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THE WORLD AROUND US

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Six Essays
based upon the Christmas Lectures
delivered at the Royal Institution 1958

by

J. A. RATCLIFFE, C.B.E., F.R.S., G. E. R. DEACON, C.B.E., F.R.S., J. M. STAGG, C.B., O.B.E., O. G. SUTTON, K.T., C.B.E., F.R.S., R. L. F. BOYD, and G. de Q. ROBIN.

Edited by SIR GRAHAM SUTTON, C.B.E., F.R.S.



THE ENGLISH UNIVERSITIES PRESS LTD
102 NEWGATE STREET
LONDON, E.C.1

First printed 1960

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The English Universities Press Ltd.,
1960

Printed in Great Britain for the English Universities Press Ltd.
by Richard Clay and Company, Ltd., Bungay, Suffolk

EDITOR'S FOREWORD

THE SIX essays which make up this book are based upon the Christmas Lectures, delivered to audiences consisting for the most part of young people, at the Royal Institution in December 1958 and January 1959. The Lectures were planned by Sir Lawrence Bragg, the Director of the Royal Institution, to mark the close of the International Geophysical Year.

It is a tradition of the Christmas Lectures that they are copiously illustrated by demonstrations, experiments and films. The essays in this book, although they follow the lectures in substance, necessarily differ from them in form. The accounts given here are not intended to be read as summaries of the work undertaken by geophysicists during the eighteen months of the I.G.Y., but as introductions to some of the problems that engage the attention of those who work in the earth sciences. As such, it is hoped that they will interest many readers, young and old, who have a lively curiosity about the world around us.

The authors wish to express their thanks to Sir Lawrence Bragg for his guidance during the preparation of the lectures, and to the staff of the Royal Institution for their skilled assistance in the demonstrations. Our thanks also go to the English Universities Press and especially to Mr. John Maitland, the Managing Editor of the Press, for making this publication possible.

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I

THE IONOSPHERE

THE IONOSPHERE, of which Mr. Ratcliffe writes in the essay which follows, is the electrified part of the upper atmosphere. Its existence was not suspected until electromagnetic waves were used for long-distance communication without the use of wires or cables. Before Marconi showed that his signals could cross the Atlantic, many physicists had come to the conclusion that long-distance communication by radio waves was impossible, because at that time there was no knowledge of the existence of the ionosphere. It is also of interest that the pulse technique, which is the heart of radar, was evolved in order to explore the ionosphere, an outstanding example of research which once seemed remote and academic in its aims proving to be of the utmost importance both in war and peace.

Mr. Ratcliffe is Reader in Physics at the Cavendish Laboratory of the University of Cambridge, but he is soon to take up a new appointment, that of Director of Radio Research in the Department of Scientific and Industrial Research. He is a pioneer worker in radio and radar and was elected to the Fellowship of the Royal Society in 1951.

I

MANY OF the investigations to be described in this book are concerned with the highest parts of the earth's atmosphere, so it is first necessary to have some idea what it is like up there. If we went to the top of a high mountain we would find that breathing was very difficult, because there is less air at the top than at the ground. If we flew at a great height in an aeroplane we could not breathe at all, we should have to have air supplied to us in a pressurised cabin. In fact, the pressure of the air, or the concentration of the air molecules, decreases continuously as we rise higher. It has fallen to about one-tenth when we have gone up 20 kilometres, and then again to one-tenth of that, or one-hundredth of the original value, in the next 20 kilometres and so on, so that the pressure 100 kilometres above the earth is about one ten-thousandth of that at the earth's surface. This is very low indeed, and at still greater heights the pressure is less than that in the best vacuum we can make in the laboratory. It is this part of the atmosphere, where the concentration of molecules is much less than it is at the ground, which we shall discuss in this chapter.

During the day this very tenuous air is irradiated by the sun, not only with the visible light which reaches us on the earth but also with ultra-violet and X-rays. These radiations "ionise" the air; that is to say, they strip electrons off the molecules which they find up there. These electrons are very light and are electrically charged, and if they are sufficiently concentrated they can reflect radio waves. That part of the atmosphere which contains enough electrons to reflect radio waves in this way has been called the "ionosphere".

The ionosphere can be explored by means of radio waves in the following way. A short burst of waves from a sender on the ground is received at the same place when it returns after being reflected by the ionosphere, and is made to deflect a spot on a cathode-ray tube so as to give a trace like that shown in Figure 1. Here the spot is made to start moving from left to right at a known

speed when the wave is emitted from the ground, and when the radio-echo returns from the ionosphere the spot is made to move vertically, as shown at the point marked "echo". By measuring the distance from the start of the trace to the start of the echo it is possible, if the speed of the spot is known, to work out the time of travel of the wave to the ionosphere and back; then, if we know the speed at which radio waves travel, we can calculate the height at which the reflection occurred. It turns out to be round about 100 or 200 kilometres.

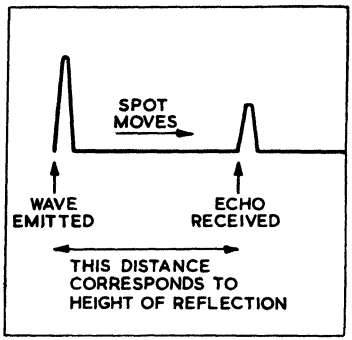


FIGURE 1. To illustrate how the trace on the screen of a cathode-ray tube is used to measure the height of reflection of a short burst of radio waves.

Different radio waves travel to different heights, and to understand why this is we must say a little more about their nature. There are many different kinds of waves, and to discuss them it is convenient to think of a series of waves on the surface of water, and to represent them diagrammatically as in Figure 2. These waves would move forwards so that at any fixed point the water moved up and down as they passed. The number of these up-and-down oscillations which occur in one second is called "the frequency" of the wave. The distance between one peak and the next is called the "wavelength". If the frequency is greater the wavelength is less. With the waves on water the frequency is about one or two oscillations per second. The radio waves we shall discuss are quite different from the waves on water; they are electric in nature and can travel through empty space. But we still speak of their speed, frequency and wavelength.

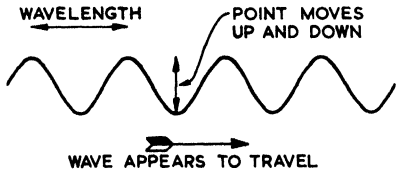


FIGURE 2. To illustrate the idea of a wave-motion.

We can make radio waves of any frequency we like by arranging

that an electric current flows back and forth in a wire at the required frequency. The wire is then the transmitting aerial. For purposes of exploring the ionosphere we make use of waves in which the current is changing very rapidly indeed, that is, waves with a very high frequency: in fact, about one million oscillations per second.

The question now arises, "What happens in our ionospheric experiment if we change the radio-wave frequency?" It turns out that if the frequency is increased we require a greater concentration of electrons to reflect the wave, and since the concentration increases as we ascend, the height of reflection of the waves increases as their frequency is increased. It is found, for example,

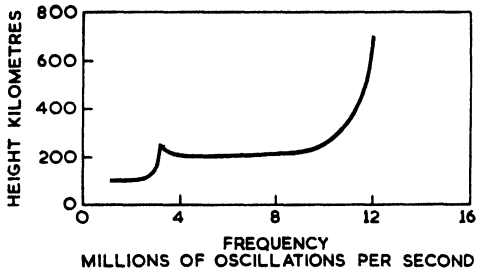


FIGURE 3. An "ionogram" or automatic record which shows the height of reflection of radio waves of different frequency.

that waves with a frequency of about one million oscillations per second are reflected from heights of about 100 kilometres, while those of frequency about five million per second are reflected from about 250 or 300 kilometres. By altering the wave-frequency, and finding how the corresponding height of reflection changes, we can find the concentration of the electrons at each height. The process is known as "ionospheric echo sounding" because we make use of the "radio-echo" from the upper atmosphere to "sound" the (upwards) depth of the ionosphere much as a mariner sounds the depths of the ocean.

A network of ionospheric observatories spread widely over the earth is engaged regularly in making soundings of the ionosphere in this way. Their apparatus provides automatic records of the kind shown diagrammatically in Figure 3. These records are known as ionograms. In them the height of reflection is plotted

against the radio frequency, and from them it is possible to calculate the concentration of electrons at different heights above the observatory. It will be noticed that in the record shown in Figure 3 there is no echo at all on frequencies greater than 12 million oscillations per second. This is because there is not a great enough concentration of electrons at any height to reflect these waves. They penetrate right through the ionosphere and get away into space.

When electron concentrations at the different heights are calculated from an ionogram of the kind shown in Figure 3 we get

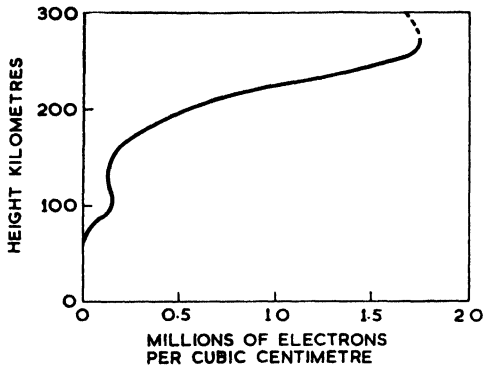


FIGURE 4. The curve shows the concentration of electrons at different heights in the ionosphere. It has been calculated from a record like that shown in Figure 3.

results of the kind shown in Figure 4, where the electron concentration is plotted as "the number of electrons per cubic centimetre" against the height measured in kilometres. The shape of this curve changes through the day, through the year and over the world. A series of electron distributions observed over England throughout a day in summer are shown in Figure 5. It is noticeable how the electron concentration is greatest near midday, when the sun's radiation is continually producing fresh electrons, and how it decreases in the night when the electrons are attaching themselves to the air molecules again and no fresh ones are being liberated. Quite different results would be found at other places and other seasons, and an important purpose of ionospheric re-

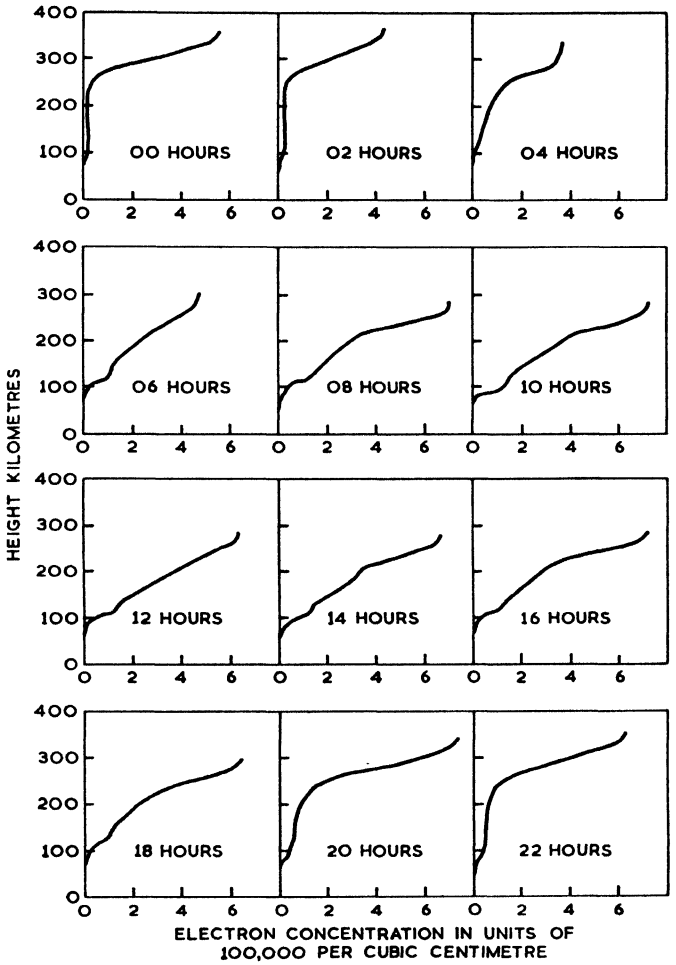


FIGURE 5. The electron distributions measured at two-hourly intervals throughout a day. Note how there are most electrons near midday, and least at 04 hours, just before sunrise.

search is to determine how these electron distributions vary from time to time and from place to place.

On some days the electron distribution is found to be quite different. An example is shown in the dashed curve of Figure 6, which should be compared with the continuous curve which shows the record for a normal day. When this sort of result is obtained at one observatory peculiar results are usually also obtained elsewhere and it is said that an "ionosphere storm" is in progress. These storms are electrical in nature and affect only the ionosphere; they are not related to the weather at ground level and are

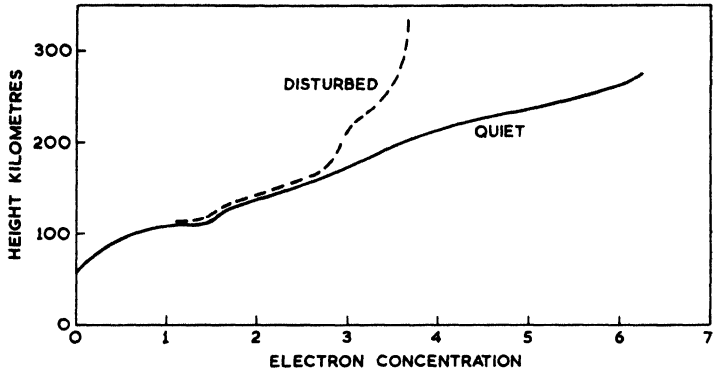


FIGURE 6. The electron distributions on a "quiet" day and a "disturbed" day, of the kind which occurs during an ionosphere storm. Electron concentrations are shown in millions per cubic centimetre.

of a nature quite different from that of ordinary meteorological storms. They are closely related to magnetic storms, which will be more fully discussed in Chapter II. It will there be mentioned that they are the result of disturbance in the sun's ionising radiation associated with the occurrence of visible sunspots. If observations of the sun lead to the expectation that an ionosphere storm of this kind is imminent a special warning is sent round to all ionospheric observatories so that ionograms can be made more frequently for the purpose of finding out in detail what changes occur in the ionosphere.

These investigations with ionospheric sounders show that the concentration of electrons increases up to a peak at a height of about 250 kilometres, but that above that level it drops off. They

cannot, however, give information about the concentration above the peak. If, however, we were situated outside the ionosphere, and could observe the high-frequency waves which penetrate the electron layer, we might be able to make deductions about these higher levels of the ionosphere. Although so far this is impossible, attempts have, however, been made with the help of an artificial satellite to do the experiment the other way round, and to observe at the ground the waves emitted from above the layer so that they have traversed it in reaching our observing apparatus.

The artificial satellite is made to radiate radio waves continuously and steadily on a frequency great enough to penetrate the ionosphere. These are observed at the ground with two pieces of

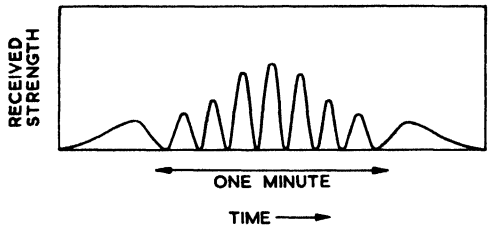


FIGURE 7. The type of record obtained when a radiating artificial satellite travels past an "interferometer" apparatus for measuring its angular position.

apparatus: one gives the direction of arrival of the waves and the other gives the speed at which the satellite is approaching or receding. If the ionosphere had no effect on the waves traversing it the angle of arrival and the speed of approach or recession should behave in a smooth and predictable way, but the presence of the ionosphere modifies the simple behaviour, and from the results it is possible to calculate something about the electron concentration above the peak of the layer.

The direction of arrival of the waves is measured by receiving them simultaneously on two aerials connected to one and the same receiver. As the angle alters, the composite signal waxes and wanes, and there are a series of positions where it vanishes. An automatic record of the ouput of the receiver looks like Figure 7, and by noting the times when the signal is zero it is possible to work out how the angle varies. It is found that it does not vary

quite as it would for a smoothly moving satellite, and the difference is ascribed to the effect of the ionosphere.

The speed of approach or recession is found by observing what is known as the "Doppler effect". This effect causes the frequency received from an approaching transmitter to be increased and that from a receding one to be decreased. The corresponding effect is often noticed with sound waves when a railway engine sounding its whistle passes by at speed. As the engine passes, the pitch of the note is heard to drop appreciably corresponding to the drop of frequency as the source changes over from approaching to reced-

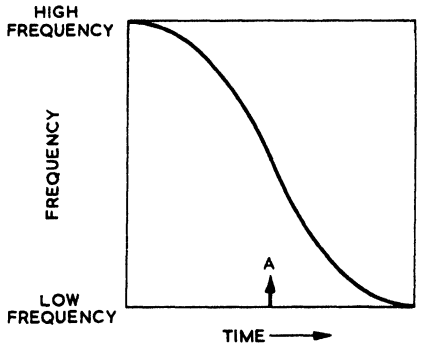


FIGURE 8. To show how the frequency received from a moving source of waves varies with time. A marks the point where the source is nearest, before the time A it is approaching, and the received frequency is high, after the time A it is receding, and the frequency is low. This is the Doppler Effect.

ing. If the observer is near the engine when it passes the drop in the note is sudden, if he is far away it is more gradual. If the pitch, or the frequency, of the note is plotted against time a curve of the kind shown in Figure 8 will result. In this figure A marks the time when the engine is at its closest point. With the radio waves special equipment has to be provided to measure the frequency, and then a curve of the kind shown in Figure 8 is drawn. Once again it is found that this curve is not of the shape which would be expected, and by examining how it departs from that shape we can obtain information about the electron concentration in the ionosphere. A curve observed as one of the artificial satellites passed near by is shown in Figure 9.

Measurements made on the radio waves emitted from artificial satellites by these and other methods have given some indication of how the electron concentration drops off above the peak of the ionospheric layer. For determining this drop-off it is fortunate that some of the early satellites passed near any one observing station twice in each day, once at a comparatively small height, about 200 kilometres, and once at a great one, about 500 kilometres. This provided measurements at two heights: much more needs to be done to find what the upper side of the layer is like at different places and times of day and season.

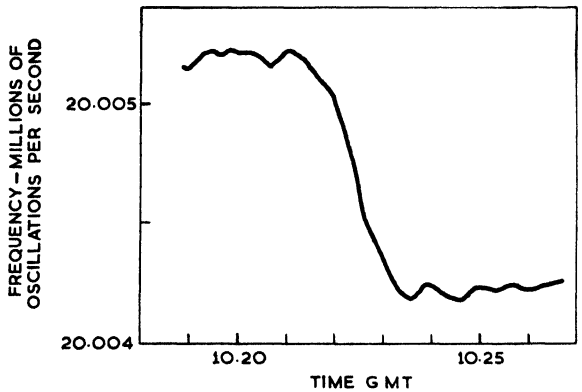


FIGURE 9. A "Doppler-curve" of the kind sketched in Figure 8, recorded on an artificial satellite. The kinks on the curve are produced by the ionosphere.

Another phenomenon noticeable in the result of Figure 9 is that the Doppler curve is not smooth but has irregular "kinks" on it. These are not yet properly understood, but it is thought that they indicate that the ionosphere is irregular in the horizontal direction. Experiments on the direction of arrival of the waves have led to similar conclusions.

Let us now consider another method of investigating the highest parts of the ionosphere, which makes use of the fact that nature provides some of the very strongest radio transmitters every time there is a lightning flash. These flashes consist of sparks several hundred metres long in which there are intense and rapidly changing currents, and they radiate waves similar to those from an

ordinary transmitter. The waves radiated by nature differ from those radiated from man-made transmitters, partly because they contain a wide range of different frequencies instead of only one, and partly because those frequencies are lower, in the range between about 100 and 10,000 oscillations per second. These lower frequencies are of the kind that we are used to in sound waves, where, for example, middle C on the piano has a frequency of about 250 oscillations per second, and the highest audible note is about 10,000 per second. Of course, the waves radiated by the lightning flash are not sound waves, they are electric (radio) waves and cannot stimulate our ears.

If we wish to receive these radio waves from nature's transmitters we must use an audio-frequency amplifier, of the kind used with a gramophone pick-up, to receive the changing electric field in the wave, to amplify it and to pass it to a loudspeaker which will turn it into an audible sound. If this is done we hear a crash or bang as each lightning flash occurs, and when the crashes and bangs from the lightning within, say, 1,000 kilometres are all received at once they make a noise like an intense artillery bombardment. The ear does not hear any musical note at all, because in each of the individual crashes all the different frequencies are radiated and are heard at the same time, and when that happens the ear does not recognise them separately, it interprets the sound simply as a violent noise. If, however, we listen very carefully we often hear, mixed up among the bangs and crashes, some very surprising noises which take the form of clear whistles. These have a characteristic form, starting with a high note and finishing with a low one, a sound which can be roughly imitated by saying "peeeooo". Analysis of these whistles has led to some interesting information about the highest parts of the ionosphere, but to explain how this is done we must first digress a little and consider the nature of the earth's magnetism.

It is known that the earth is a huge magnet, and like any other magnet, it exerts forces on compass needles near it. The region near any magnet in which these forces can be exerted is called a magnetic field, and its state can be pictured by sprinkling small iron filings round the magnet and noticing that they tend to set in the shape of curves running from one end or pole to the other. It is usual to describe the "magnetic field" round a magnet by drawing these lines, which are then called "lines of magnetic force".

They show in an idealised form how the iron filings would set. If we could map out the magnetic field round the earth with iron filings in the same way the lines of force would be like those shown in Figure 10.

Now when the low-frequency radio waves from a lightning flash enter the ionosphere they are profoundly affected by the earth's magnetic field, in two important ways. First, the presence of the field enables them to penetrate the ionosphere, although there are enough electrons to reflect them at a low level in the absence of a field; and second, the field "takes hold" of the waves, as

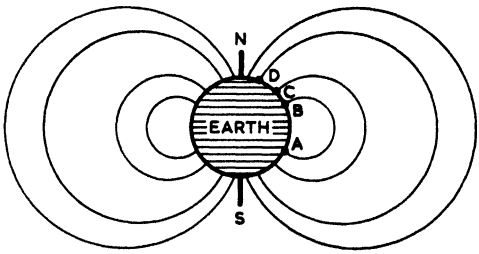


FIGURE 10. To illustrate the magnetic "lines of force" of the earth, and the origin of "whistling atmospherics".

it were, and forces them to follow it along a line of magnetic force through the ionosphere. If, for example, the lightning flash occurs at a point such as A in Figure 10 the waves will travel along the line of force shown and will arrive at a point B in the other hemisphere. We might, therefore, expect that the observer at B would hear the same crash or bang as the one at A, but this is not in fact what happens, because the waves of higher frequency travel through the ionosphere faster and arrive first. The result is that all the notes in the original wave are separated out in order, the high notes coming first and the low ones at the end so as to give the characteristic "peee-ooo" sound of the whistle. The interval of time between the high and the low notes depends on the length of the path travelled and on the concentration of the electrons, particularly those at the outermost parts of the line of force. If now whistles of this kind are observed at a series of different places on the earth, such as B, C, D in Figure 10, the corresponding line of force will reach to different distances above the earth, so that by

measuring the spread of the frequencies in the corresponding whistles it is possible to estimate the electron concentrations at these various distances. Only a few rather uncertain results have been obtained so far, they are plotted on the graph of Figure 11 as crosses, and when combined with results from artificial satellites they give the best indications we have about the electron concentration far out in the ionosphere.

