COPY FOR OFFICIAL USE

M.O. 247

AIR MINISTRY

METEOROLOGICAL OFFICE, LONDON

A SHORT COURSE IN ELEMENTARY METEOROLOGY

By W. H. PICK, B.Sc., F.C.P., F.Inst.P.

Fifth Edition (Revised)

Published by the Authority of the Meteorological Committee

LONDON
HIS MAJESTY'S STATIONERY OFFICE

Price 2s. 6d. net

COPY FOR OFFICIAL USE

M.O. [illegible] AIR MINISTRY

METEOROLOGICAL OFFICE, LONDON

A SHORT COURSE IN ELEMENTARY METEOROLOGY

By W. H. PICK, B.Sc., F.C.P., F.Inst.P.

Fifth Edition (Revised)

Published by the Authority of the Meteorological Committee

LONDON
PRINTED AND PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE
[illegible]
[illegible]
Price [illegible]

COPY FOR OFFICIAL USE

M.O. 247 AIR MINISTRY

METEOROLOGICAL OFFICE, LONDON

A SHORT COURSE IN ELEMENTARY METEOROLOGY

By W. H. PICK, B.Sc., F.C.P., F.Inst.P.

Fifth Edition (Revised)

Published by the Authority of the Meteorological Committee

LONDON
PRINTED AND PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE
To be purchased directly from H.M. STATIONERY OFFICE at the following addresses:
Adastral House, Kingsway, London, W.C.2; 120 George Street, Edinburgh 2;
26 York Street, Manchester 1; 1 St. Andrew's Crescent, Cardiff;
80 Chichester Street, Belfast;
or through any bookseller
1938
Price 2*s.* 6*d.* net

CONTENTS

Part I

GENERAL METEOROLOGY

Part II

SYNOPTIC METEOROLOGY

Part III

THE UPPER AIR

A SHORT COURSE IN ELEMENTARY METEOROLOGY

PART I.—GENERAL METEOROLOGY

CHAPTER I

Introductory

1. *The Atmosphere.*—Man lives at the base of an invisible ocean of air termed the atmosphere. This atmosphere is complex in its chemical composition, but in the lower levels near the earth's surface that composition remains practically constant. Innumerable chemical analyses of samples from these lower levels taken from various regions of the globe have failed to reveal any very appreciable differences.* But, partly by reason of different exposure to the sun and partly by reason of the different properties of the land and sea surfaces in contact with it, the atmosphere near the earth's surface, whilst remaining sensibly constant in chemical composition, reveals striking physical differences from time to time and from place to place. These physical differences may be regarded at first sight as comparatively slight, but their results are amazing; for example, 200° F. covers the range of atmospheric temperatures experienced on the earth, and this is almost negligible compared, say, with the difference between the temperature of the electric arc and that of liquid hydrogen, but, nevertheless, small as it is, it causes the great cold of the arctic regions at one end of the range and the sweltering heat of the tropical regions at the other.

The study of atmospheric conditions and changes is called meteorology and meteorology is a branch of the wider science, physics. The student will find it a great help if he will continually remember this kinship, and will keep always before him the fact that all the conditions and phenomena of the atmosphere are illustrations of the principles of physics, and that the sea of air is a vast physical laboratory in which nature is always showing some experiment or another on a grand scale. It is the function of the meteorologist to note the conditions of these experiments and to make an attempt to explain the results which become evident during the course of them.

2. *The Value of Meteorology.*—It requires no great amount of reflection to realize that the weather is an important matter to most men, no matter what their occupation may be. It is ever present, whether in peace or war, and must be taken into account in most projects. The mariner and the agriculturist find it of supreme importance. The housing engineer, engaged in erecting buildings

* Except in regard to water vapour (*see* p. 25).

(40179)

in any particular country, must have a knowledge of the climatic extremes likely to be experienced in that country. Medical men realize that there is a distinct relation between the weather and the prevalence of certain diseases. The commander-in-chief conducting military operations is brought face to face with the fact that favourable or unfavourable weather is a factor too great to be disregarded; whilst the gunnery officers have to institute a close *liaison* with the meteorologists if they are to secure accuracy of range. And, apart from specialists such as those of the classes already mentioned, even the average citizen dwelling in town or country is often enough made to realize by unfortunate experience of snow or fog or floods how dependent upon the weather is the transport which brings to him the supplies of the necessaries of life.

3. *The Value of Meteorology to the Airman.*—The coming of aviation has added yet more strongly to the importance of a study of meteorology for, to the airman, a knowledge of it is of peculiar importance inasmuch as the air is the medium in which he has his flying being and is the medium, the changes and phenomena of which may cause him considerable perturbation from time to time. A well-founded forecast of coming weather changes—and prediction is part of the work of meteorology—is to him a necessity enabling him, first, to avoid the danger which may come to him as a result of those changes; and secondly, to put himself in a position to be able to utilize those changes to his own advantage if this be possible. But it cannot be too much emphasized that these changes, important and even deadly as they may be to him, cannot be foretold by even an expert meteorologist by just a casual glance at the sky and a casual tapping of the "weather glass," but that their prediction requires a wide-flung organization, daily weather charts, much careful observation and study, and continual appeals both to precedent and to physics.

It must not be supposed, however, that prediction is the only help that meteorology can give to the airman. Forecasting is a matter of the vicissitudes of the weather, but for such matters as the floating of an airship or the working of a petrol engine a knowledge of the normal atmospheric conditions at various heights is of more importance than that of the temporary divergencies with which forecasting is concerned. Climatic data, that is data dealing with means, either monthly or yearly, of the various meteorological elements, are just as important in their own way and for their own uses as is the forecast of to-morrow's weather. Prediction is so attractive a part of the science of meteorology that there is often a tendency to consider it the only part.

CHAPTER II

Winds

4. *General.*—Wind can neither be measured like temperature nor can it be seen and painted like clouds. For these reasons man has always been ready to believe that there is something vague and illusory about it, that it "bloweth where it listeth," and that any attempts to study it are foredoomed to failure. Going back a little more than a century, it is probably true to say that less was known about wind than about any other common meteorological element. Its direction could be estimated at any moment, but its force was only able to be very vaguely indicated by the loose nomenclature of airs, breezes, catspaws, squalls, gusts, and the like.

5. *The Beaufort Scale.*—In order to lend precision to personal estimation of wind force, Admiral Sir Francis Beaufort, then Hydrographer to the Navy, devised in the year 1805 a scale of numbers ranging from 0 to 12, based upon the amount of sail that a well-conditioned man-of-war could carry in winds of various forces. The figure 0 corresponded with a calm and 12 with a hurricane "that no canvas could withstand." Sailing ships gave way to ships driven by steam, but still the tradition was carried on until by the end of the century it was realized that a restatement of its specifications was long overdue. The revised scale is given in Table I. It will be seen that separate criteria are given to the observer on coasts and inland. In the inland scale, drawn up by Sir George Simpson, F.R.S., in 1905, it will be seen that the observer is advised to take into account such points as the movements of twigs and branches and various degrees of structural damage. In the coast scale, also due to Simpson, attention is directed to the behaviour and rigging of smacks. Comparison of the estimates given by experienced sailors with the velocities recorded by instrumental measurements has enabled limits of velocity to be assigned to the various numbers of the scale.

The scale may seem somewhat crude, but in practice it is found to give good results. Its use is enhanced by the fact that at many meteorological stations no special apparatus for measuring wind is installed. For the use of observers at such stations, and for the individual making a survey of weather conditions away from a station, a scale such as the Beaufort is a necessity.

TABLE I

The Beaufort Scale of Wind Force with Specifications and Equivalents

Beaufort number	General description of wind	Specification of Beaufort scale: For coast use*	Specification of Beaufort scale: For use inland	Limits of velocity in miles per hour at about 30 feet above level ground
0	Calm	Calm - - -	Smoke rises vertically -	Less than 1
1	Light air	Fishing smack just has steerage way	Wind direction shown by smoke drift but not by wind vanes	1–3
2	Slight breeze	Wind fills the sails of smacks, which then move at about 1–2 miles per hour	Wind felt on face; leaves rustle; ordinary vane moved by wind	4–7
3	Gentle breeze	Smacks begin to careen and travel about 3–4 miles per hour	Leaves and small twigs in constant motion; wind extends light flag	8–12
4	Moderate breeze	Good working breeze; smacks carry all canvas with good list	Raises dust and loose paper; small branches are moved	13–18
5	Fresh breeze	Smacks shorten sail -	Small trees in leaf begin to sway	19–24
6	Strong breeze	Smacks have double reef in main sail	Large branches in motion; whistling in telegraph wires	25–31
7	High wind	Smacks at sea lie to -	Whole trees in motion -	32–38
8	Gale	All smacks make for harbour	Breaks twigs off trees; generally impedes progress	39–46
9	Strong gale	- - - -	Slight structural damage occurs; chimney pots removed	47–54
10	Whole gale	- - - -	Trees uprooted; considerable structural damage	55–63
11	Storm	- - - -	Very rarely experienced; widespread damage	64–75
12	Hurricane	- - - -	- - - - -	Above 75

* The fishing smack in this column may be taken as representing a trawler of average type and trim.

6. *The Tube Anemometer.*—An instrument for writing a continuous record of the wind from moment to moment with regard to its changes of velocity has been devised by W. H. Dines, F.R.S., and is generally known as the "tube anemometer." Instrumental measurements of wind have obviously very definite advantages over the cruder method of personal estimation.

The tube anemometer consists of two parts—the head and the recording apparatus.

The construction of the head will be understood by reference to Fig. 1. It is mounted on the top of a long pole which is 40 or 50 feet above the ground level and sometimes even more. The upper part of the head is free to rotate, and this ensures that

the open end of the horizontal tube *A* is kept facing the wind by the vane *V*, which is attached to the opposite end of the tube *A*. The wind, blowing directly into the open end, produces an excess of pressure there which is transmitted through the central tube of the head down to the recording apparatus below by means of flexible tubing attached to the arm *B*. The fixed part of the central tube is surrounded by another tube *S*, which is pierced by four rings of small holes. The wind blowing past these holes produces a diminution of pressure within the space between the two tubes, and this diminution of pressure is transmitted also to the recording apparatus by means of a separate length of flexible tubing attached to the arm *C*.

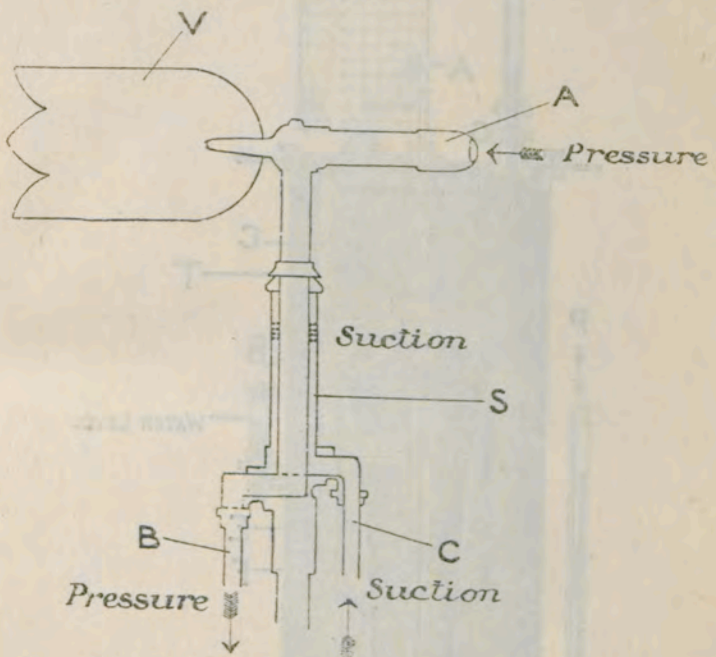


FIG. 1.—HEAD OF DINES TUBE ANEMOMETER.

The recording apparatus is seen in Fig. 2. A vessel *F*, with a peculiarly shaped inner surface *E*, floats inverted in a closed tank *T* partially filled with water. The pressure tube, that is the tube directly attached to the open end of the horizontal tube *A* (*see* Fig. 1) and in which there is an excess of pressure, opens above the water level inside the inverted floating vessel *F*, and thus the increase of pressure is transmitted to the inside of that inverted float tending to cause it to rise. This pressure tube is marked *P* in Fig. 2. The other tube, which may be termed the suction tube and which transmits the decrease of pressure caused by the wind blowing past the four rings of small holes in the outer tube of the head, communicates with the space above the float. This suction tube is marked *S* in Fig. 2. When any wind is blowing there is an increase of pressure caused within the float and a decrease of pressure caused above the float. The float therefore rises, the rise being greater the greater the velocity of the wind. A record of the motion of the float is thus a record of the wind blowing past the head.

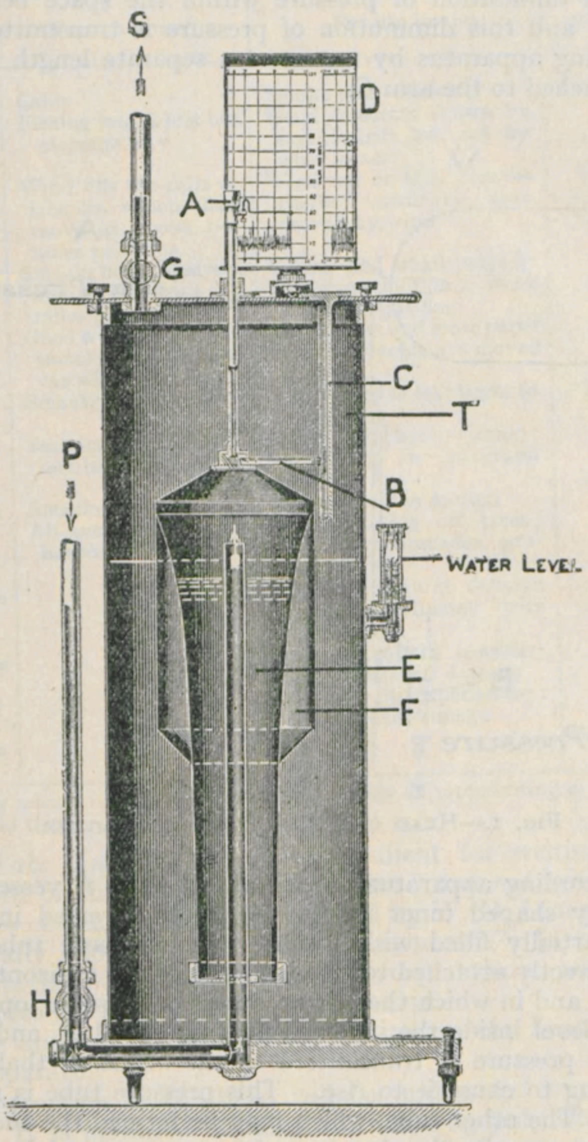


FIG. 2.—RECORDING APPARATUS OF DINES TUBE ANEMOMETER.

To face page 9.]

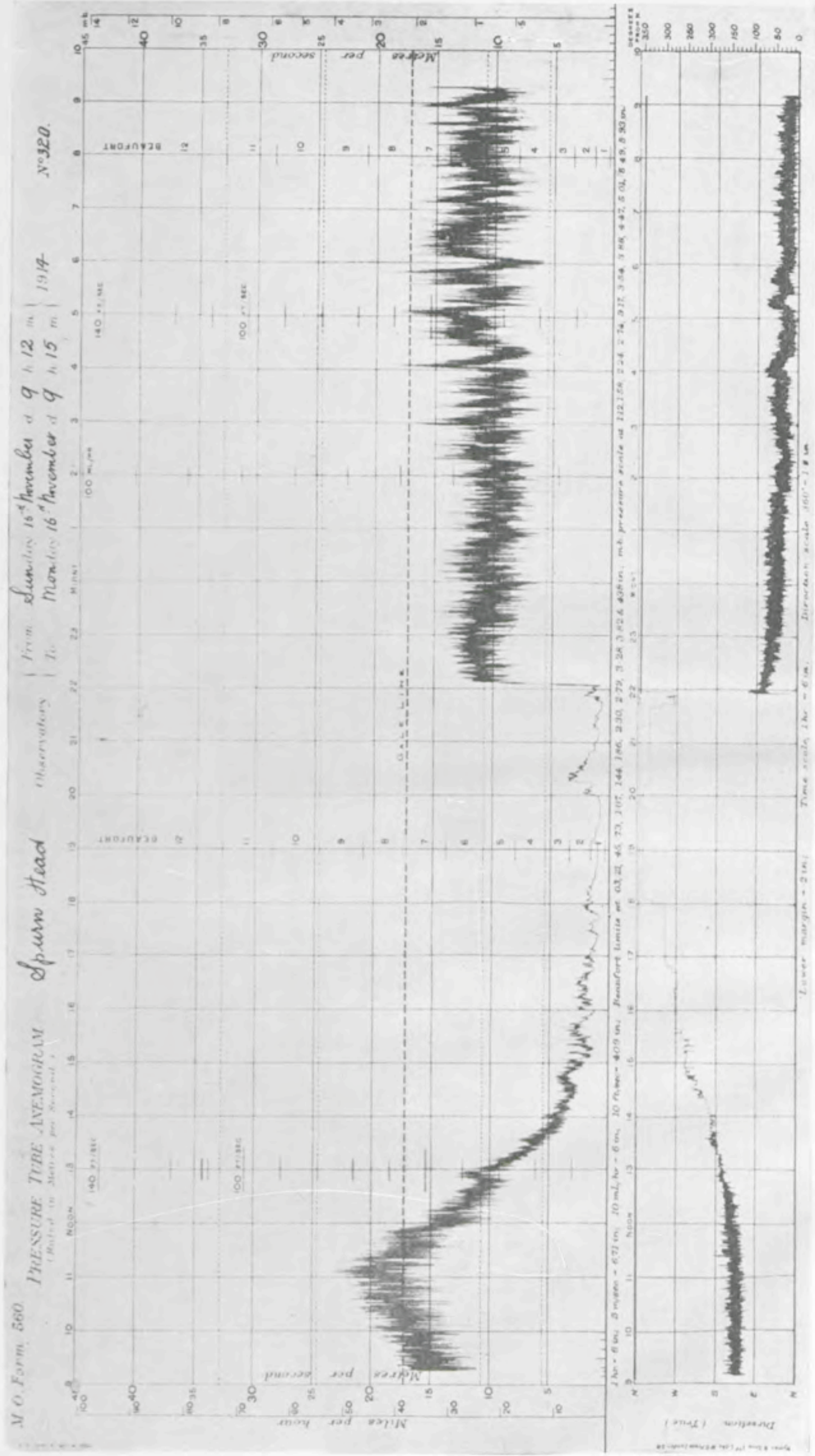


FIG. 3.—ANEMOGRAM FROM SPURN HEAD, NOVEMBER 15 AND 16, 1914.
Showing wind velocity by the tube recorder and wind direction.
Note the difference of timing between the velocity pen and the direction pen.

The arrangement for tracing this record is also shown in Fig. 2. A vertical rod *A* is attached to the top of the float. The rod passes through an air-tight cover in the top of the tank *T* and carries a pen which marks on a drum *D* which is kept rotating by clockwork. The float is kept from rotating by the device of a guide *B* attached to it, this guide working in a vertical slot *C*.

G and *H* in Fig. 2 represent stopcocks which, when opened, allow the spaces above and below the float to be placed in communication with the air of the room. This means that the pressures on either side of the float are made the same and thus the stopcocks are of great value for adjustment purposes.

The instrument as described gives only a continuous record of the velocity of the wind, but modifications of it have been devised to enable it to give a continuous record of the direction as well.

7. *The Structure of the Wind.*—An example of a " trace " given by such a combined direction and velocity anemometer is shown in Fig. 3. This particular record was taken at Spurn Head, but the lessons to be derived from it are quite general. Those lessons relate to the structure of wind. Anemometer traces are the best means available of showing what wind really is like. It is never a perfectly steady " blow," but is a perpetual succession of " gusts " and " lulls " with continual slight variations in direction. The width of the ribbon representing the velocity falls off as the velocity gets less. In other words the range of the gusts diminishes with diminishing velocity. It would seem, therefore, that gustiness represents the eddies set up by mechanical obstacles. This view is supported by the fact that if the anemometer be set up over tree tops the gustiness is found to be largely increased, whilst over the open sea it is considerably diminished. But it is equally true that gustiness is never entirely eliminated, being found even in the exposures most free from mechanical obstacles and also at heights of several thousands of feet.

8. *Squalls.*—The wind, however, is not only liable to these small but continually recurring variations known as gusts, but also to more considerable fluctuations of velocity known as squalls. Gusts must be distinctly distinguished from squalls. A squall is a blast of wind, of higher velocity than has been experienced on the average, occurring suddenly and lasting for some minutes at least and then dying away as suddenly as it arose. A gust is also a sudden increase of wind, but it is of very short duration. Squalls are probably due to definite meteorological causes, though this cannot be stated with certainty; gusts are due to the mechanical interference of obstacles in the way of the wind.

9. *The Exposure of a Wind Station.*—From what has been already said, it will be realized that the exposure of a wind station is of the greatest importance. Just as running water forms eddies and

ripples around every obstacle in its path, so will wind which is only running air; and these wind eddies once formed seem to possess the power of persisting for a while with an independent existence of their own. Wind eddies, then, must be formed at the corners of every house, over every little hillock, on the faces of cliffs, around every tree or shrub, or in the immediate neighbourhood of anything rising above the level of the ground. A wind measurement made in close proximity to any such obstacles cannot be a true measure of the general flow of the air, and for general meteorological purposes it is this general flow which is required. An observer, taking a wind observation, should be diligent in taking it in the most open exposure possible. The vitiating power of buildings, trees, and the like cannot be over-estimated. A wind vane, for example, placed just above the roof of a house is thoroughly bad: this exposure is especially commented upon, as it is so common.

CHAPTER III

The Trade Winds

10. *The Trade Winds.*—Winds may either form part of great atmospheric movements, of a scheme of planetary circulation, or they may be local in character. Of the former class, the trade winds are the outstanding example; of the latter, those accompanying cyclones and anticyclones (which winds will be treated later), or land and sea breezes, are illustrations.

Just as water will flow from places of higher level to those of lower and as electricity will flow from points of higher potential to those of lower, so air will flow from places of higher barometric pressure to places of lower. But the flow of the air, the wind, is not direct from the high pressure to the low; it is subject to deviation owing to the earth's rotation. Nor are the moving air particles unique in this respect, for every moving body on the earth is subject to the same force. The moving body keeps on its original direction; the rotation of the earth causes it to have an apparent deviation.

The general law has been stated thus. Every body moving on the surface of the earth is deflected to the right in the northern hemisphere and to the left in the southern hemisphere because of the earth's rotation.

A simple explanation of the law may be offered as follows, taking air as the example. The air, when it is apparently at rest, and a complete calm prevails, is in reality moving with great rapidity in company with the earth. The velocity due to the earth's rotation at the equator is about 1,000 miles per hour from west to east and it gradually diminishes towards the poles, where it is zero. So long as the air remains at rest relative to the earth's surface beneath it this movement is not sensible, but it at once becomes effective if the air be impelled to a latitude having either a higher or lower velocity of revolution. In the former case, air possessed of a less velocity from west to east reaches a part of the earth's surface having a higher velocity and therefore appears to be impressed with a movement from east to west, appearing therefore to be deviated to the right if the scene be the northern hemisphere and to the left if the southern, and similarly for the second case.

In the northern hemisphere, for the reason given, a current of air setting from a lower latitude to a higher gives rise to a south-westerly wind, and a current in the opposite direction to a north-easterly wind. If therefore an area of low pressure arises in the northern hemisphere surrounded by higher pressure, the primary tendency of the air to flow from the higher pressure on the outside towards the centre of the area of low pressure will be modified to impart a more easterly direction to the wind in the northern half of that area, and a more westerly direction to the wind in its southern half, the joint influence of which will be to set up a circulation round the centre of lowest pressure from west through south, to east and north, round again to the west, that is, against the motion of the hands of the clock. In the southern hemisphere a similar circulation would be established, but in the opposite direction, or with the motion of the hands of a clock.

It will be seen that, similarly, air flowing round an area of high pressure will in the northern hemisphere develop a circulation in the opposite direction to that caused round an area of low pressure, that is, passing from east through south to west and north back to east.

The general statement of the facts, thus explained, is known as Buys Ballot's law, because it was first publicly announced in Europe by Professor Buys Ballot of Utrecht. Buys Ballot's law may be enunciated as follows: If, in the northern hemisphere, you stand with your back to the wind, pressure is lower on your left hand than on your right. In the southern hemisphere, the reverse is true, for there, if you stand with your back to the wind, pressure is lower on your right hand than on your left.

These considerations become of great importance when the general arrangement of barometric pressure over the earth is taken into account. Fig. 4 shows the average distribution of pressure at sea level over the globe for the month of January and Fig. 5 that for the month of July. It is not accurate to say that the regions shown as having high pressure have that high pressure permanently: still less that the regions shown as having low pressure have that low pressure permanently. The conditions are average conditions only, a fact to be borne constantly in mind. Nevertheless the general picture which is obtained of the distribution of average pressure at sea level both in summer and in winter from a study of the maps is that of two belts of high pressure encircling the globe, the belts being enclosed approximately between the lines of latitude 30° N. and 40° N., and between the lines 30° S. and 40° S., whilst a belt of lower pressure lies along the equator. The whole system of belts shows a seasonal shift in latitude, being furthest north in the northern summer and furthest south in the northern winter. In addition, there would appear to be polar caps of high pressure. Corresponding with this pressure distribution there is a wind circulation also shown in Figs. 4 and 5, the wind circulation obeying the law due to Buys Ballot, already enunciated.

A study of the main features of the wind circulation reveals the existence of the north-easterly trade winds blowing between 30° N. latitude (approximately) and the equatorial belt of low pressure, and of the south-easterly trade winds blowing between 30° S. latitude (approximately), and the equatorial belt of low pressure, and also of the westerly winds blowing from 40° N. latitude towards the north and from 40° S. latitude towards the south.

It is interesting to notice that the name "trade" was not given to these winds because of their benefit to commerce, great as this was in the days of sailing ships, but because they are track winds keeping to one track. The north-east and south-east trades blow at sea with remarkable steadiness. This uniformity must not, however, be exaggerated. Sometimes they weaken or shift and their direction is apt to be subject to considerable variation when they encounter islands. This latter variation is most marked about the larger island groups of the Pacific Ocean, especially the Fiji and Samoa ones. Occasionally, too, they are invaded by revolving storms which control the winds temporarily; and near coasts they are interrupted by the phenomena of land and sea breezes.

The great streams of air constituting the trade winds average nearly two miles in depth. The north-east trade over the Atlantic has a mean velocity for the whole year at the surface of about 10·5 miles per hour, varying from a mean of about 7·5 miles per hour in October to a mean of about 13·5 miles per hour in April. The south-east trade over the Atlantic has a mean velocity of about 14 miles per hour for the whole year, varying from a mean of about 13 miles per hour in January to a mean of about 15 miles per hour in April, June and August.

11. *The Doldrums.*—The doldrums lie between the steady trades and in the immediate neighbourhood of the equator. The doldrum belt is a region of light and variable winds with many calms, and is characterized by cloudy skies, sultry weather, much rain and exceptionally violent thunderstorms. In the days of sailing ships this region was much dreaded by mariners, who were liable to lie becalmed there for considerable periods, with dire results in regard to their temper and health.

12. *The "Roaring Forties."*—This name is given by sailors to the region between 40° S. and 50° S. latitude. Here there is a more uninterrupted surface of ocean than is to be found in any other region, and the westerly winds blow from the outer margin of the south-east trade belt with great regularity and with greater strength than do the trade winds. The constancy of these winds, the "brave west winds," is so great that even now sailing ships are enabled to compete by their aid with steam ships in trade with New Zealand *via* the Cape of Good Hope, the return journey being made around Cape Horn.

13. *The Westerly Winds of the Northern Hemisphere.*—The westerly winds blowing from the outer margin of the north-east trade belt are by no means so steady as are the "brave west winds" of the southern hemisphere. They are very frequently interrupted by storms, and, indeed, the northern temperate zone on land is characterized by such a succession of shifting winds that the prevailing direction of wind movement from the south-west or west is not very apparent until careful records are made and examined.

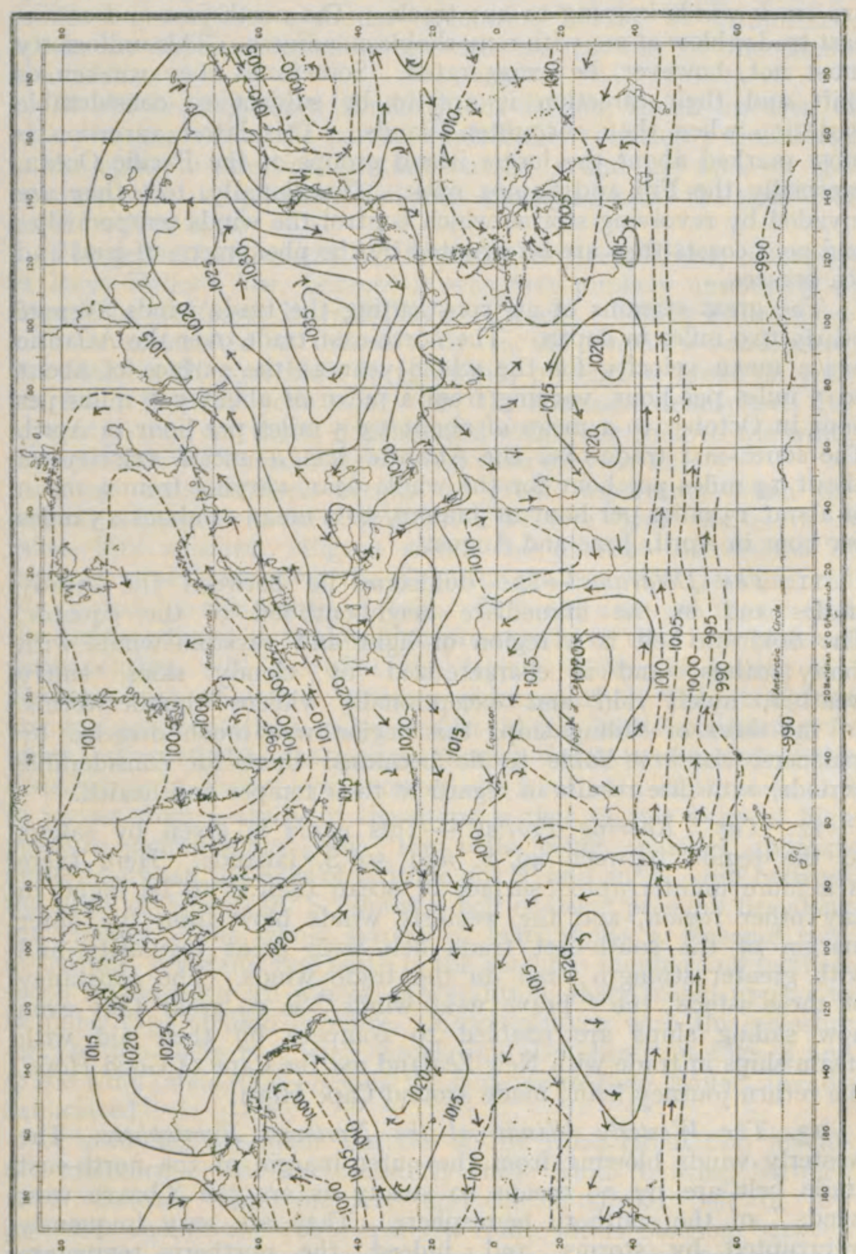


FIG. 4.—Average pressure at mean sea level and prevailing winds at the surface in January.

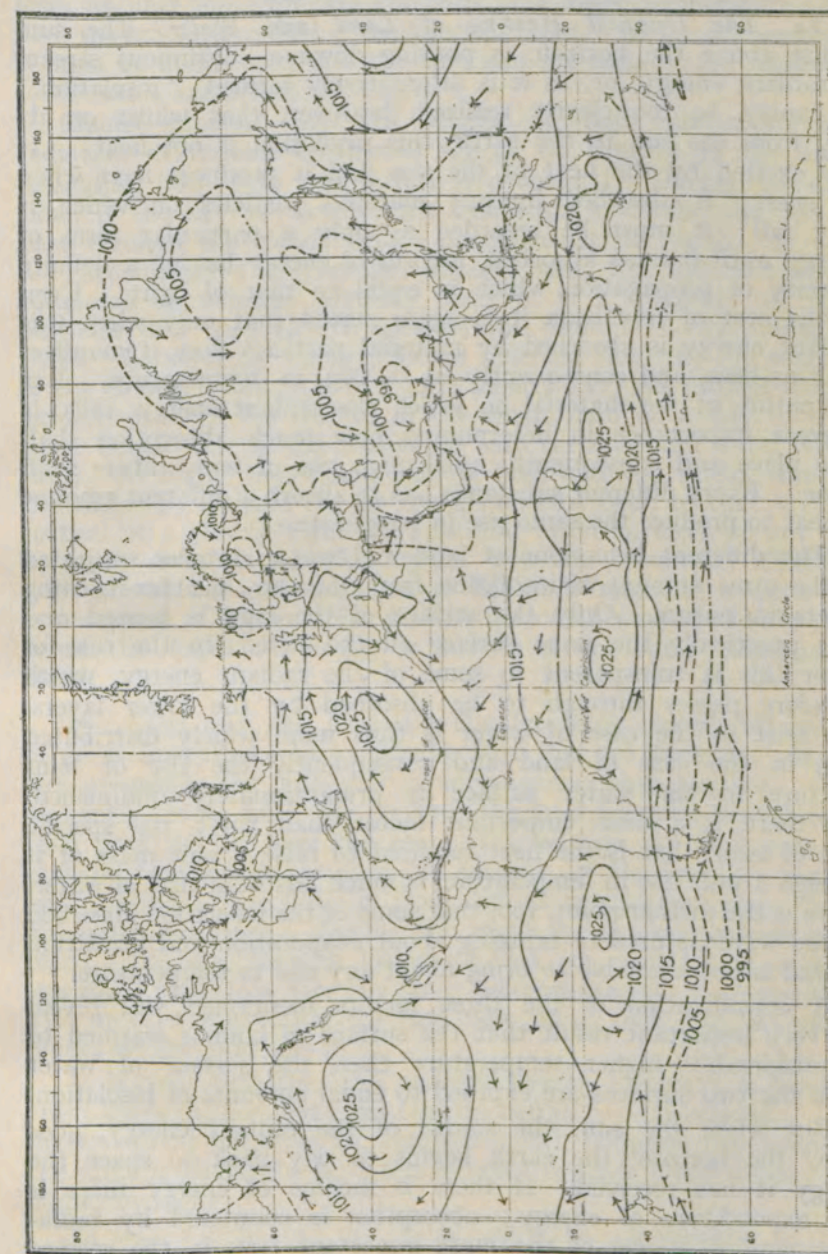


FIG. 5.—Average pressure at mean sea level and prevailing winds at the surface in July.

CHAPTER IV

Monsoons and Similar Winds

14. *The Unequal Heating of Land and Water.*—The sun, whilst above the horizon, is pouring down a continuous stream of radiant energy, or, as it is alternatively termed, "insolation." It cannot be too clearly realized, however, that whilst on its way from the sun to the earth, this insolation is not heat. It was excited by the heat of the sun and it produces heat when its energy is absorbed by any material particles on which it may fall; it must be regarded as only a particular form of energy until it is so absorbed, a form of energy having a definite velocity of propagation which is equal to that of light. Even at the cost of repetition it is again stated that only when this radiant energy is absorbed by material particles does it manifest itself as heat, and consequently as a rise in temperature. But the nature of the material on which the radiant energy falls is of great importance in determining how much absorption shall take place and consequently how much rise of temperature shall ensue. Every different substance has to absorb a different amount of heat to produce the same rise in temperature.

The different behaviour of land and water surfaces subjected to the same amount of insolation from the sun has far-reaching effects in nature. Only the surface of the land is heated and it is practically the same surface all the time. In the case of water this is transparent to some of the radiant energy, which therefore passes through to be absorbed by the lower layers. The heat in the case of water is thus more widely distributed than in the case of land and consequently the rise of temperature in the water surface is proportionately diminished. But there is a more important factor than this: the specific heat of land, that is the heat required to raise a unit mass of it through a unit rise in temperature, is much less than that of water. There is the further point, too, that some of the insolation absorbed by the water is used in bringing about evaporation and insolation so used is not available to bring about any rise in temperature.

A consideration of the three factors mentioned will reveal the very important result that the surface of land is warmed to a considerably higher temperature than the surface of water when the two surfaces are exposed to equal amounts of insolation.

