FURTHER OUTLOOK

F. H. LUDLAM & R. S. SCORER

WITH A FOREWORD BY SIR DAVID BRUNT F.R.S. (Sec., ROYAL SOC

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[Fox Photos Ltd.

The Great Smog of December 1952. Big Ben and the Houses of Parliament seen dimly just before noon, during the man-made fog which lasted for four days.

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By

F. H. LUDLAM AND R. S. SCORER

With an Introduction by

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Secretary of the Royal Society

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INTRODUCTION

I WRITE an introduction to this book by F. H. Ludlam and R. S. Scorer with very great pleasure. They have written their book from a new and refreshing standpoint, and what is most refreshing of all in its character is the bold way in which they have looked to the future. It must not be thought that meteorology is a subject which remains static. During the thirty-six years I have spent in working at meteorology, either in the Meteorological Office or in the University of London, considerable progress has been made in our understanding of atmospheric processes. Perhaps the sanest way of judging meteorology is by our increased ability to explain why it rained yesterday, rather than by our not so evident ability to say with certainty whether it will rain tomorrow.

No one who reads this book can fail to realise that the atmosphere is extremely complicated in its distribution of temperature, humidity and wind. We cannot discuss the atmosphere over, say, the British Isles, and leave out of consideration the atmosphere over the rest of the earth, since the air over the British Isles at, say, 6 a.m. today, by 6 p.m. may have been replaced by air which at 6 a.m. was over the Atlantic.

By far the most exciting event in the history of meteorology is the effort made in recent years to control the weather, whether by producing rain artificially or by dissipating clouds or fogs by artificial means. The reader will learn something of these subjects in reading Chapter VII, and he will also agree, if he reads this chapter carefully, that it is as yet too early to judge with any confidence whether it is going to be possible to produce artificial variations of weather at will. But whatever may be the final judgment as to the possibilities of man-made weather on a large scale, it is beyond question that the effort to vary the weather by artificial means is likely to teach us much that is new concerning the physics of clouds. Meteorology is rapidly becoming an experimental science on a large scale, on a vastly larger scale than can be attained in the laboratory.

I would stress these aspects of meteorology as those which at the present time indicate the points of growth of the subject.

This book, written by men who have established themselves as experts in meteorology, is recommended to the reader as a sound exposition of the growing meteorology of today.

DAVID BRUNT.

PREFACE

A MOMENT'S reflection makes it all too plain that the weather plays a leading part in determining the activities of even the most advanced of our civilised communities. Though man's climate is modified by his clothes and buildings, and all the apparatus he has gathered around him, the present era is one when erosion and modification of the landscape by the atmosphere is as intense as it has ever been in perhaps a hundred million years. Flood from rainstorm, melting snow, or air-driven tide; avalanche and landslide; drought and dust; scorching sun and deadening cold; killing fog; storm at sea; tornado on land; all these and many other violent signs of the power of the atmosphere follow in unending succession, and leave a trail of destruction and disaster for some members of the human family.

If we could know in advance, catastrophe might be transformed into inconvenience; often a few hours warning would suffice. Can improved forecasts be given, or must we be continually surprised? Can we alter the weather or guide its fury on some harmless course, or shall we remain the pawn of nature? We have looked forward to see what answers the future can give to these questions.

But the air is not always raging; beauty and tranquillity, majesty and splendour, are more common features of the skyscapes. Who in gazing at the clouds does not, like Turner, sometimes imagine fairylands and playful monsters. To know and enjoy the atmosphere we must watch and read it with purpose and imagination. To understand it scientifically does not rob it of its wonder and charm but rather helps one to know it more intimately and appreciate finer qualities that were previously missed.

In this book we have not tried to write a text on the science of meteorology, and have discussed the technicalities only in so far as it is necessary to make our discussion intelligible. Rather we have tried to explain a philosophy of the science of weather study which will enable us to understand its probable future achievements. We hope also that in describing some of the more important atmospheric processes, and some of the more entertaining aspects of its motion, the reader's appetite will be whetted. There are texts for those who wish to delve deeply into the science; for others there is always the sky to watch.

At the least some new light will be thrown on those heaving and writhing gases that form the atmosphere in which we live.

CHAPTER I

THE WEATHER WE OBSERVE

"And on the Tuesday following were seen four circles at midday about the sun, of a white hue, each described under the other as if they were measured. All that saw it wondered; for they never remembered such before."

Anglo Saxon Chronicle.

THE PRINCIPAL FORMS OF CLOUD

IN Britain there are few days when we can feel quite sure that there is no threat of rain: almost always there are some clouds in the sky which might herald showers or a storm if only we knew. These clouds have an infinite variety of shapes and patterns, but are all somehow expressions of the way in which air has risen to form them. The meteorologist classifies them by their appearance, but not simply by the shape of their outlines: he looks for the significant features which are clues to the manner in which they have grown. Sometimes the clouds form a vast sheet hundreds of miles across, indicating an extensive steady ascent of air; at other times they are scattered over the sky in isolated puffs and heaps, revealing irregular, local up-currents which the aircraft pilot finds are separated by regions of sinking air. These are respectively the *stratiform*, or layer clouds, and the *cumuliform*, or heap clouds; with either kind the prolonged ascent of air leads to successively denser clouds and finally to rain: a widespread steady rain from the layer clouds and showers from the heap clouds. The depressions which come from the Atlantic bring both kinds of rains, an individual storm bringing several hours of continuous rain followed by showers and brighter intervals in its rear.

Storm clouds

Sometimes in a spell of rough weather we awake to find that the night's gale has subsided and that the sky seems to have been washed clean; it is a clear blue after sunrise and the pure calm air is mild and smells of the sea. But the barometer remains low and refuses to rise, and we can prepare to watch for the advance of the next storm.

Before long the first signs appear in the far west and spread steadily towards us. They are thin high clouds, several miles above the ground, and in clean country air they may be well over 100 miles away when we first notice them, just above the horizon. They are made up of delicately drawn white streaks and trails, arranged in long patches and bands, and they are called *cirrus* clouds, from the Latin for a hair, in recognition of this fibrous structure (our cloud names were proposed 150 years ago by Luke Howard, a London-born pharmacist, and are now used internationally with hardly any changes). The cirrus approach steadily and after two or three hours the leading clouds are nearly overhead (Plate 1), and the barometer has begun to fall. We can then easily see that the cloud bands stretch back towards the north-west, and that the cloud details are rapidly moving south-eastwards nearly along their length (at a rate which at their height must imply a speed of 100 m.p.h. or more), although the cloud system as a whole is encroaching from the west. The clouds are becoming thicker in the west, and the spaces between the bands filled up, so that as they advance a great veil of silken cloud is gradually being drawn over the whole sky. This sheet of cirrus cloud is called *cirro-stratus.* At first it is translucent; the sun shines palely through it, and we may notice that upon the cloud and centred on the sun, but at some distance from it, there is a *halo*, a bright ring of light tinged with orange-red on the inside. This and other halo phenomena are caused by the refraction of the sunbeams through ice crystals—at the level of these clouds it is very cold: probably 70° or 80° of frost. This cirrostratus has an irregular, tangled texture and only fragments of the halo are clearly shown, but sometimes the cloud is very thin and diffuse, perhaps just a faint film over the blue sky (*cirro nebula*), and then the halo can be very bright and other rings and arcs may appear around it, some with colours as bright as those of the rainbow.

Four or five hours after the first cirrus were seen the front edge of the cloud system is nearing the eastern horizon, and overhead the clouds have thickened and darkened so much that the halo has been extinguished, and the position of the sun is marked only by a brighter patch with smudged edges. When the cloud is too dense to produce a halo it is called *altostratus*

(Plate 2). As the altostratus continues to thicken and becomes lower, patches of cloud form beneath it, making dark mottled and waved patterns; with the closer approach of the storm centre the ground wind freshens from the south, the barometer falls rapidly, and within an hour or two the first raindrops fall. The rain soon becomes heavier and the pall of cloud lowers close to the ground: it is difficult to discern any structure in this grey *nimbostratus*, the rain-cloud, but beneath it ragged fragments of scud (*fractostratus*) are driven along in the strong southerlies and may cloak the hill-tops. The penetrative eyes of radar and explorations in aircraft teach us that the rain-cloud is composed of several thick layers; at a height of a mile or two the rain changes into snow, and higher still the snow flakes become smaller and then are replaced by tenuous clouds of ice crystals which reach up to the cirrus levels. In the regions of heavier snow and rain the gaps between the cloud layers narrow or become closed, so that the cloud extends upwards continuously from near the ground to a height of 5 or 6 miles. In this murky rain-factory the airman has to navigate by instruments and be on guard against the icing of his machine.

After some hours the steady rain ends and the barometer ceases to fall; the sky becomes lighter as much of the upper cloud becomes thin and broken or clears away, but the lower overcast of ragged *stratus* clouds persists and gives an intermittent drizzle, whose drops are smaller but much more numerous than raindrops. The air has become milder and 'muggy', and the wind has veered a little to become south-westerly.

Some time later the wind becomes stronger, the sky darkens again and there is heavy rain for a short while, quickly followed by a sudden improvement in the weather. The wind veers sharply to a north-westerly point and becomes gusty and cool, the barometer begins to rise, and the low clouds lift and break. Above them thin, dappled high clouds and some cirrus now are moving from the south-west, but they are receding eastwards and soon leave a clear upper sky.

The widely-scattered low clouds are now *cumulus*, the heap clouds, which have fairly level bases and rounded tops (as seen in Plate 10). As the cool north-westerly air stream becomes well established some of these clouds grow bigger and taller, with bulging summits towering up 3 or 4 miles above their bases, looking substantial enough to walk upon. Before long we see beneath the largest clouds descending trails of rain: they have become *cumulonimbus*, the shower clouds. Usually there is a striking change in the appearance of the cloud-tops as the shower forms. At first these are made up of sharp-edged, rounded protuberances with shadowy folds and crevices; but soon the clear detail becomes smudged and the outlines ragged and soft; the bulges are flattened, the nooks and crevices become filled in and the whole of the upper part of the cloud takes on the fibrous texture of cirrus, so that early writers called it 'false cirrus' (Plate 3). Often it is drawn sideways by the stronger winds aloft, projecting beyond the cloud base in the shape of an anvil. Eventually it may separate from the lower part of the cloud, which usually subsides and dissolves with the development of the shower, drifting away as a slowly-evaporating mass of 'anvil cirrus'. The decay of the shower cloud may be well advanced less than half-an-hour after the surge up of the first bulging summits, but although each cloud is so short-lived they often grow in closely-packed groups to make up a complex shower cloud. As one tower yields up its rain and evaporates another springs up on its flanks, and the cloud mass may travel as a recognisable whole for several hours.

After some hours the vigour of the cloud growth declines; the larger clouds appear ever more rarely, the showers cease and the wind moderates. The barometer continues to rise, but more slowly, and finally even the small cumulus disappear; the whole cloud system of the storm has passed away.

Some other cloud forms

In describing this storm we have assumed that its centre passed some distance to our north. In other parts of the storm the sequence of clouds and weather may differ a little, but usually the separation of the clouds into layer types in the front and heap clouds in the rear is well marked. On the southern fringes of the cloud systems and in weaker storms the layer clouds are thinner and broken into dapples or billows. The dapple clouds which form amongst the cirrus are called *cirrocumulus* and are the most delicate; the others are conventionally divided into *altocumulus* (Plate 4) and *stratocumulus* according to their being more or less than approximately 2 miles above the ground respectively. Amongst the lower strato-

[Photo by F. H. Ludlam

PLATE 1. *Cirrus clouds heralding the approach of a storm. There are broken cumulus below.*

[Photo by F. H. Ludlam

PLATE 2. *Altostratus cloud veiling the sun.*

cumulus are included all the layer clouds which show some detail, even though they may be quite thick and without any clear chinks. Such clouds sometimes cover the sky for days on end in spells of quiet winter weather.

All the dapple clouds, except perhaps some of the high cirrocumulus, are composed of droplets even though their temperature may be well below the ordinary freezing point. They sometimes cause *coronae,* diffraction patterns of coloured rings around the sun, which are easily distinguished from halos because they are much closer to the sun, and usually have brighter rainbow colours, with the red on the *outside.* They are at their finest when the droplets are all a uniform size; otherwise the colours become mixed and there is only an *aureole,* a dull brown-red ring separated from the sun by a bluish-white zone. Because of the glare, halos and coronae around the sun must be looked at through sun spectacles or by reflection in a black mirror, but they are usually much more splendid than the fainter ones more commonly noticed around the moon.

We have now mentioned all the principal cloud forms, but there are several recognised varieties, among which, are the *lenticular,* or lens-shaped clouds (Plate 5). These are caused by the ascent of air in crossing a hill, and although sometimes they shroud the hill-top and have no clearly-defined shape, more often they occur well above it as thin oval patches. Each patch may waver a little but remains almost still: the wind blows right through it, and if a detail can be watched forming on the windward side it will be seen to grow as it moves into the cloud and then evaporate on the other side, where the air is descending again. Such clouds are very common, even in our country where the small hills are no serious obstacle to the wind.

Tropical clouds

Near the poles the stratiform clouds predominate; in temperate latitudes there is a continual alternation between layer clouds and heap clouds, or both may appear together, while in tropical and equatorial regions almost all the bad weather is associated with the heap clouds, which here have their greatest development. The characteristic storm of the hot countries is the giant cumulonimbus thundercloud, whose tops tower up to

10 miles above the ground and whose debris of anvil cirrus may be stretched out in great streamers and sheets hundreds of miles long. The dreaded revolving storms of the tropical oceans, the cyclones (also called hurricanes in the Atlantic, and typhoons in the North Pacific) seem also to be complex organisations of

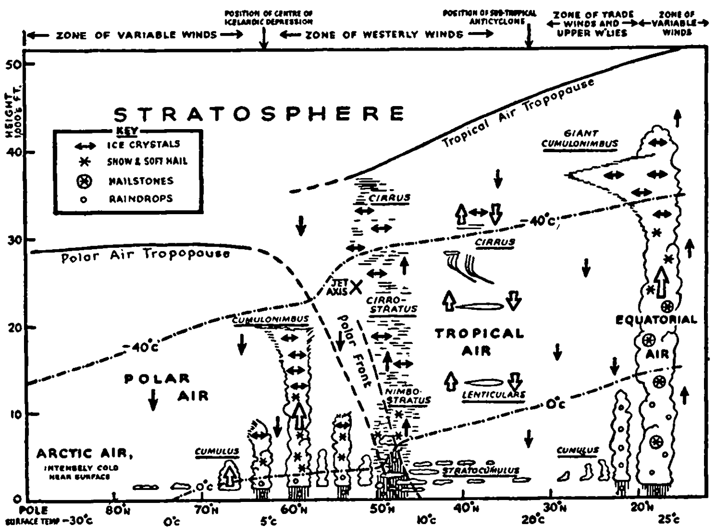


FIG. 1. *A likely cross-section of the atmosphere on a winter day, from the pole to the tropics along a meridian lying over the ocean west of Europe and Africa. In the centre of the figure lies the polar front and its system of rain clouds. All the clouds are drawn very schematically: the vertical scale is enormously exaggerated, and so is the width of the isolated clouds. The dark arrows show vertical motions in the air of a few inches a second, while the white arrows show where there are vertical motions of several feet a second. The cross at about 25,000 feet, over the polar front, marks the axis of the region of very strong westerly winds (the jet stream).*

cumulonimbus clouds: the airman flying into the rainless eye of one of these storms finds himself in a huge natural amphitheatre, surrounded by a great ring of thunderclouds. Isolated cumulonimbus commonly develop in the afternoon inland and cause storms which persist into the evening, but over the sea they seem to be rather more frequent at night or in the early morning, and are often arranged in long thin lines and belts.

Over the ocean and near coasts exposed to sea-winds, heavy showers are sometimes found falling from cumulus whose tops do not reach levels (here at heights of 4 or 5 miles) where the temperature is below freezing, and consequently they do not develop the ice crystal 'false cirrus' crowns which are so typical of shower clouds outside the tropics. This important fact has only lately been heeded by the theoretical meterorologists studying the causes of shower formation.

Summary

Fig. 1 is a scheme of a typical winter distribution of the principal cloud forms, showing their composition and the strength of the up-currents in which they are formed. They are confined to that part of the atmosphere called the *troposphere,* in which the temperature falls with increase of height. At the *tropopause* the temperature ceases to fall and becomes almost constant or even rises a little as we ascend through the *stratosphere,* which is usually very dry and only very rarely contains any clouds. The tropopause is rather low in polar regions, rising to a height of about 10 miles near the equator; in our latitudes its height is as variable as the other weather elements, and sometimes it becomes very indefinite, but usually it is found somewhere between 5 and 8 miles high. The clouds are therefore formed in a very thin shell of the atmosphere: in the figure the vertical scale is exaggerated about 200 times, and if it were shown in true proportion the clouds would have to be compressed into a layer thinner than the paper on which they are drawn.

THE OBSERVERS' INSTRUMENTS

Surface observations

On land and sea many hundreds of trained observers are constantly reporting their local weather to the weather forecasting centres. In the British Isles alone over 100 reports are made each hour. Outside Europe the density of the network of special observing stations is much less than this, and over vast regions there are hardly any special observers at all, especially between the tropics and in the southern hemisphere oceans.

To specify completely the state of the weather at a particular place we should have to measure the temperature, pressure and velocity of the air, and its content of solid, liquid and vaporous water, at all heights above the earth's surface. This is an impossible task, and in practice the weather forecasters are content with very simple observations. Practically all of these are made at the ground, but the eye observations of the sky provide a good deal of information about the state of the air at higher levels.

The weather forecaster has to consider carefully the significance of the instrumental measurements of pressure, temperature and wind which are made by the observers. He is concerned with the broad weather systems, and is interested in the very local variations which occur near the ground only in so far as they affect the ease of landing at airfields, for example. Everyone knows that wind and temperature vary notably from moment to moment and place to place over the countryside, but the forecaster cannot predict these little changes, nor does he particularly wish to know about them. The observers therefore use instruments which are not very sensitive, and try to mount them in well-exposed places where their readings are likely to be truly representative of the condition of the broad airstream which is flowing over the locality. They cannot always be successful; for example, on a clear calm night the cold ground chills a very shallow layer of air, and then the thermometer in a screen 4 feet above the grass is a poor indicator of the general character of the air over the district. On the other hand, it may be a good guide to the likelihood of fog formation.

Thus the forecaster puts the ground observations to two uses: from them he infers the general character of the airstream, and also those details of the weather at the ground, such as visibility and the reading of an aircraft altimeter at runway level, which his clients wish to know. Three instruments, the barometer and the dry- and wet-bulb thermometers, give him all the information he finds essential.

The first of these, the mercury barometer, is the only precision instrument in general use amongst meteorologists. It shows the height of a mercury column which is supported by the atmospheric pressure, and the measurement of this length is made to an accuracy of one part in ten thousand; it is carefully corrected to indicate a sea-level air pressure. Formerly this was expressed in 'inches of mercury', but now it is expressed in 'millibars', a millibar being one millionth of the unit of pressure in the centimetre-gram-second system. The barometer reading is a measure of the weight of the entire atmosphere over the place of observation, and so it is far less affected by the little variations, which are most pronounced near the ground, than the instruments measuring wind, temperature and humidity. This is why it can be given very accurately and still be very significant.

The next most precise instruments are the thermometers. These are usually of the familiar mercury-in-glass kind. The bulb of one is sheathed by a muslin cap which is kept moist, and is therefore chilled by evaporation to a degree which depends upon the dryness of the air. From the readings of the two thermometers the humidity can be deduced, and for this purpose each is read to a tenth of a Fahrenheit degree, but the forecaster requires the air temperature to be given only to the nearest degree.

Observations of surface wind are usually estimates of its average strength and direction made by the observer himself, from the feel of the wind and its effects in raising waves, bending saplings, and so on. Its strength is reported to the nearest knot, but no one pretends that the estimate is accurate. The observer may be helped by some kind of anemometer which records the wind, but has still to estimate its average from the irregular trace made by the more sensitive kinds, examples of which are discussed in Chapter III.

The anemometers and other instruments which the observer may have are not of much direct use in weather forecasting, but are useful in the investigation of the details of the weather and the accumulation of climatological data. Those commonly used are the maximum-, minimum- and grass-minimum thermometers; the recording aneroid barometer, bimetallic thermograph, and hair hygrograph, and the rain-guage.

Observations of the upper air

Just before the last war little instruments were introduced which have brought a new era into practical meteorology. They are the radio-sonde transmitters, which weigh only a few pounds and which send to a ground station radio signals from which the pressure, temperature, humidity and wind can be deduced at all levels up to a height of about 60,000 feet, at which the balloon lifting them bursts. Their great advantages over other sounding methods are the rapidity with which the results are obtained and their capacity for successful operation in all weathers, except very occasionally, when surface gales make their launching difficult. Aircraft soundings provide valuable cloud and other special observations, but are much more expensive and mostly have a much more limited ceiling, so that now they are made almost solely for research.

Over a large part of the extra-tropical northern hemisphere there are now sufficient radio-sonde stations to allow the construction of accurate maps of the three-dimensional features of the large-scale weather disturbances. These weather maps are now drawn twice daily as a routine; they have brought a new understanding of the weather systems and have been a powerful stimulus to the theoreticians who are trying to analyse their behaviour, and who formerly complained with complete justification that there were insufficient observational facts to make a real start.

Weather maps

To make possible their rapid transmission and handling the weather observations are compressed into codes, so that they consist of several groups of numbers. The forecasters at weather offices have this material plotted upon maps in the form of symbols, which have been carefully designed to be as pictorial as possible of the kind of weather they represent. The forecasters examine the completed maps and construct a picture of the structure and distribution of the weather systems.

On the maps of surface conditions they pay special attention to the *isobars*, lines along which the sea-level barometric pressure is everywhere the same. The isobars show patterns which have a very close relation to the large-scale weather systems: in general, relatively high pressure is accompanied by fine weather, while the storms are associated with low pressures. Moreover, the configuration of the isobars determines the winds near the ground. Except near the equator, the wind blows very nearly along the isobars, in the northern hemisphere with low pressure on the left, and in the southern hemisphere with low pressure on the right. The wind speed is proportional to the crowding of the isobars, so that from a few scattered barometer observations the forecaster can draw isobars and obtain a clear idea of the strength and direction of the air currents over the whole of the area covered by his maps. In practice he estimates the wind speed at any place by measuring the separation of the nearby isobars on a transparent scale from which he reads the speed directly. The scale is constructed from a theoretical relation between wind speed, air density, latitude and isobar separation. This relation is fundamental in all meteorological studies of the larger scale weather systems; it is the first great achievement of meteorological theory, and up to the present it is the only theoretical result which is constantly put to practical use. In view of its importance, we give a quantitative derivation of it in an appendix.

Instead of drawing isobars it is possible to portray the wind flow by drawing contour maps which show the variation of the height at which the pressure has a standard value. For example, when the barometric pressure is 1,015 millibars the 1,000 millibar height is about 400 feet above the ground, and on a map of the 1,000 millibar surface the contour marked '400 feet' runs through all places having a barometric pressure of 1,015 millibars. Where the barometer is high so also is the contour height, and the chart of isobars and the contour chart look practically the same, except for small variations in the spacing of the lines. The forecaster uses contour charts, usually for the 700, 500, 300 and 200 millibar surfaces (corresponding to heights of about 10,000, 18,000, 30,000 and 38,000 feet), so that he can forget the changes in air density and use the same wind-scale on all his maps. At the higher levels it is difficult to make observations accurately enough to allow the drawing of good contour maps. Quite a small slope of an isobaric surface implies a strong wind: one of a foot in a mile corresponds to a wind of gale force.

CHAPTER II

ATMOSPHERIC PROCESSES

"*There was a fierce purpose in the gale, a furious earnestness in the screech of the wind. . . .*"

Joseph Conrad.

HEAT EXCHANGES IN THE ATMOSPHERE

THE sun radiates energy into space in rays of various kinds. The bulk of the energy is sent in the form of rays of ultra-violet, visible, and some infra-red light; as we are well aware, the atmosphere is almost completely transparent to this sunshine, and that part of the radiation reaching us which is not reflected back into space as 'earth-shine' is absorbed at the earth's surface and there converted into heat. The other kinds of radiation which arrive from the sun, such as those of longer wavelength detected by radio, and those which produce aurorae and magnetic storms, are negligible as heat supplies.

It is estimated that on the average nearly half of the sunshine which reaches the outer atmosphere is reflected by clouds and the earth's surface and so is lost to us. Only about a fifth penetrates a layer of cloud, and snow-covered ground is an equally good reflector—other kinds of surface reflect about a tenth of the radiation which falls upon them.

In the high atmosphere small amounts of ozone gas absorb most of the ultra-violet light; the gas is concentrated mainly in a layer between heights of about 15 and 35 miles (only about a quarter of the total amount is contained in the troposphere), and the absorption warms the air in this layer so much that its average temperature is rather higher than that of surface air near the equator.

The earth and the air also radiate heat, but invisibly. A poker with a very high temperature is 'white hot', radiating visible light; but as it cools its radiation consists mainly of longer and longer wavelengths: it becomes 'red hot', then glows a very dull red, and eventually as the poker nears room-temperature it emits no light at all, but only an invisible infra-red radiation which can be detected by a suitable photographic plate even when it has become too feeble to warm the hand. The earth and its atmosphere radiate infra-red rays, which have wavelengths about twenty times longer than the visible ones emitted by the sun. The water-vapour in the atmosphere, and even very thin clouds, absorb this radiation very strongly. A satisfactory theory of the flows of heat by infra-red radiation in the atmosphere has not yet been developed because of the incompletely-known absorptive properties of water-vapour and the atmospheric gases over the whole range of temperatures and pressures which occur in the atmosphere, and also because of the very variable and complicated distribution of cloud and water-vapour.

However, rough but fairly reliable calculations show that the earth's surface in equatorial and tropical regions, where it more directly faces the sun, receives more heat by sunshine than it emits by its own infra-red radiation. On the other hand, the surface nearer the poles has on the average a net loss, except perhaps in the summer season, while everywhere the air in the troposphere loses heat by radiation at an average rate sufficient to cool it by between 1° and 2° C. a day. Since the average temperature of the earth is not changing, on the whole it must radiate as much heat as it receives from sunshine. Similarly the mean annual temperature near the equator is not steadily rising, nor are the polar regions and the air of the troposphere steadily cooling, so that there must be a continual transport of heat from the surface in the tropics upwards and polewards into the troposphere. The upward transport of heat near the equator is accomplished by the rise of ground-warmed air masses which results in the predominance of the cumuliform heap clouds in those latitudes. The transport of heat from the tropics into the high latitudes is partly accomplished by ocean currents, but mainly by air currents. Relatively warm tropical air flows poleward and is replaced by cooler currents from the polar regions, which are then warmed and prepared for return. It also seems that the currents cause a vertical transport of heat, upward movements occurring in the poleward travelling warm air and a sinking in the cool air making its way into the tropics.

It is these circulations, and in particular the upward movements resulting in cloud and rain, which produce our weather. The atmosphere is a great heat engine, converting part of a heat flow from the boiler (the surface, usually in tropical regions) to the condenser (the troposphere and the polar regions) into energy of movements (winds). Friction, both at the ground and within the atmosphere, constantly transforms the energy of the winds back into heat.

The motion of the atmosphere

If the sun revolved around a still, ocean-covered earth we may suppose that there would be a simple, steady circulation of the atmosphere, by which the warm surface air of the tropics was led into the high polar troposphere, where it would cool and descend to become a polar air mass which returned along the surface to be warmed again in the tropics. In fact, however, the motions in the atmosphere are made very much more complicated because the earth rotates, because of the irregular distribution of land and sea, and because they are resisted by friction.

We have already discussed in Chapter I the fundamental law of meteorology, that except near the equator the earth's rotation causes the air currents to move, not in the direction from high to low pressure but more nearly *across* the pressure gradient (or along the isobars), and so that low pressure lies to the left in the northern hemisphere and to the right in the southern hemisphere. The considerable fall of temperature from the tropics towards the poles tends also to produce a marked poleward decrease of pressure at any level in the troposphere, for the nearer we approach the poles the higher is the proportion of the atmospheric mass concentrated below this level in the colder and therefore denser polar air. Consequently, between the tropics and the poles we may expect a pressure gradient causing a great belt of westerly winds in the troposphere of both hemispheres; these currents are called *zonal,* because they are parallel to the equator.

These zonal westerly winds are indeed found in mid-latitudes on maps of mean winds, from which the day-to-day complexities of the flow have been smoothed away by combining the observations made over a number of years (see Figs. 2, 3). The patterns on these mean charts, for high levels as well as the surface, are sometimes said to show the 'general circulation' of the atmosphere, whose details in the troposphere shift and change between the winter and summer season, but keep the same general form. These seasonal changes are due partly to the reversal of the temperature contrast between land and sea, the continents in general being warmer than the oceans in summer and cooler in winter. Although our observations in the largely oceanic

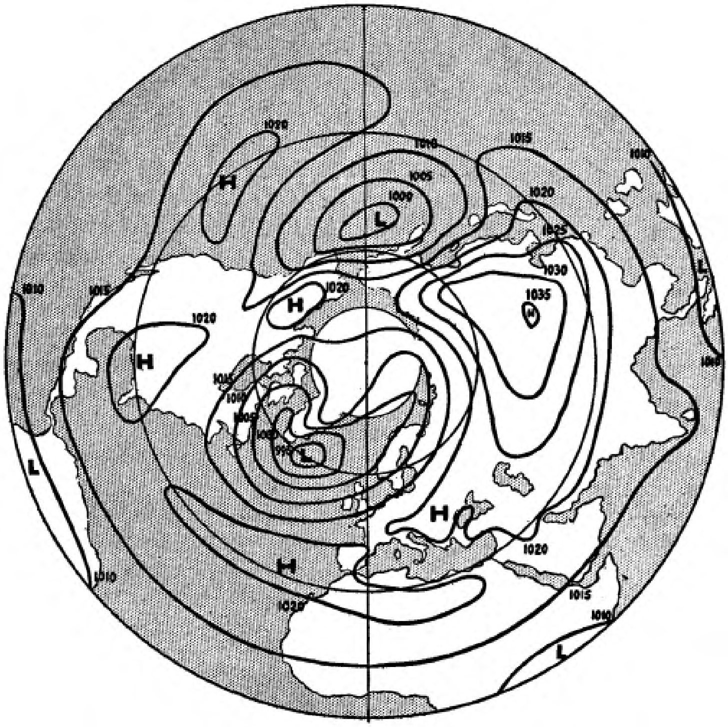


FIG. 2. *The average distribution of surface pressure over the Northern hemisphere in January. Isobars are shown at 5 millibar intervals (1,000 millibars = 29·53 inches of mercury). Prevailing winds blow approximately along the isobars with low pressure to the left, and at a speed proportional to the closeness of the isobars.*

southern hemisphere are fewer and less reliable, it seems that the mean flow patterns there are more regular and show smaller seasonal distortions.

Purely zonal winds could not perform the heat transports in the atmosphere which the radiation theory shows must occur. When the properties of the zonal currents are studied it is found that they must be *unstable*: any small irregularity in the flow leads to the growth of a disturbance which contains *meridional* movements, directed across the lines of latitude. Moreover,

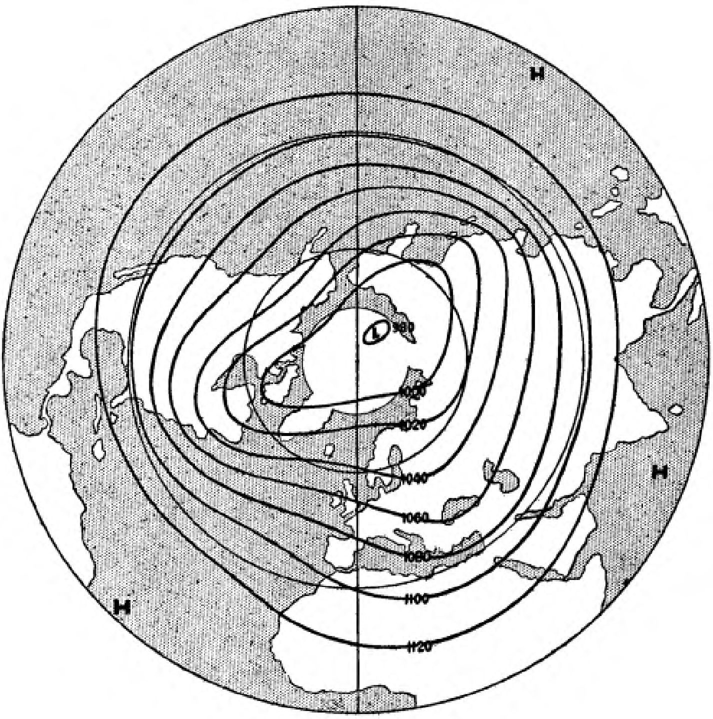


FIG. 3. *The average pattern of the wind-flow over the Northern hemisphere in January at a height of about 6 miles. The upper winds are much less distorted than the average flow near the surface, shown in Fig. 2. They are also much stronger, the same spacing of the lines here corresponding to a wind speed four times greater.*

the movements are such as would transport heat in the required way: the relatively warm air on the tropical flank of the current is diverted poleward and upward, while the cooler air on the other flank subsides and turns towards the equator.

The theory thus begins encouragingly, and we are led to identify the growing disturbances which it predicts with those which we actually find developing on our daily charts and which so complicate the observed atmospheric motion. Unfortunately this simple theory as so far formulated can describe only the *beginning* of a disturbance, because it is founded on assumptions which simplify the treatment but which are no longer correct once the initially smooth current becomes appreciably distorted. If these simplifications are given up then the mathematical treatment of the problem becomes so difficult that, so far at least, it is impossible to deal with it.

The growing disturbances reach a maturity, exhaust the local supply of available energy, and are then gradually worn down by friction; eventually friction and the continuing radiative processes re-establish an unstable zonal current and prepare the way for the growth of another disturbance. In general, the wearing down of one disturbance is never completed before the birth of another, and there are disturbances of several kinds. Our observation of them has not so far been acute enough to give us a full knowledge of their structure, their action, and of the way in which their cloud systems modify the atmospheric radiation.

At least we recognise these disturbances as essential agencies in the working of the atmosphere; we cannot expect to explain the general circulation until we understand their nature thoroughly.

Atmospheric disturbances

Apart from the mid-latitude belt of westerly winds, the main features of the mean charts are an equatorial zone of rather low pressure and weak winds, separated from belts of high pressure in about latitude 30° by the north-east and the south-east trade winds, which converge towards the equator. These trade winds are shallow currents with westerlies above them in the higher troposphere.

The convergence of the trade winds implies that near the equator there must be, on the average, an ascent of air and poleward motions in the upper troposphere in the tropics, so that there is probably some kind of meridional flow also in these regions, the circulation being completed by a sinking of air in the sub-tropical, high-pressure belt. The weather and the kinds of disturbance associated with this circulation are quite different from those found in the zonal currents of mid-latitudes, and, it must be admitted, even less well understood. Among these disturbances are the hurricanes and typhoons, the monsoons, and systems of thunderstorms. The network of observing stations is so thin that the observations, especially in the upper air, only hint at the structure of these disturbances. Although they occur in regions above which lies more than half of the volume of the entire troposphere, after this brief mention we leave them to consider the disturbances of mid- and polar-latitudes, which are those responsible for our own weather and about which more is known.

CYCLONES AND ANTICYCLONES

The polar front

A large part of the fall of temperature towards the poles occurs in mid-latitudes across a narrow belt occupying perhaps 10° of latitude. Within this belt much of the temperature change is concentrated in a narrow region, about 100 miles wide, which inclines upwards from the ground over the colder air with a slope of about 1 : 100, so that in the high troposphere it is usually several hundred miles poleward of its position at the surface (Fig. 1). This sloping region of transition between the cold polar air and the warm sub-tropical air is called the *polar front*. Near and above the polar front the westerly zonal winds reach their greatest speeds, which usually exceed 100 m.p.h. near the tropopause. Disturbances which form in this belt of strong winds grow into the travelling cyclonic storms of the temperate latitudes. These produce great distortions in the polar front: tropical air surges northward ahead of each storm and polar air advances towards the tropics in its rear, and the position of the front dividing the two air masses fluctuates over 20° or 30° of latitude, so that on charts of average conditions the rapid transition from the polar to the tropical air is obscured. Indeed, its existence and its relation to the cyclonic storms can be appreciated only by the study of sequences of charts showing the weather at particular moments.