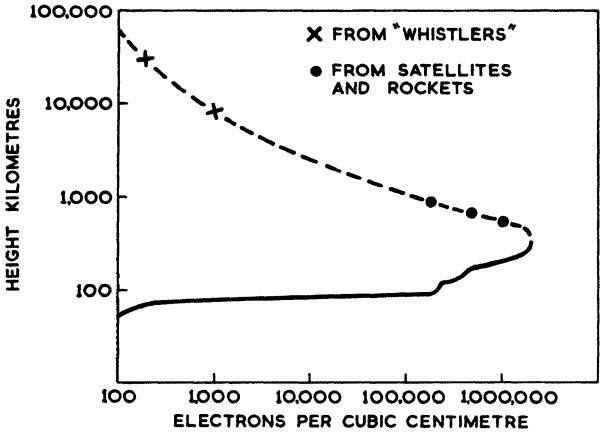


FIGURE 11. Electron concentrations at great heights calculated from observations of "whistling atmospherics" and waves emitted from artificial satellites. Note that the scale of height is "logarithmic".

Figure 11 shows that, at these great distances, the electron concentration is much smaller than it is at the peak of the layer, and it will be interesting to find out, in the future, what happens at even greater distances. It has recently been suggested that the electron concentration does not continue to decrease indefinitely as we go farther and farther away from the earth, but that the ionosphere merges imperceptibly into the outer atmosphere of the sun, which extends in a very tenuous form right out as far as the earth and even farther. It is probable that we shall soon be able to investigate these matters with satellites sent out to those great distances.

II

THE EARTH'S MAGNETISM

THE FACT that the earth is a great magnet has played a large part in the development of civilisation, for without the magnetic compass the world could hardly have been opened up as quickly as it was by the long and daring voyages of the early explorers. But, as Dr. Stagg shows, the simple concept of the earth as a great bar magnet with one pole in the Arctic and the other in the Antarctic, will not do. The real situation is far more complex, and the geomagnetician must take into account not only the vast slow surges of the earth's liquid core but also the workings of the complicated electrical machine formed by the sun, the atmosphere and the globe itself. The world of the geomagnetician does not affect our senses as does the world of the meteorologist and the oceanographer, but it has its storms and its quiet days just the same. Terrestrial magnetism has long been the study of the few, but today its importance in practical affairs, such as radio communication, is being increasingly recognised.

Dr. Stagg is the Director of Services in the Meteorological Office. He is one of the few geophysicists who have expert knowledge of two disciplines, for he is equally distinguished in meteorology and in terrestrial magnetism.

II

Is THE earth a magnet: how could we prove it? We might do it by taking a freely suspended magnetised needle from place to place, and by showing that the earth acts on the needle in the same general way as would a known magnet. More precisely, we need to prove that the earth has a magnetic field, as it is called, at every point of which it exerts on another magnet a force whose direction and strength is what it should be if a great magnet were substituted for the earth. This notion of a field of force surrounding every magnet will play an important part in considering the special case of the earth's magnetism, and we should have an idea of its pattern and properties. For a bar magnet we can get this by sprinkling iron filings on a sheet of paper laid over it. The filings are constrained to arrange themselves along lines called lines of force which fill the whole space around the magnet, and they curve farther and farther out with increasing distance from it. Figure 1 shows what happens when this experiment is done with a sphere to represent the earth with a magnet inside.

Now the earth affects a freely suspended compass needle in the same general way. Along a line near the equator the needle is horizontal; northward and southward of the equator the needle inclines progressively more from the horizontal until, on Boothia Peninsula in north-east Canada, it is vertical with its north-pole end pointing downwards and in Antarctica it is also vertical with the other end down. From such observations about the direction and strength of the field made at many places over the earth we can deduce that to magnets outside it the earth behaves broadly as if it contained a great magnet.

This is very well so far as it goes, but as soon as we examine details we find so many irregularities to account for that the simple picture almost disappears. For example, the earth's magnetic poles are not at opposite ends of a diameter through the earth's centre. The lines of force along the surface that determine the direction in which a compass needle points do not run directly

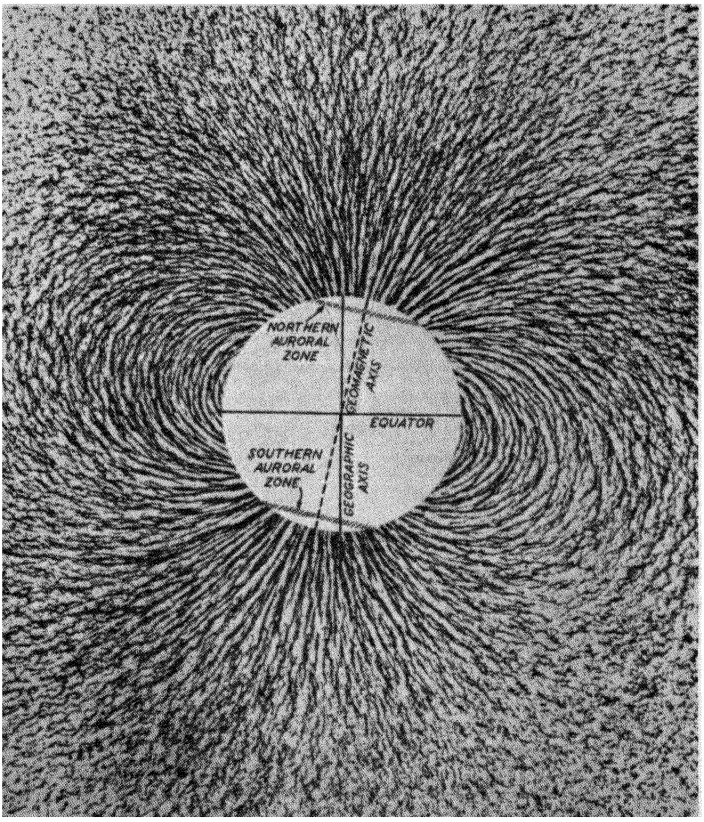


FIGURE 1. Magnetic field around a sphere with a magnet inside it.

from one pole to the other along great circles: they deviate round great regional anomalies where the earth's magnetism is much stronger or much weaker than it should be if the earth were a simple form of magnet (Figure 2). What is still more surprising is that the whole field is continually changing, slowly but not steadily or uniformly, over the whole earth's surface. Between the end of the sixteenth century and 1820 the compass needle in London gradually changed its direction from $11\frac{1}{2}^\circ$ east of true north to 24° west, and since 1820 it has swung slowly east again so that today it

points 8° west. There are great regions in both hemispheres where the variation has been greater than in London, and these regions are altering in shape and drifting, on the whole, westward.

Clearly, no kind of movement of a single simple magnet within the earth can account for all these effects, and for many years the cause of the earth's magnetism with its slow and irregular changes has been one of the great unsolved problems. It is only very recently that the outlines of a feasible theory have been worked out. From evidence about the structure of the earth's interior provided by earthquakes it is almost certain that the earth has a

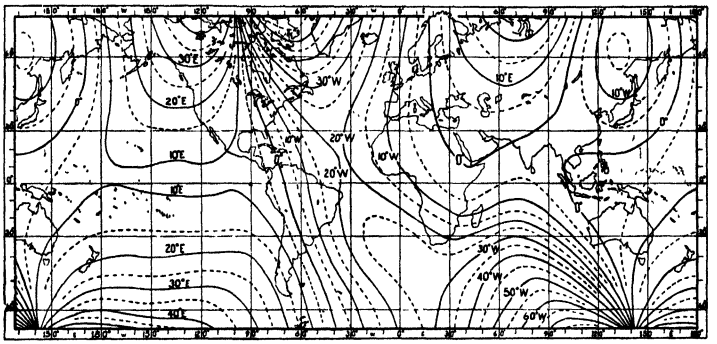


FIGURE 2. Chart of lines of equal declination, 1955. At all places along a line the compass needle makes the same angle with true north.

Reproduced from a British Admiralty Chart with permission of the Controller H.M.S.O. and of the Hydrographer of the Navy.

fluid core, probably composed of nickel–iron, extending outwards from the centre to about half the earth's radius. Partly because of the earth's rotation and partly from slight gradients of temperature, great convection cells of circulating material are set up within the core. As the material is electrically conducting, these circulating cells behave like huge solenoids carrying electric current which have their axes, and therefore their combined magnetic field, predominantly parallel though out of line with the earth's axis of rotation. But some of the smaller cells deviate from this predominant direction and so produce subsidiary poles on the earth's surface. These smaller cells can alter their shape slowly and can even grow and collapse again independently of the great central

solenoids, and so they contribute their own slow changes to the shape of the field at the surface.

No one yet has any clear idea of how the currents in the core were first excited: even the precise manner in which the field at the earth's surface is actually changing is not sufficiently well known, except over some of the land areas where accurate magnetic surveys have been made. This is one reason why so many new observatories for measuring the earth's magnetism have been set up during the I.G.Y. in parts of the world (for example, the Antarctic continent) not hitherto well explored. It is also the reason why a great effort is to be made in the next few years to chart the state of the earth's magnetism over the great areas of ocean where few measurements have ever been made. Hitherto magnetic observa-

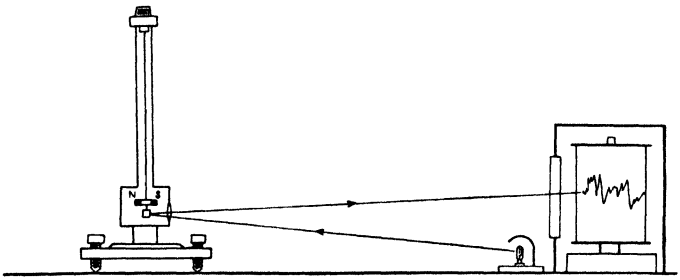


FIGURE 3. Principle of the magnetograph.

tions at sea have been possible only in specially built ships from which iron and steel have been excluded. But now a completely new type of measuring instrument has been introduced for this kind of work. Called the nuclear precession magnetometer, this instrument completely eliminates the need for magnets suspended by fibres or supported on pivots. Ensconced inside a "fish"—the name given to a special torpedo-shaped casing—it can be dragged behind any ship at the end of a long tow-line, far enough away to be unaffected by the ship's steel; and it gives accurate measurements of the earth's field recorded automatically on the ship itself.

Up to this stage we have been considering the earth's so-called permanent magnetism—that part which originates within the earth and which, though not at all constant, changes only slowly from year to year. What we have to look at now is the smaller but not less interesting contribution to the field from outside the earth. In

contrast with the slowly altering permanent field, the externally produced part varies from hour to hour, at times from minute to minute and frequently with fluctuating irregularity.

To study these transient changes we use the records from a magnetograph (Figure 3). In this simple apparatus a magnet with a mirror attached to it is suspended by a quartz fibre. A ray of light directed to the mirror from a lamp is reflected back on to a sheet of photographic paper which is wrapped round a drum that rotates by clockwork once every day. If the magnet has been steady a straight line appears on the paper when it is developed.

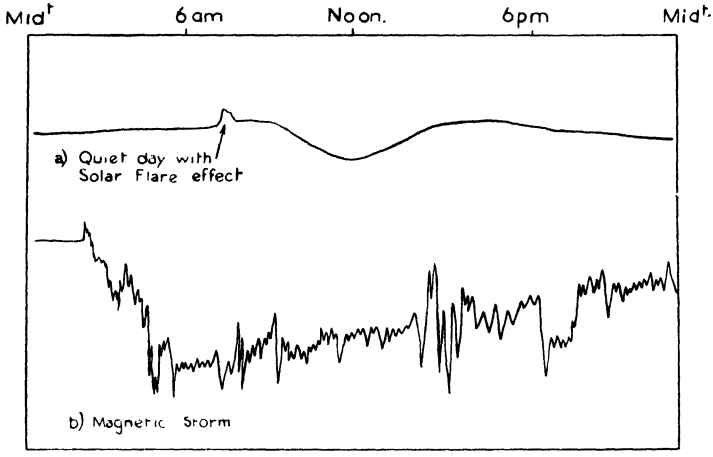


FIGURE 4. Representation of a magnetically quiet day and a storm.

But in practice it never is straight; the recording is either a smooth curve (Figure 4(*a*)) or a very irregular and rapidly fluctuating line (Figure 4(*b*)), or partly one and partly the other. Days on which a smooth, undulating curve is recorded are called magnetically quiet days; the others are called disturbed days or days of storm if the disturbance is continuous with intervals of violent activity.

The quiet days are interesting principally because of the way the regular variation is produced. By comparing the magnetograph recordings from observatories in different parts of the world we find that a quiet day in one place is usually quiet everywhere; further, as can be seen in Figure 4(*a*), most of the variation in any one locality occurs in the hours around noon when the sun is

overhead, the magnet remaining fairly steady during the hours of darkness. Whether the magnet swings to one side or the other before noon, and how far it swings, depends on the latitude of the place and on the season of the year: the variation is also greater in years of high sunspot activity than it is when the sun is quiet.

All this points to the sun as being the cause, direct or otherwise, of the variation on quiet days. Now the sun has a magnetic field, but it is not strong enough at the earth's distance to affect the earth's field directly; neither could it affect the great currents deep down in the earth's core in such a way as to produce these regular daily changes. The mechanism must be indirect and probably lies 60 miles up in our atmosphere. Just as the sun and the moon produce tides in the oceans by their gravitational pulls, so they also produce tides in the atmosphere. The important difference is that, due to the way temperature varies upward through the atmosphere, the tides produced at high levels by the sun are greater than those made by the moon: this is, of course, the opposite of what occurs with the ocean tides. Now because the conducting layers of the ionosphere are embedded in the atmosphere they also undergo the tidal motions, and, by a rather complex process, a kind of slow but massive dynamo is formed. The armature of the dynamo is the ionosphere; its rotation is the system of winds produced by the up-and-down motion of the tides, and the field is the earth's magnetic field. As each part of the earth in its daily rotation turns round to face the sun great circular whorls of electric current, amounting to 60,000 amperes on the average day, are produced in one of the lower layers of the ionosphere, and it is the magnetic field of these great currents as they move hour by hour westwards over the earth that produces the quiet-day variations at the earth's surface. Until recently uncertainty existed about the exact layer in the ionosphere at which the currents flow, but this uncertainty is disappearing. Preliminary information from rockets equipped with the kind of magnetometer we have described for use in the survey of the oceans confirms that the dynamo currents are 55–60 miles above the earth's surface, and therefore probably lie in the E layer of the ionosphere.

We shall now consider what happens during a magnetic disturbance or storm. At any time of day or night, at any season of the year, though perhaps most frequently around the equinoxes, and more frequently in years near the maximum of each eleven-year

cycle of solar activity—at any of these times the smooth, quiet-day kind of record is liable to give place to an irregular, jerky type of oscillation (Figure 4(*b*)). A magnetic disturbance has started, and it may develop into a real storm and continue for two or three days.

Unlike a storm of weather which, however severe, is restricted to particular areas of the world (depressions over the British Isles, hurricanes in the eastern United States, typhoons in the China Sea and so on) a magnetic storm is both world-wide and simultaneous everywhere. Following a quiet period, it begins most usually with a sudden increase of the magnetic force, followed by a slower but greater decrease, then a gradual build-up over several days to the value it had before the storm started. But on top of this basic pattern a recording of a storm usually also shows a series of spasmodic fluctuations, each lasting for a time that may be anything from under a minute to an hour or two. These fluctuations are greatest at places along two roughly circular zones, one in each hemisphere, where aurora is most frequently observed, and there the magnetograph needle may swing through 10° in the course of a storm. The position of these important zones needs an explanation. Like the arctic and antarctic circles around the geographical poles these zones encircle the points where the earth's surface is pierced by the axis of a hypothetical magnet inside the earth whose field represents the main features of the actual field but without its irregularities. In our hemisphere this geomagnetic axis, as it is called in Figure 1, intersects the surface in the extreme north-west corner of Greenland, so that part of the northern zone of maximum auroral frequency lies between Shetland and Iceland. That is why recordings made at the observatory near Lerwick are so important.

When a magnetic storm or big disturbance is in progress, other things are usually happening at the same time in the high atmosphere and in the space around the earth. Displays of aurora are seen in the sky during dark hours, the ionosphere is disturbed so that it ceases to serve as a reflector for short-wave radio and communications are disrupted, and big changes occur in the number of cosmic-ray particles which reach the earth. These events do not invariably occur each time there is a magnetic disturbance; but when the disturbance is really intense and world-wide—when it is a storm—they all proceed simultaneously and are generally

accompanied by the appearance of specially active areas on the side of the sun facing the earth.

One particular case gives a clue to the explanation of this most interesting combination of natural phenomena. From time to time a bright eruption or flare suddenly appears on the sun's disc. The flare may last only half an hour, sometimes less; but by the time it has been seen (and that is eight minutes after it has actually started on the sun) things begin to happen on the earth. The quiet-day magnetic variation is suddenly increased, as if the season had advanced at one leap from mid-winter to mid-summer (Figure 4(*a*)): long-distance communications by radio are blacked out and the intensity of cosmic rays is increased. As the solar flare dies down the state of the earth's magnetic field, its ionosphere and the cosmic-ray influx return gradually to normal. Then after an interval which is usually about a day the magnetic field becomes suddenly disturbed and, going through the pattern of phases already described but overlaid with much fluctuation, especially along the zones of maximum auroral frequency, it continues disturbed for a day or more (Figure 4(*b*)). Meanwhile aurora has appeared during the dark hours in both hemispheres (Figure 5). Starting with a quiet arc of yellowish-green luminescence across the sky, the aurora develops vertical-ray structure throughout the arc, the rays shoot upwards to form long streamers or curtains which move rapidly about the sky with vivid colours from green to deep red. At times they illuminate the landscape with an intensity nearly equal to full moon. And while all this is in progress communication both by radio and by cable is interrupted.

We should, perhaps, note here that magnetic disturbance and those other phenomena that accompany it do not always follow the sequence and pattern just described. It would be truer to say that no two disturbances are ever exactly alike in their magnetic, auroral or other effects. One main distinction is between those storms that start suddenly and simultaneously over the world and which can frequently be linked with solar flares or similar short-lived eruptions in the neighbourhood of sunspots—those storms on the one hand, and on the other the smaller disturbances which begin gradually, are of greatest intensity in high latitudes and cannot be linked with any specific kind of activity on the sun. It is a fact that disturbance in general waxes and wanes throughout the eleven-year cycle of sunspot activity; indeed, it was because we

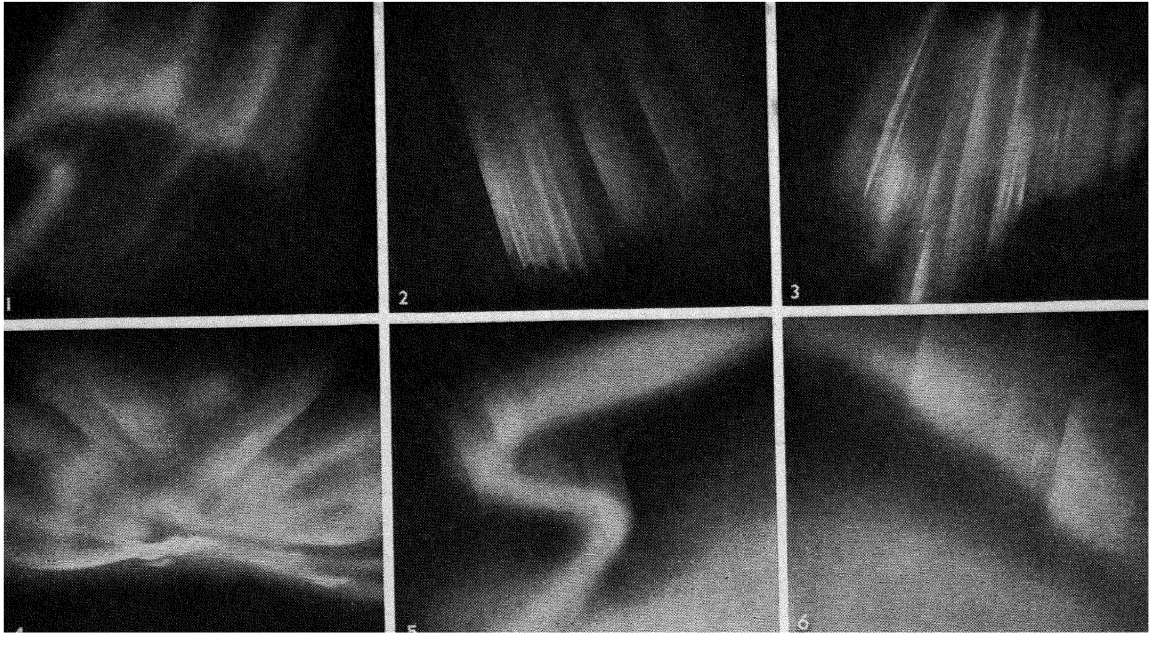


FIGURE 5. Forms of aurora. 1. Draperies. 2. Rays. 3. Curtain. 4. Corona. 5. Bands with ray structure. 6. Rayed arc.

wished to record as many disturbances as possible that 1957–58 near the maximum of the present sunspot cycle was chosen as the International Geophysical Year. It is also true that magnetic disturbances tend to follow one another at intervals of about twenty-seven days, which is the interval between reappearances of a sunspot in the same position facing the earth as a consequence of the sun's rotation. But it is just those smaller disturbances that most conspicuously show this twenty-seven day recurrence tendency, which cannot be associated with noticeably disturbed areas of the sun: the big storms which can be linked with specific occurrences on the sun usually make once-only appearances.

Many theories have been put forward to explain these widely differing effects. But with so many things to account for it is not surprising that no one theory can comprehend them all. Indeed, it will only be after the data collected from the I.G.Y. stations in both hemispheres have been studied that we shall know exactly what facts have to be explained. It is not known, for example, whether the aurora follows the same pattern in both hemispheres at the same time, or what the relation is between particular kinds of perturbation in the magnetic field and particular features of aurora in either hemisphere. These and many other similar relations have yet to be examined, but enough is known to provide a broad outline of the kind of mechanism that comes into action when a solar flare occurs.

From the fact that its first effects on the earth start as soon as the solar flare is seen, we can infer that the agent which bridges the 93,000,000-mile gap between the sun and the earth is a wave radiation, probably ultra-violet light and shorter X-type radiation. Being additional to the continuous quota that goes into forming the ionosphere, the ultra-violet radiation increases the density of ions there. This is equivalent to thickening the wires in the atmospheric dynamo, and so the effect is an increase of its output of current. This in turn strengthens the magnetic field at the earth's surface and so magnifies the quiet-day variation recorded on the magnetograph much above what it would otherwise be at that time. Meanwhile the more penetrating X radiation also ionises the atmosphere to lower than normal heights, and the additional layer of the ionosphere so formed absorbs the radio waves and blankets communications. When the flare has spent itself its output of temporarily enhanced radiation dies away and things return to normal.

