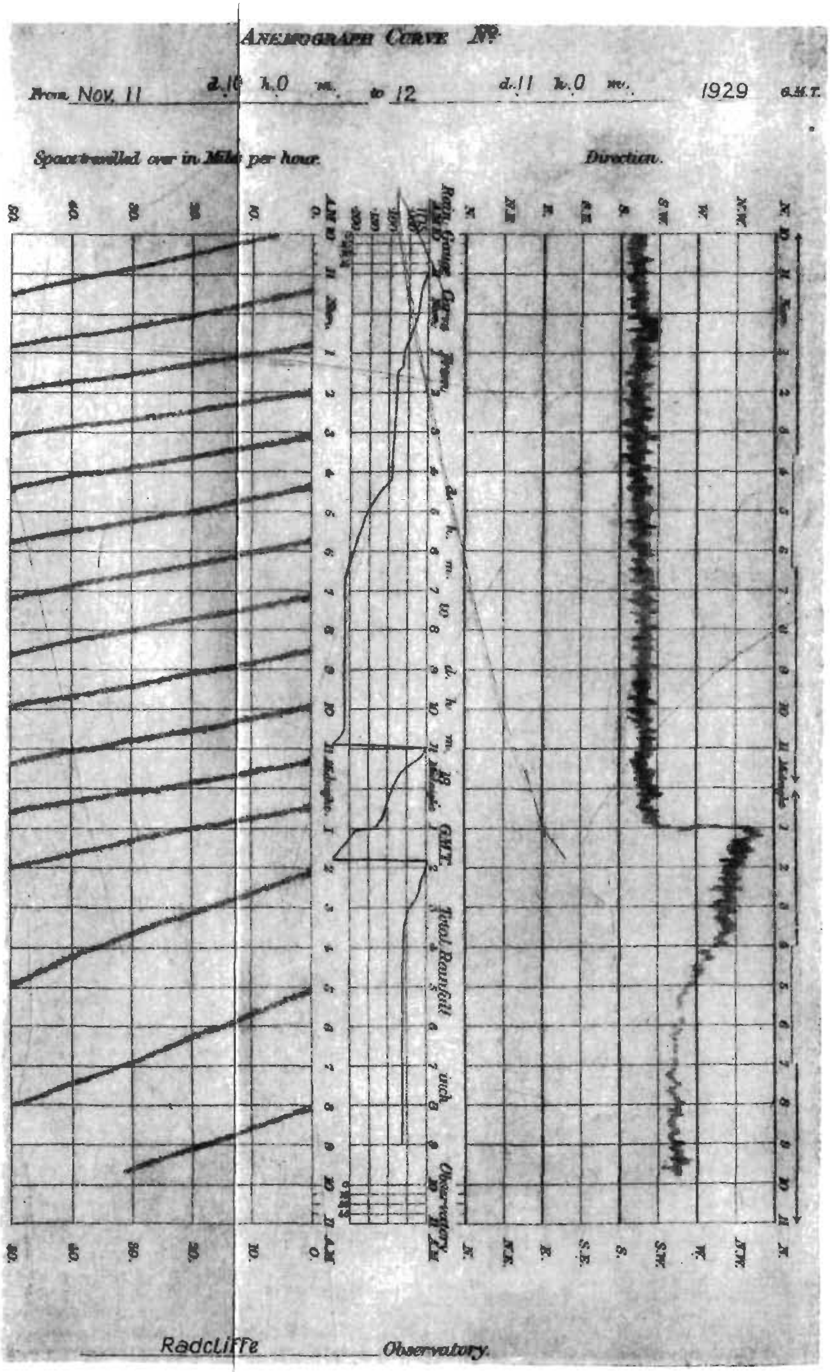


Fig. 98 *d*. Rainfall, and direction and speed of wind, November 11–12, 1929; Radcliffe Observatory, Oxford air currents are likely to be most sharply differentiated; mixing is bound to increase as the movements continue. But cyclones usually form over the ocean, and no upper air observations are available. The British Isles, where many upper air soundings are taken, are not often crossed by the sectors concerned. Scandinavia is more favourably situated, and observations made there seem to be more in accord with what theory expects.

The origin of Cyclones

This is a topic not only of great theoretical interest but also of fundamental importance for the weather forecaster. The oldest view, that a cyclone springs up where the surface of the earth is abnormally warm, according to the simple thermal theory of pressure changes, was soon seen to be untenable; no such local excess of heat could be traced where a cyclone originated, the local temperature differences that exist are rarely great enough to produce the pressure differences observed, and soundings have shown that as a whole in the troposphere a cyclone is colder, not warmer, than the mean.

Perturbations in the upper atmosphere, the precise cause of which is unknown, are believed by some meteorologists to be communicated to the lower strata, and intensified there, resulting in our cyclones, which are thus regarded as secondary features of the general circulation of the atmosphere, deriving their own internal forces from it.

The views on the structure of cyclones which have been stated in this chapter imply that the direct cause of the phenomena observed is the interaction of two currents of air, the polar and the tropical. The local pressure changes are rather the result than the cause of the air movement. The low-pressure zone of the westerlies is bounded on the south by the sub-tropical high-pressure systems of warm air, containing much vapour, and on the north by the polar high-pressure systems of cold dry air. Streams of tropical and polar air meet in the low-pressure area, the line of separation being called by Bjerknes the 'polar front'. The low-pressure zone as a whole must be assumed for the purpose of this theory to exist; the causes of its existence have been considered on p. 80. The interaction of the great outbursts of tropical and polar air along the polar front gives rise to the smaller low-pressure systems which we call cyclones. It must be noted that the terms tropical and polar do not refer necessarily to immediate origin at the tropics or poles, but rather to the directions, temperatures and humidities of the air. Thus the floods of cold continental air from the winter anticyclones over North America and Asia, constituting the 'cold waves' of the United States and the bitterly cold winter winds of north China, may be said to be polar currents. This view of their origin explains the striking fact that cyclones of the type we are considering occur only in the westerlies; no other zone is bounded by a reservoir of cold air on one side, and warm air on the other. If it is correct, the climate of the most civilized parts of the earth is largely the result of the comparatively feeble high pressures that form over the Arctic and Greenland. Antarctica has a more stable and intense high-pressure cap throughout the year, which would explain the greater vigour all the year round of the cyclones of the westerlies of the south hemisphere. Cyclonic activity is greatest in winter, when there is the greatest temperature difference between the polar regions and the sub-tropics. And certainly there is a marked tendency for cyclones to develop or deepen in regions of strong temperature contrast, as off Newfoundland, to the south-west of Iceland, and in the neighbourhood of Japan.

But it is easy to indicate many serious omissions in the theory. In particular, one obvious feature of every cyclone is the low pressure, which can only be accounted for by the removal of air. Shaw calculates that in a large depression centred over the North Atlantic in lat. 50° N. on January 31, 1926, over 2 million million tons of air must have been removed to account for the reduction in pressure as observed on the earth. Clearly no theory of cyclones can be complete unless it gives some explanation of the cause of the transference of these enormous masses of air, and of the means by which it is accomplished. Furthermore, not infrequently synoptic charts show warm and cold currents in such juxtaposition as, according to Bjerknes's theory, ought apparently to give rise to a rapidly deepening depression, and yet that result does not follow. At other times cyclones are found to go on deepening after the polar air has spread round the south of the centre and raised the warm sector from the ground. The theory throws much light on the surface air movements in many cyclones, but it certainly does not seem to provide an explanation of the genesis of all depressions.

It seems probable that various causes give rise to depressions and anticyclones, and that no one cause can be adduced to cover all cases. Some cyclones are deep, some shallow; some large, some small; some are of vigorous activity, others almost inert; some advance quickly on a definite course, others tend to hang or move erratically. It is likely that such different results are due to different processes.

Tornadoes

In Chapter XXIX it is pointed out that the south-east sector of cyclones is often the scene of thunderstorms. It is here also that tornadoes are specially likely to occur—not the tornadoes of the equatorial belt (p. 87), but the very different phenomena with the same name that are only too frequent visitations in the east and central parts of the United States, especially the central valleys, and are not uncommon in Europe, Australia, and elsewhere; a recent example is the tornado that devastated parts of Holland on June 1, 1927; there was a belt about 100 yards wide in which the destruction was complete.

Tornadoes are probably the most violent and, in their narrow zone of full activity, the most destructive, of all storms. They are whirls of wind, with a diameter usually not exceeding a mile; the wind has little strength in the outer zone, but it increases very rapidly towards the centre, and in the 'core', which may be less than a quarter of a mile across, the violence is astounding, the speed of the wind being estimated to reach even 300 miles an hour at times (Plate 13). The damage done to life and property is almost inconceivable, and some of the reports would be incredible were they not vouched for by reliable observers. Heavy objects, sheds, carts, tables, planks, cattle, horses, human beings are lifted and carried sometimes for more than a mile. Not only is there a horizontal movement of the wind, but also a vertical, in the powerful updraft in the funnel of the vortex. And additional damage is done by the low pressure inside the funnel caused by the centrifugal force in the rapidly revolving column; as the vortex comes up, the sudden diminution of pressure causes an explosive effect in closed or semi-closed places such as houses, which burst outwards; bottles are uncorked, and birds have been known to lose all their feathers. The barograph trace shows a very sudden drop and rise, forming a sharp V; sometimes the sides of the V are so close that they appear as a single

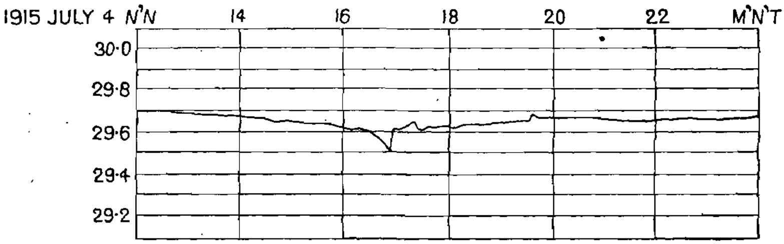


FIG. 99. Barogram of a Tornado (16 H. 45 M.)

vertical line. In the British Isles tornadoes are rare. Fig. 99 gives the barogram from the path of a tornado that passed from the Cotswolds down part of the Upper Thames Valley, without, however, doing much damage; a violent thunderstorm was associated with the disturbance, which was the more striking as the weather was quite fine before and after it. The limits of the belt of destruction are quite sharply marked; of two houses only 20 or 30 yards apart one may be completely wrecked, the other quite undamaged. The tornado advances on its path at a speed of about 20 miles an hour, but it dies away before it has travelled 30 miles. The black clouds usually give heavy rain with thunder and lightning. The objects that are sucked up from the earth are sometimes seen by observers outside the track, whirling round in the funnel, and finally flung out from its upper part. Sometimes the tornado funnel does not reach the ground, and no damage is done as it passes overhead.

In some respects tornadoes resemble thunderstorms. They almost all occur, as secondary features, in the south-east sector of the ordinary cyclones of the westerlies, and there are often several in the same tract of country on the same day. They are essentially land phenomena. Their season is spring and early summer, and they are confined to the hottest hours of the day. The interior of the United States offers specially favourable conditions for their development owing to that fundamental fact in the geography of North America, the absence of a transverse mountain barrier, which allows cold currents of air from the north to meet warm and humid southerly currents from the Gulf of Mexico. And when the instability which results from their juxtaposition is increased by the local heating of the ground under the early summer sun, both tornadoes and thunderstorms result from the violent convectional overturning. There are about 50 tornadoes a year on the average in the United States.

Dust devils and waterspouts may be classed with tornadoes in that they are essentially revolving columns of air, the one over arid lands, the other over water. But they are of much less violence.

CHAPTER XLVI

SOME TYPES OF BRITISH WEATHER

Snowstorms

Snow consists of particles of frozen water-vapour which have condensed at a temperature below freezing-point. Fig. 100 shows a typical pressure distribution for snow over England. A small depression approached from the Channel Entries, and travelled slowly eastward up the channel and over north France. The wind was easterly over England, at a temperature a little below freezing-point, and there was heavy precipitation (see p. 263). The moisture was brought by the southerly wind on the south-east of the depression, and, on meeting the barrier of dense air in the easterly current, it had to rise, and its temperature was soon reduced below freezing-point. The frozen precipitation fell through the cold east wind, and a depth of 6 inches of snow was general,

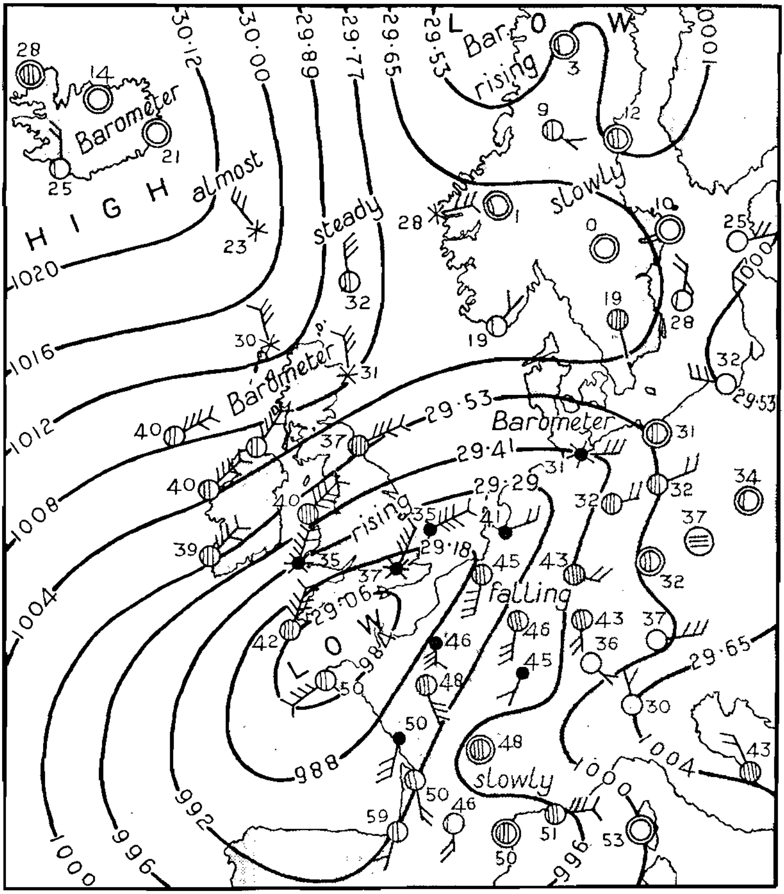


FIG. 100. December 5, 1927, 6 p.m. Heavy snow in the south of England. (For meaning of symbols see Fig. 9, p. 33)

with drifts several feet deep. Many places were isolated for days owing to the snowing up of roads, and supplies for the unfortunate inhabitants had to be sent by aeroplane. The snow was heaviest in the south of England, near the centre of the depression. In general there is most snow when the air in which the condensation takes place is not much below freezing-point; very cold air cannot contain enough water-vapour to yield very much precipitation.