It is true that before these synoptic charts were constructed some meteorological writers recognised the storms as the seat of a conflict between polar and tropical currents. Thus in 1863 the British Admiral Fitz Roy, discussing a 'cyclonic commotion', says that 'it is the NW. half which seems to be principally influenced by the dry, cold, heavy . . . polar current, and the

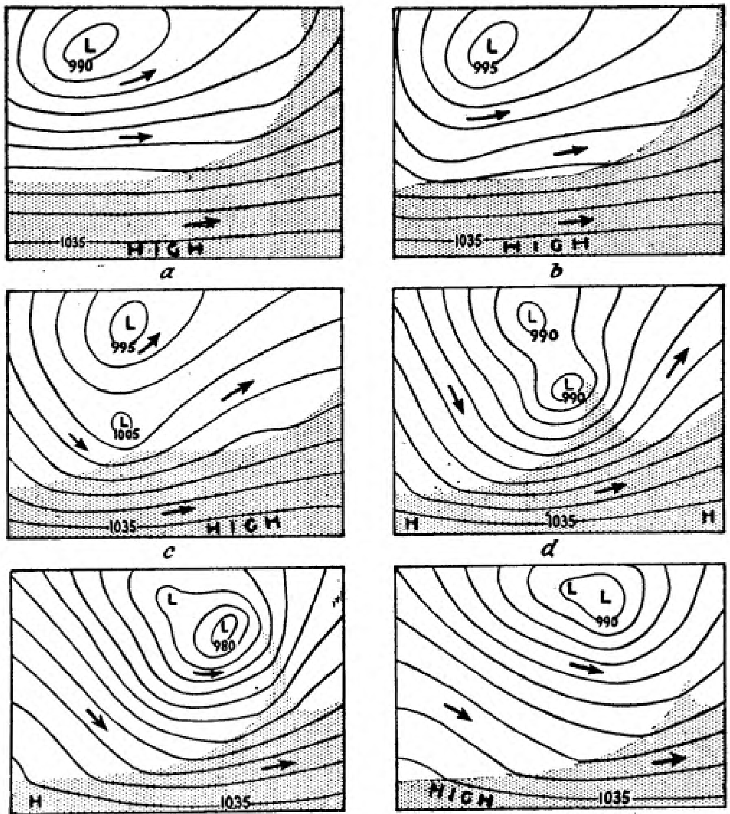


FIG. 4. *The development of a typical cyclone (after Postma). Isobars are drawn at intervals of 5 millibars and arrows show the wind direction. The stippling shows the region of warm tropical air, which is separated from the cool polar air farther north by the polar front. The width of each diagram corresponds to a distance of about 1,500 miles and the whole series extends over a period of about two days.*

SE. half of the cyclone that apparently shows effects of tropical air—(warm, moist, light . . .). On the polar side of a cyclone, continually supplied from that side, the sensible effects are chilling, drying up and clearing the air—with a rising barometer and falling thermometer; while on the tropical side overpowering quantities of warm, moist air, rushing from comparatively inexhaustible supplies, push towards the NE. as long as their impetus lasts, and are successively chilled, dried and intermingled with the conflicting polar currents.'

This fine description could hardly be improved upon today, but it was not until after the First World War, nearly 60 years later, that Scandinavian meterologists introduced the idea of the polar front and the practice of drawing it upon the daily weather maps.

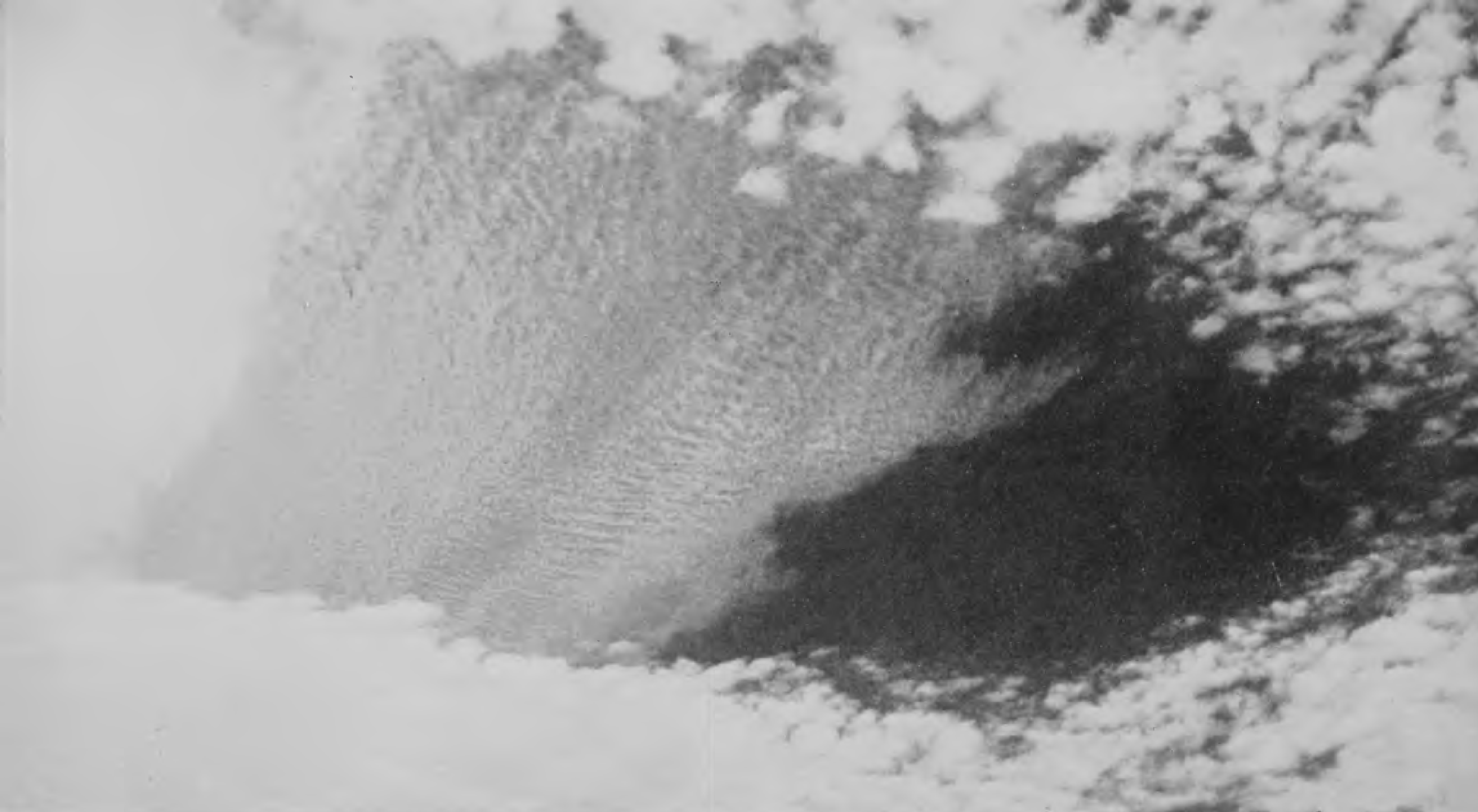
The development of cyclones

According to modern ideas the cyclone originates as a wave-like disturbance of the polar front which initially lies almost stationary in a shallow trough of surface pressure dividing almost parallel currents of polar and tropical air (Fig. 4). As the disturbance grows the pressure in it falls and the surface winds begin to circulate around the developing centre of low pressure. As the storm matures this circulation intensifies and extends upwards to higher levels, where at first there is only a wave-like deflection of the air flow in sympathy with the distortion of the front (and therefore of the pattern of temperature gradient which largely determines the high-level winds).

At first the disturbance moves in the direction of the tropical current, but at a speed slightly less than that of the air—perhaps at 30 or 40 knots. Ahead of the centre, where the warm air advances over territory previously occupied by the polar current, the polar front is called the *warm front* of the cyclone; behind the centre the cold air displaces the tropical current along the *cold front*. The space occupied by tropical air between the warm and cold fronts is called the *warm sector* (Fig. 5). The warm air enters the cyclone from the south-west and on reaching the warm front begins to climb over the wedge of cold air, while the cold air behind the cold front subsides slowly. The cold front moves more rapidly than the warm front, eventually overtaking it near the cyclone centre, so that here the lifted warm air disappears from the surface. The ascent of the warm air near the cyclone centre, over the warm front, and often also in a narrower belt over the cold front, leads to the formation of widespread layer clouds and rain in these regions. Behind the cold front the polar air moving into more southerly latitudes is

[Photo by F. H. Ludlam

PLATE 3. *Cumulus clouds and, in the background, the spreading fibrous anvil of a cumulonimbus cloud.*



[Photo by F. H. Ludlam

PLATE 4. *Dapple clouds. In the centre of the picture delicate cirrocumulus clouds are seen through a break in a layer of altocumulus clouds.*

warmed at the surface, and the convection from the ground produces the scattered heap clouds, and, if it is strong enough, the shower clouds which are usually found in the rear of the cyclone.

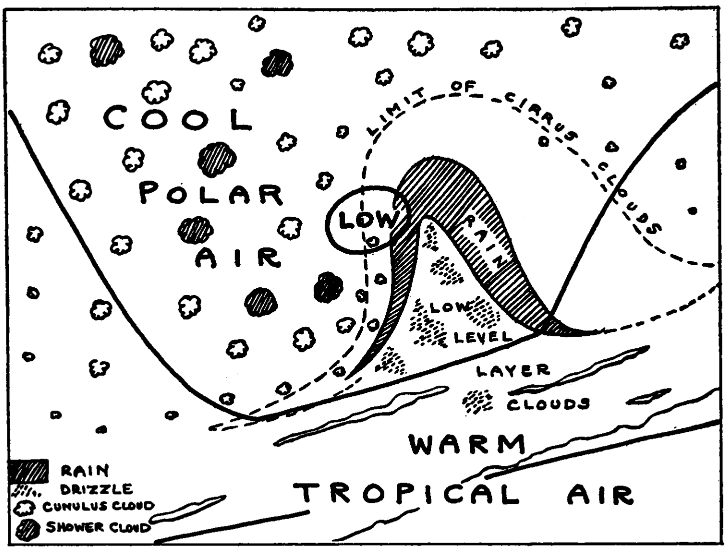


FIG. 5. *The distribution of weather likely to be associated with the maturing cyclone represented in Fig. 4d. The full lines are isobars.*

These features are all shown in Fig. 5. The reader will recognise the sequence of weather described in Chapter I as that experienced at a place lying a little south of the track of the cyclone centre, and will be able to deduce the changes of wind and weather to be expected at other places in the path of a typical storm.

Soon after the shrinking of the warm sector and the lifting of the warm air from the ground (about a day after the appearance of the first disturbance) the cyclone reaches its maturity, slows down, and usually swings poleward. With the redistribution of the warm and cold air masses and the flinging-out of the polar front to the edges of its well-developed circulation it has expended its supply of energy. It has become a vortex of polar air which extends upwards through much of the troposphere. During the next two or three days it is gradually worn down by friction or its identity is lost by absorption into other weather patterns.

Cyclone families

Before a cyclone has decayed it may be succeeded by fresh storms formed on the same part of the polar front: commonly the cyclones occur in families of three or four formed successively a little farther south at intervals of about twenty-four hours.

Behind the last member of the family the cold front is brought into the sub-tropical, high-pressure belt and destroyed. The polar air moves into the tropics as a very shallow, subsiding mass of cool air which becomes transformed by convection from the warm sea into typically tropical air. A large extent of the polar front thus becomes broken near the surface, allowing the exchange of polar and tropical air. In the middle atmosphere the front is preserved in mid-latitudes, and by processes which are not properly understood, extends down to the surface to form a new surface polar front on which renewed cyclone development occurs. In the high troposphere the polar front is from time to time analogously deformed and destroyed as large masses of tropical air surge into high latitudes, are cut off and slowly cool and sink, becoming transformed into polar air masses.

Anticyclones

Anticyclones are regions of high surface pressure around which the winds circulate in the sense (clockwise in the northern hemisphere) opposite to the circulation around cyclones; they were discovered by Sir Francis Galton in 1863, before isobars were drawn on weather maps.

The sub-tropical, high-pressure belt is composed of three or four great and persistent anticyclones; other stationary anticyclones form over the cold land masses in winter, for example, over Greenland and Siberia. In polar- and mid-latitudes travelling anticyclones are found, but they are not as common as the cyclones, which are usually separated merely by *ridges* of higher pressure where domes of polar air have nosed towards the tropics, and which only occasionally develop the closed isobars of an anticyclone. In general, anticyclones are reluctant to travel, and often their decay sets in when they begin to move. New anticyclones are most often formed in high latitudes, especially on the eastern flank of a strong poleward surge of tropical air in the upper troposphere ahead of a deep, slow-moving cyclone. In winter these intense cyclones tend to appear south of the Aleutian Islands and Iceland, and consequently the principal breeding-grounds of polar anticyclones are found over Alaska and Scandinavia. Once formed these anticyclones often become intense and persist for a week or more, during which period the atmospheric flow is greatly distorted into *meridional* rather than *zonal* currents, strong southerlies occurring on the western flank of the anticyclone and northerlies on its eastern side. The formation of such anticyclones over Scandinavia is responsible for the worst cold spells in British winters, cold surface air from the north of Europe and Russia arriving in Britain as bitter easterly winds. Over the Atlantic the cyclone paths are diverted, and on the northern fringes of storms passing into the Mediterranean there may be heavy snowfalls over England and the north of France. Eventually, however, these anticyclones begin to move and decline, tending to shift south-eastward or merge with the Siberian anticyclone, and a more zonal air flow is established which brings a welcome return of oceanic air across Britain.

In the central parts of anticyclones the weather is fair; the air of the middle troposphere subsides gently at the rate of several hundred feet a day to feed the diverging surface currents, and consequently the sky is usually free of upper clouds. In summer, over land, small convection clouds may form during the day, but in winter, where the cold currents leaving the Continent travel over the warmer sea, a layer of low strato-cumulus cloud forms and causes an 'anticyclone gloom' in great contrast to the brilliant sunshine which the airman can bask in 2,000 or 3,000 feet above the ground.

The complexity of the weather patterns

We have briefly described some of the characteristic features of cyclones and anticyclones—the disturbances of extra-tropical weather; but it would be a mistake to think of the weather patterns which we recognise as *typical* to be also the most common. The daily weather maps show us an ever-changing kaleidoscope in which exactly the same patterns never occur twice. Over some regions typical cyclones may be forming on a well-defined polar front, but elsewhere the front may be diffuse and difficult to detect; it may be dissolving, and reforming in another latitude. Over some areas subsidiary fronts, produced along a sharp temperature-contrast where the warm ocean lies along the coast of an ice-covered land mass, develop minor disturbances which complicate the patterns. Mountain barriers lie as obstacles in the path of the air currents, causing them to distort, and generating new disturbances. Tropical storms curve away from the equator and enter mid-latitudes as cyclones of unusual structure, while other cyclones form in currents of deep polar air, far from any recognisable front. On a small scale a number of troughs of low pressure and ill-defined bad-weather systems are seen, especially in thundery summer weather, whose relation to the major systems remains obscure.

Of this bewildering complexity only the largest features are at all adequately defined by the weather forecaster's information; and in his work, unarmed with any clear physical understanding of it all, he is obliged to rely on continuing its recent trend into the next day or two. His task will be discussed in Chapters V and VI. In Chapter III we shall examine the nature of the complexity itself.

THE FORMATION OF CLOUDS AND RAIN

The formation of cloud

If water-vapour, or air containing it, is cooled sufficiently, then some of the vapour condenses into a cloud of small droplets. We see this happen every day when hot vapour is expelled from a steam locomotive or a boiling kettle, and then chilled as it mixes with cool air.

In the larger-scale atmospheric motions, however, such cooling by mixing is not an important cause of cloud formations, for here the temperature differences between neighbouring volumes of damp air are so small that even if there were some means of mixing them thoroughly, at most only a thin mist could be produced. In the atmosphere clouds are formed by the cooling to which rising air is subjected. Even the very dry air of the deserts will become cloud-filled if it is lifted some

10,000 feet; over the sea a rise of more than 2,000 or 3,000 feet is rarely necessary.

If the air were perfectly clean, then a further rise of several thousand feet would be required to produce cloud, but actually it always contains numbers of small motes upon which the water-vapour can readily condense. The motes which are effective are much smaller and more numerous than the dust particles which we can see floating in sunbeams. They consist of all kinds of material; much of it is surface detritus blown up into the air over the land, but there are also salt particles from sea-spray, and in the polluted air of industrial regions there are enormous numbers of smuts and very tiny droplets containing various kinds of chemicals. Some of these help the condensation of vapour more than others, and usually during the formation of a cloud only the best grow into the cloud droplets. Consequently we find that in natural clouds the concentration of droplets varies little from a number corresponding to 1,000 or 2,000 in a thimble-full of air, although there may be many millions of motes which could serve as *condensation nuclei* if they were called upon.

The quantity of vapour condensed in a cloud depends mainly upon the extent to which the cooling is prolonged after its formation, and also upon the temperature: for the same amount of additional cooling a cloud at tropical temperatures is several times denser than one formed at temperatures around the freezing point. Inside a thick cloud there is usually enough condensed water in each cubic foot of air to make about a dozen small raindrops.

The causes of cloud formation

The physics of clouds is not yet well advanced, because it rests on a study of the vertical motions in the atmosphere, perhaps the most difficult and fundamental of all meteorological studies. Clouds can be classified into four kinds according to the ascending motions which cause them.

1. *Convection clouds*

The cumulus clouds which appear over sun-warmed ground are formed in *convection* currents, and the height at which they form agrees almost exactly with the calculated rise which would be necessary to produce cloud in the air near the surface. The up-currents evidently mostly originate at the surface. In and beneath the cumulus they have speeds of several feet a second, and so are strong enough to lift gliders, as will be discussed in Chapter IV. Sometimes, when the cumulus grow into thunder clouds, the up-currents are very strong, reaching even 100 feet a second.

2. *Orographic clouds*

Ascending motions are often, if not always, present when air flows over hills. Even over small hills these motions may affect the air in the cirrus levels, and when they are sufficiently pronounced they produce clouds which remain almost stationary, although a strong wind may be blowing. These clouds often have very smooth outlines and are called *lenticular* (lens-shaped) or *wave* clouds. The up-currents which form them are also very useful to gliders, usually being quite as strong as those inside cumulus clouds.

3. *Layer clouds caused by stirring motions*

On a cloudless night the ground radiates heat into space and cools. If the air were motionless, only a very thin layer would be chilled by contact with the ground. In general, however, the lower layers of air are stirred by motion over the rough ground, and the chilling is distributed through a much greater depth. Consequently, when the air is damp or the night cooling is great, a fog several hundred feet deep may form, rather than a dew produced by condensation at the ground.

Fog may also form when an air current moves over progressively colder regions (for example, when tropical air flows northward over the oceans): the fogs frequently found off the coast of Newfoundland are produced in this way. When there is a fresh wind the fog lifts from the surface and becomes a *stratus* cloud. Such clouds have a very variable height and thickness, but are always within 1,000 or 2,000 feet of the ground.

4. *Layer clouds caused by widespread slow ascent*

The vast cloud systems of the mid-latitude cyclones and other large-scale disturbances are caused by a prolonged slow ascent which may extend throughout the whole depth of the troposphere and is most pronounced in the neighbourhood of fronts. Here the speed of ascent may reach about half a foot per second.

The principal kinds of rain

In many cloud systems more than one of the processes mentioned above may contribute to the formation of clouds, and afterwards others may complicate their structure. For example, a widespread slow ascent may cause the air to become so damp that orographic disturbances lead to the initial formation of cloud, and later convection currents may develop inside the cloud mass. Nevertheless, in spite of these complications, we can distinguish two fundamental kinds of cloud, the scattered *cumuliform clouds*, which contain strong up-currents (perhaps separated by down-currents), and the *layer clouds*, which are much more extensive but which contain only feeble upward motions.

These differences are reflected in the kinds of rain which form in the clouds. The big cumulus clouds produce brief, heavy rains called *showers*; the layer clouds produce a prolonged and steadier, but less intense rain. The *orographic* clouds do not quite fit into either class but, in general, are associated with the layer clouds; they represent localised regions of moderately strong up-currents, and contribute substantially to the intensification of the steady rains. This is a well-known feature of mountain weather.

The formation of rain in droplet clouds

Because the condensation nuclei have not all precisely the same properties, the droplets which grow upon them during the formation of a cloud have somewhat different sizes. The larger ones settle through the air more rapidly than their fellows, and so collide with them. Not all those droplets which lie in the path of a large droplet are actually hit by it—some are carried aside by the air—but each collision is followed by a coalescence of the droplets, and so as time goes on larger and larger droplets are produced by this sweeping up of the smaller.

If this process is continued long enough drizzle drops and finally raindrops are produced. The study of rain formation is therefore resolved into consideration of the rate at which droplets can grow by this sweeping process, and of the large-scale properties of clouds, which determine whether the process is allowed to continue to the stage at which raindrops are produced.

In general, the rate at which a drop grows by sweeping up others increases the larger it becomes, so that those which were biggest when the cloud first formed are those which have the best chance of becoming raindrops. Even these may not succeed, however; for example, they may settle out of a very thin cloud before they have reached the size even of drizzle drops, and then evaporate in the drier air beneath.

The theory of these effects is not yet complete, but does indicate that if rain is to fall from a cloud it must be at least several thousand feet thick. The required depth depends upon several factors, such as the size-spread of the first-formed droplets, the strength and duration of the up-current inside the cloud; and the general temperature. Variations in these factors are important: it appears, for example, that sometimes a shower may fall from a small cumulus cloud perhaps only 5,000 feet deep, while at other times no rain forms in clouds five or six times as big.

It seems that rain forms rather more readily over the oceans, especially in the tropics. We believe that this is because of the comparative scarcity of condensation nuclei in the clean sea air, and also because the amount of water-vapour which is condensed during the rise of cloudy air is greater the higher is the temperature at which the cloud formed. These factors lead to the formation of rather large droplets in even the early stages of the growth of tropical clouds. In these regions it is quite common for heavy rains to fall from clouds which do not extend up to heights where the temperature is below freezing (above about 15,000 feet). Outside the tropics, however, clouds deep enough to produce rain almost always reach well above the level of freezing temperature, which here is often below 10,000 feet, and falls close to the ground in the colder weather. At least the tops of the clouds then have a temperature below the freezing point, and may contain ice crystals. The appearance of these crystals may quickly lead to the production of snow, hail or rain; indeed, until recently it was thought that they were responsible for all the rain which falls in regions away from the tropics.

The formation of ice crystals

Except perhaps at very low temperatures, ice crystals form by the freezing of droplets. A lake or a brook freezes when its temperature falls below 0° C., the 'freezing point', but in the laboratory it is usually difficult to freeze the smaller quantities of water held in beakers and tubes until the temperature has fallen several more degrees, and most of the tiny droplets in clouds do not freeze until the temperature is far lower. The number of crystals formed in a cloud apparently increases steadily as the temperature falls, but at first they are always far fewer than the droplets. At temperatures below −40° C. all droplets, as far as we know, freeze almost as soon as they have formed.

The formation of rain by the growth of ice crystals

At temperatures below 0° C. vapour condenses much more rapidly upon a crystal than upon a droplet. Consequently the first crystals to appear in clouds can soon grow to a size at which they begin to sweep up the cloud droplets very rapidly. Each droplet freezes as it is caught and touches the ice surface, and so the crystal soon develops into a pellet of frozen droplets and perhaps eventually into a hailstone, which may melt into a large raindrop before reaching the ground.

In the *shower clouds* of temperate and polar regions this violent initial growth of the crystals allows them to catch up, and often to outstrip the largest droplets in the race to produce a shower, although these droplets began their growth by sweeping when the cloud first formed, some time before it reached up into a region cold enough for crystal formation. If a shower is produced, it is therefore largely or wholly the ice crystals which are responsible. Often the cloud reaches high into colder regions where so many more crystals form that the share of droplets to be swept up by each becomes too small for any even to approach the size of hailstones. These surplus crystals are left floating as a fibrous crown of 'anvil cirrus', which reveals the occurrence of the shower to a far-off observer. In cold weather they may eventually reach the ground as a snow shower.

The extensive thick *layer clouds* of cyclonic storms in general contain much less water in the form of droplets than shower clouds, and ice crystals inside the upper layers grow more by condensation from the vapour than by sweeping up droplets, slowly developing into snow crystals of diverse shapes. In the lower cloud levels they melt into the rather small raindrops of the steady cyclonic rains. They may grow considerably larger where they fall through low-level wave clouds produced by hills, for these 'feeder clouds' contain strong up-currents to prolong descent of raindrops, and provide additional supplies of droplets for them to collect.

In low-level layer clouds a few thousand feet thick, such as are found in the warm sectors of cyclones, the growth of droplets by the sweeping process often produces *drizzle*. In temperate and polar regions the thicker layer clouds from which real rain falls almost always extend up into levels where it is cold enough for crystal formation and the development of snow. Practically all of this rain may therefore be regarded as melted snow, but possibly nearly as much might fall as a very heavy drizzle if crystal-formation could be prevented, and in the tropics it is likely that moderate rains of this kind often fall from thick layer clouds which do not reach the levels of freezing temperatures.

CHAPTER III

THE TURBULENT ATMOSPHERE

"*It remains to call attention to the chief outstanding difficulty of our subject.*"

Sir Horace Lamb.

THE IDEA OF TURBULENCE

THE atmosphere is a fluid. The engineer can specify the positions and shapes of the rods, wheels and plates in his machines; but the meteorologist must always approximate, usually very crudely, in describing the behaviour of the atmosphere. In making a machine the design is kept within the comprehension of man: the atmosphere, on the other hand, is infinitely complicated. Many other scientists face equally difficult problems, but in most of his researches the meteorologist has the atmosphere for his laboratory and he has far less control over his experiments. The geologist and the astronomer are also concerned very much with the scene as they find it, but they are not compelled to keep such an intense and world-wide watch as the meteorological services who may see gale or flood spring up in a few hours.

We never know enough about the weather for practical purposes, and observers the world over are ever increasing their records of it with newer and better instruments. Where will this lead us? Will the accumulated observations soon overwhelm us and become so complicated and vast an array that they are beyond our comprehension? Seen in this way the task of understanding the weather satisfactorily seems impossible. Scientists are accustomed to thinking in terms of concepts, which are precisely, and often simply, defined; but the atmosphere seems to elude such description. It is a unique thing: in the study of it we know that the material of which it is composed will obey laws discovered by physicists and chemists, but the real problem is its behaviour—not the properties of gases, of water-vapour, of ice crystals and so on, which can be studied in the laboratory, but of the particular gaseous envelope of our own special earth with the oceans, mountains and plains as we find them.

Whatever the advances in theoretical techniques or in our knowledge of the laws of nature may be the study and forecasting of the weather depends absolutely upon observing what our atmosphere actually does; but there is no point in accumulating records that will never be inspected and we must determine somehow what is worth measuring and recording, and what is not. If we can do this we shall at the same time develop a new philosophy of observing and thinking about the behaviour of our atmosphere.

Its complexity is best illustrated by the behaviour of the wind, and to this we now give our attention.

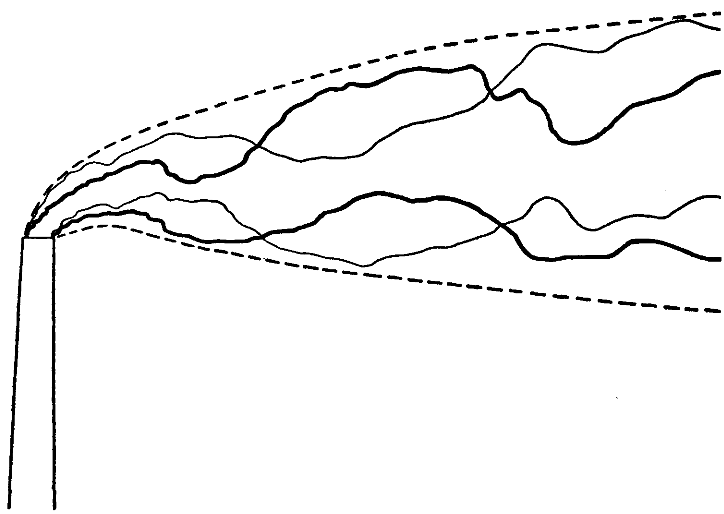


FIG. 6. *The behaviour of a smoke plume: the heavy lines indicate the outline of the plume at one moment, the light lines at another; the dotted lines indicate the limits within which the plume wanders during an hour.*

Large and small eddies

The smoke issuing from a tall chimney forms a plume which widens as it is carried away by the wind. This is represented diagrammatically in Fig. 6, where two heavy full lines represent the limits of the smoke at one instant. These two lines diverge as the smoke is mixed with an ever-increasing volume of the surrounding air. Ultimately the smoke becomes so dilute that it is invisible, but let us imagine that we can still trace the outline as far as we like by means of a pollution-measuring instrument.

At a later instant the plume, though very much the same in general appearance, is in a different position, represented by the thin full lines. Thus, as the plume widens it also wanders, and we can represent the bounds within which it wanders during an hour by the two dotted lines.

If we now watch the plume from above it will look very much the same, but during a day these dotted lines may swing round from the position 1 (Fig. 7) in the morning to the position 2 in the evening, as the wind veers from WSW. to NW.

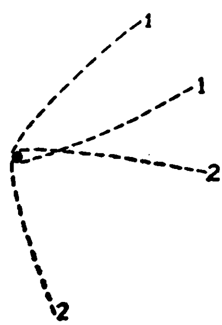


FIG. 7. *Seen from above during one hour the plume wanders between the lines 1-1 but during another hour later on the same day it may oscillate between the lines 2-2.*

Besides widening and wandering, therefore, the plume swings around the points of the compass and we cannot set boundaries to the region polluted within a year, because the plume will have been found lying in any direction at some time or other. We can then resort to drawing lines of equal pollution round the chimney. These will show the total pollution during some specified time. For October the total pollution would, perhaps, be predominantly to the ENE. because the prevailing wind is from the WSW., while in January, east winds being more common, points to the west would receive more smoke (Fig. 8). For an average over, say, forty years, all wind directions would be represented according to their occurrence but two periods of forty years would not necessarily yield the same lines. Did not our grandfathers recall that in their youth those biting east winds of winter were more common and severe? Is it an increase of the warm south-westerlies that has melted the glaciers of

Scandinavia so remarkably in the last two generations? Have not the rainbearing winds that made North Africa the Roman granary ceased to blow, and is the mild weather that enabled the Vikings to explore Greenland and America now returning after centuries of ice and snow?

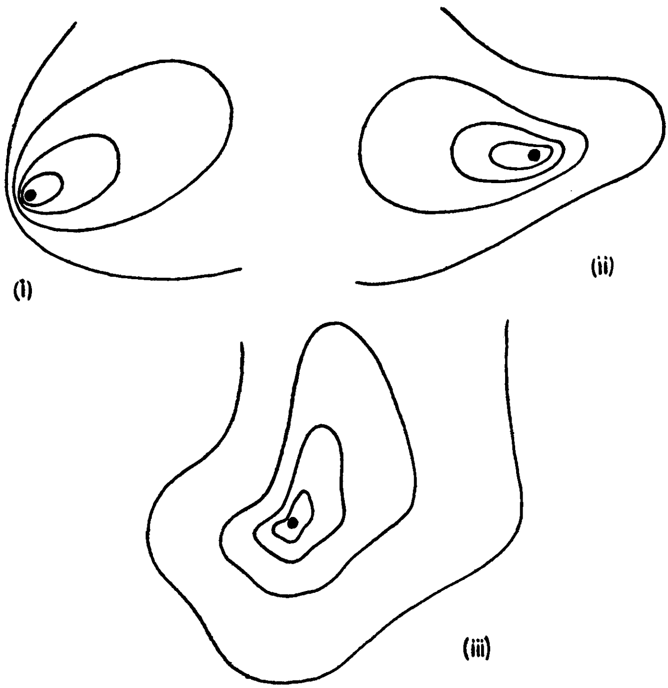


FIG. 8. *Lines of equal pollution from a chimney:* (i) *during an October with predominantly west-southwesterly winds,* (ii) *during a January with predominantly easterly winds,* (iii) *during a period of 40 years.*

These changes of long period would be evident in changes of a map like Fig. 8 for a chimney that we may imagine to have existed through the ages, and we may extend the idea back through all the geological eras with their heat and cold, their windswept deserts and luxuriant forests.

As we proceed to each longer period the representation of our smoke plume becomes less detailed. Thus at first we drew dotted lines in Fig. 6 to include the smaller wanderings; while in

Fig. 7 we drew only the limits within which the plume moved during an hour, and in Fig. 8 these hourly variations are not recorded and we only distinguish between the characteristics of different months. The motion which causes the dispersal of the smoke may be analysed into *eddies* of various magnitudes. A large eddy is one which causes a change to occur during a long *period* of time. Thus the eddies which cause the smoke plume to be crooked (Fig. 6) are smaller than the eddy which causes the movement of the polluted region from position 1 to position 2 in Fig. 7. The plume is crooked because of whirls of air and changes of wind which we can feel with our hands and faces—gusts of wind which last only a few moments, carrying the smoke first this way then that. The changes during the day may be due to a cyclone passing nearby. The cyclone may be 1,000 miles across, 20,000 times the *size* of the wobbles in the plume.

These eddies may be measured either by their period, that is, the time they take to pass a point of observation, or by their size. Sometimes it is convenient to think of them one way rather than the other. An eddy of small size may last a long time, and if we happen to be in it for a long time it may justly be regarded by us as large.

Using this idea of eddies having a time dimension we may regard the seasonal changes and even ice ages, and perhaps even the history of our planet, as eddies within some greater age, and so none of the changes studied by meteorologists is too big to be thought of as an eddy.

How small can eddies be? If we examine the smoke plume close to the chimney it is seen to have lumps all over its outside, and the smoke in these lumps is swirling round violently. These lumps are eddies that are mixing the effluent gases with the surrounding air and causing the plume to widen as it wanders. On a close examination each of these eddies is seen to contain many smaller ones, just as they themselves are contained in one of the bends of the plume. There is no limit to the minuteness with which we can analyse the motion until we come down to the very molecules, which may be regarded as the smallest kind of eddy that can exist.

Whirls can be found of every size we are capable of observing. They are mixed up among each other in a scene of indescribable chaos: the air is stirred and shuffled unceasingly. In order to comprehend this scene we must fix our attention on a few important characteristics of the motion and its effects, and we shall then find new significance in it. First, we examine one of the most important results of the motion, namely, diffusion.

Diffusion

This is a process whereby particles or molecules that are contained in a fluid are transferred from one place to another without any bulk transfer of the fluid. Thus, cigarette smoke is diffused by means of tiny eddies throughout a room in which the air as a whole may be calm, there being no steady draughts or circulations. A puff of smoke is seen to expand and become steadily more dilute until after a few minutes the whole room is slightly smoky. Small 'lumps' of air containing smoke are carried by small eddies in among clean air and there still smaller eddies break each 'lump' up into ever more minute fragments until the smoke appears to be almost uniformly mixed into the air. The motion does not then stop, but because it is now uniformly spread, the motion has no further effect on the smoke, but may, nevertheless, at that same moment be diffusing the smell of a bottle of scent that has only just been opened.

The motion of the molecules causes some diffusion but it is not as effective as small eddies. We cannot go to the extreme and say the larger the eddies the more effective they are as agents of diffusion, because they may not have any effect at all. If we create a puff of smoke 10 yards across it will spread on account of the diffusing power of eddies less than about a yard across, but the very large eddies will simply carry the puff of smoke along as a whole and not alter its appearance at all. The eddies, which are about the same size as the puff itself, cannot be said to diffuse the smoke, because they will break the puff up into two or three pieces which we can see and comprehend easily. The process is only called diffusion when very many eddies, and pieces, are involved. It is necessarily too complicated for us to describe the motion in detail in the time available for studying the problem. Though, in theory, it would be possible to describe the motion of every molecule and see how the smoke was carried from place to place, life is too short; and we are content with any description of the process that will lead us to the conclusion we want. In many cases, therefore, we shall be concerned with these eddies only in so far as they are able to transfer something contained in the air from one place to another without there being a general drift of the air in that direction. Usually, as in the case of smoke, the something is carried from places where it is abundant to where it is not.

Many things are diffused besides smoke. Heat is carried upwards to the higher levels of air from the hot ground on a sunny day. Water-vapour likewise coming off the damp ground is diffused upwards to form clouds. The momentum of a strong wind is diffused downwards to the ground, and the force that the wind exerts on objects fixed to the ground is evidence of a continuous supply of momentum from the air to the ground. On a larger scale, cyclones are eddies which transfer heat from the equatorial regions towards the poles; on a smaller scale, the tiny eddies diffuse the smell of flowers on a calm summer evening.