To explain the intervening period of about a day before the real disturbance in the magnetic field starts, we go back to the sun again. In addition to the wave radiation whose effects we have considered, the flare (or an area of the sun in its vicinity) probably expels towards the earth a cloud of positively and negatively charged particles (protons and electrons) in approximately equal numbers. This cloud travels outward with a very high speed, which is nevertheless much less than the speed of the wave radiation, perhaps about 1,200 miles per second compared with the radiation's 186,000 miles per second, and so it would take about

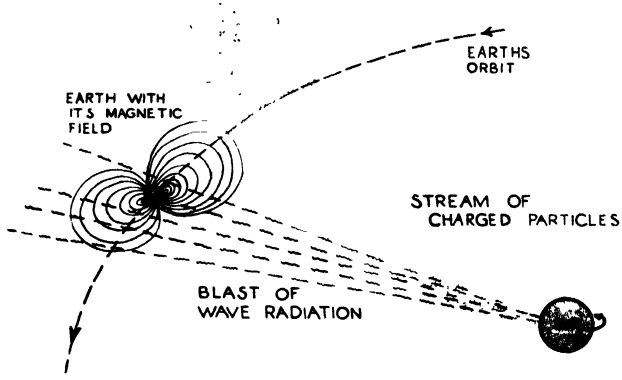


FIGURE 6. Wave-radiation and stream of charged particles approaching the earth from a solar flare.

twenty-one hours to reach the earth. Since the time needed to overtake the earth also depends on the position of the flare on the sun's disc and on the position of the earth in its orbit, the variable delay can be explained. When the cloud approaches the earth it becomes increasingly affected by the permanent magnetic field, and what actually happens after this stage also becomes increasingly uncertain. The outer lines of force of the earth's field probably act like a protective cage to stop the charges in the cloud from closing in on the earth, and while the front of the cloud is yet at a distance of several earth's radii the charges sort themselves out, the positive particles going one way round and the negative particles the other way. When they meet on the far side a great ring of electric current is formed. Now from the time of its first approach to the outer

lines of the field, the cloud begins to compress them inwards; this has the effect of increasing the magnetic force at the earth's surface, which was the first phase in the broad pattern of the storm. The formation of the ring probably starts the second phase, because the magnetic effect of the flow of electric current round the ring is to reduce the north-directed part of the field at the earth's surface. Then finally the ring of charged particles begins to dissipate, the current is gradually reduced and the field returns slowly to its normal value.

Although the earth has been shielded from the full brunt of the cloud's impact, there are weaknesses in the protecting cage—weaknesses whose position depends on the energy of the charged particles in the cloud. They lie principally along those lines of force that begin and end on the earth's surface in the zones of maximum auroral frequency. Either directly from the cloud or, more likely, out of the current ring that now encircles the earth, electrons and protons spiral at very high speeds down those lines of force towards the earth. On their way they collide with the rarefied oxygen and nitrogen at great heights in the atmosphere, and it is the luminescence produced in those collisions that we see as aurora. By the time the charged particles have penetrated down through the ionised layers of the atmosphere they have lost their high speeds; but by pouring their charges into the conducting layers and setting up winds through their heating effect they produce great disturbance currents in the ionosphere. Because the charges have approached the earth down the lines of force which terminate in the 23° zones around the geomagnetic axis poles, it is along these zones that the auroral displays are both most frequent and most intense: for the same reason the rapid fluctuations in the earth's magnetic field due to the disturbance currents in the ionosphere are also concentrated along these zones.

In the preceding paragraphs we have sketched present-day views about a solar-flare magnetic storm. A storm like this seldom if ever repeats itself after a solar rotation: the bursts of wave and corpuscular radiation expelled from the sun are short-lived. But it is otherwise with the smaller kinds of disturbance. Though the areas of the sun with which these seem to be linked are frequently devoid of any special activity, yet they behave as if they sent out a stream of particles continuously for two, three or more solar rotations. The result is that if the stream happens to lie in the plane of the

earth's orbit it overtakes and envelops the earth every twenty-seven days and produces effects similar to those already described for the storm except that, for some reason still unexplained, the sudden commencement is suppressed and the other basic phases are hardly recognisable. Further, instead of being world-wide like the storm, disturbances of this kind and the aurora which accompanies them are mainly concentrated in polar regions, and especially along the zones of maximum auroral frequency.

That, then, is the broad picture. Much of the detail has still to be filled in, and in the process some of the main features of the design may have to be altered to fit newly discovered facts. Meanwhile let us recall some of the points we have discussed. In the study of the earth's permanent magnetism and its slow changes from year to year lie the only clues we at present have to what is going on deep down in the earth's fluid core. Sixty miles up in the atmosphere the great dynamo which produces the regular daily variation in the magnetic field works only because the earth's magnetism provides the field across which tidal winds drive the streams of ions that reside there: and tens of thousands of miles out in the space surrounding the earth the distant lines of force play a dominating part in a variety of phenomena that probably depend for their effects on charged corpuscles which have come originally from the sun.

III

EXPLORATION OF THE UPPER ATMOSPHERE

IF WE are to understand how our planet stands in relation to its neighbours in space, especially the sun, we must send our instruments to the fringe of the atmosphere, and beyond. Aircraft and sounding balloons can reach only those regions in which there is still enough air to support them, and to go higher we must use rockets, the only means of exploring space known to man. In this essay Dr. Boyd explains how these ancient devices have been adapted for scientific purposes, and some of the things that have been discovered, so far, by their aid.

Dr. Boyd is Reader in Physics at University College, London. He is part author of a standard work on the higher atmosphere and is also well known as a broadcaster.

III

THE INTERNATIONAL GEOPHYSICAL YEAR, which ended in 1958, differed in many ways from previous international co-operations of a similar nature. It was more comprehensive, both as regards the number of nations taking part and in the number of the phenomena investigated, but perhaps the most important of all its innovations was the extensive use of rockets to carry instruments into the earth's upper atmosphere. In this way another dimension has been added to the study of many of the things going on around the globe.

Of course, rockets had been used before. Indeed, up to the time the I.G.Y. started, well over a hundred had been launched and quite a lot had been learnt. However, during the period of intensive effort, firings were carried out at an average rate of around three a week. In addition, eight artificial satellites were put into orbit and a start was made on the problem of deep space probing.

Many different countries have been involved in this rocket work and an enormous range of studies has been conducted. In Britain they have been carried out, and are still being continued, under the auspices of the Royal Society and with the active support of the Ministry of Supply, especially the Royal Aircraft Establishment.

Why do we use rockets? It has certainly nothing to do either with competition between nations or with space travel. Scientific research can be conducted far better by instruments than by an uncomfortable, half dazed, real-life equivalent of Dan Dare. But what kind of research is there to do?

If we look up at the stars on a clear night it is difficult to realise that anything of importance is going on in the pellucid space above us. The atmosphere falls in density quite rapidly as we ascend, and we might have been justified in supposing that above us the air just dwindles away and that is all.

This is very far from the truth. The upper atmosphere is, in fact, a scene of intense activity. Molecules are broken up into atoms. Atoms are stripped of electrons to become electrically charged ions.

Substances of great chemical activity, such as nitric oxide, are formed, and molecules and atoms are excited to fluorescence.

From distant space, cosmic rays of incredible energy crash through the air, disintegrating the very nuclei of atmospheric atoms and releasing showers of those transient particles we call the mesons. From nearer regions—the solar system itself—come tiny meteors, the debris of comets, to glow with brief incandescence as they vaporise in their encounter with the air. Occasionally a larger pebble penetrates to the lower atmosphere, glowing as a fire ball or detonating as a bolide or, more rarely, reaching the ground as a meteorite. At the other end of the scale a constant rain of interplanetary dust is slowed by the upper air in its gravitational plunge and settles silently and unobserved upon the ground. The combined influence of the sun's gravitational pull and its heating of the air causes huge gales to blow in the upper air, and this motion, together with the electrifying action of the solar ultra-violet radiation, results in great currents of electricity, which can be detected at the ground by their effect on compass needles.

All this is a tremendous challenge to research. In much our understanding is scanty and entirely new discoveries are still being made, but we must still ask whether rockets are the best means of study. Rockets are expensive, often very expensive. Must we use rockets, or would balloons do instead? Everybody knows that the air pressure falls as we ascend. This is why mountaineers must take oxygen with them for the highest ascents. In fact, for quite an altitude it falls by a factor of about ten for every ten miles we ascend. According to Archimedes' Principle the buoyancy force on a balloon is equal to the weight of air it displaces. Now 1 lb. air at ground level occupies about 12 cubic feet, so a balloon nearly 20 feet across would be needed just to lift a total weight of 30 lb., including that of the balloon envelope and the gas inside. To carry the same weight to a height of 30 miles, where the pressure has fallen by a factor of 1,000, would require a balloon of 1,000 times the volume—nearly 200 feet across. Even if it were made of material only $\frac{1}{2000}$ inch thick, the balloon itself and its gas would weigh over 300 lb., leaving nothing for instruments. Now a balloon 200 feet across, made of such flimsy material, is clearly right at the limit of technical feasibility. At heights greater than 30 miles we cannot employ airborne systems.

This, of course, is where rockets come to the rescue. Rockets do

not need air either to burn their fuel or provide their thrust. They carry their own oxygen for combustion and they obtain their thrust by reaction. It is easy to show by a simple experiment that reaction has nothing to do with having an atmosphere to push against. You need one of those rotating chairs which company directors employ to give a terrifying impression of omnipresence, and you need a heavy weight, like the balls used in "putting the weight", and a toy balloon. Sitting in the chair you raise the heavy ball to your shoulder and throw it with all your strength. The reaction of your push on the ball spins the chair round. The experiment is now repeated, this time using the toy balloon. Clearly the balloon pushes just as hard on the air, but the chair hardly moves. This is because pushing on the air has nothing to do with it. Indeed, air is just a hindrance to a rocket, as we shall see. The force of reaction which drives a rocket works in a vacuum. That is how it works best.

Quite a simple sum shows that in a vacuum a rocket, carrying a load of fuel weighing about twice as much as the empty rocket, reaches a top speed equal to the speed with which the exhaust gases leave the jet. On the other hand, if the same rocket is fired in the atmosphere it will reach only a fraction of that speed, maybe quite a small fraction. This is because air drag has wasted its energy and slowed it down. For this reason many of the smaller rockets used during the International Geophysical Year have been launched from balloons, which carried them up through the densest part of the atmosphere before they were fired. By carrying it up 20 miles in this way, a rocket which would reach only 10 miles if fired from the ground can be made to reach a height of 100 miles. This kind of arrangement is called a rockoon.

A similar result is obtained by mounting a small rocket on a quick-burning booster rocket. The booster gives the system sufficient speed to carry it beyond the dense lower atmosphere, at which height the main rocket is ignited. Many of the I.G.Y. rockets consisted of small solid-fuel combinations launched in this way.

A rocket flies like an arrow. It reaches its maximum speed in the relatively short time during which the motor is burning. Half a minute is a fairly typical duration of burning. After this the rocket coasts on up to its peak height on a journey that may take nearly 10 minutes. Like an arrow, most research rockets are

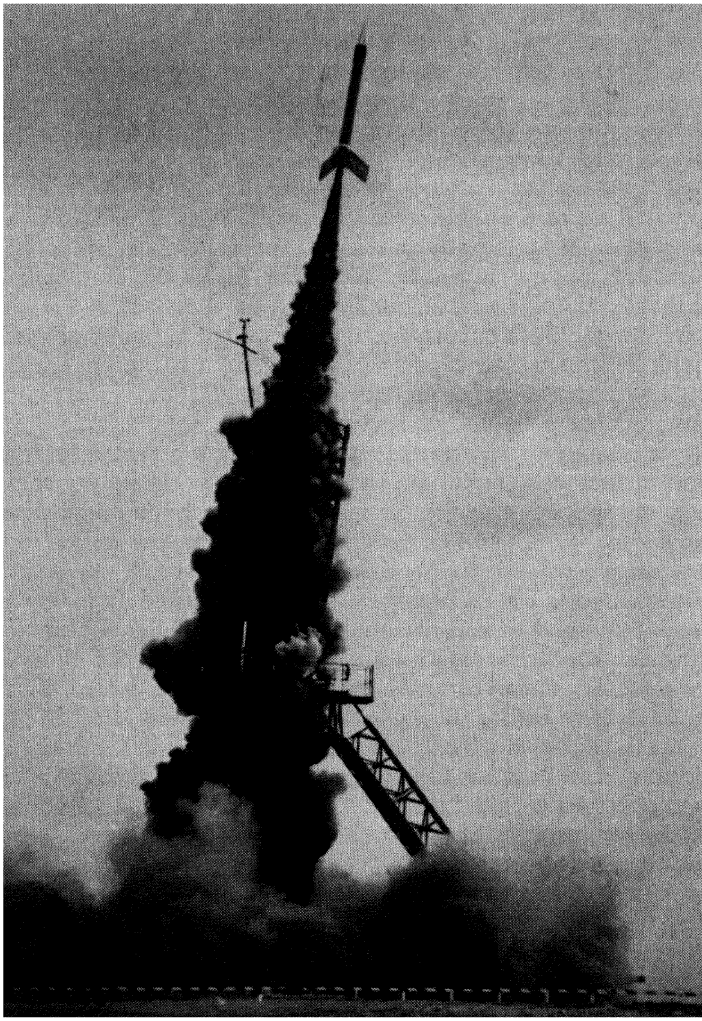


FIGURE 1. British Skylark rocket leaving tower on Woomera rocket range.

steered by rigid fins, corresponding to the feathers, though above 30 or 40 miles there is so little air that the fins are ineffective. Large rockets of the kind used to launch satellites are guided by auxiliary jets or by some means of deflecting the main jet. They may have no fins at all. Such a rocket can be fired from a simple stand, and its automatic pilot keeps it heading in the right direction, but the simpler rockets used for most research must either gain speed very quickly, so that their fins can guide them, or else they employ some such system as a tower with guide rails to steer them until an aerodynamically stable speed is reached.

A problem of no less importance than the actual transport of the instruments to great heights is the return of the information obtained. In the U.S.S.R., where there has been a great emphasis in the past on biological experiments, it has been common to recover instruments, data and specimens, often dogs, by parachute. While parachutes have been used in the West, radio telemetry is more common. The instrument readings are suitably coded and returned to ground-based receivers over a radio link. Of course there are certain kinds of experiment for which this is not suitable, experiments involving photography, for example. In these circumstances it is sometimes possible to avoid the need for a parachute, which is inevitably rather heavy and bulky, and to employ robust casettes capable of remaining light-tight after the strain of a hard landing.

The conduct of experiments in a rocket-borne laboratory is a very different business from their conduct on the earth. The measurement of temperature is a good example. Air temperature at ground level is measured by a suitably shielded thermometer—one that can be reached by the air but not by the sunlight, but we cannot simply extend a thermometer from the side of a rocket to give us the air temperature. Of course we would not expect to use an ordinary mercury thermometer in any case. It would have to be an electrical one so that its output could be fed to the telemetry transmitter, but the trouble is that it simply would not give the right answer. Even if shielded from the sunlight, it would record a temperature greatly in excess of the true air temperature, because of the heating due to the friction of the air, as the rocket pierces its way through the atmosphere at ultrasonic speeds.

Similarly, any attempt to make a direct measurement of wind by vanes or other devices on the rocket is liable to be very inaccurate

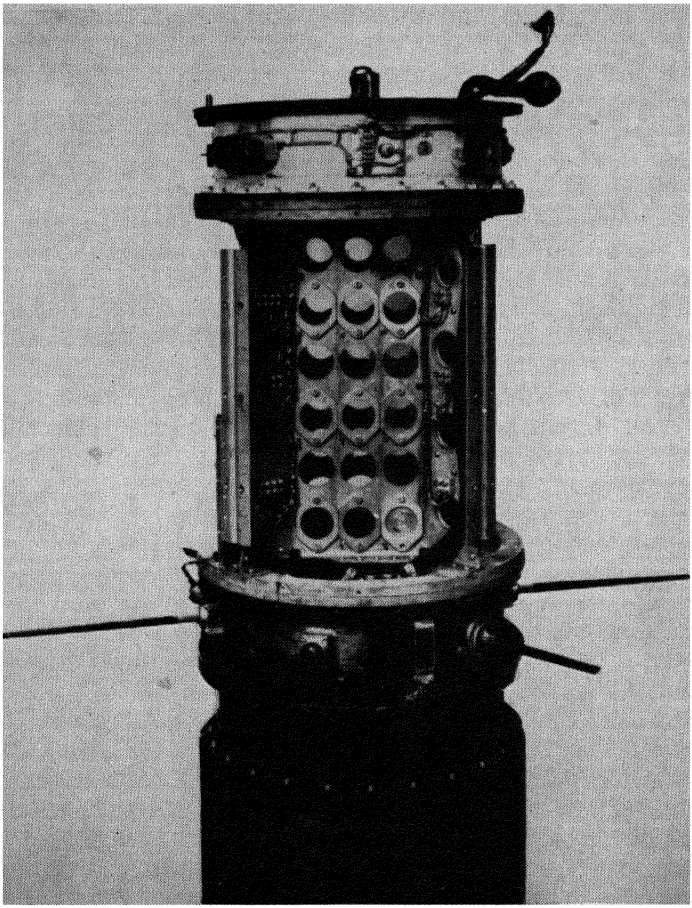


FIGURE 2. Grenade bay of Skylark rocket with cover removed showing holders of grenade barrels, and lower down, the telemetry aerials.

because of the problem of allowing for the huge effect of the rocket's motion. Now for the first fifty miles, apart from variations in humidity in the lower regions, the composition of the atmosphere hardly varies at all. On the other hand, its temperature and state of motion vary widely. To study these variations we

load our rocket with a number of grenades—eighteen in the British experiment—then as the rocket ascends it ejects and detonates these grenades at roughly equal intervals. On the ground, covering an area of 20 or 30 miles in diameter we have an array of microphones feeding recorders. These microphones are quite different from ordinary microphones. They contain a grid of fine platinum wire about $\frac{1}{1000}$ inch in diameter, heated by an electric current. A sound wave passing the wire cools it and causes its electrical resistance to change. This in turn results in a change in voltage across the ends of the grid. Such a system can be made quite insensitive to ordinary audible noise but responds very readily to subsonic, low-frequency sounds. A pistol shot scarcely registers on the recorder whereas the low-frequency pressure wave caused, for example, by gently opening a door results in a huge output being recorded. After the sound from a grenade explosion has travelled down through the atmosphere for fifty miles all the audible parts of the sound have vanished, attentuated in the thin air of the great heights, but there is still a subsonic sound wave which can be detected by the microphone and whose instant of arrival is recorded precisely, to $\frac{1}{1000}$ part of a second, on the recorder.

In addition to the microphones there are, on the ground, several very accurate ballistic cameras. In these cameras the photographic plate is positioned precisely by three diamond points. The shutter is electrically operated by remote control. With them a flash detector, containing a photo-electric cell, is trained on the sky where the grenade bursts are expected. When a grenade is fired the moment of firing is given accurately by the flash detector. The position of the flash can be found from the camera plates, by comparing the photo of the flash with the positions of known stars on the photograph. The times of arrival of the sound at a number of places are obtained by the microphones. At night the camera shutters are left open, but in the day-time the system is complicated by the need to open the shutters only when the grenade bursts appear. So fast is the electrically operated shutter that it can be made to open in less than $\frac{1}{100}$ second from the instant that the flash detector perceives the flash. Since the flash lasts nearly $\frac{1}{10}$ second, this leaves plenty of time for it to register on the photographic plates. It is easy to see that the time it takes the sound to travel to the microphones will depend on the temperature of the

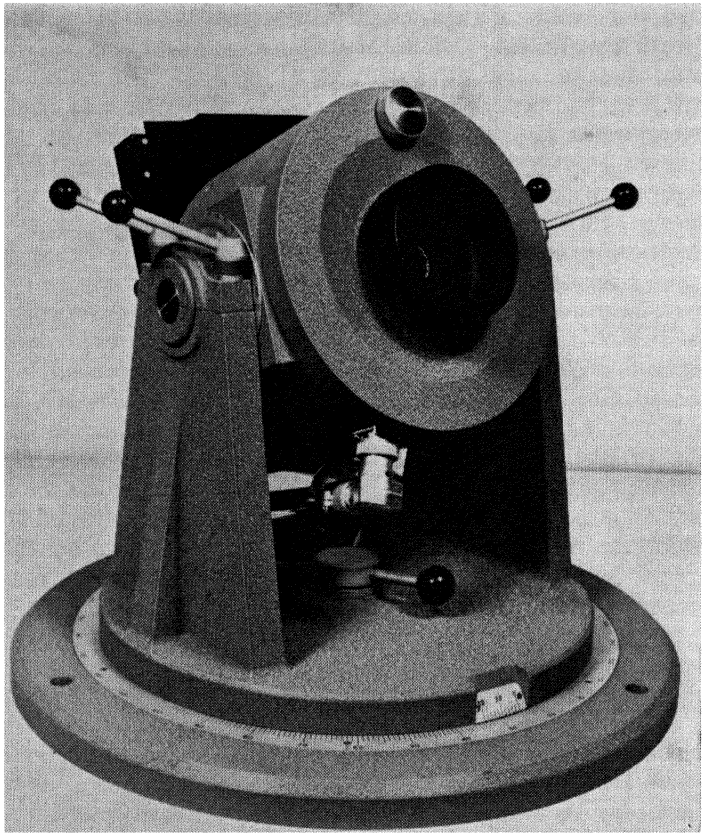


FIGURE 3. Quick-response ballistic camera developed at University College, London, for the grenade experiment on upper atmosphere, winds and temperatures.

air through which it has passed and also that microphones down wind will tend to get the sound earlier than those up wind. By observing the difference in behaviour of the sound from successive grenades the local value of wind and temperature in the regions between successive bursts can be computed. The calculation is very complex indeed, but an automatic electronic computor makes short work of it.

So far it has not been found possible to operate the grenade experiment at heights above 50 miles. The sound is too faint. Beyond this altitude therefore recourse must be made to other methods. One such method involves the release of vaporised sodium from the rocket. Inside the rocket a thermite mixture



FIGURE 4. Trail of sodium vapour glowing in the last rays of the setting sun.

(such as was used for incendiary bombs during the Second World War) is contained in an asbestos-lined oven. Small lumps of the active metal sodium are mixed with the thermite. On ignition a very high temperature is obtained which results in the emission of a long trail of sodium vapour. This vapour fluoresces in the sunlight with the characteristic yellow light of sodium. By conducting

the experiment at twilight, when the sky is still dark, although the rarefied upper layers are sunlit, the sodium trail may be seen and photographed from the ground. From its motion winds may be deduced, while a study of its light in an interferometer provides data on the temperature.

Above 50 miles the composition of the upper atmosphere begins to change. The relative amounts of oxygen and nitrogen vary and new unstable substances such as atomic oxygen begin to make their appearance. The first efforts to measure the variation of composition involved flying evacuated vessels to take samples, and indeed some limited degree of success was achieved. The experiment was appallingly difficult, however. The bottles had to be opened and closed without any leakage or contamination of the sample, and accurate analysis of a sample of gas weighing only a few millionths of a gramme had to be carried out. There were even problems arising from a selective action of the bottle opening by which light gases with quick-moving atoms, such as helium, were sampled preferentially compared with the more sluggish atoms of heavier gases such as argon.