Fig. 108, p. 287 shows a secondary over the south-west of

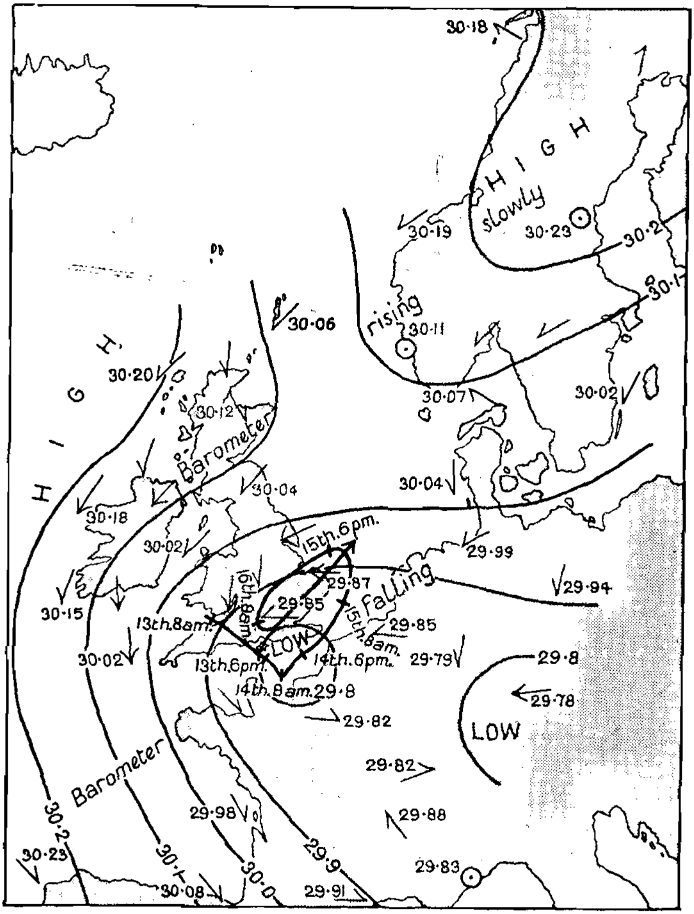


FIG. 101. June 14, 1903, 7 a.m. Long continued rain over south-east England. The thick arrow shows the course of the depression

Britain which brought heavy snow to Devon and Somerset, Wales and the Welsh Border counties.

Gales

Fig. 105, p. 285, shows the conditions that gave a violent south-west gale round the British coasts. The cyclone is deep, and the closeness of the isobars indicates a very steep barometric gradient. The essential feature for gales is closeness of isobars, representing a steep gradient, and it may be found in various circumstances. A large depression may be centred over the North Atlantic, and the British Isles may be crossed by the close isobars of its south-east sector; gales may then prevail over hundreds of miles of land and sea at the same time. More usually the centre of the cyclone that is responsible crosses the British Isles; and perhaps most frequently of all, the disturbance that is the direct cause is a secondary to some large disturbance over the Icelandic region; such secondaries often appear suddenly in an intense form, and move so rapidly that the gale arrives almost as soon as the official warning can be received. There is a tendency for the disturbance to be followed by others similar to it following a similar course.

Long spells of Rain

Fig. 101 shows the cyclone that gave a continuous spell of probably 72 hours of rain over much of the south of England; the rain fell on the left side of the cyclone's track, and owing to the curious circular track the rainy sector lay over the southern midlands for 3 days, during which the rain never ceased. The rainfall at Oxford was 3·63 inches, and the widespread floods in the Thames Valley reached almost the highest levels ever recorded.

Such long unbroken spells are very rare. The usual form of rainy spell, lasting perhaps for a fortnight, is due to a series of cyclones, the finer weather between them being merely temporary interruptions in the rain. An instance of this type of rainy spell occurred between November 10 and 23, 1928, and it is described later in this chapter.

Spring Showers

Spring showers have become proverbial. They are frequently caused not so much by any definite type of pressure distribution as by local convection, the land being heated under the rapidly increasing heat of the sun, while the higher atmosphere is still cold. They often develop in the rear of a cyclone. Owing to the low temperature of the higher atmosphere, and the vigorous convection currents that may be set up, there is a tendency for the showers to be in the form of snow. The transformation is not uncommon from the bright sunshine and blue sky of an April day to inky black

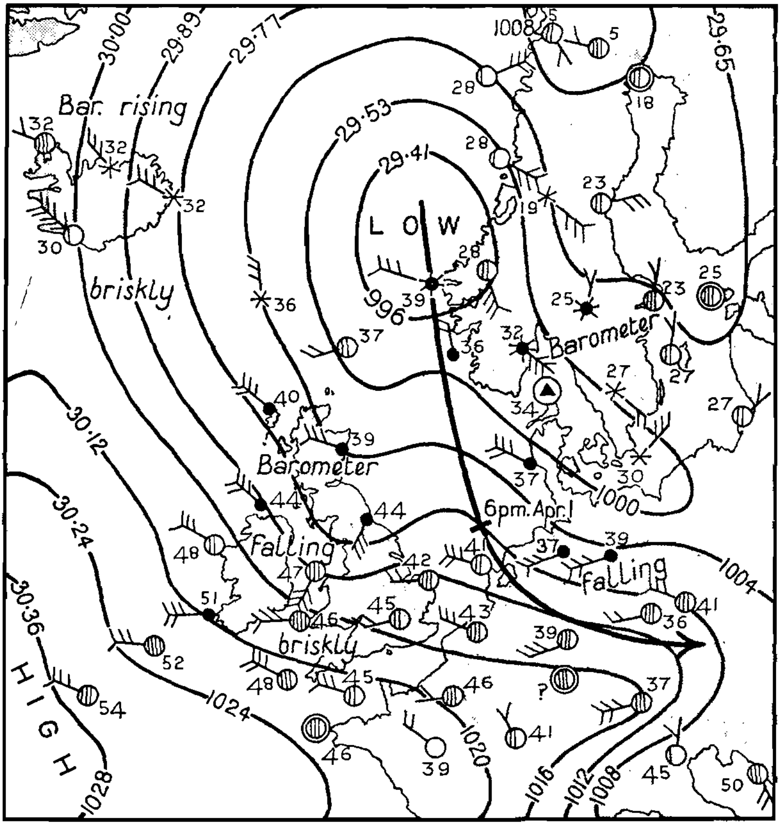


FIG. 102. April 1, 1929, 7 a.m. Spring showers. The thick arrow shows the course of the depression. (For the meaning of symbols, see Fig. 9, p. 33)

clouds, which roll up from the north-west, and in a few minutes spread a white mantle over the landscape. Line-squalls sometimes give similar weather in a more intense form. After a short time, perhaps half an hour, the clouds are past and sunshine returns.

Fig. 102 illustrates a more unpleasant type, rather frequent in the spring months. Secondary depressions move southward over the North Sea, and the east of Great Britain especially comes under their influence. The wind is between north-west and north-east, the weather cold and windy, and cold rain or snow showers fall from black overcast skies as each depression passes. Between the showers there is often strong sunshine, the wind is fresh, and the clear air gives unusually good visibility. These exhilarating intervals are the more welcome by contrast with the showers.

North-east Winds

Fig. 103 illustrates a frequent type, which gives dry, cold, and piercing north-east winds in spring; the sky, however, is often cloudless, and it may be quite warm in the sunshine if we are sheltered from the wind. This north-easterly type is less pleasant when, as is sometimes the case, the sky is overcast with stratus cloud throughout the spell. The north-east winds are valuable in drying up the land after the floods of winter, so that it can be worked in readiness for sowing. The weather is anticyclonic, and frequently continues with little change for several days, or even for two or three weeks. Spring is the only season when the prevailing winds in the British Isles are not definitely westerly; there are stations on the east coast where the dominant direction in April is east, and in most parts easterlies are among the most frequent winds.

Cold Spells

It was pointed out in Part II that cold may be produced locally, by loss of heat at times when the conditions favour rapid radiation, or it may be imported with cold winds. The former process is not so effective as the latter in the British Isles, since the land area is small, and anticyclones (it is in anticyclones that continued radiation weather is to be expected) are not likely to remain for long undisturbed on the edge of the stormy Atlantic Ocean. Our longest and most severe spells of cold are imported from the north of Central Europe. February 1929 provides an example. Throughout the whole of that month, and during the first half of March, a remarkably large and intense anticyclone covered Central Europe and Scandinavia, and gave abnormally cold weather there (Fig. 108, p. 287). The great rivers, including the Rhine and the Danube, were thickly frozen over throughout almost the whole of their courses, the south and west of the Baltic Sea was ice-bound (in addition to the north and east where shipping is normally

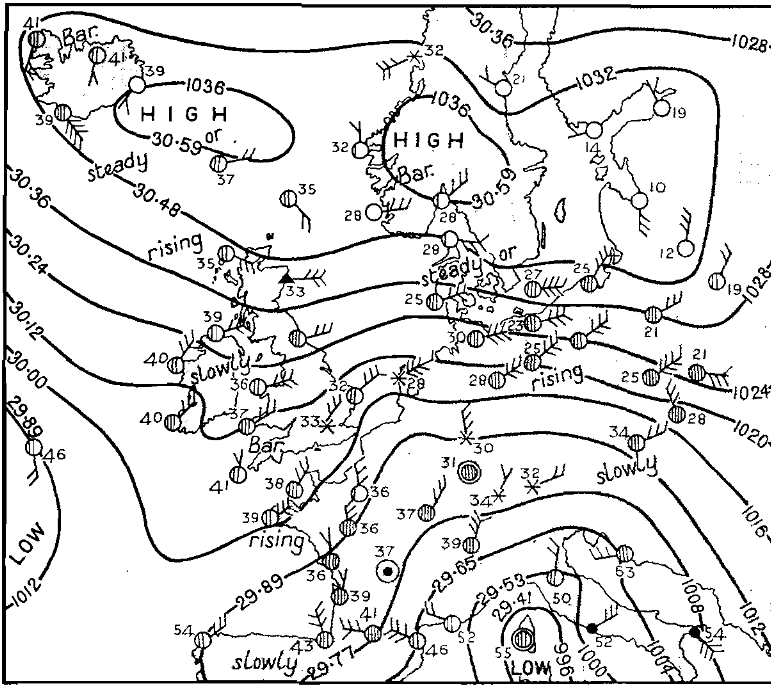


FIG. 103. March 10, 1928, 6 p.m. Cold north-east winds. (For the meaning of symbols, see Fig. 9, p. 33)

interrupted in winter), and heavy snow-storms held up the Constantinople express for several days in Turkey. In its early stages the anticyclone did not affect the weather of the British Isles, which was under the control of Atlantic cyclones. But on February 11 a slight alteration in the position of the isobars caused easterly winds to reach us, bringing the cold from Germany and Scandinavia. This was the beginning of a cold spell which lasted till the beginning of March, and it was maintained by the flood of cold wind, which kept the temperature low, not only at night but also by day. In the east of Kent the temperature remained below freezing-point for 226 hours continuously. It was the cold days and the long duration of the cold spell that were notable,

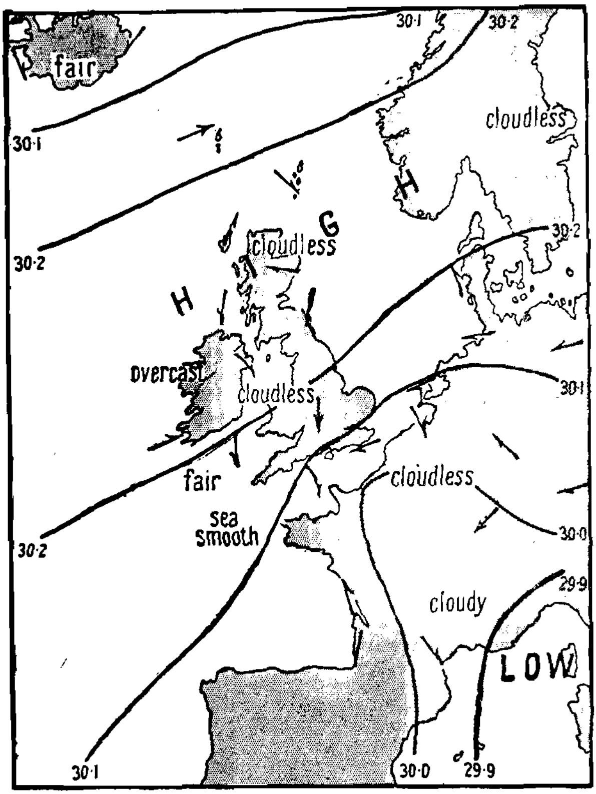


FIG. 104. August 10, 1911, 6 p.m. A high-pressure system giving abnormal heat in summer

rather than any remarkably low minima; but Ross-on-Wye recorded an air temperature of -1°. Practically the whole of the British Isles was frost-bound from February 11 for 5 weeks, with a short break; the Thames was frozen over in many parts. The continental anticyclone varied little, and the winds reached us directly from it, their direction being east, north-east, or south-east. The spell ended with the advance of an anticyclone from the Continent over the British Isles.