But when the sun, the source of the radiant energy, goes below the horizon, the earth begins to pay back to space the energy it has received. If there is income of energy there is also expenditure of energy; absorption is countered by radiation; and it is one of the most important laws in the science of heat that a good absorber is also a good radiator. The result of this is that as a land surface is a better absorber than a water surface, so also it is a better radiator than a water

surface. The total effect of this is that a land surface gets heated more quickly and rises to a higher temperature than does a sea surface during the hours that the sun is above the horizon, but loses its heat more quickly and falls to a lower temperature than does the sea surface during the hours of night. In the last sentence it must be understood that the land and sea surfaces are subjected to the same amount of insolation.

Clouds prevent the full effects of both absorption and radiation of radiant energy so far as the surface of the earth (including both land and water) is concerned. During the daytime, if the sky be cloudy, the insolation from the sun has to pass through the clouds before it can reach the earth. It does not accomplish this passage without loss, for the clouds are composed of material particles, and it is a property of such particles that they absorb some of the radiant energy falling on them. Some of the energy, too, is reflected from the top surfaces of the clouds. Consequently, on a cloudy day, less radiant energy actually reaches the surface of the earth than on a day of clear sky; hence there is less heating of both the land and water of the earth. At night, too, clouds radiate heat and also reflect some of the radiation emitted by the earth's surface back to that surface, so that on a cloudy night the land and water surfaces do not cool so much as on a clear-sky night. For the maximum effects of both absorption and radiation to be made manifest a clear sky is necessary. Fog or mist acts in a similar way to cloud; this would be expected, as fog or mist is of the same make-up as cloud.

15. *Land and Sea Breezes.*—The foregoing considerations are of great importance in explaining land and sea breezes. As the day progresses the land gets rapidly warmer than the sea. Consequently, in its turn, the air over the land becomes heated more than does the air over the sea. The warmer air then sets up upward convection currents on account of its lessened density and a cooler breeze flows in from the sea to take the place of the air which has risen. During the night the reverse process takes place. The sea, through losing its heat by radiation at a much less rapid rate than does the land, becomes warmer than the land. The upward convection currents now occur over the sea and a breeze off the land sets in.

It is clear that the land and sea breezes introduce a levelling effect upon the temperatures experienced in coastal regions. They prevent great extremes as, compared with temperatures inland in the same latitude, the land temperature is made lower by day and higher by night.

In such a region as the British Isles the phenomena of land and sea breezes are often masked by cyclonic disturbances (*see* Part II.), but in tropical regions they are much more important. In those regions the diurnal temperature variation is very marked.

and cyclonic storms are by no means so frequent. In some tropical places where the configuration of the land favours their development, the land and sea breezes attain to great strength. This is particularly the case at Port Royal, in Jamaica.

Normally, in nearly all latitudes, the land breeze sets in at about 8 o'clock in the evening and reaches its maximum strength at about 3 o'clock in the morning. Conversely, the sea breeze sets in at about 9 or 10 o'clock in the morning, attaining its maximum strength at about 3 o'clock in the afternoon.

Some doubt exists as to the depth to which the land and sea breezes extend landwards or seawards as the case may be. Along the coasts of the United Kingdom the sea breezes probably extend about 10 miles inland, whilst the land breezes reach a slightly less distance seawards. In tropical regions these extensions are greater.

16. *Monsoons.*—Well-marked differences of temperature between land and sea surfaces may arise either as a result of rapid diurnal heating and cooling, which is the cause of the land and sea breezes, or as a result of rapid seasonal heating and cooling. Over the centre of large continents far removed from the sea the seasonal variation of temperature is greatest; summer being characterized by a very high mean temperature and winter by a very low one comparatively. As a result, the pressure over the land in summer is much reduced, becoming less than that over the surrounding less warmed seas, whilst in winter the reverse is the case. Consequently winds blow outwards from the land towards the seas in winter, and inwards from the seas to the land in summer.

These winds changing with the seasons of summer and winter are the monsoons.

The monsoons of India are the best known winds of their class. The hot weather in India usually commences about February and continues until June. The heating process goes on for a considerable period before the actual reversal of wind direction takes place. When the reversal does occur, it comes suddenly and is generally accompanied by stormy weather. The wind then begins its "blow" from the south-west, mainly directed towards the high lands of the Himalayas with an appreciable turn to the right in accordance with the law of deviation due to the rotation of the earth, which law has already been enunciated. The south-west monsoon blows up to about September or October and the whole season is one of rain. The winds of the summer monsoon attain to great strength.

In winter, the summer monsoon from the south-west is replaced by one from the north-east flowing out from the main land masses towards the sea. This monsoon, flowing from such a huge area of land, is a dry wind, rain only occurring lightly and irregularly. The wind force in this monsoon is considerably less than that in the south-west one.

For most continents the monsoon effect is comparatively insignificant. Asia, especially in India and China, shows it most distinctly, and there, in fact, it is the predominating feature of the climate. Australia, too, shows it in some degree, but the reversals are hardly abrupt enough to justify the use of the special term in its usual connotation. The equatorial regions of Africa show it to some slight extent, but it hardly appears at all on the American continent. So far as Europe is concerned there seems to be a slight monsoonal effect observable on the Iberian Peninsula and that is all.

17. *Local Winds.*—Various local winds now demand more or less detailed comment.

The first of these to be considered are katabatic or gravity winds. At night there is greater radiation from high ground than from valleys, greater radiation because at higher altitudes there are less dust particles and less water-vapour particles in the air to intercept the radiation and thus to absorb or reflect it. The colder land means colder air in contact with it. Colder air is denser air, which, therefore, by gravitational action, slides down the slopes to give the katabatic or gravity winds under consideration. Such winds are purely local and very often exist without any obedience to the distribution of atmospheric pressure. Usually they are gentle in character, but in exceptional cases where the valley is long and rather steep, especially if it be fed by a plateau of gentle slope or be snow-covered (temperature thus being kept low), the down currents may attain to velocities approaching or equalling gale force.

An example on the large scale is found in the northern Adriatic in the cold north-easterly wind which sometimes blows down the slopes of the plateau to the north, and is termed the "bora". The plateau becomes very cold in the clear weather which often occurs in winter, much colder than the valleys below it, and consequently there is started a descending current of air—the bora. When high barometric pressure over western Europe coincides with the passage of a depression (*see* Chapter XIV) along the Mediterranean from west to east, the bora is very greatly re-inforced by the northerly winds in the rear of the depression, which winds are blowing in the same general direction as itself. This re-inforcement is often so considerable that the bora becomes a very squally wind rising frequently to speeds of 80 miles per hour and has even attained to 134 miles per hour at Trieste.

Another example of a katabatic wind on a large scale is that of the "mistral," which blows along the Mediterranean coast of France. In this case the more or less persistent low barometric pressure in winter over the Gulf of Lyons co-operates with the often-occurring high pressure over the snow-covered plateaus of south-eastern France that lie to the northward to produce considerable air drainage down the lower Rhone Valley, which drainage manifests itself as a cold, dry northerly or north-westerly wind. In cause and action the mistral is closely analogous to the bora but it is distinctly less violent. It is usually accompanied by clear weather and bright sunshine.

Mention must also be made of the katabatic winds experienced in Greenland and Antarctica. Both of these large areas are dome-shaped and rise to great altitudes in the interior: they are also covered with snow and ice. These conditions are ideal for the production of gravity winds, as will be realised from what has already been said, and such winds are a marked feature of the areas in question.

Two other well-known local winds, similar to each other but differing entirely in kind from the katabatic, now require attention: they are the "scirocco" and the "khamsin". Each is a southerly wind blowing in the front of an advancing depression (*see* Chapter XIV). The scirocco is the warm southerly or south-easterly wind blowing in front of a depression travelling from west to east along the Mediterranean. As this wind passes in its travel across the hot wastes of the Sahara desert, it arrives at the north coast of Africa as a hot, dry wind with its temperature still further augmented by reason of its descent from the inland plateau with consequent compression and warming (*see* sections 19 and 21). The further travel of the scirocco across the Mediterranean changes its character from hot and dry to warm and moist by reason of the taking-up of water vapour, and it is with these latter characteristics of warmth and moisture that it comes to Malta, Italy and other parts of the southern coast of Europe. The khamsin is a similar wind blowing over Egypt in front of depressions passing eastward along the Mediterranean: once again it is hot and dry by reason of its blow over large tracts of the African interior before reaching Egypt.

Yet another wind to require notice is the "föhn". This occurs as a warm, dry current blowing down the slopes on the leeward side of a range of mountains. The name "föhn" originated in the Alps, where the wind in question is very prevalent, especially on the northern slopes. A similar wind on the eastern sides of the Rocky Mountains in America is termed the "chinook". The mechanism of the action of the föhn or the chinook is instructive. The air when coming to the mountains on the windward side ascends with resulting dynamical cooling (*see* sections 20 and 21) and consequent cloud formation and precipitation (*see* section 51). When the air, after passing over the summits, descends the slopes on the leeward side, it has, therefore, lost its moisture and is a dry wind. Descending, it becomes warmed by compression as it travels through increasing barometric pressure (*see* sections 19 and 21), and reaches the valleys beneath as not only dry but also warm.

Another important local wind is the "harmattan", a very dry wind prevalent in western Africa during the months November to March. During those months (the winter of the northern hemisphere) the air over the Sahara desert cools rapidly. As a result of this cooling it becomes denser and tends to flow outward to the coast, especially to the Gulf of Guinea, to replace the lighter, because warmer, air prevailing there. As it is dry and relatively cool, it

forms a welcome relief from the moist and warmer air it replaces and thus earns the local name of "the Doctor", a name given to it in spite of the fact that it carries with it great quantities of very finely divided dust, which dust covers almost everything, and sometimes forms so thick a haze or fog as to impede navigation on the rivers.

18. *The Lull of Wind at Night.*—An extended investigation of wind records kept at any land station will reveal the noteworthy fact that, generally, the wind drops in force after sunset and remains lulled until after sunrise. This must not be taken as true for every night, for travelling cyclonic systems quite often cause this, the normal lulling, to be entirely masked. Eliminating these travelling systems, however, the statement remains true. The nightly lull is not so marked far out at sea, nor is it at even the modest height of the Eiffel Tower in Paris.

The cause of the lulling appears to be found in the following considerations:—

In daytime, especially in the summer, the surface layers of air get considerably warmed through contact with the rapidly absorbing and hence rapidly warming surface of the land. The warmed surface air then rises to mingle with the currents a little higher up. The upper air currents have more energy because they are not subjected to the friction of the earth's surface. It will be recognized, then, that the rising of some of the less energetic surface air will tend to slow down the currents just above the surface layers while the coming down of some of the more energetic air of these upper layers (coming down because colder and thus denser) to take the place of the risen air will tend to increase the velocity of the currents in the surface layers.

At night, no air rises and hence the velocity of the currents just above the surface layers tends to increase upon what it was during the day, as it is no longer subjected to any "brake" effect, whilst no more energetic upper air comes down to increase the velocity of the surface currents.

Under normal conditions, then, the wind at the surface lulls at night whilst the wind just above the surface layers, say, up to 1,000 feet, tends to freshen. During the day, the reverse happens; the wind in the surface layers tends to increase in velocity and the wind up to 1,000 feet to decrease.

As would be expected from what has gone before, the surface lulling of wind is more marked during a night of clear sky than during one which is cloudy or overcast, for it is on such clear nights that the radiation from the earth is greatest and hence that cooling is greatest; and the greater the cooling of the earth's surface the greater will be the cooling, and thus the density, of the air in contact with that surface; and such a greater density means a greater lulling of the wind.

CHAPTER V

Some Considerations on Temperature

19. *Heating due to Compression.*—The absorption of insolation is not the only means by which temperature may be raised. There is the heating due to mechanical compression. Tyndall showed this effect by his device of a glass syringe in which a piece of tinder or some other combustible substance was placed. By pushing in smartly the piston of the syringe, the combustible substance could be set alight. The same phenomenon is within the experience of any one who has pumped up the tyres of a bicycle. The pump soon becomes warm. In each case the compression of air has produced heat. In each case, too, the conditions are such that practically no heat can be transferred to, or taken from, the air compressed, either by conduction or radiation. Such conditions are said to be "adiabatic" and the heating produced is purely dynamical.

20. *Cooling due to Expansion.*—The effect considered above is entirely reciprocal. If compression causes heating, expansion causes cooling. The expanding gases have to do work in pushing away the surrounding air. To do this work they must derive energy from themselves if the conditions are assumed to be approximately adiabatic. This energy must come from the store contained in the vibration of the molecules of which the gases are composed. Consequently, the molecules vibrate a little less quickly and this, following the kinetic theory of gases, means a fall in temperature.

21. *Adiabatic Changes in the Atmosphere.*—As has already been stated, the essential matter in an adiabatic change is that no heat must either get to, or be taken from, the substance under investigation. Such a condition of things is realized in the atmosphere in the interior either of ascending or descending masses of air. Ascent or descent means entry into regions either of less or greater pressure with consequent expansion or compression and resulting dynamical cooling or heating. Such dynamical changes are of the greatest importance in meteorology as they are vital, as will be seen later, in explaining the formation of clouds and rain.

22. *The Vertical Temperature Gradient.*—In ordinary still air, that is, air without vertical components of motion, the temperature falls off generally at the rate of approximately 1° F. for every 300 feet of ascent.

The rate of fall of temperature of ascending air due to dynamical cooling is also fairly accurately known. It is about 1° F. for every 185 feet of ascent. This is termed the adiabatic gradient.

Considering air rising, then, the ascending air falls in temperature at the rate of 1·6° F. in 300 feet, whilst the surrounding air only falls at the rate of 1° F. in the same range. Thus the rising air is falling in temperature at the rate of 0·6° F. for every 300 feet compared with the surrounding air. But the rising air probably started to rise owing to the fact that, in the first place, it was slightly higher in temperature, through some cause or another, than the air which surrounded it near the ground. As it is falling in temperature compared with its surroundings during the ascent at the rate of 0·6° F. for every 300 feet it will be seen that it will soon arrive at such a height that its temperature will become equal to the temperature of its surroundings. When this point is reached, no further ascent will occur.

23. *Temperature Inversions.*—It has been said that temperature decreases in still air with ascent above ground level. Though this is generally the case, it is not invariably so. Sometimes the air increases in temperature as one ascends. Such a condition is known as an inversion of temperature. Such inversions are common during clear-sky nights in winter when radiation from the earth is able to act longest and to exert its maximum effect in lowering the temperature of the surface. The great cooling of the surface chills the air in contact with it to such an extent that its temperature falls considerably below that prevailing in the atmosphere 200 or 300 feet up.

Nor do inversions invariably occur in the neighbourhood of the surface. Quite often they are encountered in isolated layers in the upper air well above the surface. Inversions occurring thus generally mark the margins of cloud layers.

24. *Distribution of Temperature over the Globe.*—Little need be said under this heading as any good book on physical geography will give the details required. The maps used to demonstrate the distribution are constructed by the use of isotherms, that is, lines drawn through places having the same temperature. Isotherms on such maps refer to temperatures at sea level, and hence in order to find from them the actual temperature at a given place, the height of the place must be noted and an allowance of 1° F. decrease per 300 feet of elevation must be made. It should be recognized, too, that the temperatures plotted are mean temperatures over, generally speaking, a considerable number of years.

The isothermal charts for July and January are especially worthy of study. In the July chart the maxima in the centres of the great land masses like north-west India and the Sahara should be noticed. Those maxima would be expected to occur where they do because the sun is nearly overhead there and thus is pouring out a great stream of insolation which the land surfaces greedily absorb with a resulting great rise in temperature. The comparatively low temperatures of the oceans in the same latitudes as the land masses in question are also noteworthy as illustrating the different degrees of heating of land and water when subjected to the same amount of insolation. The bending of the isotherms as they strike the coasts is also interesting in the same connexion.

In the January chart the maxima occur in the land masses of the southern hemisphere as would be expected as a result of the migration of the sun across the equator towards them. The minima in the land masses of the northern hemisphere, for example, in Asiatic Siberia, should also be noticed. These northern districts receive little insolation during their winter and, hence, the good radiating power of land comes fully into play with a consequent great fall in temperature.

25. *Annual Range of Temperature.*—Facts concerning the annual range of temperature in various places may also be learned from a consideration of isothermal charts of the globe. The area of moderate annual range, that is of less than 10° F., extends over nearly all the torrid zone because there the annual variation of insolation is small. It also extends over large parts of the oceans of the southern hemisphere even up to quite high latitudes because the waters are only able to change their temperature with difficulty.

The areas of the most extreme ranges, over 70° F., are only found in the large land masses remote from the equator. Thus they are limited to the northern hemisphere as no great land masses are so situated in the southern. The greatest annual range occurs in the centre of Asiatic Siberia, where it approximates to 120° F. This is all in accord with what would be expected from what has been previously said with regard to absorption and radiation.

CHAPTER VI

Water Vapour in the Atmosphere

26. *General.**—Of all the constituents of the lower atmosphere water vapour is the most variable. At any time the total mass of it is very small compared with the mass of dry air, but the results accruing from that small amount are, from the meteorological point of view, amazingly great.

27. *Evaporation.*—The molecular theory of matter states that matter is discrete and not continuous, being made up of minute particles termed molecules. Further, the molecules are assumed to be in a state of incessant motion.

The results of the incessant motion vary, however, according to whether the matter is in the gaseous, liquid, or solid state. The molecules in the gaseous state are much more sparsely scattered than in either the liquid or solid state; collisions are much less frequent, and, consequently, the particles are much more mobile. Their impact on the walls of the containing vessel produces pressure on those walls. In the liquid state, the molecules, whilst by no means so mobile as in the gaseous state owing to the fact that they are closer together and that considerable forces are exerted between them, are yet sufficiently mobile to allow the liquid quickly to take up the shape of the vessel into which it is put. Whilst most of the molecules in the mass are not free to move far from their mean positions owing to the attractions of the surrounding molecules, yet some will attain to such a momentum that they will, when near the surface, break away from their neighbours and escape into space, thus reducing the volume of the original liquid. In course of time, continued repetitions of such escapes lead to the complete evaporation of the liquid. In thus breaking away from their neighbours, the escaping molecules do work which can only be performed at the expense of the heat energy in the remaining liquid. In consequence of this drawing out of heat, the remaining liquid is cooled and it is possible to find experimentally how much heat energy is necessary to evaporate 1 gram of the liquid. This quantity of heat is termed the latent heat of vaporization and, in the case of water, it is 600 gram-calories. It is to be noted that raising the temperature of the liquid accelerates the motions of the molecules and thus increases the rate of evaporation. In the solid state, the molecules are much less mobile than in the case of either the gaseous or liquid states. This is shown by the low compressibility of solids as well as by the slow rate at which one solid will diffuse into another.

* Many of the data in this, and the succeeding chapter, have been derived from a discourse on "The water in the atmosphere," delivered to the Royal Institution, by Dr. G. C. Simpson, F.R.S., Director of the Meteorological Office, London, and published as a supplement to *Nature, London*, **111**, 1923, April 14.

It is a mistake to suppose, however, that there is no such phenomenon as evaporation in the case of solids. The smell of camphor, for example, is due to the direct breaking away of some of its molecules, and ice is also known to evaporate directly into the vapour state. The heat required to bring about this latter change, however, is exactly the same as though the ice were first changed into liquid water and then the liquid water into water vapour. The latent heat of vaporization of ice is equal to the sum of the latent heat of liquefaction of ice and the latent heat of vaporization of water.

But whether a solid or a liquid be evaporating, the number of molecules which leave each square unit of its surface per unit of time depends only upon the temperature, the number increasing with rise of temperature.

28. *Vapour Pressure.*—Let it be supposed that water is evaporating in a closed, vacuous space. The molecules that escape from the surface of the water accumulate in the space above the water as water vapour. The concentration of this water vapour goes on increasing but the molecules of it are also in a state of incessant motion, and some of them will plunge back into the liquid water from which they originally escaped. The number of the molecules which thus return to the liquid from the vapour increases as the concentration of the latter increases. After a certain interval of time, a point will be reached at which the number of molecules which return to the liquid in any given time is exactly equal to the number of molecules which leave the liquid in the same given time. The system is then in equilibrium and the vapour is said to be saturated. It is to be recognized, however, that the equilibrium is kinetic and not static. There is no state of rest; molecules continue to leave the liquid and molecules continue to return to the liquid; but as the number of each is equal for any given time, no visible result, one way or the other, can be produced.

Though in what has been said the space above the liquid water has been taken as being originally vacuous, it could be filled with air or any other gas and evaporation would continue just as before, and at the point of equilibrium, provided the temperature had not been altered, the same number of molecules would still leave the surface per unit of time.

When equilibrium is attained for any particular temperature, that is, when the vapour is in a saturated condition, there is a definite quantity of water vapour in each unit volume of the space above the liquid water, and this quantity is the same whether there be air in the space or not. This water vapour will exercise a definite pressure upon the walls of the vessel containing it by reason of the impacts of its molecules.

The same holds true for any other temperature; there will be at the point of equilibrium a definite quantity of water vapour, different for each temperature, in each unit volume of the space above the water, and this water vapour will exert a definite pressure entirely irrespective of the pressure of the surrounding air.

For each temperature, then, the actual amount of water vapour in the air above a flat water surface when that air is saturated with water vapour may be expressed either as a mass per unit volume or, and this is more convenient in practice, by the pressure it exerts. Tables have been prepared, and are generally available, giving these data. The lower the temperature the smaller the mass of water vapour per unit of volume and the lower the pressure exerted by that vapour.

29. *The Dew Point.*—From what has been already said, it will be seen that if air, only partially saturated with water vapour, be cooled, a temperature will be reached sooner or later at which the water vapour actually present will be sufficient to saturate that air. Any cooling beyond that point, called the "dew point," will cause some of the water vapour to condense in the form of liquid water.

30. *Absolute and Relative Humidity.*—At any moment, the air contains a certain quantity of water per unit volume, a quantity which varies from place to place. It may, or may not, be saturated The actual amount of water vapour in the air is termed the absolute humidity, of that air. It is most correctly expressed as a mass per unit volume, but, in practice, is more conveniently expressed by the pressure it exerts.

The important meteorological matter, however, is the relative humidity, which may be defined as the ratio of the actual amount of water vapour present in the air to the amount which the same volume of air would hold if it were saturated. It is usually expressed as a percentage. At the dew point, the percentage is 100.

Relative humidity is a very variable meteorological element inasmuch as it depends not only upon the amount of water vapour present, but also upon the temperature of the air, which temperature is continually varying from place to place and from time to time.

31. *The Measurement of Relative Humidity.*—The instruments usually employed at meteorological stations for determining the relative humidity are the dry- and wet-bulb thermometers. These consist of two exactly similar thermometers placed in a Stevenson screen, which consists of a large wooden box with louvred sides. The screen protects the thermometers within from direct sunshine and the louvred sides permit of sufficient ventilation to ensure that the air within is a fair sample of the air without. Further, to obtain the true air conditions, it is erected 4 feet above the ground in the most open, exposed position possible. The dry bulb shows the temperature of the air. The wet bulb is exactly similar to the dry-bulb thermometer except that its bulb is covered by a piece of muslin which is kept wet by means of conducting threads leading into a small vessel containing water.

If the outside air is not saturated, evaporation will take place from the muslin. Energy is needed to break down the inter-attractions of the particles during the evaporation. This energy is obtained at the expense of the heat of the adjacent surface, that is, the thermometer bulb, which records a fall in temperature accordingly.

If the outside air is saturated already with water vapour, no evaporation takes place from the muslin; consequently, there is no fall of temperature recorded by the wet bulb and the two thermometers read the same. If the surrounding air is comparatively dry, that is, if it has a low relative humidity, much evaporation will take place from the wet bulb which will cause considerable cooling of that bulb, and hence there will be a large difference between the readings given by the two thermometers.

Theoretical formulæ have been proposed to obtain the relative humidity of the air from the respective temperatures indicated by the dry- and wet-bulb thermometers, but the phenomena occurring during the experiment are too complicated to lead to a simple yet adequate expression. Tables* have, however, been constructed giving the relationship between the two temperatures and the humidity of the air, and in practice, such tables are always used for obtaining the relative humidity of the air from readings of the dry and wet bulb.

Various instruments for automatically recording the relative humidity of the air from moment to moment have been devised. The best depend for their action upon the fact that the length of a human hair, which has been freed from fat by boiling in caustic soda or caustic potash, varies with the relative humidity of the air in which it is placed, getting longer with increase of humidity and shorter with decrease. A similar phenomenon is observed with spiders' webs, which hang much more loosely when the relative humidity of the air is high than when it is low, and also with the catgut strings of musical instruments. Other materials contract when they absorb moisture, as, for example, rope; with which fact negligent campers in tents are sometimes made painfully aware.

If the human hair—a bundle is found more convenient in practice—be suitably supported, a pen attached to the middle of it may be made to mark the relative humidity upon a properly calibrated chart placed upon a drum which is kept revolving by clockwork. Such self-recording hair hygrometers are very useful, but require great attention, as the properties of hair are subject to slow changes, so that the same relative humidity is not always shown with the same change in the length of the hair. Frequent settings against the relative humidities determined by a dry- and wet-bulb thermometer are, therefore, necessary.

* The tables in use at the Meteorological Office from January 1, 1926, are: London, Air Ministry, Meteorological Office, "Hygrometric Tables for the computation of Relative Humidity, Vapour Pressure and Dew Point from readings of Dry- and Wet-Bulb Thermometers exposed in Stevenson Screens." (M.O. 265, 1924.)

32. *Other Considerations.*—In sections 27 and 28 it was assumed that the surface of the water from which molecules were escaping was flat. This point is important, because the number of molecules which leave a surface depends upon whether that surface is flat or not. More molecules leave a convex surface than a flat one, and more molecules leave a flat surface than a concave one. The point has an important meteorological bearing inasmuch as water often appears in the atmosphere as drops, either as rain-drops or cloud particles.

Let it be imagined that in a closed vessel water vapour is in equilibrium with a flat water surface. Let it be imagined further that a drop of water be introduced into the space above the flat water surface. The drop is convex, and hence more molecules will leave each unit area of its surface per unit of time than leave each unit area of the flat water surface in the same time. But in the same unit of time the drop receives per unit area of its surface from the water vapour surrounding it just as many molecules as does each unit area of the flat water surface. That is to say, the drop in each unit of time receives less molecules than leave it. In other words, the drop is evaporating. The water evaporated from it will condense into the flat water surface, because it increases the number of molecules above that surface and thus destroys the state of kinetic equilibrium originally existing between the ingoing and outgoing particles passing through that surface.

If, however, there is no flat water surface present, and if condensation on to any body is not possible, the vapour pressure will rise above its normal saturation value until the vapour returns to the drop the same number of molecules per unit of time as it receives from it. Equilibrium will then be established between the drop and the vapour, but the pressure of the latter will be above its normal saturation value. Therefore, in order for drops to be in equilibrium with surrounding water vapour, supersaturation of the latter is necessary.

The smaller the radius of the drop the greater must be the amount of supersaturation of the surrounding vapour to prevent the drop from evaporating. It follows from this, too, that the smaller the drop the greater must be the amount of the supersaturation of the surrounding vapour if that vapour is to condense at all upon the drop. Calculations made by Wegener* show that the drops must be extremely small if the supersaturation of the surrounding vapour necessary to preserve equilibrium is to be appreciable. The drops constituting ordinary cloud particles have a radius of 0·001 cm., and for this size the supersaturation necessary for equilibrium is almost negligible, being only 0·00012 per cent; but for smaller drops the supersaturation if equilibrium is to be preserved is comparatively large, a factor which must weigh considerably in the initial stages of rain and cloud formation.

* Wegener, A.—Thermodynamik der Atmosphäre, Leipzig, 1911, p. 71.

33. *Dew.*—About sunset the temperature of the ground, and hence of the air in contact with the ground, begins to fall owing to the increasing effect of radiation. The falling temperature of the air means that its capacity for water vapour decreases, that its relative humidity increases, and that soon the air near the ground is brought very near to its saturation point. From this time onwards the further cooling of the ground by radiation lowers the temperature of the air gradually, and the dew point, the point of saturation, is soon reached. But not only is the air cooling, but also all bodies which can radiate to the clear sky. The loss of heat from all bodies is practically the same, but those bodies which are good conductors of heat and which are in good thermal contact with the ground are able to draw from the supplies of heat contained in the latter, and thus, despite the radiation, their temperatures will not fall very much. On the other hand, bodies which are bad conductors of heat are not able to draw appreciably upon those supplies of heat, and hence, not being able materially to compensate for the loss of heat due to radiation, their temperatures will fall. Rocks are a good example of the former class, and grasses of the latter.

Further, compared with air, all solid bodies are good radiators of heat. Consequently the temperature of grasses, small shrubs, and the like, may fall below the dew point of the air before the air itself reaches that dew point. Hence these solid bodies will chill the air immediately in contact with them to below its dew point and water will be condensed from that air upon them. This theory of the formation of dew was put forward by Wells in 1818. Aitken has amplified this theory by showing that much of the water deposited as dew rises from the damp ground by capillary action, and that some is actually exuded by the plants themselves.

Sir George Simpson* states the conditions which affect the formation of dew as follows :—" Any condition which prevents the cooling of the air or of the bodies on which dew usually deposits is detrimental to the formation of dew. For example, a cloudy sky prevents radiation, while a high wind equalizes the temperature of the air and of the bodies over which it passes, and by mixing up large quantities of air prevents a local fall of temperature near the ground. There are four conditions absolutely necessary to the formation of dew : (1) a good radiating surface, (2) a still atmosphere, (3) a clear sky, and (4) thermal insulation of the radiating surface. It is also necessary, if there is to be a copious deposition of dew, that the ground should be warm and moist, or there should be some other source of water vapour to maintain the supply of moisture to the surface layers of air. Dew is generally formed during all clear calm nights in situations where the air is naturally moist—for example, in marshy country and along the banks of rivers."

34. *Frost.*—When the dew point is lower than 32° F., the water vapour condenses as ice in the form of hoar frost. In the British

* Supplement to *Nature, London*, **111**, 1923, April 14.

Isles the dew point is not often likely to be below 32° F. in the late spring, the summer, or the early autumn. In the remaining part of the year the main factors which an observer, anxious to know whether frost is to be expected, has to consider are the following :—

(*a*) The likely state of the sky face between sunset and sunrise.

(*b*) The likely velocity of the wind during the same period.

(*c*) Local peculiarities of situation.

It is assumed that the observer is propounding his question just before the time of sunset.

A clearing sky and a falling wind are helpful to the formation of frost, as would be expected from what has already been said about dew formation, because a clear sky greatly favours the cooling of the earth's surface by radiation, as has been previously explained, and because calms or very light winds keep any particular sample of the air in contact with the cooling ground for a considerable period, and hence that air is given the best opportunity to become cooled itself.

The effect of situation is that air on the hill-tops becomes cooled more quickly than does the air in the valleys owing to the greater radiation from the hill-tops (*see* section 17). This means that cold air trickles down the hill slopes by gravitation and settles in the valleys. These pools of cold air thus formed in the valleys are all in favour of frost development, with the result that, as a rule, frost becomes more severe as one goes down from the hills into the valleys, and that hollows in the hill sides are colder than the unindented slopes.

A big difference in the dry- and wet-bulb readings at sunset is also a herald of frost provided that the other conditions are favourable, inasmuch as it means that the air is very dry, and that, consequently, it will need to be cooled considerably, probably to below 32° F., to reach its saturation point. The other conditions, the clearing sky and the falling wind, will bring about the maximum cooling ; this maximum cooling, in conjunction with the original very low relative humidity as shown by the big difference noticed between the dry- and wet-bulb readings, ensures that when the saturation point is reached and passed, there will be frost deposited and not dew.

The method of " smudging," sometimes used to protect crops from the damage caused by frost, is interesting, because it is a practical application of a general principle already stated. It has been said (*see* section 14) that clouds prevent the earth's surface from cooling so much as otherwise it would, because they reflect back some of the radiation to it. " Smudging " consists in building a smoky fire on the windward side of the crops to be protected so that a thick layer of smoke drifts over them. The layer of smoke acts just as a cloud in a similar position would do : it reflects back much of the radiation to the earth, and thus maintains the surface temperature at a higher level than that of the non-smoke-screened surfaces in the neighbourhood.

CHAPTER VII

Fog and Mist

35. *General.*—In section 33 it was shown that dew is a direct deposition from the water vapour in the air upon solid bodies due to the fact that the temperature of the latter falls below the dew point of the air, whilst the air itself has a temperature above that dew point. If the temperature of the air itself falls below the dew point, then an entirely different phenomenon, the formation of mist or fog, occurs.

36. *The Necessity for a Nucleus for Condensation.*—To form a water drop in the atmosphere, the basis of mist or fog formation, there must already be present some nucleus upon which the water may form. It was formerly thought that dust particles formed the nuclei for condensation, but very careful work by Assmann,* Wegener,† and Wigand‡ has shown that dust in the ordinary sense of the term is not sufficient. The results of their work point to the fact that the nuclei, whatever they are, begin to attract water to themselves before the air around them is saturated, begin to attract water, in fact, when that air is relatively dry. The nuclei seem to have some natural affinity for water and are nuclei for condensation just because of that property.

Substances are known which have such a natural affinity for water. They are termed "hygroscopic," and examples of them are calcium chloride, common salt, and sulphuric acid.

Meteorological opinion now holds that condensation does not begin upon dust particles in the ordinary sense but upon particles of hygroscopic substances occurring in the air. The nature of these particles is still open to some doubt, but it seems certain that salt, derived from sea spray or from the drying sand of the shore, constitutes a large proportion of them. Household and factory chimneys, too, belch forth great quantities of such nuclei-forming material, the chief of which is sulphur dioxide which, when illuminated by sunlight, becomes a highly hygroscopic substance capable of causing condensation in unsaturated air. The activities of volcanoes constitute another means whereby the atmosphere is supplied with nuclei-forming material.

Nuclei-free air can be prepared experimentally in the laboratory and C. T. R. Wilson has shown that air in this condition can be dynamically cooled until a state of fourfold supersaturation is

* Assmann, R.—*Met. Z., Braunschweig*, **2**, 1885, p. 41.
† Wegener, A.—*Met. Z., Braunschweig*, **27**, 1910, p. 357.
‡ Wigand, A.—*Met. Z., Braunschweig*, **30**, 1913, p. 10.

reached without condensation of the water vapour in it occurring: in other words, the air may be cooled a long way below its dew point without liquid water being deposited. But this hardly concerns the student dealing with the free atmosphere for no sample of that has yet been found, even at heights, to be free from nuclei, which is not surprising when what has been said about the sources of those nuclei is remembered.

37. *Some Lessons from Smoke Aggregations.*—It is instructive to consider some questions arising with regard to aggregations of smoke, especially with regard to the atmospheric conditions which aid in the maintenance of the smoke aggregations once they are formed, for similar conditions may apply to the maintenance of fogs, at least in part.

Imagining, then, that a smoke aggregation is formed in any way, say by the belching forth of several neighbouring factory chimneys, there are two ways in which dissipation of it may be brought about. Those two ways are—

(*a*) A wind, or
(*b*) Upward convection currents.

It is surprising how small a wind velocity is sufficient to disperse smoke, and it would appear that for the maintenance of any considerable smoke in the neighbourhood of the chimneys a calm is practically necessary.

The question of upward convection currents presents points of interest. Let it be assumed that a mass of air is carried upwards from one layer A to a higher layer B. As it rises, it gets into regions of less pressure. Consequently it expands and the expansion causes a fall in temperature. This fall in temperature has already been stated (*see* section 22) to be equal to 1·6° F. in 300 feet. It is clear, therefore, that if the upward temperature gradient of the surrounding air be less than 1·6° F. per 300 feet, the rising mass of air will, when it arrives at layer B, find itself surrounded by air which is warmer than itself. Consequently, the mass of air will have no further tendency to rise, but, on the contrary, a tendency to descend; therefore an atmosphere in which the vertical temperature gradient is less than 1·6° F. per 300 feet will tend to stop upward convection currents. The smaller the vertical temperature gradient is, the more effective does this tendency to stop upward convection currents become. If the vertical temperature gradient be actually reversed, that is, if an inversion of temperature exists, the tendency reaches its maximum effectiveness and no currents are likely to rise at all.

The atmospheric conditions, then, favouring the maintenance of a smoke aggregation once it is formed are (1) the absence of wind and (2) a vertical temperature gradient in the air of value less than 1·6° F. per 300 feet, with this latter condition reaching its maximum efficiency if an actual inversion of temperature exist.

38. *Fogs.*—Fogs are due to the condensation of the water vapour of the atmosphere upon nuclei existing in that atmosphere. The condensation is due in most cases to cooling of the air below its dew point by reason of it radiating either to the night sky or to the cold ground.

One factor, then, in the formation of fogs appears to be the cooling of the surface underneath the air in which the fog appears. But the differences of land and sea in regard to such cooling need to be borne in mind. The land surface is subject to great changes of temperature due to its great powers both of absorption and radiation of radiant energy. The extent of these changes depends, as has already been said, upon the cloudiness of the sky. Sea surfaces, on the other hand, have a very much more limited range of temperature; and, in fact, the diurnal variation is sometimes almost inappreciable.