A better approach to the problem, and one capable of being used up to very great heights, is to carry out the analysis of the air *in situ*. There are two quite different ways of doing this involving the use either of the mass-spectrometer or of the optical spectrometer.

The mass spectrometer is an instrument in which some of the atoms and molecules of a sample of gas entering the instrument are electrified—ionised—by the passage of a beam of electrons from a hot cathode. Once electrically charged, the atoms, ions now, are accelerated by an electric field. The speed they attain in this field depends on their mass or weight. In other words, it depends on what kind of ions they are—oxygen atoms (O), oxygen molecules (O_2) helium atoms (He) and so on. The speed of the ions can be measured directly by timing a pulse of ions over a short distance, or by measuring the deflection of their path in a magnetic field. In upper-atmosphere work the former method is usually employed, as it does not involve the requirement for a rather heavy magnet.

The optical spectrometric method of upper-air analysis depends on the fact that the light from the sun is modified in its passage through the air. If, by means of a prism or diffraction grating we

spread out the light of the sun into a spectrum or rainbow we can see that a whole range of colours—representing light of different wavelengths—is present. If now we put a piece of lightly coloured glass in the path of the sunlight before it reaches the prism we find that the light leaving the prism is deficient in some of the colours. Doubling the layer of glass increases this deficiency, so that the loss of light of the relevant colours is a measure of the thickness of the glass. The atmosphere is transparent to all the colours, but beyond the violet light of the spectrum is the shorter-wavelength ultra-violet light, invisible to our eyes but present all the same, important to our health and responsible for our sun tan. Fortunately the shortest of these ultra-violet rays are removed by the atmospheric constituents; otherwise we should get far more energetic radiation than is good for us. It is this absorbing power that we can make use of in the spectral analysis.

The wavelength of the sunlight absorbed by a particular constituent depends on the nature of the constituent, and the amount absorbed depends on the total number of absorbing atoms between the point of observation and the sun. By taking photographs of the sun's ultra-violet spectrum, or by measuring electrically the light intensity at several different wavelengths as a rocket ascends, we can work out the quantity of absorbing material between the heights at which one spectrum was recorded and the next.

When energy is removed from a beam of light it must go somewhere. A little of the blue of ordinary sunlight is removed by the atmosphere, for example. This is why the sun looks reddish, especially at dawn or sunset, when its rays have to penetrate almost horizontally through many miles of atmosphere. This blue light is not lost. It appears again as the blue light of the sky. When the short ultra-violet radiation is extracted from the sun's rays by the atmospheric particles some of it is scattered in this way, but ultimately its energy goes in exciting and breaking up the molecules and atoms it encounters. Many different things can happen. Electrons may be raised to revolve in more distant orbits about the nuclei of their parent atoms, or they may be removed altogether, leaving the atoms as positively charged ions. Molecules may be caused to vibrate or may be broken up into their constituent atoms. To complicate the picture still further, the fragments may react with other constitutents to form new molecules, which could not exist unchanged for long in the denser atmosphere at lower heights,

or electrons may attach themselves to atoms or molecules to form negative ions.

All this activity is not one way only. Recombination of the various fragments occurs, not of course, normally, with their former partners, but with others indistinguishable from them. The energy originally received is dissipated as heat or partly re-emitted at a longer wavelength than that at which it was absorbed. This process gives rise, both day and night, to the air-glow—a faint but marked fluorescence of the upper regions of the atmosphere.

Among rocket experiments carried out both by this country and others are measurements on the intensity, colour and variation with height of this air glow.

One of the most important and pronounced effects of the absorption of solar energy in the upper atmosphere is the breaking up of the atoms to give rise to the electrically conducting ionised layers.

This ionised region, or ionosphere as it is called, is of immense importance to world-wide radio communication, yet there is much that cannot be studied by reflection of radio waves transmitted from the ground and that is only now beginning to be studied by rockets and satellites. The accurate determination of the altitude of the higher layers is one of these problems. Because the velocity of a radio wave falls when it penetrates ionised gas, measurements of the altitude of the highest layers, by the echo time for a pulse transmitted from the ground, are subject to some uncertainty. It is not possible to study accurately from the ground the regions above the height where the density of ionisation in a layer has reached it maximum. Ground-based probing by radio also provides no answer as to the nature of the ionised particles in the ionosphere, since the waves are hardly affected by anything but the electrons.

All these problems are being tackled by rockets. The height of a rocket may be measured, using radio waves so short as not to be affected by the ionosphere. The density of ionisation may be measured by collecting the particles on a small charged electrode carried on a spike in front of the rocket and measuring the resulting electric current. Another new and elegant method has been developed by Birmingham University and used successfully for the *Rocket World Day* firing at Woomera in June 1958. The electrical

capacity of a condenser changes if the gas between the plates is ionised, the magnitude of the change depending on the density of ionisation. In this experiment a condenser, consisting of a part of the rocket nose cone insulated from the rest of the structure, is included in the tuned circuit of a radio-frequency oscillator. Information on the oscillator frequency is sent back to the ground over the radio-telemetry link, where it is decoded and interpreted in terms of the structure of the ionosphere.

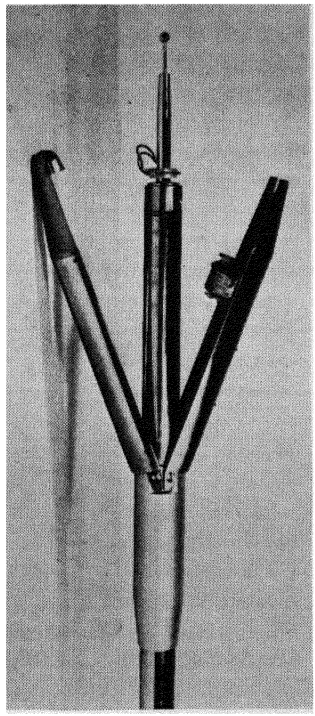


FIGURE 5. Small probing electrode for ionospheric studies with its shield opened and partly withdrawn.

To find out the types of ion present in the ionised regions we can make use of the technique of the mass spectrometer already described, only here we can dispense with the ionising electron beam, since the particles are already charged. One of the most significant results of this kind of research has been the discovery that over a considerable range of heights the most common ion is NO^+, the positively charged molecule of nitric oxide. In view of the rarity of nitric oxide among the uncharged components of the upper atmosphere, this is a most unexpected result, and is a graphic demonstration of the importance of chemical reactions brought about in these regions by the intense irradiation of the solar ultra-violet.

So far we have been thinking of that part of the solar spectrum of rather shorter wavelength than the visible light. As the wavelength shortens, the chemical and electrical activity of the rays increase, but their intensity falls. The sun's spectrum is brightest in the middle of the visible region. This trend does not continue

indefinitely, however. As shorter and shorter wavelengths are considered, eventually we reach the region of soft X-rays. They are called soft because they are much less penetrating than the still shorter wavelengths, much more penetrating hard rays. The very fact that ultra-violet and X-rays are so active in the upper atmosphere leads to their complete absorption before the lower regions

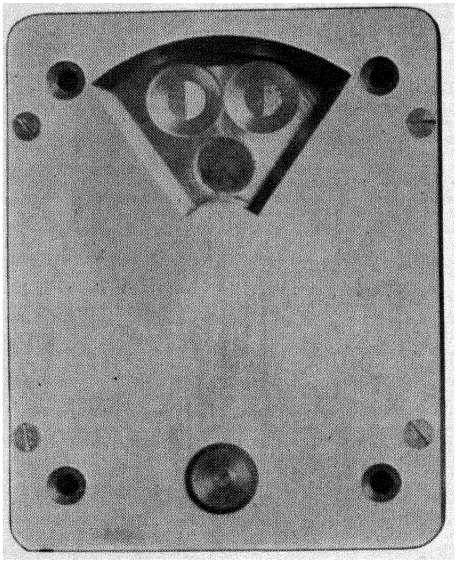


FIGURE 6. Front of camera for studying solar X-radiation. Shutter is open and the thin foil filters of the camera can be seen.

are reached. If, therefore, they are to be observed it must be from a high-flying rocket or satellite. Observation of these rays is made by carrying aloft photographic or electrical-detecting devices. The photographic detectors consist of pieces of sensitive film placed behind various metal foils. The foils are so selected that by measuring the blackening of the film the intensity and wavelength range of the X-rays may be determined. A strong electrically operated shutter closes over the delicate foils during the descent to protect them from harm when the rocket strikes the ground.

Detection of the X-rays electrically is carried out by a device like a Geiger counter. It is an electrical discharge tube with a thin foil window through which the X-rays pass to induce pulses of electric current.

With devices of this kind it has been shown that the sun emits an intense X-radiation from its outer atmosphere, or corona. This corona consists largely of hydrogen gas at the tremendous temperature of a million degrees Centigrade, far hotter than the lower luminous surface of the sun. From time to time local regions of the corona become yet more strongly heated by the passage of streams of particles through them. At these times the intensity of the X-ray emission increases, the rays become harder and the ionisation they produce in the atmosphere grows.

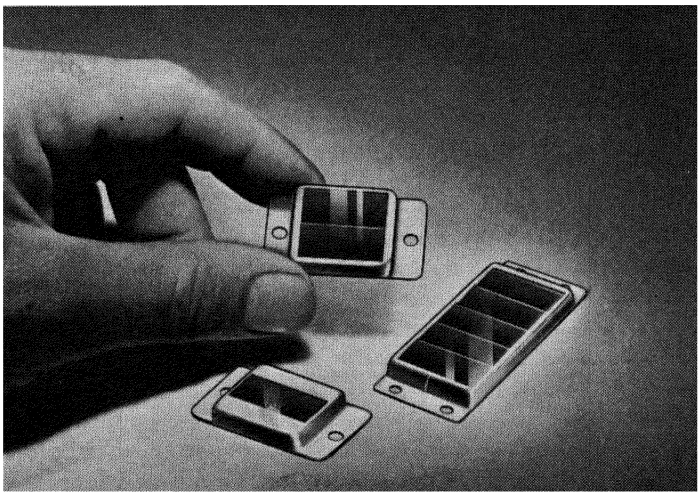
Of even more importance is the occasional increase in radiation of that component of the ultra-violet light responsible for the lowest ionisation in the atmosphere. When this occurs, during a solar flare, for example, the production of ionisation at a height of about 50 miles gives rise to widespread shut down of long-distance radio communication, due to the absorption of radio energy in this region of the ionosphere.

During the I.G.Y. attempts, partially successful, were made to observe the increase in this solar radiation during a solar flare. A flare is a local brightening of part of the sun's surface. Arrangements were made to launch rockets suitably equipped within minutes of the detection of a flare occurrence at a neighbouring solar observatory. The effort and expense of such an arrangement is very great. Clearly what is needed is means for keeping the equipment aloft for weeks on end so that when a flare occurs it is already receiving the sunlight. A satellite provides an almost ideal answer to this kind of situation, and with the advent of these little celestial laboratories the study of sporadic variations in the sun's behaviour and their effect on the ionosphere is moving out of the realm of the vertical sounding rocket into that of the artificial-earth satellite.

The advantages of artificial satellites are by no means limited to the fact that if launched high enough they can keep up a continual observation, as long as battery supplies last and the instruments remain in working order. (Now even the battery limitation is being overcome by the introduction of solar cells.) Of equal importance is the fact that a satellite gives world-wide coverage. If launched

on an orbit crossing over the poles it passes over the entire globe in about nine circuits in the course of twelve hours. This useful behaviour comes about because, to a first approximation, the position of a satellite's orbit is fixed in space, but the earth is not fixed. It rotates on its axis once in twenty-four hours, and as it does so every point on its surface passes first under one side and then under the other side of the satellite's orbit.

For a satellite launched on an orbit at some angle to the equator



[International Rectifier Corp., California.

FIGURE 7. Solar batteries as used to supply the power for artificial satellites.

and not directly over the poles the situation is not quite so favourable. An orbital inclination of 65° to the equator (the value for the Sputniks launched to date) takes in everywhere but the polar regions, Arctic and Antarctic. Lesser inclinations take in less and less but have the advantage that greater use can be made of the rotational velocity of the earth itself to help to project the satellite into its orbit. Of course there are many experiments for which an orbit around the equator is quite suitable, no world-wide coverage is required. Certain astronomical observations are in this category.

The launching of a satellite is an immensely complicated technical

undertaking. The velocity requirement itself is such that only two decades ago many people now working in the field would have regarded the feat as impractible with chemical fuels. The kinetic energy of a satellite travelling at the orbital velocity of 18,000 miles per hour is nearly 100,000 times greater than that of a car of similar weight travelling at 60 miles per hour, yet to launch a satellite weighing say half a ton by a single rocket would require far more energy than this. This is because the vast fuel containers and rocket motors must be lifted with the satellite to its orbiting height and accelerated to orbiting speed.

Everyone knows that the secret of attaining these vast velocities,

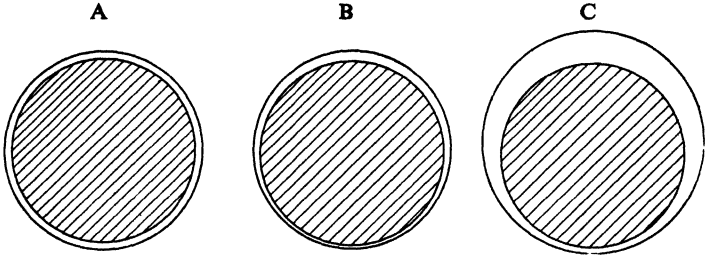


FIGURE 8. Figure illustrating the dependence of size and shape of orbit on precision of launching.

A. Velocity and direction for circular orbit. Altitude 300 miles.
B. Velocity for circle but direction in error by 2°.
C. Direction horizontal but velocity 5·5 per cent too great. (If the velocity is 3 per cent too small no orbit results.) Apogee 1,400 miles. Perigee 300 miles.

and later the even greater velocity—27,000 miles per hour—required for a lunar probe, has been the use of multi-staging. A large rocket carries on its nose a medium-sized one, and this in turn carries a rather smaller one. When the fuel contained in the largest, first-stage rocket has been consumed it falls away, the useless weight of its redunant tanks and the huge motor necessary to lift the whole combination initially, falls back to earth, while the second stage accelerates to a still higher velocity unimpeded by unnecessary dead weight. This process is repeated three or even four times with successive stages until the final push to attain the orbital velocity is given by a rocket just the right size for the job.

Attaining the required speed is a vital requirement in a successful satellite launching, but it is only one such requirement. It is

equally important to ensure that it is attained at the right height and in the correct direction. If the direction in which the satellite is moving when its final stage rocket burns out is in error by a degree or two, so that it is directed slightly upward or downward it will approach too near the earth at some point in its orbit. This is as bad as attaining final orbital velocity at too low a height. In either case the continual passage of the satellite through the denser parts of the upper atmosphere will rapidly decrease its altitude until it makes its final plunge to the earth. The same result occurs if direction of motion and height at burn-out are correct but an inadequate velocity has been reached. Too great a velocity, on the other hand, merely increases the maximum distance from the earth (the apogee height) that is attained. In practice, it is found that a closest approach (perigee height) of less than 200 miles gives a rather short satellite life.

Three phenomena cause changes in the orbital path of a satellite, and a study of these changes throws light on each of the phenomena. The most important effect, since ultimately it causes destruction of the satellite, is *air drag*. The continual battering of the satellite by the atoms of the air as it passes through it, absorbs energy from it. Now our first impulse is to say that this must reduce the speed of the satellite, but curiously it does not. It increases it. What it does is to reduce the altitude of the orbit. Because it is impossible to attain the precise orbital conditions necessary for a circular orbit, the path is always more or less elliptical, and the action of air drag is to reduce first the apogee and later, as the orbit grows more circular, the perigee as well.

We can see how this curious speeding up of the satellite comes about if we take the simple case of a circular orbit and remember that a satellite stays up because the pull of gravity is exactly balanced by the pull of the "centrifugal force" as it is called in the mechanics books. This relationship can be expressed by the equation:

$$\frac{mMG}{R^2} = \frac{mV^2}{R}$$

Here m is the mass of the satellite; M that of the earth; G the so-called gravitational constant; V the satellite velocity and R the radius of the orbit. From this we see that

$$V = \sqrt{\frac{MG}{R}}$$

In other words, if the radius of the orbit decreases, as clearly it must when energy is taken from the satellite, the speed of the satellite must increase. The explanation of this paradox is to be found in the fact that the energy imparted to the satellite by the pull of the earth as the orbit shrinks is more than enough to compensate for the loss of energy by air drag.

The time taken by the satellite to complete one circuit of the earth is

$$\frac{2\pi R}{V}$$

so that all we need do to find the effect of air drag is to measure the time the satellite takes to orbit. From this information the density of the upper atmosphere at perigee height may be found, and as the perigee slowly falls the graph of density against height may be deduced. Simple theory enables the temperature also to be determined. This is most satisfactory, since the satellite operates at heights above those where the rocket methods of finding density or temperature, described earlier, are no longer operable.

The other two major motions of the orbit arise from a gyroscopic action and result in a rotation of the plane in which the satellite revolves. If we set a gyroscope going, and then try to rotate it about an axis at right angles to its axis of rotation, we find that it will actually rotate about a third axis mutually at right angles to both. Now a satellite revolving in its orbit behaves like a gyroscope and it is subject to two forces, or torques, tending to rotate the axis of its orbit about the centre of the earth. The greatest of these forces for an orbit inclined at say 45° to the equator is due to the equatorial bulge.

The mean diameter of the earth at the equator is a little larger than the diameter at the poles, an effect arising from the forces due to the earth spinning on its axis. The extra gravitational pull of this equatorial mass tends to pull the orbit in the direction of reducing inclination to the equator. Because of the gyroscopic action, the actual motion resulting is a rotation of the whole orbit plane about the earth's polar axis. The movement of the orbit is seen, of course, as a changing path of the satellite across the heavens, and from this change the size of the equatorial bulge may be calculated with a precision greater than that with which it was known formerly.

The final major motion of the orbit results from the fact that the

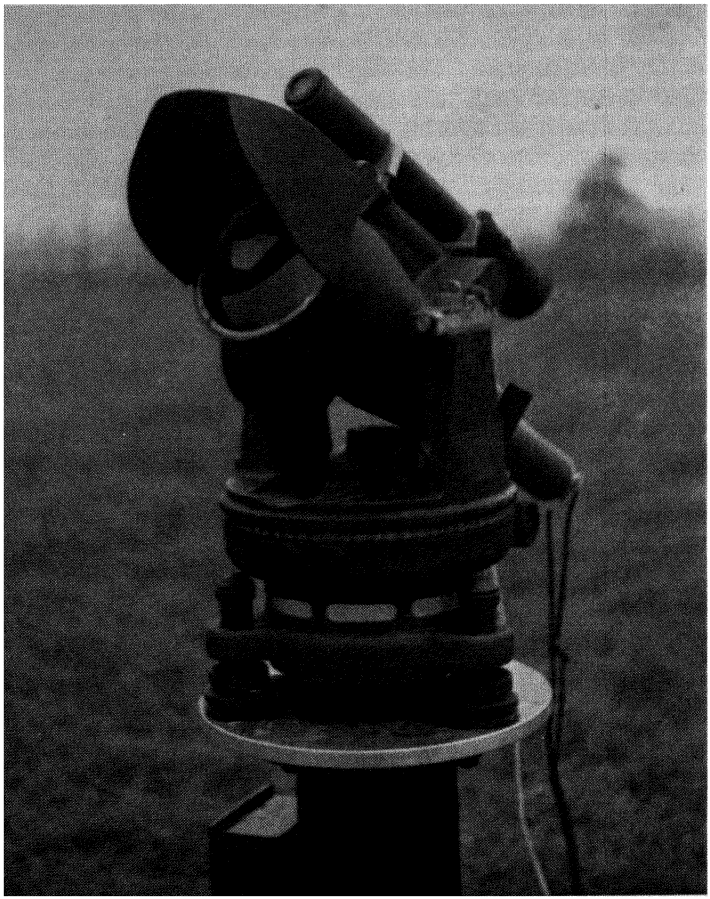


FIGURE 9. Experimental telescope for precise photo-electric tracking of satellites.

earth is continually rotating on its axis from west to east. Since the satellite orbit is not rotating with the earth, the satellite is subject to a westerly wind tending to rotate the orbit about the polar axis. Once again, because of gyroscopic action the actual motion resulting is different. This time it is the inclination of the orbit to the equator which decreases slowly with time, and in doing so it

provides data on the strength of the westerly wind, and hence fresh information on the density of the air in the orbital region.

It is interesting that all this important work can be carried out without any instruments in the satellite at all. Even a radio beacon is not essential, though it helps a great deal in keeping track of the vehicle. What is required is accurate ground-based observation equipment. For much of the work radio direction-finding equipment is not sufficiently accurate and precise optical methods must be brought into play, after sunset or before sunrise when the satellite still catches the rays of the sun though the sky is dark. The process of observing the orbit is called tracking.

For most of the accurate tracking done in this country ciné-theodolites have been used. These are very accurate ciné-cameras with scales incorporated to record the direction in which they look. For some time, however, work has been going on on a precise photo-electric method of observing the passage of the satellite. A powerful lens throws an image of the sky on a dark screen in its focal plane. This screen contains a number of slits in front of a sensitive photo-electric cell. As the image of the satellite crosses the slits the photo-cell emits a series of pulses at times which are recorded automatically with great precision. The slits are so arranged that the spacing of these pulses enables the path of the satellite across them to be accurately deduced. Its path in the heavens is found by calibrating the instrument on the stars.

The addition of a radio transmitter increases yet further the scientific returns from a satellite launching, since so much can be learnt about the ionosphere from its effect on the reception of the satellite's signals. However, to get the maximum value from such an expensive enterprise scientific instruments must be carried and experiments must be conducted in the satellite itself.

Much of the instrumentation for satellites has been very similar to that developed for rocket use, though, of course, electrical power has been at a premium and great effort has gone into keeping the consumption to a minimum. For this reason, and also because of their robustness and reliability, transistors and other semi-conductor devices have been widely used. For example in Vanguard I thermistors monitor the temperature of the satellite's structure, and the data is transmitted to earth by a transistor transmitter operated entirely by semi-conductor solar batteries. The temperature attained by a satellite depends on the heat

radiated from the earth and on the careful preparation of the satellite's surface. Observations of the value reached are of great importance to the planning of future instrument loads.