The weather became calm and beautifully fine, and though the nights were still almost as cold as before, the bright sunshine by day (it was now the middle of March) warmed the air, and there was a high range of temperature.

Most of the longest cold spells have been due to the continuance of a stream of cold air from an extensive continental anticyclone, as in the case just described. Less intense spells may be caused by an anticyclone stationed over the British Isles giving clear radiation weather; under such conditions in December and January the loss of heat by night more than balances the gain by day, but in February the sun-power is increasing fast, and the warm days make up for the cold nights.

An anticyclone lying to the north of the British Isles and giving north and north-east winds, may cause a spell of considerable cold, but as a rule such winds have travelled too far over the ocean to reach us at a very low temperature, and keen frost is not likely, though the temperature may feel unpleasantly low; there is a strong tendency for such weather to persist.

Great Heat

The general conditions favouring great heat in summer have been explained (p. 38). On August 10, 1911 (Fig. 104) the temperature was the highest ever recorded in much of Western Europe. A great belt of high pressure gave clear and cloudless skies, and the almost uniform pressure favoured very calm air even in the hottest hours of the day. The upper strata of the atmosphere were probably abnormally warm, so that no vigorous convection circulation was set up. The maximum temperature at Greenwich was 100°, at Oxford 93°, at Paris 100°.

CHAPTER XLVII

SPELLS OF WEATHER

THE high- and low-pressure systems may be said to be the smallest units which control our weather, each of the depressions operating for not more than 3 or 4 days as a rule, the anticyclones for rather longer. But weather types have a pronounced tendency to recur; one cyclone is followed by another similar to it and following the same track, and sometimes five or six may form a connected series. The weather changes are repeated with each cyclone, the 'spell' lasting perhaps for a fortnight. Then quite suddenly the sequence is broken, and a different type of weather sets in. Such spells may be regarded as weather units of the second order. It is at the time of change of spells of this kind that forecasts usually fail. As long as any series continues the forecaster's task is comparatively easy, and even empirical rules may guide him. But to forecast the change from one type to another calls for a deeper knowledge of the movements of the atmosphere than we yet possess.

As an instance of a long-continued spell of one weather type, and as showing the difficulty of forecasting a change of type, we take the period November 10–30, 1928. At the beginning the weather was cyclonic, with warm south-west winds, cloudy skies, and rain at intervals. The cyclonic activity became greater as the days passed, and the centres passed nearer the British Isles, until on Thursday November 15 the first serious gale was experienced in the English Channel. It was made memorable by the capsizing of the Rye lifeboat with the loss of 17 hands. On the previous morning at 9.50 the official forecast for south-east England was 'south-west winds, light to moderate to-day, freshening to-morrow'. But, shortly after, there were indications that a vigorous disturbance was rapidly approaching the north of Ireland, and at 1.45 p.m. the south cone was hoisted in English Channel ports to give warning that a southerly gale was expected. The gale blew up during the night, and the Rye lifeboat had gone to help a vessel in distress off Dungeness when the disaster occurred. The following day,

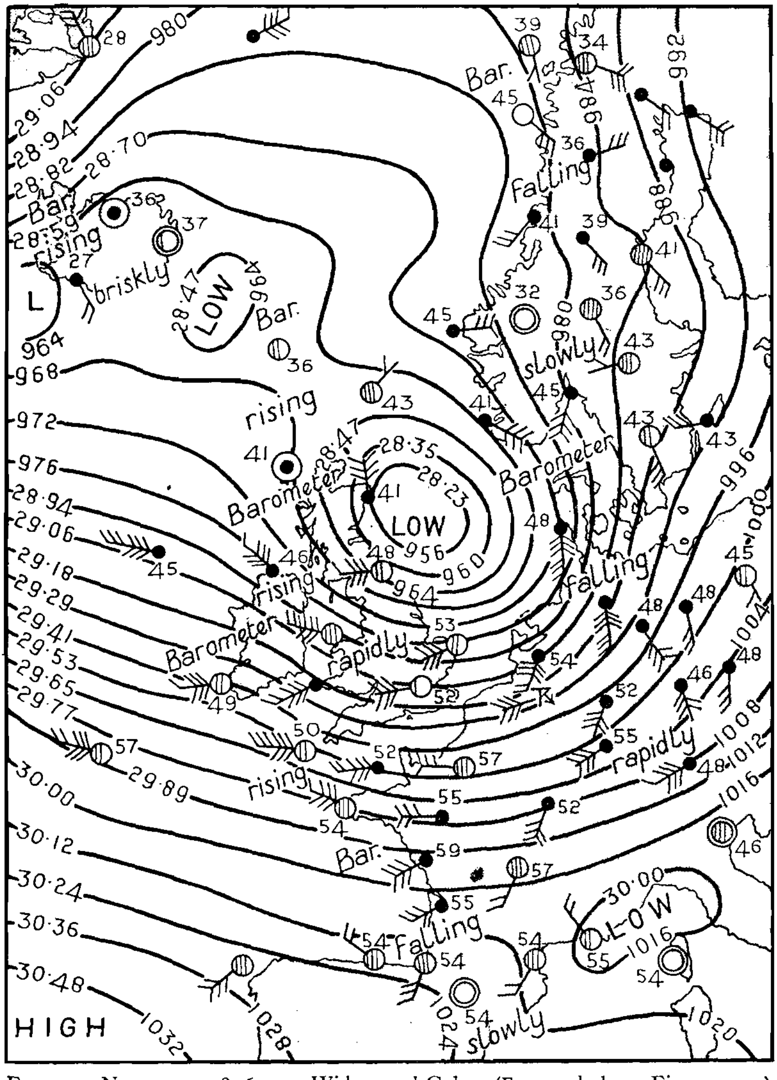


FIG. 105. Nov. 23, 1928, 6 p.m. Widespread Gales. (For symbols see Fig. 9, p. 33)

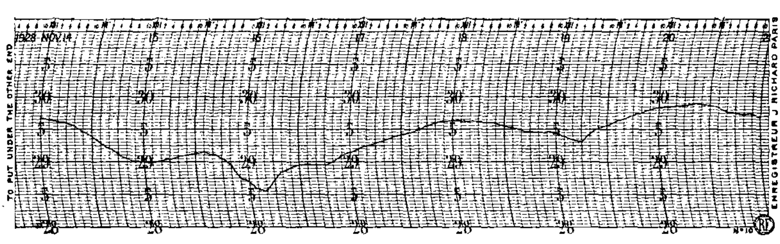


FIG. 106. Barogram. November 14–21, 1928, Oxford

Friday, November 16, was even more boisterous. An intense secondary disturbance moved rapidly from the west and crossed the British Isles, causing widespread south-westerly gales in the southern districts. Gusts of over 90 miles an hour were registered, 280 telephone lines were blown down, and very much other damage was done both

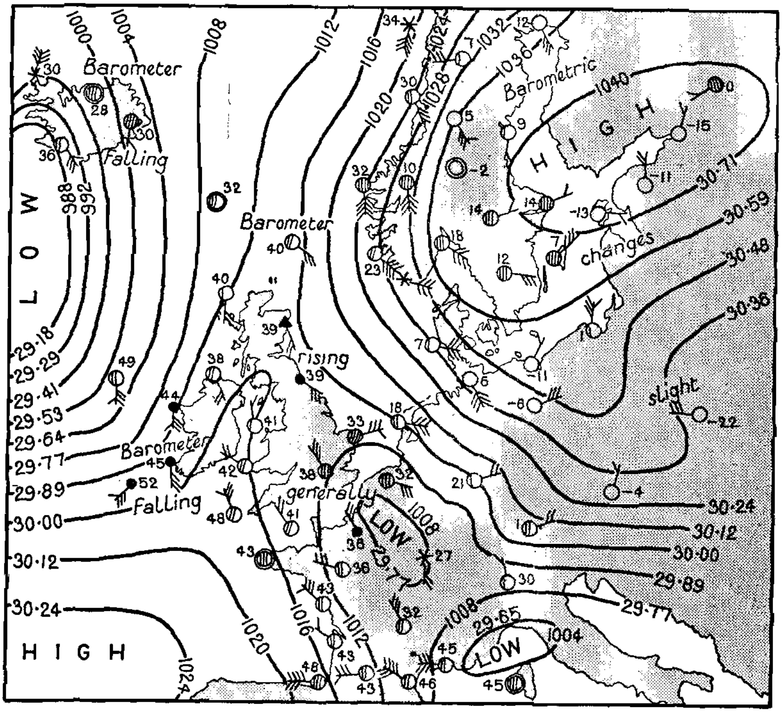


FIG. 107. February 10, 1929, 6 p.m. (For meaning of symbols, see Fig. 9, p. 33)

on land and sea; the cross-channel services had to be suspended. In rear of the cyclone the weather became fair temporarily, but other disturbances approached, and for the next few days there was an alternation of storm and fine weather. On Thursday, November 22, the official general inference was 'unsettled weather, strong westerly winds reaching gale force at times'. Early the following morning the expected gale arrived. A deep depression crossed central Scotland (Fig. 105). The wind reached 88 miles an hour at Liverpool and again much damage was done; again the cross-channel packets were unable to run.

From the 10th till the 23rd the same general type of weather had persisted, as is well shown by the barograph

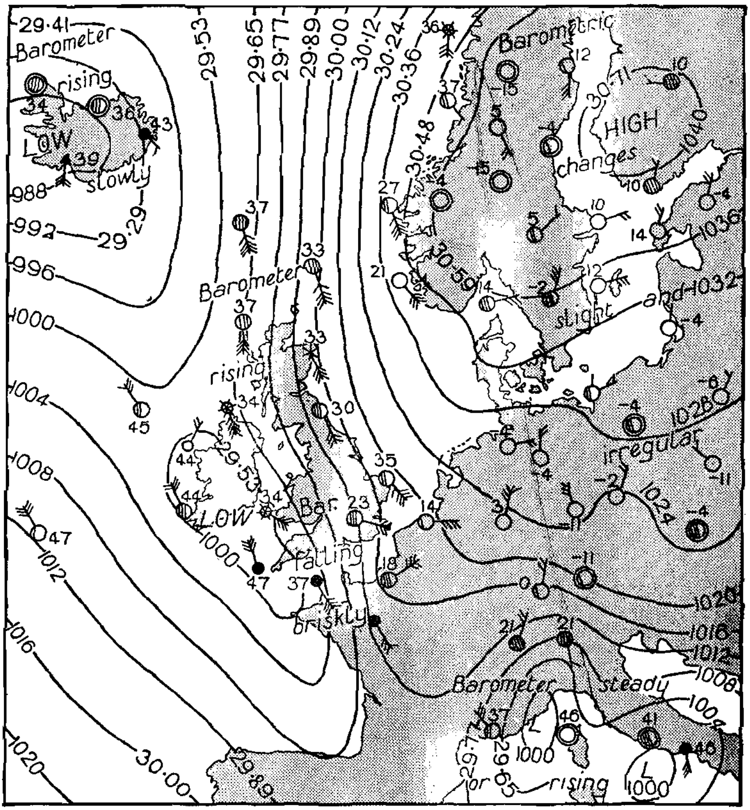


FIG. 108. February 11, 1929, 6 p.m. (For meaning of symbols, see Fig. 9, p. 33)

trace (Fig. 106). After the gale of the 23rd, pressure rose over the British Isles, as it had done after the previous disturbances, and the weather became fair. But this was thought to be merely another temporary interruption in the series of cyclones, and on Sunday morning, November 25, the official inference was 'conditions remain favourable for the approach of further depressions from the Atlantic'. Again on the same evening we were told 'A new depression is approaching Ireland from the Atlantic. After a temporary improvement winds will again back to south-west and freshen to gale force'; and on the following day 'a renewal of gales generally is to be expected'. Thus it was confidently expected that the same type of weather which had prevailed for the past fortnight would continue. But, instead, the Azores anticyclone began to extend towards the north-east, and by Tuesday, November 27, it covered the Atlantic as far north as Iceland; light northerly winds brought generally fair and cool weather to the British Isles—a complete change from the earlier south-westerly cyclonic type. The new type continued for several days.