Cyclones are agents of diffusion only if we are dealing with a problem in which many of them operate, such as the annual transfer of heat to the polar regions. For most purposes, ordinary forecasting for instance, cyclones are examined individually, for we are interested in the winds and rain that each one produces.

In order to speak of diffusion, therefore, we must first have a large number of the eddies and then examine them only for their effects in large numbers, and this depends as much on our problem as on the actual motion of the atmosphere.

Since the whole motion does not produce diffusion, we are now in a position to separate part of it and give it a name.

Definition of turbulence

Turbulence is that part of the motion which causes diffusion.[1]

Let us see what this means in the case of the smoke plume and our diagrams of the pollution. In Fig. 2 we are concerned

[1] Those who work in the study of turbulence do not usually find it necessary to define the word, because their analysis makes it plain what they are doing. No mathematical symbol is used for turbulence and this is one reason why a definition is not required. Frequently, however, the word is employed to refer to 'that part of the motion which I do not know anything about' or to 'that part of the motion which produces effects I cannot understand'. It is to avoid the unproductive discussions that ensue that turbulence is precisely defined here.

with the plume for a few minutes, while it widens out and wanders a little. The motion of the molecules and the tiniest eddies are too small to produce any observable effect. The eddies shown up by the lumpiness of the plume compose a turbulence which widens the plume; they cause the smoke emitted at one moment to extend over a wider area at a later moment. The eddies which make the widening plume wander compose a turbulence which distributes the pollution over the region between the dotted lines during a few minutes. In this diagram no bigger eddies are considered. The wind which is there seen to blow from left to right is, perhaps, due to a cyclone, and the variations of wind as 10 or 15 such cyclones pass produce the pollution for October of Fig. 8. In this figure, therefore, the cyclones compose a form of turbulence, and in the diagram for forty years the fluctuations that take a year are also agents of turbulence.

In dealing with turbulence the eddies are always treated in large numbers. It is because there are so many of them in the problem that they are not treated individually. Some effect of large numbers of them—some *statistic* obtained by putting together their separate effects—is what we measure and discuss. Turbulence has thus come to mean those characteristics of the motion which we only study statistically.

It is unfortunate that the word is also often used to refer to some different kind of effect of a large number of eddies. It would really be better to describe the effect itself. Thus a pilot flying through a large cumulonimbus cloud at 300 m.p.h. might describe the air as extremely turbulent, because he was thrown violently first up and then down in quick succession several times as he passes through several up- and down-currents. 'Bumpiness' is a better description, because it implies more accurately what was experienced. A glider pilot, circling at 30 m.p.h. within one up-current inside the same cloud could find his flight extremely smooth. The 'turbulence' experienced by the first pilot is due to his own large velocity, and there may be no appreciable diffusion of the cloud due to the eddies that concerned him. The smaller ones that were causing diffusion he probably did not notice.

It is next necessary to examine the circumstances under which it would be possible to separate the turbulence from the rest of the motion, and after this we shall see how the separation can be achieved in practice.

THE IDEA DEVELOPED

The spectrum of eddies

We have been arguing somewhat hypothetically so far. It is necessary to have some way of representing the relative importance of the eddies of various magnitudes. First, we arrange the eddies according to their period—the time taken to pass some fixed observation point. We then represent their importance by the wind velocities they produce. This is only one way in which we can sort them out, but it is a convenient one to discuss. A curve is then obtained by plotting on graph paper the velocity against the period, as in Fig. 9. Thus the point A

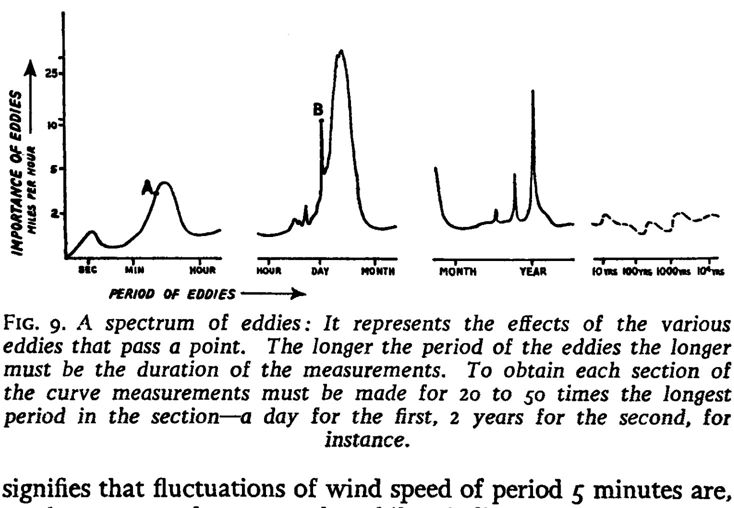


FIG. 9. *A spectrum of eddies: It represents the effects of the various eddies that pass a point. The longer the period of the eddies the longer must be the duration of the measurements. To obtain each section of the curve measurements must be made for 20 to 50 times the longest period in the section—a day for the first, 2 years for the second, for instance.*

signifies that fluctuations of wind speed of period 5 minutes are, on the average, about 3 m.p.h., while B indicates that the average daily variation is 12 m.p.h. This, the eddy spectrum, refers only to one observation point. As we shall see, places near the coast, near cliffs or woods, in valleys or in towns, will all have their own peculiar spectra; but all will possess some characteristics in common, and we shall see the importance of these in the rest of this chapter.

In order to obtain a spectrum like Fig. 9, observations must be made for a time long enough to contain several eddies of every period. For this reason the spectrum is broken up into sections in an arbitrary manner. To find out what is the average magnitude of the annual wind fluctuations, that is of the fluctuations of period one year, the wind must be measured for several years; while it is scarcely a worthwhile occupation to measure the fluctuations of period one second for several years and then analyse them all. We wish to know what these very short period fluctuations are in various seasons and at various times of day; and on a calm night they will be less than in a strong wind. The annual variations would have been sampled only over a comparatively small number of periods—perhaps a hundred; but this is not because we are particularly interested in the fluctuations of the last century but because we have no other recorded observations.

Fig. 9, therefore, is only a sample spectrum. It does not relate to any fixed behaviour of the atmosphere, nor does the whole spectrum relate to the whole of the same interval of time. The first part might be taken from a single day, the second from a year, and the third from a century; and the fourth is completely imagined, as far as we in this generation are concerned.

We shall see shortly what different kinds of instruments would be used in establishing the separate parts. Further, it will be evident that in organising any study of the weather we must have a fairly clear idea of what the spectrum is like for the extent and duration of our study.

What is a normal?

It has often been facetiously remarked that it is normal for the British climate to be abnormal. Can any of us remember a normal year? Scarcely a month passes without some freak of climate being blamed for catastrophe or failure. In weather, as in sport, new records are continually being set up; and we could, equally facetiously, say that a normal year would be so exceptional that it could not escape our notice. But could we recognise one? Do we know what a normal year is like?

It is practice nowadays to define the normal, of rainfall for instance, as the average over forty years. Thus a normal year would be one in which the rainfall happened to be about equal to that average. But a normal year would not necessarily contain normal months: a surfeit of rain in February might be cancelled by a dry August. We expect such variations and we might introduce another *statistic* besides the forty-year average to express the extent to which the distribution of rainfall over the months habitually varies from year to year. If this second statistic were incorporated into our definition of the normal it would give us a good idea of the variability of the climate, but we would not be able to use the normal as a reference value, which is one of the chief uses of the normal. When the weather forecast says 'weather will be warm for the time of year', it means that the temperature will be above the forty-year average for this time. In view of the great variability from year to year of all the elements of weather the normal need only be defined roughly, and although a forty-year average might be different from a fifty-year average, no one will notice the difference for practical purposes.

The variability of anything seems to grow as we get to know it. The British climate is very variable from some points of view but it is, on the other hand, subject to very few extremes compared with other places in the same latitude. We know a lot about it, and it seems complicated and difficult to forecast. Yet it is common for travellers to generalise about the climate in another land after only a short stay there. Sunny Khartoum, where there are six months of the year with scarcely a cloud in the sky, surely there, at least, weather forecasting is easy! Is it not normal all the time?

We find that it is so long as we enquire into no other details than cloud.

To plan a jet air liner service, run on a carefully planned schedule, requires that the weather at landing and take-off times be known in advance. The only serious problems are presented by the *haboobs*, sandstorms which sweep across the desert and bring life temporarily to a standstill, and the winds at 40,000 feet above the ground where the aircraft fly. They are as difficult as any problem in aviation forecasting. Previously no one worried much about the timing of the *haboobs*, and it is about as difficult as forecasting showers in Britain, but far more important. It was hoped that the wind at 40,000 feet would follow a fairly simple pattern—behave normally in fact—until measurements extensive enough to reveal its great variability were made. We now find that our theory is wanting and our observations are still too scanty for building up a reliable forecasting method. It is a complicated problem, and until some progress is made the making of a forecast is governed by a knowledge of what the normal is rather than by an understanding of how Nature chooses what wind to have on any particular day. Until we have collected many more observations we cannot be sure whether the idea of a normal is, or is not, a useful concept in this connection.

We would not attach much meaning to the normal weather of, say, 10th October in Britain, for in the unsettled weather usually experienced at that time of year it might equally be warm, cold, fine, or rainy. We can speak of the normal kind of weather for October with a little more significance, for we can usually tell the difference between October and June; but by reference to the weather alone we could not guess the date of a particular day with much confidence. The normal for the time of year has, therefore, some use. To obtain it we take the average over several years.

This procedure is possible because the annual cycle is so evident and dominates all others. We must next enquire whether the other fluctuations are due to enduring cyclic changes or to a confusion of variations. The daily changes provide the only other obvious cyclic ones. There are changes going on all the time which are just as large as the daily and yearly changes, but they do not occur with any regularity. In the spectrum, therefore, there are peaks at periods of one day and one year with no other such pronounced peaks. Only if a phenomenon is repeated many times we can speak of its normal behaviour, and for this reason the normals for the time of year or time of day are the only ones that are likely to have much significance. But every measurement is some sort of an average. The temperature is an average throughout some volume of air in which the thermometer has been exposed. A large wind vane indicates the average velocity of a greater volume of air than a small one. Have such averages any significance?

To answer this question we shall examine the nature of the measurements made by such instruments.

Gaps and peaks in the spectrum

Observations of wind speed will now be used to illustrate the argument, but almost any other meteorological element could be used—wind direction, pressure, temperature, humidity, cloudiness, and so on.

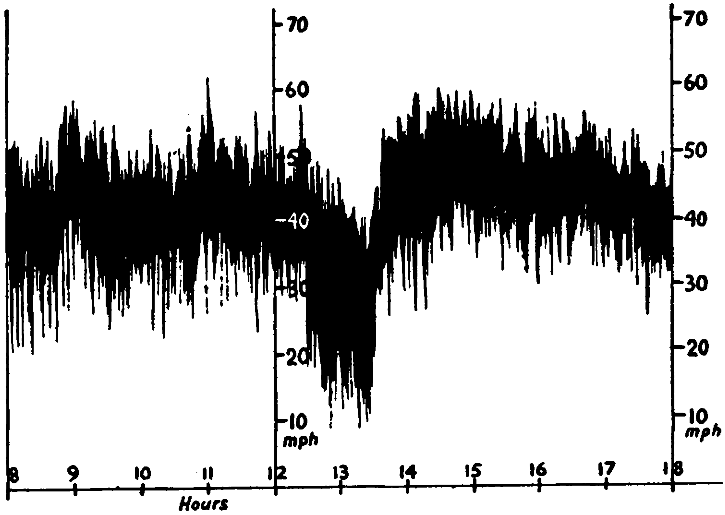


FIG. 10. *The wind fluctuations as recorded by a Dines' pressure tube anemometer.*

Fig. 10 shows the record of a Dines' pressure tube anemometer. It measures the wind speed in much the same way as an aircraft airspeed indicator, and records it by a pen on a rotating

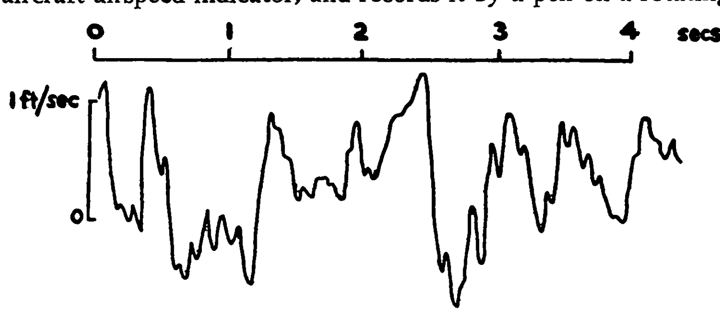


FIG. 11. *The wind fluctuations as recorded by a hot wire anemometer.*

drum. The inertia of the pen, its mounting, and the air within the apparatus, make it impossible for the instrument to record changes in wind speed whose duration is less than a second or two. The instrument thus records the average windspeed in the air that passes it during two or three seconds. The wind is seen to have fluctuated every minute or two by 5 m.p.h. or more, and the trace therefore appears fuzzy.

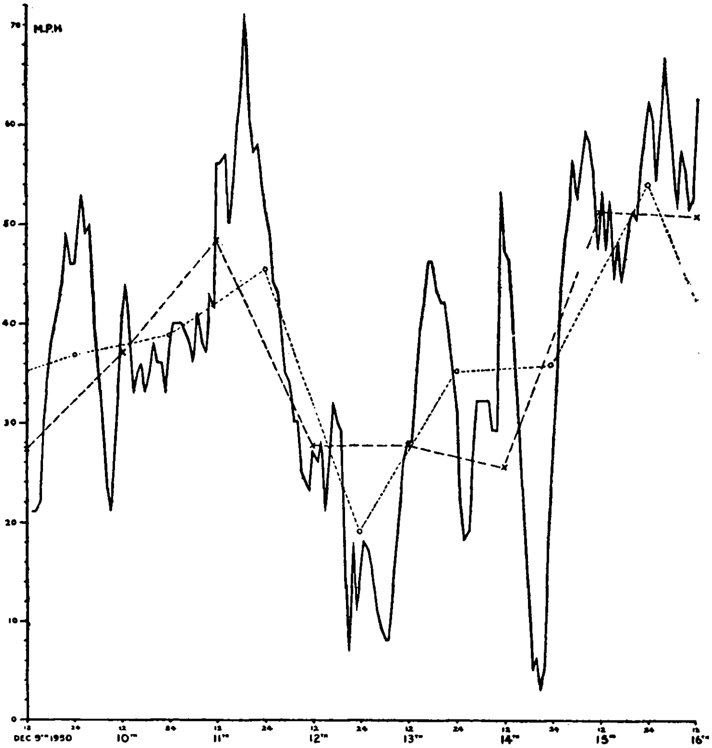


FIG. 12. *Average wind speed over successive hours as measured by a cup anemometer at Mynydd Mawr (from data in 'The Selection and Characteristics of Wind Power Sites', published by the Electrical Research Association). The continuous line shows the variations from hour to hour. The circles indicate the averages from noon to noon and the crosses the averages from midnight to midnight.*

Fig. 11 is the trace of a hot wire anemometer. This instrument consists of a fine platinum wire exposed to the wind. It is made hot by passing an electric current through it, and it is cooled more by a strong than by a weak wind. A measure of the wind is provided by the temperature of the wire, and this is deduced from its electrical resistance. The wire's thermal capacity is so small that it responds in a few thousandths of a second to changes of windspeed, and the resistance is measured virtually instantaneously by means of electronic amplifiers and is displayed on a cathode ray tube.

There is a remarkable similarity between Figs. 10 and 11. The main difference is in the time scale. We can imagine an instrument with much greater inertia presenting us with a similar trace, the chief difference being that the time scale would be marked in days instead of minutes or hundredths of a second. Fig. 12 gives this kind of information. It gives for a period of

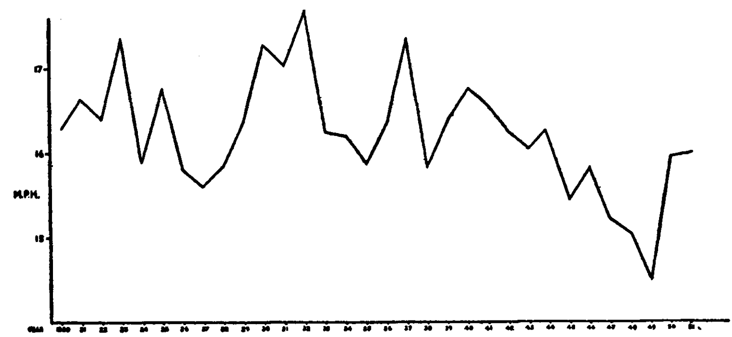


FIG. 13. *The average annual wind speed for successive years.*

a week the hourly run of wind past a cup anemometer in miles, that is the average hourly windspeed in miles per hour. The trace is not dissimilar, and if we draw, as in Fig. 13, the average annual windspeed for successive years we still see the same kind of irregular ups and downs. One thing, however, is noticeable: the range of variation of speed in Fig. 12 is much greater than in the others. The extremes are 3 and 73 m.p.h. For this reason we find on the spectrum (Fig. 9) that eddies with period from half to three or four days are of large magnitude. These eddies are the cyclones and other pressure systems that move across the oceans and continents, and they can be 'seen' passing in Fig. 12 as the wind increases and decreases.

If we wish to say what the wind was we must specify how long it was measured for. A single number cannot be used to represent the wind on 14th December (Fig. 12), because during that day the wind varied between 3 and 53 m.p.h. The crosses represent the average speeds from midnight to midnight and the circles the average from noon to noon. It is seen from the way in which the lines joining these points cross over each other that a single speed is not a good representation of the wind for twenty-four hours. The reason is simply that a period of twenty-four hours may include a large bit of one eddy, or perhaps one or two eddies, and according as to how the twenty-four hours is placed in relation to these passing eddies, the average speed is greatly increased or reduced. The two dotted lines are sometimes as much as 10 m.p.h. apart, and their failure to represent the windspeed satisfactorily arises because twenty-four hours is in the middle of a region where the spectrum curve is high (Fig. 9) and the number of eddies included in the sample period is not far from one—perhaps a half, perhaps two; but not a small fraction like $\frac{1}{50}$ or a large number like 20.

In view of this we might ask whether the hourly averages from which Fig. 12 was drawn have any real meaning. Would the figure have looked any different if the averages had been taken from thirty minutes past each hour to thirty minutes past the next? From the trace in Fig. 10 it is seen that although there are eddies whose period is not far from an hour they are not large: trends from one hour to the next are generally carried through to the hour following, and so the appearance of Fig. 12 would only be altered where it is very fuzzy: the big ups and downs would remain the same. We could guess this from the spectrum, for the eddies of period around one hour are of small amplitude.

We thus arrive at the following principle: in making measurements we should sample the air for a period for which the amplitude of the spectrum is small. In order to find out what the spectrum is like we should explore the air with an instrument which records eddies much smaller than we are likely to be concerned with.

To measure the wind at much closer instants, several times a minute for instance, it is necessary to find some period less than a minute at which the spectrum curve is low. In our example about ten seconds would be a good time-interval to choose, because there are large fluctuations of the order of a minute or two, and many others of the order of a second or two. In this way several of the smaller eddies are sampled and it does not matter much whether, say, 11 or 11½ are included. Of the larger eddies only a small part of one is included in ten seconds, and so successive measurements give a fair indication of their behaviour.

The principle cannot be applied to our complete satisfaction because there are never places in the spectrum where the amplitude descends to zero for a broad band of periods, but we can usually examine the atmosphere on a sufficiently minute scale. A Dines' anemometer, for instance, reveals all the eddies with which we would be concerned in the choosing of a wind-power site, because a large fan would be unaffected by the smaller eddies.

Annual variations require special treatment. At one year there is a peak in the spectrum but it is an isolated narrow one. It represents a regular pulsation and the year is therefore a convenient interval for taking averages over. The annual run of wind has some significance, because the year is a lone period. The daily variations, on the other hand, are obscured by the eddies of period just less than or just more than a day. In an attempt to describe the annual pulsation of the weather, meteorologists usually take average values over successive months. The variation from month to month then portrays the seasons. Some success is achieved, because at one month the spectrum is low: a month contains the passage of several cyclones, but it is at the same time only a small part of a year. Even so, we never expect normality from any month: 'February fill dyke' may be dry, we may have our 'November fogs' in January, and we may have floods in 'flaming June'.

The period of forty years used for obtaining normals is quite arbitrary. Our knowledge of the spectrum beyond about ten years is meagre and we must wait until more observations have been made. It does seem likely that there are no isolated peaks like the daily and yearly peaks. If there were, very long range forecasting of a kind would be possible. In fact, there is a broad band of periodicities which make the next century's weather as unpredictable as next month's. A more fruitful line of research would be to discover the astronomical causes for the long period changes: after all, we believe that the seasons will recur because we are acquainted with their cause.

Statistical theories of turbulence

Presented with this array of eddies the meteorologist's task is formidable indeed. Theories to deal with this kind of situation were developed mainly for problems of aerodynamics. We have defined turbulence as that part of the motion which causes diffusion; it therefore consists of the eddies which we deal with in large numbers. If our measurements are made using a low part of the spectrum, the motion due to all the eddies to the left in Fig. 9, that is of shorter period than the length of our sampling period, constitute the turbulence, and all the eddies to the right compose what is usually called the 'mean flow'. The changes in the mean flow are small during the period we are concerned with, while there are many turbulent eddies.

Statistical theories seek to represent the effect of the turbulent eddies by means of one, or perhaps two, statistics. The viscosity is such a statistic: for it represents the effect of the 'random' motion of the molecules on the mean motion of a fluid. A number enters into the equations of motion to represent the viscosity but it contains no information on how the viscosity is produced. The most famous such theory for turbulence is Prandtl's 'mixing length theory'. This idea is that if, for example, there is more smoke in one place than in another the eddies consist of small 'parcels' of air which start from a smoky region and move a distance l towards a smokeless region. They then mix into their new surroundings and thereby deliver up their excess smoke. At the same time 'parcels' of clear air are moving into the smoky region and diluting it. The distance l is called the 'mixing length' (somewhat inappropriately, because it is the distance travelled with no mixing). When l is large the smoke is diffused rapidly. Anything else that is carried by air can be diffused by the same mechanism whether it be water-vapour, momentum or heat.

It has often been argued that this theory predicts that all these different properties of air will be diffused in exactly the same way. This would certainly be true if the eddies were all of the same size and did behave as the theory supposed, but it was never believed that this was so. The idea of inventing this simple model of the turbulent process was to obtain some dynamical equations for the result. If it was found that the mixing length for smoke was greater than that for momentum the theory did not fail, as has often been argued by people advancing other theories; it simply meant that an eddy, or parcel, surrendered its smoke to its surroundings more slowly than its momentum.

In all cases the theory led to the most useful conclusion that the effect of the eddies was similar to the effect of viscosity already studied; and so the equations were familiar. Progress in applying this and other statistical theories to the atmosphere has been held up because there are no complete gaps in the spectrum, only periodicities where it is low. Furthermore, there is no single spectrum, and in order to separate the motion into a mean flow and turbulence the best time-interval to use, for sampling, may be one hour in one problem and twelve hours in another. The spectrum illustrated in Fig. 5 would not represent conditions in the region of the trade winds or the doldrums with any fidelity.

THE BEHAVIOUR OF EDDIES

The degeneration of eddies

As eddies collide or entwine each other some smaller and some larger eddies are formed. It is a law of nature that ordered energy does not arise from disordered energy spontaneously, and when two or more eddies interact in some way the result is generally a lot of smaller ones and only occasionally a bigger one. An analogy may be found in the railway shunting yard. If a group of six wagons collides with another group of six wagons and is at the same time linked to it, the energy of motion after is always less than before, and would be zero if the two groups were moving in opposite directions with the same speed. The energy becomes noise and heat, and the buffers and couplings become warm. If at the collision all the couplings were released the trucks would bounce back with various speeds, and though energy would be lost, less would be lost than if some of the couplings were held. But the energy would now be in smaller units.

The ultimate unit in the atmosphere is the molecule, and the size of eddies continually diminishes until only random motion of the molecules, that is heat, remains.

The birth of larger eddies is also inhibited by the presence of rigid surfaces which do not allow room for them (in particular, the ground has this effect). There is also a tendency all the time for the motion of a large number of eddies to produce up and down motion equal to the horizontal motion. But the presence of the ground and the stability of the air, which resists up and down motion, interfere with this. Furthermore, the atmosphere is only a shallow layer of air, effectively about 10 or 15 miles deep, and many of the eddies, such as cyclones, are virtually flat, being perhaps 1,000 miles across. These do not break up into a larger number of smaller flat ones but gradually slow down, at the same time producing many thousands of tiny ones as the wind of the cyclones is stirred up by trees and other obstacles on the ground.

There is thus a continual cascade of eddy motion from the larger to ever smaller eddies and eventually to heat. New eddies are created in a variety of ways with a great variety of sizes. All gradually degenerate. It has been calculated that if no new eddies were created, other than by the fragmentation of existing ones, the air would become practically calm in ten days. Very rarely does a single major feature of the atmospheric circulation remain for longer than this. Such features as the Azores anticyclone often dominate the airflow of their neighbourhood for much longer periods but this is either because a series of separate individual systems succeed one another in the same geographical position with only short breaks in between, or because the system is continuously supplied with new energy. From time to time even an apparently 'permanent' feature of the airflow disappears and is replaced for a short time by a quite different system.

Most of the energy of the present motion of the atmosphere has been converted from sunshine during the last four or five days and it is only because the conversion takes place in the same way over and over again that the flow of air seems to possess some permanent features. But the weather depends very much on the exact positions of the larger eddies which cannot be known more than two or three days in advance. Indeed, we probably know as much about the weather six months or six years hence as we do for two weeks hence. We shall return to this exciting, if at times rather hopeless, theme in later chapters.

The origin of new eddies

Eddies are produced in four ways. One is by the direct degeneration of larger ones. The second is similar in that small eddies are born from the energy of larger ones when 'the wind', that is the motion of a larger eddy, produces new eddies as it blows past solid objects, such as trees, buildings, hills and mountains. The third is by a process of redistribution of the

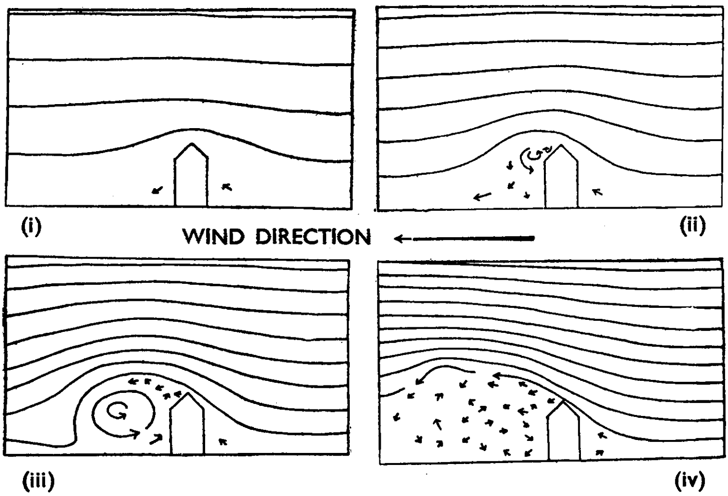


FIG. 14. *The airflow over a house:* (i) *in a light wind no eddies are formed,* (ii) *as the wind increases the air on the lee side becomes disturbed,* (iii) *a large standing eddy is formed at higher speeds, while* (iv) *in yet stronger winds the eddies break away and the disturbed conditions extend much farther downstream.*

momentum of existing eddies. This does not necessarily involve degeneration and loss of organised energy and would occur if there were no degeneration. It is akin to the combination and separation of whirls in a stream of water, and is a major concern of weather forecasters. Finally, eddies are created by convection. This is the basic process of the atmosphere. The sun heats some parts of the atmosphere more than others; the warm parts are less dense than the cold parts and tend to be displaced upwards by them.

The second of these processes may be called mechanical. It is the process at work in wind tunnels and around ships and aircraft, and has been widely studied for this reason. It produces the kind of turbulence to which the mixing length and other statistical theories have been mainly applied. Fig. 14 shows eddies being formed by a house. In (i) the air is moving slowly and only a slight effect is produced; (ii) and (iii) show the airflow in progressively stronger winds: the eddies grow larger, but even when they are as big as the house the effect of the house only extends downwind about three times its own height; in (iv) the wind is strong enough to carry away the eddies. The region in which the eddies are to be found is known as the *wake*, and in a strong wind this wake may extend downwind twenty to thirty times the height of the house. Beyond that any eddies are feeble.

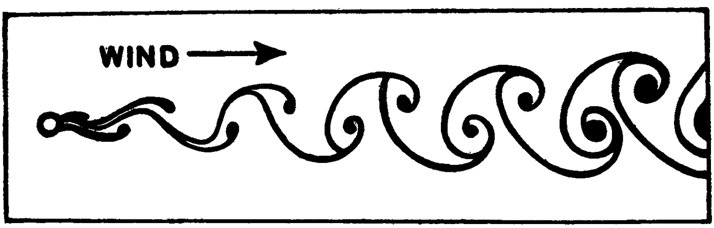


FIG. 15. *The formation of a 'Vortex Street' Eddies are shed first from one side then from the other. If the obstacle is not firmly fixed it will oscillate from side to side. Smoke emanating from the surface of a small cylinder shows how the vortices develop and move away in the air stream.*

Although the wind in the wake is more variable its strength at the ground is much less than outside. Wakes of hedges and trees, and even of wire fences, offer considerable protection to crops and stock.

A familiar example of the shedding of eddies is the singing of telephone wires. Owing to its symmetry, a wire sheds a series of eddies which rotate alternately in opposite directions, and form a *vortex street*, illustrated in Fig. 15. As the vortices are released a force is exerted on the wire, first to one side and then to the other. The wire is thus made to vibrate and give out a musical note.

Mountains are not able to produce an analogous effect in the form of mountain-sized eddies, but the air on the lee side is often very disturbed by smaller eddies. Large ranges are also responsible for the growth of cyclones on their lee side but these are

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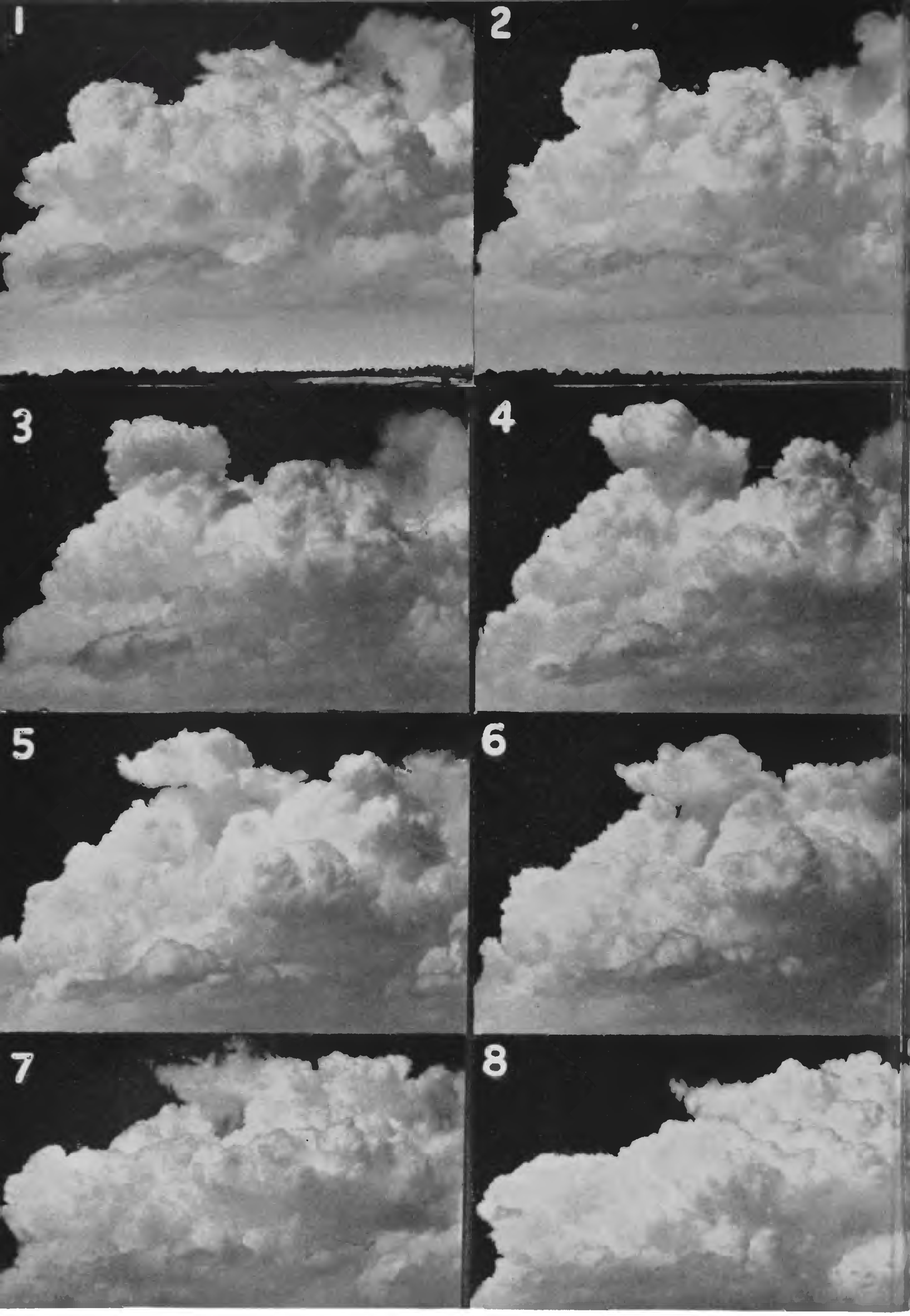
PLATE 5. *Lenticular (wave) clouds over the South Downs.*



[Photo by F. H. Ludlam

PLATE 6. *Photographs taken at intervals of 1½ minutes, showing the rise and fall of a cumulus tower.*

produced in a different manner and are not like the eddies of a wake. They depend very much on the shallowness of the atmosphere and the effects of stable stratification in a rather complicated way.

The smaller eddies produced by convection will be discussed more in Chapter IV. The larger ones are the now familiar cyclones and anticyclones.

The significant thing about all these eddies is that the creation of new ones is controlled by certain objects and relationships that define the atmospheric scene. Thus the eddy size depends very much on the length of the year and the day, the height of the tropopause, the sizes of continents, mountains, houses, and other physical objects. These things endure and are the machinery for producing eddies, which therefore tend to be the same over and over again. Some properties of the spectrum remain in spite of the vagaries of the weather and climate.

Outside the atmosphere there are causes of climatic change not properly understood and very much subjects of speculation. They can scarcely be said to produce eddies *in* the atmosphere; rather we would say that the earth is the plaything of cosmological eddies. Among possible influences are the tides in the sun, produced by the major planets, and the 'tunnelling' of the interstellar gas by the sun.

The results of turbulence

It has been shown that the effect of turbulence is diffusion of what the air contains from where it is abundant to where it is deficient. This is true in most cases, but not in all, for when a secondary influence is introduced besides the original cause of the turbulence, another property of the air may be transferred *towards* where it is abundant.

An obvious example is given by rain. Water-vapour is carried upwards by turbulence from the surface to higher layers in the atmosphere where it is less abundant. The condensation process interferes and contrives to deposit it back on the ground again, often in large quantities over a small area, producing floods. In this case the turbulence may gather the water from a large area and concentrate it on a small one.

If the turbulence is produced by convection, heat always travels to where it is least abundant. If it is produced mechanically, then it is momentum that travels towards where it is deficient. But in the former case the earth's rotation can interfere in such a way that momentum is carried in the opposite direction. This often happens in cyclones. Likewise, mechanically produced turbulence may carry heat downwards at the same time as other eddies, produced by convection and with the aid of the condensation process, are carrying it upwards.

THE EFFECT OF TURBULENCE ON THE STUDY OF THE ATMOSPHERE

Seeing order in chaos

It is in no spirit of apology for the frequent failure of weather forecasts that the complicated nature of atmospheric motion is described at such length. The implication is, rather, that the forecast is not simple to understand and use. Forecasting is not the meteorologist's only occupation, though it is the most publicised. One of his great achievements of recent years has been to discover that the turbulence is as important as any other process. When his information was scarce it was fitted into a simple model: as observations have been gathered many unjustified hopes for long-range weather forecasts have foundered.