One of the hazards faced by a satellite or extra-terrestrial probe is the eroding effect of interplanetary dust. Microscopic particles, the debris perhaps of comets, circulate around the sun and encounter the earth in its orbit. These particles are of great fundamental importance, as their presence may exert a significant cooling effect on the enormously distended corona of the sun. They

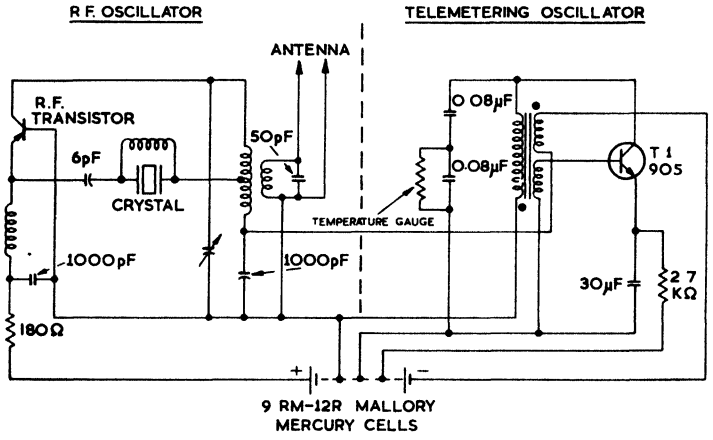


FIGURE 10. Circuit diagram of the radio beacon and telemetry transmitter, developed for a Vanguard satellite. The small power consumption and extreme simplicity of the circuit is noticeable.

are also of practical significance because of the wear they cause on any exposed surface. Thus the life of a solar battery at maximum efficiency is probably limited chiefly by frosting of the window. We have seen also that the temperature of a satellite is very sensitive to the condition of its surface. Any appreciable erosion of the surface may so change it that the equilibrium temperature is seriously affected.

The process of erosion has been studied by mounting thin conducting films of chromium on an insulated strip on the outer surface of the satellite. The changing electrical resistance of the strip is monitored and transmitted to the ground over the telemetry link.

The more basic problem of the actual concentration of these micrometeoric particles is tackled in a variety of ways, the commonest being the use of a crystal microphone. Such a microphone can pick up the very high-pitched *ping* as one of these particles strikes it or the neighbouring skin of the vehicle. Strangely the American and Russian results obtained in this way are widely divergent, and there is a great need for further experiments.

Among the experiments for which a satellite is peculiarly suitable are those on the cosmic or other corpuscular radiation. For this work rather long observing times are often required and ordinary rockets are of limited scope. The earth is a giant magnet, and because of this, charged particles are deflected towards the poles. The more energetic particles, however, or more correctly those with the greatest momentum are able to reach the denser parts of the atmosphere, and the latitude at which they do so is a measure of their momentum. It is in this way that the momentum of the cosmic rays is measured. At the surface of the earth, however, only the secondary rays, produced by nuclear collisions high in the atmosphere, are observable. To observe the primary rays experiments must be conducted at great heights, and to get the maximum data the observations must be made at a wide range of latitudes. Here a satellite launched on a near polar orbit is the ideal instrument. Moreover, it can keep up a continual observation so that cyclic or irregular variations in the cosmic rays can be detected. For these purposes Geiger and scintillation counters are carried. A scintillation counter is a photo-electric cell which records the brief fluorescence when a particle impacts a special crystal in front of it.

It was in the course of an experiment with a Geiger counter in a satellite that one of the most important discoveries of the International Geophysical Year rocket programme was made.

The first successful American satellite—Explorer I—was instrumented with a Geiger counter by Professor Van Allen, who has used rockoons to make extensive studies on cosmic rays and less-energetic particles coming from the sun. At heights of a few hundred miles (near its perigee) this counter registered the expected count of around thirty per minute. When, however, the satellite crossed the equator at a height of around a thousand miles the counter gave a negligible output. This is a most strange result, for clearly, since the cosmic rays come from outer space, their flux

cannot fall to a small value as we ascend. At first sight it looked as though the instrument had failed, but this seemed improbable, as it started to work again at the lower height. Soon the truth dawned. The satellite was encountering such intense radiation that the counter was exceeding its maximum working dose and was saturating. Subsequent work has indeed confirmed the existence of an intense belt of radiation encircling the earth and has revealed yet another at a greater distance from the earth. The origin of this radiation is still uncertain. It may come from the sun, or it may be the end product of cosmic-ray encounters in the atmosphere beneath, but whatever it is, it is certain it plays an important part in causing the aurorae, that its discovery has thrown new light on a number of atmospheric phenomena and has opened up a whole new field of speculation, study and experiment.

IV

THE LOWER ATMOSPHERE AND ITS WEATHER

THE SYSTEMATIC study of the weather is hardly more than a century old, and meteorology is therefore a very young science when compared with, say, astronomy. It came into being with the invention of the electric telegraph, for the diversity of atmospheric phenomena means that observations must not only be made simultaneously over a dense world-wide network of stations but must also be reported on the same world-wide basis within a very short space of time, if the forecasting of weather is to be possible. For this reason meteorology has long been organised on a global basis. We are still far from a complete understanding of the processes which produce weather, and even apparently simple phenomena, such as the formation of rain, have proved to be more complicated than was once thought.

Sir Graham Sutton is Director-General of the Meteorological Office. He was elected a Fellow of the Royal Society in 1949.

IV

WE LIVE at the bottom of an ocean. Not, of course, what we have come to call *the* Ocean, by which we mean the sea, but the far more extensive ocean of air which we call the atmosphere. Although the atmosphere is deep compared with the sea, it forms only a very thin skin when viewed on the scale of the earth. Of this skin, the layer in which we can breathe with comfort is only a small fraction of the whole, of depth less than a thousandth part of the radius of the earth.

Suppose that we were space-travellers, visiting the earth from some distant planet. It would be difficult to detect much trace of the atmosphere until we were in the region of the lower part of the orbit of the first Sputnik, say between 200 and 300 miles up. At this distance from the earth the pressure of the atmosphere, which measures the weight of the air above us, is less than one million-millionth of that at the ground. That means we would be moving in what is called a "vacuum" on earth, for at this level pressure is lower that that which can be achieved by the finest laboratory pumps. Over the Polar regions we should see aurora, and at about 150 miles up we should pass through one of the electrically conducting layers, the *F*-layer of the ionosphere. These are the layers which reflect radio waves and make long-range wireless communication possible. Lower down, at about 60 miles above the surface, there is another reflecting layer, the Kenelly–Heaviside or *E*-layer, and it is about here that we could expect to see some meteors or shooting stars, small particles of rock which become intensely hot and brilliantly luminous as they vaporise because of the intense heating caused by their rapid plunge into the atmosphere. But the air is still very thin at this level, and its density is only about a millionth of that at the ground, and thus far too low to allow air-breathing creatures to exist. At about 50 miles up we might also encounter some of the so-called night-luminous clouds, which occasionally can be seen from earth. Then, still nearer the earth, if we had the appropriate instruments, we should find a layer rich

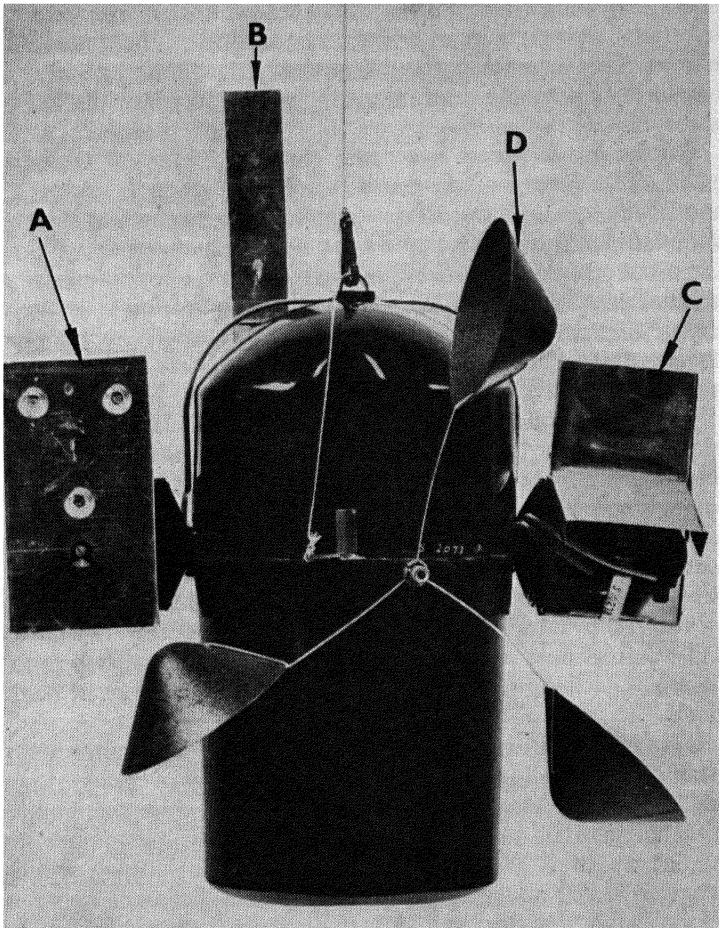
in ozone between 15 and 30 miles up and, finally, having passed through the stratosphere, we would enter the *troposphere* or region of weather, which begins between 5 and 11 miles above sea-level, depending on whether we were over the poles or the equator.

Meteorologists are interested in the whole atmosphere, but especially in the troposphere, because it is only in this relatively thin layer that we find weather, that is, clouds, fogs, rain, hail and snow. In general, the higher one goes in the atmosphere, the colder the air becomes. This seems odd at first, because by climbing up we are getting nearer the sun, from which we get all our heat. The explanation is that the rays of the sun are not very effective in heating air directly. Most of the energy in a sunbeam passes through clear air with very little absorption. If this did not happen we should spend our lives alternating between a kind of hot twilight and an intense darkness, we should never know the bright colours of a landscape. What happens is that the sun's rays heat the surface of the earth, both the ground and the sea, and it is from the warm surface of the earth that the atmosphere receives most of the energy which appears as wind and causes weather generally.

But this is not the whole story. Something quite unexpected occurs in the atmosphere at 6 or 7 miles up, and to explain this we must first consider how meteorologists measure the temperature of the air far above the ground.

Today, this is done by the instrument called the *radio-sonde* (Figure 1). The British pattern radio-sonde looks like a simple box with some smaller boxes and a little windmill on its sides. Inside the boxes are a tiny aneroid barometer, a bi-metallic strip thermometer, a piece of gold-beaters' skin (which changes in length in sympathy with the humidity, or wetness, of the air) and a radio transmitter and its batteries. The whole assembly is, in fact, a miniature meteorological observatory, which is carried high into the air by a free balloon. With special balloons it is possible to measure the properties of the atmosphere up to heights of 100,000 feet and more, but usually the height reached is about 60,000 feet.

As the balloon ascends, the pressure, temperature and humidity of the air change. The instruments respond to these changes by mechanical movements of the barometer, the bimetallic strip and the gold-beaters' skin. Inside the main container there is a small



[*Reproduced from the Marine Observer's Handbook by courtesy of the Controller, H.M.S.O.*

FIGURE 1. The British radio-sonde. (A—barometer; B—thermometer; C—hygrometer; D—windmill switch)

transmitter which sends out a radio wave which carries a high-pitched musical note. As the temperature of the air, for example, changes, the pitch of the note also changes, because the movement

of the bimetallic strip affects an inductance in the circuit of the radio transmitter. The same thing happens when pressure and humidity change, and in order not to confuse the signals, the barometer, thermometer and hygrometer are switched into the circuit in turn by the rotation of the little windmill as the balloon ascends.

On the ground there is a radio receiving station at which the pitch or frequency of the musical note is measured. Before the sonde was sent up it was calibrated in chambers in which the pressure, temperature and humidity can be varied systematically, and the pitch of the note corresponding to different conditions of the air measured and recorded. With this information it is then a simple matter to convert the measured frequencies to millibars, degrees and humidities to give a record of the state of the air up to many miles above the station.

When meteorologists began to use sounding balloons at the end of the last century, radio was unknown and they had to rely instead on small self-recording instruments, which it was hoped would be found again when the balloon burst and the apparatus fell back to earth. One of the most famous of the instruments, called "balloon-meteorographs", was designed by the English meteorologist W. H. Dines, and it continued in use until it was finally superseded by the radio-sonde. Dines' instrument was entirely mechanical and weighed only a few ounces. It is one of the most beautiful examples of design in the whole range of meteorological instruments.

Over fifty years ago the French meteorologist Tessereinc de Bort used sounding balloons to make a sensational discovery. He found that the atmosphere did not continue to grow colder indefinitely with height. His records showed that usually the temperature fell, at about 3° F. per 1,000 feet, until the balloon reached between 30,000 and 40,000 feet. Above this height temperature ceased to fall. De Bort had, in fact, discovered the region which is now called the *stratosphere*, and his discovery began a new era in meteorology.

The stratosphere is a region of cold, thin air, almost cloudless and very dry, which lies above the troposphere, or region of weather. In the stratosphere temperature at first ceases to fall with height and may even increase slightly. There are thus two distinct layers at the bottom of the ocean of air, the troposphere, in which

temperature, on the average, falls with increasing height and the stratosphere, in which it does not. The boundary between the two layers is called the *tropopause.*

The tropopause is highest above the equator and lowest over the poles. This causes the remarkable paradox that the coldest part of the whole atmosphere is over the hottest part of the earth, the equator.

Later investigations have produced more surprises. Figure 2 shows the average change of temperature with height up to about 75 miles above the surface. Above 20 miles temperature begins to increase, reaching a maximum somewhere between 30 and 40 miles. Above this the very thin air grows colder until it reaches a second minimum at a height of about 50 miles, after which

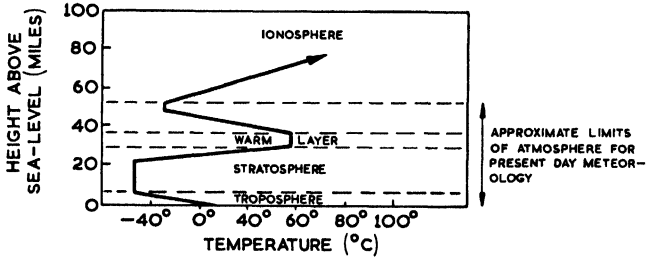


FIGURE 2. The average distribution of temperature in the atmosphere.

there is another rise of temperature, but at these levels there is so little air left that meteorologists think that conditions above the height of the second minimum of temperature, that is, above 50 miles (80 kilometres), do not have much effect on weather at the surface of the earth.

The first indication of the warm layer high in the atmosphere came from observations on meteors, but the real confirmation arose when it was noticed that very loud sounds, such as those of cannon in a battle, have often been heard at very great distances from their place of origin. In the 1914–18 War, when there were extremely intense bombardments in France, the noise of the guns could be heard up to a certain distance from the battlefield, then there was a zone of inaudibility, and after that a region, much farther away, where the guns could be heard again as a faint, low

rumble (Figure 3). After the War scientific experiments were conducted to examine this phenomenon of "anomalous propagation of sound" as it is called. When a loud noise occurs, the disturbance travels away from the source in all directions as a wave of pressure. The part of the wave which travels near the surface of the earth is rapidly broken up and attenuated, and soon becomes inaudible. But a part of the wave goes up into the sky, and the zone of abnormal audibility can be explained only by the assumption that at some great height the sound wave is bent downwards, or refracted,

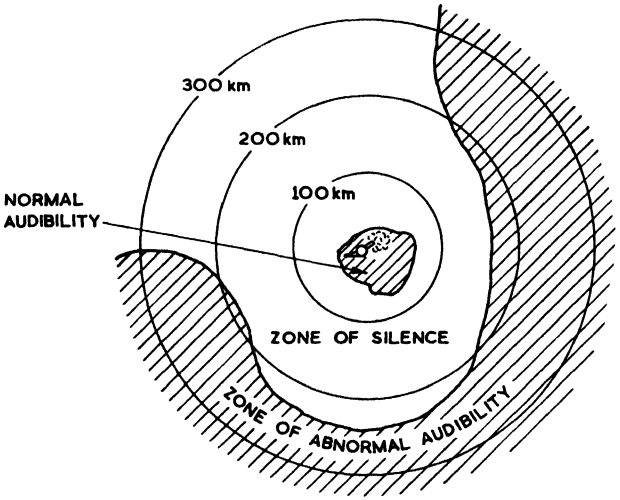


FIGURE 3. Anomalous propagation of sound.

so that it reaches the ground again, but far beyond the zone of normal audibility. A wave is refracted, or made to change direction, when it changes speed. The speed of sound depends on the nature and temperature of the medium through which it passes, and the change in direction of the sound wave indicated the presence of a layer of warm air high in the stratosphere. Since these early experiments, direct measurements by rockets have confirmed the existence of the warm layer.

The reason for the existence of the warm layer lies in the presence of ozone, which reaches its maximum concentration be-

tween 15 and 30 miles above sea-level. Ozone, which is formed from oxygen atoms by the action of sunlight (an example of what is called *photochemical synthesis*), absorbs the very short waves of sunlight, and since a gas becomes hot when it absorbs radiation, we have in this way an explanation of the warm layer which bends the sound waves downwards to earth.

Ozone was once thought to be good for health, and our fathers believed that much of the beneficial effect of a seaside holiday arose because sea air was "rich in ozone". Actually, there is very little ozone in the lowest layers of the atmosphere anywhere, and ozone, when breathed, is not health-giving but poisonous. The benefits of ozone arise in another way. The ozone layer high above our heads protects us from severe sunburn by absorbing all the ultra-violet rays of the sun below a certain limit of wavelength, about 300 Å. If by some chance this layer were removed, we should all suffer from too much ultra-violet light, and might become blind or seriously ill. However, as far as we know, there is no chance of the earth losing its protective skin of ozone. The modern picture of the atmosphere is thus something like an onion with many skins. These layers are not skins in the sense of being quite separate from each other, but they are real in the sense that it is possible to distinguish one part of the atmosphere from another.

The output of energy from the sun is, we believe, very steady. Meteorologists specify this output by the *solar constant*, which is defined to be the intensity of radiation in the solar beam outside the atmosphere at the mean distance of the earth from the sun. The value of this constant has been determined by many years of observations in high mountains (chiefly by the Smithsonian Institute of America) to be almost exactly 2 calories per square centimetre per minute. This represents an energy income for the average garden, supposed to cover a square dekametre, of about 140 kilowatts perpendicular to the solar beam. But this large energy income suffers severe taxation, partly by absorption but chiefly by reflection, especially from clouds. The reflecting power of the earth is called its *albedo*, and one of the main interests of meteorologists in artificial satellites is that they offer new ways of measuring both the solar constant and the albedo. At present we can do no more than estimate the albedo, and the figure usually accepted is 0·4. This means that 40 per cent of the sun's gift of energy to us is thrown back into space and lost. The earth also

radiates to space infra-red radiation, but much of this is returned to keep us warm by the water vapour and carbon dioxide of the atmosphere.

Let us look now at what happens on the earth in more detail. The sun heats the earth most intensely in the tropics and least of all at the poles. This unequal distribution of radiation income should produce something like the hot-water system of a house, with the boiler at the equator and the kitchen sink at the poles. With this arrangement air would be expected to rise near the equator and sink near the poles, and a crude first approximation of the motion of the air over the globe would be one in which air ascends near the equator, travels towards the poles at great heights, descends at the poles and then drifts back to the equator at the surface. If this were true, all low-level winds in the northern hemisphere would be from the north and in the southern hemisphere from the south. Of course, nothing as simple as this happens, partly because the earth rotates and partly because of the irregular distribution of land and water and the presence of water vapour in the air.

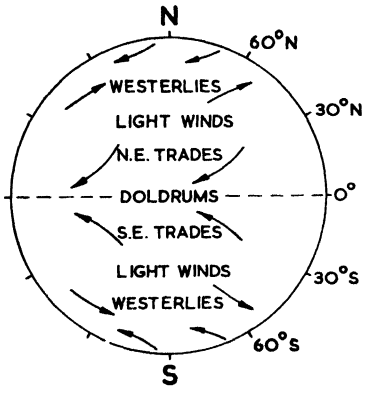


FIGURE 4. Winds on the Earth.

Suppose observers in another planet had an extraordinarily good telescope which allowed them to view the earth in sufficient detail to see the motion of clouds. What kind of picture would they form of the general circulation of the atmosphere? For a long time the impression would be of great complexity, but gradually something like a coherent picture would begin to emerge. They would see that near the equator and the poles the general drift is easterly, either north-east or south-east, and that between these two zones there is a belt of very chaotic motion with a pronounced tendency to favour westerly winds (Figure 4). This is the mid-latitude belt of the *westerlies*, in which the British Isles lie.

The north-east and south-east winds that blow from about

latitude 40° towards the equator are known as the *trade winds.* They played a very important part in the days of sailing-ships, for it was their regularity which enabled the early explorers and traders to undertake long voyages. These winds are caused primarily by the thermal circulation explained above, and the reason why they blow from the north-east and south-east instead of from north and south was discovered by the English scientist George Hadley in the eighteenth century.

It is possible to show how this happens by a simple experiment with a gramophone turntable, a cardboard disc and a crayon (Figure 5). The cardboard is placed on the turntable so that it can rotate like a record. Before the motor is started the crayon is

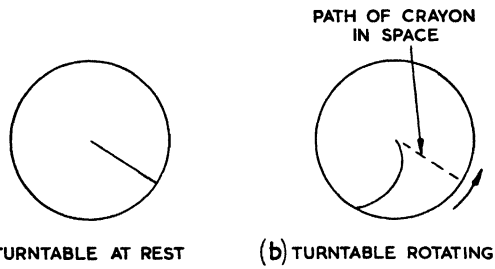


FIGURE 5. An experiment to illustrate the effect of rotation.

moved on the disc from the spindle perpendicularly to the circumference. The result is, of course, a radius, i.e., a straight line. When the turntable is rotating the same movement is made with the crayon, but this time the line it makes on the cardboard is curved, because the disc moves underneath the crayon. This model represents the earth, with the centre of the turntable as a pole and the circumference of the disc representing the equator. A body whose track in space is directly from the north pole to the equator thus appears to an observer fixed on the rotating earth to be coming from the north-east—it is apparently deflected to the right. The observer could account for this deviation by supposing that the body was subjected to two forces, one of which drives it from north to south and another fictitious force which makes it deviate to the right. The driving force, which is caused by the difference in the pressure of the air at the pole and farther south

as a result of the unequal heating of the surface of the earth by the sun, is proportional to the gradient or rate of fall of pressure with distance. The deviating force is proportional to the speed of the wind, the rate of rotation of the earth about its axis and the sine of the latitude. It is thus zero on the equator and a maximum at the poles.

The deviation of the winds from the direction of the pressure gradient is said in meteorology to arise from the *Coriolis force.* This force is very important in meteorology. If the earth did not

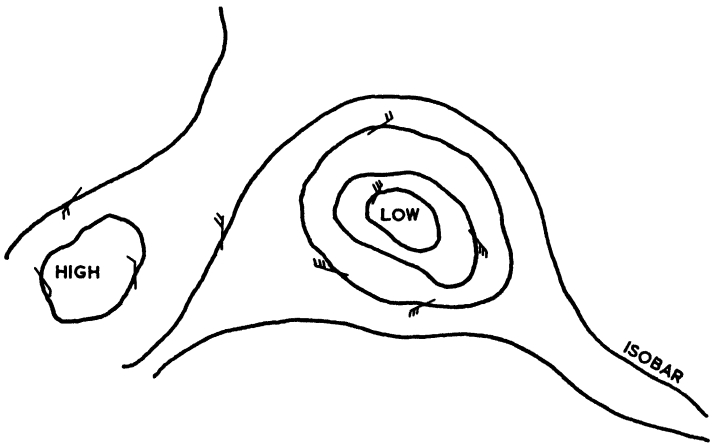


FIGURE 6. Winds and pressure (the continuous lines are isobars and the arrows fly with the wind).

rotate the air would move directly from high-pressure regions to low-pressure regions. The result of the earth's rotation is to steer the air around a centre of low pressure in an anti-clockwise fashion in the northern hemisphere, and clockwise in the southern hemisphere. This is summed up in the famous law first stated nearly a century ago by the Dutch meteorologist Buys Ballot, that if, in the northern hemisphere, an observer stands with his back to the wind, the lower pressure will be on his left hand. In the southern hemisphere the rule is reversed, and near the equator it does not apply at all (Figure 6).