For another type of failure of forecast we may refer to Figs. 107, 108. On the evening of February 10, 1929, it was rather colder than normal in England, with northerly winds. The wedge of high pressure shown in Fig. 106 over the Irish Sea was expected to move east or north-east, and to be followed by 'a secondary now off south-west Ireland; and weather over the British Isles will be unsettled generally, with rain in most districts and a moderate temperature'. South and south-west winds were forecasted, with some rain for the whole of the British Isles. But a minor modification in the general pressure distribution produced very different weather from this (Fig. 107). An intense anticyclone which had covered northern Europe for several days dominated the weather in the east of the British Isles, and the secondary in the west moved slowly south-east. There was bitterly cold, cloudy weather, with very strong winds, almost throughout the country—indeed the bleakest and coldest weather physiologically for several years. In the south-east the air was dry as well as cold owing to the nearness of the Continent. Wales, and the West Country generally, were under the influence of the secondary, and there were very heavy falls of snow. Thus on this occasion only a slight change in the run of the isobars led to south-easterly continental winds, dry and cold, instead of the expected oceanic winds which would have been mild and moist. It was the beginning of a remarkable cold spell which lasted for over a month (p. 280).

Sometimes an abnormal type of weather may persist with little variation throughout a whole season, which may be unusually rainy or dry or cold or hot. Probably the most practically useful application of meteorology would be in forecasting such seasonal types—long-range forecasting. At present this is not practicable, though interesting lines of investigation have been pointed out.

Periodicity in Weather

Abnormalities in weather depend directly on variations in the general circulation of the atmosphere, that is in the distribution of pressure, and 'spells' of weather are due to the persistence of such abnormalities. In the north-west European region sometimes the cyclone tracks are displaced northward of their normal position, and the Azores anticyclone spreads, giving us fine weather; sometimes the continental anticyclone dominates our weather, this being a frequent cause of abnormally cold winters. Again the cyclone tracks may lie farther south than usual, and the British Isles are subject to wet and stormy conditions, mild in winter, cold in summer. Such displacements may affect only a small area, or a large part of the globe. They may persist for a week or two, or for a season. Possibly the immediate cause of the great glacial periods was a change of the same type persisting for thousands of years.

It is tempting to try to establish some definite periodicity in these changes, to discover cycles of a duration of some years, or pulsations covering centuries. The necessary basis for the quest is provided by the numerous series of instrumental records, some of which go back for over 100 years—the rainfall record at Padua starts in 1725—and for the more distant past by such self-registered natural phenomena as the growth-rings in trees of great age, especially the sequoias of the Sierra Nevada, California, in which 3,000 years of growth can be traced,[1] and the beaches which mark the past levels of lakes.[2] The works of man also contribute evidence; there are remains of deserted settlements in the

[1] *Climatic Cycles and Tree Growth*—Douglass (Washington).

[2] See *The Climatic Factor as illustrated in Arid America*—Ellsworth Huntington (Washington) also, *Climate through the Ages*—Brooks (London).

deserts of Central Asia, and the abandonment may have been due to a decrease in the rainfall on which their agriculture depended. In the case of Yucatan[1] it is suggested that the Maya civilization was overwhelmed by an increase in the rainfall causing the tropical forest to run riot, so that man gave up his unequal struggle against its encroachment.

The evidence, and especially its interpretation, in these latter cases is uncertain. The actual records of temperature and rainfall provide more solid material, and mathematical analysis has discovered a large number of cycles with periods ranging from months to many years; Shaw tabulates some 130, ranging from 1 to 260 years in his *Manual of Meteorology*, Vol. II, ch. vii. Their very number is one great difficulty in using cycles as a guide to the future course of the weather. Another is the fact that even the best-marked cycles do not recur with unfailing regularity and precision; the cold and dry part of a cycle may be interrupted by warm wet years, and a severe winter or a fine summer may break the succession of seasons of the opposite type in another part of the cycle. Many cycles seem to have continued for a long period, and then suddenly to have changed their phase or died out. To add to all these and other uncertainties sundry sporadic phenomena are liable to supervene and have considerable influence on the weather—a great volcanic eruption may throw so much dust into the atmosphere that the temperature is lowered all over the globe; there may be changes in the level of the land, or in the distribution of land and sea, and this may lead to important changes in the ocean currents which exercise a most important influence on climate. We must remember, too, that changes in any one region must have consequential effects, direct and indirect, on the rest of the atmosphere. It can be readily understood, then, that 'cycles' are of little if any value for the practical forecasting of seasonal weather.

For examples of well-established cycles we may mention first that of approximately 35 years which was worked out by Brückner[2] from the available evidence of changes in the

[1] See *The Climatic Factor as Illustrated in Arid America*—Ellsworth Huntington (Washington).

[2] Brückner—*Klimaschwankungen seit* 1700 (Vienna).

surface level of the Caspian Sea, advances and retreats of the glaciers of the Alps, and other phenomena, and was found to apply to many aspects of life remarkably closely. Of the reality of this cycle there seems to be little doubt, though even it is of little use for practical forecasting. On it is based the usual choice of 35 years as the period required to give true mean values of weather phenomena. It is difficult to see what is the underlying cause of the cycle; probably it is merely a resultant of many other cycles.

The 11-year cycle of sunspot frequency seems to be clearly reflected in the weather in many parts of the world, though not in North-west Europe. A short cycle of $12\frac{1}{3}$ months is found by Brunt[1] to be recognizable in Western Europe.

Another fascinating study in the variation of meteorological elements is the correlation of the variations, whether simultaneous or consecutive, in different parts of the globe. Hildebrandsson showed that the mean pressure of the atmosphere in the Icelandic region varies inversely with that in the Azores anticyclone in winter. The mean temperature at Oslo in November and December varies very closely with that at Berlin in the following March and April. There is a close parallel between the variation in the amount of rainfall in Java from October to March, and the pressure at Bombay in the following April to September. Shaw has demonstrated that the strength of the trade wind at St. Helena varies with the amount of rain in the south of England. Walker establishes a connexion between the monsoonal rainfall in India and the variations in pressure at Cape Town and in the South Orkneys in the following December–February. A vast number of such correlations have been worked out. But the correlation is in no case complete, and any forecast based on these relationships is as liable to fail as one based on cycles.

[1] *Quarterly Journal R. Meteorological Society*, January 1927.

PART IX
LOCAL WINDS

CHAPTER XLVIII
SIROCCO, BORA, BLIZZARD

MANY places are liable to be visited at irregular intervals by winds of marked individuality. In some cases they are due simply to the high- and low-pressure systems of the westerlies, but in most the local topography plays an important part by intensifying the natural heat or cold of the various winds. These natural properties are most pronounced between latitudes 35° and 50°, because both very cold and very warm winds may make their way into that zone when the pressure distribution is favourable. Inside the equatorial and the polar zones the temperature is too uniform for such abnormalities to occur.

Hot Winds

The 'tropical' indraft in front of an east-moving depression is everywhere a warm wind, and the polar current that sweeps down in its rear is cold. In the Mediterranean region these properties are so much intensified that the respective winds are prominent enough to have earned local names. The typical warm tropical current is the 'sirocco' of the south and east of the Mediterranean Basin. A depression advances eastward along the axis of the sea, and the inblowing winds in front of it are often drawn from great distances. Not far from the south and east coasts stretch the vast deserts of North Africa and Arabia, which are hot even in the winter months, and consequently these southerly winds appear on the normally cooler Mediterranean as hot winds; they are also dry, and often dust-laden. They set in whenever the suitable gradient is established, and they continue till the trough of the depression has passed, a period of some hours or even several days. The same currents of air often continue to the middle, and even the north, of the basin, where they are still unpleasantly warm, but no longer dry, for during the passage over the sea the warm air becomes charged with moisture; the hot and dry sirocco of the south becomes a warm, moist, and depressing sirocco, ready to yield torrential downpours of rain when it is forced to rise over mountains; the Dalmatian coast has the highest rainfall in Continental Europe (183 inches at Crkvice). Sirocco winds

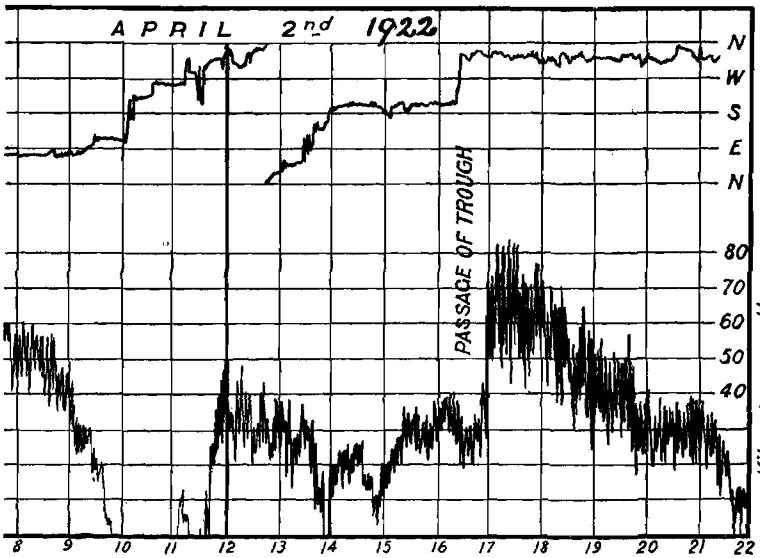


FIG. 109. Velocity and Direction of the wind during the passage of a depression at Helwan, near Cairo, giving a Khamsin, which ended suddenly about 17 H.

are most prominent in spring, for depressions are active, and the deserts are already intensely hot; the winds that blow from them appear as scorching blasts on the coasts of the Mediterranean Sea which is normally cool in spring. The name 'Khamsin' is given in Lower Egypt to the sirocco (Fig. 109).

Similar hot winds ('Santa Ana') are well known in California, which occupies the corresponding climatic position in the New World; they blow from the hot deserts on the east of the Sierra Nevada, and acquire additional heat by their descent.

The 'Hot Wave', which at times prostrates the inhabitants of the Atlantic states of America in summer, is somewhat similar. It is the indraft in front of a depression, and is very warm, and especially very moist, owing to a journey of hundreds of miles over the hot waters of the Gulf Stream. It is the high humidity rather than any excessively high temperature—for the thermometer rarely rises above 100°, and often not above 90°—that is the cause of the heat-stroke which afflicts so many city-dwellers.

Cold Winds

The cold 'polar' indraft behind the depression is derived in the Mediterranean region from the interior of Europe; it is essentially a winter visitation. The wind sweeps down with special violence where there is a break in the mountain ranges that shelter much of the coast, as at the mouth of the Rhone (where it is known as the Mistral), the head of the Adriatic Sea (the Bora), the north of the Aegean Sea, (especially in the lower Vardar and Struma valleys) and the north of the Black Sea. The mistral will serve as an example. When a depression lies over the Tyrrhenian Sea the Rhone valley acts as a funnel down which the north winds blow with great force. The air supply comes immediately from the cold, often snow-covered, central plateau and Alpine region of France—ultimately from high northern latitudes perhaps—and though the temperature is not much, if at all, below freezing-point, it appears notably cold on a coast that is accustomed to more genial conditions. The wind is violent as well as cold; even railway carriages have been blown over; houses are built without doors or windows in their north walls, and market gardens are provided with screens of reeds or trees, set some 30 or 40 yards apart athwart the wind. Though the sky is usually clear and the sun bright it is well-nigh impossible to protect oneself from the dry piercing blasts. The mistral may continue for a few hours or as long as a few days without intermission. Its violence at sea has given the Gulf of Lions its name and reputation. In the winter of 1808 Lord Collingwood, with his flag flying on the *Ocean*, was blockading Toulon, and in one of these gales the three-decker was almost lost—

'At that moment the *Ocean* was struck by a very heavy sea, which threw her nearly on her beam-ends, so much so that several of our men called out "The Admiral's gone down!" But in a few seconds I had the pleasure to see her right again. We understood afterwards that the blow completely disabled her, and that nearly all the bolts of her iron knees were broken. It was the most awfully terrific scene I ever beheld. Lord Collingwood told Admiral Thornborough a short time after that he thought the top-sides were actually parting from the lower frame of the ship. . . . This happened in December and we must have been about the middle of the Gulf of Lions, with the wind at north-west.'

Sometimes while the lower Rhone valley is exposed to the rigours of the mistral, the west coast of Italy is suffering the discomforts of damp sultry heat brought by the sirocco indraft in front of the same depression.

The cold waves of the United States are in some ways similar. The passage of a depression from west to east causes the warm damp winds in front of it to be replaced suddenly, after the trough has passed, by northerly winds, and if the pressure distribution is such that these winds sweep down from Canada, they may, and often do, bring disastrously low temperatures even to the Gulf of Mexico. Unlike the bora winds they are not localized in narrow passages, nor yet are they usually violent, but the flood of cold air spreads south over the whole land owing to the lack of a mountain barrier to dam it back. In its place of origin in Canada the air may be far below zero, and it warms as it moves south, but it may still be below 32° on the shores of the Gulf of Mexico, and cause great discomfort as well as serious damage to the sub-tropical crops grown there. The cold wave is displaced eastward with the depression, so that the eastern states usually receive ample warning of its approach.