The basic physical processes are fairly well understood: the laws of motion have been known for generations: the problem is of a new nature, one of complexity. Turbulence, in its simplest form as made in wind tunnels, has been studied with success and understanding only in the last twenty years, and a very specialised branch of aerodynamics has grown up as a result. The conditions studied can be very much to the choice of the research worker, and one of the great difficulties facing the meteorologist is that the processes with which he is concerned cannot be separated and abstracted. Their operation in the atmosphere is inextricably bound up with the special geography of the atmosphere and its surroundings.

If we were concerned with the atmosphere on a large enough scale all the eddies could be treated as turbulence by statistical methods; but it is the essence of the meteorological problem that we are interested in the minute details of individual large eddies.

We have seen how the meteorologist enters into the spectrum to gaze upwards as well as downwards at the eddies. We can expect, in the coming years, a new philosophy of turbulence and perhaps the recognition of a new kind of law of nature within the framework of which some simplicity will be given to processes which, by classical standards, are impossibly complex.

As an example of the change in outlook in recent years we may cite the idea of the *general circulation*. It was imagined that there existed a mean motion in the atmosphere which was maintained by the difference in heating between the equator and the poles, and which effected the main transfer of heat from one to the other. Eddies of all sizes were recognised to exist but were thought of as a kind of embroidery on the main pattern. The basic problem was to discover the nature of the general circulation and then the eddies would fall into place as agents of secondary processes. It is now recognised that the main processes in the general circulation are the turbulent ones: no garment exists beneath the embroidery. No single major transfer of heat is effected by a mean flow; eddies are the agents for all. This is of outstanding importance, because over most of the globe there is not a fine enough network of observations to reveal any but the largest eddies, and no one will dare to predict what new processes will be found at work when the whole globe is covered with reporting stations as densely as Europe or North America.

The limitations of our measurements

We have seen that an instrument should be designed so that the volume of air sampled by it is a small part of a large eddy and contains many small ones but avoids containing anywhere near one single eddy. To do this we should examine the eddy spectrum for regions where the amplitude is low and 'fit the instruments into' these regions. But this is not always a practical possibility. The problem of the radio-sonde illustrates this well.

The purpose of the radio-sonde is to obtain measurements of temperature, humidity and wind at all heights that can be reached by the balloon—up to about 60,000 feet. A small radio set transmits a series of musical notes which are received at the ground and converted into readings of temperature, humidity and pressure. The wind is measured by tracking the balloon by radar and finding how it is carried horizontally by the air through which it ascends. The rate of ascent is about 20 feet per second, and since the temperature decreases fairly rapidly upwards the thermometer element must be a small one, which takes up the temperature of the air passing round it in a few seconds, otherwise it will lag too far behind and record too high a temperature. If the balloon were made to ascend more slowly, in strong winds it would be carried so far from its ground station that by the time it reached high levels its signals would be too faint. In any case, it is desirable to have all the measurements made within an hour or so of each other. For all these reasons the thermometer samples a thin column of air a few inches across and 60,000 feet tall.

This is indeed a remarkable achievement, and these instruments have been a most valuable source of information about the upper atmosphere. But the atmosphere is lumpy: it contains eddies, many of which are from something like ½ to 20 miles across, and between 500 and 15,000 feet deep. In passing horizontally through these eddies the temperature varies by perhaps 3° F., and it is a matter of chance whether the balloon ascends through the warm or cool parts of them. In ascent through a large thundercloud the temperature measured may average 2° F. warmer than would have been measured outside, and this could have a serious effect on the calculations subsequently made from the observations.

In examining the temperature one item of interest is the rate at which it decreases as the balloon ascends. If it passes through the warm part of one eddy and then higher up passes through the cold part of another, the rate of decrease will appear large, while if it first passed through the cold part of one and then the warm part of another, the rate of decrease will appear very small.

It might be argued that the instrument is a bad one because it samples single eddies in this way. Either we should have several balloons ascending near to each other so that we should know exactly what the eddies were like and make our deductions accordingly, or we should use an aircraft to ascend in a wide spiral, measuring the temperature at each level over several miles instead of a few inches. By either of these techniques the great value of the radio-sonde—its cheapness—would be missed.

Perhaps it is best that meteorologists should be aware of the limitations of the instrument and make the most of the information that is obtained.

The same problem arises in measuring the wind. The measurement from the balloon is perhaps the only measurement made in a radius of several hundred miles. There is no method at present of finding out from one measurement what eddies exist. We can only hope that at great heights, where the observations are scarce and less easy to check by other methods, the eddies are fewer and less intense; but this may turn out to be a hope without foundation.

The surface pressure

The motion of the atmosphere is mainly horizontal: most of the time upward and downward accelerations are slight, and as a consequence, the air-pressure is equal to the weight of air above. This is true at any level, but the amount of air above 20,000 feet, say, can be added to or diminished by slow ascent or descent of air below. The ground, on the other hand, is a boundary to the movements of the air; the air must always remain above it. Thus if a cyclone-sized eddy exists between 20,000 and 40,000 feet above the ground, air may be moving into it or out of it and altering the pressure at 20,000 feet considerably. At the same time, another part of the same eddy between the surface and 20,000 feet may be bringing warmer or colder air underneath our observation point at 20,000 feet in such a way that the pressure at the surface changes very little. Not only may this happen, it usually does happen, in such a way that the changes in pressure at the surface are less than those taking place at higher levels. The reason for this is that the forces acting on the atmosphere as a whole are internal, while the forces acting on a shallow layer of the atmosphere are not produced within that layer alone but also by the action of the air above and below. The surface pressure is a quantity derived from the whole depth of the atmosphere and its variations are thus much less than the changes at 10,000 and 20,000 feet where the weight of only part is measured.

The importance of the atmospheric pressure at the ground has long been recognised, but when the great wind systems of the middle troposphere were first measured, meteorologists tended to pay more attention to them, and to look for the significant developments on charts of the upper air. It is something of a paradox that changes of the surface pressure, being a small residual left over from much more marked changes which nearly cancel each other out, should be so significant; but the idea is easier to grasp when we see that it is the added effect of several layers. The changes in pressure are important, because they represent changes in the atmosphere as a whole, not of one layer of it.

The 'cloud sized' eddies that make it impossible for a radiosonde to make a truly representative measurement are small enough for several of them to be found in one column of the atmosphere, and very seldom do they have a serious effect upon the surface pressure, because their separate effects are small compared with the major changes that occur in the surface pressure and they do not add to each other but tend to cancel each other out.

All other measurements made at the ground take a sample of air *at* the ground. The isotherms cannot be drawn on an ordinary weather chart, because the eddies of temperature are too small and are often smaller than the distance between reporting stations and cannot therefore be detected on the charts. The isobars, on the other hand, are found to be much more systematic, simply because the pressure is only seriously affected by the great eddies which affect all but the uppermost layers where the air is so tenuous that their motion has little influence on the air below.

The appearance of the sky

Most instruments take a single quantitative measurement of pressure, temperature, and so on, and until we can classify and represent it in numerical form an observation is of little value. If the sky looks threatening, and in fact some storm is imminent, it should be possible to describe what quality of the sky is significant and represent that quality by a number. Other numbers would be allotted to other qualities.

The clouds have been classified according to their appearance and are regularly reported according to an internationally agreed code. The variety of clouds is infinite and the classification must be based on a theory of how the weather is caused if the few categories chosen are to be useful and significant. The present system is based on the idea of *air masses*, and *fronts*—the boundaries between air masses. The nature of an air mass is revealed in part by the appearance of the clouds it contains and it is convenient and useful to divide the atmosphere up into discrete air masses in analysing the weather situation. They are found to extend often over areas thousands of miles across. At their boundaries frontal clouds are found and here also we meet much of the stormy weather found in temperate latitudes.

In recent years, since they came into general use, radio-sondes have, in spite of their limitations, provided the information on which the air mass analysis has been mainly based, and the system of cloud classification is no longer required primarily for this purpose. Without entering into any discussion of the classification, or the theories which inspired it, it is readily appreciated that new theories can lead to different aspects of cloud formation being regarded as the most important ones. The clouds give a three-dimensional picture of the condition of the air and the duration or transience of individual clouds can contribute a time dimension. It seems likely, therefore, that the cloud reporting system will eventually be modified to give information that can only be obtained economically from cloud observations.

Even if a system of indicating the turbulent motion were devised, it would be a difficult though not an insuperable task to teach it to observers throughout the world. When the sky is uniformly covered, or when only a few almost identical clouds are to be seen, it is easy to see what the sky contains. As it becomes more complicated greater experience and skill are required to interpret it. As with a piece of music or work of art, years of appreciation make possible a deeper analysis. The novice can pick out the tunes, the familiar objects—the cumulus: complicated symphonic effects and distorted shapes seem ugly or of no significance; a sky of broken, tangled, mixed and variable cloud is confusing, and a new understanding of the turbulence that created it is required. The operation of a single cloud-making process can be comprehended, but in nature many operate simultaneously, and in order to read the scene the language must be learned.

CHAPTER IV

EXPLOITING THE ATMOSPHERE

"Consider the lilies . . . they toil not neither do they spin."

THE property of the atmosphere that can most obviously be exploited is its motion. The motion is made up of two components, upward (or downward) and horizontal, and they are exploited in different ways. The motion is due originally to an uneven distribution of the input from the sun and loss to outer space of heat, and we examine first how the sun's heat, when it has been accepted by the ground, is conveyed upwards to the air above by thermal eddies.

THERMALS

The growth of up-currents

To glider pilots must go the credit of discovering how powerful are the convection currents produced when the ground is heated. Their word for them is *thermals*. The motion in a boiling pan of water is complicated enough, and if cine-photographs of cumulus clouds are speeded up about fifty times, their motion looks very similar, like writhing masses of smoke from a thousand bonfires. The reader must therefore be warned not to expect too much from some of the simple models and theories that are often given and which are only applicable in very special circumstances; but we can examine the various influences at work and see how they can each dominate the scene, or interfere, or combine together.

Heat passes through a solid body by conduction, but this is a very ineffective process in a gas compared with the transport of heat by the motion of hot and cold lumps of the gas itself. The heat of the ground is communicated to the lowest 5 or 10 feet of air mostly by radiation and by the smallest eddies. From there it is carried upwards mostly by convection currents.

A mass of air, perhaps as small as a shrub or as large as an elm tree, which has become warmer than the surrounding air, rises. As it rises it mixes all over its outside with the surrounding cooler air and keeps shedding its outer shell, leaving behind a wake of lukewarm air while the hotter air from inside goes on upwards. Very soon it is all mixed into the surroundings and all that is left is the lukewarm wake, four or five times the size of the original mass. Because this residue is slightly warmer than its surroundings, and is therefore rising slowly, all the while mixing more and more into the surroundings, for a time there is a region where, if a second tree-sized mass of hot air rises, it will be protected from the rigours of having to rise in unwarmed air. It will therefore rise farther than its predecessor and between them they will leave a wake perhaps ten or fifteen times the size of each.

Again, if another mass of hot air starts its ascent it will get a lot farther before it is thoroughly mixed into the surroundings, if it too follows the prepared path. Not only will it get farther this way, but if it leaves the ground near enough to the others and follows them soon enough it will be sucked into their wake.

In this way, provided we can keep up a supply of the tree-sized masses of hot air at the ground, this accumulated wake will grow even bigger. Other wakes may be growing near at hand and they will act on each other in much the same way as the tree-sized masses did. The larger and higher ones will draw the neighbouring small ones into them and grow yet higher. There is no obvious limit to this process except that set by the supply of heat to the air at the ground, or by an *inversion*. An inversion is a level at which the air no longer gets colder as we go higher, so that warm air may not rise beyond an inversion any more than oil, rising from the depths of water, will ascend above the water surface because, though lighter than water, it is heavier than air.

As the thermals rise higher and higher they become wider and more dilute, that is to say, there is less temperature difference between them and the surroundings through which they are ascending. Close to the ground thermals will be many and small, and may be 3° or 4° warmer than the rest of the air around them. The higher we go the larger they are found to be, but now they may be 1°, or less, warmer then the surroundings.

Larger thermals are a more efficient mechanism for carrying heat upwards, and although they have a smaller excess temperature, they may nevertheless rise as rapidly as the smaller hotter ones.

Keeping up the supply.

There are two conditions necessary for this process of growth to continue.

One is that the tree-sized thermals should be created in the first place; or that some at least should be created, though they could well be much larger than a tree. This is brought about by the non-uniformity of the ground, through the agency of roads, houses, fields, varieties of crops and soils, bare rocks, lakes, woods, concrete runways, gasworks, railway yards, and so on; for each of these kinds of surface acquires its own peculiar temperature in the same sunshine. The thermals rise from the hotter spots.

The temperature which the ground reaches depends not only on its colour or on chemical processes, such as in vegetation, or even on the evaporation of water drawn up through the roots, but also on the conductivity and thermal capacity of the surface. A metal surface in strong sunshine feels hot, not only because it is hot, but also because the reservoir of heat within it can be rapidly tapped, metal being a good conductor of heat. Just as it can deliver up a lot of heat rapidly to one's hand so it can to the air. A stone or concrete surface behaves likewise, whereas dry sand or chalk is relatively ineffective.

But this cannot be carried too far, for if a good conductor is deep the heat is carried into its depths and it can only warm up slowly. Thus, wet clay being deep never gets as hot as the thin metal of a motor-car body, which often becomes too hot to touch in the sunshine. On the other hand, chalk may warm up readily.

This is not all, however, for a far greater effect is produced over patches of higher ground. They have a start, and give the heat to the air higher up to begin with, and just as cold air drains downhill warm air drains uphill and comes off the top of a hill either as a continuous stream or in lumps. This draining of air from the surrounding countryside enables a hill to keep up a steady supply of hot air. Cumulus clouds which form at the top of thermals when they reach high enough nearly always appear first over hills and later, if at all, over the lower ground. It may be noted that most chalk and limestone is an outcrop, and clay is usually low lying. It has been said that the convection currents are better over chalk than over clay because the chalk gets hotter, but a more probable cause is its greater altitude.

The shadows of clouds created by the thermals permit some bits of ground to get hotter than others. This is an important complication and it is difficult to predict its effect.

The second requirement is that the supply of thermals should be continued in order that large ones should be born. If a thermal is once begun hot air has risen off a piece of ground and has been, usually, replaced by a cooler mass of air; it takes some time, perhaps ten minutes, for this air to get warm enough to rise also, and so the original thermal can only drain others into its wake if it moves to another place where thermals are just about to ascend. Thus, except beneath clouds forming over high ground by the process already mentioned, thermals will grow best if there is wind to move them along over new sources. A particularly good way to achieve growth would be for the thermal to drift along the crest of a ridge so that the supply of warm air is kept up continuously, or over a series of good though separate sources, which must therefore be nearly in line. The way in which thermals grow is thus affected by the lie of good sources in relation to the wind direction. The shadows of clouds are again an additional complication.

If the wind is stronger at higher levels the tops of the thermals get blown forwards and the wakes are stretched and more rapidly mixed into their surroundings. Thus, although motion of the air across the ground is helpful to the thermal building process, the motion of one layer of air relative to another is harmful.

Another effect of the wind is to arrange the thermals in lines, for those that set off from the ground exactly downwind of a good source, such as a small hill or a steel works, will, for the most part, reach higher, because they will ascend in the wake of thermals from the good source. Thus, if there is only one good source and many mediocre ones, the good one will have a line of well-developed thermals on the downwind side of it.

Finally, because in a wind the air near the ground is stirred up by trees, hedges, buildings, and so forth, the heat is more rapidly transported through the lowest 100 feet or so. Thus the very small thermals, which are inefficient and require much hotter ground than larger ones, are not required when it is windy: their job is already done.

How long does growth continue?

The sun's heat is for practical purposes all put into the ground and only from there into the air, mostly in the daytime. In one day, therefore, the process of building bigger thermals out of small ones can only reach a certain stage. How big do they grow?

At any time convection has reached up to a certain height. Up to that height small thermals are amalgamating into bigger ones, and above it a few are penetrating into hitherto unwarmed air and thereby slowly raising the level up to which the amalgamation can take place. Large thermals will be more common later in the day therefore, if other influences are unchanged. When the hottest hour has passed the flow of air up hillsides will be slowed down and will eventually go into reverse. The air over the hills will then begin to sink down into the valley bottoms and lift up the air over the valley.

Owing to the effect of condensation into clouds, to be discussed in a moment, when air is lifted any cloud within it can become a source of heat for new convection. Thus, if a large cloud forms in the thermals over a hill and then, as the process goes into reverse in the evening, it drifts over a valley, it is kept going without any heat being supplied from the ground. This effect operates over very wide areas and often over Britain a few large cumulus are fortunate enough to find themselves within large masses of slowly rising air, generally over valleys, and they continue to grow late in the evening when all the others have evaporated. Without a continued supply of heat from the ground or a general slow lifting motion of the air, cumulus clouds would die out in twenty or thirty minutes.

Air in which thermals are carrying heat upwards is warmed more than the neighbouring air and so becomes a thermal on a much larger scale. Thus, while thermals ascend in abundance over the hills, the air over hilly regions ascends as a whole. This wholesale ascent has the effect of cooling the air and at the same time, provided cumulus clouds are present, warms it in places where the compensating, sinking motion is taking place, that is, in places where thermals are not carrying heat upwards. The heat from the thermals is thus spread over a much larger volume of air than that into which they ascend. By this in-direct process the sunshine warms the air over the valleys even if no thermals ascend there.

The process occurs on many scales: in valleys 20 to 30 miles across, or like the narrow seas off the south coast of Spain, where a line of cloud forms over the middle of the sea at night and towering cumulus grow over the surrounding mountains by day; or even in the vast plains of North America between the Appalachians and the Rockies, where thunderstorms are most common at night and occur over the mountain ranges most often by day, it can be seen at work. It is not always a simple circulation one way by day and the other way by night, as indicated in Fig. 16, because the mountains and valleys have

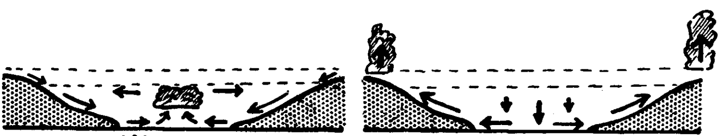


FIG. 16. *Circulation of air by day and by night in the Alboran Channel between Spain and Morocco. By day towering cumulus appear over the mountains; by night a line of cloud forms over the middle of the sea.*

complicated shapes, and so irregular down and up surges of air in the hours before and after sunset frequently occur. (Plate 12.)

In calm, sunny weather in summer sea breezes blow in across the coasts of Britain. This causes the air to rise over the whole country and the air aloft is thus kept cool even though thermals keep pouring heat upwards into it. The air over the neighbouring sea sinks and is warmed. Likewise, when a north-westerly wind blows across Britain, unless some broader process connected with active depressions or anticyclones cancels it out, more air comes in across the north-west coasts in the lowest 1,000 to 2,000 feet than goes away to the south-east. The air over the land ascends to make room for it, and this keeps it cool; thermals carry the heat upwards for much longer than they would if this ascent did not occur. To forecast cloudiness in such an airstream it is necessary to estimate whether the broad processes will permit this ascent or not.

Over the sea there are no hedges or houses to help the growth of big thermals, but they grow nevertheless. Nor has the sunshine much effect, because it scarcely alters the sea temperature when there are waves of any size, and wind, to keep it stirred. The convection occurs when air is moving from cool sea to warm sea and the lowest layers are thereby heated. Convection then carries heat to the upper layers also. Thermals are not prevented from growing by their own shadows nor by the cooling of the surface when cold air replaces them, as often happens over land. The supply of heat is not dependent upon continued sunshine, because convection currents in the sea continually bring fresh warm water to the surface and the water that has surrendered its heat to the air sinks beneath. Indeed, the sea is the most powerful source of heat known on earth. Even over the hottest lands the greatest thunderstorms that develop are paltry in comparison with those giants of convection—the tropical cyclones—which form over the ocean. These cyclones decline rapidly when they invade the land and find that their heat source is soon exhausted.

The temperature over the desert is often unbearably high, and the air extremely unstable, and yet the air does not stir, because there is no feature to act as a focus for the beginning of a growing thermal. If one does begin to grow, the layer of hot sand is so shallow that its heat is soon exhausted and the thermal growth is halted. The heat that is carried up ascends in tiny thermals only. If some outside agency disturbs the air a thermal can be started—an aircraft swooping low over the ground, even a vulture's flapping wings or the sweep of a fan at arm's length. If it can be set in rotation and kept supplied with rotating air, a thermal can grow to great heights. We may find a region of air already possessing some rotation on the edge of a village for instance, where the wind is stronger over the bare desert than over the village whose huts and trees slow it down. The drawing-in of the air from all sides under the ascending air causes the rotation to increase, as in water going down the bath plug hole. This rotation keeps the thermal together and, provided rotating air can be supplied to it, it will continue to reach upwards as a revolving column, sometimes to 5,000 or 6,000 feet. The strong winds at the foot of this whirl blow the dust up from the ground so that it is carried up, making the whole column visible: it is then known as a *dust devil*. When the source of rotating hot air at the ground is exhausted the lower end leaves the ground and it continues its upward ascent until it fades away.

The effect of clouds and showers

The main effect of condensation is to provide additional heat for the convection process when the latent heat of condensation is released. The thermals thus get a new lease of life when they reach the condensation level, and once a cumulus cloud has formed, if it can last long enough to collect a few more ascending thermals, it will grow into a big cloud, inside which the amalgamation process begins all over again. Small thermals thus often just struggle up into the cloud base, but if they manage to get inside the cloud they will at once join others which also draw on this new source of energy. Up they go, possibly to the top of the cloud, where they will form a new tower reaching up into fresh air, paving the way for a further growth of the cloud.

Often new towers are blown off to one side by the wind and the wakes of these thermals evaporate into the drier surrounding air. When this happens the latent heat must be returned and they then produce a mass of chilled air which sinks rapidly. Usually this sinking is easy to see before the evaporation is complete (Plate 6).

When rain is formed the cloud acts as a kind of filter. Air comes in at the bottom and its moisture is condensed into droplets which are caught by larger drops sinking through the cloud. The air goes out at the top or sides deficient in water. Eventually the falling drops grow too big to be supported by the up-current and they fall out of the bottom as rain. The rain drags the air down with it, and when it is below cloud base it chills the air by evaporating into it and demanding from it the latent heat of vaporisation. The air thus becomes a 'negative thermal' of cold air which, on reaching the ground, spreads out and appears to us as a sudden gust of cool air. We shall have more to say about the rain produced by convection in Chapter VII.

Exploiting thermals

With this very brief description of thermals in mind, how can we imagine them to be made use of? Pollen, seeds, and insects are carried up to great heights and transported over perhaps hundreds of miles before being deposited again on the ground or sea. Vultures remain aloft in them for many hours scanning the scene for carrion from a great height, watching their neighbours for many miles around, so that they may follow any one of them that swoops down upon a corpse: they cover the sky like a great net, and if one knot in that net is drawn to the ground its neighbours are drawn towards it. Out of a ' clear ' sky many vultures will descend upon carrion within a few minutes. This explanation of vultures' behaviour was discovered by Philip Wills when he soared among them in a sailplane in South Africa.

Vultures are often seen to start on a flight but soon return to their perch once or twice before finally making off. This is because at the first or second attempt they found no thermal. They are not good fliers and depend on soaring to gain and maintain the height required for spotting their prey.

Swallows and similar birds which feed on insects often go up to perhaps 5,000 or 6,000 feet with the thermals that carry the insects up; while many larger birds, such as buzzards, herons, and storks circle round in thermals, presumably to gain height for observation purposes or to be spent later in travelling some distance.

Desert locusts are conditioned to delight in flying when the weather is suitable for thermals. The up-currents thus help them to remain aloft. When there are no up-currents they make no attempt to fly. They fly, apparently for the fun of it, in no particular direction, and so they are carried by the wind which, under the conditions in which they fly, is usually towards regions where convection will be yet more vigorous. After perhaps many weeks they end up where the convection clouds are large enough to cause fresh rain to fall upon the desert, and this provides them with a suitable breeding ground. They are carried there by an instinct to fly under certain weather conditions. The weather has its vagaries and sometimes the rains occur in one place, sometimes in another, and so an instinct to go to a particular geographical area at a particular time, as displayed by birds, butterflies, or eels, would be useless. Their particular place is that to which the wind, full of thermals, carries them! The role of thermals in their life-cycle was discovered by an entomologist, Dr. Rainey, who is also an experienced glider pilot.

Finally, man has entered the scene. If a glider can be launched into a thermal at a height where it is wide enough for the pilot to circle within it, and the up-current is greater than the

[Photo by Bob Symons

PLATE 7. *High level wave clouds in the lee of the Sierra Nevada, California. The wind is blowing through them from right to left.*

[Photo by courtesy of General Electric Company, Schenectady, U.S.A.

PLATE 8. *A γ-pattern of ice crystals produced in a thin supercooled layer cloud by seeding with dry ice pellets.*

sinking speed of the glider, he can ascend in it. Modern gliders have a sinking speed of 2½-3 feet per second, and thermals of 5, 10, or even 15 feet per second are common on sunny days in Britain, and above about 1,000 feet they are frequently wide enough to turn within. This kind of *soaring*, that is remaining airborne with no motive power, was begun in Germany by Wolf Hirth and his associates in the late 1920s and is now an international sport. From the writings of pilots such as Hirth and Wills,[1] and from descriptions of their flights, one realises that for many soaring is a delightful addiction. Man comes to new terms with nature in this silent flight, where the birds come and fly with him and behave towards him with exemplary but friendly courtesy.

Let it not be thought that successful soaring is simply a question of learning to pilot the aircraft. The student must learn to recognise thermals, to know where to look for them and how to make the most of them. The complexity of the countryside, with the added interference of the shadows of the clouds themselves in the process of thermal growth makes thermal hunting a task which, from time to time, defeats even the best pilots. But apart from the interest of competition present in any sport, soaring brings a new viewpoint from which many of the troublesome worries of earthbound man are seen as trivialities.

Because they can support birds and gliders, thermals are seen to be a source of energy. This energy, though put in at the ground, is only realised through the progressive operation of the buoyancy over great depths, perhaps as much as 5, 6 or even 7 miles, of air. Thus any mechanical contrivance designed to harness that energy must span these great depths. A much more practical opportunity of harnessing energy of convection is in deriving it from the wind, which is, after all, produced by the largest convection systems—cyclones and anticyclones.

WINDMILLS

Of all the sources of mechanical power to be tapped, other than himself and animals, the wind is most evident to man, and he has exploited it for several thousand years. His prodigal nature has allowed him to let his wind machines fall to pieces with old age, unreplaced, while he wastes his greatest capital asset and

[1] See *On being a bird* by Philip Wills (Max Parrish).

raw material—coal—as solid fuel, polluting his cities with filthy acrid smoke, in appliances with which even the most ancient windmill would compare favourably for efficiency. Perhaps it is too obvious and old an idea to catch his fancy—simply to let a fan rotate in the wind—and it is partly because it is not taken seriously enough that a wind-power unit is a single order to the builder and is, as a result, expensive. Even so, electric power generated from the wind on properly chosen sites can be as cheap in Britain as that derived from coal.

The science of choosing good sites is not well advanced, and can never be exact because it depends so much upon the landscape as we find it; but certainly one old fallacy has been exploded, namely, that it is bound to be windier on a mountain top, and therefore windmills should be put there.

As we stand at the top of Helvellyn or Snowdon we can face the wind and feel that it is stronger than we are accustomed to find below, or than we experienced on the way up; but often this is simply because there are no trees, crags and gulleys, no houses or hedges, and it is perhaps 10° F. colder than in the valleys below, so that the wind seems stronger to us. Also we stand in the lowest 6 feet of air, while the blades of a modern wind-driven generator may be 100 feet long. We are used to living in the protected hollows between objects taller than ourselves and cannot therefore deduce that where *we* find the wind stronger it is necessarily a good site for the generator. The best hills are often, in fact, relatively small isolated ones with smooth rounded surfaces, free of trees and other obstructions. Beyond 300 or 400 feet the size of the hill only makes a difference if the greater altitude provides a barer, smoother surface. On the dome of a great mountain we can easily find great variations of wind on and around a small hump 100 or 200 feet high, and so sites must be chosen with considerable care. In many parts of the world the strongest winds are to be found in valleys, and then there is no point in going to the less accessible mountain tops. The Rhone Valley and the Straits of Gibraltar are examples of such places, and many others are to be found around the Mediterranean. In Britain, however, the mountain barriers are not such effective obstacles, and instead of flowing round the edges of the mountains and spilling through the gaps, the deeper cold air masses of these more northerly latitudes readily flow across our highest ranges.

In order to avoid interference from hills upwind, which might produce a region of slack wind over our site, it is preferable to choose them on coasts with prevailing winds from the ocean. British research teams have found some very promising sites, and perhaps in a few decades we shall be tapping several million kilowatts from a thousand wind-driven generators. It is a definite possibility, and could help to remove smoke and grime from many of our towns.

HILL SOARING

We are accustomed to think of waves in terms of water-waves which are caused by the wind or by someone throwing a stone into a pond. There is no such outside agency to stir and push the air around, and even if there were, because it has no upper limit, no waves quite analogous to water-waves could pass through it. Let us be wary of analogies because they can be misleading. The air is not like the sea or a pond but only like itself.

The wind blows nearly horizontally and, apart from thermals, the up and down motion is mostly very small in comparison with the horizontal wind, perhaps half an inch or less a second compared with many feet per second. Mountains, however, often have slopes of 1 : 30 or steeper, and then the vertical motion must amount to about 1 foot per second, or with steeper slopes or stronger winds 3, 5 or even 20 feet per second. If the wind is blowing at 40 feet per second up a slope of 1 : 10 it is also going up, over that point, at 4 feet per second. If a glider can fly forwards through the air at 40 feet per second it will remain over the same point of the ground, but if it sinks through the air at only 3 feet per second it will be carried upwards from the ground at 1 foot per second. This technique is known as *slope soaring* and is practised widely by seagulls and other birds over cliffs, or even over a terrace of houses in a town. The art is to remain in a place where the air is going up faster than the glider sinks through the air: it becomes more difficult at greater heights because there is not always an obvious relationship between the slope of the ground and the places where the air is blowing uphill. This is illustrated by the streamlines of Fig. 17.

Flights of this kind of over fifty hours duration were made in the early days of gliding over the dunes of East Prussia. At many gliding sites in Britain it is only necessary to get a glider off the ground a few feet and it can soar up to several hundred feet above the hill for as long as the wind lasts.

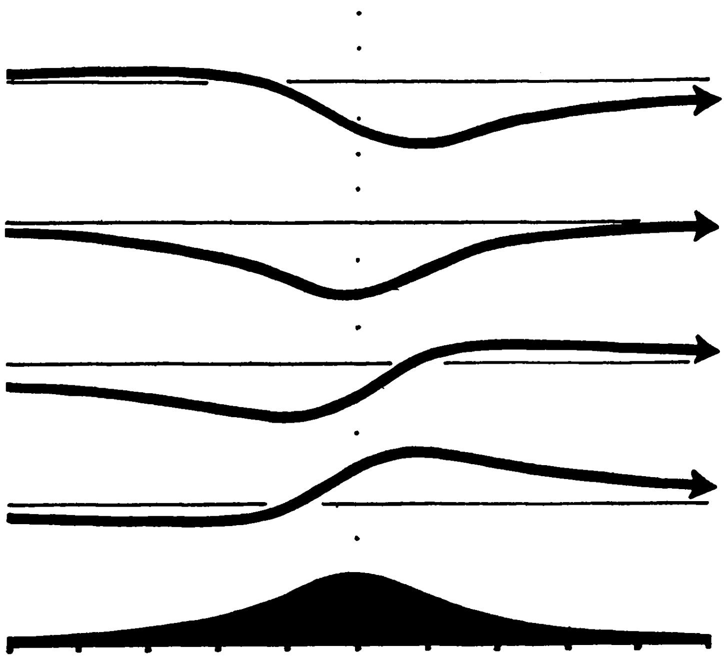


FIG. 17. *The paths of an air current over a mountain ridge. We note that the flow is not the same shape at all heights. This is only one example, and the flow with a different wind speed could be very different.*

If the hill is only 200-300 feet high, the effect of the hill diminishes upwards so that it is not possible to soar more than about 500-1,000 feet above the hill in normal conditions. Over some bigger hills the height a glider can reach is not increased in proportion, though the hills make good soaring sites; but under certain conditions, which are not at all uncommon, soaring to very great heights—ten to twenty times the height of the hill—is possible. The phenomenon is then known as a *wave*.

What are waves?

The science of soaring, no less than any other, has been full of surprises. It was discovered that thermals could be exploited contrary to expert advice that they were not strong enough. Though the experts might have watched the clouds more carefully and seen the strength of their up-currents there was, and still is, no mathematical theory which could have been used to predict their strength. The great magnitude of waves was also a surprise sprung upon the meteorological world by glider pilots and there was no excuse, in this case, because mathematical explanations have been readily produced after the event, and could have been produced before had meteorologists been more concerned with watching and understanding the atmosphere than with making forecasts for the aviation world and the general public. Meteorologists should not be blamed, however, for they were compelled to be general practitioners who had not enough time to advance their science.

Under certain circumstances, which are usually present when the wind at high levels (20,000-30,000 feet) is stronger than below and in more or less the same direction, the influence of a hill is noticeable at prodigious heights, and usually, though not always (for a variety of reasons), one or more waves are found on the downwind side of the mountain. The characteristics of the lines of flow are illustrated in Fig. 18, which is a particular calculated example.

The surprising thing about waves is that it had been thought that if the air were stable, so that forces were present which resisted up and down movements, it would be more likely to go round a hill than over the top. It was therefore expected that the vertical movements over hills would be greater when the air was unstable. This belief was encouraged by the growth of thermals over hills, for these were confused with the smooth lift found over hills when the air was stable and it was thought that this lift had been increased by the instability. It was found after more careful investigation that by far the most extensive regions of lift were present in currents that were stable, often exceptionally so. An explanation is called for.

Without introducing some complicated dynamical concepts we cannot give a complete explanation of the phenomenon. To be sure, if it were easy to understand the idea would not so long have eluded us. We may, however, begin to see how waves come about in this way: if air is lifted it is cooled, and so in the crest of a wave (along CD in Fig. 18) the air is colder, level for level, than in the troughs (along AB and EF) on each side. This

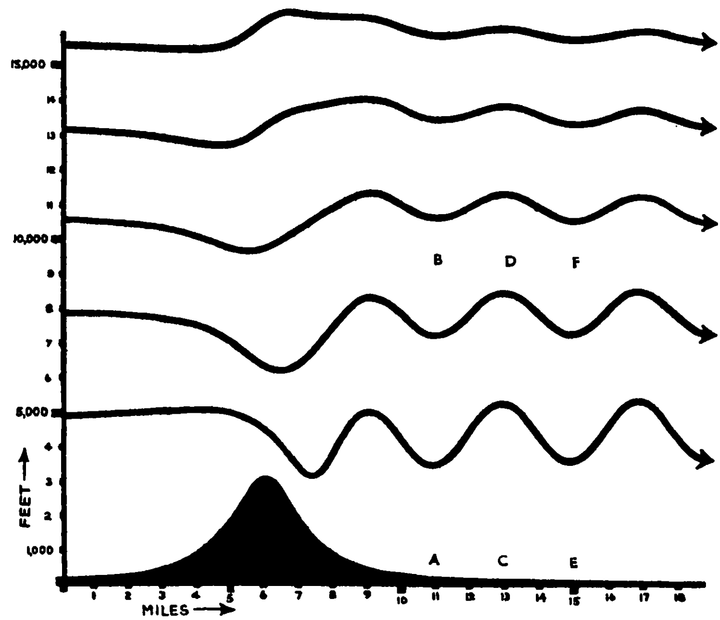


FIG. 18. *The path of an air current in which waves can form. When the air stream has been set in oscillation there may be, under favourable conditions, as many as 100 waves on the lee side of the mountain. Three waves are included in the diagram.*

only happens when the air is stable, because only then does lifting the air make it colder than the air at its new level that has not been lifted. Since it is colder the column CD is also heavier, and it therefore begins to sink while the air in columns AB and EF begins to rise. All the time the air is moving horizontally. The column CD therefore moves into the position of the column EF. As it sinks it overshoots the equilibrium level, like a spring bobbing up and down, and it sinks too low, reaching the bottom of its descent just as it gets to the position EF. If the weight on an elastic string were moving horizontally as well as bouncing up and down it would go along some path similar to the streamlines of Fig. 18. Thus the waves remain more or less fixed in space with the air passing through and bouncing up and down as it does so.