In the atmosphere the supply of energy from the sun causes a hierarchy of motion systems, some very large, like the great trade-

wind belts, others smaller, like the depressions which bring rain and changeable weather to this country or the anticyclones which bring fine, settled weather in summer and, only too often, fog in the winter, and others smaller still. We shall now look at some of these systems in more detail.

The fiercest wind system, the *tornado*, is also one of the smallest. Tornadoes occur in all parts of the world, but most frequently in the U.S.A. and in Australia. A tornado is something like the whirlpool that one sees at the drainage hole of a bath. Photographs show a dark, writhing funnel, like an elephant's trunk, extending from a black cloud to the ground. In the atmosphere a tornado occurs when conditions are favourable for the rapid upward motion of moist air—for example, when cold, dry air lies over warm, wet air. When this kind of situation is shown on the weather map the forecasters in America send out a "severe weather" warning. "Severe weather" might be anything from a thunderstorm to a tornado, and no one can say with certainty whether a tornado will form and reach the ground. The storm is characterised by fierce spiral motion around a vertical axis. It averages only a couple of hundred yards across, or even less, and often lasts for less than half an hour. During this time it is unbelievably destructive. There are no reliable records of the maximum speed reached by the whirling air, because any wind-recorder which by chance was located in the path of the tornado is certain to be destroyed, but calculations made from the damage caused suggest that winds often reach 300 miles an hour and perhaps 500 miles an hour in a very violent storm. The path of the storm is often not more than a few miles in length. Pressure drops rapidly as the funnel approaches, and many buildings are destroyed simply because they explode outwards. Freak effects are also common, such as showers of frogs which have been whipped up by the fierce updraught and carried for miles before they are deposited.

Next in size comes the *hurricane*, or *typhoon*. These are storms which originate, for the most part, in the warm tropical seas, especially near the West Indies. They are much smaller in extent than the depressions which sweep over the British Isles, and usually average only a couple of hundred miles across. Their characteristic features are abnormally low pressure, high winds (often greater than 100 miles an hour), exceptionally heavy rain, thunderstorms and in the centre of the turmoil a calm area, the "eye" of the storm.

If such a storm reaches land it causes widespread devastation by wind pressure and flooding.

It is fortunate that not all the storms that originate in the warm tropical seas become fully developed hurricanes, and of these only a few pass over land. Most tropical storms do not get beyond the gale stage. A great deal of work is being done by American meteorologists to find out the causes of hurricanes, and it now seems that the critical process which decides whether or not a tropical storm will reach hurricane force is the formation of the "eye". Within the eye, the air is stiflingly hot and humid but calm, in contrast to the wild turmoil all around. From recent studies it seems that for the winds to reach true hurricane force there must be a calm, hot, central region, within which air descends and is thrown out again by centrifugal force at lower levels.

The tornado and the hurricane are examples of *convection*. When warm, moist air finds itself below cold, dry air it ascends, cools by expansion and condenses much of its water into drops. Every gram of water that condenses in this way releases 600 calories, so that an enormous amount of energy is made available. This is the energy that drives the winds.

The *depression*, or *mid-latitude cyclone*, which is so familiar in this country acquires its rotational energy as a result of the change of potential energy into kinetic energy. Such a depression is born when a warm, humid current from the tropics flows side by side with a cold, dry current from the polar regions. Soon a wave forms on the common boundary of the streams, and this ultimately becomes a depression, with warm and cold fronts. The cold air undercuts the warm air, which is thus forced to condense its water. Ultimately, the centre of gravity of the whole mass is lowered, for finally the cold air is entirely beneath the warm air. The potential energy of the system is reduced, and much of it reappears as kinetic energy, or energy of motion. Naturally, the whole process is much more complicated than is indicated above, and meteorologists spend much time in tracing the exact sequence of events in a depression, for much of forecasting depends on this analysis.

The main problem of meteorology is to follow the transformation of energy from the sun's output of radiation through all its changes in the hierarchy of dynamical systems. The problem is complicated, chiefly because of the presence of water vapour in the atmosphere, which acts not only as a storehouse of heat (i.e.,

energy) but also as a means by which energy is transferred. We must therefore look at the way in which rain is formed if we are to get a clear picture of how the atmospheric engine works.

Why does it rain? At first, it seems that this is a very easy question to answer. When hot air rises it expands, because of the fall of pressure with height. As air expands it cools, and if the cooling is continued far enough the water in the air condenses into tiny drops. This is what happens in a steam locomotive. Water is heated in the boiler to produce water vapour (steam) at high pressure; the vapour is then allowed to expand in the cylinder by pushing the piston forward and thus to drive the wheels. The condensed vapour appears as white puffs from the funnel.

However, this does not explain rain. The drops of water that are formed by condensation in this way are too small to fall to the surface rapidly. This is the reason why clouds, which may contain anything from thousands to millions of tons of water, do not quickly sink to earth. The tiny drops do not float in the air in the sense in which a stick floats on water, for water is about 800 times denser than air. They fall, but at such low velocities that they appear to float, and this is true of all small bodies, even tiny particles of rock, that are in the air.

Why, then, does it ever rain—or to put the question in another way, why do some and not all clouds rain? If water is to fall from a cloud it must be in the form of drops large enough to descend rapidly, so that the problem of the formation of rain amounts to finding out how large drops form from drops in some clouds and not in others.

An average raindrop represents the aggregation of about a million cloud drops. At first sight one is tempted to say that rain forms by water continuing to condense on the small drops until these grow large enough to become raindrops, but calculation shows that this process by itself is far too slow. If only this process were available the result would be that no drops larger than a few hundredths of a millimetre in diameter would be formed (raindrops have diameters of one or more millimetres) in the time available, and these drops would evaporate before they reached the ground. We must look for some other mechanism for the formation of raindrops.

We now believe that rain is formed mainly in two ways. One, which will not be discussed at length here, occurs mainly in the

tropics, and in thunderstorms. In this case many raindrops are formed by a few very large drops sweeping up smaller drops. This is called the *coagulation process.* The second method, which is believed to be the process which produces most of the rain that falls on this country, is rather more interesting. It was worked out in detail by the Scandinavian meteorologist Professor Bergeron, and is generally called by his name.

One often hears of the temperature of 0° C. or 32° F. called the "freezing point" of water, but it would be more accurate to call it the "melting point of ice". Water has no definite freezing point, and very small drops of pure water, like those found in high clouds, usually remain liquid at very low temperatures, down to about —40° C. Such drops are called "supercooled". If they touch a particle of ice they freeze immediately.

Many of the clouds that bring rain to the British Isles contain vast numbers of supercooled drops in their upper layers. With them there are often relatively small numbers of ice crystals. In a mixed cloud of supercooled drops and ice crystals the ice particles grow at the expense of the drops because of the difference between the saturation vapour pressure of water over ice and over water, respectively. Soon these ice particles becomes snowflakes and begin to fall at an appreciable rate. These snowflakes are star shaped and very fragile, and they throw off tiny splinters of ice which form more snowflakes—a "chain-reaction" takes place. As the snowflakes fall, they enter warmer layers of air and melt into raindrops. Most of the rain that falls in this country is believed to be melted snow.

The Bergeron process has suggested the possibility of making rain artificially. Naturally, those who live in rainy climates, like that of the British Isles, are not as much interested in rain-making as those who live in arid or semi-arid climates, such as parts of America, Africa and Australia. The Bergeron process starts with a relatively small number of ice crystals in a cloud of supercooled drops. If the ice crystals are not present in sufficient numbers rain is unlikely to fall, and the modern way of making rain is to put into the top of the cloud substances which cause ice crystals to form. Such substances, when in finely divided form, are called *freezing nuclei.* The best freezing nucleus is undoubtedly ice itself, but it is difficult to put powdered ice in large quantities into a cloud which may be 20,000 feet or more high. Another substance which pro-

motes freezing of supercooled drops is silver iodide, and many attempts have been made to start or increase rainfall by sending up clouds of silver iodide smoke from the ground. It is very doubtful, as yet, whether such methods have ever succeeded in making rain. All that can be said with certainty is that the increase, if any, is not more than about 10 per cent of the normal rainfall, and is most likely to be successful when the silver iodide particles are generated on the windward slopes of high mountains, for example the Sierras.

This brings me to the last question, and most difficult of all to answer. Shall we ever control the weather? The question might have been answered with more assurance at the beginning of this century. At that time there was no source of energy controlled by man which was large enough to have any effect on the movements of the atmosphere over large areas. Weather is caused by the sun supplying vast amounts of energy every minute to the earth, and also because the atmosphere contains water which can rapidly absorb, store and release heat in very large quantities.

Today, we have under our control unlimited amounts of energy from nuclear fission, but the biggest nuclear bomb made so far releases only a very small fraction of the energy fed into the atmosphere by the sun. Even a small thunderstorm represents an energy release equivalent to about ten atom bombs of the type used in the last War. Despite what many people would like to believe, there is no evidence to show that recent bad summers in Britain were connected in any way with atom-bomb tests, whether in the Pacific or in Russia. It has been suggested that thermo-nuclear bombs might be used to melt much of the ice in the Arctic. How would this affect weather on a large scale? The answer is that no one knows, with certainty, although one American meteorologist has been bold enough to guess. Dr. Harry Wexler, who has studied this problem, thinks that it might be possible to change our weather by such a project, but, unfortunately, the change might go the wrong way. He thinks that if a tremendous amount of heat were released in the Arctic we might have much more snow in winter, and that is something that no one in this country wants to see.

However, the experiment is not likely to be tried for a long time to come, and perhaps never. As yet, we know too little about the general circulation of the atmosphere to make a confident prediction of the results. One of the main purposes of the meteorological

studies in the I.G.Y. is to find out more about the way in which air moves around the globe. When the results of this great enterprise have been studied by scientists we may be in a position to answer questions about weather control with more assurance. It may be possible now to *interfere* with weather by the concentrated release of vast amounts of energy at certain points on the earth, but this is very different from saying that we can ever hope to *control* weather on a large scale to man's advantage.

V

THE SEA AND ITS PROBLEMS

OF THE earth's total surface of about 197 million square miles, 141 million square miles, or nearly three-quarters of the whole, are covered by the sea. The study of the oceans must therefore loom large in the physics of our planet. Yet despite centuries of observation, often crude but sometimes remarkably well planned and recorded, much remains to be learned, and in the essay which follows Dr. Deacon has indicated some of the leading problems and the ways in which they are being studied. Physical oceanography is a subject which calls for the highest mathematical skill and great ingenuity in the design of instruments, and as such has claimed the lifetime devotion of some of our ablest scientists. The sea has done much to shape the pattern of life in this country, and it is therefore natural that we regard its study as fascinating and rewarding.

Dr. Deacon is the Director of the National Institute of Oceanography at Wormley, Surrey. He is known all over the world for his work on physical oceanography and was elected a Fellow of the Royal Society in 1944.

V

SCIENTIFIC METHODS are proving so effective in the earth and heavens that it is not surprising to find them being used to discover new wonders in the oceans, and the experience of generations of skilful sailors is being enriched by the inquiring outlook of scientists. This is rather surprising to the sailors but was foreseen very long ago by scientists. In 1694 the opinion of Sir Isaac Newton was asked on a new schedule of mathematical studies prepared by Mr. Paget the mathematics master at Christ's Hospital, and he was fairly outspoken about some of its deficiencies, especially in the section that dealt with the teaching of navigation. In a letter to the Treasurer* he denounced it as little more than "the use of Instruments and the bare practise of Seamen in their beaten road", and maintained that "the Mathematical children, being the flower of the Hospitall are capable of much better learning". He said there should be more reasoning about force and motion which would help a mariner "in inventing new things & practises, and correcting old ones or in judging of what comes before him" . . . "and let it be further considered whether it be most for the advantage of Sea affaires that the ablest of our Marinners should be but mere Empiricks in Navigation, or that they should be alsoe able to reason well about those figures, forces, and motions they are hourly concerned in". He commended the wisdom of an appeal made by an earlier mathematician Mr. Oughtred, that Masters of Ships and Pilots should set down observations of "the secret motions or agitations of the Seas" and "what else they shall observe at Sea worthy consideration" as well as the obvious information about course, compass, behaviour of the ship, wind and current, and that they should "be pleased freely to communicate the same with Artists, such as are indeed skilfull in the Mathematicks and lovers & enquirers of the truth". Mr. Oughtred had no doubts that this would "tend to ye perfecting of Navigation, and

* Correspondence of Sir Isaac Newton, edited by J. Edleston (London, 1850), pp. 279–292.

the help and safety of such whose Vocations doe inforce them to commit their lives and estates in the vast Ocean to the providence of God". Newton rounds this off with the well-known quotation "I will add, that if instead of sending the Observations of Seamen to able Mathematicians at Land, the Land would send able Mathematicians to Sea, it would signify much more to the improvement of Navigation and safety of Mens lives and estates on that element".

It seems that the "Mathematical children" did not in the end

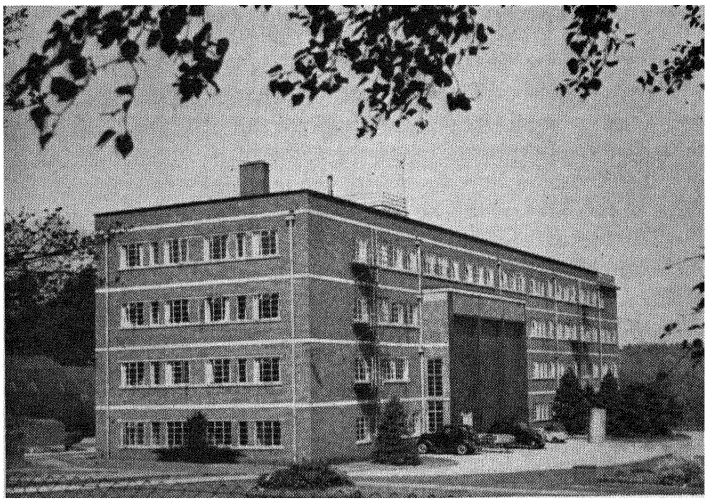


FIGURE 1. The National Institute of Oceanography, Wormley, Godalming, Surrey.

have much teaching in mechanics, only "so much gunnery as is necessary for sea service" and some of the expectations of Mr. Oughtred and Sir Isaac Newton are not yet fulfilled. There have been tremendous improvements in tables, charts, sailing directions and now radio-navigational aids, but little has been done about less obvious needs.

Records of ocean currents have been collected systematically for more than a hundred years, and they have been used in the preparation of charts of the average current in most parts of the

world and how they change from season to season, but we know very little about the day-to-day changes, and about the factors that are important in regions of variable current. Aeroplanes could not make profitable flights with nothing better than charts of average winds, and although ships are more independent, they too could make good use of more detailed information. Waves have a considerable effect on the speed and fuel consumption of ships, and on the usefulness and safety of harbours and sea defences, but wave measuring is a new technique. It is only six years since a ship was first fitted with apparatus that gives a continuous and reasonably accurate record of the waves.

Here was a backward science, and it could play little part in the opening campaign for the International Geophysical Year. But such a world-wide programme would not be complete without it. The circulation in the atmosphere depends to a large extent on the interaction between the oceans and atmosphere, and their physical problems have much in common. Atmospheric disturbances produce corresponding disturbances in the water; changes in the polar ice-caps and bending of the earth's crust cause changes in mean sea-level, and the changing magnetic fields and electric currents in the sea are linked to events in the earth and the ionosphere. Fortunately there were just enough marine scientists to take advantage of these opportunities.

The main idea, as in other aspects of the programme, was to concentrate on problems that would gain most from a wide network of simultaneous observations, and the oceans with their world-wide movements of energy and water have many such problems. The first target was to improve our understanding of the sort of waves that are commonly called tidal waves, the second to study changes in mean sea-level and the third to learn more about the circulation of water in the depths of the ocean.

The rise and fall of the tide can be measured against a pole or jetty, but for precise study it is better to use an automatic gauge in which the rise and fall of a float moves a pen across a recording drum. The float must be protected from the action of waves by enclosing it in a well or trunk which communicates with the sea outside through a small hole or pipe. A wire from the top of the float passes over a wheel, and through a simple mechanism controls the pen, which draws a tidal curve as the drum is rotated by a clock. The paper is usually left on the drum for seven days, and

although in most places there are two tides a day the curves do not get too mixed up because the same tide is fifty minutes later every day and the tides vary in range, being greatest near full and new moon.

To obtain good records great care is needed. The recording drum must not be too small. The clock must be accurate and the mechanism without backlash and friction. The height shown on the record must be checked against direct measurements made down the well, and the starting-point of the scale must be related

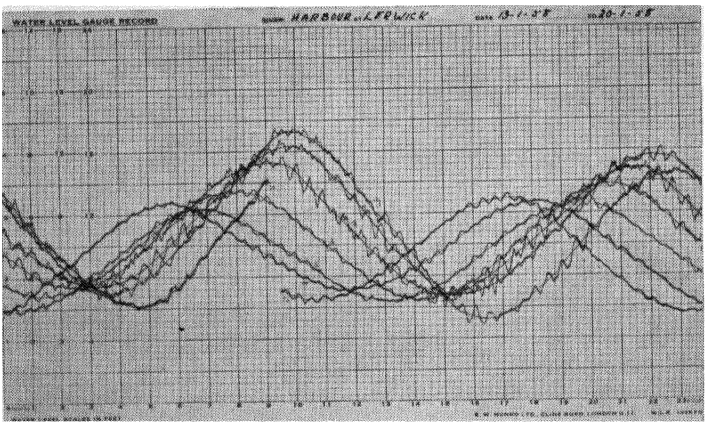


FIGURE 2. Tide records at Lerwick for the week 13 to 20 January 1958. The smooth lines were drawn in by hand.

by accurate surveying methods to a fixed mark on shore, preferably one already included in the Ordnance Survey. If these precautions are taken good results can be obtained by improvised methods even under very difficult conditions. In the Antarctic improvised gauges have been set on the sea ice so that they go up and down with the tide while the pen is worked by a wire attached to a fixed weight on the bottom.

However good the gauge, it does not always draw a smooth curve, because the rise and fall of the tide is often disturbed by oscillations which are much longer than ordinary sea waves and shorter than the tides. It would not do to smooth them out by making the hole or pipe leading to the tide well very small, since

this would prevent the level inside from following the level outside quickly enough to give a sufficiently accurate recording of the tide. If the object is to get the best possible measurement of the tide the observer is recommended to choose a protected site near the mouth of a harbour, not one far up a bay or gulf in which the water is likely to have its own oscillations.

If a flat dish is tilted gently and restored to its horizontal position the water will oscillate backwards and forwards, and the simplest oscillation is when the water is set swinging so that the level at the middle remains unchanged while at the two ends the water rises and falls alternately. Oscillations of this kind were recognised in lakes two hundred years ago, and a detailed study of their occurrence on the Lake of Geneva was begun by Dr. Forel in 1873. In a rectangular reservoir there are simple end-to-end and side-to-side oscillations like those in a dish, but in such a large irregular shape as the Lake of Geneva different parts of the lake and indentations round the edges have their own oscillations. But among all these waves which cross and mingle Dr. Forel was able to demonstrate the rocking of the whole water about fixed lines, and when he found an oscillation with a period of about an hour and a quarter he was recording the fundamental oscillation of the lake from end to end. The local name used for the oscillation in the Lake of Geneva is "Seiche", and the great interest and charm of the investigations made by Dr. Forel have led to this name being generally adopted in scientific studies of natural oscillations.

Any disturbance of the basin, large or small, is likely to set the water in oscillation, but some are more effective than others. In pursuing the question it is necessary to distinguish between *free* and *forced* oscillations. The natural oscillations which continue with gradually decreasing amplitude after the initial disturbance has ceased to operate are called *free* movements. Oscillations like the tides, that are maintained by continuous application of rhythmic changes in the attractive forces of the moon and sun as the earth rotates, are called *forced* movements. The largest oscillations are likely to occur when the period of the free oscillation is about the same as that of the impulses given to the water by variations in the maintaining force. This is called *resonance*. It can be compared with the working up of a swing; provided the timing is just right, the repetition of a small force will build up a large swing.

An earthquake will shake a dish, and Dr. Forel mentions the rocking of water in the basin of a fountain, but he concluded that in general the vibrations due to earthquakes are of too short a period to excite resonance in a lake. But among the older records there are plenty of examples of unusual oscillations being attributed to this cause, one of the most dramatic being reported oscillations of about ten minutes period and 2½ feet amplitude on Loch Lomond on the day of the Lisbon earthquake. It may be a problem of growing interest as we learn more about long-period oscillations in the earth's crust.

We cannot think of a whole ocean being rocked by an earthquake, but in parts of the world where there are steep submarine slopes, such as the western North Pacific Ocean, disturbances of the sea floor are only too common. A large disturbance is likely to cause giant oscillations that send a group of long surface waves across the ocean. They are not likely to be observed by ships in the deep ocean because they may not be more than 1 or 2 feet high with as much as 100 miles between successive wave crests. They are called long waves because their wavelength is long compared with the depth of the water, and the speed of such waves depends only on the depth of water according to the formula $v = \sqrt{gh}$, where v is the velocity, g the acceleration due to gravity and h the depth of water. Most of the deep ocean has a depth of about 2,500 fathoms, and this gives a speed of 472 miles per hour. Although they are too long and low to be visible in deep water, they slow down and increase in height when they enter shallow water, and may finally crash on to the coast 20 or 30 feet high.

One of the worst catastrophes of recent years began with a submarine earthquake near the Aleutian Islands at 2 a.m. on 1 April 1946. Less than five hours later the first wave reached Hawaii and wiped out much of the waterfront. One hundred and fifty-nine people lost their lives, and the loss might have been greater if the second wave, higher and twelve minutes after the first, had not warned everyone who could to rush to safety before the third and highest wave arrived. The first wave reached the coast of California early the same evening, the coast of Peru early next morning and it was still large enough to wash away an old hut left by the British Graham Land expedition on the Antarctic coast the same afternoon.