The thick " pea-soup " fogs, characteristic of London and other large industrial centres, require some mention. The atmosphere in those centres is full of actual particles of carbon and the like, emitted in the smoke from the many chimneys. The water forming the basis of the fog is deposited upon the small hygroscopic particles, the nuclei, already discussed. When the drops are once formed they absorb the carbon and dust particles and, in consequence, become dark. The fog would form without the black smoke particles but it would be a white fog and not a black one. Smoke abatement would, therefore, not do away with fogs, but it would do much to make the fogs occurring white and not black, and to this extent is worthy of much consideration.

39. *Fog at Sea.*—The famous fogs of the Newfoundland Banks are a typical example of the formation of fog at sea. In the region of that island, the temperature of the sea water is kept low by reason of cold currents from the Arctic flowing into it. In the summer time it is surrounded on all sides, except the north, by considerably warmer regions. Air blowing across the Banks, then, from south, east, or west, is cooled by contact with the cold waters. If the air blowing in is nearly saturated with water vapour, the cooling produced is sufficient to bring it down to its saturation point and water condenses around the nuclei in the air and a fog is formed. This is especially the case with southerly winds.

So far as England is concerned it is important to notice the frequent formation of sea fogs by reason of the arrival of air on our south-west coasts from equatorial latitudes. The prevalence of fogs at Scilly and at the mouth of the English Channel is largely to be ascribed to this cause. The air in contact with the water becomes cooled, resulting in the formation of a shallow temperature inversion in which fog is formed, the latter process being brought about by eddy motion consequent on the frictional effect of the surface of the water on the air passing over it, the eddying producing the necessary mixing.

40. *Fog on Land.*—Fogs occurring on land may be divided into the following main categories :—

(*a*) radiation fogs ;
(*b*) smoke and dust fogs ;
(*c*) fogs in tropical air moving poleward ;
(*d*) fogs in coastal regions due to the drifting in of sea fogs that were formed in a warm current of air moving over a colder sea ;
(*e*) fogs formed in warm air moving over cold ground.

All the above, with the exception of (*b*) are water-drop fogs.

Radiation fogs are formed generally between sunset and sunrise and occur mostly in autumn and winter. The conditions promoting their formation are a mainly clear sky and a light surface wind or calm : the first condition permits radiation out to space to be abundant and hence allows the ground, and the air in immediate contact with the ground, to become greatly cooled, while the second condition acts by keeping the mass of air long enough in close proximity to the surface of the ground to enable it to become thoroughly cooled. Radiation fogs usually disperse before midday but sometimes in winter, particularly if the sky becomes overcast, they persist for some days.

Smoke fogs, purely as such, are of comparatively rare occurrence. They occur when the accumulation of smoke in the atmosphere is so great as to make the obscurity sufficient to justify the use of the word "fog." This degree of obscurity is defined in the next section. Smoke fogs are a product of large towns and of industrial areas. The worst type of fog in such towns and areas is obtained, however, when a smoke fog coincides with a water-drop one. These " pea-soup " fogs have already been treated in section 38.

Dust fogs, purely as such with no smoke component in them, occur fairly frequently in desert regions : for example, such fogs are often experienced in western Africa at the season of the " harmattan " (see section 17).

Fogs formed in tropical air as it moves poleward may occur either during the day or night: the air travelling over a long track from tropical or sub-tropical regions is cooled to below saturation point partly by reason of its movement towards higher latitudes and partly, often enough, by reason of its travel over cooler seas.

The fourth type is really a variant of the one just considered : it is that of fogs in coastal regions due to the drifting in of sea fogs formed by a warm current of air moving over a colder sea. This type, too, may occur either during the day or night. In England, fogs of this kind are frequently experienced off and over the south-west coasts and these fogs have already been treated in section 39.

The fifth type of fog specified is that formed in relatively warm air moving over cold ground. This case is one in which a warm, moist current passes over ground which is cold either because of being snow-covered or frozen or for some other reason. Such fogs are not of frequent occurrence nor are they persistent. They may be produced either in day-time or night-time.

It has also to be noticed that low cloud actually enveloping and down to the surface on elevated ground will constitute fog for an observer on that ground.

(For a treatment of the "high fogs" produced above cities and industrial areas under anticyclonic conditions, the reader is referred to section 89. As the fogs in question are not at ground level, they have not been included in this present section.)

41. *Mist.*—It is a matter of some difficulty to distinguish between fog and mist. The practical method of differentiation is based on how far one can see: it is usual to limit the term "fog" to a condition of obscurity of the atmosphere in which objects at a distance of one kilometre (roughly 1,100 yards) are not visible, and the term "mist" to that condition of obscurity in which objects at a distance of one kilometre are visible but not objects at a distance of two kilometres. (Haze is defined similarly to mist from the view-point of distance of visibility: for the differentiation between the two, mist and haze, the reader is referred to the next section.)

Mists and fogs are similar in many respects to clouds, but there is one fundamental difference which makes it very undesirable to describe them as "clouds near or on the ground." As will be seen later (Chapter IX) clouds are nearly always caused by temperature changes due to adiabatic cooling when air ascends. This means that clouds are due to pressure changes in the mass of air itself. Pressure changes, however, play little part in the formation of mists and fogs. The cooling of the air which causes these latter phenomena is due, not to pressure changes, but either to the ground underneath becoming cooled and communicating that cooling to the air or to the drift of the air over a cooler surface.

42. *Haze.*—Further difficulty is introduced by haze. Haze may be due to smoke or dust due to the neighbourhood of a town, or to dust raised from the ground by wind, or to irregularities of density in the atmosphere and consequent irregular refraction of the light such as occurs over the flame of a bunsen burner. It seems well to limit the use of the term "haze" to those occasions when the air is dry, and to use "mist" when the air is wet. The dividing line is generally taken as 80 per cent relative humidity, but a skilled observer is usually able to see if the obscurity is caused by dust particles or irregular refraction, or by condensed water vapour.

43. *Visibility.*—Visibility, with which haze, mist and fog are intimately connected, is measured at meteorological stations by selecting a number of objects, such as church towers, buildings, and the like, within definite limits of distance and determining at the time of observation which object can be seen, whilst the one at a greater distance just beyond it cannot be seen. At night, distant lights are similarly used.

The whole subject is, however, a difficult one. The state of visibility, of good or bad seeing, depends upon a considerable number of factors. It depends not only upon the meteorological conditions prevailing at the time but also on the conditions which have gone before. It depends, also, upon the geographical location of the place with regard to sources of atmospheric pollution in the form of dust, smoke, salt particles, etc. The structure of the upper air, too, is important, especially with regard to temperature.

A few of the results that have been obtained may be noted. Generally, horizontal visibility increases at inland stations with increase of wind velocity but something like the opposite is true for stations on the coast. With regard to wind direction, the correlation that usually exists between that and horizontal visibility at a given place can generally be explained by the prevalent humidities and dust and pollution contents associated with the various wind directions. On days when convection upward from the surface is strong, horizontal seeing at the surface of the ground is usually markedly better than it is on days when such convection is weak or non-existent. In this connexion it is to be noted that inversions of temperature near the ground are a cause of bad seeing as they prevent the upward convection currents. Again, good seeing is generally associated with low relative humidity of the air and poor seeing with high relative humidity.

44. *The Variation of Fog with Place and Time in England.*—It is a matter of considerable importance to the practice of aviation, especially with regard to the choice of sites for aerodromes and to the selection of air routes, to discuss the distribution of fog with regard to place. A recent paper by Entwistle* enables some conclusions relating to this with regard to England to be placed on record.

The author examines sixteen stations and gives for each station the number of days per hundred on which visibility was less than 500 metres and 2000 metres respectively. The figures were obtained by computing the frequencies for each of the hours 7h., 13h. and 18h. G.M.T. over the period 1920–5 and averaging these frequencies to obtain the frequency for the day.

Arranging, then, the stations in order of frequency it was found that, generally speaking, the stations showing least fogginess were all situated on the coast near sea level; the freedom from fog of such stations is attributed partly to the fact that the wind at them rarely falls sufficiently to permit the formation of fog, and partly to their small diurnal range of temperature owing to their proximity to the sea. Inland stations with open exposures follow next in order of fogginess, whilst at the end of the list come stations showing the largest amounts of fogginess, stations lying in close proximity to large manufacturing cities where the predominating factor is smoke pollution. These statements are general, and in any particular case the topography of the district must be closely regarded.

* "Meteorology in relation to the selection of aerodrome sites." By F. Entwistle. Read before the III Congrès International de Navigation Aérienne at Brussels, October 1925.

With regard to the relative frequencies of fog and mist at different seasons, the stations situated on the coast near sea level have a larger proportion of fog or mist in spring and summer as compared with other stations, although autumn is relatively a foggy season. Conditions are most favourable during the latter season for the development of fog over land areas and the fog at these coast stations in the autumn would be due mainly to the drift of inland fog over the sea. The low visibilities in spring and summer, however, are due to sea fog, which readily develops at these seasons when air which has become warmed in passing over adjacent land areas, drifts over the relatively cold sea, or when air reaches the south-west coasts from equatorial latitudes. The air in contact with the water thereby becomes cooled, resulting in a shallow temperature inversion in which a sheet of fog is formed.

With regard to stations other than those of the stations situated on the coast near sea level, autumn and winter stand out pre-eminently as the foggy seasons : whilst summer is the season most free from fogs, which are confined, for the most part, to a few early morning mists.

The author also treats of the diurnal variation of fog and mist at different stations other than those lying low on the coast, and finds that there is, generally speaking, a well-marked maximum in the early morning which varies from season to season, occurring from one to two hours after sunrise. This is followed by a rapid improvement in visibility, the period from noon to 18h. being comparatively free from fog. Even in autumn, one of the foggy seasons, the improvement in the afternoon is still well marked, but in winter it is much less so. This diurnal variation suggests as an explanation the normal diurnal increase in eddy motion in the atmosphere. During the night, convection having ceased and the wind fallen light, the ground becomes cooled by radiation. Provided the cooling is carried sufficiently far and the ground is sufficiently moist, the resulting atmospheric stratification is analogous to that which we considered in connexion with the formation of sea fog, and very little turbulence is necessary to produce fog in the surface layers by mixing. During the period immediately following sunrise, the slight warming of the lowest layers of the atmosphere, whilst insufficient to cause convection on an appreciable scale, causes a slight increase in turbulence which extends the mixing of the surface layers, causing an increase in the amount of fog. Further warming, however, brings about convection sufficiently vigorous to extend the mixing upwards so as to include drier air and this process, together with the general rise of temperature and increase in the wind speed, causes a progressive dispersing of the fog, which continues throughout the day till towards sunset.

Further matter relevant to that treated in this section will be found in section 49, in which the question of aerodrome siting with regard to low cloud is discussed.

CHAPTER VIII

Clouds

45. *Classification.*—Cloud phenomena are "infinite in their variety." Certain types may be selected as standard, but even a short period of observation reveals that the types selected do not exhaust the clouds actually appearing. All manner of intermediate types occur. The series of clouds is continuous. Nevertheless it is necessary to have some classification.

Luke Howard in 1803 was the first to propose some such classification. He distinguished three principal cloud forms—

(1) Cirrus cloud (which included all types of fibrous or feathery appearance).

(2) Cumulus cloud, having rounded tops and being generally lumpy in appearance.

(3) Stratus cloud, applying to all clouds lying in level sheets.

This classification suited the purposes of those comparatively early times when accurate observation was in its infancy. In course of time, however, attention was directed to smaller degrees of difference, and the need for a more detailed classification became apparent.

46. *The International Classification.*—Matters came to a head in 1894, and at a meeting of the International Meteorological Committee held in that year at Uppsala the publication of a cloud atlas, which should at the same time be a classification, was entrusted to MM. H. H. Hildebrandsson, A. Riggenbach and L. Teisserenc de Bort. The first edition of the atlas was published in 1895, and a new edition, incorporating the improvements suggested at the International Meteorological Conference at Innsbruck in 1905, appeared in 1910.

Progress of knowledge concerning clouds and cloud formation did not cease, however, but went on apace ; and with the passage of the years a revision of the Innsbruck edition became necessary. That revision was commenced in 1923 by the International Commission for the Study of Clouds and terminated in 1930 with the publication of a new atlas and classification. This classification, consisting of 10 main types, backed by international authority and agreement must be regarded as the standard until some International Commission of the future again is impelled by growth of knowledge to revise.

47. *The International Cloud Forms.*—Definitions* and descriptions of the 10 types of clouds are now given. In brackets after the names of the clouds are the abbreviations usually employed to denote those clouds.

(1) **Cirrus (Ci.).**—Detached clouds of delicate appearance, fibrous (threadlike) structure, without true shadows, generally white in colour. Cirrus clouds take the most varied shapes, such as isolated tufts, thin filaments pencilled on a blue sky, branched filaments in feathery form, curved filaments ending in tufts, etc. Often they are arranged in bands which traverse part of the sky as arcs of great circles and which by perspective effect converge towards two opposite points on the horizon. (Often cirrostratus and cirrocumulus participate in the formation of these bands.)

(2) **Cirrocumulus (Cc.).**—Small rounded masses or white flakes without shadows, arranged in groups or lines or sometimes in the form of ripples such as those formed on the sand on the sea shore.

(3) **Cirrostratus (Cs.).**—Thin veil of whitish clouds sometimes entirely diffuse and giving the sky a milky appearance, sometimes showing more or less distinctly a fibrous structure like a tangled web. The veil often produces halo, around the sun or moon.

(4) **Altocumulus (Ac.).**—Rounded masses or discs, more or less large, arranged in groups, in lines or in rows, following one or two directions and sometimes so crowded together that their edges are joined.

(5) **Altostratus (As.).**—A veil of a colour more or less grey. Sometimes the veil is translucid resembling a thick layer of cirrostratus and through it the sun or moon can be seen dimly gleaming as through ground glass. At other times it forms a thick layer of dark, grey hue, indistinct or fibrous, or, more rarely, wavy.

(6) **Stratocumulus (Sc.).**—Large, lumpy masses or rolls of dull, grey cloud frequently covering the whole sky and sometimes giving it an undulating appearance. Generally, the layer of stratocumulus is not very thick and the blue of the sky often appears in the gaps.

(7) **Stratus (St.).**—A uniform layer of cloud, like fog in appearance but not lying on the ground. When this cloud layer, lying very low, is broken into ragged masses, it may be distinguished by the name **Fractostratus (Fs.).**

* The definitions given are, in the main, free translations or adaptations from the French of the "Atlas International des Nuages et des Etats du Ciel." Paris à l'Office National Météorologique, 1930.

(8) **Nimbostratus (Ns.)***—A low layer of structureless and rainy-looking cloud, sombre grey in colour. When rain or snow falls from this cloud, it is of a continuous nature but precipitation is not an essential of the definition of the cloud.

(9) **Cumulus (Cu.).**—Thick cloud whose summit is dome-shaped and exhibits protuberances, while the base is nearly horizontal. When the cloud and the sun are on opposite sides of the observer, the surfaces facing the observer are more brilliant than the margins of the protuberances. When, on the contrary, it is on the same side of the observer as the sun it appears dark with bright edges. When the light falls sideways, as is usually the case, cumulus clouds show deep shadows.

True cumulus has well-defined upper and lower margins, but there are sometimes to be seen ragged clouds—like cumulus torn by strong wind—of which the detached portions are continually changing in shape : to this form of cloud the name **Fractocumulus (Fc.)** may be given.

(10) **Cumulonimbus (Cb.).**—Great masses of cloud rising in the form of mountainous towers of which the upper parts, of fibrous texture, sometimes spread out in the form of an anvil. From the base local showers of rain or of snow, occasionally of hail or soft hail, usually fall. Sometimes the massive heaps at the summit have attached to them **Cirrus Nothus** which delicate cloud consists of the ice-crystal tops characteristic of well-developed cumulonimbus. Cirrus nothus was formerly termed "false cirrus" and is in the form of wisps or filaments closely resembling ordinary cirrus in appearance.

Mention is also made in the classification of certain shapes that may be assumed by most or all of the 10 types of cloud. Of these shapes, three are noted here as being the most interesting.

(*a*) **Lenticularis (Lent.).**—The form taken by certain clouds, especially during days of föhn, of scirocco, of mistral, etc., showing an ovoid form with sharply defined edges and sometimes irisation. This cloud exists at all levels from cirrostratus to stratus. Clouds so shaped are denoted as cumulus lenticularis (Cu. lent.), altocumulus lenticularis (Ac. lent.) and so on.

* At a meeting held at De Bilt on October 7, 1933, the International Meteorological Committee passed the following resolution :

> 17. The Committee approves the introduction of the term Nimbostratus—with the definition given in the New International Atlas of the Clouds—into the nomenclature of clouds and the substitution of the term Fractonimbus in place of Nimbus as an optional name for the "ragged low clouds of bad weather" (Cloud Code $C_L = 6$).

It will be noticed that by this resolution the term Nimbus disappears from the International Cloud Nomenclature as the name of a specific cloud, the word nimbus now appearing only in the combinations Cumulonimbus, Nimbostratus and Fractonimbus.

(*b*) **Cumuliformis (Cuf.)**.—A special form that certain clouds present when their upper parts grow up like cumulus. This form may be noted at all levels from cirrus to stratus.

The most important member of this group is **Altocumulus Castellatus** (Ac. cast.) which may be defined as a layer of altocumulus on which some of the separate clouds have developed cumuliform heads or turrets. (This cloud is useful to the forecaster as a precursor of thunder.)

(*c*) **Mammatus (Mam.)**.—This name applies to all clouds of which the lower surface shows rounded projections or pap-like protuberances. Clouds so marked are denoted as altostratus mammatus (As. mam.), and so on.

48. *Other Considerations.*—The 10 main types of international classification are subdivisible into—

(*a*) Cloud sheets.
(*b*) Heap clouds.

Cumulus and cumulonimbus are heap clouds and the remaining types cloud sheets. The heap clouds are characterized by considerable vertical structure but do not form horizontal layers. The cause of their formation, ascensional movement of air, will be treated in the next chapter. The height of heap clouds is very variable. It has been estimated that the mean height of their bases is approximately 4,500 feet, but they are often found much lower, and the height of their summits varies from about 6,000 feet up to even 25,000 feet.

Cloud sheets, on the other hand, are characterized more by horizontal extension than by considerable vertical structure. Sometimes the sheets have breaks in them, sometimes they have not. Quite often, indeed, the sheets are represented by just a few isolated clouds in a mainly blue sky. The sheets vary considerably in thickness and, often, the sky shows several cloud sheets or layers existing at different levels at the same time.

The height of cloud sheets is also very variable. Cirrus, cirrostratus and cirrocumulus are generally above 25,000 feet; altostratus and altocumulus are generally between 10,000 and 25,000 feet; and stratocumulus, nimbostratus, and stratus are generally below 7,000 feet.

Cirrus, cirrostratus, and cirrocumulus clouds are composed of ice crystals. It is important to notice that halos only occur in these very high clouds, inasmuch as halos are an optical phenomenon due to regular refraction of the light of the sun or moon as it passes through ice crystals. This point will occur again later in connexion with the forecasting of weather and with weather lore.

49. *The Variation of Low Cloud with Place and Time in England.*—In section 44 will be found a discussion upon the variation of fog with place and time in England based upon a paper by Entwistle.

Of equally great importance to the practical aviator is the variation of low cloud with place and time in England, which matter is discussed in the same paper. The results gained may be briefly summarized as follows. The stations which show the smallest frequencies of low cloud (below 500 feet and below 1,000 feet) are situated on or near the coast near to sea level. There are, however, fairly large differences between individual stations on account of their geographical positions. The next smallest frequencies of low cloud are found at inland stations in the Midlands and east. Following these come two stations on the west or south-west coast and in each of these cases there is high ground in the vicinity and they are remarkable for the relatively high frequency of very low cloud, that is cloud below 500 feet, with the highest frequency in the summer months. The explanation appears to be found in moist or even foggy air drifting from the sea over the less regular and warmer land surface, with the result that stirring would ensue. The result of this stirring would be to warm the superficial layers, perhaps causing the fog to dissipate, but at the same time producing cooling and condensation at a somewhat higher level: in other words a layer of low cloud would tend to be formed. The high ground plays a part in that it would tend to produce a general lifting of the air assisting the cooling and consequent formation of the cloud. After these south-western or western coast stations, follow other stations where the increased frequency of low cloud may be ascribed in the main to their altitude above sea level.

The diurnal variation of low cloud at different seasons follows closely the same lines as that manifested by fog (*see* section 44). There is, for example, the same maximum occurring after sunrise and the well-marked improvement in the middle of the day, especially in spring and summer. The similarity indicates that the same causes operate in the two cases in bringing about the normal diurnal change, these causes being set down in section 44. During the night, however, the turbulence would not be sufficient normally to carry the surface air far enough upwards to produce condensation and its effect would be limited to the lowest layer.

Autumn and winter are shown to be the seasons in which the diurnal variation of low cloud is the least marked, a result in accordance with expectation.

The results set out in this section and in section 44 suggest to the author whose paper has been so largely drawn upon that, from a meteorological point of view, the best site for an aerodrome would be on the coast near sea level. The suitability of such a site would be discounted to a certain extent, however, by exposure to strong winds and gales. For an inland station, the best site would be one at a low elevation with an unrestricted exposure such that there would be free drainage for chilled surface air. The worst sites would be those in the neighbourhood of manufacturing areas, sites on high ground or sites on the coast exposed to moist winds (usually from the south-west or west in Great Britain), especially with high ground to leeward.

The selection of a site for an aerodrome is a matter of great importance to practical aviation, and enough has been said to demonstrate that, in that selection meteorological considerations, especially with regard to low cloud and visibility, should play an important part.

50. *General.*—There is no royal road to a knowledge of cloud forms except the strenuous one of diligent observation of the face of the sky on as many occasions as possible, together with a careful comparison of what is observed with the descriptions of cloud forms already given. An atlas of cloud forms, ready at hand, is a very useful aid.

Such a study will be found at once delightful and useful ; delightful because clouds are the main component of the variety and exquisite beauty of the face of the sky, and useful because, as will be seen later, it affords most valuable information to the forecaster anxious to know what the weather is likely to be. Clouds are alike beautiful and significant, and a study of them is confidently recommended to all.

CHAPTER IX*

The Formation of Clouds, Rain, Hail and Snow

51. *Condensation by Dynamical Cooling.*—This is the chief, and perhaps the only, cause† of cloud-making. In all cases where a vertical or obliquely ascending motion is given to air, the air rises into regions of diminishing pressure. Such diminishing pressure upon the rising mass of air means that that air expands. As has been already stated, this expansion takes place adiabatically ; that is to say, considering the interior of the rising mass of air, no heat is either given to that interior or taken from it. Such adiabatic expansion is necessarily accompanied by cooling, inasmuch as expansion means that work must be done in pushing back the surrounding air and that the energy necessary for the accomplishment of this work must come from the internal supplies held by the air in the rising mass. Such subtraction of energy from the molecules of the air in the mass means that the amplitude of vibration of those molecules is diminished. This, in its turn, means that cooling takes place in the interior of the ascending air.

The ascending air, then, merely because of its gain in elevation, cools. The rate of the cooling (*see* section 22) due to this cause is 1·6° F. in every 300 feet of ascent. The temperature gradient upward of the surrounding air is, generally, about 1° F. in the same number of feet. This means that the rising air loses 0·6° F. for every 300 feet rise compared with the surrounding air. In a longer or shorter time, then, that rising air will arrive at such a height that its temperature, originally greater than its surroundings, becomes equal to that of its surroundings and no further ascent will then take place through the ordinary processes of convection.

Before this position of comparative equilibrium is reached, the ascending air may have cooled to its dew point. The nuclei present, however, may be so small that condensation cannot at once take place, as supersaturation would be required to maintain the drops formed. The air, then, continues to rise until it is sufficiently supersaturated to allow of water being deposited on the small drops. The moment, however, that water is thus deposited, the drops, by reason of their increase in size, require a less supersaturation. A small drop in supersaturated air is, in fact, in a state of unstable equilibrium : the moment its size is increased at all, water is deposited upon it until it reaches such dimension that there

* In this chapter, as in chapters VI and VII, the writer is indebted to Sir George Simpson, *see* Supplement to *Nature, London,* **111**, 1923, April 14.

† Dr. A. Wegener, in Chapter 16 of his "Thermodynamik der Atmosphäre," Leipzig, 1911, gives the reason for this view.

is practically no supersaturation in the surrounding air, for the amount of supersaturation necessary for equilibrium decreases rapidly with increasing size. It has already been stated (*see* section 32) that cloud particles, as shown by direct measurement, have a radius of about 0·001 cm. and that drops of this size only require 0·00012 per cent supersaturation of the surrounding air for equilibrium. This supersaturation is practically negligible and it may be said therefore that the air in a cloud is not in a state of supersaturation, but the initial supersaturation, often necessary before condensation actually begins, is noteworthy.

As soon as condensation has actually begun, further deposition will continue upon the drops so long as the air current continues to ascend. The drops will thus increase in size until they fall as rain.

52. *The Fall of Water Drops through the Air.*—Some consideration of the laws governing the fall of water drops through the air is necessary before the actual formation of rainfall is treated.

In a vacuum, all bodies fall at the same rate with a constant acceleration. When, however, bodies fall through a resisting medium, such as air, they do not continually increase in velocity but only increase until the air resistance is exactly equal to the weight of the falling body under consideration, when the latter thenceforward continues to fall at a constant speed. This speed is not strictly uniform, but decreases with the increasing density of the air in the lower layers.

The rate at which a rain drop falls depends upon its size. The steady speed ultimately attained is called the " terminal velocity " and Lenard has prepared the following table* (Table II) showing how the terminal velocity in still air varies with the size of the drops.

TABLE II

Terminal Velocities of Water Drops falling in Air

Diameter of drop		Terminal velocity		Diameter of drop		Terminal velocity	
mm.	in.	metres/sec.	miles/hour	mm.	in.	metres/sec.	miles/hour
0·01	0·0004	0·0032	0·007	3·0	0·118	6·9	15·4
0·1	0·0039	0·32	0·71	3·5	0·138	7·4	16·5
0·5	0·020	3·5	7·9	4·0	0·157	7·7	17·2
1·0	0·039	4·4	9·8	4·5	0·177	8·0	17·9
1·5	0·059	5·7	12·6	5·0	0·200	8·0	17·9
2·0	0·079	5·9	13·2	5·5	0·216	8·0	17·9
2·5	0·098	6·4	14·3				

* Extracted from the "Meteorological Glossary" (4th issue). London, Meteorological Office (M.O. 225 ii.) p. 336.

The frictional resistance offered by air to a drop depends upon the relative motion of the two. It does not matter whether the air be still and the drop moving, or vice versa, or whether both are moving with different velocities. The terminal velocities given in Table II may be looked upon, therefore, as the velocities with which air must be moving vertically upward to keep drops of the diameters stated floating, without rising or falling. Lenard, in fact, actually obtained his results from experiments with vertical air currents and drops of known size.

The important fact to notice is that the terminal velocities do not increase indefinitely with the size of the drops, but that when the drops attain to a certain diameter the terminal velocity remains constant at 8 metres per second (25 feet per second or 17·9 miles per hour) for further increases in size.

This is due to the fact that the drops become deformed, flattening out horizontally so that the air resistance is increased. For diameters greater than 5·5 mm. (0·216 in.) the deformation becomes so great that the drops break up before the terminal velocity of 8 metres per second is reached.

It follows, therefore, that no rain can fall through a current of air ascending at a greater velocity than 8 metres per second. In upward currents of velocity greater than that limit, the drops are either carried up intact or after being broken up into smaller drops.

It is known that upward currents having such velocities do exist from time to time. The drops formed in such currents are afforded ample opportunity to increase in size, and it is therefore probable that such currents carry up with them great quantities of water. The large drops so formed have two ways of reaching the earth; first, by being carried on into the outflow of air above the region of violent convection, or second, by a sudden stoppage of the upward convection. Such sudden stoppages are probably the cause of the very heavy rains experienced in what are termed " cloud bursts."

53. *The Formation of Rain.*—It is pertinent at this point to outline briefly the process which causes rain. When the wind circulation is such that the air currents flow towards a common centre, as is the case in cyclones (*see* Part II), the only way by means of which the air can escape is by upward motion. Its ascent is accompanied by the phenomena of expansion and cooling. When the dew point is reached condensation commences upon the nuclei present. The drops formed at first are very small, probably of the order of 0·002 mm. diameter, and thus they are carried upward with the rising air. The further ascent means further cooling and more condensation of water upon the drops, thus increasing their size. When the diameter reaches 0·2 mm., the drops are falling relatively to the air at the rate of about 1 metre per second, which is more rapid than air currents normally rise and thus the cloud begins to rain.

54. *Condensation at Temperatures below the Freezing Point.*—In a consideration of condensation occurring at temperatures below the freezing point, there are two cases to examine :—

(*a*) when the condensation commences before the temperature falls below the freezing point ;

(*b*) when condensation only commences after the freezing point has been passed.

The first of these two cases comes into operation when the ascending currents continue until the temperature of 32° F. (the freezing point) is reached and passed, the dew point being above 32° F. The point arises as to whether the water drops freeze after the freezing point is passed and, if they do, what form they take.

Now, observations have been made in balloons and on mountain tops, and these have revealed the fact that water drops, certainly in the liquid form, can exist with temperatures as low as 0° F. It is clear, then, that small drops can be supercooled a long way without solidifying. Exactly how far such supercooling can be carried is not known but, in any case, the state is one of instability. If, for any reason, a few drops do solidify, they find themselves at once in a greatly supersaturated atmosphere and condensation in the solid form rapidly takes place upon them. The equilibrium over the other drops is at the same time destroyed, and the water drops rapidly evaporate, the water distilling from the drops on to the ice particles.

Most big clouds formed as a result of an upward current of air are divisible into three parts. First, there is the lowest layer where the cloud particles are in the form of liquid water drops ; next, there is a region where the cloud particles are still water drops but in which the latter are more or less supercooled ; and thirdly, there is the highest region of the cloud where the drops are frozen into ice, this region being usually called the " snow region."

55. *Hail.*—There is no sharp line of demarcation between the snow region and the region of supercooled water. For quite a distance ice crystals and supercooled water are co-existing. If a supercooled water drop impinge against an ice crystal it at once solidifies and, at the same time, imprisons a little air. Consequently, the ice crystal increases in size and will begin to fall if the velocity of the ascending air be not too great. But as it falls it passes through the entire length of the region of supercooled water with the result that it grows still more, and imprisons more air, arriving at the bottom of the supercooled region as a ball of soft ice without any definite crystalline structure.

If the velocity of fall of the ball through the supercooled region has been at all great, it arrives in the region where the temperature is just 32° F. with its own temperature lower than 32° F. Consequently any further falling means that water is directly deposited upon it, which water covers the surface of the ball with a uniform layer of liquid which quickly freezes as a hard, transparent covering with little or no air imprisoned in it. Finally the ball falls out of the base of the cloud as a hailstone.

Hailstones cut open to reveal their structure show the soft core of white ice and the hard transparent layer of clear ice which are in conformity with the theory of formation which has been outlined.

But there is a further addition to be made to the life-story of large hailstones. An ascending current of air is not steady but composed of increases and decreases, of gusts and comparative lulls. A hailstone which has reached the lower part of the cloud may meet one of the gusts and be blown upwards and thus be forced to go through the whole process again, a layer of white, soft ice being formed around the previous transparent layer, and another transparent layer being added around that. Further repetitions of the carrying up add additional layers. A hailstone, if cut open when it finally falls after such a protracted history, would show several concentric layers of white and clear ice. Such hailstones have frequently been found.

Two conditions, then, seem essential for the production of large hailstones :—

(*a*) the clouds must possess great vertical structure so that the three regions—the water region, the supercooled region, and the snow region—are well developed.

(*b*) there must be present ascending currents of air of considerable violence so that the hailstones, once formed, may be whirled up and down several times.

Warm regions best favour the production of these conditions for there the high temperature reached by the ground during the hours the sun is well above the horizon favours the formation of violent ascending currents and, at the same time, condensation starts at comparatively high temperatures, thus making the water and the supercooled regions of the clouds to be of extensive depth.

56. *Soft Hail.*—If the point where the temperature is just 32° F. (the freezing point) be near to the ground, the hailstones in falling from that point to the ground do not have much water deposited on them and so the hard, transparent layers (*see* section 55) covering the soft, white core are more or less absent and the hail arrives at the ground as just the original soft white ice. It is then known as " soft hail." It is assumed that there are no violent upward currents present so that the hail is not subjected to rapid whirlings up and down.

57. *Further Consideration of Condensation at Temperatures below the Freezing Point.*—In section 54 it was stated that there are two cases of condensation occurring at temperatures below the freezing point. The first of these two cases has already been considered in sections 54–56. The second case is when the condensation only commences after the freezing point has been passed.

Sir George Simpson approaches the subject from a study of fogs and iridescent clouds seen in the Antarctic.* He describes one occasion, for example, on which he was enveloped in a fog during sunshine. A white bow was seen on the fog opposite the sun in the position usually occupied by a rainbow. The formation of such a bow, however, could only be explained on the assumption that the fog was composed of small drops. The temperature of the air was −21° F. Experiments on iridescent clouds also led him to the conclusion that the effects observed in them, as well as in the fog, could only be produced by the refraction of light by small spheres. Iridescent clouds, however, are only formed in very low temperatures in polar regions or at very high elevations in temperate ones. His general conclusion then was, that supercooled water exists at much lower temperatures than is usually thought possible.

It is clear that the air, in which the water drops formed to give the effects already referred to, was far below the freezing point in temperature. The problem is how water drops can form at such a temperature.

Sir George Simpson† states that the solution of the problem is to be found in the chemical fact enunciated in the following quotation‡ :— " As has been shown time and again, when a new phase, which is finally solid, makes its appearance suddenly, whether from vapour or solution, it appears first as a liquid ; it may run through many intermediate (labile) forms before reaching its final solid form. Sulphur, for instance, forms globules, which crystallize later. Crystallization as spherolites is well known."

When, then, water vapour condenses at low temperatures it forms, first of all, in liquid drops which crystallize afterwards.

58. *Snow.*—Once the first crystals are formed, further condensation takes place, but now the vapour condenses directly into the solid form without going through the intermediate liquid stage. Water crystallizes in the hexagonal form. Snow flakes are formed of one or more ice crystals and the variety of patterns formed as the result of the agglomeration of the crystals is almost infinite. When snow falls with comparatively high temperatures, large, wet flakes are often the result ; with lower temperatures, the flakes are smaller ; and, if the temperature be much below the freezing point (32° F.) " snow dust " results, that is, the crystals are so small as to appear like dust.

59. *Sleet.*—Sleet, which is such a common phenomenon in such countries as the British Isles, may be defined as the precipitation of snow and rain together, or of partially melted snow. It is, perhaps, snow which has fallen through an inversion of temperature. The layer of comparatively warm air thus encountered causes a partial liquefaction, especially if the temperature be much over 32° F. as it often is in an inversion comparatively near the ground in temperate latitudes.

* See *London, Quart. J. R. met. Soc.*, **38,** 1912. p. 291.
† Supplement to *Nature, London,* **111,** 1923, April 14.
‡ " The Chemistry of Colloids, and some technical applications," By W. W. Taylor, London, 1915, p. 18.

60. *Glazed Frost.*—Glazed frost is, in England, a comparatively rare phenomenon. It is important, however, inasmuch as when it occurs it greatly impedes transport, even rail locomotion being rendered difficult. In the previous section it was stated that sleet is caused by snow passing through an inversion of temperature, in which passage it is partially liquefied, the temperature experienced being over the freezing point. If, however, the surface temperature is below the freezing point, the partially melted snow will re-freeze when it reaches that surface so that a layer of ice is formed on all objects on the ground exposed to the precipitation. It is this layer of ice which constitutes glazed frost.

CHAPTER X

Weather

61. *The Beaufort Notation.*—It is found extremely convenient to have some notation in which the weather, either prevailing at the time or which has been experienced, can be briefly but comprehensively expressed. Such a notation has a great value for use on synoptic charts, a consideration of which will be found in Part II of this book.

For use in the United Kingdom, Admiral Sir Francis Beaufort who, it will be remembered, has already been mentioned in connexion with the Beaufort scale for wind, introduced a system of notation consisting as a rule of the first letter of the phenomenon to be indicated. Various additions to his notation have been made from time to time.

The Beaufort weather code, however, makes no reference to several important matters such as gales or the various optical phenomena which frequently occur. Moreover, it is not international in character—and internationalism is a very desirable asset in such a study of world-wide phenomena as is meteorology. Consequently, by international agreement, a code of symbols in place of letters has been arranged. Neither the Beaufort nor the International Code is quite comprehensive and, naturally, overlapping occurs. The scheme of both is given in Table III for purposes of reference.