This may sound simple enough but the complexities arise when we try to calculate the motion. The atmosphere has no upper limit, but since these waves are usually less pronounced in the stratosphere than down below, when we calculate what the air current must be like in order that the whole wavy motion should be contained in the lower layers of air (below, say, 50,000 or 100,000 feet), we find that the distribution of wind velocity is just as important as the stability already mentioned. It is possible to calculate, as in Fig. 18, what the flow would be like if the airstream were simple; but all the actual airstreams we observe are much more complicated and very difficult to represent by mathematical formulae.

In particular, it is very difficult to calculate the wave-length—the distance between two wave crests—but it is fairly easy to examine the state of the airstream and decide whether there will be waves. In Britain conditions suitable for waves occur very frequently, and when waves occur the influence of the hill seems to extend up to very great heights, higher in some cases than aircraft have ever reached. The evidence for this is in the clouds.

Wave clouds

The air is cooled as it passes through each wave crest and if it contains enough water-vapour some may be condensed to form cloud. Such clouds exist only where the air is cooled sufficiently, that is, in the wave crests. The waves are almost fixed in space: they shift around a little, usually in a downwind direction, though not always, but their motion is small compared with the speed of the wind that blows through them. A careful examination by naked eye of wave clouds readily reveals, as mentioned in an earlier chapter, that vapour is continuously being condensed on the upwind side and evaporated on the downwind side. We can tell that there is a wind by the movement of small fragments of cloud passing through the main cloud mass, but if we keep our eye fixed and notice whether there is any movement of the cloud relative to a pole, or tree, or building, we can see that wave clouds remain motionless in space often for hours on end. These are the now familiar lenticular clouds.

These clouds have a smooth appearance when they are found at high levels (Plate 7), but often lower down we only see a row of stratocumulus clouds in the wave crest. It is as if the air were stirred up by convection and the smooth cloud is broken up into lumps. In a single photograph the clouds look very like any other stratocumulus, but a careful watch will reveal that each lump forms on the upwind side of the wave, moves through it, and evaporates on the downwind side. This kind of stratocumulus often forms over hills in the evening.

The lenticular clouds of middle levels (5,000-25,000 feet) are very common in most parts of Britain, and are most often seen in the morning and evening, though they may occur at any hour. They often form directly above the stratocumulus just mentioned. Higher up still cirrus wave clouds are sometimes seen where there are hills more than about 500 feet high. A most interesting feature is that they often form long streamers, like enormous pennants flying from invisible masts. To understand how these streamers can form we have to consider the growth and evaporation of cloud in air which rises and sinks as it passes through a mountain-wave.

Depending upon its initial humidity, there is a level, called the *condensation level*, at which droplets will form as the air is lifted. Above another level, which at low temperatures is rather more than 1,000 feet below the condensation level, ice crystals could grow in the lifted air. However, ice crystals can practically always only form by the freezing of droplets; for this reason we call this other level the *ice evaporation level*. Although no crystals appear as the air rises through this level they may form higher up by the freezing of droplets produced at the condensation level; these crystals do not evaporate again until the air sinks below the ice evaporation level. While the air is between these levels the crystals grow, but droplets cannot exist.

It sometimes happens that clear air approaching a hill is above its ice evaporation level; if, then, droplets form and freeze when it rises in the mountain-wave, the crystals do not evaporate as it returns to its original level: instead they continue to grow and form a long streamer of ice cloud which often trails hundreds of miles downwind. These cirrus banners cannot form unless a substantial proportion of the droplets in the wave cloud turn into crystals, and in the few minutes which they spend in the cloud this is unlikely to happen unless the temperature is below about −40° C.

Pride of place among wave clouds goes to the *mother-of-pearl* clouds. These have been most often seen in Norway, partly because there is a long range of high mountains lying across the west winds in northerly latitudes. They have been reported from Scotland and Alaska and even as far south as Silesia, but it is most common for the kind of wind current necessary for the formation of these clouds to occur between 60° and 65° N. The clouds themselves are so high, 80,000-100,000 feet, that they are brightly illuminated by the sun when darkness has engulfed their watchers below, and they derive their name from the bright bands of colour which they display, known as iridescence. Our artist has depicted on the jacket of this book a stratospheric glider of the future soaring above one of these clouds. Similar coloured clouds are common among the lenticulars of middle levels but they do not shine as spectacularly after sunset. Mother-of-pearl clouds are thought to be situated in the ozonosphere, that warm region above the stratosphere that absorbs most of the ultra-violet sunshine. (See p. 24.)

DYNAMIC SOARING

The romance of the albatross

To fly fast requires energy; to fly high, oxygen; but to fly slow and low is surely the supreme triumph in which the skill of the flier transcends that of the designer. Man has, it is true, stayed aloft for many hours at little more than 100 feet over the dunes of the Baltic, but this is a clumsy feat compared with the prowess of the albatross which has mastered the art of soaring over the southern oceans, often for many hours within a few feet of the sea surface. He uses the technique known as dynamic soaring, whereby, if he flies from one air current into another of different velocity it takes time to adjust his speed to that of the new current, and during that time he experiences a force from the air which can be directed upwards by his wings.

Over the oceans of the southern hemisphere, where the westerly winds prevail almost throughout the year and maintain moderate waves on the sea surface, the albatross may be found.

The air in the hollows between the waves, and particularly close to the lee side of waves, is moving more slowly than the air above the wave crests. Flying in a downwind direction, the albatross may enter this region and remain airborne close to the sea as he gradually takes up the velocity of the air. Then, just before he must flap his wing or settle upon the water, he turns into wind and soars up into strong air current above the wave tops, rising 10 to 20 feet. While he assumes the velocity of his new surroundings he can choose a new hollow into which to descend and repeat the procedure.

By skilful use of the many variations of wind velocity close to the sea surface he may soar for hours, perhaps even days, his only expenditure of energy being in steering his way among them. His continual circling and turning has led some observers to describe him as 'strong of wing', as if straight flight would require less effort, but his flight is, in fact, the most effortless possible. No highly complicated aerodynamic sense organ is required to make this behaviour as instinctive as that of a man walking over rather uneven ground. Man is too large to be able to manoeuvre himself in any craft in the small space between the waves; and birds much smaller than the albatross have not enough momentum to exploit the air motion with such complete success as the Great Southern Albatross.

When there is no wind the albatross remains airborne by soaring above the moving waves. As a wave moves along it lifts the air above it, and the bird gliding on the forward side is all the time in rising air.

The question has often been posed: Why is the greatest of the albatrosses found only in the southern hemisphere? He lives over the ocean all his life except at breeding time, and though well suited to live and hold his own on and over the water, he is not by nature a successful coastal or land bird. He lives by his ability to soar almost without effort and scan the ocean for his food. It has been suggested that the westerly winds of the higher latitudes of the southern hemisphere blow unabated year in and year out and so keep the albatross airborne; in the northern hemisphere he would be too often becalmed. But this seems unlikely, because he has been observed wave-soaring when the wind was calm. His technique of supreme laziness almost inevitably leads him downwind, though he can at times progress upwind. In the northern hemisphere he would be blown against the shores of great continents which are to him impenetrable and inhospitable. He cannot even launch himself into the air from the ground. But around Antarctica he may go on and on, girdling the earth time and time again, returning with no difficulty to his favourite haunt for breeding.

In distant worlds of other galaxies, where the only land is scattered islands, an 'albatross' may reign supreme; in others, where great continents span the globe from pole to pole, none is to be found.

SOARING POSSIBILITIES

Undoubtedly in the best waves there is no reason why a properly designed glider should not soar to a height of 20 miles, but the feat of the designer would be greater than that of the pilot. In order to remain aloft at these great heights a conventional aircraft would have to pass the sound 'barrier', because the lift on the wings would be so small in the rarified air at ordinary speeds that the aircraft could not maintain height. This must be avoided, because to soar in a wave the glider must not fly much faster than the wind or it will sink too rapidly, and so the glider must have very large wings which are not very suitable for flight near the ground, where it would probably be unable to fly fast enough to remain in the up-current of the wave.

The glider would also have to be pressurised because it is otherwise impossible to live for long above about 44,000 feet, even when breathing pure oxygen, owing to the small amounts of oxygen taken in at each breath at such low pressures.

At Bishop, in California, where the most effective wave known is found (see Plate 7), Edgar and Klieforth soared to *44,500 feet*, the present altitude record, and there is no doubt that they could have gone higher if they had been properly equipped. Indeed, the difficulty was not to go higher but to avoid doing so, for the up-currents were so strong. They released from the towing plane at 9,500 feet. Within ten minutes they were at 27,000 feet! An hour after release they were at 38,700 feet; some exploration of the up-currents brought them down to 31,000 feet again, after which they climbed to 40,000 feet in nineteen minutes. Here they entered the stratosphere and were soon able to ascend at 500-1,000 feet per minute up to

44,000 feet, where they had to make a deliberate descent. In two and a quarter hours they had climbed 35,000 feet unaided. The return to base at 4,000 feet took only seventy-five minutes. It is unlikely that a height of more than 60,000-70,000 feet will be achieved at Bishop because of the structure of the winds there. Above this height glider design becomes increasingly important. Gliders will probably first reach 100,000 feet in Norway. The other most likely places are on the borders of Alaska and Canada, over the Andes of Southern Patagonia, or the Southern Alps of New Zealand. Not enough is known at present about Antarctica to say whether Graham land, for instance, offers possibilities.

If 60,000 feet could be reached in California one evening, the pilot could then glide all night to arrive next morning over the state of Texas, where thermal soaring would then be taken up to complete a single flight of 1,500 miles or more, before landing that evening.

From 100,000 feet over Oslo, a sailplane could glide perhaps 1,000 miles to Moscow, but the flight could not be continued much farther on the following day, because at the time of year of the best conditions in Norway thermals are not good in the neighbourhood of Moscow. In extremely favourable conditions it might be possible to reach the Ural mountains in one glide from Oslo, and then by soaring in waves southwards along them, it might be possible to reach Turkistan after two days in the air. This would certainly be a most remarkable achievement.

Across the sea very few flights have been made. The English Channel has been soared across twice from Britain, though never from France. The narrower Straits of Gibraltar have never been crossed, though it could almost certainly be done using large cumulus clouds in September or perhaps in April, if not also at other times, with considerable ease. Many overland flights have been made by skipping from wave to wave, the most remarkable being that of Joachim Küttner of 375 miles in four hours in California on 19th March, 1952, on the same day as Edgar and Klieforth broke the altitude record. He started in the famous wave at Bishop. In his report he stated his belief that flights of this kind of twice the length would soon be made.

No wave flights across the sea have been made. It would certainly be possible to cross the North Channel in waves from the mountains of Antrim, or to soar from Kintyre to Arran or to

Ayr. Waves abound both over the Scottish mainland and over the Western Isles and many enclosed lochs could be crossed. Wave flights to and from Sardinia are a distinct possibility, and the seas around Japan offer similar but at present unexplored possibilities.

Although many lines of cumulus, at times hundreds of miles long, can be found over the ocean, particularly in the North Atlantic, they give neither safe height nor time for rest and reflection that would be required on a long flight. Nor are they usually well placed with regard to land for using them to cross the ocean; indeed, the possibility of soaring across any but narrow seas seems faint unless some startling discovery is made. Most good soaring conditions are associated with particular localities, and the oceans possess no feature capable of influencing the air motion on the scale required for soaring except by producing thermals. The only thermals that could be relied upon would be in the larger clouds, and progress by them would be slow and uncomfortable, and with present techniques only possible in daylight. The journey from Iceland to Scotland would probably be too great for one day.

THE VALUE OF SOARING

Economy of operation of gliders and the challenge the pilot takes up when he is launched into the air are not the chief reasons why soaring is of scientific interest. The pilot can exploit only what the atmosphere provides and depends upon it entirely for his success; he has, therefore, in common with the meteorologist, a close interest in the motion of the air. To glider pilots we owe the recognition of many important aspects of air motion described in this chapter, and although there is necessarily a limit to what can be discovered in this way, it is by no means nearly reached yet.

It is possible to soar in and investigate many mysterious surges of air which are found near hills and valleys in the evening; gliders can investigate the detail of mountain waves in a way that is unsafe and even impossible for heavier powered aircraft; and at suitable places, such as at Bishop, they may soar into the stratosphere and investigate the detail of eddies (which jet-propelled aircraft pass through too quickly) and so discover their true nature.

The rain-making problem will be discussed at length in Chapter VII, but it is appropriate to remark here that in order to 'seed' a cumulus cloud and make it rain, a close acquaintance with the anatomy of such clouds will probably be required. The knowledge is best gained by soaring inside them, and the most successful artists in cumulus seeding will probably be experienced glider pilots. To treat a cloud effectively the cloud must probably be entered and explored, and the best place and time must be carefully chosen to inject into it a carefully prepared cartridge.

We are familiar with the obvious dependence of plant life upon the caprice and benevolence of the atmosphere. The researches of Rainey have recently shown us how the behaviour, indeed the whole life cycle, of the desert locust exploits the fact that thermals behave in a particular way; the albatross is seen to live only where the atmosphere's habits suit it; Wills has demonstrated the vultures' dependence upon thermals. Cheels and ravens too have been able to grow strong in claw and beak and give a much smaller proportion of their weight to wing-flapping muscles than smaller birds which have not learned to remain airborne by soaring. Storks and similar large birds spend a great deal of their time on the ground and are reluctant to remain in the air if flapping is required: nevertheless, they migrate many hundreds or even thousands of miles on the wing, and to do this they soar to great heights in up-currents. These species live, not according to the state of the atmosphere, but according to the subtleties of its motion, and we may soon find that the life of many other creatures takes its rhythm from the air in this way. It may be that our familiar friends, the swallows, exploit convection currents for their great journeys in the spring and autumn, as they undoubtedly do for catching insects. Perhaps some secrets of evolution are tied up not only in the past climate as we ordinarily think of it, but in the minute dynamical processes which accompanied it.

CHAPTER V

THE ART OF FORECASTING

> *"What they needed was a couple of hundred years training and experience."*
>
> Back to Methusalah.

THE FEASIBILITY OF FORECASTING

BEFORE the onset of a heavy shower the sky darkens and we recognise that heavy rain is imminent. But perhaps an hour previously we could have seen the swelling cumulonimbus 20 or 30 miles away up-wind, and so could have made a successful forecast of the shower. In locating the growing shower cloud, observing its movement and predicting its arrival, we follow the procedure of *extrapolation* which is still the basis of modern weather forecasting.

One observer can see for himself the whole of an approaching shower cloud, but the large weather-systems, such as the cyclonic storm, can be studied only by examining reports from a number of observers stationed throughout the great area over which they extend. An observation of the existence of a shower cloud has little value several hours later, because its life is considerably less, but the characteristic life of weather-systems increases with their size, becoming two or three days for those as large as cyclonic storms. If, therefore, reports revealing their position and nature can be assembled within a few hours it becomes possible to make fairly reliable forecasts for a day or two ahead by continuing the trend of their observed behaviour.

The development of forecasting services

It was not until about 100 years ago that plans were begun to organise the making of simultaneous observations of weather over wide areas. The initiative came principally from seamen, who wished not only for indications of existing storms but also for climatological summaries of ocean weather as a help in choosing routes favourable for quick passages. When the synchronous observations were plotted upon charts the large-scale weather-systems were clearly recognised for the first time. At first only reports of the surface wind and the weather were made, but when these were entered upon charts in their correct geographical position they soon served to reveal the cyclone and the anticyclone as the principal large-scale features of mid-latitude weather. After some years the detail in the reports was increased and readings of barometric pressure were included. The depression of the barometer in cyclonic storms was clearly indicated on the weather charts, but it was some time before the close relations between the wind and the isobars, and between the weather and the isobar pattern were discovered. It seemed that if these relations could be firmly established, successful scientific forecasting would be attained. The electric telegraph allowed the rapid collection of observations made overland, and with the laying of a cable across the Atlantic it became possible in England to follow the eastward movement of pressure disturbances over America. For a while it was believed that forecasting our weather would be simply a matter of extrapolating the paths of these disturbances across the ocean, but the first attempts were frustrated, largely, it appeared, by lack of observations from the Atlantic itself; the American storms became lost or altered on their way, while others sprang without warning upon our western coasts.

Just before the First World War, the application of radio made it possible to collect numerous observations from ships at sea, but it was soon found that their inclusion in the charts only emphasised that the isobar patterns did not entirely govern the weather, which is not a simple sequence of cyclones and anticyclones, but consists of a ceaseless interplay of diverse complicated systems. The frequent birth of new systems and their continual transformation were not understood and could not be anticipated; extrapolation of isobar movements was useful up to a point, but could rarely produce a reasonably good forecast for two days ahead and often provided only a poor guide to the next day's weather.

After that war the development of aviation gradually altered the nature of forecasting services. The importance of giving seamen warnings of gales shrank beside the necessity of providing aviators with detailed information and forecasts concerning the surface weather at airfields and the weather well above the ground along the routes between them. In Britain the Meteorological Office was placed under the control of the Air Ministry, and before long its departments dealing with aviation requirements and with forecasting in general were combined. Increasingly, weather observations were made at airfields rather than at lighthouses and special observatories. Aircraft were used daily to sound the atmosphere up to about 20,000 feet.

These trends were greatly accelerated during the Second World War. The service providing forecasts for aircraft operations during periods several hours ahead was expanded enormously, and the detail in the forecasts greatly increased, including information on the winds, temperatures, clouds and icing likely to be encountered at all levels in the troposphere. Whole squadrons of aircraft were used to make the observations required for preparing these forecasts, but the most significant technical advance was the development of radio-sounding balloons, which provided measurements of pressure, temperature, humidity and wind up to heights well within the stratosphere. The cheapness of these instruments allowed the organisation of a network of sounding stations which, for the first time, permitted the routine study of the 3-dimensional structure of the large-scale weather systems, thereby introducing a new era in meteorology. Ships specially equipped to make these soundings were stationed on the oceans, and since the end of the war have been maintained by international agreement.

In recent years the great expansion of civil aircraft services and the introduction of jet aircraft have further increased the demands upon the forecasting services. They are now quite dominated by aviation interests, which probably absorb four-fifths of their effort, and which could not function without advice on this scale from the forecasters. Of small importance, by comparison, is the other work of the official weather services, for example, the provision of climatological data and forecasts to the public and to public services, industries, agriculture, road-transport and shipping, although there is little doubt that all these interests could use special forecasting services to their economic benefit. Although some meteorologists deplore this circumstance, it must be admitted that the development of aviation has been the principal spur to the advance of meteorological knowledge and research. Largely as a result of its stimulus, there now exists a network of observing stations which over more than half of the northern hemisphere is adequate for the early recognition and study of the large-scale weather systems, at all levels from the surface to well within the stratosphere.

THE ANALYSIS OF THE WEATHER

The preparation of forecasts begins with a study of the existing weather, revealed by reports from this network of observing stations, and from commercial ships and aircraft.

At a major forecasting office ground observations are received hourly, usually by teleprinter, from several hundred observing stations within a few hundred miles, and every three or six hours by radio from selected stations scattered over the hemisphere. The results of radio-sounding balloon flights made at about 200 stations are received at six- or twelve-hourly intervals. A quantity of further information is received intermittently, including, for example, high-level observations from civil and reconnaissance aircraft, sea-temperatures observed off coastal stations, the locations of thunderstorms deduced from measurements of the radio 'atmospherics' which they cause, and radar observations of the distribution of rain clouds. The flow of data from these sources is so great that there is not time for one forecaster to assimilate it all, and it is customary to divide the work of forecasting between a central and satellite offices (almost always located on airfields). At the central office all the data is available, but the forecasters and a large assistant staff concern themselves primarily with the analysis and prediction of the large-scale weather systems, digesting the observations from an entire continent or even a hemisphere. The result of this work provides a general background for that of the satellite-office forecasters, and is sent to them together with a selection of observational data which allows them to add detail describing the small-scale weather (for example, the form, amount and height of cloud) over the localities or air-routes which concern them.

The observations arrive as groups of numbers, which are interpreted by assistants and speedily plotted as symbols upon charts of appropriate scales. The codes into which the observations are compressed and the symbols by which they are represented upon the charts are ingeniously designed to be as economical and pictorial as possible. Occasionally, to the dismay of the assistants, they have to be extended or altered in order to incorporate new kinds of information or to satisfy new views on what data is most significant. From a set of observations made simultaneously several charts are prepared, showing the weather elements reported at a number of levels from the surface up to a height of about 10 miles.

The forecaster analyses the distribution of weather shown on the charts. He draws isobars to show the pattern of air pressure, probably also isotherms to show the temperature distribution, and perhaps other lines to represent the wind flow and the recent changes of pressure. He locates and marks the positions of the fronts which separate the principal air masses and link the cyclonic storms. The distribution of cloud, rain and some other features are not usually delineated on the charts, which already can be understood only by the practised eye, but are visualised after a careful inspection of the plotted observations and are then stored mentally.

This is exacting work. Rarely are the observations sufficiently plentiful to indicate without ambiguity the exact structure of the weather patterns; rather the forecaster needs constantly a judgment born of experience to find errors which have arisen during the making, transmitting or plotting of observations; to recognise and eliminate purely local influences (perhaps the effects of hills or lakes beside the reporting station) which make some observations unrepresentative of the weather on the scale he is concerned with; and above all, to detect those subtle indications which are the first signs of impending changes in weather systems, or of the genesis of new ones. During his study he continually compares his analysis with that shown on the charts for other levels and for earlier hours, ensuring that they are mutually consistent and completing his mental picture of the structure, motion and state of evolution of the weather systems. All the while, he has to watch the clock; the analysis and forecast must be made as quickly as possible to reduce the interval between observed weather and forecast weather, and thus to improve the prediction. The forecaster can rarely afford to spend more than an hour over his analysis, and some of this time may have to be sacrificed to allow the plotter to enter upon the chart late information from some important region.

THE PREPARATION OF FORECAST CHARTS

With the completion of his analysis of the existing weather systems, the forecaster is prepared to extrapolate their behaviour and make his forecasts. At first he concentrates on pressure patterns; he constructs charts for twelve or twenty-four hours ahead showing the expected surface pattern of fronts and barometric pressure, and the expected patterns of pressure and temperature at several upper levels. The patterns at different levels may need some adjustment to make them consistent with each other, and the forecaster is likely to make other modifications under the prompting of his experience, for reasons which he finds difficult or impossible to explain. It is in these modifications, however, that there lies the difference between good and poor forecasts.

We may suppose that an expert cricketer, who fields in the slips, would find it equally difficult to say how he decides exactly where to fling his hand when catching the ball which glances from the edge of the bat. Regarded as a scientific problem this might seem impossible, involving an accurate prediction of the path of the ball as fleetingly indicated by the stereoscopic judgment of the eyes, but in practice, experience of similar occasions combined with acute perception of the batman's action and the previous flight of the ball, allows it to be caught before conscious thought can begin to help.

Although the judgment of the forecaster is naturally guided by some scientific knowledge of the structure of weather systems, this serves mainly to direct his attention to the more significant features of the observations, and so far has been of lesser direct value than his accumulated experience of the behaviour of the patterns shown on his charts.

Interpreting forecast charts

When the forecast charts have been drawn the forecaster envisages the weather which is likely to be associated with the details in their patterns. Usually he considers separately the weather within the various masses and that along the frontal zones which separate them. The predicted movements of the air currents imply some heating or cooling at the surface which may modify the weather previously reported within them; the weather to be associated with the fronts is indicated by certain simple methods of frontal structure, suitably modified in the light of the recently observed weather, the distortions suggested by the predicted air currents, and, again, the forecaster's experience. The complicated effects of topography have also to be considered: for example, the intensification and prolonging of rain near hills. The effects produced on the local weather by a mountain range vary enormously according to details in the air flow, and in the temperature and moisture distribution, and illustrate the general difficulty which the forecaster faces: there is no theory for predicting these effects quantitatively, and if there were it would most probably fail for lack of sufficiently detailed observational data. The forecaster has therefore to rely on the broad associations which can be found between some known features of the air currents and the weather near the mountains. The local forecaster who constantly *experiences* this weather becomes more thoroughly aware of its peculiarities, and therefore more adept at predicting its behaviour than the distant forecaster, whose only information consists of a few coded observations and whose interest is not so direct.

THE USEFULNESS OF FORECASTS

In writing out a forecast it is necessary to consider first those features of principal interest to the enquirer (for example, surface wind for the seaman or sunshine for the film producer), and secondly, the way in which the forecast will be used. Usually the forecast is worded with especial care to make it concise and unambiguous, and also to indicate the forecaster's confidence in its various details. He may introduce words such as 'perhaps', 'probably' and 'risk of', which are intended as a help to the user of the forecast in making his plans, and not necessarily as a means of making the forecast less definite and therefore less likely to be wrong. Ideally the user of the forecast should have discussions with the forecaster, acquainting him with the particular problem and assessing the likelihood and the consequences of error in the forecast. Thus the crew of an aircraft are 'briefed' personally by the forecaster, discuss the relative merits of alternative routes, the best ways of combating particular weather hazards, the airfields likely to be available for diversion should the weather make a landing at their destination impossible, and so on. They may also be given charts of the existing and forecast weather from which they can, during their flight, recognise any errors which are developing and alter their plans accordingly. In these ways they extract the utmost value from the forecast, even though it eventually proves to be a poor one.

On the other hand, a forecaster faced with the problem of reducing into a few words of a radio broadcast the great complexities of the weather over an entire country during the next twenty-four hours may well say, 'occasional rain or showers in all districts'. A farmer who acts on this advice might, however, have found upon enquiry that in his particular neighbourhood the chance of rain was negligible, and it would then afterwards be fairer to say that it was his method of using a forecast, rather than the forecast itself, which was wrong.

In general, we can say that the possible usefulness of a forecast is not the same as its accuracy, and that in many activities planning based on weather forecasts would, over a long period, show an economical benefit even though individual forecasts were occasionally very inaccurate. If, however, we urge that the public should make more effort to appreciate the forecaster's problems and his potential usefulness, we must also admit that he would do well occasionally to stand aside from his charts for a week or two and rely on the broadcast advice of his fellows, to learn how misleading this can sometimes be.

IMPROVING THE FORECASTS

It is generally agreed amongst forecasters that during the last twenty or thirty years there has been no noticeable increase in the accuracy of general forecasts for a day ahead. There have certainly been great advances in the organisation and usefulness of the forecasting services, and a big increase of detail in those forecasts which are prepared for special activities, such as aviation. Equally there has been a great extension in our knowledge of the atmosphere, but this has not yet led to any material improvement in the prediction of the pressure pattern for a day ahead, which is still the basic step in preparing forecasts. At present this pattern is obtained simply by extrapolation of recent weather, modified according to the judgment of the forecaster. Although it is difficult to define how the forecaster acquires the ability to use this technique, there is a general belief that there is little prospect of further developing it, and that the only hope of making substantial progress lies in the introduction of more scientific methods. The establishment of the science, as distinct from the art of forecasting, will require a great advance in our physical understanding of the nature of weather systems, but is a goal which the research meteorologist has already set about attaining.

CHAPTER VI

THE SCIENCE OF FORECASTING

"It's no job for an amachoor, take my word for it."
The Specialist.

COMPUTING THE FORECAST

THE principle that every occurrence has its cause is deeply rooted among the convictions of scientists, and the success with which man has been able to express mathematically the relationship between an occurrence and its cause has been almost intoxicating in recent generations. Ordinary algebraic equations are used to express one form of relationship which determines one quantity from others. Thus, for instance, we have the familiar relationship

$$x = vt,$$

which tells us that the distance x travelled is equal to the velocity v multiplied by the time of travel t. If v and t are known, x can be calculated, or if x and v are known, t may be calculated, but the equation only works if v is a constant.

If v varies from place to place and time to time we write $v = v(x, t)$ to signify that the place x and the time t are required to be known before v is known. On a car journey the speed depends upon the place—whether the road is straight or crooked, in town or country, and the time—the amount of daylight, the density of other traffic. We may suppose that the speed is known if the place and time are specified. The speed is the rate at which the distance is changing and this is written symbolically thus

$$v = \frac{dx}{dt}$$

dx is a small distance and dt is a small interval of time and it is seen that $dx = v\ dt$, which is very similar to our first equation, which is *algebraic*. This second one applies to each point of the journey separately, the value of v being different at different points and times; whereas our first equation applies to the whole journey because v is the same all the time everywhere, and we could leave out the *d*'s. Equations involving *d*'s are called *differential equations* and describe not a direct relationship between quantities but a statement of how they change in relation to each other. In the example of the car journey, in order to know the time taken over a particular distance, we would have to know which road the journey was made on, because v depends on x, and when the journey was made, because v depends also on t. Furthermore, we would not know the time at which the later part of the journey was made, nor therefore the speed at which it was made, until we knew how the earlier part had progressed. In order to discover the time at which the journey would be completed we have to know when and where it started, and then follow its progress bit by bit until it is complete. Many differential equations can be transformed into algebraic equations: they are then said to have been *integrated*—the small intervals denoted by the *d*'s have been integrated into a single formula.

Most of the physical and dynamical processes we understand are represented by differential equations. If we know the strength of sunshine we know the rate at which the ground is being heated. The physical properties of the ground, such as colour, thermal capacity and conductivity, determine the rate at which sunshine will be diffused back into space, used to raise the temperature of the top surface and the underlying layers. If we knew the rate at which eddies carried the heat upwards from the ground to the air above, the rate at which the air loses heat to outer space, and so on, we could calculate its rate of change of temperature. The dynamical laws could then be applied to calculate its motion and thereby we would discover its condition at a later time. *In principle*, given the physical condition and state of motion of the air to begin with and a description of the processes, in the form of differential equations, any subsequent state of the atmosphere could be calculated.

Owing to the irregular shape of the coastline, the contours, and the nature of the soil and what covers it, no mathematical description of the processes would be simple enough for the equations to be integrated into an algebraic equation which could then be solved. It would be necessary to solve the equation by a *step by step* process. This means, that we would replace the differential equation by a simple algebraic one which is approximately equivalent to it for a short time, and so calculate the state of the atmosphere at the end of that short interval.

This would be used as a beginning point for the next stage in which the approximate algebraic equation would be different because conditions would have changed.

This would obviously be a very complicated process, and to perform all the calculations before the weather we were attempting to forecast had actually occurred, would be a formidable task indeed. In most problems involving differential equations, it does not matter how long it takes to calculate the answer, within obvious limits. If it takes three months to compute the flow of air over an aircraft wing the value and permanence of the answer make the calculation worthwhile; but no weather situation is repeated and so every one must be calculated separately, and therefore with great speed, if at all.

At last, with the advent of modern electronic high-speed computing machines, a tool is available which promises to be capable of doing the job. It is as if in order to enter our promised land we must cross a great mountain range—that mass of calculations. Alone with pencil and paper, or even with ordinary mechanical computing machines, we are unable to make any progress. The modern machines have now carried a few to the top of the range from where the promised land can be seen. What do they see? Every newly explored land is of interest, most contain wealth of some kind. What are the first impressions and for what are we entitled to hope?

The use of the equations

Long before computing of the forecast was seriously considered, many attempts were made to use the equations which express, in mathematical form, the physical and dynamical laws which the atmosphere obeys. Perhaps the most interesting was the *analogue method*. This simply says that the equations are always the same: it is only the initial state that is different; all we require, therefore, is to find an occasion on which the initial state was the same as the present one and we can confidently expect the weather to develop in the same way. Of course, an exact analogue to the present weather could not be found, but it was expected that a sufficiently close approximation could be found for the differences in subsequent behaviour to be significant only after a few days. The idea was almost bound to fail because, as we now know, the motion of the upper air may be very different on two occasions for which the surface maps look very similar, and upper air charts have not been constructed for long enough for a library of possible weather situations to be collected. Even the task of classifying weather situations so that the analogue would be found in a hypothetical library is almost insuperable. To know how to make a proper classification presupposes that we know what the significant features of a situation are, and if we could get to that stage we could probably do without the analogue.

Many forecasters have long contended that the complexity of the atmosphere is so great that, even if calculations were carried out to forecast the weather, the decision of whether to accept them as the forecast to be issued to the public would always have to be left to an experienced forecaster. If machines are to be used, let them carry out certain limited calculations only, and present the result to the forecaster for his consideration. When a restricted use of machines has been established let us extend their application, each time bringing in a new physical or dynamical process. Every time a forecaster places a wind scale on the isobars he uses the scale as a machine to solve the dynamical equations. But the scale is only approximate, and it would be useful to have a machine which could carry out complicated operations on the information represented on the chart to deduce more accurate results. Since the complete calculation of the forecast is a very distant goal, the machines should be used to present the effects of some of the more important processes which are at present estimated in a very crude manner by the forecaster. The calculations may not lead to an improvement in the forecasts if the processes still untouched by the machine are the ones whose effect is most difficult to guess. For instance, the machine could be made to calculate the effect of the inertia of the air on its future flow by assuming that there were no eddies smaller than 500 miles across, and it might be found that on the assumption that the process described by the equations used was the only important one, a forecast for the next forty-eight hours was very successful on some occasions. Yet, on many other occasions, the effect of the smaller eddies might be overwhelming, the situation being completely transformed by the heat, water-vapour and momentum transferred by them. Then the machine's forecast would be wrong, and the judgment of the forecaster would be required to assess, on each occasion, the importance of the effect that the machine was computing.

But if we should try to include all the important effects, assuming that the machine is equal to the task, what then?

Instability

If we cannot solve simple equations we need not consider more complicated ones. The first task, therefore, is to include in them only the most important processes. This also reduces the complexity of the calculations. If the situation is taken simple enough to begin with, so that it can be given a simple mathematical description, the equations can be solved. If the very simplest case, with the wind blowing everywhere along lines of latitude, is taken, the flow is found to be unstable in such a way that a small disturbance, theoretically no matter how small, will grow into a cyclone perhaps 2,000 miles across. Although this may give some insight into the way in which energy is transformed and disturbances grow, it suggests that small disturbances which pass undetected may grow in two or three days to be the dominant feature of the weather situation. A slight error in the specification of the initial state of the air presented to the machine might lead it to forecast a disturbance in completely the wrong place.

This conclusion may have offered some comfort to forecasters in their continued inability to forecast accurately for more than a day or two ahead, for it would seem that depressions grow out of such small beginnings that they cannot possibly be detected far in advance. Must we abandon all hope of forecasting farther ahead, even with machines to help? The simple case of flow along lines of latitude is not the only unstable state; most simple situations would develop violent whirls and eddies if slightly disturbed from equilibrium, and, because it is impossible to give a precise description of the slight disturbance, the life history of the eddies is unpredictable. Yet these very eddies are the stuff of which the weather is made!

The fallacy in this counsel of despair lies in the assumption that the atmosphere is like the simple situation postulated. The flow was supposed to be in a condition which it could never get into. Instability occurs in the atmosphere, and its existence is manifested by the movements the air undergoes as it gives way to the forces released, but never is the whole, or even a large part of the atmosphere, so finely poised that a slight disturbance develops catastrophically. We may imagine a flexible chain lying on top of a smooth horizontal rod in such a way that the slightest displacement of one link that passed undetected in our inspection of the chain would cause it to slip off the rod and carry the whole chain after it. This state is somewhat analogous to the condition supposed for the atmosphere in the above argument. The actual state is as if the chain were hung in loops alternately over the two sides of the rod. A simple calculation based on the number of links hanging in the various loops would tell us exactly how the chain would slip off the rod.

Thus there is no theoretical ground for believing that instability is a major reason for the difficulty of forecasting, and a minute description of the initial state is not required; a crudely approximate specification will do.

GIVING PROBLEMS TO A MACHINE

Having satisfied ourselves that by approximating to the actual state no major forecasting errors will arise from this cause alone, it is necessary to find not only a theoretically possible method but a practical method of presenting the problem to an actual machine. We have to specify enough of the unknown quantities in the equations for the rest to be determined. The vertical component of velocity, though it is responsible for all the interesting aspects of the weather, cannot be measured directly because it is too small in comparison with the ascent and descent of air over a fairly small area, in thermals, for example, and it is the average rate of ascent or descent over a large area that is important.

Every column of air is rotating to some extent about a vertical axis, partly because the wind is not uniform and partly because it is on a rotating earth. If the air ascends more air must come in horizontally underneath it to take its place. Air that was originally spread over a large area in the layers near the ground is thus drawn together to form a thicker slab covering a smaller area, and this causes its rotation to be speeded up. If, therefore, the rate at which the speed of rotation is increasing can be measured, an estimate of the rate of ascent of air above can be made. The speed of rotation can be determined from the isobars because the wind blows, nearly enough for this purpose, along them with a speed inversely proportional to their spacing.

The rate at which the isobars are changing their position can be calculated from physical and dynamical equations, which involve the vertical component of velocity. From these two relationships one can be obtained which, in effect, enables one to calculate the rate at which the isobars are changing, given only their initial pattern. In principle, therefore, given a chart of isobars, the configuration at some later time can be calculated.