After this disaster a warning service was set up. Seismograph

reports are collected at a central observatory in Hawaii, and if the focus of the earthquake seems to be at a place where it is likely to cause a sea wave, tide-recording stations are warned and the information they give used to prepare a general warning. Thanks to

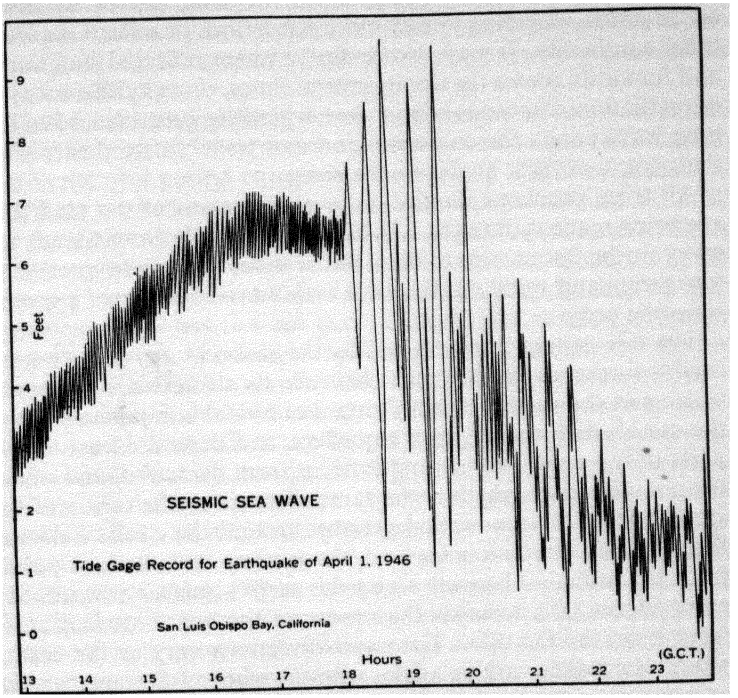


FIGURE 3. Tide record showing the arrival of a seismic surge on the coast of California.

Reproduced from "Most Ominous Wave", by E. John Lang, *Sea Frontiers, Bulletin of the International Oceanographic Foundation, The Marine Laboratory, University of Miami, Coral Gables, Florida*, Vol. 4, p. 212, 1958.

this network and the co-operation of all the responsible authorities, no lives were lost when another destructive wave reached Hawaii on 4 November 1952. In the Pacific Ocean these seismic waves or surges are called "tsunamis", which in Japanese means a harbour wave, and is reasonable, since the long waves affect coasts and harbours but not ships at sea.

When the coastal waters along the west coast of the American continent are disturbed by long-wave activity from a distant source the tide gauges show that all the local bays and harbours go on oscillating for several days. This may be due to the subsequent arrival of further energy from the same source by other ocean paths, including one or more refractions or reflections from other continents. It may also be due to waves reflected backwards and forwards across the ocean several times, or to a different type of oscillation, known as edge waves, which are generated when the long wave enters the coastal region and travel fairly slowly with their crests at right angles to the coast.

All these problems require more observations of the kind that are being made during the I.G.Y., and especially from islands far away in the ocean, where they are of little immediate interest to navigation and could not be made without the backing of a special scientific project.

The tide-raising force exerted by the moon at any place on the earth's surface is the difference between its attractive force on the water and the earth. It is only the horizontal components along the earth's surface that have any effect, and these are least on the parts of the earth nearest and farthest from the moon, and round the circumference which is the same distance as the centre of the earth is from the moon, and greatest around the circles half-way between this circumference and the nearest and farthest points from the moon. They act along the earth's surface towards the earth–moon axis, towards the moon on the near side and away from it on the far side. The exact directions vary as the earth–moon axis makes varying angles with the plane of the equator, but as a rough generalisation the water at any point is pulled first in one direction and then in a roughly opposite direction twice in 24 hours 50 minutes as the earth rotates. The two variations are not the same except when the moon happens to be in the plane of the equator so that there is a diurnal as well as semi-diurnal effect. The solar forces vary in a similar way, but are something less than half as strong. The effect of the tide-raising forces can be shown to be small (about 6 inches over 1,000 miles) except where the size, shape and depth of part of the ocean and its interaction with neighbouring parts favour resonance with the 12-hour 25-minute or 24-hour 50-minute periods. In most parts of the oceans there seems to be some form of resonance and the tides are large com-

pared with the natural oscillations of bays and harbours, so that these appear only as notches on the tide curve. In lakes the tides are much smaller than the seiches. There is a possibility that the tides may in certain circumstances excite local oscillations, one possibility being that part of the energy of a tidal stream flowing along a coast may be deflected into the narrow entrance of a harbour so that it is made to vibrate in much the same way as the air in an organ pipe.

Before discussing long waves and surges of meteorological origin it must be observed that there are some waves of two to three minutes period caused by the varying height of groups of ordinary waves breaking on a shore. Ordinary waves are the most obvious effect of wind on the sea, but they are short waves whose wavelength is small compared with the deep ocean, and until they get very close to the coast their rates of travel depend only on their wavelengths. They too can carry energy right across the oceans, and as they go, the longer wavelengths get farther and farther ahead of the shorter waves. The swell that arrives on a distant coast at a particular time contains a rather narrow range of wavelengths, and this tends to produce a strong beating effect and well-defined, alternating groups of high and low waves. Only the energy of the waves travels: the water particles travel round circles in deep water or ellipses in shallow water. But the circles and ellipses are not quite closed, and there is a very small forward movement of water. When the wave enters very shallow water and breaks there is a sharp increase in this forward transport, and a group of high waves sends forwards a long wave somewhat less than a twelfth the height of the swell. At the same time the forward acceleration has to be balanced by an outgoing long wave of about the same dimensions.

Long waves of this kind may be one of the sources of energy which excite troublesome oscillations known as range action in certain harbours. The natural period of a harbour is in about the same range as the surf beats. The rise and fall in the harbour is small, but the horizontal movements are sufficient to cause backward and forward movements of ships moored to the quays sufficient to cause damage and snap mooring lines if the moorings are not continually tended and other precautions taken. At the worst ships have to leave the quays. The oscillatory currents near the harbour entrance or past the prominent knuckle

of a jetty can also be hazardous to a ship manoeuvring at slow speed.

The trouble occurs mainly in harbours on ocean coasts where in perfect weather there may be a thunder of surf due to swell which has travelled from distant areas of strong wind. A simple observation on such coasts will show that the water tends to run farther up the beach every 2½ minutes or so. It is of real practical importance to know how closely such things are responsible for exciting harbour resonances, and some of the I.G.Y. recordings should be a great help.

Careful observations at Bermuda, which can be regarded almost as a small observation point in deep water, show that the changes in water level during the passage of a hurricane are explained almost entirely by the changes in atmospheric pressure. The sea acts like an inverted water barometer: it rises under areas of low pressure and falls under areas of high pressure, and the rate at which these changes take place allows equilibrium to be maintained if the water is deep. If, however, the water is shallow the rate at which the air disturbance travels may be nearly the same as the rate of travel of a freewater wave in that depth; under these conditions resonance occurs and the atmospheric disturbance adds energy continuously to the wave.

During the evening of Saturday, 20 July 1929, a large wave some 20 feet high took many people by surprise on the south coast beaches in Kent and Sussex. It caused some damage and got into the newspapers and the *Meteorological Magazine*. Professor Proudman, in his book on the dynamics of the oceans, shows that the conditions favoured resonance. The disturbance was an east-to-west line squall, travelling northwards at 40 miles an hour. The squall brought a sudden increase in air pressure equivalent to little more than ½ inch of water, but it was travelling at just the right speed for a long wave in the mean depth of the Channel south of Kent and Sussex.

Disturbances of this kind are not uncommon in the English Channel. Sometimes the change in pressure or wind is so small that it is hardly noticeable, but a quite unexpected wave causes the water level to rise and fall several feet in as many minutes. The local name "boar" is used at Plymouth and "run" or "sitch" in the River Yealm. The name "sea bear" is used on the coast of Germany, and in the Baltic the "sea bear" is sometimes dangerous.

The hurricane waves on the U.S. Atlantic coast and the storm surges which have from time to time caused floods on our west coast have similar origins: a sharp disturbance involving a change of pressure or wind has to move at the right speed over a long enough stretch of shallow water.

From the 'Daily Mail' 22 July 1929

20FT. WAVE.

WOMAN DROWNED WHILE FISHING.

The tidal wave which accompanied the great wind and rain storm that broke over the east and south-east coasts on Saturday night created much alarm. Right from Yarmouth in the east to Worthing in the south the effects of the unusual phenomenon were felt.

At Bury St. Edmunds the storm was the worst within memory. A fireball considerably damaged the spire of St Peter's Church, and pieces of flying masonry tore holes in the balcony awning of the adjacent West Suffolk Hospital, where patients were just being moved indoors.

Mrs. Lilian Pollard, of Chertsey-road, Woking, Surrey, was the victim of a wave which dashed up the beach at Hastings. It swept over the boat in which she had been on a fishing expedition with her husband and two other men. Boats dashed to the rescue, and the men were revived. Mr. White said:

I was rowing towards the shore, with the sea as smooth as a plate. Halfway through the harbour, at about 100 yards from the shore, I saw a wave about 20ft. high. We could not avoid it. I turned the boat end on, the wave hit us, and over we went. I have never seen anything like it in my life.

Mr. Wilkins, an official of Hastings Pier Company, said:—

Suddenly it became dark, and beyond the pier I saw what looked like a white wall on the water. It dashed up the beach at a great speed, and in a couple of minutes or so had spent itself.

WHIRLWIND.

At Folkestone a huge black cloud appeared, and a whirlwind churned the sea into a mass of foam. The tide was low, but water rushed in to several feet above high-water mark, scattering people on the beach and smashing small craft. A number of people were drenched to the skin, and treated at the hospital for shock and injuries received on the rocks

Arthur J. B. Balkham, 16, of Thanet-gardens, Folkestone, who was fishing from the rocks, was swept away, and vanished before the eyes of helpless onlookers.

Great crowds on Brighton beach saw a long white lone of foam rushing in, and fled wildly. A man and woman, imprisoned under a capsized boat, were dragged out by an attendant who dived beneath it.

A wave swept 150 yards up the beach at Worthing and overtook men, women, and children. At Kingston lightning struck the awning wire of a punt, and a boy was flung into air, the turned a somersault, and fell into the boat again

FIGURE 4. 20-foot wave.
Cutting from the *Daily Mail*, 22 July 1929.

The giant storm surges which occur on our east coast, like the one that caused the disastrous floods at the end of January 1953, can be generally shown to be due to surges entering the northern part of the North Sea and being greatly intensified by the effect of the wind. The geostrophic effect of the earth's rotation also plays

a part, and the wave generally moves round the sea, southwards along our east coast and northwards along the continental shore. We have a warning organisation for storm surges centred at the Central Forecasting Office of the Meteorological Office at Dunstable, which is as effective as that operating for seismic surges in Hawaii. But there is still need for research to get earlier warnings and rules that are more generally applicable.

The observations at Bermuda seem to show that long waves are not propagated from a storm in deep water, but there seems to be some evidence of them from Japan and the U.S.A. A preliminary I.G.Y. report from U.S. stations in the Pacific Ocean mentions that their recorders have picked up long waves from hurricanes. The first arrivals consisted of long waves of ten to twenty minutes period, and these were followed by great intensification of swell and surf beat.

Some forty long-wave recorders were installed for the I.G.Y. in all parts of the world. With the help of ingenious hydraulic or electric filters they smooth out most of the tidal oscillations as well as the ordinary waves. The records from tide gauges can also be used.

If the ordinary waves, long waves and tidal waves are all smoothed out of a water-level record there are still changes in the mean level from month to month and year to year and long trends over many years. The observations are made by measuring hourly water levels from the tidal records and averaging the readings over each month and each year, taking care not to include any uncompleted parts of the principal half-daily and daily tides.

The results show that mean sea-level is not such an unalterable datum as might be supposed. There are considerable fluctuations which are not merely local phenomena but similar over quite extensive areas. One cause is regional changes in the volume of water. If the mean temperature of the water down to a depth of 100 fathoms increases from 50° to 51° F. the water column expands by about 1 inch. A decrease in the mean salinity of the same water column from 35·0 to 34·9 parts per thousand would make the level of the same weight of water stand $\frac{3}{4}$ inch higher. In the North Atlantic temperate region the mean level is generally about 10 inches higher in late summer and autumn than it is in spring. Seasonal changes in the balance between rainfall and evaporation play some part. The evaporation is greatest in winter when cold

air blows over relatively warm water; and in winter more water is stored in the arctic ice and on land as snow and ice-cover, and in the ground, rivers and lakes. Fluctuations in mean atmospheric pressures, winds and currents can also affect the water level. It is not easy to separate one effect from another, because a change in temperature or salinity is often related to a change in wind.

Near oceanic islands in the tropics the fluctuations in monthly mean sea-level are very small, but at the head of the Bay of Bengal they may be as much as 5 feet. Taking an average over all the oceans indicates that there is nearly 1 inch less water in the oceans at the end of the northern winter than there is at the end of the northern summer. This may be due to the much greater proportion of snow-covered land in the northern winter.

Careful levelling across the Isthmus of Panama has shown that the mean sea-level at the Pacific end is 8 inches higher than at the Atlantic end when an average is taken over the whole year. In October, the wet season, the difference in mean level is 12 inches, and in February, which is relatively dry, there is hardly any difference at all. The difference seems to be mainly due to the water in the Gulf of Panama being much less saline and less dense than the water in the Caribbean Sea. The question is sometimes asked why can there be such a difference when the two oceans are joined round Cape Horn, but when account is taken of all the changes in temperature, salinity, barometric pressure, wind and currents that take place in the 8,000 miles of ocean between the two ends the difference is no longer remarkable. Surveys along the U.S. Atlantic and Pacific coasts show rises of about 1 foot from Florida to Maine and from South California to the state of Washington.

The same meteorological and climatological factors whose seasonal changes produce variations in monthly mean sea-level also change from year to year and cause variations of mean annual sea-level. There is also a nineteen-year variation in mean sea-level due to a tide of this length which depends on a nineteen-yearly periodic change in the orbit of the moon relative to the equator. It may amount to a few inches. The year-to-year variations are usually not more than a few inches, but they often show a general trend, and in the south of England the mean sea-level is at present rising about 6 inches in 100 years relative to the land. There is also archaeological evidence to suggest that the rise has gone on at about the same rate since the time of the Roman occupation, and

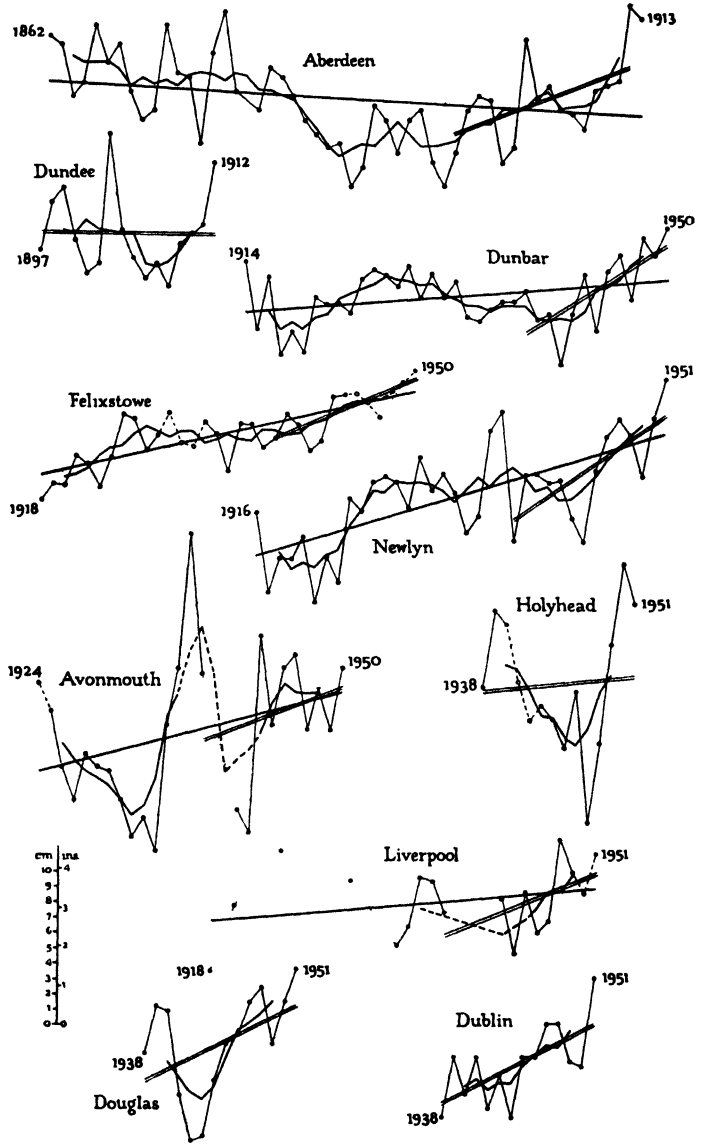


FIGURE 5. Changes in annual mean sea-level round the British Isles.

Reproduced from "Present Vertical Movements of the British Isles", by H. Valentin, *Georg. J.*, Vol. 119, p. 299, 1953.

geological evidence to show that changes at about this speed in falls of water level as well as rises have taken place in previous ages. The present rate of rise is about the same in the Netherlands and on the east and west coasts of the U.S.A., but in the north of Scotland and in Alaska the rate of rise of water level is much less. This is because the land in these northern countries is still recovering from the great load of ice that weighed them down in the last ice age. In Finland the land is still rising relative to the water, more than 1 foot in 100 years, nearly 3 feet in the north-west.

There can be no doubt that the level of water in the oceans is at present rising as the arctic gets warmer and glaciers recede. This warms the water in the northern parts of the ocean as well as adding more to it, but the changes in the shape of the earth's crust are also important. The slow rise of the sea bottom in great shallow northern seas, such as Hudson's Bay and coastal areas north of Canada and Siberia, must have an appreciable effect. These are problems of great interest in connexion with studies in climatology, glaciology and the physics of the earth. They also begin to be of importance to engineers. Six inches in 100 years seems very little, but there are very large areas of highly populated and industrialised land below the level of ordinary spring tides, and it is only the sea walls round the coasts and rivers that keep the water out. To add an extra 6 inches to these walls and to all the docks would be a very large undertaking, and the need cannot be discussed very fully till there is better understanding of the factors that contribute to the changes. Fifty new tide gauges have been installed in all parts of the world, many of them on oceanic islands and other places where they will do most to provide a more adequate cover of the oceans than has been possible while records have been available only from the principal ports. The I.G.Y. observations, lasting 18 months, will not themselves solve any of the main problems, but they have done much to rouse interest in the subject, and much of the work will continue. The International Council of Scientific Unions and U.N.E.S.C.O. have made lasting arrangements to deal with the records, the Liverpool Tidal Institute being the chosen centre for the work.

The waves, long waves and tides move energy about the oceans, but not water. The water movements can be attributed indirectly to the heat of the sun. The earth's atmosphere is very transparent to the short-wave radiation from the sun, and after some reflection

back to space from the clouds and the earth's surface most of the incoming radiation is absorbed in the ocean and land surfaces. But since the sea and the land do not grow much warmer every year, they must lose as much as they gain. They do this partly by long-wave radiation, partly by conduction and partly by the evaporation of water. The long-wave radiation is partly absorbed in the atmosphere, mainly by the water vapour and carbon dioxide. Conduction of heat from sea and land also warms the atmosphere, and the condensation of rising water vapour has a large heating effect. This heat is finally radiated back to space, but the tropics would become unbearably hot and the polar regions unbearably cold if there were not great transports of heat from low to high latitudes in the atmosphere and oceans.

The circulations in the atmosphere and oceans have much in common, but that in the atmosphere is much more active. One of the important considerations is that the atmosphere is heated at the bottom by the sea and land and cooled at the top by radiation, whereas in the ocean both heating and cooling take place at the top. It follows that the winds are the most important driving force of the ocean currents, and it seems to be generally agreed that the winds transport more heat than the currents. But the effect of the currents is by no means negligible: they carry warm water to high latitudes and return cold water to low latitudes, and do much towards determining where most heat is fed to the atmosphere. We cannot yet say much about the effect of the deep-water circulation, but there is growing evidence that it is largely driven, like convection in a dish, by regional differences of heating and evaporation.

The I.G.Y. programme has been concerned mainly with the general circulation in the oceans and particularly with the deep currents.

As a result of 150 years ocean exploration we have sufficient information about the temperature and salinity of the surface, deep and bottom water in most parts of the ocean to trace movements of water from one end of an ocean to the other. One of the most remarkable movements starts in the North Atlantic Ocean, where cold water of high salinity sinks and spreads southwards at depths between 1,000 and 1,500 fathoms. In the eastern half of the Atlantic Ocean it is reinforced by highly saline water which flows as an undercurrent out of the Mediterranean Sea. It climbs to a much higher level as it approaches the Antarctic region, and some

of it, diluted by the high rain and snowfall and by melting ice and snow, returns northwards above the North Atlantic water. Some, which has been cooled, without being much diluted, by mixing with the coldest water from the antarctic continental shelf, turns back to the north as a bottom current. The remainder can be traced round the Cape of Good Hope in the Indian Ocean and even south of Australia into the Pacific Ocean.

One of the main objects of the I.G.Y. oceanographic programme

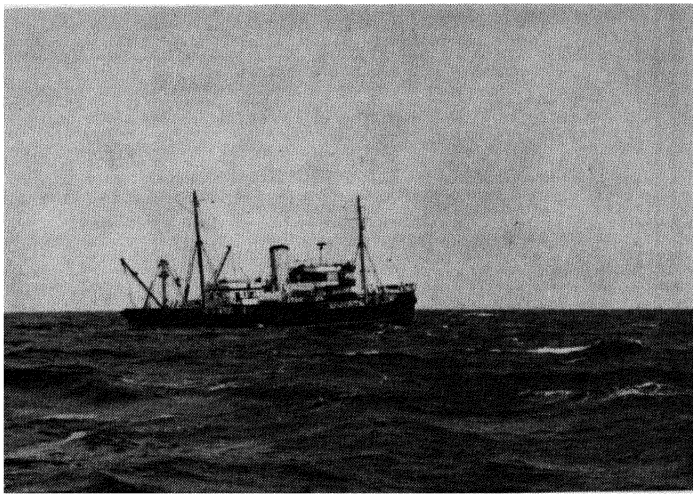


FIGURE 6. The Royal Research Ship *Discovery II* in the Gulf Stream.

has been to extend these ocean surveys, and some eighty ships from twenty countries have taken part. The British contribution has included detailed observations at all depths along three lines across the Atlantic Ocean, on four other long lines across the eastern half of the ocean, and shorter lines in the Bay of Biscay and off the coasts of Portugal, Spain and North Africa. All of this work has been done in close co-operation with U.S. scientists. Our Fishery Research vessels have made similar observations in the Barents and Greenland Seas and between the Shetlands, Faeroes and Iceland. H.M. Survey ships have made observations in the Straits

of Gibraltar and Bab-el-Mandeb. The Marine Biological Association has made a series of detailed observations in the Bay of Biscay. Research ships from U.S.S.R., U.S.A., Germany, Japan, France and other countries have also had ambitious programmes,

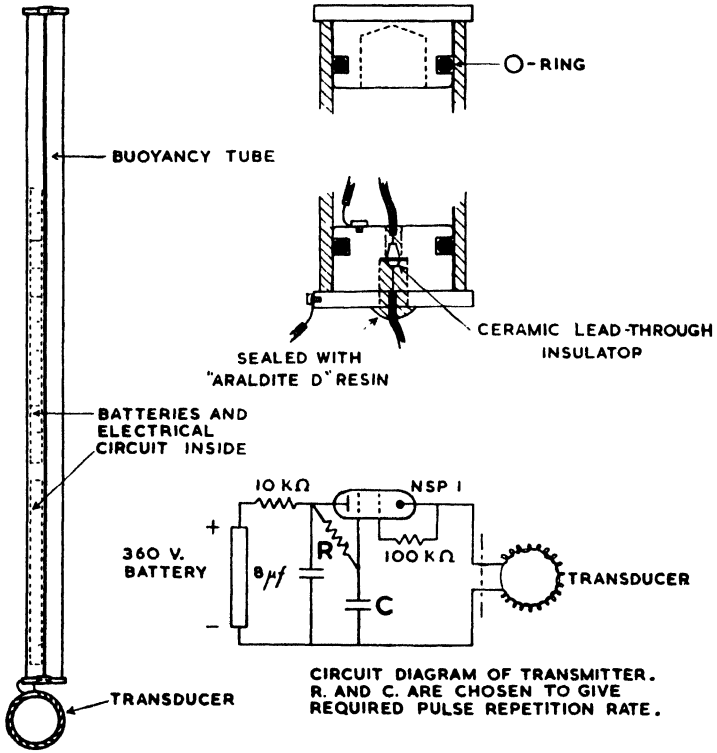


FIGURE 7. Sketch of a neutral-buoyancy float.