TABLE III

The Beaufort Weather Code and the International Weather Symbols

Beaufort Letter	International Symbol	
b	···	blue sky, whether with clear or hazy atmosphere.
bc	···	sky partly cloudy.
c	···	cloudy, *i.e.*, detached clouds with openings between.
d	❟	drizzle.
e	···	wet air without rain falling, a copious deposit of water on trees, buildings or rigging.
f	≡	fog; range of visibility less than 1,100 yards.
g	···	gloom.
h	▲	hail.
l	<	lightning.
m	═	mist; range of visibility 1,100 yards or more, but less than 2,200 yards.

Beaufort Letter	International Symbol	
o	···	overcast, *i.e.*, the whole sky covered with one impervious cloud.
p	▽	passing showers (of rain).
q	···	squalls.
KQ	···	line squall.
r	●	rain.
rs	✱	sleet, *i.e.*, rain and snow together.
s	✱	snow.
t	···	thunder.
tl	⫪	thunderstorm.
u	···	ugly, threatening sky.
v	0	unusual visibility of distant objects.
w	⌓	dew.
x	⊔	hoar frost.
y	···	dry air (less than 60 per cent humidity).
z	∞	haze; range of visibility 1,100 ards, or more, but less than 2,200 yards.

The under-mentioned phenomena possess no Beaufort letters:—

✱→	snowstorm.
↔	ice needles.
⊠	snow on ground.
+	drifting snow (high up).
+	drifting snow (near the ground).
⚑	gale.
≡	ground fog.
V	soft rime.
▼	hard rime.
∾	glazed frost.
⊕	solar halo.
Φ	solar corona.
◡	lunar halo.
◡	lunar corona.
⌒	rainbow.
⌓	aurora.
⋀	zodiacal light.

Beaufort used small letters in his notation but under later conventions a capital letter is used to denote intensity of the phenomenon to be noted, while occasions of slight intensity are indicated by a small suffix $_0$. In addition, continuity is indicated by a repetition of the letter and intermittence by prefixing the letter i. Thus we have :—

R	heavy rain.
r	moderate rain.
r_0	slight rain.
RR	continuous heavy rain.
rr	continuous moderate rain.
ir_0	intermittent slight rain.

The occurrence of a phenomenon in the vicinity of the station is denoted by enclosing the symbol within brackets. Indices (^{0,2}) may be added to the symbols to denote intensity.

62. *The Control of Weather Changes.*—The chief factors controlling the weather of any area may be briefly summarized as follows :—

(*a*) The diurnal variation of insolation from day to night.

(*b*) The annual change of insolation from summer to winter.

(*c*) The passage of cyclonic and anticyclonic areas and their attendant smaller storms. (An extended consideration of these systems is given in Part II of this book.)

63. *The General Weather of the various Zones.*—In order to gain a broad view of weather in its general relation to latitude, it is interesting to consider very briefly the general weather experienced in the various zones into which the globe may be divided.

64. *The Torrid Zone.*—The Torrid Zone, which embraces about half of the surface of the globe and has a large oceanic area, is chiefly characterized by a regular sequence of diurnal changes, with a comparatively regular and steady change from season to season. The days are very much alike ; clouds increase in the morning and decrease in the evening, and the night skies are mostly clear. Rain occurs chiefly in the afternoon when it occurs at all as, at that period, convectional up currents have reached their maximum. This regular daily routine of weather changes is seldom interrupted by cyclonic storms.

The Torrid Zone should, however, be divided into two sections : first, the doldrums, and secondly, the trade-wind belts.

The weather of the doldrums, the region between the trade-wind belts, is hot, moist, and cloudy with frequent rains returning day after day with much regularity. Calms are frequent, and the wind generally does not exceed a few miles per hour in velocity. Thunderstorms of terrific violence occur from time to time. As would be expected, that part of the region which has land as the greater part of its surface has much more pronounced weather changes than does the part which is mostly sea.

The trade-wind belts at sea are characterized by the constancy of the winds which blow from approximately the same direction and with the same speed both day and night. Moderate amounts of cloud occur in the daytime, but are dissipated as night approaches, and rain is not frequent. Cyclones occasionally enter these belts and control both weather and wind. The annual and diurnal ranges of temperature are small.

In the trade-wind belts on land, the dryness of the air and the increase in the diurnal range of temperature compared with the belts at sea are the most remarkable features. In the hot seasons the temperature during the day may reach to a very high maximum, but the nights are cool.

The monsoon regions, especially of India, provide the greatest extremes experienced in the Torrid Zone. The weather in one season is comparatively cold and dry ; that in the other warm and sultry with much rain.

65. *The Temperate Zones.*—The Temperate Zones differ from the Torrid Zones in that in them chief control of the weather is taken by the non-periodic phenomena of cyclones and anticyclones. Consequently, the winds and weather do not show the regularity which characterizes the zone already considered. Weather is not diurnal, and the changes are more frequent and more capricious. A study of the weather and wind sequences associated with the travelling systems of cyclones and anticyclones which will be given later, will reveal more clearly what these changes are.

66. *The Frigid Zones.*—It must be remembered that in very high latitudes the diurnal control of weather is completely, or almost completely, lacking. For two or three months in the depth of winter the sun does not rise above the horizon ; for two or three months in the middle of summer it does not sink below it. The weather changes much as it does in the lower latitudes of the Temperate Zones according to the control of passing cyclones and anticyclones ; and in areas, like North Russia, which are inhabited the main features of the meteorological year are the times of the thawing and freezing of the seas and rivers.

PART II—SYNOPTIC METEOROLOGY

CHAPTER XI

Introductory

67. *General.*—Modern meteorology must be regarded as the work of an organization and not of any individual. One of the chief duties of a meteorological office nowadays is the making of forecasts of weather, and this involves the co-operation of hundreds of people. The making of synoptic charts is an essential part of the process of forecasting. By a synoptic chart is understood a map of the geographical area under consideration showing the distribution of the various meteorological elements such as wind, pressure, temperature and the like over that region for a given point of time. Such maps are usually prepared four times daily for fixed hours of observation, which, in the British Isles, are 1 o'clock and 7 o'clock in the morning, and 1 o'clock and 6 o'clock in the afternoon, times being Greenwich mean time. Their preparation connotes a corps of observers and a well-arranged distribution of meteorological stations. It is the duty of such stations to take, at the prescribed hours, careful observation of the meteorological elements required and to transmit the results of their observations to the central office, to reach that office as soon as possible.

The speed of transmission of these messages is obviously very important. The synoptic charts have to be prepared, and the forecasts of coming weather based upon them have to be issued, as soon as possible, for speed in issuing forecasts is a most commendable meteorological virtue, inasmuch as weather changes in such a region as the British Isles occur, sometimes, very rapidly, and these changes, as in the case of gales, may involve much damage and even loss of life. Forecasts issued promptly may often enable the authorities concerned to take such precautions as may minimise both the damage to property and the danger to life.

Here, then, in the question of speed of transmission enters a third factor: the factor of adequate and rapid means of communication between the observers and the central office, where the maps are prepared and the forecasts issued. Ordinary telegraphy, wireless telegraphy and the telephone have done much to secure the efficiency of modern forecasting. Each link in the chain is very important; the observers at the outlying places of observation must be thoroughly competent, the means of communication they have with the central office must be rapid and exact, which is a matter of thoroughly competent telegraphists, and the forecaster drawing the charts and forecasting from them must also be thoroughly competent.

But it cannot be too much emphasized that even an expert meteorologist is not able to do much in the way of good forecasting if he has no current synoptic chart. No amount of knowledge of weather saws and maxims is of much avail. Even a thorough knowledge of cloud forms is not sufficient, and the " weather glass " with the legends around its dial is a snare and a delusion. Synoptic charts, properly interpreted, are the essential matter in sound forecasting; and the interpretation involves much appeal both to physics and to precedent.

CHAPTER XII

Pressure and its Measurement

68. *The Pressure of the Atmosphere.*—Perhaps the most important meteorological element entered upon synoptic charts is the pressure of the atmosphere as determined at the various meteorological stations contributing to the preparation of those charts.

Pressure is the most important of the meteorological elements because all the other elements—wind, humidity, and the rest—seem to depend upon it, or, rather, upon its changes. The characteristic of fluid pressure which must be borne in mind—and air is a fluid—is that of transmission. If water be considered, that water will flow through any crevice, no matter how small, in order " to find its own level." The same is true of air, except that air does not take so long. In any room there are some crevices and through these crevices the air will flow in the endeavour to settle down in equilibrium, and such equilibrium is attained very rapidly. Therefore, the atmosphere is regarded as having the same pressure at the same levels so long as the air is not moving; and movement of the air is regarded as a component in the equalizing process.

69. *The Measurement of Pressure.*—The pressure of the atmosphere is measured by means of barometers, and barometers are of two kinds: first, those in which the pressure is balanced by the weight of a column of liquid, and second, those in which movements of the flexible lid of a box which is nearly exhausted of air are recorded.

The barometers in which a column of liquid is the main feature will be considered first. The making of a simple barometer of this type is an easy matter. A glass tube, about 33 inches long and closed at one end, is taken and completely filled with mercury. It is next inverted with a finger pressed tightly against its open end. The next step is to immerse the finger, and the end it is closing, under the surface of mercury contained in a bowl. The tube is brought into the vertical position and the finger withdrawn. On withdrawing the finger the mercury drops. When things have become steady it is found that a column of mercury, about 30 inches in height above the level of the mercury in the bowl, is still maintained in position in the tube. It is so supported by the pressure of the air acting downwards on the surface of the mercury in the bowl. The space above the mercury in the tube is a vacuum, that is, it is

practically entirely free from air, and is termed the " Torricellian vacuum " after Torricelli, the Italian, who first, in 1643, performed the experiment just described. Repetitions of the above experiment performed in rapid succession on the same day may show no difference in the height of mercury supported. A daily experiment done for several days in succession, however, will reveal that the height supported varies appreciably from day to day.

The experiment could be repeated using other liquids than mercury. Water, for example, could be used, but as mercury is, approximately, $13\frac{1}{2}$ times as heavy as water, it is clear that, if the atmosphere supports about 30 inches of mercury, it would support about 405 inches of water, or nearly 34 feet, which would make the length of tube required extremely long and cumbersome in working. Nearly all liquids suffer from the same practical disadvantage and mercury, on account of its high density, remains clearly marked out as the most suitable liquid for barometric purposes. Moreover, its opacity makes it peculiarly easy to read. A great additional advantage is that its vapour has a very low pressure at ordinary temperatures and this makes possible the existence of a nearly perfect vacuum above it.

The standard mercurial barometers, such as the Fortin pattern and the Kew pattern, used at meteorological stations, are made on the same principle as the simple barometer whose construction has already been described. For details of the refinements introduced to obtain a high degree of accuracy in the Fortin and Kew patterns the student is referred to " The Meteorological Observer's Handbook."*

70. *Corrections to be applied to Barometer Readings.*—The height of the mercury as read needs to be corrected for—

(*a*) The temperature of the instrument.

(*b*) The latitude of the place where the instrument is set up.

(*c*) The height of the cistern of the instrument above sea level.

These corrections are necessary in order that the pressures when plotted on the synoptic charts shall be strictly comparable.

The correction for the temperature of the instrument is due to the errors introduced by the expansion and contraction of both the mercury and the metal scales. If two barometers were placed at exactly the same level, one in the warm air of a room, the other in the colder air outside in the open, the one in the warm room would read the higher, but the actual pressure exerted by the atmosphere as the levels are equal would be the same. The correction is carried out and strict comparison is secured by reducing all readings to

* M.O. 191. Issued by the Meteorological Office, London, and published by H.M. Stationery Office.

what they would be if the temperature of the instrument were some standard* temperature.

The curvature of the earth is not perfect and the force of gravity varies according to latitude, reaching a maximum at the poles and a minimum at the equator. Thus, if there were uniform atmospheric pressure over the whole globe, a mercurial barometer at the equator would read higher than one at either pole. To avoid errors due to this variation of gravity with latitude all barometric readings are corrected to what they would be if the instrument were in some standard latitude, which latitude is taken to be 45°.

The correction for height above sea level is clearly necessary if readings all over an area are to be comparable in view of the fact that pressure decreases with height. What is needed in synoptic charts is a knowledge of the changes of pressure due to general causes and not to such ones as are due to local configuration. This error is avoided by correcting the readings to what they would have been if situated at a standard height. The standard height selected is that of mean sea level, which differs slightly from country to country, but in the British Isles is an arbitrary level at Liverpool. The differences of the level taken as sea level in different countries are not great enough seriously to vitiate the use of the readings from those various countries as comparable upon synoptic charts.

The barometric pressures, then, appearing on the synoptic charts are those which would have been read if all the barometers supplying readings were at the standard temperature at a height equal to mean sea level, and situated in latitude 45° N. or S.

71. *Barometric Units.*—The purpose of the barometer is to give the value of the pressure of the air. Owing to the convenience of the mercury barometer, it became the custom to express the pressure in terms of the height of the column of mercury, inches being used in England and millimetres on the continent of Europe. If a water barometer had been in general use, the value would no doubt have been expressed in feet or metres of water. In an aneroid barometer neither inches of mercury nor feet of water are intrinsically suitable, but nevertheless inches of mercury formed the standard in this country.

Pressure is, however, not a length but a force per unit area, and it is usually expressed in this way, except in the particular case of

* In the case of barometers graduated in millibars the standard temperature is generally 285 degrees on the absolute scale of temperature, *i.e.*, 12° C. above the freezing point of water. For the older barometers graduated in inches the standard conditions were the hypothetical ones that the mercury should be at the temperature of the freezing point and the scale at 62° F. In practice this meant that the correction was zero at 28·6° F. The barometers used on the continent of Europe are commonly graduated in millimetres; for such instruments the standard temperature is generally taken as that of the freezing point of water.

the pressure of the atmosphere. For example, the pressure in a steam engine is expressed in lb. per square inch.

By a fortunate coincidence the pressure of the atmosphere near the earth's surface is very nearly one million times the fundamental unit of pressure in the metric system, that is, 1 dyne per square centimetre, and it is therefore not merely of scientific value but also of practical convenience to use this system. The millibar is 1,000 of these fundamental units and the pressure of the atmosphere near the earth's surface is approximately 1,000 millibars. The millibar is a conveniently sized unit and a mercury barometer can be graduated in such a way that the pressure in millibars is read off with great ease.

The derivation of the millibar is now given more completely.

The unit of force on the C.G.S. (centimetre-gramme-second) system, now used universally for most scientific work, is the force which produces an acceleration of 1 centimetre per second per second in a mass of 1 gramme, and is termed a dyne.

The unit of pressure in the C.G.S. system, as already stated, is 1 dyne per square centimetre.

The dyne is, however, a very small unit and so a megadyne, that is, one million dynes, called a bar, is adopted as the practical unit of force, and this leads to the use of the millibar.

1 bar is equal to the pressure of 1 megadyne per square centimetre, that is, to 1,000,000 dynes per square centimetre;
1 millibar = $\frac{1}{1000}$ of a bar and is therefore equal to the pressure of 1,000 dynes per square centimetre.

1,000 millibars, that is, 1 bar, are equivalent to the pressure of a column of mercury 29·531 inches (750·1 millimetres) high at a temperature of 32°F. (0° C.) under the conditions of gravitation existing in latitude 45° N. or S.

In Table IV will be found values facilitating conversion from one system of barometric units to another. The values refer to standard conditions of temperature and latitude.

TABLE IV

Conversion Table for Pressure

Inch	Millimetre	Millibars
1	25·4	33·8627
0·0394	1	1·33
0·0295	0·75	1

The principal advantage of using the millibar as a unit is that a pressure quoted as a number of millibars is completely definite; millibars can be used just for pressure and for nothing else.

For a full explanation of the corrections and reductions to be applied to barometer readings, the reader is referred to the "Meteorological Observer's Handbook."*

72. *Aneroid Barometers.*—The second type of barometer in general use is that in which the compression or recovery of a box which is nearly exhausted of air and has a flexible lid is recorded. Such barometers are termed aneroids. An aneroid consists generally of a circular metallic chamber hermetically sealed which has been rendered nearly vacuous. The lid is made of very thin elastic metal, and by an arrangement of levers and springs the movements of this elastic lid are recorded by a needle moving over a dial.

The pressure within the box is very small, whilst the lid is carrying the weight of the outside air upon it. Any increase in outside pressure pushes in the lid slightly and any decrease allows the lid to recover. If the dial be properly calibrated the needle recording the movements of the lid gives the pressure of the outside air.

Aneroids do not require correction for latitude or temperature, but only for height above sea level and for index error. Whilst extremely suitable for explorers and for mountaineers on account of their portability and comparative lack of fragility as compared with mercurial barometers, aneroids are not accepted as being sufficiently accurate for use at meteorological stations as their mechanism introduces errors beyond the limits allowed.

Aneroids are very useful in the rapid determination of heights. As a rough rule it may be said that the barometer falls 30 millibars per 1,000 feet of elevation for low altitudes. Starting, then, with a normal pressure at sea level and marking that as 0 feet, the dial of the aneroid may be calibrated in heights instead of pressures. Arrangements can be made to enable the zero height mark to be adjusted to the actual pressure existing at any place, so that heights above that place can be read off to a fair degree of accuracy directly from the dial.

73. *Barographs.*—The ordinary barograph is really an aneroid barometer fitted with a lever recording on a chart or a drum, the drum being kept revolving by clockwork. By using such an instrument a continuous record of the pressure from moment to moment is obtained. The great use of a barograph is to show how the pressure is varying. It must be standardized daily by comparison with readings given by a mercury barometer.

74. *The Diurnal Variation of the Barometer.*—An examination of barograph traces taken in quiet weather over a long period reveals one striking fact, and that is a definite diurnal variation of pressure.

*M.O. 191 Issued by the Meteorological Office, London.

There is a slight rise of pressure between about 4 o'clock in the morning and 10 o'clock in the morning, and also between about 4 o'clock in the afternoon and 10 o'clock in the afternoon, with corresponding falls in between. This diurnal variation is most marked in the Torrid Zone and becomes less distinct with increasing latitude. This would be expected as the cause of the diurnal pressure variation is to be found in the diurnal variation of temperature. Fig. 6 shows the variation in diagrammatic form. The variations in the figure are exaggerated.

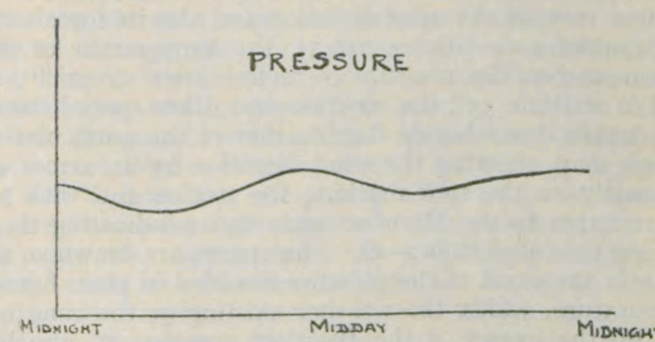


FIG. 6.—DIURNAL VARIATION OF PRESSURE.

CHAPTER XIII

The Making of Synoptic Charts and some Lessons derived from them

75. *The Foundations of a Synoptic Chart.*—The forecaster receives from several stations distributed over the region for which he is concerned observations taken at precisely the same hour. These observations include the wind direction and also its force estimated on the Beaufort scale (*see* section 5), the temperature of the dry-bulb thermometer, the pressure corrected down to 32° F., and to sea level in latitude 45°, the weather and other special data. He sets the details down beside the location of the particular station on a blank map, showing the wind direction by an arrow with its point actually on the spot marking the station and with feathers equal in number to the Beaufort scale figure indicating the force, calms being indicated thus :—O. The arrows are drawn so as to be travelling in the wind. The pressure is added in plain figures as is the temperature, whilst the weather existing at the time is either denoted by the letters of the Beaufort notation of weather (*see* section 61) or by a conventional picture code. Whether the pressure at the place is rising or falling or steady, as denoted by the barograph there, is shown by means of a conventional sign (*see* Table V), and the amount that the barograph has varied within the three hours preceding the hour of observation is added, also in a conventional code, generally by a figure showing the number of tenths of millibar of change.

TABLE V

Conventional Signs to illustrate Barograph Behaviour

Barograph behaviour		Conventional sign
Rising, then falling	The barometer is now higher than, or the same as, three hours ago.	+ —
Rising then steady, or rising then rising more slowly.		+ O
Unsteady		U
Steady or rising		+
Falling or steady, then rising; or rising then rising more quickly.		— +
Falling then rising	The barometer is now lower than three hours ago.	— +
Falling then steady; or falling then falling more slowly.		— O
Unsteady		U
Falling		—
Steady or rising then falling; or falling then falling more quickly.		+ —

The actual change in the pressure at the station within the past 3 hours is termed the "barometric tendency" and, as has already been stated, is usually given in the United Kingdom in tenths of a millibar. The conventional sign indicating the type of variation is termed the "characteristic" of the tendency. The code figures used in practice to report the variation depend, it will be noticed, on the position of the pen on the chart with regard to its position 3 hours before.

76. *Isobars.*—The most important thing on a synoptic chart is the pictorial representation of pressure distribution at sea level which is secured by drawing what are termed "isobars". Isobars are lines drawn through places at which the pressures, corrected for temperature and latitude and reduced to sea level, are the same. The isobars are usually drawn for definite pressures with fixed intervals of pressure between them. In English practice it is customary to plot the barometric readings to the nearest tenth of a millibar and to draw the isobars either for every two millibars, in which case the isobars are those of even number, i.e. 990 mb., 992 mb., 994 mb., etc., or for every single whole millibar, if the scale of the chart be exceptionally large. As it is generally the case that no stations supplying observations actually have these definite, round-number pressures, the isobars are drawn by a process of interpolation.

When travelling along an isobar, pressure remains continually higher on one side than on the other ; and thus an isobar must return to its starting point if the area considered be large enough. This means that every isobar must form a closed curve.

Isobars are almost exactly analogous to the contour lines appearing on an ordinary geographical map, the areas of high pressure corresponding to the hills, and those of low pressure to the valleys. This analogy is an instructive one for the student to bear in mind and is referred to further in section 78.

77. *Buys Ballot's Law.*—A study of synoptic charts caused Professor Buys Ballot of Utrecht to enunciate in 1857 the famous law which bears his name, which is as follows :—If, in the northern hemisphere, you stand with your back to the wind, pressure is lower on your left hand than on your right. In the southern hemisphere the reverse is true, for there, if you stand with your back to the wind, pressure is lower on your right hand than on your left.

The student should satisfy himself as to the truth of this law by referring to as many synoptic charts as possible, in addition to the ones shown in Figs. 16 to 18.

A further point to be noticed is, that the winds seem closely to follow the lie of the isobars, but show, generally, a tendency to turn inwards towards the low pressure. This deviation from the true lie of the isobars is generally between 0° and 45°, but is sometimes greater. The attention paid by the wind direction to the isobar direction is greatest in polar regions. As the equator is approached the attention paid is less; it is, however, still quite noticeable at 20° N. or S. latitude. Nearer the equator still the attention paid is very little and, actually, at the equator itself is non-existent. Crossing the equator means that the directions of the wind with regard to pressure are exactly reversed in accordance with Buys Ballot's law. The change over is not noticeable, however, in practice owing to the fact that the equatorial regions constitute a belt of low pressure, the Doldrums, in which only light and variable winds blow as a rule and in which calms are frequent.

78. *The Strength of the Wind.*—Another lesson to be derived from a consideration of a collection of synoptic charts relates to the strength of the wind. Hardly any map will fail to reveal to the observant student that where the isobars lie close together the wind is strong, and, where far apart, weak. This is quite what would be expected, remembering the analogy between isobars and contour lines. On a geographical map, contour lines close together indicate steep gradients or slopes, down which it may be imagined that, if a stream existed, the water would rush tumultuously; contour lines far apart, on the other hand, indicate gentle gradients or slopes down which the water in the stream would flow slowly. What applies to contour lines applies to isobars. Isobars close together, that is, steep pressure gradients, mean that the air flow is rapid, that is, that winds are strong; isobars far apart, that is, slack pressure gradients, mean that the air flow is gentle, that is, that winds are light. Isobars very far apart mean that the air flow is inappreciable, and calms result.

79. *The Gradient Wind.*—It will be seen, then, that it should be possible to calculate the wind speed at any place from the pressure gradient at that place as shown by a carefully drawn synoptic chart. This can be done, and the result obtained is termed the gradient wind. In practice, however, the wind existing at the surface is found to be, as a rule, less than the calculated gradient wind. This is due to the friction of the surface of the earth; the calculated gradient wind agrees with, in most cases, the actual wind met at about 1,500 feet above the surface.

CHAPTER XIV

Types of Pressure Distribution

80. *Introductory.*—Many thousands of synoptic charts of the British Isles have been prepared for various hours, but no two charts have ever been found to be identical; and what applies to the British Isles applies to any other region. Similar the charts may be with regard to some features, but that is all. The variety of distribution is endless.

But emerging from the many variations, seven main types* of isobaric distribution may be recognized. Those seven types are as follow :—

(*a*) Depression or low;
(*b*) Anticyclone or high;
(*c*) Col;
(*d*) Secondary depression;
(*e*) V-shaped depression;
(*f*) Wedge of high pressure or ridge of high pressure;
(*g*) Straight isobars.

The main features of each of these types will now be considered.

81. *Depressions.*—Depressions are parts of the atmosphere where the pressure is low. They appear on synoptic charts as series of closed isobars, approximately oval or circular in shape, with the minimum pressures occurring in the centres.

The sizes of depressions vary enormously. One example may have a diameter of 1,000 miles or more; another, a diameter of much less; others, too, which constitute the tornadoes of the United States of America, have very small diameters indeed, often only one hundred yards or two hundred yards. A depression in which the barometer is very much lower in the centre than it is on the margins is said to be deep; one in which there is comparatively little difference of pressure between the centre and the margins is said to be shallow.

Alternative names for a depression are "low" and "cyclone." The use of the term "low" has now become popular and little can be said against it; but care needs to be exercised in using the term "cyclone." In America, especially in newspaper reports, the term "cyclone" is applied to what is more properly called a "tornado," that is, a depression of extremely small diameter which

* For a classification of pressure distribution into 28 types, the student is referred to "Aids to forecasting," by E. Gold, F.R.S. (*London, Geophys. Mem.*, No. 16, 1920). This is the best extended classification of types of pressure distribution known to the present author.

is accompanied by exceptionally steep pressure gradients, and, consequently, by exceptionally violent winds which cause great damage. In the British Isles, the connotation of "cyclone" is that of a large area of low pressure accompanied by broad sheets of cloud, comparatively large areas of rain, and winds which may, or may not, be violent. The two uses of the term "cyclone" need, therefore, to be carefully differentiated. The English use is distinctly the more generally accepted scientific one, and even American meteorologists, as apart from the American general public, so use it, calling their smaller whirling storms by the correct name of "tornadoes." Any use of the word "cyclone" in this book must be taken as having the scientific connotation.

The winds in a depression obey Buys Ballot's law (*see* sections 10, 77). One very convenient way of stating the relation of wind direction to depressions is to say that in the northern hemisphere winds blow in an anti-clockwise direction around the centre of low pressure. The winds, too, generally exhibit quite markedly the tendency to turn inwards towards the low centre; and their forces depend upon the steepness of the pressure gradient, that is, upon the distance apart of the isobars.

82. *Depressions: the Old and the New Ideas.*—The further treatment of depressions, to be adequate, must explore two paths, the old and the new. On the one hand there are the older ideas mainly due to the Hon. Ralph Abercromby (born 1842, died 1897), one of the greatest of English meteorologists, which ideas held the field almost indisputably until just after the close of the European War (1914–8) and which are still of considerable help in certain cases; and on the other hand there are the new ideas due to V. and J. Bjerknes, formulated in Norway during that war and now universally accepted as constituting a great advance in knowledge of the structure and behaviour of depressions.

83. *Depressions: the Older Ideas.*—Continuity may be regarded as the basis of the older ideas as opposed to discontinuity as the basis of the newer ones. The older ideas regarded depressions as regions of low pressure, surrounded by closed isobars, continuously curved and having no sharp angles, with the winds, in the main, backing or veering gradually and without any abrupt changes or "discontinuities" in direction; while the weather prevailing at a given place within the ambit of a depression was regarded as just a function of the position of that place in relation to the centre of the depression irrespective of any other consideration. How greatly these ideas differ from the newer ones will be appreciated after the next section has been read.

The nomenclature employed in the older ideas is shown in Fig. 7. It is included here as the terms employed are the common coinage of all but the most recent books on meteorology. Reference is made more fully in section 85 to the travel of depressions and hence the

"path" is marked in the figure. The "trough" marks the period of lowest barometric pressure during the passage of a depression over a place.

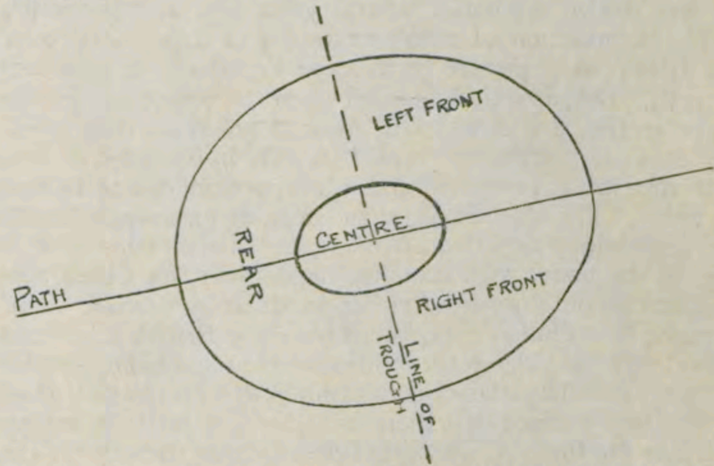
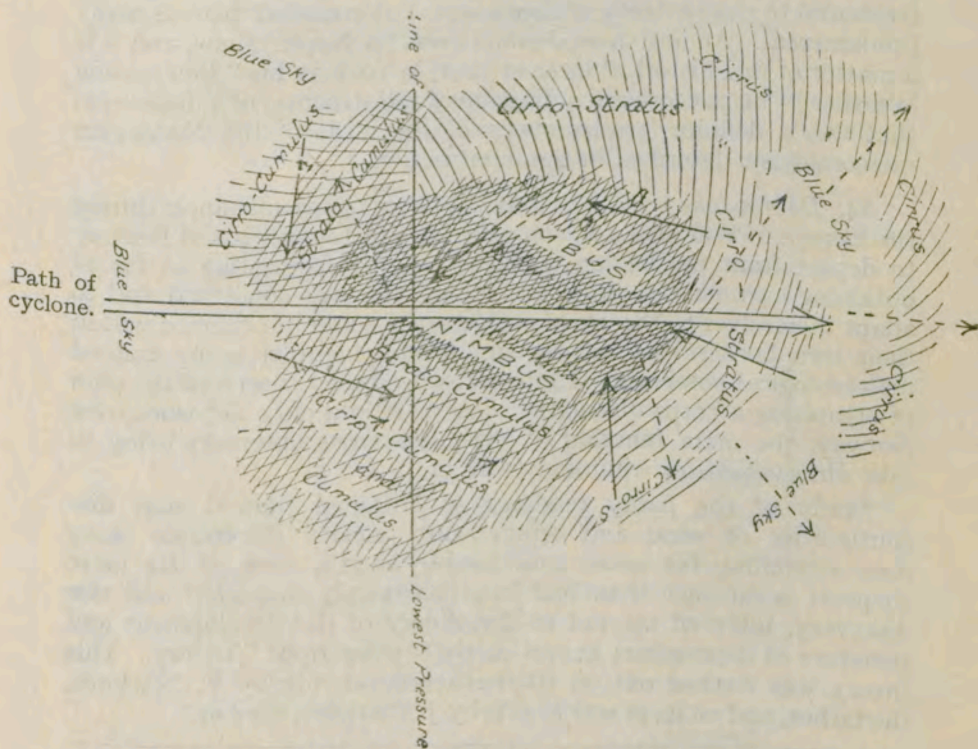


FIG. 7.—NOMENCLATURE OF A DEPRESSION AFTER ABERCROMBY.



——→ Wind direction at the earth's surface.
- - - -→ Wind direction in the region of the cirrus cloud.

FIG. 8.—DISTRIBUTION OF CLOUD IN A DEPRESSION ON ABERCROMBY IDEAS.

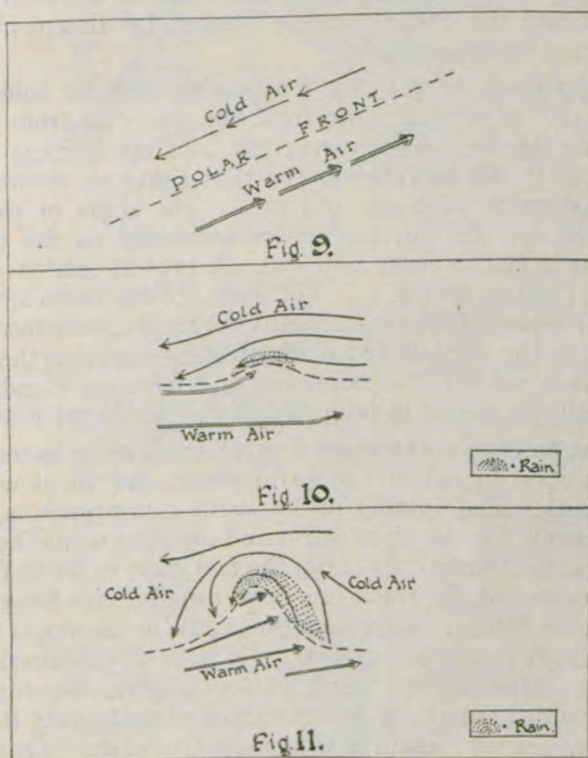
The distribution of cloud as conceived on the older ideas is seen in Fig. 8, which figure also shows the wind direction both at the earth's surface and at the height of the cirrus cloud. The figure as shown was drawn originally several years ago as a generalisation based on examination of many examples of depressions over the British Isles ; as a picture of average experience it still contains much truth. But, as will be realised when the new ideas described in the next section are considered, most depressions that reach the British Isles are " occluded " and it is only in occluded depressions that the distribution of cloud and rain approximates to that shown in the figure. The older ideas, then, working on average conditions in the depressions experienced over the British Isles were really dealing, in the main, with occluded depressions, for which type the generalisations put forward were approximately correct. The preponderance of occluded depressions over the British Isles explains, therefore, why the older generalisations were regarded as satisfactory for so long. But the satisfaction was not entirely universal. Doubters there were who realised that there were discontinuities in the systems regarded as continuous, discontinuities such as the abrupt changes of wind and temperature sometimes experienced along the trough line, and who were not content to regard those discontinuities as incidental to the anatomy of depressions but regarded them as really fundamental. Among these doubters was Sir Napier Shaw, and it is a matter of real historical interest that, in 1911, in his " Forecasting Weather "* he put forward a diagram of the structure of a depression that was a definite foreshadowing of the ideas of the Norwegian meteorologists described in the next section.

84. *Depressions : the New Ideas.*—Force of circumstances during the European War (1914–8) compelled the meteorologists of Norway to depart from the beaten track of weather forecasting so far as obtaining current data from other countries was concerned and to adapt themselves to the use of such data as could be obtained within their own borders without expensive equipment or many trained meteorological observers. To meet the need they conceived the plan of organising a corps of amateur observers in a close net-work over Norway, the main function of these numerous observers being to take observations of wind and weather.

Study of the many readings so obtained showed that discontinuities of wind and temperature, clearly discernible along lines stretching for some considerable length, were of far more frequent occurrence than had been previously suspected and this discovery, followed up, led to the theory of the development and structure of depressions known as the " polar front " theory. This theory was worked out on its mathematical side by V. Bjerknes, the father, and on its practical side by J. Bjerknes, the son.

* SHAW, W. N. " Forecasting Weather." London, Constable and Co., Ltd. First Edition, 1911.

The theory may now be briefly outlined. The polar regions are covered by a mass of cold air and the equatorial regions by a mass of warm air. There is no steady, continuous change from the cold air to the warm air, but the two masses are separated by a surface of discontinuity termed the " polar front." The air on the northern side (considering the northern hemisphere) of this surface of separation is termed " polar air " ; it is normally cold, dry and comparatively free from cloud : the air on the southern side is termed " equatorial air " ; it is normally warm, moist and comparatively cloud-filled. The distinct difference in properties of these two air masses is a point to be strongly emphasised as it is vital to the working out of the theory. Depressions form along this surface of discontinuity, the polar front, and constitute the means whereby interchange takes place between the cold and the warm air. The mechanism of this formation of depressions appears to be as follows. The cold, polar air flows from the north-east towards the south-west along the northern side of the surface of discontinuity while the warm air flows from the south-west towards the north-east on the southern side of the surface. This arrangement is shown in Fig. 9. It is not an entirely stable arrangement but subject to disturbance. The usual form of disturbance, as shown in Fig. 10, is for the cold air to bulge



Stages in the growth of a depression.

southwards and the warm air northwards, thus causing a northward bulge of the polar front. This northward bulge, once having started, continues to develop, the cold air on the northern side swinging round at the back and emphasising the distortion of the polar front in the manner shown in Fig. 11. This emphasised distortion is the new depression just born and it normally travels north-eastward along the polar front, carrying with it the characteristics of wind and weather produced as a result of the reactions between the two very different air masses concerned.