Various forms of these equations have been proposed but in all cases it is necessary to know, not only the pressure distribution at the ground, but also at all heights in the upper atmosphere. In fact, a 3-dimensional description of the condition of the atmosphere must be given to the machine. The measurements of temperature and pressure by radio-sonde balloons, together with similar measurements on the ground, provide the raw material, but they cannot be given directly to the machine for a variety of reasons, now to be discussed.

The distribution of pressure can be represented by giving its values at a set of points arranged in some simple orderly manner over the earth's surface. It could be given at all points where the lines of latitude and longitude at intervals of 2° intersect; or we could choose a square grid of points equally spaced on the map, which is a distortion of the earth's spherical surface on to a plane. The reason for doing it this way is that it greatly simplifies the operations which have to be carried out by the machine; it means that each point value will be treated in a manner similar to all the others and so only one set of operations has to be planned in the machine. But this is not the most important consideration.

Over the ocean and some continental areas the observations made at one time are not, by themselves, enough to determine the isobars. The charts are drawn by an experienced forecaster and his knowledge of what kind of patterns do occur, combined with the charts for earlier instants, lead him to conclude that certain configurations exist. When a depression forming off Cape Hatteras moves out into the middle of the Atlantic, where observations may be 500 miles apart, it can only be located accurately by taking its previous positions and movement into account, together with knowledge of what such systems have done in the past. To make a machine do this would indeed be a formidable task and is not seriously contemplated.

Thus the information given to the machine consists of a description of the latest chart, drawn with the forecaster's skill and experience. The values of the pressure, or some equivalent information, for every point of the network are stored in the machine, together with the programme of operations the machine has to carry out on these values. When the operations are complete the machine gives out on a strip or page of paper a series of numbers which will be the calculated values of the pressure at the same set of points twenty-four or forty-eight hours later, this interval being included in the programme.

Models and refinements

It is in a very distant dream only that we contemplate the machine telling us the weather. Forecasters will be more than content for some years if a reliable forecast of the pressure distribution can be computed. Most of the major errors in forecasts made at present are due to erroneous forecasts of the pressure distribution. In any case, the forecasting of weather on the basis of the predicted pressure chart is a very complicated matter, involving so many local topographical and diurnal influences and a detailed knowledge of the existing weather, that no one has considered computing it.

Many of the physical influences which affect the weather operate in a very complicated way, and their very complexity reduces their overall effect on the large weather systems. Other effects, though admittedly important, only matter when they operate for several days. If an anticyclone remains for a long period a physical process—radiation—must be operating to keep the upper air in it cool. Without this process the anticyclone would not remain for more than a day or two at most without large changes. Even so, it would remain for this short time. The same processes operating in many parts of the atmosphere would be largely cancelled out. Thus the cooling at night of the air near the ground is offset by the warming during the day, and though the temperature changes are important in determining the changes of weather throughout the day, they have less effect on a large weather system which lasts for several days.

As a first approximation, therefore, all these external influences are ignored. The atmosphere is imagined to possess a certain distribution of temperature and velocity and the equations describing the dynamical processes are used to discover how the pattern in such an atmosphere would develop if it were left to itself, with no radiation, no friction, no condensation of water-vapour (i.e. no clouds), and no eddies too small to be represented on a weather chart (i.e. no eddies less than about 100 miles across). The heat that is put in in one place is converted into motion in another. The motion redistributes itself and is dissipated into small eddies in yet a third place. If the region for which the forecast is made is mainly occupied with the process of converting the heat into large (cyclone sized) eddies and with redistributing it, while the processes of heat input and dissipation are either small or cancel each other out, this simple purely dynamical model atmosphere will behave very like the actual one.

The first model used was one in which the redistribution of the eddying motion was the only one taken into account. This is called the *barotropic model*, and it is one in which the wind over a point is the same at all heights. This is clearly not the case in the actual atmosphere; nevertheless, useful results were obtained by using for the wind an average value for all levels. The vertical velocity is ignored completely but the model gives a forecast of the pressure distribution, or rather a kind of average one for all levels, and from this the forecaster has to deduce what the vertical motion would be.

In order to include the process of converting other forms of energy into motion more complicated models have been introduced. These allow for vertical motion as well as horizontal and also for the differences in density of neighbouring air masses, from which the motion springs. They describe atmospheres which would, if set in certain simple types of motion, be unstable like the real atmosphere, and cyclones would grow out of next to nothing. Thus these models are capable of imitating the process in the real atmosphere whereby motion is produced. They are still able to redistribute it like the barotropic model. These are usually called *2½-dimensional models*.

The actual atmosphere is 3-dimensional. In representing its condition by values of pressure, temperature and velocity, at the points of a network, spaced perhaps as much as 300 miles apart, we approximate to it. We cannot possibly describe its condition every 5 miles, even if the observations were made, simply because the information would be so voluminous that it could not be used in any forecasting procedure. If we decide on a spacing of 300 miles, then a cyclone 1,000 miles across will have about 3 points of the network on a line across it. The amount of information given about the cyclone in the vertical direction must be of a comparable nature. The barotropic model, in effect, gives information about only one level, which it is hoped will be a good average of all levels, and if we extend the detail there is no point in describing the cyclone at more levels than is useful. Three levels will give about as much detail in the vertical direction as is already given in the horizontal; more would be redundant. The 2½-dimensional model, therefore, represents the atmosphere at three levels only. If some day the network spacing were reduced to 100 miles, then it would be appropriate to represent ten different levels, but the number of points in space would be multiplied by about 30 and the amount of work in the computations increased perhaps 100,000-fold! There is, therefore, a practical limit to the minuteness with which we shall calculate the forecast with a purely dynamical model atmosphere, and present day 2½-dimensional models are not far from that limit.

If we wished next to insert into the equations the physical processes, the complexity will of course be increased, but the difficulties are not too great as far as the computing is concerned. The problem is to know what quantities to put in—how much heat is added or lost, how much momentum is transferred by small eddies, what is the effect of clouds and rain? Here again the judgment of the forecaster will be required, early on at least; but it is hoped that during the next few years forecasts based on the 2½-dimensional model will be made for temperate latitudes where air masses from polar and equatorial regions meet and often produce the main features of the weather by their interplay alone.

Of course, to ignore all but the simple large-scale dynamical processes cannot produce good forecasts for more than a day or two ahead. Now, therefore, we discuss how the other processes can be included.

Pure extrapolation: rates of change

As we have seen, extrapolation into the future of the trends that he has observed in the recent past is what the forecaster has done for many years. Whatever computations are performed and however many of the physical and dynamical processes are included in them, any forecast amounts only to a kind of extrapolation. The equations are used to calculate from the chart the rate at which the pressure pattern is changing. If the forecast is only required for a short period, then it is good enough to assume that the rate of change will remain constant throughout the period and calculate the forecast on that assumption. For longer periods it is necessary to calculate how the rate of change itself is changing, and then how that second rate of change is changing—and so on. We can go as far as we like in this if we have the equations, but, in practice, it is unlikely that anything beyond the third rate of change will be used.

If a negative sign were put to all these rates of change, then the past weather would be obtained. In fact, the past weather is known; and so, theoretically, the rates of change, to as high a degree as we like, can be calculated, and from them the forecast. The forecaster ordinarily does this in a crude graphical or mental manner, but it could be mechanised, and indeed this has been one of the methods seriously considered by meteorologists.

The method of pure extrapolation can be improved by various means, taking advantage of our knowledge of the processes. It is not as easy method to operate as might be thought at first sight, because it is not evident what it is that ought to be extrapolated. Should it be the pressure at a point, the motion of a particle, or what? In answering this question a knowledge of how the atmosphere works is essential.

We can see that if a method of extrapolation can be worked out all the physical processes that have been operating recently will be taken into account in the forecast, and so we have a method of including more than the 2½-dimensional model. But new situations are continually being created and new forces and processes of energy conversion set going: some of these the 2½-dimensional model will recognise while pure extrapolation will ignore them.

The use of normals

In June the heat put in by the sun is the same in any year. The weather in June is more or less the same each year, and the use to which the atmosphere puts the sun's heat is more or less the same too. The same can be said about other times of year; and about places, for the shape of a coastline or mountain range is always the same and their influence similar in similar situations. If we can discover what is the sun's input in June, and anything else that influences the weather at any time, then we can discover how any weather situation will exploit or be ruled by it. The equations, for this purpose, are divided up into the parts we know, which are those peculiar to the actual situation at the moment, such as the pressure distribution, and those which we don't know, because they are too complicated, like the effect of radiation and small eddies. In the place of those we don't know the normal values can be inserted so that all the information required for the integration of the equations is complete and the forecast can be made. The problem then is, what are the normal values?

At a first guess we could use the average values for as many years as there exist observations. It would be equivalent to saying that on this occasion the effect of the small eddies will be equal to their average effect over the last twenty years (or more if we have the observations). The danger is then obvious, for we know that in any one year the weather for a short period may be vastly different from the weather of the same period in other years, and we can scarcely suppose that the operation of complicated physical and dynamical processes will be the same.

At this point we return to our analogues. It is desirable not to use the normal calculated as the average of *all* occasions but the average of *all similar* occasions. Thus, if a burst of cold air from the north in December is the dominating feature of the weather situation we would insert in the equations, for those items or processes too complex to be described in detail, the average values for all previous occasions on which the same kind of airstream was dominant at that time of year. We are faced with the same problem as in the use of analogues alone for making the forecast, that of classifying and storing in some library all past weather situations on record. The problem is not so acute, however, because the analogue is only used for part of the forecasting process, probably that part which accounts for the processes not recognised in the $2\frac{1}{2}$-dimensional model.

The role of the forecaster

The wheel has now turned full circle: each consideration leads to another and eventually back to the first. When a numerical forecast is prepared daily in a few years' time, every method will play its part. Behind all the hum and buzz of machines will remain the forecaster. He will draw his chart, in a way never quite the same as another forecaster would have drawn it; it will be submitted to a numerical process in a machine, using 'normals' judged to be appropriate to the situation by the forecaster; the machine will present him with a forecast pressure map and on the basis of this the forecaster will predict the future weather. We cannot foresee his skill being any less important however much he is assisted by machines; rather will he require greater skill and understanding, and still, as now, the qualities both of artist and scientist.

THE MACHINE OF THE FUTURE

Hitherto the nature of the calculations which meteorologists have chosen in the forecasting process has been largely determined by the nature of the existing machines. These machines are *general purpose machines*, designed to carry out any kind of calculation that is normally needed. *Special purpose machines* have also been constructed to carry out more efficiently calculations which only occur in a restricted group of problems, and their memory, or number storage, is of a special kind.

A general purpose machine represents numbers by a series of 0's and 1's only; a storage location in the machine's memory consists either of a 'yes', representing 1, or a 'no', representing 0. The 'yes' may be an electronic pulse and the 'no' the absence of one. The memory is arranged to contain many numbers, and it must contain them accurately: a 'yes' must not turn into a 'no' or the whole future calculation may be thrown out of gear, and for this reason the closeness with which the numbers are stored is strictly limited. If the yesses and noes are made too small the imperfections of the machine, its wiring, its capacities, its potentials, may create errors.

In meteorology small errors in information do not matter, but if the machine is liable to make an error in the numbers which tell it what operations to carry out the whole computation will be falsified. A special purpose machine for weather forecasting, therefore, requires two kinds of memory: an accurate reliable one for its instructions, and a closely-packed one for storing information in which slight errors make little difference.

To understand the difference we may imagine the picture on a television screen to be composed of dots, like a photograph in the newspaper, and these dots to be the memory of the machine. Each row of dots represents a number. If the dot is bright it is a 'yes', if dark, a 'no'. If now two neighbouring dots on different rows become exchanged, a 'yes' exchanging with a 'no' (which is a possibility in a kind of storage rather similar to a television screen which is actually used in many machines), two numbers will be made wrong, and the consequences may be serious. For instance, the number 1001 might be changed to 0001: a human computor would spot this mistake and correct it but a machine could not. If, on the other hand, the 'no' dots on the screen actually form a chain so as to represent an isobar on the weather chart, so that the picture actually presented on the screen looked like the chart with dark lines where the isobars were drawn, an interchange of two dots will only create an error of position of the isobar less than the errors already existing in the original drawing. Because such errors will not matter, the dots may be more closely packed on the screen and many technical difficulties will be avoided.

Let us look at the kind of machine which might be made. The instructions would be permanently wired into it and not dependent on fleeting electronic pulses for their continued existence. The forecaster draws his chart with each isobar in a different monochromatic colour. The chart is placed in the machine and a series of coloured lights are flashed in succession over it, and at each the machine takes an impression and records an isobar. The programme of operations is then carried out and a forecast chart is flashed on a screen, and it is either copied by hand or photographically and presented to the forecaster. He thinks it is unreasonable, he does not like it, so he redraws his original chart and uses a different 'normal'. He is satisfied with this second attempt, and so he presses a switch which reverses the sign of the quantities stored in the machine and a 'forecast' of the past pressure map is made. If it is different from the actual map for the past, the forecaster must satisfy himself that some new influence which was not operating then is coming into play, otherwise the past map should be produced by putting the forecasting procedure into reverse. When he is satisfied with the forecast pressure map, he makes his forecast of the weather. We envisage the machine taking perhaps five minutes to do its part of the forecast.

What are the operations it will perform? In existing machines the values of the pressure, and so on, are stored for each of the points of the network. The machine takes each point in turn and adds and subtracts various multiples of the values at the neighbouring points or performs more complicated but equivalent operations, like multiplication. It also uses certain basic sets of values at the points which represent the latitude and various similar quantities which are the same in all weather situations. It will, when the time comes, use some 'normal' values for each of the points in the calculation. The answer is given as a set of values at the same points and the forecaster must draw the isobars.

It has been shown by Ragnar Fjortoft of Copenhagen, one of the leading workers in this field, that in the case of the barotropic model, all the operations that are carried out by the ordinary general purpose machine can equally quickly be carried out by a process of graphical addition and subtraction of charts in a special way which operates directly on the isobars, and does not need to represent them by values at points of a network. There is good reason to suppose that a similar procedure could be used for any model atmosphere, and so all that is required is a machine to carry out these operations. This should present no serious difficulty, since steadiness of hand is the only quality required of the forecaster in these operations: no judgment is required.

Will forecasts be improved?

There can be no doubt that a machine of this kind would be of enormous value and would improve the accuracy of forecasts, but we must not be led into thinking this will soon be achieved or that forecasts will then immediately be possible for several days ahead. The atmosphere remains as complicated as ever and we shall never fathom the depths of its complexity to our satisfaction. Advance will be gradual.

We can now see the promised land, but it is vast and awe inspiring. We can see here and there a small plot that we can till, a channel we can navigate, but we can foresee only slow progress in the taming of the wild scene, and at every stage skill, imagination, judgment will be required. Though occasional success may be achieved, it seems that there will always be times when the forces and processes in operation are so working that a forecast for more than two days ahead cannot be made with much confidence. Progress there will be, but spectacular successes are not to be hoped for.

CHAPTER VII

WEATHER CONTROL

And Elijah . . . said unto Ahab . . . "There shall not be dew nor rain these years, but according to my word."

I Kings 17 1.

THE ENERGY OF WEATHER SYSTEMS

THE operations of the atmosphere are conducted on a vast scale and involve transformations of enormous amounts of energy. The basic source of the energy of weather systems is sunshine, which on a summer afternoon supplies energy to each square mile of the countryside at a rate such that, if it could be tapped and fed into the electricity grid, the supply would be worth about £10,000 an hour. The heating of the ground may instead lead to the formation of thunder clouds, each of which is a disturbance about equivalent to the detonation of an atom bomb, or about 20,000 tons of ordinary high explosive. The construction of even a small shower cloud demands the setting into brisk motion of about 10 million tons of air, and during its growth air is fed into the cloud base at the rate of perhaps 100 million cubic feet every second. Yet such a cloud is an insignificant detail in the cloud system of a tropical cyclone, in which it has been estimated that energy is transformed at a rate equivalent to the explosion of several atom bombs every second.

In the face of such magnitudes it appears at first unlikely that man, with the power at present at his disposal, could control the weather, or even modify its course. Nevertheless, already he is accustomed to exerting an important influence on very small scales; for example, he modifies the small-scale weather, or *micro-climate*, in which he lives, by wearing clothes, erecting shelters, lighting fires, and so on.

THE MODIFICATION OF MICRO-CLIMATES

Temperature and activity

Air temperature has a powerful effect on man's activity. Muscular effort is accompanied by the production of heat, which must be disposed of if the body temperature is not to rise to a dangerous level. In hot climates, where the temperature approaches or even exceeds the body temperature, it is impossible to be energetic, particularly if the air is also damp and it becomes difficult to lose body-heat by the evaporation of sweat. A temporary change of air temperature, or of body temperature due to sudden activity, can be accommodated by alterations in the supply of blood to the skin and in the amount of sweating, but a few weeks of prolonged difficulty in losing body-heat are followed by a marked drop in physical and mental activity. The individual becomes lethargic, growth is braked or even stops, fertility is reduced and resistance to infection impaired. It is, therefore, not surprising that the great civilisations have grown up outside the tropics, in regions where the day temperatures are not excessive and the night and winter climates can be controlled by wearing clothes and building houses. Recent improvements in the heating of houses appear to have led to a tendency for the newer civilisations to appear even farther towards the poles, and this shift can be regarded as an achievement of the control of indoor climate.

The regulation of temperature, humidity, ventilation and illumination inside buildings can be complete, and in this respect the design of modern factories and offices has outstripped that of our dwelling-houses. These are still mostly heated by the inefficient and dirty open coal-fires, subject to uncomfortable draughts, and sited without any regard for the local climatic features. Thus we commonly have larders with south-facing walls, sitting-rooms with a cheerless northern prospect, and many ill-fitting windows on walls subject to the cold east winds of winter. In England the persistence of weather types is much shorter than in more continental climates, and has not imposed such recognition as, for example, in the south of France, where windowless walls sheltered by pine trees face the cold northerly 'mistral' winds, or in Sweden, where the central heating of houses is so satisfactory that it is fashionable to mount a thermometer outside a window to give warning of the coldest mornings.

Smoke and fog—The pollution peril

Although the city dweller is so thoroughly sheltered from the open-air climate that he may travel home several miles without knowing whether it is raining, he is sometimes painfully reminded of man's capacity for modifying weather when he suffers an attack of 'smog', a compound word built of 'smoke' and 'fog'. The widespread use of fuel makes the atmosphere of all cities very smoky, so that from a distance their position is marked by a cloud of haze. Usually this pollution is diffused away in the wind and the city dweller hardly notices it, although the visitor from the country remarks on the smoky smell and the small amount of the sky that can be seen through the haze, which weakens the sunshine and contributes to the pallor of the inhabitants. Even so, over London the grime in the air settles out at the rate of about 100 tons per square mile per fortnight, discolouring and corroding buildings and exposed metal-work, and causing millions of pounds worth of damage every year. When the air over a city is left stagnant for several days in foggy weather the pollution accumulates near the ground; the fog persists all day, paralysing traffic, and becoming dark (Frontispiece), irritant and even poisonous (because of fumes from the sulphur in coal and from industrial plants), in contrast with the clean white mists of the surrounding countryside, which may even bask in winter sunshine during the day. The classic examples of dangerous 'smogs' are those which occurred in the Meuse Valley in December 1930, causing sixty-three deaths, and at Donora, near Pittsburgh, in October 1948, when twenty people died. (Of the people who died many had previously suffered from lung and heart trouble.) But probably much worse are the fogs suffered from time to time by the people of London. In a four-day fog during November 1948, and during the following fortnight, deaths due to lung and heart diseases, typical of severe irritation of the lungs, numbered 360 more than the normal. Even worse was the more recent three-day fog of December 1952; it has been stated authoritatively that this fog was responsible for the deaths of some 4,000 people during the three subsequent weeks, and perhaps also for another 8,000 in the next two months, for throughout this period the death-rate continued to be abnormally high. Quite apart from the inconvenience which these fogs cause, disrupting transport services, aiding street crimes, ruining nylon stockings, and so on, they must be regarded as *killing* fogs whose control has become an urgent problem. It would be a mistake to think that they are dangerous only to elderly and ailing people, and no more than a discomfort to the young and healthy: they show that the pollution of the city air is a health hazard which is always present and only occasionally exaggerated until its effects are obvious. There is reason to suspect that the pollution is responsible for the high prevalence of respiratory diseases—pneumonia, bronchitis, tuberculosis, lung cancer and heart troubles—in the smoky industrial regions, which has long been recognised but previously attributed to poorer food and housing standards. If the smogs provoke the public to demand a scientific enquiry into their dangers and vigorous measures to reduce air pollution, then they will not be wholly an evil.

There are only two ways to reduce pollution, and both may be expensive, at least initially. Industrial processes can be redesigned and plants rebuilt so that no pollution is manufactured, or it is collected in the plants; or the waste products can be more efficiently dispersed into the atmosphere. Here the meteorologist will be asked for advice, and, in particular, he may occasionally advise an industry that the diffusion in the atmosphere cannot prevent a harmful accumulation of its waste products, so that the only remedy is to stop the operation of the plant. The industry will doubtless want warning of such unfavourable weather conditions, and their supply will be a new responsibility and anxiety of the weather forecasters. If we should fear that these preventive measures may be too costly, we must remember that this filthy pollution is unnecessary and a disgrace to a civilised community, and that it costs our country some two hundred million pounds *every year* in waste, damage and ill-health.

Fog dispersal

From time to time attempts have been made to disperse fogs, with an eye on the economic importance of any successful method of removing the nuisance and danger of fogs on airfields. A major difficulty is that practically all fogs occur in air which is not quite still, so that to maintain an area free of fog it has to be removed from a much larger volume than just that over the area at any moment. During the last war it was found possible to make a clear path along a runway by burning petrol along its edges, and so heating the air and evaporating the droplets, but at such expense that the method can only be used in military operations or in unavoidable emergencies (to clear a thick fog from an averaged-sized runway, petrol must be burnt at the rate of about 500 gallons a minute). A more promising idea can be applied only if the fog is accompanied by several degrees of frost, and therefore only rarely in this country; this will be mentioned again later in this chapter.

Agricultural micro-climates

Hedges and wind-breaks provide a simple example of a means of modification of micro-climate to the benefit of plants and animals, and we have glass-houses which allow a great deal of control of the climate in which special crops are grown. The air inside a glass-house receives heat by sunshine and is preventing from sharing it with the upper layers by convection or turbulence, and so becomes warmer than the outside air. In summer it is sometimes necessary to prevent the temperature from rising too high, and this may be done by ventilating the glass-house, or by streaming water over its roof. On the other hand, in the coldest months it may be difficult to keep the temperature high enough at night and, particularly, to compensate the diurnal change in outside temperature, because of the great lag in the conventional heating systems. The control of climate inside our present glass-houses is therefore far from perfect, but research is all the time being directed at its improvement by cheap and simple methods, while plant physiologists are trying to find exactly what conditions are the best for the growth of particular crops.

One of the most important aspects of the artificial modification of small-scale climate is the prevention of frost damage, which is especially troublesome to fruit and vegetable growers in the late spring. The night frosts which occur in this season are due to radiation in quiet, cloud-free conditions, and it is only in a very shallow layer near the ground that the temperature falls below freezing. In the United States, where oil is plentiful and cheap, oil burners have been used successfully for many years, especially in orchards. The burners are installed in the orchards, separated by distances of a few yards, and lit only at the onset of a frost. In other countries fires of coal, peat or wood are used. The fires raise the temperature at a few feet above the ground by several degrees, at a cost which amounts to only a few per cent. of the damage which might be caused by the frost. However, in recent years in the United States the cost of the fuel and labour for operating the oil burners, and the nuisance of their smoke (they are known as 'smudge-pots'), have led to experiments with other methods. More efficient burners have been constructed which warm the ground by radiation from glowing plates, and wind machines have been used to mitigate the frost by distributing the night cooling over a greater depth of air. A typical machine mounts large propellers about 30 feet above the ground and protects a few acres at a cost of rather less than £1 an hour. Experiments have also been made with helicopters as wind machines. The stirring produced by hovering a little above the trees in an orchard can raise temperatures near the ground beneath the aircraft by about 5° F., and by about 2° F. 25 yards away. By moving about the helicopter can protect nearly ten times the area covered by an ordinary wind machine at a rather smaller cost per acre hour. However, although the oil burners operate at a cost of nearly £1 per acre hour, they are apparently still regarded as a more reliable protection and their use has not yet been abandoned.

PROSPECTS IN WEATHER CONTROL—CLOUD SEEDING

These examples show us that man's activities can certainly have an influence on the weather, though sometimes unintentionally and usually over an extremely small region. Within the last decade there have arisen new possibilities of altering the weather on a much larger scale by provoking or preventing rainfall, as a result of new knowledge of the behaviour of droplets and ice crystals in clouds. Experiments to test these fresh ideas have been largely indecisive but occasionally startlingly successful. They have given rise to a good deal of uninformed controversy, and before discussing them, we must review the process by which rain forms naturally, and consider how it might be helped or hindered artificially.

The importance of droplet and crystal nuclei

In Chapter II we described the modern theories which try to explain the obvious fact that some clouds produce rain or snow, while others do not. At their birth, all clouds are composed of very tiny particles, and in all clouds there are processes at work tending to combine these multitudes into a comparatively few big particles, which can reach the ground as snowflakes, hailstones or raindrops. We recognise the process of dominating importance to be the sweeping up of the smaller particles by their bigger fellows; if to begin with the cloud particles are all much the same size this process gets a very slow start and may then fail to accomplish the production of rain before the entire cloud evaporates. This often, indeed usually, happens in droplet clouds, but when they are supercooled and become infected with a few ice crystals the heavy preferential condensation on the crystals gives the process a flying start, for they very quickly become much bigger than the droplets and then begin to sweep them up at a great rate. Even so, the death of the whole cloud often prevents their continued growth into hail or snow, and we see that because of the limited life of most clouds the rate at which the sweeping process gets under way is critically important for rain formation. The initial pace of the process depends upon the disparity in the sizes of the first-formed droplets, or upon the exact stage at which the first crystals appear, and these features are determined by the properties of the population of nuclei which are available for the droplet and crystal formation.

Now although vast numbers of these nuclei are called upon during cloud formation, they are so tiny that altogether they represent only a small quantity of matter; for example, all the droplet nuclei used in the building of a shower cloud over the ocean would make about a sackful of sea salt, while the special ice nuclei responsible for the birth of all its ice crystals may compose only an ounce or two of some solid material. Here then may be a weakness in nature's indifference, for this means that it is easily within our power to supply a cloud with artificial nuclei of some special kind, to compete with or replace the natural nuclei, and thus to change the initial constitution of the cloud, conceivably with profound repercussions on its development and its ability to form rain, hail or snow. The prospect arises of interfering with the weather on a grand scale, as was envisaged by the German cloud-physicist, Findeisen, already before the war. His studies of ice-crystal nuclei (which he regarded as all-important in rain formation) led him to prophesy in 1938 the eventual scientific control of the weather:

'The recognition of the fact that minute, quantitatively inappreciable elements are the real cause setting into operation weather phenomena of the highest magnitude makes it certain that, in time, human science will be able to effect an artificial control on the course of meteorological phenomena . . . It can be boldly stated that, at comparatively moderate expense, it will in time be possible to bring about rain scientifically, to remove the danger of icing, and to prevent the formation of hailstones. Through the energy transformations thus secured various other weather phenomena will be brought under some degree of control.'

The search for artificial ice nuclei

Findeisen's observations of the clouds over Central Europe convinced him that in the atmosphere crystals usually do not form until the temperature has fallen below about $-15°$ C. There may be some which appear at higher temperatures, but they are extremely rare, and it is quite common to see supercooled droplet clouds showing no traces of any ice crystal content. Some of these clouds could be made to produce rain if they could be infected with nuclei which allow the formation of crystals at temperatures only a few degrees below $0°$ C., and throughout the war Findeisen and his assistants sought to find some highly efficient ice nuclei. They examined the activity of numbers of dusts and powders in their experimental cloud chamber, but were only partially successful: the best was a dust consisting principally of kieselguhr, a siliceous earth used in making dynamite, on whose particles ice crystals could form at a temperature of about $-8°$ C. A contraption for expelling a trail of this dust was installed in a Heinkel aircraft, and used in September, 1942, to seed a small supercooled cloud (temperature $-8\frac{1}{2}°$ C.) over Prague. Some minutes afterwards the cloud changed into a trail of falling snow crystals. This appears to be the first recorded deliberate and successful modification of a natural cloud by the use of artificial ice nuclei, and it marks the beginning of a new and exciting branch of experimental meteorology.

Findeisen's work was increasingly hampered by the development of the war, and came to an abrupt end when he met an unknown fate at the time of the liberation of Prague. It was not until after the war that methods of making vast numbers of highly efficient ice nuclei were found, and the discovery was made in the laboratories of the General Electric Company at Schenectady in the U.S.A.

The discovery of efficient artificial ice nuclei

Irving Langmuir, an Associate Director of the General Electric Company's Research Laboratory, a renowned physicist and a Nobel Prize winner, and Vincent Schaefer, his assistant, came to the study of ice nuclei as the result of an unplanned sequence of researches in apparently unrelated subjects. These began just before the war with an investigation into the design and action of gas-mask filters. In the course of this work they had to make and study various kinds of smokes, and they learnt a lot about the properties of the smoke particles, how they scattered light, and how they were trapped upon fibres when the smokes were drawn through a filter. This work had hardly finished when they were asked to examine the production of smokescreens; they applied and extended their knowledge of smoke behaviour, and finally made a smoke generator whose performance was several hundred times better than the best then known. Similar generators were used on a large scale during the crossing of the Rhine, and after their adoption by the U.S. Navy, not one of their ships was damaged by the formerly menacing Japanese suicide attacks.

Independently of this work Langmuir was then asked to devise some way of overcoming 'precipitation static', a severe radio interference which had become a serious difficulty in the operation of aircraft over Alaska and the Aleutian Islands. This interference is the result of the strong electrical charging of an aircraft when it flies through a snowstorm, and to examine it Langmuir and Schaefer decided to expose metal test-bodies to the snowstorms at the Mount Washington Observatory. The winter weather at this place is extremely severe: it is usually shrouded in cloud, the average temperature is about $-20°$ C. and the average wind force is more than gale strength. Schaefer found that any body exposed in a snowstorm became covered with ice formed by the collection and freezing of supercooled cloud droplets, so that the Observatory was a poor place for studying precipitation static, but a good one for investigating icing phenomena. As the Secretary of War was just as concerned about the icing of aircraft, Langmuir and Schaefer turned their attention

[Photo by courtesy of Commonwealth Scientific and Industrial Research Organisation, Sydney, Australia

PLATE 9. *1 and 2 show widespread cumulus with tops at 23,000 feet. 3 shows one cloud towering upwards nine minutes after seeding. In 4, thirteen minutes after seeding, it is seen reaching to 29,000 feet. Later it rose to form an anvil still higher and rain fell for 2½ hours. There was only one other shower, a small one, within 100 miles.*

[Copyright—Project Cirrus, Signal Corps Engineering Laboratory

PLATE 10. *An area of New Mexico at 09.45 a.m., before the cloud seeding operation. The clouds are cumulus and are mostly small, but they are high above the ground and have supercooled tops.* (*See also Plate 11.*)

to this instead. They began a series of remarkable researches in which their previous work on smokes was a great help. In this way they were naturally led to study supercooled clouds and the ice nuclei whose inefficiency or rarity is responsible for their prevalence in the atmosphere. They used a large refrigerator for making supercooled fogs in the laboratory, and with this one day Schaefer accidently discovered how to produce fantastic numbers of crystals in any supercooled cloud.

It is only necessary to cool a small part of it very suddenly to a temperature lower than −40° C. In the chilled air multitudes of extremely small droplets form by a spontaneous condensation, in which no special nuclei are needed. Ordinarily these would vanish immediately the air began to warm again, but if their temperature is below −40° C. they freeze, and the crystals formed do not evaporate but continue to grow, for they will flourish in any supercooled cloud, whatever its temperature.

The easiest way to chill suddenly some of the supercooled cloud is to throw into it some chips of solid carbon dioxide, which looks rather like ice and is called 'dry ice': it doesn't melt, but evaporates directly into the gas while keeping a surface temperature of about −70° C. If chips of it fall through a supercooled cloud they leave white trails of millions of tiny ice crystals, which at first are too small to be seen individually, but which soon grow and then sparkle as the light glances off their facets. Pieces of dry ice no bigger than a pin's head produce hundreds of millions of ice crystals, which are gradually spread throughout the whole supercooled cloud by turbulent air movements, so that it becomes entirely transformed into an ice cloud, the water in all the droplets evaporating into the air and then condensing on the growing crystals.

Here then is a technique for introducing abundant supplies of crystals into a natural supercooled cloud: instead of seeding it with a dust of rather inefficient ice nuclei, we may fly over it and drop small pellets of dry ice, which inoculate the cloud with enormous numbers of the most efficient ice nuclei possible—tiny ice crystals themselves. Schaefer first tried the outdoor experiment on 13th November, 1946, when he dropped six pounds of crushed dry ice into an isolated supercooled cloud about 4 miles long and with a temperature of −17° C. Within five minutes the whole cloud became transformed into a dense trail of snow crystals. In the same winter several similar experiments clearly showed the remarkable efficiency of dry ice as a seeding agent.

Soon afterwards Dr. Vonnegut, working in the same laboratories, found that crystals of silver iodide promote the freezing of supercooled water at a temperature of about $-4°$ C., and that a smoke of fine silver iodide particles can cause the freezing of the droplets in a supercooled cloud of this or a lower temperature. The smoke can easily be made by dissolving silver iodide in acetone and leading the solution into a spray-gun fed with compressed hydrogen (or the butane supplied in bottles for gas-cookers); if the gas is lit the spray droplets in the hot flame are vaporised, and the silver iodide vapour emerging from the flame is chilled suddenly by mixing with the air to condense into a hardly visible blue smoke. In this smoke the silver iodide particles are extremely small, and there are tremendous numbers. Their efficiency as ice crystal nuclei seems to suffer a little on account for their smallness, but even so, using a pint or two of a 10 per cent solution at an operating cost of about £1 an hour, there are produced about 10^{10} (ten thousand million) ice nuclei every second which can cause the freezing of droplets at about $-10°$ C., and roughly a thousand times as many which are active at about $-20°$ C. Such a generator, therefore, has an output equivalent to the entire ice nucleus requirements of a thunder cloud every second. Leaving aside the technical matter of how these nuclei might be efficiently sown, we will consider what effects might result from the seeding of different kinds of clouds with ice nuclei.

CLOUD SEEDING

The seeding of layer clouds

As we have already mentioned, thin layer clouds of supercooled droplets are quite commonly found at levels where the temperature is between 0° and about $-15°$ C. When they are explored in aircraft it is possible to detect very small concentrations of ice crytals in or just beneath the clouds, but from a distance no sign can be seen of their presence. The up-currents in these clouds are very feeble, and a crystal which forms inside them is easily able to fall out of the clouds as soon as it has grown a little larger than the droplets, and in the dry air beneath it quickly evaporates. (At still lower temperatures rather more of the first-formed supercooled droplets freeze, and the crystals which fall out of the clouds may form distinct trails. At temperatures approaching − 40° C. there are usually so many crystals that their growth consumes all the liquid droplets, and within a few minutes of its formation a cloud becomes transformed entirely into wispy trails of cirrus.)

In all these thin layer clouds the total quantity of condensed water is very small, and they could not be made to yield more than a slight sprinkle of rain. However, spectacular changes in the appearance of such a cloud arise when it is thoroughly seeded with ice crystals, by dropping into it pellets of dry ice, or by laying a trail of silver iodide smoke through it. In a narrow path along the track of the aircraft the cloud becomes transformed completely into a trail of crystals; gradually the turbulent motions in the cloud layer diffuse these crystals sideways, so that after some minutes a long lane a few hundred yards broad has been affected. This lane is clearly visible because the crystals in it have a sheen different from that of the droplets in the remainder of the cloud (Plate 8). After a little while the crystals at the edges of this lane become so diffused that as they spread into the supercooled cloud each has a large share of the available water, and grows big enough to settle down into the drier air beneath the original cloud-level. The crystals then evaporate, and the cloud disappears altogether in a broad strip surrounding the seeding track, and the final result of the seeding is thus a long hole in the cloud. After an hour or two all the crystals made during the seeding are thoroughly diffused or evaporated and the cloud-forming processes are likely to reassert themselves, so that the hole becomes filled in again with supercooled cloud. Many such experiments have now been made, using aircraft to seed high clouds which can be watched from the ground over a wide area, and are perhaps the most striking demonstrations of the effectiveness of seeding agents.