In the southern hemisphere the land masses in temperate latitudes are not large enough to have such reservoirs of cold air in winter as feed these cold winds of the northern hemisphere, but the 'Southerly Burster' of the New South Wales littoral belongs to the same class. A V-shaped trough of low pressure crosses the region from west to east, with the V pointing north. In front of it the hot northerly winds (known as 'brickfielders') carry heat and dust from the arid interior, like the sirocco of the Mediterranean.

As the trough passes there is a sudden change to a violent south wind, which appears very cold by contrast, although, as it comes from the ocean, its temperature is well above freezing-point. The hot 'zonda' and the succeeding cold 'pampero' of the Plate estuary are very similar.

Blizzards

In the interior of Canada, Siberia, Greenland, and Antarctica most of the precipitation in winter is in the form of snow, and the land is snow-covered. At the low temperatures of those regions the snow falls in fine dry crystals, not in large flakes, and if the wind blows violently under the influence of a depression the snow-dust is swept up from the ground; at the same time snow may be falling from the clouds, and the raging winds are soon opaque with the flurrying white particles. The temperature is far below freezing-point, often below zero, but not so low as it may be during calm weather, though to those unfortunate travellers who are out of doors it feels much colder owing to the rapid movement of the air. What with the cold, the bewilderment produced by the howling gale and the dancing snow-whirls, and the complete loss of direction in the opaque atmosphere, blizzards have claimed many victims.

Dr. Simpson[1] describes the blizzards of Antarctica—

'In a true blizzard the wind is accompanied by clouds of driven snow. The snow is in the form of exceedingly fine grains which penetrate through the smallest chink or hole in a house or tent. The whole air appears to be full of drift, so that it is impossible to see any great distance, and when it is at its worst even a tent cannot be seen for more than a few yards. Not only does the drift make it difficult to see, but any one exposed to it seems to become bewildered and to lose all power of thinking clearly. For these reasons it is sheer folly to attempt to travel in a blizzard even when the temperature is relatively high and the wind at one's back.'

Brehm's description of the buran of Siberia portrays a very similar storm—

'The wind changes and blows harder and harder from east, south-east, south, or south-west. A thin cloud sweeps over the white ground —it is formed of whirling snow; the wind becomes a tempest; the

[1] Simpson, G. C., *British Antarctic Expedition: Meteorology*.

cloud rises up to heaven; and maddening, bewildering even to the most weather-hardened, dangerous in the extreme to all things living, the buran rages across the steppes, a snow hurricane, as terrible as the typhoon or the simoom. For 2 or 3 days such a snow-storm may rage with uninterrupted fury, and both man and beast are absolutely storm-bound. A man overtaken in the open country is lost, unless some special providence save him; nay more, even in the village or steppe-town, he who ventures out of doors when the buran is at its height may perish, as indeed not rarely happens.'

These storms are known as blizzards in Canada and the Polar regions, and as buran in Russia and Siberia (purga in the Tundra).

CHAPTER XLIX

FÖHN WINDS

MANY Alpine valleys are noted for the not infrequent occurrence of hot dry winds in the winter half-year. For days previously the weather has been unusually cold, the snow-covered valley being filled with cold damp stagnant air, often fog-laden (inversion of temperature), under the influence of an anticyclone. Then comes a sudden change; the wind blows from the south, first in spasmodic gusts, later in a strong steady current, and there is a remarkable rise in temperature, sometimes as much as 40° in 24 hours, and drop in the humidity. The snow melts so rapidly that the wind is known in some districts by the name 'schnee-fresser', but the streams may be swollen to dangerous floods. The air is so dry that the wooden houses are liable to catch fire from stray sparks, and whole villages have been burnt down. Notices similar to the following are to be seen in many Alpine villages:

DAS RAUCHEN

Bei Föhnwetter im Freien ist bei einer Busse von Fr. 2–10 verboten.

BUCHS, den 20. März 1911.
Der Gemeinderat.

The föhn may last even for several days, and the abnormal dry heat has a depressing nervous effect. But it is of considerable value in some valleys in hastening the ripening of fruit in autumn. Many valleys have on an average 30 to 40 föhn days a year.

The föhn wind resembles the sirocco of the south Mediterranean in its qualities, and before its meteorology was seriously studied it was even thought to be identical, the warmth and dryness being brought from the Sahara to the Alps. But investigation showed that this view was untenable. The south wind itself is due to the presence of a depression over North-west Europe, but the peculiarities of the föhn in the Swiss valleys are the result of the Alpine ranges and valleys themselves. In order to reach the valleys the winds have to cross the Alps and descend; descent causes compression and therefore warming and drying. But if the southerly current is to be maintained it must be fed from the south side of the Alps. The wind must rise to cross the ranges, and just as much heat is lost adiabatically in the ascent as is gained by the descent to the same level on the north side; no abnormal warmth is to be expected. But another factor is involved, for as the winds rise and cool on the south side they are soon unable to contain their water-vapour; clouds form and rain falls. The front of the mountains is covered with thick clouds and the mountain torrents roar under their load of flood and pebbles. But let us look at the scene from the north side. The masses of cloud ('föhn wall') can be seen rising above the ranges and pouring through the passes, but as the wind carries them down on our side they rapidly dissolve, and after some few hundred feet of descent they have disappeared. Now the evaporation of the clouds requires just as much heat as is liberated in their formation. But the former process is completed in a few hundred feet of descent, the latter has continued for several thousand, and thus its effect is much greater. An example will make this clear (Fig. 110). We assume that the south wind reaches the foot of the Alps at a temperature of 70°, and almost saturated with vapour, being the damp indraft in front of a depression. Ascending it cools approximately 1·6° in 300 feet of ascent, so that at 3,000 feet it has cooled 16°, to 54°, and we may suppose that clouds have formed and rain begins to fall. Latent heat is now being liberated, and the cooling by ascent is partly counteracted, the actual rate of cooling being reduced to perhaps 0·8° for 300 feet. This continues to the top of the range, which we may assume to be 9,000 feet, and there the temperature will be 38°. Now the descent begins. At first much of the heating due to compression is used up in the evaporation of the clouds; but there is much less cloud to evaporate than was formed in the ascent, for the condensed vapour has been falling as rain. We may assume that 600 feet

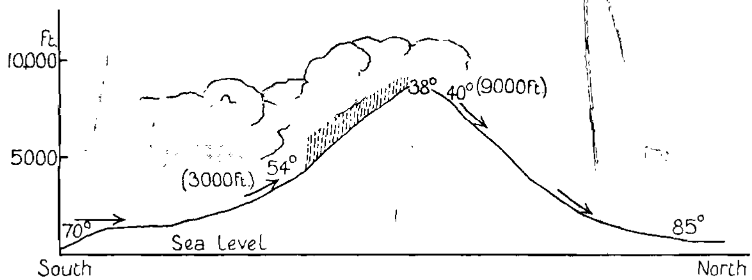


FIG. 110.

of descent will suffice, and during it the temperature will have increased 1·6° (taking the rate of heating to be the same as the rate of cooling while clouds were forming in the ascent). In the remaining 8,400 feet of descent to reach its original level the air heats at the full rate of 1·6° for each 300 feet, and would attain a temperature of 85°. Such high readings are not found in the Alps partly because the northern valleys are 3,000 or 4,000 feet above sea-level, but even a temperature of 45° or 50° is a very noticeable change from the previous cold.

But föhn winds sometimes occur when there are no clouds and no rain on the mountains, and the liberation of latent heat during the condensation of water-vapour fails us as an explanation. In these cases the air may be descending from an anticyclone which covers the region, and it blows down the valleys towards the depression to the northward without having previously crossed the mountains. It often happens that the föhn wind starts and continues to blow for several hours in this way, after which cyclonic influences extend over the region, and cause a south wind to cross the heights, giving heavy rain on the south side.

It is only the deep enclosed valleys which contain these remarkable oases of warmth, for the air loses its heat as it spreads over the plains. The most favoured spots are where side valleys from the high Alpine ranges on the south join the great longitudinal valleys of the upper Rhone and Rhine, the Inn, and other rivers; the Ill valley round Bludenz, and the upper Aar, Linth, and Reuss valleys. Föhn winds are not unknown on the south side of the Alps, though less noticeable there since the wind blows from the north, and is therefore cool by its origin; and these valleys themselves are usually warm owing to their southern aspect, so that the warmth of the föhn wind is not heightened by contrast. Some explanation seems to be demanded for the descent of warm air into the narrow valleys which were filled with very cold air, a condition of stable equilibrium; it might be expected that the southerly wind would blow from ridge to ridge over the tops of the intervening valleys, and leave their cold air in possession. The turbulence that is always set up between two currents of different velocities is probably the main cause of the mixing, and thus of the removal of the cold valley air; the warm föhn first reaches the valley bottom in gusts, and afterwards blows steadily when the cold air is all removed. Ficker (*Innsbrucker Föhnstudien*) has investigated the matter carefully, and concludes that the föhn wind is drawn downward by the flowing away of the inversion layer of cold air which always precedes it; the cold air drains away slowly, and owing to the disturbed conditions associated with the depression which is passing along on the north, it is not replaced. As the inversion layer becomes shallower the southerly wind, which is already blowing above it, is drawn downwards, and finally reaches the bottom of the valley as the föhn. Such spasmodic bursts of the föhn as are shown in the curve for Rotholz (Fig. 111) are due to the temporary reassertions of the cold inversion air after the föhn first starts.

The investigation of the föhn of the Alps has given the clue to many other warm winds. The west coast of Greenland provides a specially interesting example; the interior of Greenland is a lofty plateau, completely covered with everlasting snow and ice, and yet, when the wind blows strongly from the east, there is a decided rise in temperature along the fiords of the west coast, so much so that the natives find it unpleasantly warm; the heat is due to the föhn effect in the winds descending from the plateau. The Chinook winds of Alberta, Montana, Wyoming, and Colorado are a better-known example; the ranges of the Rocky Mountains drop steeply to the high plateaux on the east, and in favourable

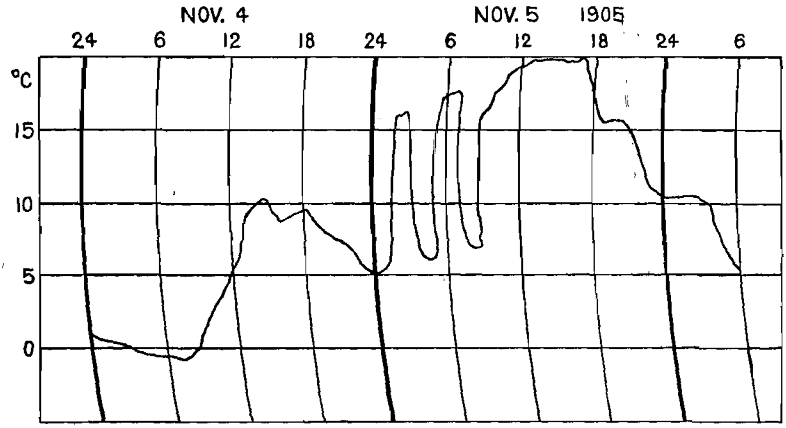


FIG. 111. Temperature during a Föhn at Rotholz, Inn Valley, near Innsbruck. The Föhn began at midnight, November 4–5

conditions the strong damp west wind which has crossed the mountains from the Pacific Ocean is so warm when it reaches the plains on the east that in winter the snow is melted and the pasture laid bare for grazing. In this case the effect is widespread on the leeward side of the mountains, and is not confined to enclosed valleys. It is of great value to agriculture in enabling stock to graze in the winter.

The Berg winds of the littoral of the Cape Province, South Africa, are of a similar type. They become heated simply in blowing down from the plateau; there is generally no liberation of latent heat by the condensation of water-vapour. The plateau itself, in spite of its elevation, often enjoys temperatures in the day time as high as are normal at sea-level, and if the wind blows down from the plateau to the coast it is warmed by compression far above the coast temperature.

CHAPTER L

MOUNTAIN AND VALLEY BREEZES; LAND AND SEA BREEZES; HARMATTAN

Mountain and Valley Breezes

THESE are winds which are caused entirely by the topography; indeed, it is only when the general atmosphere is calm that they are developed, and their occurrence is a sign of settled weather, just as their cessation presages stormy conditions. At night the wind blows down the valleys as a steady cold stream, which generally sets in soon after sunset and continues till morning. It is due to the draining down of the surface air which has been chilled by the rapid radiation of heat from the higher ground, and thus belongs to the genus of katabatic winds (Chap. XVI). The cold dense air makes its way down the various tributaries into the main valleys, where it is still cold although its temperature is raised by compression in its descent. The mountain breeze is generally of only moderate force, but in suitable localities, as where long valleys, draining snow-clad mountains, debouch on a hot plain, or a warm ocean, it may be violent.

A calm spell follows sunrise, and then the wind direction is reversed, a gentle breeze setting up the valleys. Its explanation is not quite so simple as that of the mountain breeze. In Fig. 112 ABC is a section of a valley; the mountain breeze has died away and the air in the valley is at rest. AC is a horizontal plane on which the pressure is uniform. As the sun's power increases the valley sides are heated and the air in contact with them expands. A column of air BD, over the middle of the valley, expands to a greater height than a shorter column such as EF, and the originally horizontal plane of equal pressure becomes curved upwards, as denoted by the dotted line AD′C. The air starts to move down the isobaric slope, and the result of this action going on everywhere is a steady movement of air up all the slopes, and especially up the main valleys, as long as the temperature is rising. The ascending currents meet one another round the summits, and the vapour they contain is condensed into the thick clouds which so often envelop the mountain tops in the hot hours of the day in settled weather; in the night and the early hours of the morning the peaks stand clear and cloudless, but wisps of clouds are seen to form about midday, and grow thicker and thicker into dense cumulus thunderheads, and often a violent thunderstorm rages in the afternoon. Local names have been given to the mountain and valley breezes where they are specially regular, as Tivano and Breva on Lake Como, Oberwind and Unterwind in the Salzkammergut.