Those characteristics and reactions demand description. Fig. 12 should now be consulted—it is really Fig. 11 over again in an amplified form—for a closer study of the structure of a depression. The two currents of air of different properties compounding the depression are clearly shown marked as " cold air " and " warm air," while the dotted line reveals the polar front now divided into two sections marked, respectively, " warm front " and " cold front." The area contained within the bulge of the polar front, contained, that is to say, between the warm front and the cold front, is shown marked as the " warm sector." It will be seen that the warm sector contains the warm or equatorial air concerned in the depression while the rest of the area covered by the depression is composed of the cold or polar air concerned. The two lines of discontinuity, the warm front and the cold front, are marked by abrupt changes in wind direction and temperature.

The happenings at the two fronts may now be considered in greater detail. Along the warm front the warm air from the warm sector, being lighter, ascends over the cold air forming a sloping surface: and it will be remembered that rising air is the essential for the production of cloud and rain. The slope of the surface between the two air currents varies according to the conditions existing but is of the order 1 in 100. A typical section through a warm front is shown in Fig. 13. The ascent of the warm air gives rise to the cloud sequence shown—from the very high cirrus down through altostratus to the nimbus and nimbostratus—and thus the approach of the front is marked by increasing and lowering cloud, and rain begins to fall, increasing in intensity as the clouds get lower.

With the passage of the warm front, there is a rise in temperature consequent upon entry into the warm sector, and the cloud lifts and tends to break. The weather in the warm sector remains, however, generally cloudy for the air is warm and moist as would be expected from its equatorial origin and from the fact that, so far as the British Isles are concerned, its track has been usually over large stretches of the Atlantic Ocean. Rain sometimes falls in the warm sector but it is not usually heavy in character: it is to be explained in one of three ways—either as the result of topography, any high ground causing ascent of the air, or as due to lack of uniformity in temperature in the air current, again causing ascent, or as due to convergence, which cause is explained more or less fully later (*see* section 95).

Behind the warm sector there is, following in its rear and undercutting by reason of greater density, a further supply of cold air. Once again, therefore, there is upward motion of the air in the warm sector. This upward motion is more vigorous than the gradual ascent of air at the warm front and is accompanied usually by cumulonimbus clouds and a short period of rainfall of a squally, showery type, sometimes very heavy in character and sometimes also accompanied by thunder. A sharp fall of temperature is also experienced with the passage of the front. A typical section through a cold front is shown in Fig. 14. Other phenomena associated with cold fronts include the very distinctive line squalls and these special squalls are treated in section 96.

(In Fig. 12 the shaded area is the area of precipitation (rain, snow, sleet or hail as the case may be) and it is clearly to be seen how much greater is the area of precipitation due to the warm front than is that due to the cold front.)

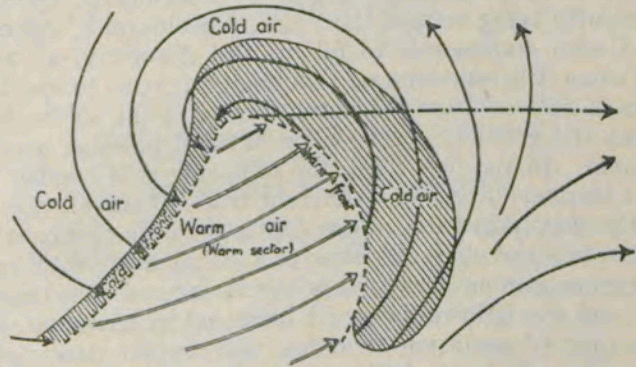


FIG. 12.—IDEALIZED DEPRESSION.

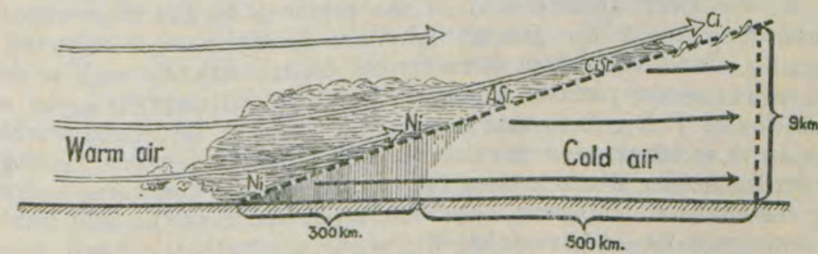


FIG. 13.—VERTICAL SECTION THROUGH A WARM FRONT.

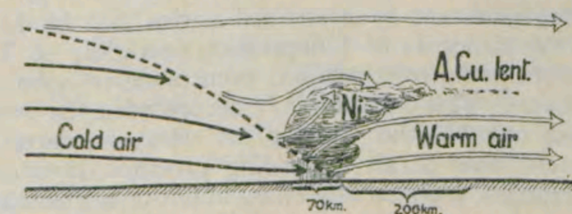


FIG. 14.—VERTICAL SECTION THROUGH A COLD FRONT.

In the rear of the cold front the air is usually polar in type, having come from high latitudes. This polar air is unstable in character, the instability being due to the increasing lapse rate of temperature (*see* section 125) in the air as it travels southward, the layers at and near the surface becoming heated. With the passage of the cold front, therefore, the weather takes the form appropriate to such unstable air with bright periods interspersed with occasional showers and cumulus or cumulonimbus clouds.

The picture given of a depression having definite warm and cold fronts, and hence a definite warm sector on the ground, must not, however, be taken as true of every depression, this well-marked structure being only present, as a rule, in depressions more or less newly formed. With progress of time and as the depression advances, the cold front overtakes the preceding warm front and thus in due course lifts the warm sector entirely from the ground. When this happens only one line of discontinuity remains discernible on the surface and the depression is said to be "occluded," the one line of discontinuity being termed the "line of occlusion." An occluded depression soon commences to fill up and die away, as would be expected when it is remembered that the energy, so to speak, of the depression is derived from the actual lifting of the air in the warm sector from the ground. Such an occluded depression may be one of two kinds. In the first kind, the following cold current may be somewhat warmer, owing to a different track of travel, than the air forming the supply in front of the depression. In this case the line of occlusion has the characteristics of a warm front with low cloud and continuous rain or drizzle. For the second case, the reverse may happen ; and the following current being colder than the supply in front, the line of occlusion then has the characteristics of a cold front—squally rain and a falling temperature.

As has been already said in the previous section depressions when they reach the British Isles are nearly always occluded. Usually, these depressions form far out on the Atlantic and, while the warm sector persists, increase rapidly in intensity, it being a rule due to J. Bjerknes that depressions continue to deepen whilst the warm sector remains in existence. But this very growth, leading to strengthening winds, causes the undercutting of the warm sector by the cold air in its rear to become rapid and thus the cold front quickly gains on and overtakes the warm one with the result that occlusion of the depression is soon accomplished.

It will doubtless not have escaped notice that in the foregoing account of the structure of a depression according to J. Bjerknes and his co-workers no reference has been made to isobars and very little to pressure. This omission is in accord with the way the ideas were worked out by the Norwegians who concentrated almost entirely on the flow of air, regarding pressure distribution as of minor importance. Isobars, however, cannot be neglected altogether and it is therefore necessary to consider their relationship to the

fronts. These isobars form closed curves around the centre of a depression (the apex of the northward bulge of the polar front in Fig. 11) but they do not, according to the Norwegian meteorologists, run smoothly as in the older conceptions due to Abercromby and others, but form more or less sharp angles where they cross the warm and cold fronts or the line of occlusion. An ideal Bjerknes depression, showing isobars, is depicted in Fig. 15. The angles are much less sharp across a line of occlusion than across either a warm or a cold front.

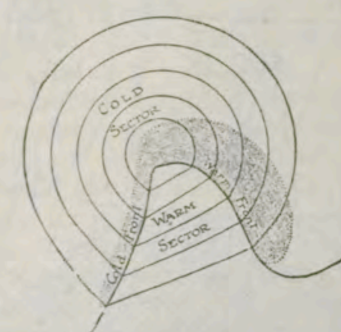


FIG. 15.—DEPRESSION AFTER BJERKNES, SHOWING ISOBARS
(The stippling shows the rain area.)

An actual weather chart showing a depression over the British Isles with a well-defined warm sector is shown as Fig. 16. The wind, temperature and present weather are shown for various stations, in addition to the isobars marked in millibars. The rain area is shown shaded while the warm and cold fronts are distinctively marked. The strength of the winds is denoted by the flèches on the arrows—a full length flèche indicating two steps on the Beaufort Scale (*see* section 5) and a short flèche one step. The chart should be carefully studied in the light of what has already been said.

A note may usefully be added here as to the procedure adopted in drawing such charts as the one shown in Fig. 16. The winds, pressures, temperatures and other data are first placed at or alongside the various stations. From this point onwards, practice differs : some put the isobars in first while others put the fronts in first from a consideration of any discontinuities in wind and temperature that may exist and from the cloud forms, weather, etc., reported from the various stations. It is more in accord with the way the Norwegians developed the theory that the fronts should be put in first but it will doubtless be appreciated that, often, the putting-in of those fronts is a matter of considerable difficulty. To put in the isobars first is easier probably for the beginner but the more experienced forecaster puts in the fronts first as emphasising the more salient features of the chart and as giving to his subsequent isobars a more correct run.

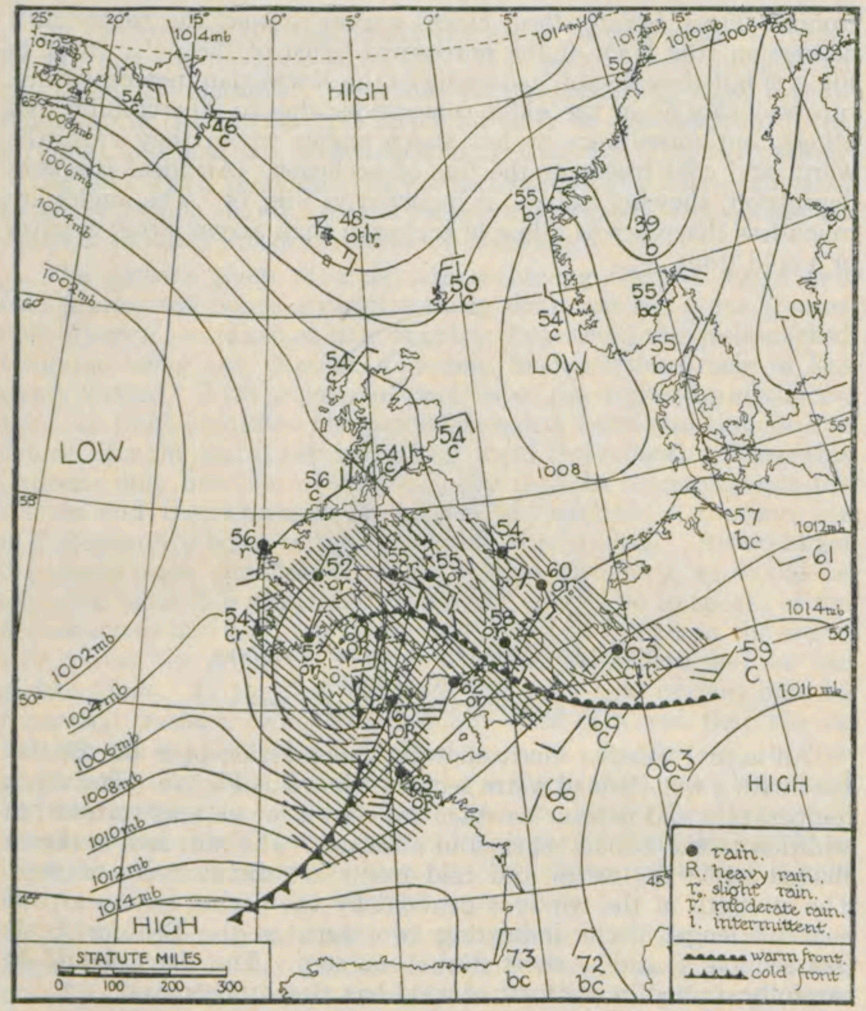


FIG. 16.—DEPRESSION on September 17, 1930, at 18h.

85. *The Travel of Depressions.*—An examination of synoptic charts for a succession of days reveals the fact, already referred to, that depressions are not stationary but travel. Generally speaking, considering their centres, they travel from a westerly point to an easterly one, with a tendency towards north, so that a large number move from south-west to north-east. Nevertheless, depressions are fickle things and it remains true that "no path can be drawn so tortuous and so out of the way that we can fairly say it must be ruled out as a possible path for the centre of a cyclonic depression."* But clearly the direction of travel of a depression is a matter of vital importance to the winds and weather of any particular region

* SHAW, W. N. "Forecasting Weather." London, Constable and Co., Ltd., 1911, Chapter 15.

with which a forecaster is concerned and the prediction of that travel, therefore, becomes a matter of prime moment for him. Moreover, he realises that it is of little avail to rely upon the average of the behaviour of past depressions: he must deal with the one actually advancing and deal with it as an individual possessing its own characteristics.

86. *To Determine the Direction of Travel of any particular Depression.*—This, as has been already stated in the previous section, is a matter of prime importance to the forecaster.

Perhaps the one clear-cut case is that of a depression possessing a well-defined warm sector; for it is a rule that a depression moves parallel to the isobars in that warm sector. A consideration of Fig. 15 shows that the isobars in the warm sector in that diagram of an ideal Bjerknes depression are drawn as straight lines and it is these lines which indicate the direction that the depression will travel. Reference should also be made to Fig. 16. This rule, when it is possible to apply it, works very well, there being very few exceptions, but as has been already stated only comparatively few depressions reaching the British Isles possess a warm sector on the ground, nearly all being occluded, so that few opportunities to apply the rule present themselves to the forecaster concerned with these Islands.

With regard to the other depressions, those not possessing a warm sector on the ground, the forecaster uses a variety of aids to the end of predicting their direction of advance.

The first aid is that of past history. The assumption is made that if a depression has pursued a definite track within the comparatively recent past as represented by the preceding two or three synoptic charts it will continue to maintain that direction more or less unchanged. The rule thus stated is one that must, however, be applied with considerable caution. A depression, travelling, for example, over the Atlantic, often obeys the rule so long as it is over the ocean, but when it approaches the European coast and begins to draw in dry air from off the land in place of moist air from off the sea it frequently changes its direction of advance. Mountain ranges also often constitute the factor causing a change in the direction of advance, a factor of considerable importance in a country like Norway where a high range of mountains faces the sea along almost the entire length of the western seaboard but not of so much importance in the British Isles. Yet another point is the preference that depressions appear to show for travelling along waterways, where possible, instead of over land: it is this preference which may account for the fact that many depressions reaching the British Isles from the west travel up the English Channel if that route be at all a possible one; it may also account for the number of depressions that move southward down the North Sea.

But perhaps the most important aid open to the forecaster is that afforded by the barometric tendencies, that is, the changes in the barometric pressure within the three hours immediately preceding the fixed hour of observation at the various stations contributing to the synoptic chart. The assumption that he makes in this case is that the depression will travel towards the place of greatest fall not too much in front of the system. The objection to be urged against this rule is that the tendencies are past history and that it does not follow that because the barometer has fallen considerably at a place within the past three hours it will continue to fall considerably there within the ensuing three hours. In practice, however, the method of predicting travel towards the places where the greatest barometric falls have occurred is found to be fairly successful. A note of warning with regard to the practical application of the rule needs to be given, however. It sometimes is the case that the biggest falling tendency on the map is not just in front of the centre of the depression but at some considerable distance in front. This distant biggest fall is not necessarily the pointer showing the way the depression will go but is more likely to be indicative of the formation of a secondary depression (*see* section 91) in the region of the place where the big fall is noted.

In further reference to barometric tendencies, the work of Nils Ekholm, of Stockholm, some thirty years ago, merits attention. Ekholm advocated the drawing of charts in which it is the pressure differences from the last observation which are plotted and not the actual pressures observed at the time. Thus lines of equal pressure difference, called "isallobars," are obtained. Examination of successive isallobaric charts reveals that the groups of isallobars travel similarly to the groups of isobars, but in the view of Ekholm more regularly than the latter do. The isallobaric charts, therefore, become useful helps in determining where the greatest barometric falls are likely to occur. The British Isles suffer in using Ekholm's method because of their extreme western position; before the isallobaric groups are well defined they have travelled past. More modern work on isallobars is described in section 95.

A further useful aid in practice is to be found in a study of the wind directions at the various stations. By Buys Ballot's law it is recognised that when the wind direction is changing, the distribution of pressure is changing also. A change of force alone, without any change in direction, just means that the isobars are maintaining their general lie unaltered, but are either crowding more together or becoming wider apart. A change of direction means that the relative distribution of the high and low pressures is changing. The "backing" of a wind, that is, its changing in an anti-clockwise direction, is a sign of the coming of a depression. That this is so is evident from the consideration that one depression follows another depression with a greater or less interval in between. By Buys Ballot's law, the winds in the rear of the depression which has passed are north-westerly; those in front of the depression which is approaching are south-easterly.

A station, then, in the line of advance of the coming depression often reveals the coming of that depression by a backing of its wind long before the centre appears on the chart: and it is a fair assumption to say that the coming depression will advance more or less directly towards the station or stations showing the backing. The importance of the meteorological observations taken at Valentia, Blacksod Point and Malin Head, on the western coast of Ireland, and of those taken on ships off that coast, can hardly be overestimated in this respect with regard to depressions from the Atlantic Ocean advancing on to the British Isles.

Wind study is necessary for yet another method of anticipating the approach, and predicting the line of advance, of depressions, which method is due to Gabriel Guilbert.* An examination of synoptic charts reveals the fact that the wind forces at the various stations are sometimes not in accord with what would be expected from the pressure gradients at those stations as shown by the charts, and that sometimes, also, the wind directions differ from what they should be considering the lie of the isobars. So far as direction is concerned, Guilbert considers that the wind is an abnormal one if it deviates more than 40° from the run of the isobar. He treats these abnormalities of force or direction as significant, and has formulated a set of empirical rules in which he employs these abnormalities as means to predict the progress of isobaric groups. It is obvious that the method implies that the wind exposures of the stations considered are perfect. This is so seldom the case and abnormalities of wind are produced so often at many stations because of some unavoidable imperfection of exposure that the method needs using with the utmost care.

A selection of Guilbert's empirical rules is now given:—

(*a*) A depression with winds above normal force (as compared with the pressure gradient) on all sides will fill up; one with winds below normal force on all sides will deepen, and hence, depressions which are, apparently, weak will change to give strong winds or gales.

(*b*) Those parts of the depression in which the winds are below normal force, as shown by the pressure gradient, indicate the direction in which the depression will move; thus, when a depression consists partly of winds that are above normal and partly of winds that are below normal, it will move in the direction of least resistance, that is, in the direction where the winds are below normal.

(*c*) Pressure increases from right to left across the line of winds too strong for the gradient. In other words, a wind above normal transfers pressure from the right to the left.

* Guilbert, G., "Nouvelle Méthode de Prévision du Temps," Paris, Gauthier Villars, 1909.

(*d*) Depressions are attracted towards the regions of least resistance; towards regions of light airs or calms, and, above all, of divergent winds (divergent, if blowing in opposition to the normal direction corresponding with the run of the isobars).

(*e*) The existence of several anomalies in the directions and forces of the winds at various stations in a limited area at the same time decides the sudden formation of an important depression over that area.

It must be confessed, however, that, whilst in Guilbert's own hands his method has given some astonishingly successful forecasts, many other forecasters have found it difficult to use with much success. As has been already said, it needs to be used with extreme care, and with a real knowledge of the wind exposures of the stations where the abnormalities are occurring. Granted that care, the method can be of real value in cases where prediction by other means is difficult.

87. *The State of Growth of Depressions.*—Of equal importance to the direction of travel of a depression is the question of its state of growth, the question as to whether it is developing in intensity, that is to say, getting lower in barometric pressure in the centre, or whether it is filling up, that is to say, getting higher in barometric pressure in the centre. Travel and state of development must alike be considered by the forecaster.

Some aids to the end of determining the state of growth of a depression are now given.

It has already been stated that a depression with a well-marked warm sector is still in the condition of intensification; and it can be added that this intensification is likely to be the more vigorous if the barometric pressure is falling at all decidedly in that warm sector. On the other hand an occluded depression is filling up. Similar information in cases where it is difficult to analyse the depression according to the Norwegian plan is often afforded by barometric tendencies. A normal Abercromby depression, moving uniformly, has pressure falling in front and rising behind, and the two rates of change are more or less equal. If, however, the rate of fall in front is found to be appreciably slower than the rate of rise behind then the depression is filling up and, as is the case with all depressions which are filling up, the speed of advance is likely to diminish. If on the other hand the rate of fall in front is appreciably faster than the rate of rise behind, or if pressure is falling both in front and behind, then the depression is growing deeper.

Guilbert also dealt with this problem of growth and decay and his empirical rules (*a*) and (*e*) set out in section 86 should be consulted at this point.

88. *The Rate of Advance of Depressions.*—Depressions advance at very variable speeds. Across the British Isles a speed of 20 to 30 miles per hour is very usual: sometimes, however, this speed is

considerably exceeded, and sometimes depressions stay more or less stationary for appreciable periods, though such a lack of movement is only usually found associated with depressions that are filling up.

The forecaster finds the predicting of the rate of advance of depressions one of the most difficult parts of his generally difficult task. Few general rules can be given: each depression must be treated on its own merits, having due regard to the pressure distribution prevailing over large areas around it and to its own make-up.

89. *Anticyclones or Highs.*—Anticyclones are the opposite of depressions. Here, the maximum barometric pressure occurs in the centre of the closed isobars, which are approximately oval or circular in shape. An example of an anticyclone is seen in Fig. 17. The great distinction between the wind and weather experienced in an

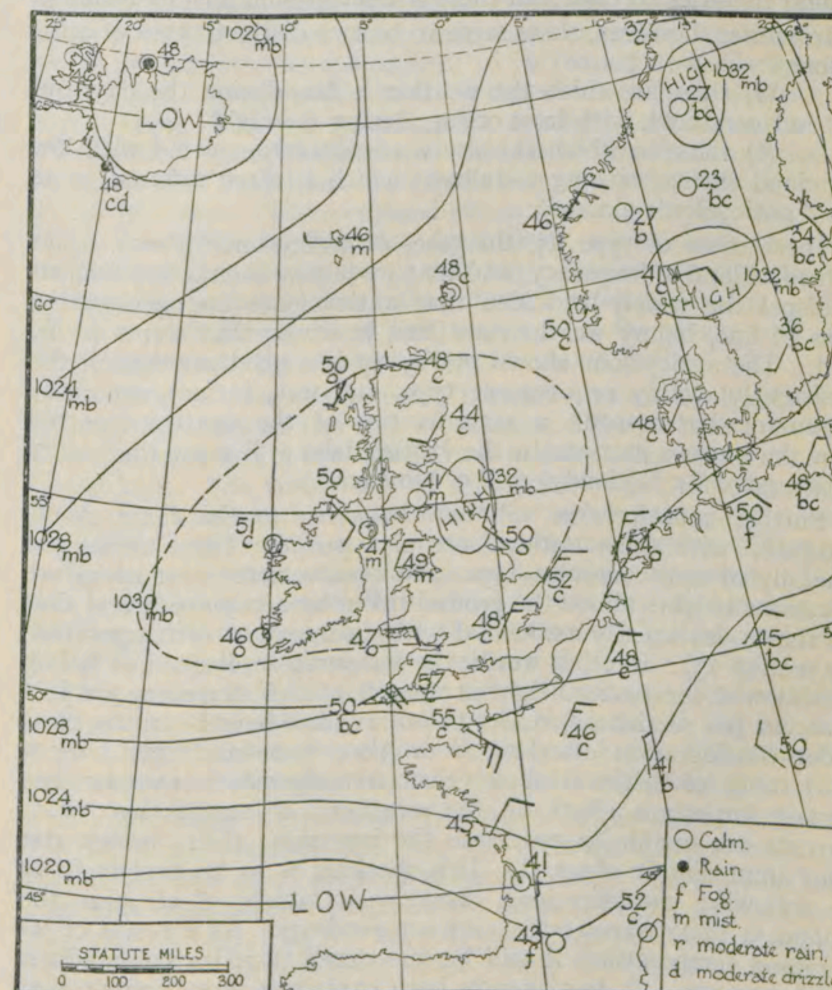


FIG. 17.—ANTICYCLONE on October 12, 1927, at 7h.

anticyclone and the wind and weather in a depression is that the latter are often violent, whilst those in the former are very rarely so. Moreover, anticyclones travel much more slowly and irregularly than do depressions and, in fact, seem more stable, often remaining more or less stationary for several days. They can, perhaps, be regarded as comparatively isolated and inert masses of air taking little part in the circulation going on about them. With regard to wind directions, it will be recognised from an application of Buys Ballot's law that the winds in the northern hemisphere in an anticyclone blow clockwise round the centre of high pressure. This should be compared with the wind-blow round a depression.

In summer, anticyclones generally bring fine, quiet weather during the day with much sunshine and a high temperature, while at night the skies are clear, but there is much ground mist or even fog.

In winter, however, there seem to be two distinct types of anticyclones :—

(*a*) those in which the weather is fine during the day and and very cold, with frost or fog, during the night.

(*b*) those in which the sky is persistently covered with low cloud sheets, causing a dullness which is often referred to as " anticyclonic gloom."

These cases of type (*b*), the cases of anticyclonic gloom, occur with considerable frequency, and that frequency should be sufficient to dispel the widely-held idea that anticyclones are, necessarily, areas of fine, balmy weather, an idea, however, that seems to die hard. The anticyclone shown in Fig. 17 is a good example of the persistently cloudy or overcast type, and was, in fact, especially chosen for that reason : a consideration of the weather reported from the various stations in the British Isles will show that every station gave " c " (cloudy) or " o " (overcast).

Further consideration will now be given to the cloud sheets associated with these anticyclones of type (*b*). These sheets are generally of stratocumulus type, and observations of temperature at various heights above the ground taken by aeroplane reveal that the sheets are usually associated with an inversion of temperature (*see* section 23) : in other words, the temperature, instead of falling steadily with increasing height at the rate of 1° F. for every 300 feet of ascent (*see* section 22) ceases to fall at some height—in the cases under consideration often 2,000 or 3,000 feet—and rises over a short range of height instead. Such a temperature inversion has a most important effect on the weather : it means that rising currents are unable to penetrate the inversion, their further rise being immediately checked. This checking is to be explained by the following considerations. Imagine a bundle of air near the ground, a little warmer than its surroundings. As a result of its increased temperature, it will be less dense than its surroundings and hence rise. It has already been explained in section 51 that rising air loses 0·6° F. for every 300 feet of rise compared with the

surrounding air ; so that the rising bundle of air steadily loses its original advantage of being warmer than its surroundings. Imagine now, that, before it has actually lost all that advantage, it encounters an inversion of temperature in the surrounding air. That inversion means that the surrounding air jumps up one or more degrees in temperature. At once, then, the rising air is colder than its surroundings and not warmer : being colder it is now more dense than the surrounding air and hence no further rise is possible. The rising column of air, therefore, on reaching the inversion, is forced to spread out like a mushroom, and if it carries cloud that cloud also spreads out to form a sheet which is the characteristic of the type of anticyclone being considered.

But the inversion with its cloud sheet and its check on rising currents has another and very striking effect so far as dwellers in London and other large industrial cities are concerned. In such large industrial centres smoke and other impurities are constantly being passed into the atmosphere to be carried upwards by rising air currents and then dispersed by the winds at high levels in the atmosphere. But the inversion, at a height, say, of 2,000 feet, checks these rising currents and the smoke and dust contained in them are thus forced into the cloud sheet also formed by the action of the inversion. The combined cloud, smoke and dust then forms under favourable conditions a dense layer, which shuts out much of the daylight, giving the " high fog " familiar to city dwellers in which day is turned into night, although at street level the atmosphere is fairly clear. It is this stoppage of the smoke and dust that has given to the inversion layer the name of the " lid."

90. *Cols.*—A col is the region between two anticyclones. It is the meeting place of two sets of winds of different directions—one set attached to one of the anticyclones and the other set to the other anticyclone. The winds are all anticyclonic and therefore light. They may, however, be of quite different temperatures and relative humidities. Condensation by mixing is therefore given full opportunity to manifest itself, and fogs and mists are frequent. These fogs and mists are especially marked in winter : in summer, the mixture of the air streams, with their different physical conditions, makes the development of thunderstorms likely.

Cols seldom persist for long on a weather chart. The bounding anticyclones do generally remain, but the area of low pressure between them forms an admirable path and lure for advancing depressions and these depressions soon displace the cols.

91. *Secondary Depressions.*—Secondary depressions, sometimes referred to as " secondaries," are low-pressure systems contained within the ambit of a parent or primary system. Secondaries vary from mere sinuosities or bulges in the isobars bulging outward from the centre of the primary to fully developed disturbances with their own systems of closed isobars. Such a fully developed secondary is shown in Fig. 18.

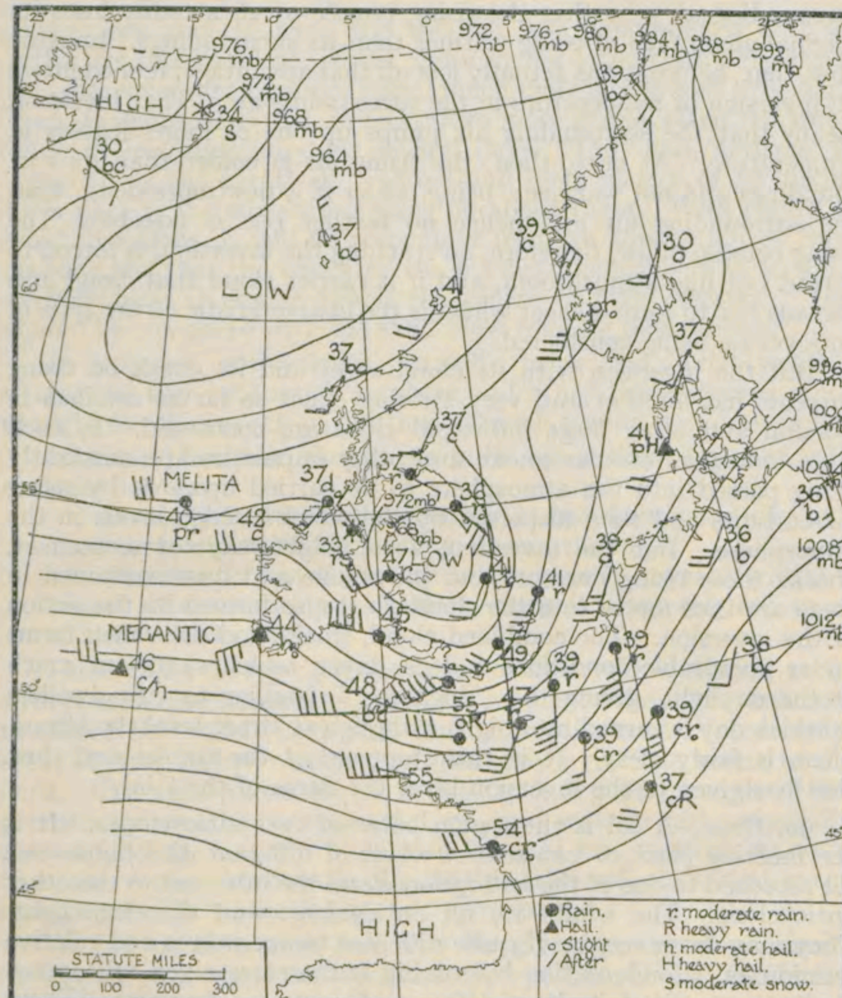


FIG. 18.—SECONDARY DEPRESSION on January 12, 1930, at 18h.

Secondary depressions, whether fully developed or just bulges, usually travel in an anti-clockwise direction around the primary, and generally move at a faster rate than does that primary. This means that, as a rule, they progressively alter their relative position with regard to the centre of the primary. Sometimes, the secondary grows while the primary diminishes, so that from the study of one chart only, without reference to the preceding three or four, it is difficult to say which is the actual primary and which the secondary.

When the secondary depression is fully developed, that is, has its own system of closed isobars, it displays warm and cold fronts, which in time degenerate into an occlusion, and reveals the same wind and weather distribution as in ordinary depressions. The less developed secondaries, the sinuosities, while not showing the complete

wind and weather systems of the fully developed varieties, yet often produce showers if just a bulge, or much low cloud and rain if in a more advanced state than that of just a bulge.

It will be realised, therefore, that the alterations in weather brought about by even comparatively slight bulges are sufficiently great to call for great care in the drawing of the isobars on the synoptic charts used for forecasting purposes.

It is interesting to notice the wind behaviour in the region between the secondary and the primary. In Fig. 18, taking the centre over northern England as the secondary and the centre off northern Scotland as the primary, it is clear that, between the two depressions, the easterly winds due to the northern part of the secondary must balance in greater or lesser degree the westerly ones due to the southern part of the primary, and that, in consequence, calms or light airs should result. This area of calm or light airs is seen from the figure to be the midland districts of Scotland. The gales, severe in places, blowing in the Irish Sea, the English Channel and the southern North Sea are also worthy of notice as it is quite a common feature of English weather that strong winds or gales should occur on the southern side of a well-developed secondary depression.

It is further of interest to note that, according to the ideas of the Norwegian meteorologists, led by J. Bjerknes, a secondary depression usually finds its origin on the southern end of a line of occlusion.

92. *V-shaped Depressions.*—V-shaped depressions take their name from the shape of the isobars which are in the form of a V with the point generally directed towards the south-east. The trough line forming the V is usually, so far as such depressions over the British Isles are concerned, a line of occlusion. This line of occlusion may show either warm-front or cold-front characteristics. Those showing warm-front characteristics have the air behind the line of occlusion warmer than the air in front so that this warm air rises over the colder to give much low cloud and continuous rain in front of, and at, the line of occlusion, followed by mild, cloudy conditions after the passage of the line with a veer of wind usually from south-easterly or southerly to south-westerly or westerly. Those showing cold-front characteristics—and these are by far the more numerous—have the air behind the line of occlusion colder than the air in front so that the colder air undercuts the warmer to give squally, showery conditions with a fall in temperature accompanying the wind veer previously mentioned. When the sharp point of the V becomes rounded off, as always happens in due course, the system is usually termed a " trough of low pressure."

93. *Wedges or Ridges of High Pressure.*—Between two depressions there occurs, generally, what is known as a " wedge " or " ridge " of high pressure. The wedge is usually shaped like an inverted V, and it moves in an easterly direction with the two depressions which it separates. As would be expected from what has been said

about depressions, the eastern, or front, side of a wedge is a region of fair weather with light northerly or north-westerly winds, and the western, or rear, side a region of southerly winds and increasing and lowering cloud as the second depression approaches. In the centre of the wedge winds are very light in force and variable in direction. If fine weather quickly follow a depression, it is frequently the sign of a wedge: in which case, bad weather will follow again comparatively quickly.

94. *Straight Isobars.*—Quite often, the isobars on a synoptic chart run almost straight over a large area. Such straight isobars are the outermost margins of a large depression whose centre is located a considerable distance away. The winds approximately follow the lie of the isobars and their direction is determined by the position of the centre of low pressure. Almost any type of weather may accompany straight isobars, largely dependent upon the direction of the parallel isobars, their relation to the pressure centre, and the season of the year. For example, in winter in the British Isles, straight north-south isobars bring northerly winds with squalls, and sometimes snow or sleet: but in summer, cloudy and thundery conditions often prevail with an entirely similar isobaric arrangement.

The commonest type of straight isobars over the British Isles is the "south-westerly," which is the one in which the isobars run practically parallel from south-west to north-east, with the centre of the big depression, of which the isobars form a part, somewhere in the Icelandic region. Straight isobars of this type are very favourable for the formation of secondary "bulges." The weather under these south-westerly conditions varies considerably, from bright to overcast with showers, and, sometimes, even steady rainfall is experienced.

95. *Convergence and Divergence.*—Before concluding this chapter, which deals in the main with synoptic charts and inferences to be drawn from them, some reference to the phenomena of convergence and divergence is called for as those phenomena are of considerable importance from the view-point of synoptic meteorology.

Convergence is a coming together of the air streams over a given region while divergence is the opposite, a blowing apart of the air streams. Imagine a square of the earth's surface and further imagine that a uniform westerly wind is blowing across the square. This condition of things is represented by the first of the three diagrams in Fig. 19 and it is clear that as much air leaves the right side of the square as enters in at the left. In this case there is neither convergence nor divergence. Now imagine that the westerly flow is not uniform but blows inward a little from the north along the northern side of the square and inward a little from the south along the southern side. This state of things is represented in the second diagram in Fig. 19 and constitutes convergence: it is clear that more air is leaving the square on its right hand side than is entering on the left. The converse case to this is shown in the third diagram in Fig. 19, where the wind is blowing a little outward along both the northern and southern edges of the square: this constitutes divergence, less air leaving the square through its right-hand side than is entering through the left-hand one.