In very cold weather the seeding can be done from the ground, using a silver iodide smoke generator. For example, on 10th December, 1952, the French meteorologist, M. Dessens, in this way seeded a low-lying layer cloud in Clermont-Ferrand; its base reached to the ground, where the temperature was about −7° C., so that it was actually a *supercooled fog*, which could be seen from a neighbouring mountain observatory to be about

700 feet deep. About 3½ ounces of silver iodide were dispersed as a smoke during an hour. A few minutes after the generator was lit many small ice crystals appeared in its neighbourhood. A little later crystals fell in great numbers, and for an hour the fog became thin and patchy over an area about half a mile across and extending a mile downwind. The fog was re-established when the generator was extinguished.

Experiments of this kind show that it may sometimes be possible to clear away entire layers of fog and cloud, which prevent the ground from enjoying sunshine, if they are sufficiently supercooled. Unfortunately, in this country the fogs are rarely colder than $-5°$ C., as they must be if seeding with silver iodide smoke is to have a chance of success. In colder climates supercooled fogs are more common. A widespread and persistent one greatly helped von Runstedt's final offensive on the Western Front in the last days of 1944, because it prevented the effective use of the Allied air forces. Clearly such fogs might be dissipated by seeding far more cheaply than by burning petrol in FIDO installations, but much exploratory work is needed to discover the best ways of performing the seeding and its real potentialities.

The thick layer clouds which occur in association with cyclonic storms and other large-scale disturbances are evidently capable of producing abundant falls of rain, but in these clouds the natural processes of drop- and crystal-growth have plenty of time to operate and effect a natural and probably very efficient release of rain. Although in particular regions of such cloud systems layers may occur which would yield some additional rain after a seeding, no one has yet shown that it should be possible to produce any significant increase in the total rainfall, or to redistribute it more conveniently.

Thus, although the layer clouds may provide very striking demonstrations of the effectiveness of seeding materials, it seems that they are not clouds from which any additional rainfall can be obtained. On the other hand, it might well be possible to interfere with the formation of rain in the thick layer clouds by 'over-seeding' them, spreading so many crystals into them that, after sharing the available supply of water-vapour, each crystal must still be very tiny. The upper parts of the clouds would then be composed of a floating ice dust, and there would be no supercooled clouds in which to begin rain production by the growth of comparatively rare ice crystals. To be effective over the area covered by a cyclone such a seeding would have to infect enormous volumes of air, so that there would be great practical difficulties in accomplishing it. Moreover, it could hardly prevent the formation of rain by the coalescence of droplets in those lower parts of the layer clouds which are not supercooled. It might, therefore, have no noticeable results in the tropics, and its effectiveness in temperate latitudes would often be uncertain.

The seeding of orographic clouds

Perhaps more promising as sources of additional rain or snow are the supercooled wave clouds which form over mountains. They are always present in stormy weather, and then substantially augment the snow or rain which falls through them from higher layers. They also frequently form over some mountain ranges in otherwise fair weather, and may persist for several days without producing anything more than a slight drizzle upon the mountain tops. The droplets which form on the windward side of one of these clouds are carried across it by the wind, and after some ten or twenty minutes reach the trailing edge of the cloud and are evaporated. This interval is almost always too short for the processes of drop- or crystal-growth to produce raindrops or snowflakes, and so these clouds rarely cause any appreciable rainfall unless they form part of a larger system of storm clouds. However, it is possible that by continuously seeding the windward edges of the fair-weather mountain clouds enough crystals could be given a better start for a steady light snow to fall from the body of the cloud. If this were maintained for several hours or days it could lead to the accumulation of a substantial depth of snow on the mountains. But such benefits could be expected only in particular localities where the mountain weather is especially favourable.

The seeding of cumulus clouds

A large cumulus cloud may cover a square mile of countryside and contain enough condensed water to provide it with up to half an inch of rain. Although the individual cloud rarely lasts more than half an hour, during this period it is fed by a strong up-current, and so we might hope, by a suitable stimulation, to make it yield even more than this amount of rain. Probably we have all noticed in sultry weather the approach of towering cumulus clouds which have, after all, passed away or evaporated without causing the threatened storm. Certainly there seems no scarcity of large cumulus which fail to produce a shower because some subtle condition is not quite fulfilled.

Until a few years ago it was believed by many meteorologists that this condition is the formation of ice crystals in the cloud tops. There was some evidence that in hot climates showers fall from clouds whose tops do not reach high enough to become supercooled, but although the local meteorologists were quite convinced of this, they did not obtain any *conclusive* evidence and publish it. In extra-tropical regions it was observed that shower clouds were practically always tall enough to have well supercooled tops, and this fact was regarded as support for the belief that the showers are produced by the process of ice-crystal growth.

On the other hand, it was noticed that cumulus sometimes tower to heights where the temperature is as low as $-20°$ or $-30°$ C. without producing a shower. It was concluded that in these clouds, as also in many smaller ones, nature fails to provide nuclei needed for crystal formation, and that the provision of such nuclei would inevitably have resulted in shower formation. Findeisen therefore sought to measure the day-to-day variations in the ice-nucleus content of the atmosphere, and began the search for artificial nuclei which would permit the formation of crystals as soon as the temperature has fallen a little below 0° C.

We have already described the successful conclusion of this search, but now it seems that the manner of shower formation is not so simple, and that the mere possession of these nuclei is not enough to ensure the success of attempts to provoke it. The apparently capricious natural transformation of cumulus into shower clouds appears to be due more to variations in their general structure rather than to a variability of the temperature at which crystals form within them. It is necessary to consider anew how the structure of the cloud governs the shower formation.

The formation of showers

As we have described in Chapter IV, a large cumulus cloud is composed of a number of separate thermals or 'bubbles' of rising air, which are warmer than the surrounding clear air, and their wakes, which may be colder than the clear air. The evaporation of droplets at the edges of the cloud chills the air and destroys its buoyancy, so that the cloud grows upwards only by the continual protrusion of its interior. The size which it attains depends upon the rate at which bubbles of warm air are fed into its interior: if the supply slackens, the continuous evaporation of the cloud flanks causes it to shrink, while if the supply ceases, the whole cloud disappears within a few minutes.

The most abundant condensation occurs in the bubbles of air which rise through the middle of the cloud: in these restricted volumes the droplets are the largest and the most numerous, and the processes of drop- or crystal-growth proceed most rapidly. However, they have a limited time in which to work: the time taken for the air to rise from the base of the clouds, where the droplets first form, to the summits, where there is a rapid mixing and evaporation into the clear air outside the cloud.

The process by which the larger droplets sweep up the smaller may, during this period, lead to the formation of numbers of large drops whose fall-speed exceeds the speed of the up-current near the cloud top. These drops are not then carried to the cloud edges and evaporated, like their small fellows, but burrow back into the heart of the cloud and continue to grow, finally falling out of its base as raindrops. Similarly, if ice crystals form at some level in the cloud, their growth may be rapid enough to prevent them from being lifted to the outermost parts of the cloud and from becoming involved in the rapid evaporation there: if so, they quickly become small hail which settles back through the up-current and becomes large hailstones or, finally, raindrops. Whichever process may be the more important, if it is to succeed in initiating a shower it must be well advanced by the end of a particular period. For the sweeping process of droplet growth, this period is the time taken for air to rise through a cumulus from its base to its summit. For the process of crystal growth, it is the corresponding time required for air to rise to the summit from the level at which the crystals first appear. If the average speed of the up-current is great, then, in a cloud of a particular size, these periods may be too brief to permit shower formation. Alternatively, we may expect that clouds containing strong up-currents will not produce a shower unless they are much larger than shower clouds in which there are only weak up-currents.

Clearly, then, the formation of a shower depends not merely upon the size of the cloud, or upon the appearance of crystals somewhere in its tops, but also upon factors such as the speed of its up-currents and, of course, upon the rate at which the processes of drop- and crystal-growth can work inside it. This last is determined by the disparity in the sizes of the first-formed droplets, and by the exact abundance of the droplets provided for sweeping up. All these factors vary greatly from day to day and place to place, so that they exert a very marked influence on shower formation. Our understanding of their nature and importance is so limited that we cannot certainly attribute to any one factor the failure of a shower to form in a particular cumulus cloud.

For this reason we cannot be assured of success when we modify only one factor—the ice crystal content—in seeding the supercooled top of a cumulus. However, there is a chance of success, since by introducing crystals where the temperature is barely below 0° C., we give the process of crystal-growth a better start than it gets naturally, for we know that very few crystals form naturally until it is much colder. This chance of success, moreover, must improve the taller is the supercooled part of the cloud, for then the crystals inside it have a longer time for growth. The experiments so far made indicate that there is a fair chance of success while the cloud top is still a few thousand feet below the level it would need to reach before shower formation began by the growth of naturally occurring crystals. This tentative conclusion suggests that there is a rather limited class of clouds which are too small to produce natural showers, yet large enough to be suitable for seeding with ice crystals.

Seeding cumulus with water sprays

In some clouds, however, it may be possible to accelerate the process of drop-growth by coalescence. In warm weather this process is more likely to be responsible for the formation of natural showers than the process of crystal-growth, and if it can be aided the opportunity arises of causing shower formation in clouds whose tops do not reach high enough to become supercooled, and which therefore cannot be seeded with ice crystals.

This has been attempted in a number of experiments in which the bases of cumulus have been seeded with finely-sprayed water, or with finely-ground common salt. In the damp air the tiny salt crystals very quickly attract enough water to become droplets, and the object in each method is to seed the cloud with droplets rather larger than those occurring naturally. They grow by sweeping up the smaller cloud droplets, and because they are so much bigger initially they have a better start and are more likely to attain the size of raindrops. The seeded droplets must not be too big, however, for then the up-current in the cloud might not be able to lift them into the upper regions which are most rich in condensed water. The potential growth of each cannot then be fully realised, and only an inconsiderable sprinkle of light rain could result. Exactly the best size of droplet to use has not yet been determined, but a number of the first experiments, made in Australia, have already been successful in provoking substantial showers. This method of seeding clouds may prove to be the most suitable to employ in warm climates, but it does demand the seeding of individual clouds by aircraft: the seeding cannot be performed by a ground generator. Further, it appears that seeding clouds with ice crystals possesses an additional advantage, in that on some occasions it may stimulate the growth of the seeded clouds.

Stimulating cloud growth by ice crystal seeding

Most of the experiments in which cumulus have been seeded with ice crystals have had no certain effect. In a number, however, the cloud has quite clearly been provoked to produce a shower, and in a very few of these there has been an unexpected and spectacular growth of the cloud after its seeding. The cloud has rapidly developed into a cumulonimbus towering far above all the other cumulus in sight and giving heavy rain. The first result of this kind was reported from Australia in 1947; a cloud seeded with dry ice rose about 3 miles above the general level of the cumulus tops and gave two inches of rain over an area of about 30 square miles (Plate 9). A similar occurrence has been reported from New Mexico (Plates 10, 11).

These explosive growths are probably caused by the conversion of a large part of the originally supercooled cloud top into an ice cloud. This wholesale freezing is accompanied by liberation of latent heat, which may often be sufficient to raise the temperature of the cloud air by 1° or 2° and thus substantially increase its buoyancy. It then becomes capable of rising some further distance; ordinarily this effect might be barely noticeable, but if the conditions outside the cloud happen to be favourable it can be strikingly enhanced. A clue to this behaviour can be seen in the transformation of towering cumulus into natural storm clouds; when the temperature inside the rising clouds approaches −40° C., crystals rather suddenly become the predominant cloud elements. Previously the details on the cloud edges were clearly defined and had sinking motions produced by the evaporation of droplets and the chilling of the cloud air; now, however, the evaporation at the cloud edges seems prevented: the mixing now gives the cloud a diffuse outline, and the frozen cloud top is flattened and spread sideways into an *anvil cloud.* The wind may gradually draw out the anvil cloud into a vast sheet extending many miles from the parent cloud. The cessation of the evaporation leads to the anvil cloud becoming broader at the top than in the middle, where it is composed of fresh rising bubbles of unfrozen cloud, quite unlike the big cumulus composed of droplets. This characteristically has a broad base and tapers upwards: those bubbles which rise through its middle reach the highest, for they are protected longest from the evaporation and chilling which constantly proceeds near the cloud edges.

The reluctance of the frozen cloud tops to evaporate is due to the fact that ice crystals can exist in air of relative humidity less than 100 per cent (with respect to liquid water). This effect is the more marked the lower is the temperature: at −40° C. a crystal does not evaporate unless the relative humidity is below 68 per cent. Thus, at the edges of a frozen cloud top, the evaporation is greatly reduced or even prevented. Not only does this lead to an increasing accumulation of frozen cloud at high levels, altering the cloud shape, but it also reduces the chilling at the cloud edges and thus favours its growth.

A similar fostering of the cloud growth may begin at higher temperatures when a seeding transforms a substantial cumulus top into a crystal cloud, provided that the outside air is rather damp. Fresh bubbles of cloud air rise up into the seeded top, which remains as a persistent hood, and are at first likely to be composed predominantly of supercooled droplets, not having

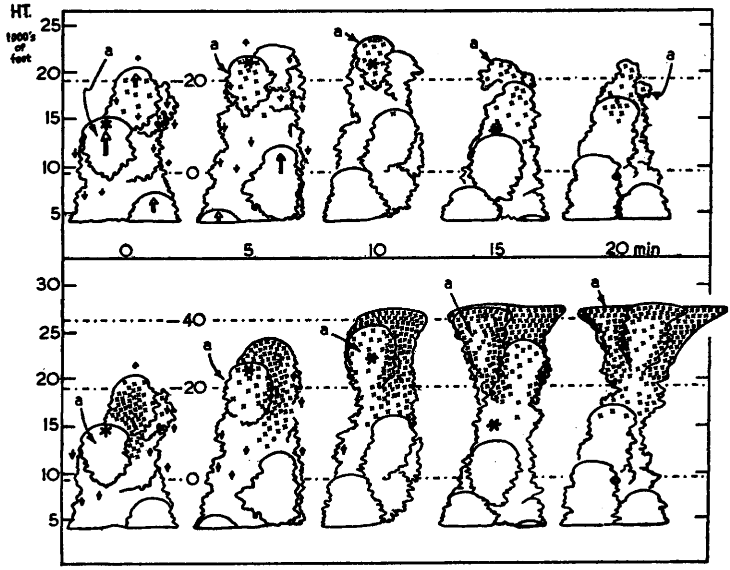


FIG. 19. *Natural shower formation and its possible modification by seeding.*

The pictures show at 5 minute intervals changes in the structure of large cumulus clouds which are composed of 'bubbles' of warm air. The crosses represent ice crystals, one of which in the bubble 'a' is marked by a large star. In the upper sequence this grows into a hailstone which settles out of the bubble 'a' and completes its growth into a raindrop inside other bubbles. In a somewhat smaller cloud it would have too little time for growth, and would be caught in the evaporation of the cloud near the summits, and a shower would not develop.

If a seeding near the cloud tops converts them into a dense ice cloud, as in the first picture of the lower series, this evaporation may be prevented, so that the cloud grows and develops a spreading anvil top. Inside the later bubbles the naturally-formed ice crystals have plenty of time to grow into hailstones or raindrops.

been affected by the original seeding. At the edges of these bubbles, inside the frozen hood, the droplets evaporate, but the vapour condenses upon the neighbouring ice crystals. Thus the evaporation is no longer causing a chilling and the eating-away of the bubbles; on the contrary, heat is liberated around the bubble edges, their buoyancy is increased and their rise encouraged. The cloud may therefore tower upwards to greater heights, and inside the freshly rising bubbles rain or hail may form by natural processes. The seeding would then only indirectly have caused shower formation, by stimulating the cloud growth. Its action is illustrated schematically in Fig. 19.

The conditions in which such a stimulation can be achieved may be special and uncommon, but deserve careful study. It is widely recognised that once a shower cloud has formed, new clouds and showers develop preferentially on its flanks. This probably is because the showers drag down and chill a down-current of air which spreads out at the ground (causing the squall of cool air which often heralds a thunderstorm); this chilled air acts rather like a scoop in encouraging the rise of fresh thermals, so that there is an abundant supply of bubbles for new clouds at the shower edges. Thus, if one shower can be provoked artificially, others may develop naturally; almost certainly this happened in the Australian experiment mentioned above, for the rain stimulated there continued to fall in the neighbourhood for two hours, showing that many more than the initially affected tower must have been involved. In some conditions, therefore, we might reasonably hope by a single seeding to cause a series of heavy showers lasting several hours and travelling over an extensive area.

The prevention of hail and thunderstorms

If *all* the air rising into cumulus clouds were so thoroughly seeded with ice nuclei that every tower became completely frozen upon rising above the level where the temperature is a few degrees below 0° C., then the formation of showers would be seriously hampered, for the sweeping processes cannot operate when all the cloud particles are solid. In particular, it might be possible to prevent the formation of destructive hailstones and squalls which often accompany heavy showers. In Britain hailstones larger than marbles are rather rare, but in some warmer climates falls of hail as large as golf or even cricket balls are a serious hazard and cause much damage to crops.

In parts of northern Italy, France and Switzerland, there is a conviction that it is possible to prevent hailstorms by firing into the clouds rockets carrying an explosive charge. The details of this procedure have not been described in any scientific publication. There are good grounds for supposing that silver iodide smoke generators might be more effective, but their application remains to be investigated.

Since the generation of thunderstorm electricity appears to be associated in some way with the growth of hailstones, it has also been suggested that thorough seeding with silver iodide smoke might prevent the occurrence of lightning. This also would be valuable in some places, for example, in the timber forests of the Rocky Mountains, where lightning frequently causes disastrous fires. But our understanding of the processes at work inside clouds is too limited to permit us more than a hope that the prevention of lightning will become possible.

LARGE-SCALE WEATHER MODIFICATION BY SEEDING

If, as we have indicated, the successful seeding of one large cumulus cloud may transform it into a shower cloud, which propagates itself for some hours, travelling all the while, then we must recognise that seeding can modify the weather substantially over a large area. Langmuir believes that on several occasions in New Mexico seedings, either by ground generator or by aircraft, caused heavy showers and thunderstorms to develop over extensive tracts of the country. His conviction has been challenged by critics who claim that there is no convincing evidence that these rains were caused by the seedings rather than by purely natural processes.

However, instead of discussing these occasions in more detail, Langmuir has claimed effects on an even grander scale, following the regular periodic operation of a silver iodide generator at Socorro, in New Mexico. After some preliminary trials it was operated on Tuesday, Wednesday and Thursday of each week, beginning on Tuesday, 6th December, 1949.

A few days later a period of unusually heavy rainfall began over States well to the east and north-east. To examine the possible relation between these rains and the New Mexico seedings, Langmuir analysed rainfall data from twenty stations whose positions are shown in Fig. 20. He found that during the five weeks before seedings started the average daily rainfall in this group was small, averaging 0·035 inch; four days after the seeding began there was an abrupt increase, and during the following nine weeks it averaged 0·211 inch, six times as much. Before seeding began there was no appreciable seven-day periodicity in the rainfall, but in the next nine weeks there was a pronounced weekly periodicity. The average daily rainfall was a maximum (nearly 0·3 inch) on Tuesdays, 3·7 times as great as a minimum 0·08 inch) on Saturdays. Throughout this

FIG. 20. *Position of the seeding station (Socorro) and of twenty stations whose rainfall during the seeding period has been analysed by Langmuir (see Fig. 21).*

period the rains over the area drained by the Ohio and Mississippi rivers were much heavier than farther west: very little rain fell west of the 95° W. meridian, and there was drought in New Mexico, Texas and Oklahoma (Fig. 23).

Towards the end of January, 1950, because it was thought that the heavy rains might have been affected by the seedings, the amount of seeding was reduced: after 29th January seedings were made only on Tuesdays and Wednesdays, and only in alternate weeks. The average daily rainfall of the twenty stations then decreased: for the four weeks before seeding it was 0·05 inch, for the four weeks after seeding began it was 0·23 inch, and in the next four weeks 0·21 inch, but following the change in the seeding schedule it became 0·13 inch and in the next month 0·12 inch.

A further examination of the rainfall during the seedings showed that at Pittsburgh, the easternmost station of the group, the rains arrived a day or two later than at the westernmost stations, about 700 miles nearer Socorro. By taking average

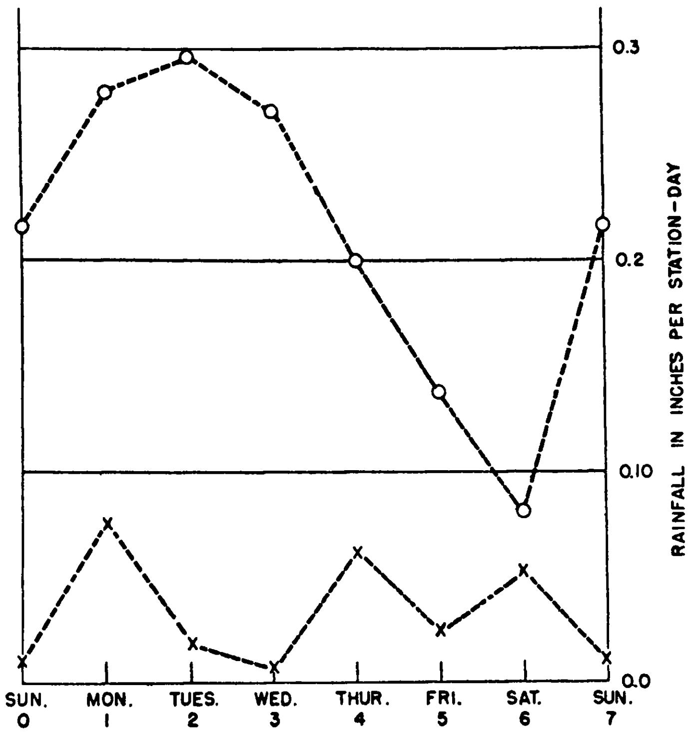


FIG. 21. *The average daily rainfall at the twenty stations shown in Fig. 20 for the five weeks before seeding began* (x---x), *and for the first nine weeks of the seeding period* (o---o). *The rainfall during the seeding period was greater and fell mainly early in each week.*

daily rainfall for the whole group of stations the weekly periodicity in the rains must therefore have been reduced. This was confirmed by combining the records from three of the stations on a line lying roughly north to south. For these the average Tuesday rainfall was seven times greater than the average Saturday rainfall; eleven of the thirteen successive Tuesdays were wet days (an average of more than 0·1 inch per station day), but only one of thirteen Saturdays.

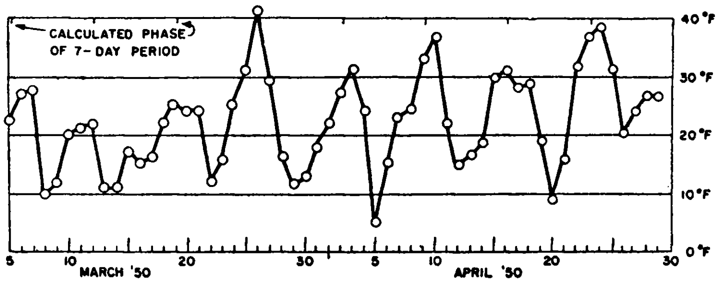


FIG. 22. *Average daily temperatures at about 10,000 feet (700 millibars) during March and April 1950 at the nine intersections of the 80°, 90° and 100° W. meridians and the 35°, 40° and 45° N. parallels.*

During the seeding period striking seven-day periodicities were found in some other features of the weather. Examples are shown in Figs. 21 and 22, and Fig. 23 shows the relation to

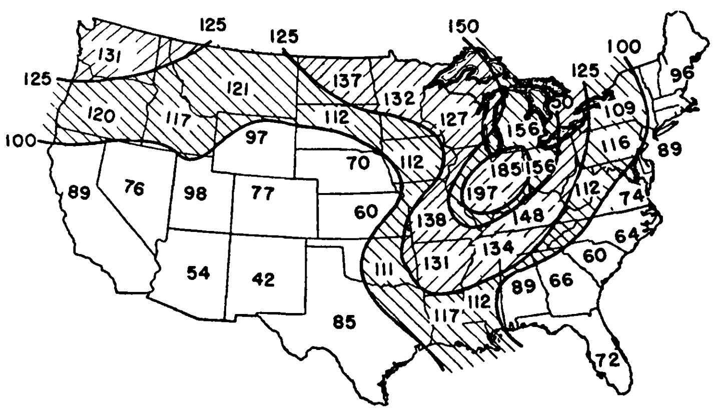


FIG. 23. *Average per cent of normal precipitation for each State for December 1949 to April 1950.*

the normal of the rainfall for the period December, 1949, to April, 1950. According to Langmuir, these periodic changes began suddenly within two weeks of the start of the periodic

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PLATE 11. *Towering storm clouds at 10.45 a.m., rising from the region of clouds seeded twenty minutes earlier. Taken one hour after Plate 10.*

PLATE 12. *An unusual cumulonimbus cloud. It was not high enough to reach levels where the temperature was below freezing point. There was no anvil. The rain continued to fall from it for about 80 minutes. It drifted out to sea just before sunset and was kept going by an upsurge of air (p. 77). An abundance of sea spray nuclei made rain possible without the aid of ice crystals (p. 148). The pictures were taken 15, 38 and 52 minutes after the rain began.*

[Photo by R. S. Scorer

seedings and ended suddenly within two weeks of their cessation, eighty-two weeks later. Most of his striking statistics, however, are drawn from the first five months of the seedings; Langmuir states that after August, 1950, the periodicities became sporadic, and he attributes this to the non-periodic commercial seeding operations which during this year were rapidly increasing in most of the western States, and which used up to a hundred times more silver iodide than was generated at Socorro.

Langmuir considers that his statistics prove that the Socorro seedings, using about 2 lb. of silver iodide each week, were the cause of the periodic weather changes, at distances of thousands of miles from the generator. He has not yet convinced official meteorological opinion, in spite of his impressive evidence, partly because meteorologists are aware of striking periodicities which occur occasionally (although a search in the records does not seem to have produced any quite so remarkable), but principally because there is no accepted explanation of how the silver iodide could have produced these effects. Langmuir thinks that in the winter months the silver iodide smoke would drift ENE., and be diffused over large areas, before producing extensive showers in the region of the Mississippi valley. The rain-water reaching the ground must have been condensed during the formation of the shower clouds, and the latent heat liberated during the condensation may appreciably warm the entire air mass; Langmuir suggests that this widespread warming might help the formation of cyclones, which so often occur in this region. Langmuir does not think that the silver iodide is directly responsible for all the rainfall in regions thousands of miles from the generator, but admits that there may have been a natural tendency for rainfull to occur in periods of about five to seven days, and suggests that the main effect of the seeding was to fix the phase. He is therefore not disconcerted by the fact that the periodic rainfall continued each week even after it was arranged that the seedings should be made only on alternate weeks.

While there is only such a tenuous thread of surmise to relate physically the weather periodicities to the seedings, the only conclusive test of Langmuir's hypothesis must lie in the repetition of the experiment. Unfortunately, because of the widespread commercial seeding operations in the U.S.A., it is not possible to make a controlled test there. We may suppose that the ideal region for renewing the experiment would be one in which strong convective activity occurs in tropical air masses which are commonly drawn into the neighbourhood of the polar front, and upwind of which is a land mass with a dense network of observing stations. The north of Spain or Portugal might be suitable places, especially as they may not yet have been invaded by private seeding enterprises.

If another seeding experiment should prove it possible to influence the weather thousands of miles from a generator dispersing silver iodide or some other, perhaps more efficient agent, then apart from scientific issues, tremendous political problems would be raised.

In the United States legal arguments are already in progress over excessive pumping of water from underground sources, for this lowers the water table also in nearby regions, perhaps causing wells in neighbouring States to run dry. If the connection between seeding and rainfall becomes as clear as that between pumping and loss of underground water, then seeding enterprises will become involved in the same problem: how much of the water below our feet and above our heads are we entitled to draw off, perhaps to the detriment of our neighbours?

Worse will follow, however, if it becomes plain that seedings can influence the weather on a large scale, so that widespread drought, prolonged cold, or even some less uncomfortable visitation, descends upon an adjacent continent. We can imagine 'cold wars' in a more literal sense, perhaps replaced by 'dry wars', and special 'anti-seeding' seedings after the pattern of radio-broadcast jamming. How such seeding wars would affect the political scene we shrink from considering; we will suppose that influencing the weather on a large scale will come about, if at all, only after methods of international co-operation, now so clearly needed for control of atomic energy, have become well tried and established. In the meantime, we can discuss the economic value of present techniques of seeding localised clouds.

THE SEEDING OF INDIVIDUAL CLOUDS TO INCREASE RAINFALL

As far as we know the cloud systems of the large-scale atmospheric disturbances are efficient rainfall-producers, and no one has drawn attention to any parts of them in which seeding could be expected to increase the rainfall. In seeking sources of additional rain we turn to the clouds which represent small-scale disturbances—the orographic clouds and the cumulus. Of these, the orographic clouds are restricted to particular localities. The cumulus often occur in great numbers together, but their general character is then controlled by the large-scale properties of the air masses in which they are found. We might therefore suppose that it is unlikely that any substantial modification, such as must occur during shower formation, could be induced in every large cloud of the whole population. In our present state of ignorance, however, it could equally well be argued that the seeding of numbers of the large clouds might so alter the properties of the entire air mass that the growth of every cloud would be stimulated, thus aiding the production of additional rain.

Whatever might occur, we can regard the seeding operations as effectively aimed at *re-distributing* the general rainfall: it could hardly be increased generally for any long period without also increasing evaporation from earth and sea, and this would require an increase in the pace of atmospheric movement. We know, however, that this pace is set by features on which we can have no significant influence, such as the supply of heat from the sun. This restriction is not serious, for probably more than half the world's rain falls back into the oceans or upon land where it is not especially needed. Moreover, there are of course many particular localities in which quite a small increase of rainfall would bring benefits of enormous value. For example, in some American cities a meagre water supply severely restricts the population and its activities; in other places water has to be fetched from another neighbourhood at great trouble and expense, while even in wetter climates there are hydro-electric plants which could convert extra rainfall over a particular catchment into a valuable supply of electrical power. In some districts, such as in Queensland and in the Sudan, the yield of crops is governed mainly by the amount of rain which falls during a few weeks of the year, early in the growing season.

It is in localities such as these that rain-making may prove practical and beneficial. At present, reservations and uncertainties are sprinkled into every discussion of the likely effects of seeding operations. We can certainly see, however, that the economic prospects vary greatly from one place to another, according to the particular characteristics of the local cloud populations.

In Britain, for example, persistent thick orographic clouds are uncommon over our small mountains, and it would be to the cumulus clouds that we should look for sources of additional rainfall. It will probably be established that because of our cool climate, and because in our predominantly sea air all cumulus are naturally infected with rather large droplets of sea spray (Plate 12), the seeding of our cumulus must be with ice crystals rather than a water spray. If so, the suitable clouds are those in a limited size range, which, nevertheless, might be nearly as numerous as those which cause showers naturally. As, however, the latter are the bigger and more vigorous, we could not expect by seeding *every* suitable cloud to obtain more than about half of the rainfall which falls naturally in the form of showers. In most of our districts this probably amounts to no more than about a third or a quarter of the total rainfall. On this reckoning we could not hope to increase the annual rainfall of any district by more than some 10 or 15 per cent. The achievement of this figure requires that every suitable cumulus should be seeded successfully. If this were to be done by using an aircraft, extraordinary skill in locating and treating each cloud in the critical early stage of its growth would be necessary: once a cumulus tower has reached its peak usually it subsides within a minute or two and is soon in a decaying condition, quite unsuitable for seeding. It is almost impossible both to be sure which nascent towers will continue growing and be worth seeding, and to reach them at the right moment. It might seem better to use ground generators dispersing silver iodide smoke, which is carried away by the wind and diffused over a large area, and eventually drawn up into growing clouds by the convective up-currents. This method of seeding also has some disadvantages, however; the smoke is not quite such an efficient seeding agent as dry ice, and it may provide a continuous supply of ice nuclei to a cloud in such a way that the sweeping process of rain formation is hindered by the wholesale freezing of cloud droplets. It is a poor seeding technique to use in the experiments which are needed to establish the effects of seeding, for the smoke becomes invisible as it leaves the generator and it is almost impossible to be sure of its subsequent drift, and to decide how much, if any, enters a particular cloud.

In other countries, and even in particular localities in our own country, the maximum attainable increase in rainfall might be greater. To assess the possibilities in some given region a consultant meteorologist would need to know, not only how various kinds of cloud react to seeding operations, but also what kinds occur in the region and how frequently. At present neither the theoretical understanding nor the observational data for this assessment exist. The meteorologist would need to make a survey of the local cloud systems for at least a year before he could express even a considered opinion. He would pay especial attention to features such as the tendency for cumulus clouds to form repeatedly over certain hills or other ground features, which would be of the greatest importance in planning seeding operations, but which now pass unrecorded and even unnoticed. Using the results of his survey he would consider the best seeding techniques, deciding where to place smoke generators or whether the use of an aircraft would be necessary. Finally, he would organise and instruct a team of operators who would have to recognise the cloud systems suitable for seeding and direct the seeding procedure.

Assessing the results of the seeding of an individual cloud is less difficult than establishing the effects of a series of seeding operations intended to influence the rainfall over a large area from a variety of cloud systems: this raises problems which are discussed in the next chapter.

CHAPTER VIII

UNCERTAINTIES

" *We know a great deal more about the weather than we understand.*"

Neils C. Beck.

OBJECTIVE METHODS

WE have seen, in previous chapters, that forecasting is largely an art. The present generation, brought up to worship science and its methods, finds this somewhat repugnant. It is assumed that any forecasting method which works can be taught, described and practised by the disciple with reasonable success; that the method does not depend on inborn skill or flair. Of course we know that even among scientists there are men whose inspiration has been outstanding, but all the results of their researches can be learned and used by many other scientists of average competence; yet the fact remains that no great forecaster has ever written a tract that has found a place among the teaching texts of meteorology. Nor are the best forecasters either the best teachers or the best researchers. Modern students spend much time in the search for 'objective' methods of achieving what the forecaster achieves by experience and by some kind of 'know how' which he is unable to pass on to others. These methods attempt to describe a clearly defined way of arriving at a result by going through straightforward, though perhaps tedious, routines. In these routines estimates of various quantities may be required, but instructions on how to make these estimates are generally provided. The idea simply is that if the forecaster can do this he must have some method—even if he cannot describe it. If we can find a method and describe it, then it will become available to many more people—to those who have not acquired the skill through experience.

At the other extreme the modern generation worships self expression. Children are invited to take up crayons and express themselves—to develop their imaginations. The implication of this to weather forecasting is that good forecasters are born, not made, and that in anything where there is an element of art the inspiration cannot be taught but is waiting in a few to be developed if only the opportunities are provided. Such hopes for easy success based on a naïve faith in genius cannot be entertained in weather forecasting. Among all the sciences, meteorology relies more on maturity than others because, besides the principles and methods which any student can learn, the geography of our earth and the detailed qualities of its atmosphere must be deeply assimilated; otherwise the student soon finds himself dealing with abstractions which have little to do with the weather. This maturity is hard won. It is not to be had by sky-gazing and waiting for inspiration, but by grappling continually with the problems the atmosphere poses; and it comes after a record bristling with failures which make valuable marks upon the memory.

Thus, although we have described in Chapter VI some objective methods which show great promise, the fact that a method is objective does not alone justify hope for success. Many such methods turn out to be hopelessly irrelevant to the real atmosphere.

But if we cannot have our Mozarts in the forecasting world, cannot the modern science of statistics set in order for us the accumulated experience, not only of one forecaster but of many? After all, the weather records cover far more than one man could possibly assimilate; might we not, by learning how one man draws on his experience get a machine to draw upon all the records of the past? The idea is one of great possibilities, evidently; but before discussing the objections to the actual techniques employed in such objective methods an objection more fundamental must be explained.

No two people see the same thing exactly. If it is a clearly defined scene that they are examining, such as the pages of a book, they might agree that for practical purposes the book seems to be the same to both of them. Yet reviewers do not agree; we do not all see the same meaning in it. Not only upon what we are looking at but upon what methods we use, upon what prejudices we have and upon what assumptions we make, even unconsciously, depends the picture that is ultimately imprinted on our memory.

These methods, prejudices and assumptions are acquired during our whole life. No two people quite agree. Scientists agree perhaps more than most people because they are used to the same discipline, but these qualities which determine what we see in what we examine must be put into the processing of all the past weather records.