An interesting variation to the ordinary valley breeze is sometimes to be observed during the daytime in deep

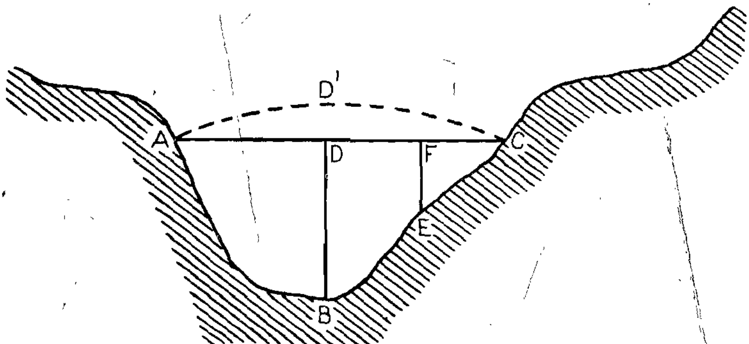


FIG. 112.

mountain valleys, where one side is still snow-covered, and the other, the sunny side, almost bare—a condition which is frequent in spring. A surface current blows down the cold snow slopes, and up the bare slopes opposite which are strongly heated by the sun, so that a revolving system tends to be formed, with its axis along the valley.

Land and Sea Breezes

The more rapid heating of the land by day and cooling by night must tend to produce corresponding pressure differences, slight, but in hot countries appreciable in the coastal belt, so that if it is desired to obtain the true mean pressure care should be taken to avoid confining the necessary observations to hours when either the day or the night conditions are established. Even in temperate latitudes the difference suffices to cause the wind to blow from land to sea at night and from sea to land by day, but in the cooler parts of the zone the winds are not prominent, and on many coasts they are hardly recognizable, since the insolation is not powerful enough; moreover the slight local effects produced are usually masked by the more general movements of the atmosphere. But in sub-tropical latitudes, as on the shores of the Mediterranean Sea, they are regular features, especially in summer, and within the tropics they are of daily occurrence and very important; on the Guinea coast the sea breeze is called the Doctor, and the cool air is so valuable for Europeans that their houses are built in positions where the full benefit may be enjoyed. The breeze sets in 3 or 4 hours after sunrise, and the rapid diurnal rise of temperature is at once checked, or even reversed (Fig. 17, p. 45), so that the warmest part of the day is much less hot than in the interior. The sea air is damp as well as cool.

The sea breeze does not have an appreciable influence more than some 15 to 25 miles inland, and its vertical extent is generally less than 1,000 feet. It first begins some miles out at sea, and gradually approaches the land; for the increasing heat over the land causes the air to expand not only vertically but also seaward, thus keeping the sea breeze away at first. The land breeze is first felt on land, and extends over the sea.

The Harmattan

'That terrible wind that carries the Saharan dust a hundred miles to sea, not so much as a sand-storm, but as a mist or fog of dust as fine as flour, filling the eyes, the lungs, the pores of the skin, the nose and throat; getting into the locks of rifles, the works of watches and cameras, defiling water, food, and everything else; rendering life a burden and a curse.' (P. C. WREN.)

The north-east trades blow over the Sahara and continue over the Guinea lands to the Gulf of Guinea in the dry season; even in the south of Nigeria there is a pronounced break in the rains in January, and in most of the Guinea lands there are 4 or 5 months with hardly any rain. When the north-east wind blows specially strongly from the desert the dryness is intensified, and the humidity may fall below 10 per cent. Vegetation is withered and woodwork shrinks.

This wind has earned a local reputation and the name of Harmattan. It carries much fine dust, and this, as well as the excessive dryness, is so irritating that we soon pray for the return of the rains and moist air. The Harmattan is frequent during the dry season in the neighbourhood of the Sahara, and is less frequent towards the south, becoming rare near the sea.

PART X. SOME CLIMATIC TYPES

THE SUDAN, THE MEDITERRANEAN LANDS, THE WESTERLIES (VANCOUVER ISLAND, MANITOBA)

CHAPTER LI

SEASONAL RHYTHM; THE SUDAN

Except in the zone included between some 6° or 7° of latitude north and south of the Equator, the seasonal rhythm is one of the most important elements of climate. The seasonal change may be slight or very great; in some regions the change is one of temperature, in others the rainfall and humidity change also; in the Polar regions the simple astronomical change between the long winter darkness and the long summer daylight is the most prominent element. Strong seasonal changes seem to be favourable both directly and indirectly to the highest human development, except where the change is so great as to involve extreme and paralyzing heat or cold for long periods; at any rate the most advanced civilizations have evolved in lands where the year goes round with a strong, but not excessive, seasonal rhythm. But at the Equator the monotony tends even to bring about the undoing of civilizations that may be introduced. White men, lacking the stimulus of their native invigorating climate, lose their physical and mental energy, and are the more liable to succumb to virulent parasitical and other diseases; the parasites that are the scourge of such lands appear to flourish in proportion as higher organisms suffer from the everlasting heat and moisture, the hot-house conditions without respite.

To illustrate and emphasize the significance of seasonal changes we now give general descriptions of the climates of certain countries where they are prominent.

The Sudan type

Geographically we may apply the term Sudan to a belt which stretches across Africa from Abyssinia to French Guinea and Senegal, whose coasts are washed by the Atlantic

Ocean; it is bounded approximately by the parallels of 8° and 15° N. It includes the Anglo-Egyptian Sudan in the east, Nigeria (north of the Benue River), and the French Sudan in the west, as well as vast tracts that are still not developed. The seasonal rhythm is one of rainfall chiefly.

January is the middle of the dry season. The sun is overhead in the southern hemisphere, and the equatorial low-pressure belt is drawn south. Over Asia and North Africa there are high pressures, and the trade wind blows steadily from the north-east and north; the air is dry, having passed over the thirsty sands of the Sahara; there are no local pressure irregularities such as those of the westerlies, and not a drop of rain falls; from the beginning of November till the end of March is a season of drought almost everywhere, and in the drier northern tract the dry season starts a month earlier and continues a month later. The fresh winds soon dry up the land, and by January most of the smaller streams have disappeared. The luxuriant summer-green vegetation withers, and the leaves fall; the ground is thick with dust; the banyan trees raise their gaunt thick leafless boughs, and the savanna grasses are sere and brown. Though the temperature is not low, for we are within the tropics, the midday sun, even at its lowest, is 55° above the southern horizon, almost as high as in June in England, and frost and snow are quite unknown. This is a definite resting season for plant life, and many animals hibernate owing to the drought. When the air is clear, the sky blue, and the sun shining brightly, the landscape, though dead, is not uncheerful. But frequently the air is thick with haze and dust, and smoke from the burning grasses, which are fired by the natives to improve the next year's growth. The savanna sometimes blazes and smoulders for thousands of square miles, and the dense volumes of smoke darken the air even as far as the Guinea coast. Though the sky is without clouds, the sun is visible only as a pallid disk in the grey haze, and serves rather to emphasize than brighten the lifeless and cheerless prospect.

As the year advances the sun mounts higher day by day as it returns to the northern hemisphere, and the weather becomes hotter, for the sky is still cloudless. In April the sun is overhead, and the heat becomes intense; the dry and dusty land is parched, and only the largest rivers still flow. No trees can survive except such as have provided themselves with effective devices to resist desiccation. The mean monthly temperature in March, April, and May exceeds 80°; the thermometer in the shade rises above 90° day after day; the nights are cooler, but the temperature does not fall much below 70°. It becomes more and more furnace-like as the sun passes north in May. The period from March to May is a hot dry season, after the cool dry season which lasts from November to February.

Now comes a change. With the sun the equatorial low pressures have been creeping northward, invited by the intense heating of the arid lands, and in May the trough of lowest pressure lies about 12° N. This is the southward limit of the dry trades, which here meet light and variable southerly winds that have been drawn across the Equator and are richly charged with water-vapour; the low-pressure belt brings equatorial conditions as it swings north. In the Sudan the northerlies die away, and the arrival of the rains is hailed by the natives, though not by Europeans, with delight.

The rains usually begin with a tornado:

> 'In a leaden and motionless sky appears a strange sign—a kind of dark-coloured dome rising from the horizon, taking unwonted and terrifying shapes; great semicircles of cloud rise and range themselves one above the other in thick and heavy, but clearly defined masses, the whole glowing beneath with metallic lustre; and all the while not a breath stirs. Then of a sudden comes a great and awful gust, a tremendous sweep that lays low trees, plants, and birds, and whirls the mad vultures round and round, overturning everything in its passage. The full force of the tornado is let loose; everything shakes and totters to its foundations; Nature writhes under the terrible might of the tempest. For the space of some twenty minutes all the windows of heaven are opened upon the earth, a deluge of rain revives the parched soil, and the wind blows furiously, strewing the earth with leaves, branches, and wreckage of all kinds. And then suddenly the storm subsides; the cyclone is past, and the sky is once more clear, motionless, and blue.' (P. Loti.)

During the rains the air is moist. The mornings are clear, and the sky a pure deep blue, but towards noon massive cumulus clouds are seen swelling upwards; soon the sky is overcast, and a torrential downpour begins, with vivid flashes of lightning and crashing peals of thunder—the convectional type of rainfall. The rains transform the landscape. In a very short time vegetation springs into activity; the brown dusty landscape becomes green and the trees put forth their leaves. The air is heavy with the enervating smell of rank growths and the perfume of blooms. The water-courses are brim-full with their muddy rushing torrents, and the low-lying land is covered with extensive floods. The rains last

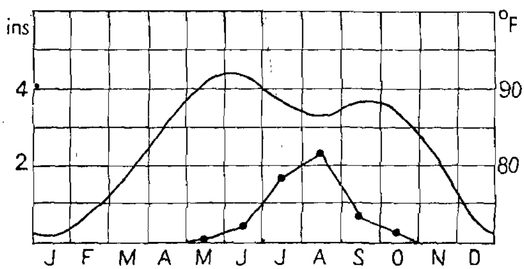


FIG. 113. Mean Temperature and Rainfall, Khartoum

from May to September, a period of intense life for the plant and animal kingdoms. Then the low-pressure trough retreats southward; north-east winds set in again, and the dry season is re-established. The dense clouds of the rainy season screen the earth from the overhead sun, and the rain cools the air, so that not only is the midday temperature appreciably lower than during the dry hot months just before, but there is a pronounced drop in the curve of mean monthly temperature (Fig. 113).

The duration and intensity of the rains are less in the north of the Sudan than in the south; Timbuktu (lat. $16\frac{1}{2}°$ N.) has only 2 rainy months, July and August, and the mean annual rainfall is only 9 inches; Khartoum has only 5 inches. These towns are situated near the farthest northward advance of the low-pressure trough. At Lokoja (lat. $7\frac{1}{2}°$ N.) at the junction of the rivers Niger and Benue, the rains last from April to October, inclusive, and the mean rainfall is 49 inches. North from the Sudan the rain becomes less and less as we enter the Sahara, where there is no rainfall that can be depended upon; and even in July and August the cloudless skies give a clear passage to the rays of the overhead sun; there is no vegetation to shelter the earth. The desert sands are too hot at midday for the bare skin to touch, and although the nights are much cooler, since the heat is lost rapidly by radiation, yet a great area of the south of the Sahara has the highest mean summer temperature on the globe.

On the south the Sudan merges into the equatorial belt where the rainy season conditions of the Sudan continue for most of the year. At Akassa in the Niger delta January is the only month with less than 3 inches of rain; the wettest month, October, has 25 inches, and the next wettest, June, has 19 inches, the mean annual total being 144 inches. Thus there is practically no dry season, and in that low latitude there is no season that can be called cool; the mean temperature for April, the hottest month is 80°, for August, the coolest, 76°, only 4° lower. There is a monotonous enervating hot-house atmosphere throughout the year, very favourable to the fast growth of a rank vegetation. But white men sicken and die.

The Sudan type of climate covers great areas on each side of the equatorial belt in both hemispheres. The monsoon climates of India and the north of Australia resemble it, though having certain peculiarities of their own.

CHAPTER LII

THE MEDITERRANEAN TYPE

Most of the lands round the Mediterranean Sea have a similar climate, and one which has been specially favourable to the nurture of some of the earliest civilizations. The seasonal rhythm is strongly marked, and temperature, rainfall, and weather are all involved.