Convergence means, as has been already shown, that more air is leaving the right-hand side than is entering at the left. But the square was already full of air at the beginning with the uniform flow: the excess of air which is the result of the convergence has therefore to be disposed of, and this disposal takes place by the escape of air over the top. In other words, a rising current is set up and as rising currents give rise to cloud and rain these effects follow from convergence, if the convergence be sufficiently strong and sufficiently prolonged. A similar argument will reveal that divergence produces a down current, the deficit in the original quantity of air covering the square being only replaceable by air coming down from above. Descending, or subsiding, air is air that is being compressed and hence becomes warmed, the converse of air that is rising becoming cooled. The warming tends to evaporate any cloud existing and hence divergence, with its subsiding air, is associated with clearing or clear skies.

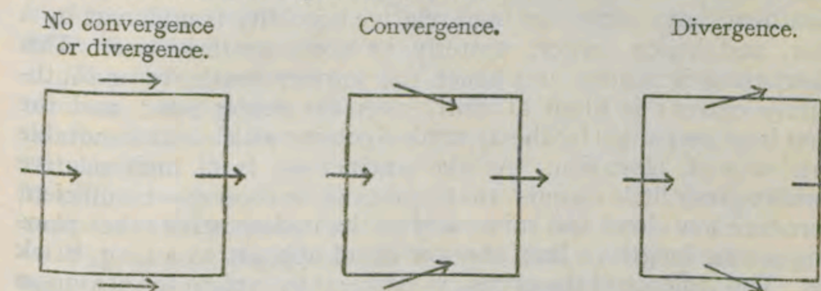


FIG. 19.

It has been shown* that, theoretically, with certain reservations, "isallobaric lows" (*see* section 86) must be regions of convergence and "isallobaric highs" regions of divergence. These facts go far to explain the cloudy, rainy weather associated with a rapidly falling barometer and the clearing weather associated with a rising one. The connexion between barometric changes and weather is seen to be very intimate, indeed.

* "The modification of the strophic balance for changing pressure distribution, and its effect on rainfall." By D. Brunt and C. K. M. Douglas. *London, Mem. R. met. Soc.*, **3**. No. 22. 1928.

CHAPTER XV

Special Phenomena

96. *Line Squalls*.—A line squall is a heavy squall of wind which is accompanied in a country like the British Isles by the passage of a long arch of low, black cloud, which often stretches in approximately a straight line for several miles, and from which heavy rain or hail falls for a short time. Thunder and lightning, too, often occur during the passing of the squall. The squall is also accompanied by a veer of wind from some southerly or south-westerly point to a westerly or north-westerly one, together with a sudden drop in temperature and a sudden rise of barometric pressure. The actual wind squall lasts for only a few minutes but is often extremely violent. In brief, the phenomena accompanying a line squall are quite characteristic and cannot be mistaken.

The explanation of such a squall is to be found in the fact that it is invariably associated with a well-marked cold front and that means, as has already been pointed out in section 84, that a warm southerly or south-westerly current of high relative humidity is undercut by a colder, and hence denser, westerly or north-westerly one. This undercutting is sudden and hence the warmer southerly or south-westerly current is lifted abruptly over the colder one; and the ascent is accompanied by the dynamical cooling which is an inevitable result of such elevation. As the warmer air is of high relative humidity, very little ascent—that is, very little cooling—is sufficient to produce low cloud and rain: and as the undercutting takes place along a long length of line, the low cloud appears as a long, black arch. The violence of the uprush is sufficient to explain the heaviness of the rain and also to explain the hail which is so often a feature of line squalls. The sudden drop in temperature and the sudden rise in barometric pressure are the results of the substitution of the colder air in the rear for the warmer air in front.

As has been already noted, the foregoing description of the phenomena accompanying line squalls applies to the British Isles and to countries situated similarly geographically. The essential feature in such countries is that the warm current in front of the squall is moist. In some parts of the world, however, the current in front is dry and that means that it has to be raised to a great height by the colder current behind before it is cooled down to saturation point, with the result that the squalls may pass without rain or even without cloud.

Line squalls constitute an exceptionally serious menace both to shipping and to aircraft. Happily, however, the forecasting of their travel is not marked by very serious difficulty. In the British Isles, they usually move from west to east or from south-west to north-east

—movement from an easterly to a westerly point is practically unknown—and their speed of advance lends itself to comparatively precise computation by reason of the fact that in active depressions any given part of a cold front advances with a velocity which is approximately equal to the component, perpendicular to the front, of the gradient wind (*see* section 79) in the cold air in its rear. These considerations mean that due warning of the coming of line squalls can be given with considerable accuracy of timing to localities in their track.

Reference may fittingly be made here to those South American storms to which the name "pamperos" is given. Pamperos are line squalls and show all the essential characteristics of those disturbances. They brush up great clouds of dust from the dry pampas and are accompanied by drenching rains and almost incessant lightning for a short period: they are greatly feared by sailors in the estuary of the Rio de la Plata.

97. *Thunderstorms*.—Two conditions are required for the production of a thunderstorm:—First, an adequate supply of moisture for cloud development; and second, a steep temperature lapse rate (that is, a large fall of temperature with height) extending for a very considerable range upward from the cloud base, a range which is probably never less than 10,000 feet, and which is probably much more in the case of severe storms.

The first condition specified is that of an adequate supply of moisture for cloud development in the lower regions of the atmosphere. In the British Isles, the phrase "lower regions of the atmosphere" may be taken to connote the first 10,000 feet of height, though in most storms that occur the moisture necessary is supplied mainly by the first 5,000 feet.

The second condition specified, that of a steep temperature lapse rate upward over a considerable range from the cloud base, is dependent on the meteorological situation prevailing, and may arise in the following ways:—

(*a*) Strong surface heating of the ground on clear days, provided that the upper air is relatively cold.

(*b*) The existence of a warm, damp current in the region up to 5,000 feet, approximately, with relatively colder air at greater height.

(*c*) The undercutting of warm, moist air by a cold current.

(*d*) Warming at the base of deep polar currents travelling southward.

Thunderstorms of type (*a*) usually occur in the afternoon when the heating of the ground and the surface air layers by the sun has attained its maximum effect. In the British Isles they are, as would be expected, mainly phenomena of the summer half-year (May–August), and are most frequent in the early part of that period, for then the upper air is more likely to be relatively cold.

Thunderstorms of type (*b*) are due to warm, damp air in the first 5,000 feet or so having relatively cold air above. They frequently occur in summer in the British Isles, when a spell of anticyclonic weather is breaking down and depressional conditions are beginning to spread in from the Atlantic or up from France, these depressional conditions causing an intrusion of warm air in the first 5,000 feet, approximately. It is worthy of notice that the conditions outlined may occur during the night as well as during the day, and that thus some nocturnal thunderstorms may be explained.

Thunderstorms of type (*c*) are usually associated with cold fronts, especially with those well-marked ones giving rise to line squalls, with which latter phenomena it has, indeed, already been remarked (*see* section 96) that thunder and lightning often occur. These storms may be experienced at any time of the year and either by day or night.

Thunderstorms of type (*d*) are usually of slight intensity and, so far as the British Isles are concerned, occur quite frequently near the western seaboard in winter and fairly frequently near the eastern seaboard in summer, with a temperature frequently below normal at the surface, but with a very much greater deficiency above. They are associated with deep, polar currents, moving southward, that have had their lower layers warmed as a result of that southward travel. Apart from the warming due to this movement from higher latitudes to lower ones, an interesting paper by Newnham* reveals another method of obtaining the same end, especially in winter. That other method is found in the heating by the warmer ocean of the lower layers of a colder current of air. The deep, polar currents, to which reference has already been made, travel in many cases over large tracks of ocean before reaching the British Isles. The water is warmer than the air, and thus warms the lower layers of that air, producing a steep temperature lapse rate upward. In these circumstances, therefore, the expectation of thunderstorms in polar air which has passed over a wide stretch of ocean before reaching land is often realised, and investigation shows that many of the thunderstorms occurring in northern and western Scotland come into this category. A large depression with its centre north of Scotland forms one suitable pressure distribution for such storms, the northerly winds in its rear being usually composed of polar air and crossing a great expanse of relatively warm ocean before they turn to traverse the British Isles as westerly ones.

All thunderstorms, then, of whichever of the four types (*a*), (*b*), (*c*) and (*d*) described above, are seen to depend upon a convectional overturning of the atmosphere; and the characteristic cloud of thunderstorms, the cumulonimbus, is itself evidence of

* "On the formation of thunderstorms over the British Isles in winter." By E. V. Newnham. *London, Prof. Notes, met. Off.* No. 29, 1922.

great convection. The development of that cumulonimbus cloud from simple cumulus is interesting and instructive, and may be seen stage by stage in the development of thunderstorms of types (*a*), (*b*) and (*d*). In the cold-front type of storms (type (*c*)) the progressive building-up is not discernible.

Imagine, then, that the development of a thunderstorm on a summer's afternoon is being watched. The cumulus clouds formed in the morning are seen with their level bases and sharply contoured tops. A little while, and here and there it will be noticed that some of the clouds are growing taller than their fellows. As the growing taller progresses, so does the rate of growth: and soon, some of the clouds reach towering sizes, their summits attaining heights up to 20,000 feet. Then the summit of this or that towering example flattens out, until the whole assumes the shape of an anvil—the cloud at this stage, in fact, is often referred to as an "anvil cloud." At first, the edges of the anvil top are hard and clear cut. A curious change, however, soon supervenes, for wisps or filaments of cirrus-looking cloud appear and cover the anvil as with a fleecy mantle. This cirrus-looking cloud is cirrus nothus (*see* section 47), often referred to as "false cirrus." This appearance of the cirrus nothus marks the full development, and when that development is attained the whole appearance of the "thunder cloud," as it is sometimes called, is that of an anvil of great size which has been covered with a cloth of exceptionally delicate texture—and such a cloud in being is usually accompanied by a thunderstorm.

98. *The Theory of Thunderstorms.*—If drops of water are allowed to splash upon a metal plate, the water gains a minute positive charge of electricity, and an equal negative charge is shared by the plate on the one hand and the air in the immediate neighbourhood of the splashing drop on the other. The largest charges are found when distilled water is used and even small amounts of dissolved substances in the water make a considerable difference to the results obtained. With sea-water, indeed, the effect is reversed, the water becoming negatively charged after splashing. But the presence of a solid obstacle to cause splashing is not really necessary to produce the separation of electricity. The breaking-up of a jet of water into spray and the splitting of drops of water by a current of air produce similar effects.

The last-named case—the production of electric charge as the result of the mere breaking-up of a drop of water by a current of air—is of particular interest in meteorology because it forms the basis of the theory put forward by Sir George Simpson* to account for the production of the electrical stresses in the atmosphere which precede the discharge of lightning in thunderstorms.

* Simpson, G. C. "On the electricity of rain and its origin in thunderstorms." *London, Philos., Trans.*, A. **209**, 1909, pp. 379–413.

It has already been pointed out that ascending currents are necessities for thunderstorms. In ascending, the air expands and gets rapidly cooler (*see* section 51), with the result that, before long, the water vapour in the air begins to condense and to form droplets. The drops rapidly increase in size and would ordinarily fall as rain. But if the ascending current exceeds 17·9 miles per hour in vertical velocity, the drops cannot fall through it (*see* section 52) but are carried upward. Moreover, no raindrop can grow beyond 5.5 millimetres in diameter (*also see* section 52). At this point it becomes unstable and breaks up into droplets.

But—and this is the essential point—each time a division takes place, the resulting droplets gain positive charges and the surrounding air an equal negative charge. Because of the weight of the water droplets to which they are attached, the positive charges cannot rise so readily as the negative charges which are in the form of free electrons. The rising air currents, then, act as separators of the positive and negative charges, leaving the positive charges below and carrying up the negative ones. The positively charged water droplets quickly combine to form larger drops, and these, in turn, are re-broken up with the result that the droplets resulting gain a further positive charge and the rising air a further negative one. Each time, therefore, that a division takes place there are gains in both the positive and the negative charges—and the divisions, re-combinations and re-divisions may be repeated conceivably hundreds of times to the production of large electrical stresses which are relieved by lightning flashes. Further consideration shows that the positive charges become localised in the region of the base of the cloud where the larger water drops are collected while the negative charges are carried up by the rising air to be spread over a much larger volume than that occupied by the positive charges.

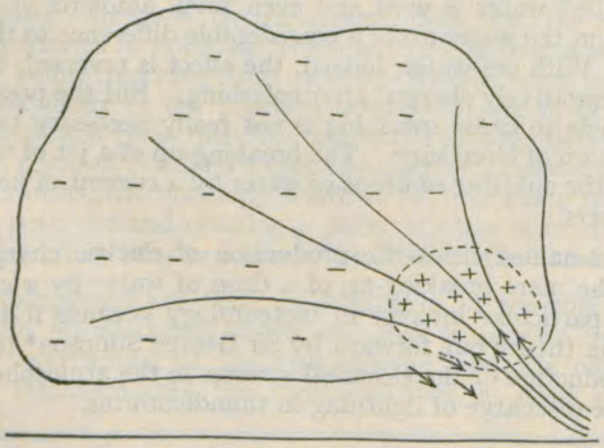


FIG. 20.—Illustrating the formation of a thunderstorm.

Thisd istribution of the electricity in a thundercloud is shown in Fig. 20, the thundercloud being assumed to be moving from left to right. The continuous lines drawn upward on the extreme right of the figure denote the up-current while the short arrows denote the down one. The sign + represents positive electricity and the sign — negative electricity. The localised area of positive electricity is not fixed but moves up and down with the variations in the rising current.

Fig. 20 also furnished an explanation of the observed facts that the heavy rain in the front part of a thunderstorm is usually positively charged while the steadier rain in the rear part is usually negatively charged.

The theory outlined above, fascinating though it is, has not, however, escaped criticism. It will be seen that it connotes that where convection is most vigorous, and hence electrical separation most active, the cloud should be negative above and positive below. That this distribution actually is the normal one has been questioned by C. T. R. Wilson,* Schonland†‡ and Craib†, Wormell§ and others who hold that the lower pole of a thundercloud carries a negative charge. Simpson‖ has argued, however, that the contradiction may be more apparent than real and that his theory is nót vitiated by it. The final solution of the question awaits further research.

99. *Lightning and Thunder.*—Lightning may be defined as the flash of a discharge of electricity between two clouds or between a cloud and the earth. Distinction is usually drawn between " forked " lightning and " sheet " lightning : in the forked variety the path of the actual discharge is visible, while in the sheet variety it is only the flash of illuminated clouds which is seen, the illumination being due to the light of a discharge the actual path of which is not seen. It will be realised, therefore, that forked and sheet lightning are not really different but that sheet lightning is only an effect due to unseen forked lightning.

Thunder is the noise which follows a lightning flash. It is attributed to the vibrations set up by the sudden expansion, due to the intense heating, of the air through which the flash travels, followed by quick cooling and hence contraction. These vibrations travel outward to give the noise of the thunder, it being remembered that sound is essentially a matter of air waves. That thunder sometimes rolls for quite an appreciable time is due to the fact that the sounds emanating from different sections of the lightning flash have different distances to travel to reach the observer : while reverberations or

* WILSON, C. T. R. *London, Proc. roy. Soc.* A. **92,** 1916, p 555.
† SCHONLAND, B., and CRAIB, J. *London, Proc. roy. Soc.* A. **114,** 1927 p. 229.
‡ SCHONLAND, B. *London, Proc. roy. Soc.* A. **118,** 1928, p. 233.
§ WORMELL, T. W. *London, Proc. roy. Soc.* A. **115,** 1927, p. 443.
‖ SIMPSON, G. C. *London, Proc. roy. Soc.* A. **114,** 1927, p. 376.

changes in intensity of the noise of a single thunder roll are explained by the crookedness of the lightning flash giving rise to the thunder being considered.

It is interesting to note that the distance of the lightning flash away may be approximately estimated by timing the interval in seconds that elapses between the flash and the resulting thunder and taking every five seconds of that interval to represent one mile of distance. This simple rule is based on the facts that light has such a large velocity (186,000 miles per second) that it may be assumed to reach the observer simultaneously with its production while sound travels with a speed which is, very roughly, one mile in five seconds.

100. *Cloud-bursts.*—Cloud-bursts are only exaggerated thunderstorms. They occur chiefly in hilly or mountainous districts, and manifest themselves as exceptionally heavy rainfalls (sometimes with hail) in very short periods of time. They are probably caused by the sudden stoppage of ascending air currents as the hills or mountains are crossed. As was shown in section 52, an ascending air current of sufficient velocity is able to support a great quantity of accumulated water in it. If this upward current be suddenly stopped, the water, which it had been supporting, falls, and if the accumulated stores were great the fall is extremely heavy and rapid.

101. *Tornadoes and Waterspouts.*—The connotation of the name " tornado " varies somewhat in different parts of the world.

In West Africa, the tornado is the squall which blows out of the front of a thunderstorm at about the time the rain commences. These West African tornadoes occur most frequently during the transition months between the rainy and dry seasons.

In the United States of America the name " tornado " is applied to the small but very violent, anti-clockwise whirlwinds of one hundred or two hundred yards in diameter which advance towards the east or north-east at a speed of from 20 to 40 miles per hour, the very strong winds, sometimes above 200 miles per hour in velocity, destroying practically everything within the direct path. Another factor in the great destruction caused is that the very rapid decrease of barometric pressure near the centre of the tornado (which is really an intensely deep depression of small diameter) allows the air inside buildings to produce an explosive effect. Apart from the violent winds, the most characteristic feature is the funnel-shaped cloud which hangs downward and which is generally in a whirling condition. The activity of one tornado lasts for about half-an-hour.

These American tornadoes especially favour the Mississippi valley and occur chiefly on hot afternoons in the summer months. They are associated with thundery conditions especially in secondary or V-shaped depressions where the interaction of wind currents with a large difference of temperature makes for very violent, upward convection. Thunder and lightning, with heavy rain, generally accompany the tornadoes.

Waterspouts with the funnel-shaped tornado clouds occur at sea or over large lakes. They occur more frequently in the tropics than elsewhere. The funnel cloud descends, and, as it descends a cloud of spray or vapour forms over the sea or lake immediately beneath the point of the funnel. Finally, the funnel point touches the surface and the cloud of spray or vapour takes on the appearance of a column of water. Violent winds generally circulate around the funnel-shaped cloud. Like the tornadoes on land, waterspouts last only for about half-an-hour.

102. *Hurricanes and Typhoons.*—Tropical depressions are often of small diameter, from 50 to 300 miles, with very steep pressure gradients, and consequently with winds circulating around them of great violence. Such systems occurring in the western Pacific, near Japan and the Philippine Islands, are termed " typhoons " ; if near the West Indies, " hurricanes " ; and if in the Indian Ocean, " cyclones." The use of the term " cyclones " in this connexion needs to be carefully differentiated from the usual use of that term in Great Britain (*see* section 81).

Hurricanes, typhoons or " cyclones " are accompanied by great masses of cloud, from which rain falls in torrents, and very strong winds which, however, are not quite so violent as those experienced in tornadoes.

The systems move along fairly regular routes. If land be encountered the storms weaken and often die away.

One peculiar feature is the well-marked nature of the centre. As the hurricane, typhoon or " cyclone " travels, the wind rages with great violence but, in the centre, drops to almost a dead calm. This change occurs abruptly and the clouds may even break and blue sky appear. The diameter of the calm area may be from 10 to 30 miles. As the system continues to travel, however, and the centre passes over the observer (generally away to the eastward in the northern hemisphere), the winds rise again as abruptly as they dropped, attaining quickly to a violence equal to that which they had before, but blowing now from the reverse direction, as would be expected from Buys Ballot's law. The centre, on account of its peculiar characteristics, is often referred to as " the eye of the storm," and has been termed, poetically, " the whirlwind's heart of peace."

CHAPTER XVI

Forecasting

103. *Forecasts.*—The first use of synoptic charts for forecasting weather was made by Admiral R. Fitzroy in 1860, and it was he who invented the special meaning of the term "forecast" to avoid the somewhat unfortunate connotations attaching to such terms as "prognostic" and "prophecy."

As issued now, a forecast generally covers a period ahead which is not greater than 36 hours. It is published, as a rule, in a definite form, which is as follows :—

(1) A statement of the anticipated direction and force of the surface wind and the changes therein which are expected during the period of the forecast.

(2) A statement concerning the probable state of the face of the sky with regard to cloud, together with statements concerning the incidence and type of precipitation, if any, and concerning the temperature likely to be experienced, especially as to whether that temperature is likely to be greater or less than the normal for the time of year, or higher or lower than at the time of making the forecast.

(3) Notes with regard to such occurrences as thunderstorms, fog or night frosts, if any of such occurrences are expected during the period of the forecast.

Forecasts issued for special purposes contain additional matter to that already specified in the above. For aviation, for example, the anticipated winds at selected or demanded heights are included, together with a detailed statement concerning visibility and the changes expected therein : while for seamen, statements concerning the state of sea and of visibility are included.

After the forecast, there is often a statement under the heading of "Further Outlook" which gives in brief and general terms the conditions likely to be experienced in the 24 hours or so following the period covered by the actual forecast.

104. *The Practice of Forecasting.*—In the making of such a forecast as has been described, the forecaster depends practically entirely upon the synoptic charts before him, together with special additional data received from certain stations concerning upper air winds and temperatures. He examines the current charts and determines what types of isobaric distribution and what types of air currents are prevailing. From a further consideration of the chart, in conjunction with the two or three previous ones, and perhaps also with examination of charts of similar general features taken from the same season in previous years, he endeavours to determine the probable movements and changes in the isobaric groupings and the air streams shown and tries to visualise what the charts of 6, 12 and 24 hours ahead will look like. He then makes

up his mind as to how far the particular regions for which he is forecasting will be affected from the view-point of wind and weather by those movements and changes in isobaric groupings and in air streams that he has decided will happen.

It will be recognised, then, that the making of a sound weather forecast is by no means an easy matter, but connotes that the forecaster shall have at his ready disposal a well-organised stock of meteorological and physical knowledge, which knowledge can only be obtained by diligent study, and the ability to use which can only be gained as the result of much practice. The forecaster is in much the position of a physician : to be successful he must be able to diagnose rapidly but soundly, must be able to determine quickly which factors are essential and which non-essential, and then having judged the factors by his diagnosis, he must be able to predict the future action of those factors, and to interpret that action in the light of his particular needs. Forecasting is, in short, a scientific process based upon physics, precedent and soundly-sifted experience : and the ability to forecast well is an ability that has to be diligently wooed and is even then only hardly won.

It is further desirable to declare roundly that no one method, whether that due to Abercromby, to Guilbert, to Bjerknes, or to any other yet known, contains the total whole of forecasting truth. Each method has its help to offer according to the charts before, and the demands upon, the forecaster : but, even so, experience shows that each method will give its failures from time to time, even in situations when the stage seems peculiarly set for its particular use. The forecaster of experience, then, realising from that experience the difficulty of his task, will confront the charts before him with the weapons afforded by all the known methods, and will then choose the weapon that the need of the moment demands : and the fact that even with maximum care and adequate use of the theories and methods known, failures still occur only reveals that the need for continued research into the problems that forecasting the weather presents is insistent, continued research the stimulus for which is to be found in the great, and often vital, help that accurate forecasts of weather can offer to man in so many of his manifold activities on land and sea or in the air.

In connexion with the matters treated in this section it may not lack in interest to refer to a few of the situations of peculiar difficulty that confront the forecaster in the British Isles from time to time. The first of these is that tendency to persistence of type which the weather occasionally shows in pronounced form and which, up to the present, has baffled adequate explanation. The tendency is particularly noticeable after a spell of dry weather has prevailed. It seems in these circumstances that something more than the normal is required to break down the spell : depressions appear to threaten, but pass away without giving the rain that normally they would give. The converse holds true, often enough, in conditions that have been persistently rainy: under these conditions it is often to be remarked that even the smallest secondary "bulge" is able to give rain in quantity when normally it would pass with only a sprinkling or a shower. This inertia, so to speak, this desire to maintain what has been, is a capricious and perplexing factor, but one to which experience teaches a forecaster to give considerable weight. A second situation of peculiar difficulty is when observations on the west coast of Ireland give slight though definite indications of a depression approaching from the west, while any previous reports from ships on the Atlantic that may have been received have given no inkling of the disturbance. In these circumstances even the most experienced forecaster may well be in doubt as to whether a major or a minor disturbance will result and as to its direction of travel. A third baffling situation is that encountered when, after anticyclonic conditions have prevailed for some time, the barometer begins to fall generally, and to persist in that fall for some considerable time, without there being any depression on the map to account for the fall, or without any deterioration in the weather accompanying the fall. The forecaster realises that the fall cannot go on indefinitely without the weather breaking, but the timing of that break-up is a matter of very great difficulty.

105. *Forecasting by a Single Observer.*—It is instructive to attempt to realise what a single observer can do to forecast coming weather without any synoptic charts or instruments available to him or without any knowledge of what the weather conditions are in other localities.

Remembering Buys Ballot's law and what has been said about the sequence of weather events in a depression (*see* section 84), he should be able generally to recognise the approach of such a system. Careful noting of the speed of the cloud changes occurring should also enable him to say whether the depression is advancing rapidly or slowly. But his forecasts, based on these observations, must, of necessity, be rough, for he is handicapped by not knowing either the size of the depression or whether it is developing or not.

He may often, moreover, be able to forecast the formation of frost and of radiation fog by a study of the principles set out in sections 34 and 40, respectively, while a careful observing of the development of "anvil clouds" (*see* section 97) should lead him to a successful forecasting of some thunderstorms, though not at any great distance ahead.

On coasts and at sea, the single observer may derive help from a careful consideration of the changes occurring in the swell and in the state of sea.* Sky colorations, too, are not without value: one

* *See* "A note on the value for forecasting of observations of swell on the open sea." By W. H. Pick and F. E. Coles. *London, Quart. J.R. met. Soc.* **56**, 1930, pp. 57–8: and "Value of observations of sea disturbance at stations on our western coasts in forecasting depressions advancing from the Atlantic." By W. H. Pick and F. E. Coles. *London, Quart, J.R. met, Soc.* **56**, 1930, pp. 129–30.

interesting case of such is that of a distinctly green coloration of the sky, or part of it, which, in the British Isles at least, appears to occur only when vigorous depressions are situated to the north or west of those Islands and to mean also high winds at the cirrus level,* while in tropical oceans it is regarded as a herald of a hurricane or typhoon.

Granted, however, that the single observer is possessed of a barometer or of a barograph, the latter the most useful instrument, perhaps, from the view-point of forecasting that he can possess if he is limited to one, then his forecasts can gain somewhat in precision by a careful consideration of the rate of variation of the pressure changes taking place, coupled with a knowledge of the wind and cloud changes also occurring. For example, a rapid fall in the barometer would lead him to suspect the coming of a fast-moving depression and of strong winds or gales: while a sharp rise after a depression has passed would lead to the forecast of a wedge of high pressure advancing as opposed to a continued slow rise giving notice of an anticyclone.

But when all is said, the best that a single observer, with or without a barometer or barograph, can do to forecast for even a short period is very little, and "further outlooks" are quite impossible for him. In short, synoptic charts are the foundation of successful forecasting, and, without them, very little is possible.

106. *Long-range Forecasts.*—Much work has been done in the endeavour to find means to forecast the coming of weather changes at a greater distance ahead than three or four days. It cannot be said that, up to the present, very much success has resulted.

If the problem be put in the form of asking what the weather in such a place as London, for example, will be this day week, then the only answer is that the succession of pressure types is, apparently, so irregular that the weather at such a distance ahead cannot be forecast beyond giving the average for the time of year. There are almost certainly laws underlying the apparently irregular succession of isobaric groupings, but they have not yet been found, though probably they will be in course of time. Three or four days ahead, in such a region as the British Isles, seems the extreme distance for which a forecaster can predict satisfactorily, even under the most favourable of pressure distributions which would be that of a large and slow-moving anticyclone over the country.

But certain results have been reached with regard to a periodicity in the sequence of certain meteorological elements, results which are sufficiently encouraging to lead to hopes that more may yet be done. To take an example, Brückner of Berne, so far back as 1890 concluded, from an examination of all available rainfall data, that, in Europe, there is a variation of rainfall with an average period of

* "The significance of a green sky." By W. H. Pick. *London, Quart. J.R. met. Soc.* **56**, 1930, pp. 350–2.

35 years, and hence he was able roughly to predict wet periods and dry periods, each approximately of 17 years' duration. H. C. Russell has suggested, similarly, a period of 19 years for the variation in the rainfall of Australia, a result which has been confirmed by other workers.

Much, too, has been attempted in the correlation of sunspots with terrestrial weather. The mean period of frequency of sunspot numbers is, approximately, 11 years. It is known that sunspots are due to vertical disturbances in the sun's atmosphere, such disturbances being of huge extent. It is known, too, that the spots bear a definite relationship to terrestrial magnetic records. Many weather phenomena, such as "cyclones" in the Indian Ocean (*see* section 102) and the rainfall in Scotland, have been subjected to statistical examination in attempts to correlate them with the periods of the spots, but the results have not been very satisfactory.

But there is a danger about periodicities in general when attempts are made to apply them to actual forecasting for a given stretch of time or for a given date. That danger is clearly pointed out in the following quotation*:—"There is at once a fascination and a curious inconclusiveness about many of these attempts to identify the period of variation of the meteorological elements. The periodicity shows itself when records for long intervals are studied, but it is apt to be illusory as a guide to the meteorological character of any particular year. An example of the fascination and the difficulty here referred to may be given from the consideration of the seasonal variation of rainfall in our own country. Nothing is more certain about the seasonal variation of that element than that the rainfall tends to a maximum in October and a minimum in March; any curve of average monthly values taken for a long period of years will give that result, and, consequently, one is perfectly justified in assuming that the assignment of a seasonal periodicity in rainfall with a maximum in October represents something real, yet, if one were to hazard a prediction that the coming month of October will be the rainiest month in the current year, the facts might belie the prediction."

Another method of attacking the problem of long-range forecasting is to endeavour to prove a connexion between one set of phenomena occurring in one part of the world and another set of different phenomena occurring in another part at a later date, thus placing the two in the form of cause and effect. As all weather is, doubtless, the result of a general atmospheric circulation over the whole globe, little objection on the logical side can be urged against these attempts, and some have been very successful. Sir Napier Shaw† has shown, for example, that a remarkably close parallelism exists between the seasonal variation in the trade wind at St. Helena

* Shaw, W. N. "Forecasting Weather." London, Constable and Co., Ltd., 1913, Chapter 17, p. 357.
† See *Nature, London*, **73**, 1905, p. 175.

and the rainfall in the south of England: while in India reasonably successful seasonal forecasts, largely concerned with monsoonal rainfall, and making use of antecedent conditions as far away as South America, have been made throughout the present century by Sir Gilbert Walker and his co-workers. Yet another case is that W. Wiese has found that the ice conditions in the Barents Sea are dependent on a number of antecedent conditions extending at least as far as the equator: while E. H. Smith* has suggested a similar possibility for the ice around Newfoundland. In general, therefore, this method of finding relations between meteorological conditions in different parts of the world is to be considered as perhaps the most promising one from the view-point of long-range forecasting.

* The International Ice Patrol. *London, Met. Mag.*, **60**, 1925, p. 229.

CHAPTER XVII

Weather Lore

107. *Weather Maxims.*—Ever since man has thought at all, he has generalized about the weather with the result that a very large number of weather maxims are now in existence, these maxims being intended as means whereby the weather to come may be forecast.*

A few of these maxims are true, a larger number contain a partial truth, a very large number indeed are completely fallacious, and some are mutually contradictory. But this does not seem to matter at all; these maxims are part of the popular current coinage of conversation, and often enough, definite action is based upon them, which definite action leads frequently to a failure which need not occur if the user of the weather maxim but take the trouble to examine the foundations of the belief in which he puts his trust.

Very few of the common weather sayings stand the test of statistical examination, and this is hardly a matter for surprise when the propensity of man to count the "hits" and to neglect the "misses" be remembered.

Consider the prediction, for example, associated with St. Swithin's Day (July 15th) in England :—

"If St. Swithin greets, the proverb says,
The weather will be foul for forty days."

Even the most cursory investigation of this over a few years demonstrates its unreliability. There is a further point about this saying, however, which is interesting and that is, that other nations close at hand have similar predictions connected with other saints and other days. In France the day of augury is that of St. Medard (June 8th), in Belgium that of St. Godelieve (July 27th), and in Germany that of the Seven Sleepers (June 27th). It is clear, therefore, that giving to each of these predictions equal value, in quite a circumscribed portion of western Europe it would be foul weather continuously for a very long period, a doctrine to which even the most inveterate grumbler concerning the weather could hardly truthfully subscribe.

Sayings concerned with the weather likely during a given month are often equally unreliable. For example, the second of the months of the year is frequently referred to as "February Fill-dyke," this being, presumably, a statement of belief in it as a time of much rain; but, as a matter of statistics spread over a long period, February in the British Isles is one of the driest months in the year.

* The interested student is referred to "Weather Lore. A Collection of Proverbs, Sayings, and Rules concerning the Weather." By R. Inwards, London, 3rd edition, 1898.

An examination, too, of the month of March over long periods reveals the fact that no reliance whatever can be placed on the couplet—

"March, black ram,
Comes in like a lion and goes out like a lamb."

Many sayings, too, are in existence that endeavour to show a connexion between the weather in one period of the year and that in another, such as that which declares that if the end of October and the beginning of November be wet, then the January and February following will be frosty and cold, except after a very dry summer, but statistical investigation has shown clearly that such sayings have very little in them.

There is a great number of sayings existing which endeavour to relate the behaviour of wild and domestic animals to weather and its changes. Some of these sayings depend simply on the response of the animals in question to the weather actually existing at the moment, and, as such and limited to such, some reliance may be placed upon them. Especially is this so in the case of considerable changes in humidity as both men and other animals are affected by the change from dry to wet air, and *vice versa*. But this is an entirely different matter from attributing to animals a foresight, in the case of coming weather, denied to man. Such a foresight has never been proved. To take an example, investigation has shown that no reliance at all can be placed upon the supposed instinctive foresight of such animals as beavers and squirrels in preparation for severe winters.

Another very popular belief is that the phases of the moon are able to exert an influence upon terrestrial weather, but this, too, has never been demonstrated as having an objective reality to the satisfaction of meteorologists.

In some of the sailor's weather maxims, however, more truth can be found, for these can often be related to the types of pressure distribution appearing on synoptic charts. For example, the saying—

"First rise after low
Foretells a stronger blow,"

is quite true of the squalls and general increase in wind velocity which are often experienced as the trough line (*see* section 83) of a depression passes. Similarly, the couplet—

"Long foretold, long last;
Short notice, soon past,"

is often true, inasmuch as the larger depressions with their larger areas of bad weather travel more slowly, as a rule, than do the smaller depressions; and, therefore, their warning signs of high cloud and backing winds are in evidence for a longer time.

In the land saying—

"Rain before seven,
Fine before eleven,"

there is sometimes truth as it is usually connected with the passage of a small secondary depression. Similarly, the fact that depressions often follow one another quite closely lends point to the saying that—

"A Nor-wester is not long in debt to a Sou-wester."

But it cannot be too strongly emphasized that even those sayings that can be connected with synoptic charts are simply general statements to which many exceptions occur. Halos, for example, around the sun or moon are generally regarded as signs of coming bad weather, and as they are a concomitant of cirrostratus and cirronebula clouds, which clouds are a feature of the fronts of depressions (*see* sections 83 and 84), the belief has a good deal of truth in it; but high clouds with halos sometimes occur in the rear of depressions when they cannot be considered as a sign of bad weather, but of quite the reverse.

Many sayings relate to sky colorations in their relation to weather. There is, for example, the very well-known one—

"A red sky at night
Is the shepherd's delight;
A red sky at morning
Is the shepherd's warning,"

which often gives reliable prognostications, but, on the other hand, quite often proves "a broken reed."

Rainbows deserve some reference in this connexion. By reason of the physics of their formation, the centres of rainbows are always exactly opposite the sun. In regions, therefore, where areas of rain generally travel from westward to eastward, as in the British Isles, rainbows give some indications of coming or departing rain; for rainbows in the east, and hence in the afternoon, denote clearing weather, the rain forming the bow having passed the observer, but if seen in the west, and therefore in the morning, rain is approaching.

In short, no weather maxim should be accepted, no matter how popular or how often quoted it may be, unless it has been subjected to statistical investigation, including, if possible a comparison with many synoptic charts over a long period, and has not been found wanting. Very few maxims can survive such a searching test, as has been already said, and many of them must be regarded as unworthy of modern acceptance. It is a complete fallacy to believe, as so many people do, that just because a thing is often said that there is, therefore, something of truth in it.