Observations made by average observers all over the world cannot each contain a description of the weather as it would have been seen by one with a critical eye and a thoughtful mind. The information is straightjacketed into certain stereotyped forms by strict reporting procedures. The sky must be reported in terms of certain precisely defined types of cloud, and the observer cannot write: ' none of the types fits the sky as I see it; I have an inexplicable premonition that there will be a storm tonight '. Perhaps there is a storm that night, and perhaps it was not forecast at the central office 100 miles away: but in examining why the forecast was not correct, the forecaster can never know what qualities it was that struck that observer and made him feel that the forecast was wrong. Perhaps some fundamental clue is lost for ever.

As he accumulates his experience such scenes as this become imprinted in the memory of the keen and observant forecaster, and at some later date a similar scene confronts him. This time he is less mystified: the atmosphere's behaviour gradually becomes familiar to him. And it may be that another forecaster, with slightly different methods, prejudices and assumptions, will not find that he gets to know the atmosphere as well as his colleague does.

Bearing in mind, therefore, that on account of the way they were made, past observations may not contain the really vital clues as to how the air behaves, let us examine what the records can do for us.

Forecasting by statistics

Statistical methods are the last resort, to be turned to only in the absence of others. In ordinary physical and dynamical methods a chain of argument leads from a set of assumptions or observations to a conclusion, but in statistical techniques all the ideas are less precise. We find ' probability ', ' significance ' and ' chance ' cropping up all the time, and because we have not had cause to wonder whether we know what these words mean in everyday life it is easy for us to arrive at plausible conclusions.

To illustrate this we may cite the example of extra-sensory perception. No one has any idea how thought transference can take place and so ordinary scientific methods cannot be used for investigating the process. The only method left—the last resort—is to make a statistical analysis of the supposed results of extra-sensory perception. A common experiment is to see what successes can be gained in card guessing and it was at first found that a greater success was achieved than could be ascribed to chance, and this was adduced as evidence that some other process was at work. Philosophers have, on the other hand, also begun to wonder what we can ascribe to chance—for it may be that by making an incorrect supposition about chance we have found 'something requiring explanation', and have tended to 'explain' it by introducing the new hypothesis, which most people find unacceptable, that extra-sensory perception exists.

Since our ideas of chance and randomness are somewhat nebulous, we may find that, when we look at the historical records of past weather, we can see some semblance of order in them. The most entertaining pastime of browsing over records of the past is by no means confined to meteorologists. Commentators on sport can converse almost endlessly upon events of past years, and many completely fallacious arguments based on statistics are put forward in columns of daily papers, advising gamblers how to place their bets or fill in their pools coupons.

The temptation to extrapolate into the future trends which we have observed to be taking place in the recent past is almost irresistible. We may note that the climate of northern Europe has been getting warmer over the last fifty years—and this is a very interesting fact which has great economic and social consequences—but we are not entitled to say that it will continue to do so. Nor, if we observe that during the last decade it has ceased to get warmer are we justified in expecting anything in particular, except that the weather of the next few years will *probably* be rather like the last few. Only if a sequence of events is repeated and the atmosphere seems to have become set in some pattern of behaviour can we expect the same again.

Climatologists have searched in vain for periodic patterns in the records of the past, but we can only report that the only convincing conclusion is that the sequence of days and nights and of the seasons will continue. There is nothing to tell us what next year will be like, except that we can usefully assume that it will not be very different from other years, though we might even be disappointed if an extreme of some kind did not occur and no record was broken. We can only expect a trend to continue if we are assured that the influences that cause it are continuing to operate.

The attraction of any objective method of forecasting is that it always gives some answer, while the forecaster himself can say 'I don't know'. Of these methods the statistical one has an added advantage, in that it expresses its conclusions in terms of probability and chance, and if the event to which the greatest likelihood is ascribed does not take place, the forecast was not wrong, for this was merely one of the 'failures' to be expected from time to time. Any other method is judged right or wrong, and when it fails, the failure is more or less complete and we have grounds for complaint. Statistical methods do not get discarded when they 'fail'.

We are naturally interested in extremes of weather and the frequency with which they occur, and whether a statistical investigation can indicate how soon they will again befall us. Engineers must strike a balance between stinted design and extravagant caution in preparing against floods or gales; they will not wish to avoid an extreme that will not occur until their work has been replaced perhaps 100 years hence, but they must not take risks for the sake of small economy. In practice, unless the cost is prohibitive, their work is designed to withstand conditions rather worse than the severest on record.

As an example we may consider the rainfall in a catchment area. From 100 years' observations we can gain some idea of the average rainfall. During that time there will have been severe droughts and floods. On the assumption that the next 100 years will be a sample, like the last 100, from a much longer period during which the same conditions governing rainfall are operating, we can make a reasonable guess at the number of droughts and floods that will occur. We may say that the probability of having more than 2 inches of rain in March is 60 per cent., meaning that in about 60 of the next 100 years the rainfall will exceed that amount, and we would not be dissatisfied with the estimate if it happened in 70 or 50 years instead; but if the chance of the rainfall exceeding 9 inches is 1 per cent., the information is of doubtful value. Are we to regard a 1 per cent.

chance as negligible, or as a contingency to be prepared for in the next 100 years? The difficulty arises because the idea of probability has meaning only in relation to a large number of occasions. If the probability is in fact 1 per cent., we could not justifiably consider ourselves unlucky if two or three such heavy rains occurred in the century, or lucky if there were none, because they would be scattered in a random manner, not uniformly, throughout the centuries. That three, or none, should occur during a period of 100 years is in no sense a contradiction of the estimate of 1 per cent.; it is what we should expect. In practice, therefore, small probabilities are useless in forecasting extremes and, usually, the past extremes must be regarded as simply a rough indication of what the future holds in store.

This, however, is not all, for new extremes will be experienced, and because the climate is changing these cannot be forecast statistically.

The rainfall at Bidston, in Cheshire, has an annual average of about 29 inches. During the 85 years for which records have been made, the rainfall was less than 35 inches except in 2 years. In one of these it just exceeded 36 inches, but in the other it was nearly 46 inches. Statisticians have computed that, on the basis of the records, a rainfall of this amount is to be expected once in 14,000 years! This claim is only justified if the period during which the observations were made was not exceptional. It might be that a period of 85 years with only one year in which the rainfall exceeded 40 inches is exceptional; but we have no records. Whatever arguments there may be (and they have been considerable) about exceptional occurrences of this kind, their conclusions will not be relevant to what we may expect in the near future. We know neither whether the period for which we have records gives us a fair guide to the frequency of rare occurrences, nor whether the forces which determined the weather during the period on record will combine in the same way in the future.

It is as well to point out that estimates of the likelihood of extremes are not based even primarily on the few cases on record but on the behaviour of the many. A rainfall of 9 inches in March would be considered less likely if the rainfall had always been between 4 and 6 inches in the past than if it had varied between 1 and 8 inches; but any attempt at a numerical estimate of the likelihood of a fall of 9 inches requires a further hypothesis about the nature of the collection of observations. In statistical theory, the observations must be assumed to be a sample from a much vaster store of past, future, or, at any rate, theoretically possible observations, all determined by the same influences. In meteorology this hypothesis is scarcely ever justified.

Apart from the interest that any forecast arouses, objective, and in particular statistical, methods of forecasting possess an advantage already mentioned, namely, that they always give some sort of answer. If a decision has to be made and the weather plays some part in the ultimate results of that decision, a weather forecast ought to be obtained if possible. Forecasters are used to giving advice to people whose decisions rest almost entirely on the forecasts and are often conscious of a burden of responsibility outside their proper sphere. In cases where ordinary forecasting methods can give no answer at all, statistical methods are legitimately resorted to. The forecast given is then most accurately described as a statement of the general characteristics of the weather during the period for which records are available. Statistical methods will never differentiate between one year and another, or one day and another. The forecast for 1960 is the same as for 1961.

The correctness of forecasts

When a forecast asserts that rain is probable, no statistical estimate is intended. If the chance is said to be 60 per cent., this is not an estimate of a random probability but of the confidence with which the forecast is made, and this is determined, not by any statistical analysis of previous observations but by the degree to which the forecaster understands the developments taking place. On some occasions he may be most uncertain but may, nevertheless, be able to make a valuable forecast, and without doubt, if the weather has any effect on one's activity, benefit can be derived from consulting him. The maximum benefit is obtained by a careful choice of the questions asked and not by demanding a forecast of the weather without reference to one's proposed activities. The best forecaster is, therefore, not necessarily the one who can give the most accurate description of the weather according to some arbitrary or supposedly objective standard. He must understand fully his client's problem. If the client must make a burdensome decision the forecaster can often ease the burden: in fact, he may even determine the decision without carrying the responsibility, for if the decision rests on the technical advice he gives he can put the view that will lead to the decision of his choice.

For example, let us suppose that two pilots ask for a forecast of the weather conditions on a long route. To one pilot it is evidently vital that he should go, and so the forecaster will explain in detail how to act if the forecast proves wrong and where conditions will be better if the weather at his destination makes a landing there impossible. The flight will be made, for the pilot receives advice which justifies it. Because the forecaster perceives that the mission of the other pilot is not urgent, he emphasises to him the dangers and uncertainties and even refuses to commit himself in some of his answers. Clearly the risk is too great and the flight is cancelled. Both pilots are justified by advice which is scientifically sound and contains no reference to the circumstances or purposes of the flights. The two forecasts do not disagree in substance, but each is tailor-made. In fact, it is the forecaster who decides whether the flights will take place. We can imagine a similar situation in which two patients receive advice from their doctor and take different actions under similar medical circumstances. The doctor, however, must take the patient's wishes into account in giving his advice because they affect the treatment: the forecaster is free from such restraints, and so the decision can truly be said to rest with him. This is not a hypothetical example, and cases have arisen in which the pilot has changed his mind about making a flight on hearing the same forecast phrased by a different forecaster.

Apart from such considerations we might wish to compare the abilities of two forecasters to estimate the future course of the weather. A system of marking the closeness with which the forecast approximated to the subsequent weather could be devised. The system must allow the forecaster to express uncertainties, possibilities and risks in order to be of value, because a rigid system of right or wrong does not do justice to the complexity of the forecasting problem. If the forecasters knew the system of marking, the winner would probably be the one who could, by verbal manipulation, avoid losing more marks than the other, without necessarily having a better idea of what the weather was to be. On the other hand, if they did not know the marking system, then the important factor of fitting the forecast to the needs of a client would not enter into the test.

In view of the inevitable uncertainties, correctness may not be the most important attribute of a forecast. We may illustrate how the client's need enters into the problem by the following illustration.

On the day before the landing of airborne troops at Arnhem in 1944, hundreds of gliders and their towing aircraft had to be arranged on their airfields, ready to leave in quick succession the next morning. Gliders and tugs were to be heavily laden, and at some airfields only the longest runway could be used. The most important part of the forecast weather was the predicted surface wind, for the marshalling officers had to dispose all the aircraft so that each tug could meet its glider at the downwind end of the runway in order to take off into the wind. The central forecasting office predicted a north-west wind, and it happened that at two neighbouring airfields a wind of this direction would be directly across the longest runway. On the basis of this forecast alone it was impossible to decide how to marshall the aircraft. On one airfield the local forecaster added, that if the prediction were wrong the wind would very probably be more westerly, and the aircraft were arranged accordingly. On the other airfield no additional advice was sought, and the aircraft were arranged to take off in the opposite direction. In the morning the wind was WSW.; it was too late to re-marshal the aircraft, and on this airfield they had actually to take-off in the direction of the wind; luckily it was light and the mistake had no serious consequences. The value of this forecast depended entirely upon further consultation between forecaster and client. Some use can always be made of the advice, however uncertain the forecast.

This last statement does not imply that a client's question can always be answered. The advice may simply be a description of the circumstances which make it impossible to give an answer to the question posed. This is not useless advice if intelligently used. However, clients are not always disposed to make an effort to understand the advice, and if they cannot get a direct answer from the first they are often inclined to go to another forecaster who will give one. Even if the second forecaster has made a complete guess, the client hopes it will be an inspired guess and better than no advice. At the very least, he has obtained an answer, and this has perhaps relieved him of the burden of making some decision.

In meteorological matters Providence is playful and even the most earnest endeavour may be cheated of success. It is not always its relation to the weather that is most striking, but the fact that a forecast was right or wrong. The failures of a big organisation, like a state weather service or of a man of high professional standing, are long remembered together with the successes of the amateur or charlatan, and since we all possess some knowledge of the ways of the weather, we can easily achieve some success. It is the difficulty of making a numerical assessment of the correctness of a forecast that lays the field open to impostors.

Testing rainmakers

No two clouds, days or weather situations are so nearly similar that an experiment with the weather can be repeated precisely. The variations which occur in the natural sequence of weather are so large, that unless the rainmaking methods had fairly spectacular success, one could not be certain whether they had any effect at all. An idea of these variations is gained from the following eleven numbers which give the percentage of average October rainfall which fell during October, 1952, at eleven stations listed consecutively for north and east Scotland in the Monthly Weather Report: 197, 124, 112, 136, 73, 72, 73, 130, 142, 79, 82. The month was wetter than average at six stations and drier at five, and rainmakers would indeed be satisfied if they could produce such variations.

If cloud seeding did in fact cause an increase of 10 per cent. in the rainfall, in order to prove by the statistics that the increase was associated with the seeding, and was not simply a natural variation, it would be necessary to carry out the experiments over many decades. During this time the seeding would have to be done, not at regular intervals always in the same place but in a carefully planned random manner. For instance, it might be that the seeding was only effective in certain weather situations which occur on, perhaps, only one day in ten. On these days it might only be effective if not overdone—if it had not been done the day before, for instance—or if it were well done and had been done thoroughly the day before, or if it had been done the night before but not on the day itself on which the rain occurred. Since we know that seeding can be effective, but we are not sure of the exact circumstances, all these various possibilities must be included in the test. In fact, the variety of weather is so great that it is not possible to set up a controlled experiment to test the effect of one single variable (in this case the rainmaking operations), simply because so many other things are varying at the same time. It can probably be said that we are not ready to plan the test at present, and when we are ready such a test over a long period will not be the best way to investigate the effectiveness of a rainmaking technique.

Furthermore, since the techniques proposed almost all apply to shower clouds, the statistics must apply to the shower type of rain. Past records are from very widely spaced rain-gauges and from all kinds of rain. They are practically useless for comparison because they are mostly sparsely distributed in those dry regions where rainmaking is most desired. For the reasons already given, a long series of experiments, beginning now, would take so long to carry out that the techniques would be outmoded before any results were obtained. The effectiveness of the methods must be demonstrated on individual occasions in such a way as to carry conviction. The conviction may not be universal,' for it will depend on the beliefs of the interpreter of the experiment, but it must so depend, and there appears to be no objective test that can be made.

In many respects the problem is like that of testing whether any skill is required to make a certain forecast, and whether a forecaster can, with justification, claim that a correct forecast was not a lucky chance. His claim is best tested by those most expert in forecasting and familiar with the methods used. The success of attempts to make rain can only be judged by someone who knows what to expect in the absence of the attempt, and is familiar with the theory on which the attempt is based.

Success in making rain thus has nothing to do with selling one's services as a rainmaker to those not competent to judge. Indeed, the very fact that rainmaking is unlikely to increase the total rainfall by more than about 10 per cent. plays into the hands of the impostor, because apparently he cannot be tested by statistics. The economic benefit from a small increase may be so great as to induce a farmer to employ any rainmaker. But it seems probable that because this 10 per cent. will be made up of great increases on a few occasions a 'rainmaker' should be able to demonstrate his prowess.

Modern sorcery

We are more inclined to view objectively the activities of others, and it is easier to see the errors of witchcraft when we are not concerned to practise it. We may even regard the rituals of savages or of our rivals as wicked and malicious. Evil, or at least discreditable, motives can easily be ascribed to those who seem to us to have a vested interest in untruth as we see it.

Natural philosophy is unassailable, for it is an edifice built by reasoning upon hypotheses; the conclusions it reaches cannot be gainsaid if the argument is correct. In meteorology, no less than in any other science, there has been assembled a body of theory to deal with the behaviour of the atmosphere, and so long as we only try to understand the processes by making acceptable hypotheses and deducing results, like what is observed, the argument is academic. When natural philosophy enables us to make machines we are satisfied if they do all that their designers claim for them, and if we set our scientists a new task we are prepared to wait until a solution to the problem has been found. Time does not enter critically in such cases, and often we dream of the things our successors will be able to do after another century of scientific progress: the future is beyond our grasp and we do not despair because of it. But the problems of controlling and forecasting the weather are different.

Throughout historic time, and perhaps since man came into being, he has had his methods of bringing rain or of stopping it, of abating the wind, and of guarding against thunderbolts. Inevitably they have often been successful, because the rain does start and stop. Failure has often been regarded as evidence, not against the method but for the efficacy of the method employed by an enemy. Methods have always been tried, because as the weather usually seemed the worst of living memory, and it has frequently been catastrophic, man has always been impatient to attempt weather control. However confident we may feel that our proposals are in a different category from the sorcery of the past, we must temper our conceit. Witchcraft has died out, not because it is no longer believed in but because it is irrelevant to our present needs: modern society abounds in practices that are quite arbitrary and frequently outrage our moral sense. A method of controlling the weather will be widely employed, not so much because it is understood, or even because it is believed to work, as because it might work—and we do want the result so very much!

The ancient Mexicans offered the bleeding hearts of man to the sun in the belief that only in this way could its energy be renewed. Their dreadful wars to obtain victims for their sacrifices were regarded as a grim necessity, and no doubt the more thoughtful of their priests observed a very high correlation coefficient between their mid-winter offerings and the turn of the season.

It would be invidious to cite examples of forecasting and rainmaking techniques whose success has been acclaimed but whose explanation has proved erroneous, when we have no other to offer that will not likewise wither under a later analysis. The point may be illustrated by an example of Shaw's. Suppose vaccination to be made compulsory so that only vagrants escape it. In smallpox epidemics the death-rate among those vaccinated is lower than among those who are not. If the full facts are concealed, perhaps not deliberately, it can be 'proved' by the statistics that vaccination reduces the death-rate, whereas it is, in fact, a method of labelling all but vagrants, who, being of the poorest physique, will inevitably succumb to disease. It could equally be argued that to wear a silk hat will make a man wealthy.

The error is so patent in cases that do not concern us that we feel we must inevitably see the error of our own ways if they are pointed out to us. The weather is influenced by many more factors than an outbreak of smallpox: surely, then, we would also see that our cherished beliefs on how to make rain and to forecast the weather are as insecurely founded, and that we practice them because we think they work, because we think they might work, or perhaps only because we know of no other undiscredited method and desire very much the result.

Natural philosophy is built upon; and as it progresses it explains away and improves upon our technology, which is our sorcery. All we need are grounds for hoping our methods will work and that we have no cause to fear disaster from them; we are then entitled to use them. We may even believe that the grounds will ultimately be shown to be false by an improved natural philosophy, but for our daily needs we must do our best.

Sorcery is the practice of magic; so is technology, in the sense that we only know it seems to work. We know that magic was not actually worked, but a magician would think only that our magic was more effective than his. The analogy is even closer than we might like to think, for as technology becomes more complicated the more does it depend on trial and error or upon the more sophisticated statistical techniques. We search for a method of obtaining the desired result and may hypothesise that some process is operating in order to explain our technique: our forebears imagined events to be governed by spirits, and thought that if a sorcerer performed a lottery in order to obtain guidance, then the spirits would determine the result of the lottery and thereby indicate their intentions. Their method of correlating their actions with events may often seem to us less direct than our own. Not always, however, for the hypothesis of controlling spirits led man to chase dust devils with spears, and to cut at the wind with swords when it oppressed him, and to light fires to scare away the rain, which from the sound it made as it fell upon the flames clearly did not like the heat; and this is certainly more direct than the operation of a silver iodide generator, that modern incense candle whose smell will please the clouds and make them rain.

But all these methods will seem equally ludicrous to a generation possessed of a far more advanced natural philosophy.

LONG RANGE FORECASTING

What are the possibilities? Weather types

In previous chapters we have discussed how a forecast is made by starting with the present situation and extrapolating it into the future. This extrapolation can be made in a variety of ways: it may be the forecaster's intuition born of experience, or a numerical or graphical method which assumes that the trends of the recent past will continue, or perhaps it is a highly sophisticated computation, using the basic dynamical equations which give an accurate description of the more important processes. In each case the forecaster uses his experience over a period of years, or the behaviour of the weather in the last day or two, or the basic equations of fluid motion, or perhaps a bit of all, to carry out the operation of transforming the weather of the present into the weather of the future. He always uses the latest information about the weather as the starting point, and is always very much influenced by its recent history.

External agencies, such as the heat input from the sun, supply energy which the atmospheric engine transforms as it works, and it is this working that we call the weather. The turnover is enormous—so large that the engine would come to a standstill in a few days if the input and output ceased. It is reasonable to expect, therefore, that the manner in which the engine is working now is unaffected by how it was working more than a few days ago: it is as if all the energy in the system the week before last has been used up and completely replaced by energy put in since then. A simple analogy may be given: the speed of a train ten seconds hence is very much determined by what it is now, whatever the driver may do, but its speed an hour from now depends entirely on its course and the action of the driver in the meantime. By controlling the input and output of energy the driver in a few minutes can bring the train to any speed of which it is capable, however fast it is travelling now. On the face of it, therefore, it would seem impossible to forecast beyond the time it would take for all traces of the present weather situation to be obliterated. All it is then possible to do is to look at past records and, as a forecast for a particular date, to give a description of the kind of weather that has been experienced in past years on that date. We can say, for instance, that 8th September is much less likely to be rainy than 20th October in Britain, or that 3rd February will be much colder than 3rd May —but we can never be sure! Furthermore, we are not really making a forecast for a particular day but for all days of that date in future years. This *forecasting by statistics* makes no attempt to use the weather of the moment, because it assumes it cannot help to know it. In this chapter, by long range forecasting, we mean the attempt to forecast a week or more ahead on the basis of the weather of the moment, using some method of transforming it into the future weather.

It is implied, therefore, that there is hope of doing this only if the present weather situation not only contains energy, which will be exhausted in about a week, but also some means for controlling the input and output of energy from the atmosphere, thereby continuing to determine the weather after all traces of its own energy are gone. It has long been observed that some features of the weather endure for about a fortnight and occasionally for as much as a month. Among these features are the Azores High and the Icelandic Low which can be seen on charts showing the average, or mean, pressure distribution for a month, a season, or even a year; but from time to time highs and lows appear in other places and, even so, endure for a long period. The first kind, like the Azores High, are situated where they are because of the shape of the continents and oceans. Similar lows and highs are found in the Pacific Ocean. The second kind may be thought of as an alternative to the first. The atmosphere operates in any one of several ways, the favourite way being with an Azores High and an Iceland Low, so that these features dominate the mean patterns; but it can also operate with an Azores Low, and does from time to time. There are also many other patterns of pressure which it finds acceptable, and in each of these patterns the energy input and output from and to outer space is guided in such a way as to perpetuate the pattern.

Of course each pattern does not perpetuate itself indefinitely; it only tends to perpetuate itself. The more common patterns are the modes of working in which the atmospheric engine finds itself most easily. These patterns are the well-known weather types, and some may be favoured at a particular time of year—the east winds of February, the north-westerlies of April, or the calms of September—but we can have them at almost any time—north-westerlies in February or September, east winds or calms in April, and so on.

A type of weather may often persist for many weeks because it contains mechanisms for perpetuating itself. These mechanisms are not entirely understood and will not be discussed here, but forecasters are well acquainted with their results.

Mean charts

If the chart of the average conditions during a spell of one type of weather is drawn it looks quite different from the average, or mean, chart for another type of weather. Thus, if one type is prevailing, this fact is more readily revealed by drawing a mean chart for the last few days than by drawing the latest chart. In a period of transition from one type to another the mean chart changes first in one place, and the change gradually spreads all over, and by the time it has reached the last corner it has begun to change again in the first place. The study of these mean charts has advanced about as far as the study of six-hourly charts had reached in the 1920's. It is possible now to give a forecast of the weather type to be experienced a week hence in quality very similar to the detailed forecast for a day or two ahead made 30 years ago, and such forecasts are made regularly by the Extended Forecast Section of the Weather Bureau in Washington. The head of this section, Mr. Jerome Namias, has been the chief pioneer of this work.

Just as in the 1920's many years' experience was, and for that matter still is, needed to make a forecaster competent to give forecasts for the next day or two, so now the art of long range forecasting takes years to learn; but we can expect that it too will become more and more of a science, and it is natural to wonder whether by an extension of the process another similar step forward might be made. The answer is almost certainly 'no'.

In this matter we depend very much on the actual way in which the weather is found to behave. Systems like depressions pass in a day or two, weather types last for a week or two, but beyond that we have not yet recognised any kind of behaviour other than the annual variation of the seasons, and we know that the causes for that are astronomical. They therefore do not depend at all on the present weather and do not come within the field of forecasting as here defined. Unless we can find some kind of behaviour in terms of which to express our forecast there can be no other kind of forecast to make. Meteorologists have often wondered whether we might forecast for much longer periods than the duration of weather types by a knowledge of the behaviour of the sun, whose moods have long been suspected as the cause of cold winters, dry summers, lean years, and the like.

Forecasting by sunspots

We have seen that though the atmosphere itself may guide the energy input it does not contain any store of energy by knowledge of which we can predict the air's behaviour for more than a day or two. Heat accumulated in the oceans, snow cover on the continents, and other influences at the earth's surface may have their influence, but the chief influence making a season one year different from that of another has long been thought to be the sun.

Considering the easy way in which speculations into the origin of the universe, whatever that may mean, of the galaxies, and of planetary systems have been made in recent years to satisfy man's thirst for an overall philosophy wherewith he may feel wise in the face of his most evident ignorance, perhaps we ought not to be surprised that so much attention has been available for these subjects while we still know very little in detail about our sun. If man in his paltry earth can engulf the whole of creation in his thoughts he can feel proud and can often sincerely believe a cosmology that enables him to do so. A philosophy of life and creation takes away the humiliation of our impotence so long as it is believed in, and since man's progress has usually been made by testing his wild guesses and finding them wrong, it means that his philosophy is of value only so long as it refers to the unknowable. As soon as it becomes open to verification it is no longer a thing to be believed in but is merely something someone is going to find out about, a particular fact and no longer of basic significance. As long as man could engage in fancies about the sun it was a basic element in his philosophy—the source of life and a god. But now it is just a particular star; it has no general or eternal significance; its interest for us lies in its particular behaviour and it is no longer an object of interest to cosmologists. The tedious task of understanding how the actual sun behaves in detail is left to those whose interest does not lie in the eternal, to the like of meteorologists, in fact, who are concerned with the actual circumstances of our life. Along with miners, seafarers, farmers and engineers, we deal with life as we find it and as we have to live it, while those who ought to be ready with the answers to our questions about the sun—the astrophysicists—busy themselves with 'red giants', 'white dwarfs', and all the other dramatis personae of modern cosmology.

The most apparent measure of the sun's behaviour is its spottiness, and as it is about the only thing that has been measured for many years, meteorologists have for decades searched for fluctuations of climate in sympathy with the so-called sunspot cycles which are about 11 years in length. But it is unsatisfactory to find a correlation between two things if we cannot understand the causal connection, and so all claims have been met with scepticism.

Recently Dr. Harry Wexler supposed, as others had done, that periods of large and small numbers of sunspots correspond to periods of maximum and minimum output of energy by the sun. He then argued that by varying its output the sun affected the world's weather, and that maps of this effect could be obtained by taking the difference between the average conditions for sunspot maxima and for sunspot minima. He therefore found the average pressure for January at times of sunspot maxima and the same for sunspot minima and drew a map showing the difference of these for North America. He did the same for temperature and rainfall, and so obtained maps of the effect of greater heating by the sun.

But since the heating by the sun is greater at the end of spring than at the beginning, the same patterns of pressure, temperature and rainfall should be found in maps showing the difference between February and May, for instance. On constructing these maps, Dr. Wexler found a striking similarity.

This simple experiment may be the beginning of a new technique of forecasting the weather of a season or even further ahead by predicting the behaviour of the sun. And this fits in well with our previous ideas because the sun, being much larger and therefore more slowly changed, will contain in its present condition more information about what it will be like many months or years hence than the earth's atmosphere whose energy is renewed every week.

Sunspots are scarcely understood at all. Perhaps they are due to tides in the sun produced by the planets, perhaps by tunnelling through changing concentrations of interstellar gas. They may be the mechanism or perhaps only a symptom of the variations in the sun's radiation. Perhaps a new technique, like the use of radio telescopes that led to the discovery of invisible radio stars, will discover for us the causes in the heavens: in the meantime here is new scope for the compilers of almanacks.

APPENDIX

THE GEOSTROPHIC WIND EQUATION

"These questions about movement lead partly far away into high mathematics."

Ruskin.

UNLESS acted upon by some force particles move in straight lines. Particles upon the surface of the earth move in curved paths because the earth is rotating in space. In order to follow these curved paths they are acted upon by a force, which is proportional to the acceleration to which they are subjected. If we can calculate the acceleration in space of a particle which appears to move in a 'straight line' on the earth, that is along a great circle, we know the force to which it must be subjected.

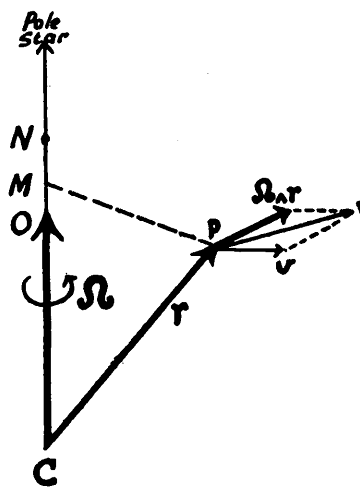

FIG. 24. *P is a point on the earth's surface,* $\mathbf{v}$ *the wind velocity, C the earth's centre and N the north pole.* $\Omega\wedge\mathbf{r}$ *is the velocity produced by the earth's rotation and* $\mathbf{V}$ *is the velocity in space of the air at P.*

The air is subjected to a force from high towards low pressure at right angles to the isobars, and if it is moving almost in a 'straight line' this pressure force must be exactly that which is required to make the air move on its truly curved path in space.

If C is the centre of the earth, N the north pole and P the position of a particle in the atmosphere, then the rotation of the earth can be represented by a *vector* (a line which has direction and magnitude) whose direction is along the axis of rotation CN and whose length is a measure of the speed of rotation; in Fig. 24 this vector is CO, and this we represent by the symbol $\mathbf{\Omega}$, Ω being the *speed* of rotation.

If the point P is fixed to the earth its velocity will be in a direction perpendicular to CP and to PM, the perpendicular from P to CN, and of magnitude $\Omega \times$ PM. This velocity we represent by $\mathbf{\Omega}_\wedge \mathbf{r}$ where $\mathbf{r}$ is the symbol for the vector CP, which is the position of P relative to the centre of the earth. $\mathbf{\Omega}_\wedge \mathbf{r}$ simply means a vector perpendicular to both the vectors $\mathbf{\Omega}$ and $\mathbf{r}$ and equal in magnitude to the product of the length of one and the length of the perpendicular from the other on to it.

If now the point P is moving over the surface of the earth with a velocity represented in magnitude and direction by the vector $\mathbf{v}$, then the total velocity of P in space, which we denote by $\mathbf{V}$, is equal to the sum of the two component velocities, and we write:

$$\mathbf{V} = \mathbf{v} + \mathbf{\Omega}_\wedge \mathbf{r}.$$

The two components must be added according to the parallelogram law.

This equation applies not only to the vectors representing velocity and position but to any vectors in this way: $\mathbf{V}$ is the rate of change of the position (the velocity) of P in space, $\mathbf{v}$ is the rate of change of the position of P relative to the earth, $\mathbf{\Omega}$ is the angular velocity of the earth, and $\mathbf{r}$ is the position of P. $\mathbf{V}$ and $\mathbf{v}$ are therefore symbols denoting the rates at which $\mathbf{r}$ is changing, and the equation would be the same whatever the vector $\mathbf{r}$ signified. We may denote $\mathbf{v}$ by the symbol $\frac{\partial}{\partial t}\mathbf{r}$ which simply means the rate of change of $\mathbf{r}$ relative to the earth, and then we can write the equation thus:

$$\mathbf{V} = \left[\frac{\partial}{\partial t} + \mathbf{\Omega}_\wedge\right]\mathbf{r}.$$

It is now in a form suitable for application to vectors other than $\mathbf{r}$. If we replace $\mathbf{r}$ by $\mathbf{V}$ then we must replace $\mathbf{V}$ by $\mathbf{A}$, the rate of change of velocity, that is acceleration, of the particle in space. We note also that $\frac{\partial}{\partial t}\mathbf{r} = \mathbf{v}$. Then

$$\begin{aligned} \mathbf{A} &= \left[\frac{\partial}{\partial t} + \Omega_\wedge\right]\mathbf{V} \\ &= \left[\frac{\partial}{\partial t} + \Omega_\wedge\right][\mathbf{v} + \Omega_\wedge \mathbf{r}] \\ &= \frac{\partial}{\partial t}\mathbf{v} + \Omega_\wedge \mathbf{v} + \Omega_\wedge \frac{\partial}{\partial t}\mathbf{r} + \Omega_\wedge[\Omega_\wedge \mathbf{r}] \\ &= \mathbf{a} + 2\Omega_\wedge \mathbf{v} + \Omega_\wedge[\Omega_\wedge \mathbf{v}]. \end{aligned}$$

In this way we have obtained an expression of **A** in terms of quantities we can measure upon the earth. **A** is the acceleration in space and is therefore equal to the force to which the air particle is subjected by the pressure. **a** is the acceleration of the particle relative to the earth, that is as measured by an

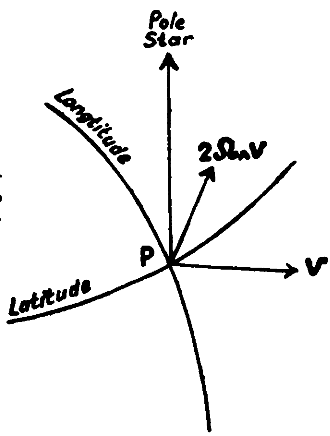

FIG. 25. *The earth's rotation produces a* geostrophic force *equal to* $2\,\Omega_\wedge\mathbf{r}$ *perpendicular to the wind* $\mathbf{v}$ *and the line through P parallel to the earth's axis.*

observer on the earth. $2\Omega_\wedge\mathbf{v}$ is a vector perpendicular to the velocity ($\mathbf{v}$) relative to the earth and to the polar axis, and whose magnitudes can be directly calculated while $\Omega_\wedge[\Omega_\wedge \mathbf{r}]$ depends only on the earth's rotation (Ω) and the position of the particle ($\mathbf{r}$), and so all particles are equally subjected to this acceleration which is the so-called *centrifugal force* and causes the earth to be an oblate spheroid, flattened at the poles. The earth's surface therefore slopes slightly and gravity thereby provides a force to give the acceleration $\Omega_\wedge[\Omega_\wedge \mathbf{r}]$.

When the acceleration is zero and the air is moving in a straight line over the earth, the only component of **A** that the pressure gradient has to supply is $2\boldsymbol{\Omega}_\wedge \mathbf{v}$. An idea of the direction of this acceleration is obtained by drawing a line through the particle perpendicular to a line joining it to the pole star (i.e. a line parallel to the earth's axis and therefore to $\boldsymbol{\Omega}$) and to its velocity in such a way that the three lines in that order thus form a right-handed screw. This vector will be seen to aim down into the ground in Fig. 25, and we are concerned here only with the horizontal component, because it is the horizontal accelerations that we are associating with the horizontal variations of atmospheric pressure. This component is obtained by taking only the vertical component of the vector P→polar star. This multiplies the magnitude of the acceleration by sin ϕ, ϕ being the latitude.

The formula, therefore, arrived at is that in order to keep a particle moving in a straight line over the earth an acceleration (to the left in the northern hemisphere) is required, of magnitude

$$2\Omega v \sin \phi.$$

In this v is the magnitude of $\mathbf{v}$.

In the southern hemisphere where ϕ is negative the acceleration is to the right. Thus, if we find that the air is moving with only a small acceleration relative to the earth so that $\mathbf{a}$ can be neglected (and this is generally approximately true), we know that the pressure must be producing the acceleration just calculated; thus the air is moving with low pressure on the left in the northern hemisphere with a speed, v, that can be calculated if the pressure distribution is known.

A mathematician will appreciate that there is no mystery about the symbolic operations we have executed to obtain this result; he is familiar with this kind of procedure. As this is the simplest of all the dynamical equations in meteorology, the reader will probably agree with the motto at the head of Chapter VI. Indeed, although this formula is in daily use by meteorologists the world over, we doubt whether more than a very small minority could readily justify it.

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"If you would appear to know anything, by far the best way is actually to know it."

The Golden Bough.