In summer there are high pressures over the North Atlantic and Western Europe, very low pressures over the south of Asia, and the south of the Sahara; the Mediterranean region, lying between these great centres of action, is swept by north-west winds, which blow strong and fresh, and approach the character of the trades. The sky is almost cloudless (Fig. 114) and of a deep blue, and the glare of the sun is reflected from the white rocks; the air is beautifully transparent, cyclonic disturbances are few in the west, almost unknown in the east; the air is dry, rain is very rare, and in most of the east practically absent. Over the sea and on the coasts the strong breeze prevents excessively high temperatures despite the bright unclouded sun; the July mean is about 75°. The weather remains nearly the same day after day, but sometimes the wind blows stronger, and great waves roll along with white crests. On

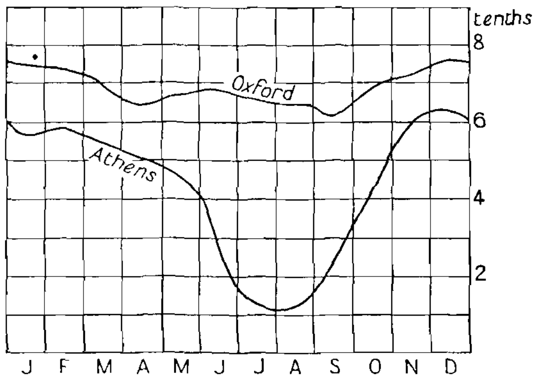


FIG. 114. Mean cloudiness at Athens (Mediterranean) and Oxford (Westerlies)

land it is much hotter, the mean exceeding 80°; it is hotter than in many parts of the tropics, and work must be suspended during the middle of the day. As there is no rain the land is dried up, all rivers except the largest disappear, and vegetation withers, except the evergreen shrubs and trees which are able to survive thanks to their small dark green leaves carefully protected against evaporation by a hard glossy skin, and their deep roots; the land is dusty and the evergreen shrubs are rather grey than green. The heat is specially trying in places in the interior that are sheltered from the wind. On the coasts the sea breeze sets in every day about 9 a.m. and brings welcome cool and damp air. In the western Mediterranean summer, in the intense form we have described, lasts only over July and August, but in the east it covers the period June to September. The dry summers are the most outstanding feature of the Mediterranean climate. The region is a semi-arid one, lying between well-watered Central Europe and the completely arid Sahara, and the chief drawback in his natural surroundings with which man has to contend is insufficiency of water. Artificial irrigation is necessary for successful agriculture, and even the domestic architecture has sometimes been designed to collect and store all the rain that falls, the roofs sloping inwards instead of outwards as in lands where the main object is to get rid of an over-abundant rainfall.

In autumn the winds become less uniform and regular; the low pressures over south Asia are rapidly filling up, and the Azores high pressures are less intense than in summer. The waters of the Mediterranean Sea remain at a high temperature after the summer, and give out much heat, so that the autumns are warm and damp—unpleasantly so at many places. Cyclones begin to appear, some coming from the westerlies of the Atlantic, others springing up over the warm sea, and they soon become both vigorous and numerous in the western basin; the weather is similar to that of the westerlies and gales are not uncommon. Very heavy rain falls as cyclones approach, a fall of 4 inches being by no means uncommon, especially on the mountains which overlook the Mediterranean on almost all sides. The land that was lying deep in dust in the parching summer months is soon saturated, and vegetation begins to revive. But great damage is often done by the violence of the rainstorms. The water-courses which were great wide channels of sand and pebbles in summer, quite dry, or containing a few feeble trickles and small pools of water, are suddenly filled with torrents which bring down the soil and stones that have been swept from the treeless mountain sides. On the Mediterranean littoral of France, North Spain, and North and Central Italy, autumn is the rainiest season of the year; winter, though still damp and rainy, yet brings an appreciable decrease in the amount of rain, which increases again to a secondary (in some parts, a primary) maximum in spring. But on the southern shores and especially in the eastern basin of the Mediterranean the rain begins in October, increases to a maximum in December, and then decreases again through spring to the rainless summer (Fig. 115). Winter is the rainy period yet it is the 'season' for visitors who seek pleasure and health. The weather, though of the same type as that of the westerlies, is more pleasant. The temperature is somewhat higher, especially during the day, the humidity very much lower and the sunshine is much brighter and more abundant owing to the clearer air and less cloudiness; for though the rain may fall very heavily in the neighbourhood of the cyclonic centres the weather soon brightens and the sun shines the more brilliantly through the air that has been washed clean by the rain. The following table provides an interesting comparison between the Mediterranean and North-west Europe:

Mean daily amount of heat expressed in gramme-calories per sq. cm.

	Montpellier. Lat. 43° 36′	*Stockholm. Lat. 59° 20′*
Jan.	82	12
Feb.	127	28
Mar.	184	67
Apr.	229	198
May	296	313
June	311	**403**
July	**325**	359
Aug.	295	231
Sept.	225	137
Oct.	135	49
Nov.	90	10
Dec.	61	3

The long summer days in Stockholm's high latitude give it much more insolation in summer than Montpellier, but Montpellier scores very heavily in winter, receiving more than twenty times as much heat as Stockholm in December, owing to the longer days, the higher sun, and especially the drier air and clearer skies. The number of rainy days, too, is comparatively small—at Nice 67 in the year, though the rainfall is 31 inches; the south of England has a similar amount of rain, but the number of rainy days is nearly three times as great. Frost and snow are by no means unknown even at sea-level on the north coasts, but the snow does not lie long; it is very rare in the south; many of the surrounding mountains are snow-covered during the winter months, but only the Sierra Nevada of the south of Spain retains a few patches throughout the year. The frost is not severe, and though the temperature may occasionally fall 15° below freezing-point at night it is very rare for it to remain below freezing-point all day. The sunshine is abundant, not only in summer, when high records are to be expected in view of the cloudless and rainless conditions, but also in winter.

Health resorts must be carefully chosen. In summer it is too hot everywhere near sea-level, and even the natives who can do so seek relief in the mountains. In winter the northern coasts are liable to suffer from strong cold winds which are drawn from the interior of Europe, where the temperature is well below freezing-point, in the rear of a cyclone over the warm sea. Hence it is very important that there should be a good mountain shelter on the north; the French and Italian Rivieras are protected by the Maritime Alps and the Apennines, but the flat lands round the mouth of the Rhone are often afflicted for days together by the bitter blasts of the mistral (p. 294). These cold winds may be avoided by choosing a resort on the south coast. But here there is a risk of unpleasantly dry, and at times hot, winds from the deserts of North Africa and Arabia, the sirocco, described on p. 292; it is most frequent and unpleasant in spring when cyclones are still active over the Mediterranean, and the deserts from which the air is drawn are already heated up by the approach of the overhead sun. The sirocco is not confined to the south coasts, but its passage northward over the sea reduces its temperature and increases its humidity, so that in the Aegean and the Adriatic its unpleasantness consists in its damp mugginess.

The Mediterranean climate, then, is distinguished by its hot rainless summers, its warm rainy autumns, its cool rainy winters and springs, and its bright skies and abundant sunshine not only in summer but also in winter. It is restricted to the immediate littoral, generally not exceeding a width of 20 or 30 miles, of the sea on whose warmth and humidity it depends. There are endless local peculiarities depending largely on the nature of the shelter from north winds. The rainfall is very variable in amount, from under 10 inches a year on the Egyptian coast (where, however, the scantiness of the rainfall really precludes classification as Mediterranean) to over 180 inches in the mountains of Montenegro overlooking the Adriatic.

The main features of the Mediterranean climate are repeated in four other regions, the coast of California, the south-west corner of Australia, the district round Cape Town, and Central Chile. The area is not great, but these regions are important in the economy of the world by reason of the valuable fruit and cereal products of their intensive agriculture.

CHAPTER LIII

THE WESTERLIES

Vancouver Island, British Columbia (Figs. 116 and 117).
THIS is chosen to represent the regions on the windward coasts of the continents in the belts of the westerlies, viz. North-west Europe, including the British Isles, the west of France and most of Norway, the coasts and islands of British Columbia, the south of Chile, the South Island of New Zealand.

Vancouver is a mountainous island with a little low ground round the coast; it is really a part of the coastal range of mountains which was left when the neighbouring parts sank beneath the sea; most of the interior is more than 3,000 feet above sea-level. It lies full in the course of the westerlies all the year; the seasonal change is one of temperature and of intensity of the weather type, not one of wind system as in the Sudan and the Mediterranean.

In winter the westerlies blow strong under the control of the deep and active low-pressure system south of the Aleutian Islands; gales are frequent as cyclone follows cyclone, and the rainfall is heavy. In front the wind is southerly, mild, and very rainy; but after 24 hours or so the disturbance passes, the wind blows fresh from the north, and the blue sky is flecked with light white clouds. The mean rainfall for December at Victoria is 6 inches, and Victoria is on the lee side of the island; on the west coast there is 14 inches or more, and in the mountains more than

30 inches. Frost is neither frequent nor severe on the west coast (zero has never been recorded), and snow does not

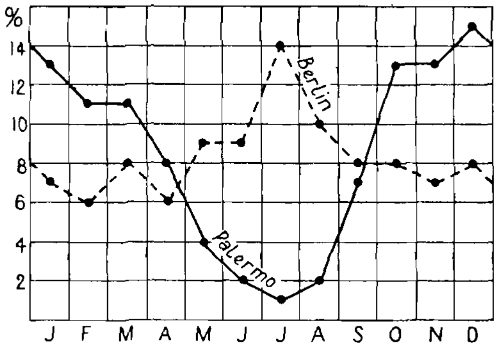


Fig. 115. Mean monthly Rainfall (percentage of yearly total) at **Palermo** (Mediterranean) and Berlin (Central Europe)

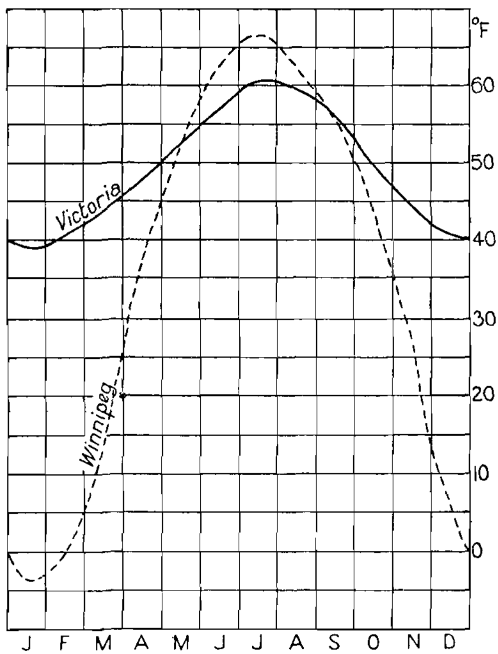


Fig. 116. Mean Temperature

lie long; it is rather colder in the east, and the mountains in the interior are snow-capped for several months. In January the mean temperature is about 40°, the same as in the British

Isles; at night the thermometer usually sinks to near the freezing-point, and the day maxima occasionally reach 50°. This is remarkably warm in view of the low altitude of the sun and the short days in this latitude; at Winnipeg, in the same latitude, but in the far interior of the Continent, the mean temperature for January is −3°, the minimum at night about −15°, and the highest reading by day only about 7°. The winter heat in Vancouver is imported from over the Pacific by the moist winds; it is *not* produced by the direct local insolation.

March brings signs of spring—the days draw out and the sun rapidly gains power; but the wind is still strong and the cooling effect of the ocean now keeps the temperature low. Moreover, there are many returns to winter conditions; snow flurries and bitter north winds nip the early vegetation. Winter and summer struggle for the mastery till at last towards the end of May summer is established. The sub-tropical high-pressure system over the North Pacific extends far northward, and the Aleutian depression almost disappears. The prevailing winds are still westerly and north-westerly, but disturbances are rare; the ocean breezes are fresh and invigorating, and the sky is clear. The weather in June, July, and August with their long summer days is very fine and sunny; it seldom rains (the mean rainfall in July at Victoria is only 0·4 inches), but the temperature is never uncomfortably high, rarely exceeding 90°.

In September autumn begins; the sun declines rapidly, the air is cooler, and very damp at night. But there are often very delightful, calm, cloudless and warm days in September and October.

In November, with increasing cyclonic activity, the disturbed and rainy weather of winter sets in, but the sea air is still comparatively warm; on the west coast of Vancouver November, December, and January are the rainiest months of the year, each with more than 14 inches of rain. Even the coast of the mainland has 17 inches of rain in the three months November, December, and January, together.

Vancouver, and the similarly situated regions in the other continents, are in the most favoured part of the westerlies, for owing to their windward exposure they are exempt from extreme cold in winter, and from aridity—the scourges of the temperate belt in the interior and east of continental masses. Thus round Vancouver frost is never severe, and the sea is never frozen, thanks to the winds which have blown for hundreds of miles over the ocean and to the warm drift that spreads over the east side of the North Pacific. But in Labrador, in the same latitude on the east side of the Continent, the land is snow-covered for 8 months, and the shore can hardly be reached by boats owing to the wide belt of ice-floes and icebergs carried down from the Arctic by the cold Labrador current.

The climate of the interior of the Continent will now be described.

Manitoba (Figs. 116 and 117)

This region is representative of the spacious plains in the interior of North America and Eurasia in temperate latitudes; in the south hemisphere there is no very large land mass in these latitudes. The outstanding features of the climate are the intensely cold winters, the dry air, and the moderate to scanty rainfall.

In winter the mean barometric pressure over the interior of North America is high. The land is generally snow-covered, and heat is lost rapidly by radiation during the long nights; the cold becomes especially intense in still clear anticyclonic weather, and $-46°$ has been recorded at Winnipeg. The cold air, even when saturated, can hold little vapour, and when it is warmed by contact with the body it becomes very dry. This cold crisp weather, with bright sunshine by day, and brilliant starry skies at night, is very pleasant and exhilarating.