108. *The "Weather Glass."*—In the period between the invention of the barometer (1643) and the introduction of the synoptic chart (about 1860) the weather maxims handed down from antiquity were reinforced by personal observations of the barometric pressure. It is no matter for surprise, therefore, that the period in question was characterized by most persistent attempts to interpret barometer readings in terms of coming weather. The "weather glass" was one of the results: and, as used now, usually consists of a

mercury or aneroid barometer, the height of which is indicated by a hand moving over a dial inscribed with legends which run as follows:—Very Dry, Set Fair, Fair, Change, Rain, Much Rain and Stormy.

These legends are obviously not very satisfactory because they are written against particular readings of the barometer irrespective of locality or the height of the instrument above sea level. Moreover, if synoptic charts impress one fact upon the student of them more than another, it is that it is the relative distribution of pressure which is the all-important matter, and not the actual barometer reading at any one place. Nevertheless, the legends and their positions are based upon experience and, hence, are not without value; but they alone are not sufficient to give sound forecasts in the absence of synoptic charts.

An extension of the legends on the "weather glass" is to be found in the comprehensive list of instructions* for the use of the barometer to foretell weather, issued by Admiral Fitzroy in about the year 1860. Once again these rules are based upon wide experience, and, consequently, give often enough sound results. The coming of synoptic charts has, however, thrown an entirely new light upon weather and its changes, and Fitzroy's rules can now only be recommended for use in those circumstances when it is impossible for the inquirer either to draw and interpret a synoptic chart for himself, or to get, by wireless telegraphy or otherwise, a forecast based upon such charts.

* Reprinted in London, Meteorological Office, "The Weather of the British Coasts." (M.O. 230, 1918).

PART III—THE UPPER AIR

CHAPTER XVIII

The Variation of Wind with Altitude

109. *A Note on Units.*—Any discussion on what may be termed "aerology," the study of the upper air, introduces afresh in an acute form the question of units. A previous reference bearing on this vexed question in present-day meteorology has been made in section 71.

The subject of units is more acute in the study of the upper air for various reasons. In the first place, the study is a comparatively new one and practically all the work in it has been done, and the results published, in C.G.S. units (*see* section 71); heights being measured in metres or in kilometres, velocities in metres per second, and temperatures in degrees Centigrade (or, more generally, marking another diversity, in absolute degrees). This means that any writer writing for English readers and, hence, desirous of using the units familiar to those readers, that is to say, putting heights in feet, velocities in miles per hour, and temperatures in degrees Fahrenheit has to change the data of the various original publications into the English units. The transformations obviously lead to awkward numbers as the scales on the one side cannot be expressed in simple round numbers of the scales on the other.

In the second place, the discussion of such a matter as upper air temperatures on the Fahrenheit scale involves the use of negative signs, and, as has been well said,* "a scale of temperature including "positive and negative signs is dangerous for the observer, trouble- "some for the computer, awkward for the printer, and misleading "for the reader." The use of the Centigrade scale involves the same trouble, which, however, is avoided if the absolute† scale be used.

The fact must, however, be faced that the two previous parts of this book have been written using the English units, as those units are at present very much more familiar to the readers for whom it is mainly intended. That being the case, a change of units in the present part seems unjustified as involving a serious break in continuity, and as likely to lead to confusion. Nevertheless, it is extremely desirable that the student should spare no effort to make himself familiar with the C.G.S. system, inasmuch as that is the

* London, Meteorological Office, "Observer's Handbook," 1919 edition.

† "The measure of temperature is so chosen that the volume of a mass of gas at constant pressure, or the pressure of a mass of gas at constant volume, is proportional to the temperature. It is the temperature on the Centigrade scale increased by 273." (London, Meteorological Office, "Observer's Handbook," 1919 edition.)

system in which most research work in the study of the upper air is being published, and as it will ultimately probably come into general use in meteorological science.

A compromise, then, seems the best way. To secure continuity the data and tables appearing in the discussion of upper air conditions which follows will be expressed in English units, but wherever possible the C.G.S. units will be given as well.

It should be noted that, in transformation from one system to another, such matters as a certain number of kilometres will be expressed in an approximate round number of feet, and a certain number of degrees absolute as a round number of degrees Fahrenheit, decimal points being omitted, except where the accuracy denoted by them seems important.

110. *Wind near the Surface.*—The Meteorological Office, London, has issued* an interesting table (Table VI) which endeavours to connect the velocity of the wind at heights up to 100 feet (30 metres) above open grass land with that occurring at 33 feet (10 metres).

TABLE VI

Wind at Various Heights above Open Grass Land compared with Wind at 33 feet (10 metres)

Height in—											
metres– – –	0·5	1	2	3	4	5	10	15	20	25	30
feet (approx.) –	1·5	3	6·5	10	13	16	33	50	66	82	100
Ratio to wind at— 33 feet (10 metres)–	·50	·59	·73	·80	·85	·89	1·00	1·07	1·13	1·17	1·20

A note appended to the table is also interesting. The note reads:—"It is to be understood that the ratios shown above are "only approximate. The increase of wind with height is more "rapid in proportion when the air is not disturbed by convection, "*i.e.*, in cold weather and at night; it is less rapid under the "opposite conditions."

The note is valuable because it gets at once to the difficulty that is involved in any discussion of winds near the surface. The air near the surface is in a continual state of eddying, the eddies being due to irregularities in the surface of the ground over which the air is moving, and also to changes in the temperature of that surface, and consequently of the air in its proximity. Reference has already been made to these eddies in the discussion of the gustiness shown by anemometer traces (*see* sections 7 and 9). The effect of these eddies is to promote the mixing of adjacent masses of air and, in general, the lower masses gain in momentum at the expense of the higher ones. If eddying be reduced through any cause, the lower layers become checked by friction with the surface

* Annual Summary of the *Monthly Weather Report*, 1916.

of the land, whilst the upper layers gain by not being subjected to the loss of momentum due to mixture with the lower ones, which are less energetic. Taylor has developed the theory of eddy motion in the atmosphere in two important papers,* to which the student is referred.

In view of what has been said concerning the varying turbulence of the air layers near the ground, it would appear that it is a very difficult matter to find any simple relationship existing between the wind in one layer near the surface and another.

Attempts have been made, however, to find some simple formula which shall accomplish the desired end.

In 1880, Stevenson† gave a formula for approximate wind velocity up to 51 feet. His formula was—

$$V = v\sqrt{\frac{H+72}{h+72}}\,.$$

where V = the wind velocity at height H, which is the velocity to be found,

and v = the known wind velocity at height h.

H and h are measured in feet.

Later, in 1883, Archibald,‡ as a result of observations made with kites, gave a formula for wind velocities between 300 feet and 2,000 feet. It will be noticed that he avoided the layer in immediate proximity to the surface. His formula was—

$$V = v\left(\frac{H}{h}\right)^{\frac{1}{4}}$$

where V, v, H and h, have the same meanings as in Stevenson's formula.

Sir Napier Shaw and Captain Cave, in 1910, as a result of observations on small, hydrogen-filled balloons, put forward the formula §—

$$V = \frac{H+a}{a}V_{\circ}$$

where V = wind velocity at height H,

$V_{\circ}$ = wind velocity given by a well-exposed anemometer,

and a = a numerical constant for the particular site.

The observations were carried out at Ditcham Park, in Hampshire. The formula only applies for heights up to 1,500 feet.

* TAYLOR, G. I. "Phenomena connected with turbulence in the lower atmosphere." *London, Proc., roy. Soc.*, A., **94**, 1918, p. 147. "On eddy motion in the atmosphere," *London, Philos. Trans.*, A., **215**, 1914, p. 1.

† *Edinburgh, J. Scot. met. Soc.*, **5**, 1880, p. 349.

‡ *Nature, London*, **27**, 1882–3, p. 243.

§ First Report, Advisory Committee for Aeronautics, Reports and Memoranda, No. 9.

None of the formulæ mentioned, however, have been found to be entirely satisfactory when compared with actual results.

Some later attempts, too, merit mention. Chapman,* for example, has put forward an empirical rule, that the speed of the wind in the lower layers is a linear function of the logarithm of the height. His formula takes the form—

$$V = a\log H + b,$$

where V is the wind velocity required at height H,

and a and b are constants which not only vary from place to place, but also for different sets of observations taken at different times of the day at the same place.

Hellmann,† in 1917, gave a very similar formula—

$$V = a\log(H + c) + b,$$

where a, b, and c are constants, and H and V have the same meaning as in Chapman's formula.

111. *Extent of Surface Turbulence upwards.*—It is pertinent, at this point, to inquire as to how far upwards the turbulence attributable to eddy motion extends. In this connexion the results obtained from the anemometer placed on the top of the Eiffel Tower in Paris are of great interest. The head of that anemometer is, roughly, at a height of 1,000 feet (more exactly, 305 metres) above the ground and its records reveal the fact that the disturbing effects of the surface certainly extend to that height. It would be expected, too, that the effect of turbulence should be felt at greater heights in summer than in winter, as it is in summer that the effect of temperature in forming eddies is given its fullest opportunities. The term "surface layers," then, meaning the layers affected by surface turbulence, is usually taken to mean the air up to 6,000 feet in winter and up to 9,000 feet in summer.

It must be recognized, however, that even above the level where surface turbulence ceases to affect matters, the atmosphere still remains complex, and that the behaviour of the wind there cannot be expressed in simple statements.

112. *Methods of measuring Upper Winds.*—The measurement of winds in the upper air, by means other than by that of determination of cloud velocities, is of comparatively recent growth. The measurements are usually made either by following the motions of small hydrogen-filled balloons,‡ or by observing the smoke drift from

* CHAPMAN, E. H. *London, Prof. Notes, met. Off.* No. 6. 1919.

† *Berlin, SitzBer. Ak. Wiss.* **10**, 1917, pp. 174–97.

‡ For details of the methods employed, *see* either "The Structure of the Atmosphere in Clear Weather," by C. J. P. Cave, Cambridge University Press, 1912; or London, Meteorological Office, "The Computer's Handbook," Section II., Subsection I.

shells bursting at known heights.* Kites, too, have been used, but are hardly to be compared with the other two methods.

It is clear, however, that both the small-balloon and the shell-burst methods are only possible in those conditions when low cloud is more or less absent. A method has been devised whereby the wind at a given height even above cloud sheets can be calculated from the bursting of bombs at that height; but not very much work has been done on it as yet. It will be recognized, therefore, that the means available for determining the wind at heights are limited, and are available only in clear-sky (that is, clear of low cloud) weather. This limitation needs to be borne in mind in what follows.

113. *Wind Velocity between the Surface and* 8,000 *feet.*—This layer includes the surface layers and gives, also, a little information about what is just beyond the height where the surface turbulence is, at times, eliminated (*see* section 111). It is best treated by reference to a special set of observations, and the set chosen is that performed by Dobson,† at Upavon, using the small-balloon method with one theodolite. The observation ground was 600 feet (183 metres) above sea level, and was characterized by an exceedingly open exposure.

Dobson arranged his 97 ascents with regard to the wind direction at the surface. With north-easterly surface winds, the gradient wind velocity (*see* section 79) as calculated from the current synoptic charts was reached at a height of about 3,000 feet (915 metres), and then the velocity began to diminish: first, an increase up to 3,000 feet, and then a falling off. With south-easterly surface winds the velocity increased to reach the gradient wind speed at just under 1,000 feet (approximately 300 metres), and then showed little deviation from that value with increasing height. With south-westerly surface winds, the velocity increased to reach the gradient wind speed at about 1,500 feet (approximately 500 metres) and thenceforward continued to increase slightly. With north-westerly surface winds, the gradient wind was reached at just under 1,000 feet (approximately 300 metres), and, thereafter, the wind showed a fairly regular, considerable increase up to the limit of Dobson's observations, namely, 8,000 feet (approximately 2,500 metres).

The general result, then, to be obtained from this work is that mean wind velocity increases from the surface up to about 1,000 or 1,200 feet (roughly 300 to 400 metres), and that, thenceforward, the behaviour is more eccentric, depending to some extent upon the surface direction, and, as he showed in another analysis of the same observations, also upon the strength of the wind. The curves

* London, Meteorological Office. "The Computer's Handbook," Section II., Subsection I.

† "Pilot balloon ascents at the Central Flying School, Upavon, during the year 1913." By G. M. B. Dobson. *London, Quart. J. R. met. Soc.*, **40**, 1914, p. 123.

which he drew to illustrate his conclusions show very clearly that the increase of wind speed between the surface and the 1,000 or 1,200 feet level is not linear. This statement should be compared with the various formulæ given in section 110.

It is interesting to notice that similar work done at coast stations reveals that the wind behaviour between the surface and 8,000 feet (roughly 2,500 metres) is even more complicated there than that shown by Dobson's results at Upavon, an inland station. This would be expected as a consequence of the juxtaposition of land and sea; the land on the one side with its atmosphere filled with eddies and general turbulence, and the sea on the other with its atmosphere, to a great extent, free from turbulence.

114. *Wind Direction between the Surface and* 8,000 *feet.*—So far as general changes of direction are concerned in this layer, the most marked feature is the "veer" (that is, change of wind in a clockwise direction) from the surface direction. This veer is particularly marked in the first 2,000 feet. The surface wind deviates from the lie of the isobar at the surface, as has been previously stated (*see* section 77), and the veer brings it more or less into parallelism with that isobaric lie at the height of about 1,500 to 2,000 feet (approximately 500 to 650 metres). The veer is then carried on slightly beyond the isobaric lie at heights between 2,000 feet (650 metres approximately) and 8,000 feet (2,500 metres approximately). The one curious exception appears to be the case of north-easterly winds at the surface. These winds veer as do the winds in the other three quadrants, but do not quite reach the lie of the surface isobars even at heights well above 2,000 feet (650 metres).

115. *Some Abnormalities.*—In general, as has been said, the wind shows an increase in velocity from the surface up to, say, 2,000 feet. Not infrequently, however, it is found to fall off from the surface upwards, or from some point near the surface. This is exceedingly likely to happen when there is no very definite pressure gradient on the surface so that katabatic or anabatic winds are likely to prevail there (*see* section 17). Such winds have no relation to the pressure gradient, and in such cases the wind very near the surface may have a velocity which is much greater than that prevailing, say, at 500 feet and above. Quite often, too, the wind at quite a low height in such cases is found to be entirely reversed in direction from what it is actually on the surface; this, again, is to be expected from the lack of relationship between katabatic and anabatic winds and the pressure distribution.

It is interesting to notice, too, that when the wind at the surface is easterly, there is often a tendency for the wind velocity to decrease with height above it. Such easterly currents, too, are often of comparatively little thickness, so that it is quite common to find great changes of direction at no great height above them.

Moreover, it needs to be emphasized that to any general statement made about wind behaviour at heights above the surface numerous exceptions exist.

116. *Wind between* 8,000 *and* 25,000 *feet.*—The first point to be stressed under this heading is that very little help need be anticipated from the pressure distribution at the surface as a means of predicting what the wind direction or force at 8,000 feet (approximately 2,500 metres) or over is likely to be.

It needs to be remembered, too, in what follows, that owing to the fact that actual experimental observations, by following small balloons from the ground or by watching shell-burst similarly, are only possible in the absence of much low cloud, the results obtained for this particular layer are those for practically clear-sky weather.

C. J. P. Cave* has divided his observations of winds up to 25,000 feet into five groups :—

(*a*) Those which show " solid currents " ; that is, those in which, after the gradient velocity has been reached, there is little change either in direction or velocity up to approximately 25,000 feet (7,500 metres approx.).

(*b*) Those which show a continued increase in velocity after the gradient velocity has been reached, which continued increase is unaccompanied by much change in direction.

(*c*) Those which show a decrease of velocity after the gradient velocity has been reached.

(*d*) Those which show great changes, or even reversals, in direction in the layer under consideration.

(*e*) Those which show an upper wind (either in the north-west or south-west quadrant) crossing the lower wind and probably blowing out from a distinct low pressure centre.

The following comments upon the various groups are also largely taken from Cave's book.

So far as the British Isles are concerned, it appears that group (*b*) is the commonest form of wind distribution. Most of the increase in velocity, however, occurs in the lower part of the range.

Group (*c*), comprising those winds which show a velocity falling off with height, seems almost entirely restricted to easterly winds and is not manifested frequently.

The big directional changes, which are the characteristic feature of group (*d*), seem nearly always to be preceded by the dropping of the wind to very low velocity at the particular heights where the changes are to occur. They are due to the superposition of two currents of air of great difference in direction upon one another under conditions which are not made evident by the current synoptic charts of the surface.

* " The Structure of the Atmosphere in Clear Weather." By C. J. P. Cave. Cambridge University Press. 1912.

Groups (*d*) and (*e*) are closely connected with the production of thunderstorms ; and a sounding of the upper air which reveals either a great change of direction in the upper layers (group (*d*)), or an upper wind in the north-west or south-west quadrant crossing a lower wind (group (*e*)), may be taken as indicating a great risk of a thunderstorm occurring in some part of the neighbourhood of the place of sounding

Much further investigational work is needed, however, and also the perfecting of some experimental means of measuring wind direction and velocity above low cloud, before really definite statements concerning the wind behaviour between 8,000 and 25,000 feet can be made.

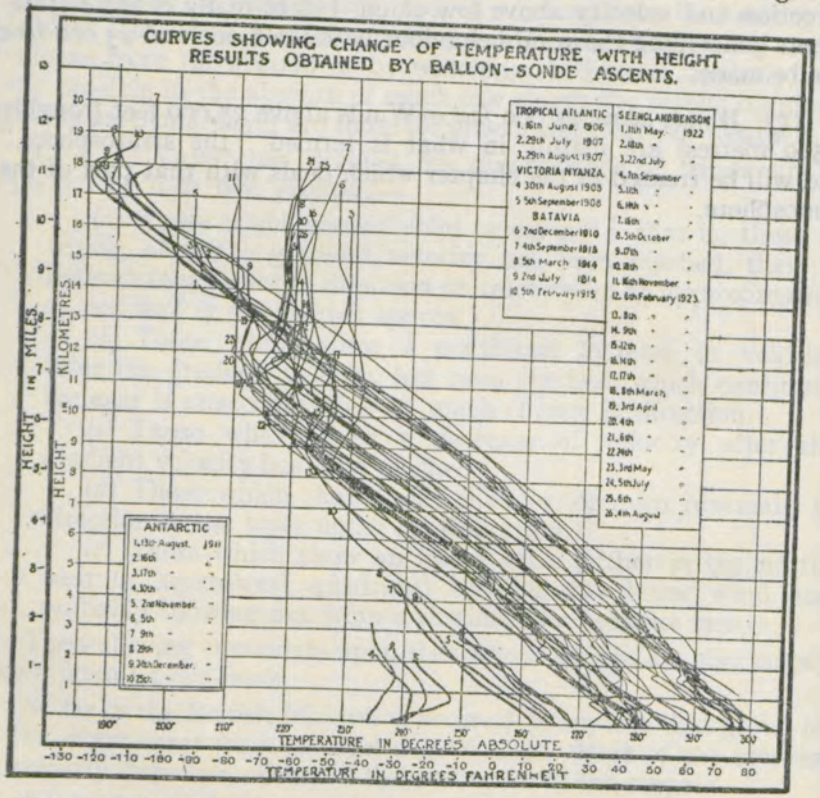
117. *Winds above* 25,000 *feet.*—Winds above 25,000 feet (roughly 7,500 metres) are mainly in what is termed " the stratosphere," and will be treated in the chapter which deals with that part of the atmosphere.

CHAPTER XIX

The Troposphere and Stratosphere

118. *Temperature Measurements in the Upper Air.*—Measurements of temperatures in the upper air are obtained chiefly by the use of either balloons or kites.*

The data obtained reveals when plotted a most remarkable result. This result will become evident upon reference to Fig. 21,



The separate curves represent the relation between temperature and height in miles or kilometres in the atmosphere. The numbers marking the separate curves indicate the date of ascent at the various stations as shown in the tabular columns. The difference of height at which the isothermal layer is reached, and the difference of its temperature for different days or for different localities, is also shown on the diagram by the course of the lines.

FIG 21.

---

* For details of the methods employed, the reader is referred to "The Free Atmosphere in the Region of the British Isles," London, Meteor. Office, M.O. 202, 1909, which contains a Report by W. H. Dines, F.R.S., "On apparatus and methods in use at Pyrton Hill."

which shows the temperatures obtained in various soundings taken in different localities.

The diagram shows that all the soundings manifest a decrease of temperature with elevation up to a certain height, but that after that the temperature ceases to fall.

Considering any one ascent, it is found that the change from the region of falling temperature to that of steady, or hardly changing, temperature is generally fairly abrupt. The place of change is, indeed, often marked by an inversion of temperature, that is, by an increase of temperature with height, which inversion, however, does not persist through any great thickness of atmosphere, and soon the steady or hardly changing state is reached.

A further examination of Fig. 21 will show that the height at which the change occurs varies.

It is clear, then, that the atmosphere may be regarded as divided into two definite parts so far as temperature is concerned :—

(*a*) a lower portion in which there is a fairly regular and considerable lapse, or fall, of temperature with height ; and

(*b*) an outer shell in which there is no material change of temperature with height.

The lower portion, that in which the fall of temperature with height does occur, is called the " troposphere," and the outer portion, that in which no material change of temperature occurs with height, is called the " stratosphere." Both these terms were suggested by Teisserenc de Bort. The level of change from the troposphere to the stratosphere is termed the " tropopause."

119. *The Height of the Tropopause.*—As a general rule, the boundary between the troposphere and the stratosphere is quite definite, but, in some cases, the temperature gradient ceases gradually, and, in others, it stops for some distance and then starts again. Also, inversions of temperature in the neighbourhood of the boundary are, as has already been mentioned, quite frequent.

Some definition of what, in these varying cases, is to be taken as the level of the tropopause is clearly called for ; and the following are the instructions issued on the point by the Meteorological Office, London.

Type 1. When the stratosphere commences with an inversion, the level of the tropopause is the height of the first point of zero temperature gradient.

Type 2. When the stratosphere begins with an abrupt transition to a temperature gradient below 2° absolute per kilometre (that is, 3·6° Fahrenheit per 3,280·8 feet) without inversion, the level of the tropopause is the height of the abrupt transition.

Type 3. When there is no such abrupt change of temperature gradient, the level of the tropopause is to be taken at the point where the mean fall of temperature for the kilometre next above is 2° absolute or less (that is, for the 3,280·8 feet next above is 3·6° Fahrenheit or less), provided that it does not exceed 2° absolute (3·6° Fahrenheit) for any subsequent kilometre.

The height of the tropopause varies at the same place at different times. The mean height of the tropopause at various places is given in Table VII.

TABLE VII*

Mean Height of the Tropopause

Place	Period of observation	Number of observa-tions	Mean height of tropopause	
			Kilometres	Feet (to nearest 100)
Scotland - - -	1908–1914	29	9·8	32,200
Ireland - - -	1908–1914	27	10·1	33,100
Manchester - -	1908–1914	73	10·3	33,800
England, S.E. - -	1908–1914	167	10·7	35,100
British Isles - -	1908–1910	150	11·1	36,400
,, ,, - -	1912	52	10·0	32,800
Berlin - - -				
Strassburg - -	1904–1909	212	10·5	34,400
Vienna - - -				
Petrograd - -	1904–1909	41	9·6	31,500
Paris - - -	1904–1909	90	10·5	34,400
Italy - - -	1904–1909	46	11·0	36,100
Paris - - -				
Hamburg - - -	1904–1909	158	10·6	34,800
Brussels - - -				

A glance at Table VII suggests that the height of the tropopause is dependent to some extent upon latitude; and this is the case, it being lowest near the poles. The boundary level between the stratosphere and the troposphere seems, in fact, to slope downward from the equator towards the poles. This suggestion has received strong support from some ascents carried out on Lake Victoria in the equatorial regions of Africa in which the stratosphere was not encountered until a height of 55,800 feet (approximately 17 kilometres) was reached, which is about 16,000 feet (approximately 5 kilometres) above the usual maximum height in Europe.

The level of the tropopause over Europe, too, varies with cyclonic and anticyclonic conditions on the surface, being lower with cyclonic conditions than with anticyclonic.

* This table has been taken from "The characteristics of the free atmosphere." By W. H. Dines, F.R.S., p. 60. *London, Geophys. Mem.*, No. 13, 1919. The table has been re-arranged, part omitted, and heights expressed in feet as well as in kilometres.

This suggests that there might be a definite connexion between the level of the tropopause and the barometric pressure at the ground level. This is, in fact, found to be the case, the mean level being lowest with the lowest pressures, and rising with increasing pressures.

120. *The Stratosphere.*—Care needs to be exercised in thinking about the distribution of temperature in the stratosphere, a care which is rendered all the more necessary because of the rather unfortunate name of "isothermal layer," which was formerly given to that outer portion of the stratosphere. The stratosphere *is* practically isothermal in the vertical direction, but it is not isothermal in the horizontal one. That is to say, if an observer with a thermometer, starting at the base of the stratosphere, could ascend straight upwards, he would find practically no change in the readings afforded by his thermometer at various stages of his ascent, but if he moved horizontally through the stratosphere, either at the level of the tropopause or along some level higher up, he would find definite and appreciable changes recorded. It is clear, therefore, that the name "isothermal layer" for the stratosphere is very unsatisfactory as liable to lead to wrong ideas; and it has now been superseded, the term "stratosphere" having come into general use.

121. *Temperature in the Troposphere.*—As would be expected from what has been already said about the variation of insolation received under different conditions by the earth's surface, and by the further differentiation effected by the two components of that surface, land and water (*see* section 14), the temperature of the air in the 2,000 or 3,000 feet (650 or 900 metres approximately) just above the earth's surface is subject to considerable fluctuations. It has been stated, too, that inversions of temperature near the ground (*see* section 23) are quite common.

Despite these fluctuations, however, it is valuable to examine the mean temperature at various heights. Table VIII is that given by W. H. Dines*; it shows the mean monthly temperatures for England. Mr. Dines "smoothed" it to get rid of artificial irregularities. His table is in kilometres and absolute degrees. In Table IX his data have been transferred to read in feet and degrees Fahrenheit to meet the situations concerning units set out in section 109.

122. *The Seasonal Variation of Temperature in the Troposphere.*—It is interesting to inquire as to how far upward the seasonal variation of temperature, which is so marked a feature of the ground level, extends. An examination of the data given in either Table VIII or IX for England, and also of similar tables which have been prepared for other localities, reveals the fact that the seasonal variation extends upwards for about 30,000 feet (roughly 10 kilometres), after which there is little change.

* *London, Geophys. Mem.*, No. 13, 1919.

Table VIII

Mean Monthly Temperatures for England, smoothed

Height in kilometres	January	February	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
	200° Absolute +											
14	16	17	19	21	22	23	22	21	19	17	16	15
13	16	17	19	21	22	23	23	21	19	18	17	16
12	17	18	19	20	21	22	22	21	20	19	18	17
11	17	17	17	19	20	21	22	22	21	20	19	18
10	20	20	20	22	24	25	26	26	26	24	23	21
9	24	23	24	26	29	32	34	33	33	31	28	25
8	30	29	30	32	36	38	41	41	41	38	35	32
7	37	36	37	39	42	45	47	48	47	45	41	38
6	43	43	44	46	49	52	55	55	54	51	49	45
5	50	49	50	52	56	59	61	62	61	58	55	52
4	57	56	57	59	62	65	67	68	67	64	61	58
3	63	62	63	65	68	71	73	74	73	70	67	64
2	67	66	67	70	73	76	78	79	78	75	72	69
1	71	71	73	76	79	82	83	83	81	79	75	72
0	76	76	77	82	85	88	89	89	86	83	80	77

Table IX

Mean Monthly Temperatures for England, smoothed

(Expressed in degrees Fahrenheit with heights in feet)

Height in feet (nearest 100)	January	February	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
	Fahrenheit (nearest degree)											
45,900	−71	−69	−65	−62	−60	−58	−60	−62	−65	−69	−71	−72
42,700	−71	−69	−65	−62	−60	−58	−58	−62	−65	−67	−69	−71
39,400	−69	−67	−65	−63	−62	−60	−60	−62	−63	−65	−67	−69
36,100	−69	−69	−69	−65	−63	−60	−60	−60	−62	−63	−65	−67
32,800	−63	−63	−63	−60	−56	−53	−53	−53	−53	−56	−58	−62
29,500	−56	−58	−56	−53	−47	−42	−38	−40	−40	−44	−49	−54
26,200	−45	−47	−45	−42	−35	−31	−26	−26	−26	−31	−36	−42
23,000	−33	−35	−33	−29	−24	−18	−15	−13	−15	−18	−26	−31
19,700	−22	−22	−20	−17	−11	− 6	0	0	− 2	− 8	−11	−18
16,400	− 9	−10	− 9	− 6	1	7	10	12	10	5	0	− 6
13,100	3	1	3	7	12	18	21	23	21	16	10	5
9,800	14	12	14	18	23	28	32	34	32	27	21	16
6,600	21	19	21	27	32	37	41	43	41	36	30	25
3,300	28	28	32	37	43	48	50	50	46	43	36	30
0	37	37	39	48	54	59	61	61	55	50	45	39

123. *The Daily Temperature Range in the Troposphere.*—A similar inquiry may be put with regard to the diurnal variation of temperature, which is again so marked a meteorological feature of the ground level. Whilst it is certain that this diurnal variation decreases very rapidly with height and becomes very small, being, indeed, less than 2° Fahrenheit at 4,000 feet (that is, less than 1·2° Centigrade at about 1¼ kilometres), it seems impossible to say at what height, if any, it ceases to exist at all.

It depends to some extent upon locality. Lieut-Col. Gold,* for example, working up results obtained at Berlin gives a daily variation there at 1 kilometre (approximately 3,280 feet) of 0·85° Centigrade (1·53° Fahrenheit) with the maximum occurring at 6 p.m., and a daily variation at 2 kilometres (approximately 6,560 feet) of 0·64° Centigrade (1·15° Fahrenheit) with the maximum occurring at noon ; whilst for Petrograd he gives the daily variation at 1 kilometre as 0·72° Centigrade (1·30° Fahrenheit), the maximum occurring at about 2.30 p.m.

124. *Yearly Mean Temperatures for different Heights in various Areas.*—A point of great interest is seen when the mean temperatures for different heights in certain selected areas are examined. Table X, showing some of these mean temperatures, is extracted from one given by W. H. Dines.†

The remarkable feature revealed by the table is the extraordinarily low temperature prevailing in the stratosphere over the equator.

125. *Temperatures over Depressions and Anticyclones.*—Equally interesting results are revealed by the observations that have been taken in the upper air over depressions and anticyclones on the surface. Once again, we are indebted to W. H. Dines for the statistics that illustrate the matter. His figures appear in Table XI which has been extracted with some re-arrangement and addition from one given in "The Computer's Handbook" (Section II), issued by the Meteorological Office, London. The depression figures are those connected with low pressures on the surface, the mean of the pressures being 984 millibars (29·06 inches), and the anticyclonic figures those connected with high pressures on the surface, the mean of those pressures being 1,031 millibars (30·45 inches). It will be noticed, too, that the mean pressures, as well as the mean temperatures, are given for the various heights.

* GOLD, E., "The international kite and balloon ascents," *London, Geophys. Mem.* No. 5, 1913.

† *London, Geophys. Mem.*, No. 13, 1919.

TABLE X

Mean Temperatures for different Heights at different Places

Height		British Isles, 1908–11		Continent (Europe), 1902–7		Petrograd		Equatorial	
Kilometres	Feet to nearest 100	Absolute	Fahrenheit	Absolute	Fahrenheit	Absolute	Fahrenheit	Absolute	Fahrenheit
20	65,600	220	−63·4	—	—	—	—	193 ?	−112 ?
19	62,300	220	−63·4	—	—	—	—	193 ?	−112 ?
18	59,100	220	−63·4	—	—	—	—	193 ?	−112 ?
17	55,800	220	−63·4	—	—	—	—	193	−112
16	52,500	220	−63·4	—	—	—	—	195	−108·4
15	49,200	220	−63·4	—	—	—	—	198	−103
14	45,900	220	−63·4	218·6	−65·9	—	—	203	−94
13	42,700	219·8	−63·8	218·5	−66·1	—	—	211	−79·6
12	39,400	219·8	−63·8	218·8	−65·5	222·2	−59·4	219	−65·2
11	36,100	219·6	−64·1	220·2	−63·0	221·7	−60·3	227	−50·8
10	32,800	223·1	−57·8	223·4	−57·3	222·4	−59·1	235	−36·4
9	29,500	228·9	−47·4	228·6	−47·9	224·9	−54·6	243	−22·0
8	26,200	235·0	−36·4	235·0	−36·4	229·6	−46·1	251	−7·6
7	23,000	241·8	−24·2	242·2	−23·4	235·9	−34·8	258	5·0
6	19,700	248·9	−11·4	249·7	−9·7	242·6	−22·7	265	17·6
5	16,400	255·5	0·5	256·1	1·6	249·0	−11·2	272	30·2
4	13,100	261·7	11·7	262·3	12·7	255·0	−0·4	279	42·8
3	9,800	267·7	22·5	268·0	23·0	260·9	10·2	285	53·6
2	6,600	272·6	31·3	273·1	32·2	266·2	19·8	290	62·6
1	3,300	277·0	39·2	277·6	40·3	270·9	28·2	295	71·6
0	0	282·6	49·3	280·9	46·2	276·1	37·6	300	80·6

British Isles Data.—*London, Geophys. J., Ann. Suppl.*, 1912, p. 93. Petrograd Data.—Rykatchew, M.; *Met. Z., Braunschweig*, **28**, 1911, p. 7. 90 observations.
Continental Data.—Wagner, A.; *Met. Z., Braunschweig*, **27**, 1910, p. 97. 380 observations. Equatorial Data.—Dines, W. H.; *Washington, D.C., §Mon. Weath. Rev.* **43**, 1915, p. 553.

TABLE XI

Average Values of Pressure and Temperature at various Heights over High-Pressure and Low-Pressure Areas

Height		Depressions			Anticyclones		
Kilometres	Feet to nearest 100	Pressure (millibars)	Temperature (° A.)	Temperature (° F.)	Pressure (millibars)	Temperature (° A.)	Temperature (° F.)
15	49,200	116	—	—	123	—	—
14	45,900	135	224	−56	146	215	−72
13	42,700	157	226	−53	171	215	−72
12	39,400	183	225	−54	201	217	−69
11	36,100	212	225	−54	235	221	−62
10	32,800	247	225	−54	273	226	−53
9	29,500	288	226	−53	317	233	−40
8	26,200	335	227	−51	366	240	−27
7	23,000	388	232	−42	422	247	−15
6	19,700	449	240	−27	483	254	− 2
5	16,400	516	248	−13	552	261	10
4	13,100	591	255	0	628	267	21
3	9,800	675	263	14	713	272	30
2	6,600	767	269	25	807	277	39
1	3,300	870	275	36	913	279	43
0	0	984	279	43	1,031	282	48

An examination of Table XI shows the following points :—

(*a*) That up to 10 kilometres (roughly 33,000 feet) temperatures over cyclonic areas are lower than those over anticyclonic ones ; but that, above that level, that is, roughly from the base of the stratosphere upwards, temperatures over the low pressures are higher than those over the high.

(*b*) That even at the greatest heights examined the low pressure evident at the surface in depressions continues to manifest itself.

This latter point (*b*) seems to suggest that depressions on the surface must be deemed to extend to great heights, a matter of interest in any discussion as to the origin of cyclones and anticyclones. It is now thought, indeed, that pressure changes on the surface are mainly due to changes occurring in the stratosphere.

The old idea that the cores of depressions are composed of relatively warm moisture-laden air must also be discarded. Table XI shows clearly enough that the lower layers over depressions have temperatures which are relatively low compared with the surroundings. Comparison, too, of the temperatures over depressions reveal the fact that they are actually lower than the normals for the levels considered.

126. *Temperature Gradients in the Troposphere.*—Normally, the temperature falls off with height until the stratosphere is reached. The rate of change per kilometre step of vertical height is termed the "temperature gradient." Although normally, as has been said, the temperature falls with height, the reverse is often noticed, so that the temperature gradient may be either positive or negative. By international agreement it is deemed positive when the temperature is falling on the particular step of height examined, and negative when the temperature is rising. An inversion of temperature (*see* section 23), then, is just a change from a positive temperature gradient to a negative one. Such inversions in the various layers of the troposphere are quite common, happening almost invariably in and just above layers of fog, and frequently in and just above clouds.

The term "gradient," however, seems to have become somewhat overworked in the subject and it is better to restrict it to changes on the horizontal. Another term, "lapse" (Latin, *lapsus*, a slip), is coming now into use in the discussion of temperature and pressure changes in the vertical. Using the newer nomenclature, "vertical temperature gradient" becomes "lapse rate."

Measurements of this lapse rate have been fairly numerous.

Berson,* for example, dealing with data obtained from manned balloons towards the close of the last century, drew attention to the marked constancy of the lapse rate, about 5° Centigrade per kilometre (9° Fahrenheit per 3,300 feet, approximately), up to a height of 4 kilometres (roughly 13,000 feet), and to the sudden and considerable increase in its value in the next and succeeding layers. He attributed the change to the fact that the level of 4 kilometres marks roughly the upper limit of the lower clouds, and that near this height inversions of temperature are more frequent than at neighbouring heights, inasmuch as temperature inversions are characteristic of the top of such cloud layers.

Values deduced by E. Gold from later manned balloon ascents on the continent (1901–7) do not show the peculiarity commented upon by Berson quite so clearly, but, nevertheless, it is still distinctly noticeable. Gold's values† are given in Table XII.

* "Wissenschaftliche Luftfahrten," Edited by R. Assmann and A. Berson, Braunschweig, 1899, 3 vols.

† *London, Geophys. Mem.*, No. 5, 1913.

TABLE XII

Upward Temperature Gradient

Height :— kilometres - feet (in hundreds)	0–1 0–33	1–2 33–66	2–3 66–98	3–4 98–131	4–5 131–164	5–6 164–197	6–7 197–230	7–8 230–262
Gradient :—								
°A.	4·3	5·1	5·1	5·8	6·2	6·9	7·5	6·2
°F.	7·7	9·2	9·2	10·4	11·2	12·4	13·5	11·2
Number of cases	50	50	44	40	34	22	10	3

Similar work in determining temperature gradients or lapse rates in the upper air done in various places reveals the fact that the gradient ceases to exist at different heights in different latitudes, the higher the latitude, that is, the nearer the Pole, the lower being the height. This would be expected from what has already been said (*see* section 119) about the lowering of the level of the tropopause with higher latitudes.

127. *Winds in the Stratosphere.*—Any statement concerned with winds at such a great height as is connoted by the stratosphere must be tempered by the fact that comparatively few experimental soundings have been made reaching such heights, and then only in clear-sky condition, inasmuch as the small-balloon method, practically the only one possible, cannot be used to high altitudes in the presence of low cloud. The results obtained, then, can hardly be used, at present, to make sound generalizations. What generally seems to happen, however, is that there is very little change of direction shown, either in the transition from the troposphere to the stratosphere, or in the actual stratosphere itself; but that velocity falls off fairly rapidly. The falling off in velocity is in agreement with the equality of pressure which is found in the stratosphere. It seems hardly possible to say much more at present about the winds in the stratosphere; better experimental methods for sounding the atmosphere at such great heights being needed, and especially some method applicable in all types of sky conditions.

CHAPTER XX

Pressure, Density, and Humidity in the Upper Air

128. *Variation of Pressure with Height.*—The variation of pressure with height is closely connected with the temperature of the air. The formula in general use is :—

$$h_1 - h_0 = C\theta\,(\log p_0 - \log p_1)$$

where h_1 and h_0 are the heights at two points vertically over each other, p_1 and p_0 the pressures at those points, θ the absolute temperature of the column of air between those points, and C is a numerical constant. If heights are measured in metres, C is 67·4; if in feet, 221·1.

Speaking quite strictly, the formula only holds if temperature conditions are uniform, but no great error is introduced if θ is taken as the mean temperature of the air between the two points.

But it is just the determination of what is to be taken as θ, the mean temperature, that presents difficulty in practice. As has been already shown, the temperature in the first few thousand feet is subject to great fluctuations, and no lapse rate could be assumed which would be adequate to meet all possible cases.

Obviously, the best plan would be to make actual observations of the temperature, say, at every 500 feet, on every occasion that the formula was to be used. The mean of these many readings would give a fairly accurate θ. But this is quite clearly out of the question on most occasions, and, even if it were possible and if the temperatures were taken by actual observation of a thermometer on an aeroplane, it must be remembered that the accuracy of such observations is somewhat seriously in doubt; first, because there is a vicious circle in that aeroplane heights are measured by altimeters (*see* section 129) which depend entirely upon measurements of pressure and have to be calibrated on a temperature assumption, and, second, because the thermometers carried are, to some extent, affected by the aeroplane, and especially by the necessarily hot engine.

In view of this, the one course remaining is to adopt such a standard lapse rate of temperature as shall afford the best possible approximation to general conditions. This rate is usually taken as 6° Centigrade per kilometre (that is, 3·3° Fahrenheit per 1,000 feet). Hence, if one temperature actually existent be known, the value of θ can be readily calculated.* When cases of temperature

* Of late years Toussaint's formula for the change of temperature with height has received much recognition. The formula is—

$$T = T_0 - 6 \cdot 5\,h,$$

where h is measured in kilometres and T_0 is the temperature at the surface and T the temperature at height h, both T_0 and T being measured in degrees Centigrade.

inversion at the surface are suspected, the temperature actually occurring at or near that surface would obviously be a very bad starting point.

129. *The Altimeter.*—In view of the almost universal use of the altimeter in modern aircraft as an indicator of height, some discussion of it seems pertinent.

It is an ordinary aneroid barometer (*see* section 72) graduated to show heights instead of actual pressures, and the mechanism is so devised that the height scale may be uniform. The fact that it is really an instrument for measuring upper air pressures even though it expresses them as heights justifies the inclusion of the consideration of it in this particular chapter.

It is clear that the scale of the altimeter must be graduated with regard to some definite temperature. That temperature is taken in England as 50° Fahrenheit (283° absolute), this particular standard being due to Airy. Airy's rule for correcting the readings given by his height scale reads as follows :—When the temperature differs from 50° Fahrenheit, the recorded height is to be in/decreased by the $\frac{1}{1000}$th part of every $\frac{1}{2}$° above/below 50° Fahrenheit. Speaking more strictly, the fraction should read $\frac{1}{1020}$ instead of $\frac{1}{1000}$. When the absolute scale is used, the rule becomes as follows :—When the temperature differs from 283° absolute, the recorded height is to be in/decreased by the $\frac{1}{283}$rd part for every degree above/below 283° absolute.

When no actual temperature observations are made on the aeroplane itself, so that the temperature at any level is not experimentally known for the purpose of correcting the height recorded by the altimeter, then a lapse rate of 1·5° absolute (2·7° Fahrenheit) per 1,000 feet should be assumed.

The temperature correction is not, however, the only one that must be made if the height scale is to show even an approximately correct reading.

In the formula previously quoted (section 128) :—

$$h_1 - h_0 = C\theta\,(\log p_0 - \log p_1),$$

if h_0 be sea level, then it may be written as zero and p_0 becomes the pressure at sea level.

Further, remembering that the formula applies to points vertically beneath one another, p_0, at any moment of observation, at any moment of reading the altimeter, is implied to be the pressure at sea level immediately underneath the observer. But the pressure at sea level differs from place to place and from time to time. The observer has set his altimeter scale at zero against the sea-level pressure of his starting point. Obviously, then, if the observer retain the same zero on his instrument throughout a long flight, his height readings will be much in error.

Meteorology can do much to help the observer in this matter. Let it be assumed that he is preparing to make a flight from London to Carlisle, and that he contemplates starting at 10 a.m. By the time of start he could be supplied with a synoptic chart showing the distribution of pressure over England at, say, 7 a.m. that same morning. Fortunately, horizontal changes of pressure are fairly persistent, and such a synoptic chart would be of service to him for some hours after it was drawn. From it, he would be able to see at a glance the pressures that prevailed at 7 a.m. along his route and, by looking at the barometric characteristics and tendencies (*see* section 75) also recorded on the chart, would be able to see, especially if provided with a forecast of coming pressure changes by a competent meteorologist, what the pressure at sea level would be likely to be at any known point of his route. During the flight, then, he could alter the zero of his altimeter to agree with the sea-level pressures over which he is flying, and hence his instrument will give him a much closer approximation to his true height. The method outlined may not be perfect, but it is a far superior one to that which assumes that the sea-level pressure at London is the same as that at Carlisle, and that it will not alter appreciably with time.

An even better method, when it is available, is that, on passing over or near to a meteorological station, he should obtain the sea-level pressure prevailing at that station directly from it by means of wireless telegraphy and then correct his altimeter accordingly.

The altimeter is, however, an unsatisfactory instrument, mechanically, for measuring pressures, and hence heights, because of the " lag " which characterizes it. The " lag " becomes evident in that the mechanism will not record the proper pressure at once. Especially is this the case if it has been kept at a low pressure, that is, a great height, for an hour or so ; on its return, it indicates less than the proper pressure, that is, more than the proper height, and only gradually recovers. Other mechanical defects due to the effect of the acceleration of the aeroplane upon it also arise in practice.

130. *Mean Pressures in the Upper Air.*—There is no method of measuring directly the pressure at various heights in the upper air with accuracy. W. H. Dines used the following to arrive at the pressures required. A small hydrogen-filled balloon has a meteorograph attached. A meteorograph* is a small light instrument which gives an automatic record of pressure and temperature. The balloon, carrying the meteorograph, is released and its course is followed from the ground by means of two theodolites at the ends of a long base line. This means that the height of the balloon, at any given time, can be calculated trigonometrically without much likelihood of serious error. The surface pressure

* For a description of the meteorograph, *see* London, Meteorological Office, " The Dines Balloon meteorograph and the method of using it " by L. H. G. Dines. M.O. 321, 1929.

is read from a standard mercurial barometer. Let it be supposed that this surface pressure is x millibars. When the meteorograph is recovered (after it has fallen owing to the bursting of the balloon), its continuous record of temperature will enable the mean temperature between the recorded pressures of x and, say, y millibars to be determined. Hence the height at which the pressure was y millibars can be computed. A similar operation can be worked through using the pressure of the y millibars at the computed height as starting point; and, so continuing, the pressures at various heights can be obtained.

Table XIII is extracted from the larger table given by W. H. Dines.* It shows the mean pressures at each kilometre height up to 20 kilometres (roughly 66,000 feet) at various places, and reveals that there is no appreciable variation in mean pressure with longitude, but that there is with latitude, the pressure being lower in higher latitudes than in lower, though the Canadian values seem somewhat exceptional, perhaps owing to paucity of observations.

131. *Seasonal Variation of Pressure at Various Heights.*—Another interesting store of statistical data is given by W. H. Dines in the same publication as that from which Table XII was extracted. Table XIV is a copy of that given by him (with the exception that a column giving heights in feet is included) and shows the mean pressures at various heights over England for the various months of the year. The lower pressures in the winter at the higher levels should be noted. They are produced chiefly by the seasonal changes of temperature at those heights. Dines shows the range in the last column and states that, if uniform temperature above 15 kilometres (approximately 49,000 feet) had been assumed, the range at 20 kilometres (approximately 66,000 feet) would have been 5 millibars.

132. *Densities in the Upper Air.*—The density of a sample of air is the weight, or, better, the mass, of a measured volume of it. It depends upon a variety of factors: the composition, the pressure, the temperature. It increases with pressure, decreases in reversed proportion to the absolute temperature, and also decreases with increasing content of water vapour.

The actual formula, taking account of these various factors, which allows of the density being calculated is as follows:—

$$d = d_0 \frac{p - \frac{3}{8}e}{p_0} \times \frac{T_0}{T},$$

where d is the density to be found, and d_0 is the density of perfectly dry air under the conditions $p_0 = 1{,}000$ millibars (29·53 inches) and $T_0 = 290°$ absolute. These conditions give $d_0 = 1{,}201$ grams per cubic metre. p is the barometric pressure in millibars of the sample of air under consideration, and e is the pressure of water vapour in the sample.

* London, *Geophys. Mem.*, No. 13, 1919.

TABLE XIII

Mean Pressures in Upper Air

Height: Kilometres	Height: Feet, nearest 100	Petrograd	Scotland	Manchester	Berlin	S.E. England	Brussels	Paris	Vienna	Canada	Equator
		Millibars									
20	65,600	55·0	55·0	55·2	54·8	54·9	54·5	56·0	55·0	—	53
19	62,300	64·0	64·2	64·6	64·0	64·1	63·7	65·6	64·4	—	63
18	59,100	74·5	74·8	75·4	74·8	75·0	74·5	76·6	75·2	—	75
17	55,800	87·0	87·3	88·0	87·4	87·5	87·2	89·6	88·0	—	90
16	52,500	101	102	103	103	102	102	105	103	—	107
15	49,200	118	118	120	120	120	120	123	121	120	128
14	45,900	138	138	140	140	140	140	143	142	142	152
13	42,700	161	161	164	164	164	164	167	165	167	178
12	39,400	187	187	192	192	192	193	195	193	195	209
11	36,100	218	219	224	225	224	226	228	226	228	244
10	32,800	255	256	261	262	261	263	266	263	266	283
9	29,500	297	299	302	305	303	305	309	306	309	327
8	26,200	346	348	352	354	352	353	357	354	358	376
7	23,000	400	402	407	408	407	408	412	409	413	430
6	19,700	461	464	468	470	469	470	473	471	475	491
5	16,400	529	532	537	538	538	538	541	539	543	558
4	13,100	606	608	613	614	615	615	617	615	618	632
3	9,800	692	694	698	699	699	699	701	700	703	713
2	6,600	787	787	793	795	795	794	796	795	798	803
1	3,300	896	894	898	900	900	899	900	900	903	903

TABLE XIV

Seasonal Variation of Pressure at each Height over England

Height: Kilo-metres	Height: Feet, nearest 100	Jan.	Feb.	March	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.	Range, millibars
		Millibars												
15	49,200	116	116	117	119	121	123	125	125	123	122	120	117	9
14	45,900	135	135	136	138	141	144	146	146	144	143	140	137	11
13	42,700	159	158	159	161	165	168	170	170	168	167	165	160	12
12	39,400	187	186	187	189	193	196	198	199	197	195	193	188	13
11	36,100	218	218	218	221	225	229	232	232	231	228	226	220	14
10	32,800	255	254	255	258	262	267	270	271	269	266	263	257	17
9	29,500	297	296	298	302	305	310	314	314	313	309	305	300	18
8	26,200	345	345	347	350	353	359	362	363	361	357	353	349	18
7	23,000	399	399	401	405	409	414	417	418	416	413	408	403	17
6	19,700	462	462	463	467	471	476	478	479	477	473	470	466	17
5	16,400	530	530	531	535	539	543	546	547	544	541	537	533	17
4	13,100	607	607	608	611	615	619	622	623	620	617	613	610	16
3	9,800	693	693	693	697	700	704	706	707	703	700	698	696	14
2	6,600	789	788	789	792	794	798	799	799	797	794	791	790	11
1	3,300	898	897	897	898	899	902	903	903	900	899	898	898	6

Neglecting water vapour altogether, the formula takes the simpler form—

$$d = d_0 \frac{p}{p_0} \times \frac{T_0}{T},$$

and the error introduced is quite small.

TABLE XV

Mean Densities for different Heights, South-East England.

Height: Kilometres	Height: Feet nearest 100	Temperature: ° A.	Pressure: Millibars	Density: Grams per cubic metre
20	65,600	219	55	87
19	62,300	219	64	102
18	59,100	219	75	119
17	55,800	219	88	139
16	52,500	219	102	162
15	49,200	219	120	191
14	45,900	219	140	223
13	42,700	219	164	261
12	39,400	219	192	305
11	36,100	220	224	355
10	32,800	222	261	409
9	29,500	228	303	463
8	26,200	234	352	524
7	23,000	241	407	589
6	19,700	248	469	658
5	16,400	255	538	735
4	13,100	262	615	819
3	9,800	268	699	909
2	6,600	273	795	1,014
1	3,300	278	900	1,128
0	0	282	1,014	1,253

Table XV, again extracted from a larger one given by W. H. Dines,* gives some idea of the value obtained. The values given take no account of water vapour and this makes them a little too high, as a reference to the first of the two formulæ just given will make clear. The error, as has been already said, is, however, quite small even in the lower layers, where it is greatest; in the higher layers, it is almost negligible. The variation of gravity with height has also been neglected, but, once again, the error introduced by so doing is very small.

It should be noted that the density decreases with elevation. This is due to the fact that the diminution of pressure and the

* *London, Geophys. Mem.*, No. 13, 1919.

decrease of density due to that diminution has a greater effect than the decrease of temperature and the increase of density due to that cause.

These questions of pressure, temperature, and density of various levels in the atmosphere have a very great importance in the problems of buoyancy arising in connexion with balloons or airships.

133. *Humidity in the Upper Air.*—As would be expected, relative humidity shows, in general, an increase with height up to the levels of the lower cloud layers, that is, up to the height of 1 to 2 kilometres (3,300 to 6,600 feet approximately), but after that it falls off fairly rapidly and at great heights seems always to be very low. An inversion of temperature in the upper atmosphere is nearly always characterized by a low relative humidity, this again being in accord with what would be expected.

134. *The Height of the Atmosphere.*—Very few soundings of the upper air to a greater height than 20 kilometres (roughly 12½ miles) have been made, but it is quite certain that the atmosphere extends much above that height. Formerly, the height of the atmosphere was given as about 80 kilometres (roughly 50 miles), that being the height at which the air would have no appreciable pressure. This figure, however, has had to be considerably amended as a result of the observations made on meteors. Meteors, or "shooting stars," are small solid bodies, entering the earth's atmosphere from outer space. Their velocity is so great that they generate enough heat, either by actual friction or by the compression of the air in front of them, to render themselves luminous. If various observers note the apparent position of the same meteor with regard to the stars, data is afforded whereby the angular altitude of each observer's line of sight may be determined. The intersection of these different lines of sight enables the height of the luminous streak due to the incandescent meteor to be computed. From the results so obtained, it is thought that the atmosphere extends with sufficient density to produce the phenomena of luminosity in meteors to a height of about 300 kilometres (roughly 188 miles). How far beyond this level traces of the atmosphere extend is, at the moment, purely a matter of speculation.

135. *The Constituents of the Upper Atmosphere.*—Much consideration has been given during the past few years to the nature of the gases in the upper layers of the atmosphere and notable papers on this subject by S. Chapman,* Milne,* Lindemann,† Dobson,†‡ Vegard§ and others have appeared.

Formerly, it was thought that the highest layers of the atmosphere were almost entirely composed of hydrogen, but opinion has

* *London, Quart. J. R. met. Soc.*, **46**, 1920, p. 357.
† *London, Proc. roy. Soc.*, **102**, 1923, p. 411.
‡ *London, Quart. J. R. met. Soc.*, **49**, 1923, p. 152.
§ *London, Phil. Mag.*, **46**, 1923, p. 193.

veered away from that belief, experimental observations of the amount of hydrogen at the earth's surface showing its presence there only to a very limited extent, and it being thought that if hydrogen were generated from the earth it would probably enter into combination with oxygen by the action of lightning and, perhaps, of sunlight, and thus that little or none would ever reach the upper layers.

Chapman and Milne, in their joint paper, neglecting hydrogen as a constituent of the upper atmosphere for the reason given, and also assuming, first, that large-scale mixing effectively stops at approximately 20 kilometres (roughly 12½ miles) and that molecular diffusion alone determines the constitution above this height, and secondly, that above the tropopause the temperature remains approximately constant to great heights, arrive at the conclusion that the very highest layers of the atmosphere—that is, those above 200 kilometres (roughly 125 miles)—are composed almost entirely of helium.

Lindemann and Dobson attack the same problems by observation of meteors, or "shooting stars," and arrive at very different results, concluding that temperature does not remain constant for great heights above the tropopause but rises abruptly at about 60 kilometres (roughly 37½ miles), maintaining itself high up to about 160 kilometres (roughly 100 miles), falling again thereafter. This increase of temperature they argue to be due to the absorption by oxygen of the smallest wave-lengths of the sun's radiation to form ozone. They conclude, in addition, that the uppermost atmospheric layers are composed predominantly of nitrogen, and that hydrogen and helium are absent.

Vegard, on the other hand, uses the spectrum of the aurora borealis for his data, reproducing something very similar to that spectrum in the laboratory. He, too, denies the existence of hydrogen and helium in the upper layers, and believes that it is nitrogen alone that forms the outermost atmosphere.

A consideration of the results obtained reveals that much remains to be done in the investigation of the highest atmospheric layers and further researches will be awaited eagerly, as those layers must play a great part in the make-up of such fascinating phenomena as magnetic storms and the aurora borealis.

Apart from its actual value in the subject, the change of view brought about by this quite recent work does emphasize the fact that meteorology, like all live sciences, is dynamic and not static, and that its bounding edge is continually advancing.

APPENDIX

Further Reading

For information concerning the conduct of a meteorological station, and for details of the various instruments employed, together with tables necessary for the proper working up of the readings afforded by the instruments, the student is referred to "The Meteorological Observer's Handbook" issued by the Meteorological Office, London.

The best and most exhaustive treatise on the subject of meteorology is "The Manual of Meteorology" by Sir Napier Shaw with the assistance of Elaine Austin (Four volumes. Cambridge University Press). Smaller and single-volumed text-books giving general treatments of the subject are A. E. Geddes' "Meteorology" (Blackie) and W. J. Humphreys' "Physics of the Air" (Philadelphia, Franklin Institute). An admirable outline of the subject, provocative yet authoritative, is to be found in D. Brunt's "Meteorology," published by the Oxford University Press in the series known as "The World's Manuals," and an extended, advanced and excellent treatment in the same author's "Physical and Dynamical Meteorology" (Cambridge University Press).

G. A. Clarke's "Clouds" (Constable and Co.) is strongly to be recommended for its particular subject, while A. W. Clayden's "Cloud Studies" (John Murray, London), though much older, is still well worth the reading.

For fuller discussions of the problems arising in connexion with forecasting weather from synoptic charts, Sir Napier Shaw's "Forecasting Weather" (Constable and Co.) will repay careful study. It is particularly valuable in that it concentrates attention upon the intimate relationship existing between physics and meteorology. A really good treatment of the subject of forecasting as practised now is that of "The Weather Map" by J. S. Dines (H.M. Stationery Office, London, Second Edition, 1930). From the historical point of view, "Weather" by the Hon. R. Abercromby,* the worker and writer who did so much to crystallise knowledge concerning forecasting from synoptic charts, is full of interest and still remains full of instruction: while all interested in the modern methods as devised by the Norwegian school should study "Practical examples of polar-front analysis over the British Isles in 1925–6" by J. Bjerknes, (*London, Geophys. Mem.*, No. 50).

For discussions of the conditions prevailing in the upper air, the student is referred to Vol. IV of the "Manual of Meteorology" by Sir Napier Shaw, with the assistance of Elaine Austin, already mentioned. Other books that will repay attentive reading are C. J. P. Cave's "The Structure of the Atmosphere in Clear Weather" (Cambridge University Press), W. H. Dines' "The characteristics of the free atmosphere" (*London, Geophys. Mem.* No. 13), and E. Gold's "The international kite and balloon ascents" (*London, Geophys. Mem.*, No. 5).

A sound and clearly written book giving information concerning the climates experienced over the world is W. G. Kendrew's "The Climates of the Continents" (Oxford University Press).

For definitions of terms employed and for short but authoritative articles upon various aspects of the subject, arranged alphabetically, "The Meteorological Glossary" (H.M. Stationery Office, London) can be unreservedly recommended.

It must not be forgotten, however, that meteorology is a distinctly live science, and that new and important work is being done in it daily in various countries and published in various forms and languages. So far as the United Kingdom is concerned most new work is to be found in the current publications of the Meteorological Office, London (especially in the two series known, respectively as *Geophysical Memoirs* and as *Professional Notes*), of the Royal Meteorological Society (*Quarterly Journal* and *Memoirs*), and of the Royal Society. If the student wishes to maintain himself abreast of new knowledge and of new viewpoints in the subject, a periodical inspection of these publications is essential.

* A new edition of this book revised by A. H. R. Goldie was published in 1934.

INDEX.

(Numbers refer to Sections.)

ABRIDGED LIST OF PUBLICATIONS PUBLISHED BY THE AUTHORITY OF THE METEOROLOGICAL COMMITTEE

A complete list will be forwarded on application to the Director, Meteorological Office, Air Ministry, London, W.C.2

Publications may be ordered (unless otherwise indicated) directly from the Sale Offices of His Majesty's Stationery Office at the addresses shown on the title page, or through any bookseller.

1. HANDBOOKS, TEXT-BOOKS, TABLES

Barometer Manual for the use of Seamen. A Text-book of Marine Meteorology. 11th edition, 1932. (No. 61.) (8vo.) 2*s*. 6*d*. Postage 3*d*.

Cloud Forms. Definitions and descriptions with photographs of Clouds. 3rd edition, 1934. (No. 233.) (8vo.) 9*d*. Postage 1*d*.

Computer's Handbook. Issued in Sections. (No. 223.) (8vo.) :—

Introduction. C.G.S. Units of Measurement in Meteorology, with their abbreviations and their equivalents. 1921. 3*s*. 6*d*. Postage 1*d*.

Section II. Subsection I. The Computation of Wind Components from Observations of Pilot Balloons and Shell Bursts. 1920. 2*s*. Postage 1*d*.

(*The remaining sections are out of print.*)

Decode for use with International Code of Wireless Weather Messages from Ships, adopted by the International Meteorological Conferences, 1929 and 1935. 5th edition, revised to 1st December, 1937. (No. 329.) (8vo.) 6*d*. Postage 1*d*.

Dines Balloon Meteorograph and the Method of using it. By L. H. G. Dines, M.A. (No. 321. 1929.) (8vo.) 2*s*. Postage 2*d*.

Examples of Weather Maps showing Typical Distributions of Pressure. (Reproduced from the **Weather Map,** *q.v.*) 2nd edition, 1932. (No. 337.) (8vo.) 3*d*. Postage ½*d*.

Fishery Barograph. A note on the use of the barograph in anticipating gales and instructions for the care and maintenance of barographs lent to fishing communities. 2nd edition, 1935. (No. 333.) (8vo.) 2*d*. Postage ½*d*.

Gazetteer of British Meteorological Stations used in the preparation of Synoptic Reports. (No. 319. 1931.) (8vo.) 8*s*. Postage 5*d*.

Amendment No. 1. (No. 319. 1936.) 2*s*. Postage 1*d*.

Amendment No. 2. (No. 319. 1937.) 2*s*. Postage 1*d*.

Overseas Supplement. (No. 319/1. 1933.) 2*s*. Postage 1*d*.

Hygrometric Tables for the Computation of Relative Humidity, Vapour Pressure and Dew Point from Readings of Dry and Wet Bulb Thermometers exposed in Stevenson Screens. 3rd edition, 1931. (No. 265.) (8vo.) 1*s*. Postage 1*d*.

1. HANDBOOKS, TEXT-BOOKS, TABLES—*cont.*

Marine Observer's Handbook. 6th edition, 1936. (No. 218.) (8vo.) 3*s.* Postage 4*d.*

Measurement of Upper Winds by means of Pilot Balloons. (No. 396. 1936.) (8vo) 1*s.* Postage 1*d.*

Meteorological Corrections for the use of Gunners. Notes on. By D. Brunt, M.A., and J. Durward, M.A. (No. 241. 1921.) (8vo.) 3*d.* Postage ½*d.*

Meteorological Glossary (continuation of the **Weather Map,** *q.v.*). 2nd edition. Entirely rewritten, 1930. (No. 225ii.) (8vo.) 4*s.* 6*d.* Postage 4*d.*

Meteorological Observer's Handbook. Instructions in the care and manipulation of meteorological instruments and in the making of observations both instrumental and non-instrumental. 1934 edition. (No. 191.) (8vo.) 5*s.* Postage 4*d.*

Supplement No. 1. Instructions for Meteorological Telegraphy. 3rd edition, 1936. (No. 191/1.) (8vo.) 2*s.* Postage 2*d.*

Supplement No. 2. Instructions to Observers at Auxiliary Climatological Stations. 2nd edition, 1933. (No. 191/2.) (8vo.) 3*d.* Postage ½*d.*

Supplement No. 3. Instructions to Observers at Normal Climatological Stations. 2nd edition, 1931. (No. 191/3.) (8vo.) 2*d.* Postage ½*d.*

Supplement No. 4. Instructions to Observers at Climatological Stations at Health Resorts. 2nd edition, 1931. (No. 191/4.) (8vo.) 3*d.* Postage ½*d.*

Meteorology in Relation to Air Navigation. Reprint of Chapter XVII of the "Manual of Air Navigation." Vol. I. (No. 327. 1937.) (Demy 8vo.) 1*s.* Postage 1*d.*

Observer's Primer, being Short Instructions in the Method of Taking and Reporting Readings of Temperature and Rainfall, specially prepared for Meteorological Observers in the British Colonies. 2nd edition, 1930. (No. 266.) (8vo.) 3*d.* Postage ½*d.*

Tables for the Reduction of Meteorological Observations. Published by the Indian Meteorological Department. Includes Tables for finding the Absolute and Relative Humidities from Readings of Wet and Dry Bulb Thermometers. (4to.) 2*s.* Postage 5*d.*

Weather, Currents and Ice for Seamen, A Handbook of. By Captain L. A. Brooke Smith, R.D., R.N.R. (No. 379. 1935.) (8vo.) 4*s.* Postage 4*d.*

Weather Forecasting for Seamen, in the Eastern North Atlantic and Home Waters. By Commander L. A. Brooke Smith, R.D., R.N.R. (No. 246. 1921.) (8vo.) 6*d.* Postage 1*d.*

Weather Map. An introduction to Modern Meteorology. 2nd edition, 1930. Reprinted 1933. (No. 225i.) (8vo.) (*See also* **Meteorological Glossary,** *in continuation of the* Weather Map.) 3*s.* Postage 2*d.*

Wireless and Weather—An Aid to Navigation. By Captain L. A. Brooke Smith, R.D., R.N.R. Reprinted from the **Marine Observer. Vol. IV,** with Appendices. (No. 297, 1928.) (4to.) 5*s.* Postage 6*d.*

Wireless Weather Messages. Particulars of Meteorological Reports issued by Wireless Telegraphy and Wireless Telephony in Great Britain, Gibraltar, Malta, Middle East and Iraq. 11th edition, 1938. (No. 252) (8vo) 1*s.* 6*d.* Postage 2*d.*

(*Supplements issued as necessary and priced separately.*)

2. JOURNALS

Marine Observer. From January, 1924. (No. 262.) (12¼ in. by 9⅞ in.) In substitution for the monthly issues of Meteorological Charts of the North Atlantic Ocean and East Indian Seas. Published monthly to December, 1932 and thereafter quarterly for the first month of each quarter, with supplements for the intervening months. Quarterly numbers, 4*s.* each. Postage 3*d.* Monthly supplements, 6*d.* each. Postage 1*d.*

(*Annual subscription, including Supplements,* 21*s.*, *post free.*)

Meteorological Magazine. Symons's Meteorological Magazine, incorporated with the Meteorological Office Circular. (8vo.) Published monthly. 6*d.* Postage ½*d.*

(*Annual subscription, from February to January,* 6*s.* 6*d.*, *post free.*)

3. PUBLICATIONS OF DATA (Current Periodical Issues)

British Rainfall. (8vo.) A Report upon the progress of Rainfall Investigations and full records of the Rainfall of each year, with Maps and illustrations :—

1865 to 1879, each 5*s.*
1880 to 1918, each 10*s.*
1919 to 1921, each 12*s.* 6*d.*
1922 to 1936, each 15*s.*
(*Some of the earlier volumes are out of print.*)

Daily Weather Report. 1. British Section (12½ in. by 13 in.) 2. International Section (4to.) 3. Upper Air Section (4to.) Subscription 13*s.* post free, per official quarter for two or three sections, 6*s.* 6*d.* per official quarter for one section. Single copies, price 1*d.* each. Postage ½*d.*

Orders or correspondence should be addressed to the Director, Meteorological Office, Air Ministry, Kingsway, London, W.C.2. Cheques and Postal Orders should be made payable to the "Secretary, Air Ministry," and crossed "Bank of England, a/c of H.M. Paymaster-General."

Monthly Weather Report. (4to.) The publication of the Monthly Weather Report began in 1884. Contains summaries of observations from about 330 Stations in the British Isles, with Charts. Monthly Parts and Annual Summary, each 1*s.* Postage 1*d.*

(*Annual subscription, including Introduction and Annual Summary,* 15*s.*, *post free.*)

Observatories' Year Book, from 1922. (4to.) In continuation of Parts III (2) and IV of the British Meteorological and Magnetic Year Book. Volumes for 1922 and 1923, each 63*s.* 1924, 57*s.* 6*d.* 1925 to 1931, each 63*s.* 1932 to 1935, each 42*s.*

Réseau Mondial. (4to.) Monthly and Annual Summaries of Pressure, Temperature, and Precipitation at Land Stations, generally two for each 10 degree square of Latitude and Longitude. From 1910 :—

Charts.—1910, 8*s.* 6*d.* ; 1911, 3*s.* 6*d.*

Tables.—1910, 15*s.* ; 1911 to 1913, each 7*s.* 6*d.* ; 1914, 18*s.* ; 1915, 24*s.* ; 1916, 22*s.* 6*d.* ; 1917, 22*s.* 6*d.* ; 1918, 21*s.* ; 1919, 22*s.* 6*d.* ; 1920 and 1921, each 24*s.* ; 1922 to 1925, each 25*s.* ; 1926, 12*s.* 6*d.* ; 1927 to 1930, each 15*s.*

Weekly Weather Report. (4to.) Published in weekly numbers from February, 1878, to February 25, 1928 (at prices ranging from 2*d.* to 9*d.* each) and thereafter in annual volumes referring to the Seasonal Year (i.e. from the beginning of Spring to the end of Winter). Volumes for 1928–9 to 1931–2 each 15*s.* ; 1932–3 to 1936–7, each 7*s.* 6*d.*

4. PUBLICATIONS OF NORMALS OR AVERAGES

Normals of Meteorological Elements for the British Isles. Book of. (No. 236.) (8vo.) :—

Section I. Monthly Normals of Temperature, Rainfall and Sunshine for Stations. 2*s.* (*Out of print.*)

Section II. Normals, Weekly, Monthly, Quarterly and Seasonal for Districts. 9*d.* Postage 1*d.*

Section III. Maps of the Normal Distribution of Temperature, Rainfall and Sunshine. 1*s.* 6*d.* Postage 1*d.*

Section IV. (*a*) Range of Variation of Temperature and Rainfall (*b*) Frequency Tables for Hail, Thunder, Snow, Snow Lying and Ground Frost. 3*s.* 6*d.* Postage 1*d.*

Section V. Monthly Normals of Rainfall. 4*s.* Postage 1*d.*

Section VI. Normals of Relative Humidity. 9*d.* Postage 1*d.*

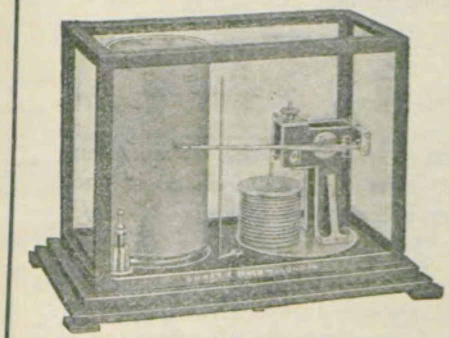
Averages of Bright Sunshine for the British Isles, for periods ending 1935. (No. 408. 1936.) (8vo.) 1*s.* Postage 1*d.*

Averages of Temperature for the British Isles, for periods ending 1935. (No. 407. 1936.) (8vo.) 1*s.* 3*d.* Postage 1*d.*

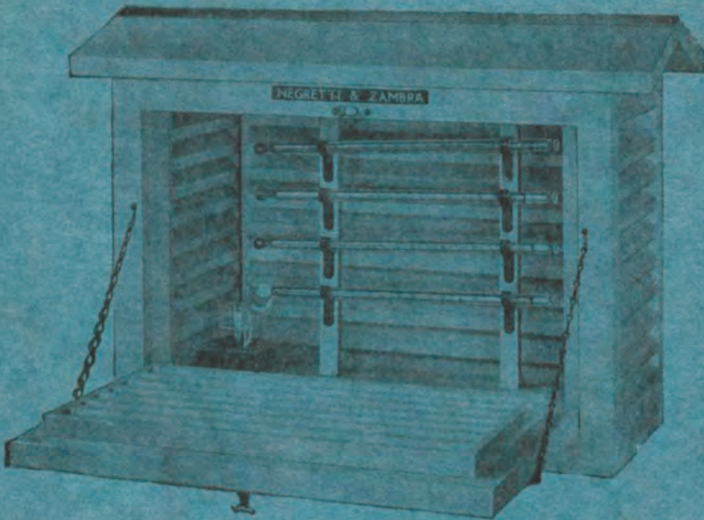
Averages of Humidity for the British Isles. (No. 421. 1938.) (8vo.) *In the press.*

Monthly Normals of Percentage Frequencies of Surface and Upper Winds over Malta, Egypt, Palestine, Trans-Jordan and Iraq. Mainly between the years 1921 and 1932. (No. 405. 1936.) (8vo.) 2*s.* Postage 1*d.*

(40179) Wt. 3240/2211 2,250 4/38 Hw. G.371



ADVERTISEMENT


NEGRETTI & ZAMBRA