But such conditions do not always prevail, for the westerlies with their procession of cyclones and anticyclones pass right across North America. As a cyclone approaches the southerly winds bring clouds, warmer weather (though the temperature is still below freezing-point), and often a heavy snowfall, and behind it bitterly cold north-west winds sweep down from the Barren Lands. Sometimes a blinding blizzard hides the land-marks; the temperature, as measured by a thermometer, is not so low as during the calm anticyclonic spells, but with the rapid air movement it is far more piercing. Owing to the low vapour capacity of the cold air there is not much precipitation; it consists entirely of snow, and the mean depth of snowfall in the year at Winnipeg is 49 inches; farther west it is rather less. Winter is the season of least precipitation.

In spite of the delights of the clear days of frosty air and bright skies, with the snow sparkling in the sunshine, the long winter (5 months have a mean temperature far below freezing-point) must be admitted to be a forbidding time, and life is hard, dull, and monotonous on the boundless prairies. Too often the cheerless grey sky descends on all sides to the featureless horizon, and even the shrieking blizzard may be a welcome break in the monotony. Throughout the winter lakes and rivers are frozen.

As the sun rises in the heavens in spring the temperature rises fast, though frost is liable to be severe in May, and is occasionally recorded even in June. The snow soon melts, the surface of the ground dries, and as oceanic influences are remote the curve of air temperature reflects with little 'lag' that of the sun's altitude; spring is a short transition season from winter to summer. The land heats so rapidly that convection becomes active since the higher atmosphere is still cold, and there are smart showers of rain, often in thunderstorms, as early as April, when the wheat is sown. The rain becomes heavier in May and June, the latter month having the highest mean rainfall in the prairies (but at Winnipeg July has a slightly higher total than June); this early rain is ideal for the growth of wheat. The rain falls chiefly in the hot hours, and is soon over, so that there are high sunshine records in the long summer days on the wide wheat lands; the agricultural possibilities are almost as great along the Peace River as on the international frontier owing to the longer duration of sunshine in the higher latitude. The mean temperature in July is about 65°, some 5° higher than in Vancouver Island or the south of England. In late summer the rain is considerably less, and the heat is often oppressive on the long days when the ground is baked hard and dry. In September frost must be expected at night, and in October it may be severe; the cold increases rapidly, the mean temperature being 13° lower in October than in September, and 20° lower in November than in October, a drop equal to that from July to January in England. September and October often give delightful weather, the warm lazy days being followed by crisp frosty nights. No efforts must be spared to get the wheat transported by water before the rivers and lakes freeze up in November, and bring all shipping to a standstill till the following April.

Manitoba, then, is a land where the seasonal change of temperature is the most prominent feature in the climate, and controls almost every department of life. In the intense cold of winter outdoor work on the land is suspended, but the coming of spring rouses feverish activity, and labour comes into great demand for sowing, and later for harvesting and transporting the crops.

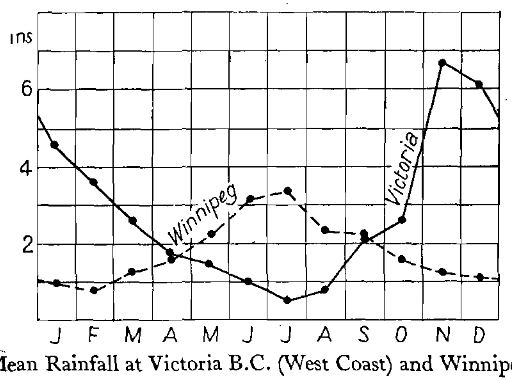


FIG. 117. Mean Rainfall at Victoria B.C. (West Coast) and Winnipeg (Interior)

EQUIVALENTS

TEMPERATURE, °F. AND °C.

Fahr.	Cent.	Fahr.	Cent.	Fahr.	Cent.	Fahr.	Cent.	Fahr.	Cent.
°	°	°	°	°	°	°	°	°	°
−20·0	−28·9	**+10·0**	−12·2	**+40·0**	+ 4·4	**+70·0**	+21·1	**+100·0**	+37·8
19·5	28·6	10·5	11·9	40·5	4·7	70·5	21·4	100·5	38·1
19·0	28·3	11·0	11·7	41·0	5·0	71·0	21·7	101·0	38·3
18·5	28·1	11·5	11·4	41·5	5·3	71·5	21·9	101·5	38·6
18·0	27·8	12·0	11·1	42·0	5·6	72·0	22·2	102·0	38·9
17·5	27·5	12·5	10·8	42·5	5·8	72·5	22·5	102·5	39·2
17·0	27·2	13·0	10·6	43·0	6·1	73·0	22·8	103·0	39·4
16·5	26·9	13·5	10·3	43·5	6·4	73·5	23·1	103·5	39·7
16·0	26·7	14·0	**10·0**	44·0	6·7	74·0	23·3	104·0	**40·0**
15·5	26·4	14·5	9·7	44·5	6·9	74·5	23·6	104·5	40·3
15·0	26·1	15·0	9·4	45·0	7·2	75·0	23·9	105·0	40·6
14·5	25·8	15·5	9·2	45·5	7·5	75·5	24·2	105·5	40·8
14·0	25·6	16·0	8·9	46·0	7·8	76·0	24·4	106·0	41·1
13·5	25·3	16·5	8·6	46·5	8·1	76·5	24·7	106·5	41·4
13·0	25·0	17·0	8·3	47·0	8·3	77·0	25·0	107·0	41·7
12·5	24·7	17·5	8·1	47·5	8·6	77·5	25·3	107·5	41·9
12·0	24·4	18·0	7·8	48·0	8·9	78·0	25·6	108·0	42·2
11·5	24·2	18·5	7·5	48·5	9·2	78·5	25·8	108·5	42·5
11·0	23·9	19·0	7·2	49·0	9·4	79·0	26·1	109·0	42·8
10·5	23·6	19·5	6·9	49·5	9·7	79·5	26·4	109·5	43·1
10·0	23·3	**20·0**	6·7	**50·0**	**10·0**	**80·0**	26·7	**110·0**	43·3
9·5	23·1	20·5	6·4	50·5	10·3	80·5	26·9	110·5	43·6
9·0	22·8	21·0	6·1	51·0	10·6	81·0	27·2	111·0	43·9
8·5	22·5	21·5	5·8	51·5	10·8	81·5	27·5	111·5	44·2
8·0	22·2	22·0	5·6	52·0	11·1	82·0	27·8	112·0	44·4
7·5	21·9	22·5	5·3	52·5	11·4	82·5	28·1	112·5	44·7
7·0	21·7	23·0	5·0	53·0	11·7	83·0	28·3	113·0	45·0
6·5	21·4	23·5	4·7	53·5	11·9	83·5	28·6	113·5	45·3
6·0	21·1	24·0	4·4	54·0	12·2	84·0	28·9	114·0	45·6
5·5	20·8	24·5	4·2	54·5	12·5	84·5	29·2	114·5	45·8
5·0	20·6	25·0	3·9	55·0	12·8	85·0	29·4	115·0	46·1
4·5	20·3	25·5	3·6	55·5	13·1	85·5	29·7	115·5	46·4
4·0	**20·0**	26·0	3·3	56·0	13·3	86·0	**30·0**	116·0	46·7
3·5	19·7	26·5	3·1	56·5	13·6	86·5	30·3	116·5	46·9
3·0	19·4	27·0	2·8	57·0	13·9	87·0	30·6	117·0	47·2
2·5	19·2	27·5	2·5	57·5	14·2	87·5	30·8	117·5	47·5
2·0	18·9	28·0	2·2	58·0	14·4	88·0	31·1	118·0	47·8
1·5	18·6	28·5	1·9	58·5	14·7	88·5	31·4	118·5	48·1
1·0	18·3	29·0	1·7	59·0	15·0	89·0	31·7	119·0	48·3
−0·5	18·1	29·5	1·4	59·5	15·3	89·5	31·9	119·5	48·6
0·0	17·8	**30·0**	1·1	**60·0**	15·6	**90·0**	32·2	**120·0**	48·9
+0·5	17·5	30·5	0·8	60·5	15·8	90·5	32·5	120·5	49·2
1·0	17·2	31·0	0·6	61·0	16·1	91·0	32·8	121·0	49·4
1·5	16·9	31·5	−0·3	61·5	16·4	91·5	33·1	121·5	49·7
2·0	16·7	32·0	0·0	62·0	16·7	92·0	33·3	122·0	**50·0**
2·5	16·4	32·5	+0·3	62·5	16·9	92·5	33·6	122·5	50·3
3·0	16·1	33·0	0·6	63·0	17·2	93·0	33·9	123·0	50·6
3·5	15·8	33·5	0·8	63·5	17·5	93·5	34·2	123·5	50·8
4·0	15·6	34·0	1·1	64·0	17·8	94·0	34·4	124·0	51·1
4·5	15·3	34·5	1·4	64·5	18·1	94·5	34·7	124·5	51·4
5·0	15·0	35·0	1·7	65·0	18·3	95·0	35·0	125·0	51·7
5·5	14·7	35·5	1·9	65·5	18·6	95·5	35·3	125·5	51·9
6·0	14·4	36·0	2·2	66·0	18·9	96·0	35·6	126·0	52·2
6·5	14·2	36·5	2·5	66·5	19·2	96·5	35·8	126·5	52·5
7·0	13·9	37·0	2·8	67·0	19·4	97·0	36·1	127·0	52·8
7·5	13·6	37·5	3·1	67·5	19·7	97·5	36·4	127·5	53·1
8·0	13·3	38·0	3·3	68·0	**20·0**	98·0	36·7	128·0	53·3
8·5	13·1	38·5	3·6	68·5	20·3	98·5	36·9	128·5	53·6
9·0	12·8	39·0	3·9	69·0	20·6	99·0	37·2	129·0	53·9
9·5	12·5	39·5	4·2	69·5	20·8	99·5	37·5	129·5	54·2

INCHES AND MILLIMETRES

Inches.	Millimetres.	Inches.	Millimetres.	Inches.	Millimetres.	Inches.	Millimetres.	Inches.	Millimetres.
0·05	1·3	3·1	78·7	6·1	154·9	9·1	231·1	31·0	787·4
0·1	2·5	3·2	81·3	6·2	157·5	9·2	233·7	32·0	812·8
0·2	5·1	3·3	83·8	6·3	160·0	9·3	236·2	33·0	838·2
0·3	7·6	3·4	86·4	6·4	162·6	9·4	238·8	34·0	863·6
0·4	10·2	3·5	88·9	6·5	165·1	9·5	241·3	35·0	889·0
0·5	12·7	3·6	91·4	6·6	167·6	9·6	243·8	36·0	914·4
0·6	15·2	3·7	94·0	6·7	170·2	9·7	246·4	37·0	939·8
0·7	17·8	3·8	96·5	6·8	172·7	9·8	248·9	38·0	965·2
0·8	20·3	3·9	99·1	6·9	175·3	9·9	251·5	39·0	990·6
0·9	22·9	**4·0**	101·6	**7·0**	177·8	**10·0**	254·0	**40·0**	1016·0
1·0	25·4	4·1	104·1	7·1	180·3	11·0	279·4	41·0	1041·4
1·1	27·9	4·2	106·7	7·2	182·9	12·0	304·8	42·0	1066·8
1·2	30·5	4·3	109·2	7·3	185·4	13·0	330·2	43·0	1092·2
1·3	33·0	4·4	111·8	7·4	188·0	14·0	355·6	44·0	1117·6
1·4	35·6	4·5	114·3	7·5	190·5	15·0	381·0	45·0	1143·0
1·5	38·1	4·6	116·8	7·6	193·0	16·0	406·4	46·0	1168·4
1·6	40·6	4·7	119·4	7·7	195·6	17·0	431·8	47·0	1193·8
1·7	43·2	4·8	121·9	7·8	198·1	18·0	457·2	48·0	1219·2
1·8	45·7	4·9	124·5	7·9	200·7	19·0	482·6	49·0	1244·6
1·9	48·3	**5·0**	127·0	**8·0**	203·2	**20·0**	508·0	**50·0**	1270·0
2·0	50·8	5·1	129·5	8·1	205·7	21·0	533·4	51·0	1295·4
2·1	53·3	5·2	132·1	8·2	208·3	22·0	558·8	52·0	1320·8
2·2	55·9	5·3	134·6	8·3	210·8	23·0	584·2	53·0	1346·2
2·3	58·4	5·4	137·2	8·4	213·4	24·0	609·6	54·0	1371·6
2·4	61·0	5·5	139·7	8·5	215·9	25·0	635·0	55·0	1397·0
2·5	63·5	5·6	142·2	8·6	218·4	26·0	660·4	56·0	1422·4
2·6	66·0	5·7	144·8	8·7	221·0	27·0	685·8	57·0	1447·8
2·7	68·6	5·8	147·3	8·8	223·5	28·0	711·2	58·0	1473·2
2·8	71·1	5·9	149·9	8·9	226·1	29·0	736·6	59·0	1498·6
2·9	73·7	**6·0**	152·4	**9·0**	228·6	**30·0**	762·0	**60·0**	1524·0
3·0	76·2								

INDEX

PRINTED IN GREAT BRITAIN AT THE UNIVERSITY PRESS, OXFORD
BY JOHN JOHNSON, PRINTER TO THE UNIVERSITY