Reproduced from "A Neutral-buoyancy Float for Measuring Deep Currents", by J. C. Swallow, *Deep-Sea Research*, Vol. 3, p. 74, 1955.

and there is now much to be done in publishing and working out the information.

Although we know much about the journeys made by recognisable water masses starting from exceptional climatic regions, we know very little about their speeds, or of the forces involved. If some atomic waste is buried in deep water we do not know how

long it will take to get to other places and other depths, and we know too little about the physical processes to be able to make a reliable estimate. We have long waited for a method similar to the balloon and radio-sonde techniques use in meteorology. Dr. J. Swallow of our National Institute of Oceanography managed to

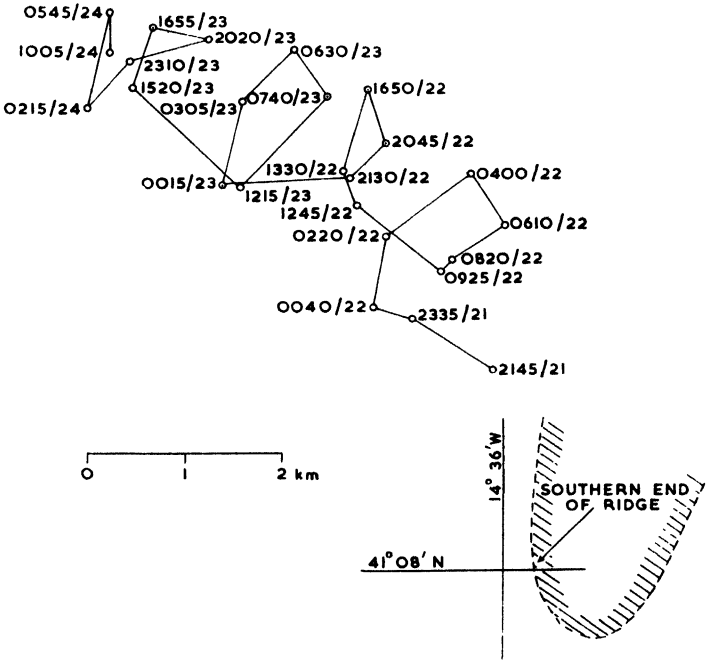


FIGURE 8. Track of neutral-buoyancy float at a depth of 1,300 feet 200 miles west of Portugal. It shows "tidal ellipses" superimposed on a slow drift to the north-west.

develop something in time for the I.G.Y. The balloon is replaced by a float made of aluminium tubes which are less compressible than sea-water. This means that when the float is loaded so that it sinks below the surface the increasing water pressure makes a smaller increase in the density of the float than in the density of the surrounding water, so that the float tends to gain buoyancy. By carefully adjusting the weight and thickness of the tubes they

can be made to float at any depth, and when there they are quite free, drifting with the current.

Batteries and an acoustic transmitter are part of the load, and as the float drifts it sends out acoustic signals at regular intervals. A ship at the surface can use these to plot the path of the float. The usual method is to use two hydrophones, one near the bow of the ship and another near the stern. When the float signal arrives simultaneously at both hydrophones the float is directly on the beam and its bearing is known; similar bearings taken from other known positions give the position of the float, and it can be followed by repeated observations of this kind. It is not easy to keep a sufficiently accurate record of the ship's movements, but it can be done with the help of tightly anchored radar-marker buoys, whose positions can be checked by echo-sounding from the ship on to recognisable features on the bottom. The task is much easier when the work is being done in one of the areas where radio-navigational aids can be used.

Many measurements have already been made. One of the first problems, of great theoretical significance as well as practical interest, was to study what happens below the Gulf Stream. This was done in co-operation with the Oceanographic Institution at Woods Hole in Massachusetts, in an area just outside the coastal shelf off South Carolina. Near the surface there was plenty of evidence of the strong northward movement. At depths near 5,000 feet there was little horizontal movement, but floats at 8,000–9,000 feet showed speeds of as much as $\frac{1}{3}$ knot towards the south affording evidence of a large transport of water opposite to the surface current. Floats used between San Francisco and the Aleutian Islands showed very small velocities, but U.S. scientists have since worked below the South Equatorial Current and demonstrated the existence of a deep counter-current with speeds of 2–3 knots. On the eastern side of the Atlantic Ocean the deep currents generally flowed at 1–2 miles a day, but were remarkable for the way they change from place to place and time to time. One of the floats was followed for forty-eight days. Outside the Straits of Gibraltar the highly saline undercurrent from the Mediterranean Sea was found to be concentrated near the Spanish coast, where it travelled westwards at about $\frac{1}{2}$ knot at depths between 3,000 and 4,500 feet. On its southern flank there were eddies of the highly saline water and one float travelled round an ellipse about 12 miles

long and 10 miles wide in 7 days. When the positions of the floats are fixed often enough they show that there are tidal streams at all depths.

The sea observations have already done much to stimulate further theoretical and practical study of the general circulation of the oceans. They have given a clear indication that the deep-water movements carry as much water as the surface currents and that we shall not understand the changes in the surface currents and their effect on climate and fisheries till we also understand the deep circulation.

The I.G.Y. oceanographic programme has been an undoubted success. It has brought a wealth of new data and fresh interest in the oceans. It seems to have shown us how to get together, and there have been many pointed international discussions. On the last I.G.Y. voyage made by our research ship *Discovery II*, from which she returned on 15 December, four laboratories and three countries were sharing the work. This must help us in inventing new theories and practices, and correcting old ones, and in judging what comes before us.

VI

THE ANTARCTIC

THE POLAR regions were once regarded as the most inaccessible areas of the Earth's surface, and it is not so many years ago that the North Pole and subsequently the South Pole were first reached, by journeys made on foot in conditions of great hardship and peril. Today, the picture is very different. The Arctic is now crossed regularly by commercial aircraft and even places near the Pole itself can be reached fairly easily and quickly. During the International Geophysical Year the great land mass of Antarctica had more human beings living on it than ever before, including a large group at the South Pole.

But even if the heroic days of Peary, Nansen, Amundsen, Shackleton and Scott have gone for ever, it is still not an easy matter to take a large expedition to Antarctica to explore its desolation. In this essay Dr. Robin, who knows the frozen south as well as anyone, outlines some of the scientific problems of Antarctica and describes how scientists live and work in the appalling conditions of the long winter night.

Dr. Robin is the Director of the Scott Polar Research Institute at Cambridge.

VI

SCIENTIFIC INVESTIGATIONS are carried out in the polar regions, not because the scientists concerned particularly want to go there, but because these regions are the most suitable parts of the earth's surface for certain observations. The aim of this chapter is to tell you about these regions and about the problems which have to be tackled.

The main problems to be met with in the Arctic and Antarctic arise from the cold, and from winter darkness. At the north and south poles night and day last for six months each at a stretch. This is because the poles always face the same direction in space. At the north pole in winter the Pole Star is always seen overhead, although the stars closer to the horizon move right around the compass once a day, staying at the same height all the time. The poles are thus the only places where the spin of the earth does not make the sun, moon and stars rise and fall once a day. Instead, it is only the movement of the earth around the sun, and the tilt of the axis of the earth, that make the sun rise and set once a year at the poles. The farther we move from the poles, the more the sun will rise and fall in the sky in the course of a day, but at midsummer everywhere within the Arctic Circle the sun will stay above the horizon for the whole twenty-four hours. Of course, midsummer in the Arctic occurs when the earth has moved into a position where the north pole is tilted most towards the sun, and at the same time the south pole will be tilted farthest away from the sun in the middle of the Antarctic winter.

In England during winter the sun is only up for eight hours a day, while in summer we have sixteen hours of sunshine a day. Even this variation in the hours of sunshine makes a big difference between winter and summer temperatures; but the result of six months' night at the poles is to make the air really cold, both at the north and south poles and in the Arctic and Antarctic round about.

There are, however, some striking differences between the

Arctic and Antarctic in spite of their equally long days and nights. The central region of the Arctic consists of an ocean which is covered by floating ice floes mostly between 5 and 20 feet thick. During summer the upper surfaces of these ice floes melt, and in many areas the floes crack and drift apart, leaving lanes of open water, in which a submarine can surface close to the north pole itself, as shown in the photograph on this page. Now that submarines using nuclear propulsion are available, it is possible to cross the Arctic Ocean under the ice from Alaska via the north pole to the North Atlantic Ocean in about four days, whereas sur-

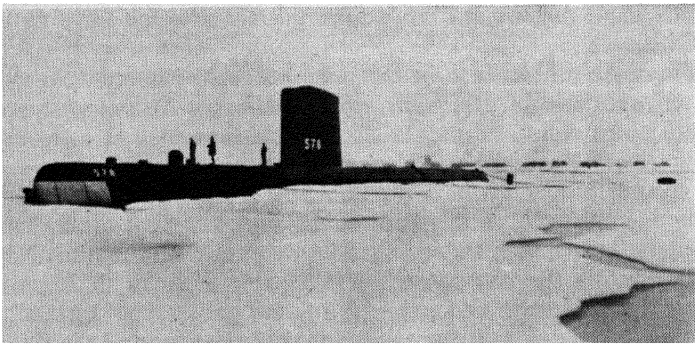
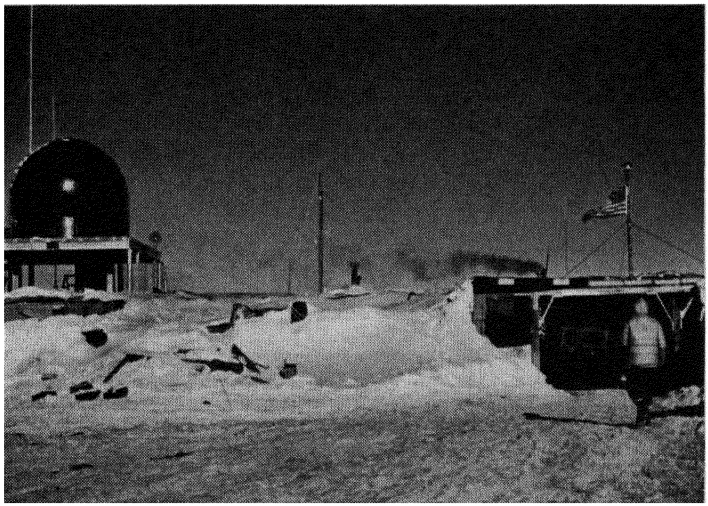


FIGURE 1. U.S. Nuclear Submarine *Skate* surfaced between the ice floes of the Arctic Ocean. In the background are the buildings of the U.S. I.G.Y. station Alpha, built on a large ice floe.
Official U.S. Navy Photograph.

face ships have spent three years and more crossing the Arctic, and have never penetrated as far as the north pole. Although nuclear submarines hold much promise of providing a new means of studying the Arctic Basin, much valuable work has been done over a number of years from scientific stations built on large ice floes. Supplies and men have been flown in by air from North America and the U.S.S.R. to establish these floating stations, which have carried out studies principally in the fields of meteorology and oceanography as their ice floes drift around the Arctic Ocean. More recently, unmanned automatic stations have been left in the ice, which periodically report the weather conditions by radio to shore stations, and at the same time the shore stations use direc-

tion-finding equipment to determine the position of the transmitters. As a result of these investigations we now know that much of the Arctic consists of an ocean as deep as the other great oceans, but covered by relatively thin pack ice.

Conditions in the Antarctic are very different. The south pole is about 10,000 feet above sea-level on the great land mass of Antarctica. Because the pole is so high, being more than twice as



[*Reproduced by permission of the Trans-Antarctic Expedition.*

FIGURE 2. U.S. Amundsen–Scott I.G.Y. station at the south pole. The dome houses a radio theodolite for following balloons in order to measure upper winds.

high as any mountain in Great Britain, it is always cold there. It is much too cold for the ice to melt even in midsummer. The photograph above shows the south pole station, built by the Americans, pretty well buried under the snow. There is a garage on one side; a barber's pole which was thought to mark the side of the south pole at first, although later it true position was found to be a little farther away; and a big dome which houses a radio theodolite for following balloons in order to measure winds in the upper atmosphere.

The much more extreme conditions of cold obtaining at the

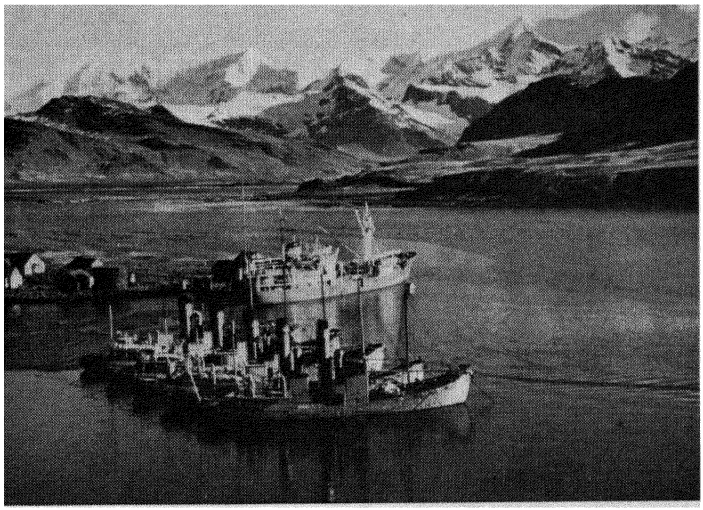
south pole, with its high, continental situation, than at the north pole, where there may be patches of open water, are also found farther away from the poles. For example, on the east coast of Greenland, about 73° north, grasses and small flowers grow in the summer and herds of musk oxen are able to live there throughout the year, eating grasses, leaves and, in winter, roots which they can reach through the snow. But the Antarctic coast a thousand miles away from the south pole shows a very different scene, even in summer. In the Weddell Sea, for instance, there is mile after mile of coast-line formed by ice cliffs about a hundred feet high. Just occasionally there is a break in the cliffs and the ice slopes more gently to the sea, so that it is possible to land stores and equipment from a ship on to the ice.

In order to find in the Antarctic the kind of thing which is met with on the east Greenland coast about 1,000 miles from the north pole, it is necessary to travel about 2,000 miles away from the south pole, or double the distance, which shows how much colder the Antarctic is. The illustration of South Georgia, with a whaling factory ashore, a few whale catchers in the harbour and glacier-covered mountains in the background, shows country which is very like East Greenland at 73° north; but it is located at 54° south, a similar latitude to Belfast.

There is one other major difference between the Arctic and the Antarctic. The Arctic is much closer to Europe, Asia and North America, that is to say to the most densely peopled regions of the world. Airlines fly regularly over the Arctic Ocean, and indeed practically over the north pole, and most places in the Arctic can be reached within a couple of days, or even a few hours in an emergency operation.

By comparison, there is little flying done from the southern continents to the Antarctic mainland; at the moment only the Americans are both able to afford and organise it from New Zealand. Everyone else has to go there by ship, and if they require aircraft for use in field operations these are taken there on the ship also. Travelling by ship to the Antarctic has its hazards, in spite of the development of powerful ice-breakers. In the Weddell Sea in the early part of this century both the *Deutschland* expedition under Filchner and Shackleton's *Endurance* expedition were trapped in the ice and unable to establish the bases which they intended to set up on shore. The story of the crushing of the

Endurance in the pack ice, and of the eventual rescue of the party, is one of the greatest classics of Antarctic exploration. It was not until the second half of the century that bases in the Weddell Sea were established, thanks to the use of more powerful ships. Even then, however, some stations in other parts of Antarctica have had to be closed and personnel flown out, because the supply ships could not penetrate very heavy pack ice guarding the approaches.



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FIGURE 3. South Georgia, showing the whaling station at Grytviken. The scenery here 2,000 miles from the south pole is similar to the east coast of Greenland 1,000 miles from the north pole.

However, in spite of such hazards a number of different countries managed to put scientific stations on the Antarctic continent during the I.G.Y. of 1957–58. The I.G.Y. stations are shown on the map on page 106. From this map it is possible to see which countries took part in Antarctic observations at that time; the United Kingdom, Belgium, Japan—who evacuated their base during 1958 because of difficult ice conditions but re-established it during 1959—Australia, New Zealand, Russia, the U.S.A., France, the Argentine and Chile all had bases in Antarctica. The Americans built one base at the south pole, and the Russians had

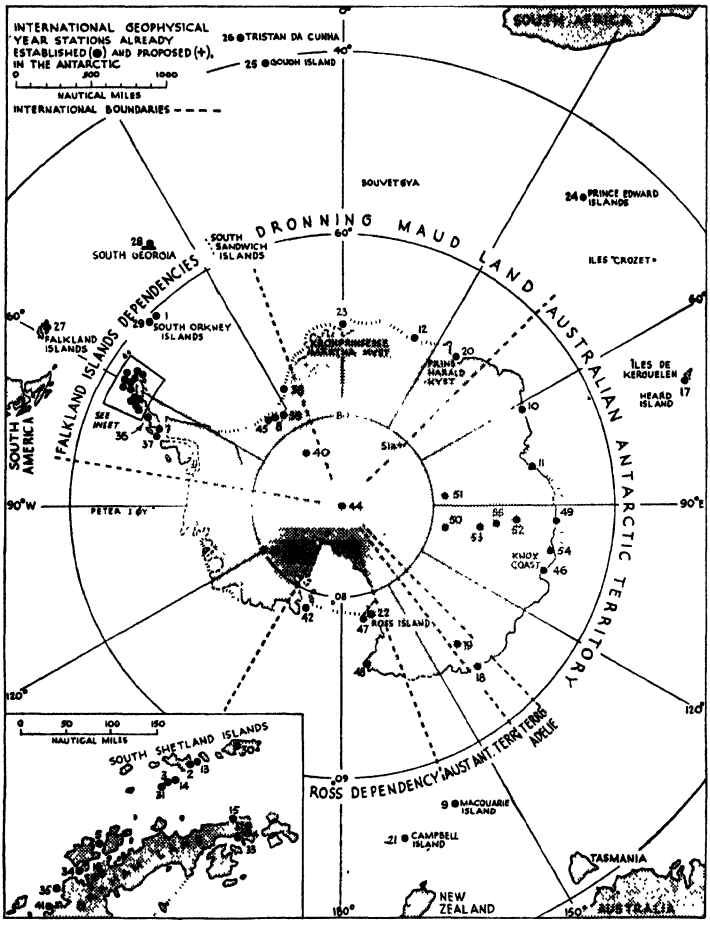


FIGURE 4. I.G.Y. Stations in Antarctica and Sub-Antarctic Islands. Argentina 1–8; Australia 9–11; Belgium 12; Chile 13–16; France 17–19; Japan 20; New Zealand 21–22; Norway 23; South Africa 24–26; United Kingdom 27–41; United States 42–47; United States/New Zealand 48; U.S.S.R. 49–55.

reached the Pole of Inaccessibility, or the part of the continent farthest from any coast-line, by the end of the I.G.Y. Most of these bases continued in operation after the I.G.Y., as much still

remains to be learned from the investigations started up at that time.

Before the I.G.Y., the lowest air temperature recorded in the world had been in Siberia, and was −94° F., or 126° of frost. In 1957, at the south pole, the Americans recorded a temperature of −102° F., or 134° of frost. The Russians were not dismayed by this beating of the Siberian record. In August 1958, at their Vostock base, the temperature went down to −125° F., or 157° of frost.

The very low temperatures occur when no appreciable radiation from the sun warms the surface of the Antarctic ice sheet. During these winter months some heat is supplied to these regions by the circulation of air from warmer areas farther north, and some of the summer-time heat from the sun which entered into the ice is conducted back to the surface to help warm the air. However, the polar ice sheet itself radiates heat out into space whenever there is a clear sky, and the temperatures fall in consequence until the loss by radiation equals the supply of heat. Of course, the great height of the ice sheet also means that temperatures will be lower, since air temperatures fall off rapidly with increasing height at these elevations.

As heat is radiated into space from the surface of the ice, the air in contact with it is chilled and thus becomes heavier than the air above it. Wherever there is an appreciable slope of the ice surface this layer of heavy, cold air tends to flow downhill, as does any fluid, and the steeper the slope, the greater the flow. The steepest slopes of the Antarctic ice sheet occur near the coast, and it is here that these "katabatic" winds reach their greatest intensity. The late Sir Douglas Mawson wrote about these winds in another classic book called *The Home of the Blizzard.* At his base at Cape Denison the average wind speed during a whole year was 50 miles per hour and maximum speeds reached over 100 miles per hour. More recently a French expedition in Adélie Land in 1951 experienced weather which was just as bad. Recent studies of these katabatic winds have shown that they do not flow down the line of greatest slope, but they are deflected by some 30° or so by the "Coriolis Force" described by Sir Graham Sutton in Chapter IV. It has been pointed out on theoretical grounds that this will tend to produce greater winds on the west side of a large depression, such as may lead down to a coastal bay, than on the eastern side.

However, if it is possible to build a station on flat ice, such as an ice shelf, then one can escape the effect of katabatic winds altogether, as they die out completely within a very few miles of the foot of an ice slope.

Not only does cold of the intensity experienced in the Antarctic make geophysical work a chilly job at times, but it also affects various materials so that they can no longer be used in the same way as they are in warmer climates. For instance, when the temperature goes down to around −110° F., which is the temperature of "dry ice", rubber snaps like a stick of wood instead of being pliable and elastic as we know it. So rubber cannot be used for a flexible material at this temperature. Nor is a mercury thermometer of any use at very low temperatures. Mercury freezes at about −40° F., and becomes a solid lump. Here the answer is to use some sort of spirit thermometer. A butane thermometer will in fact register temperatures considerably lower than those provided even by the Antarctic.

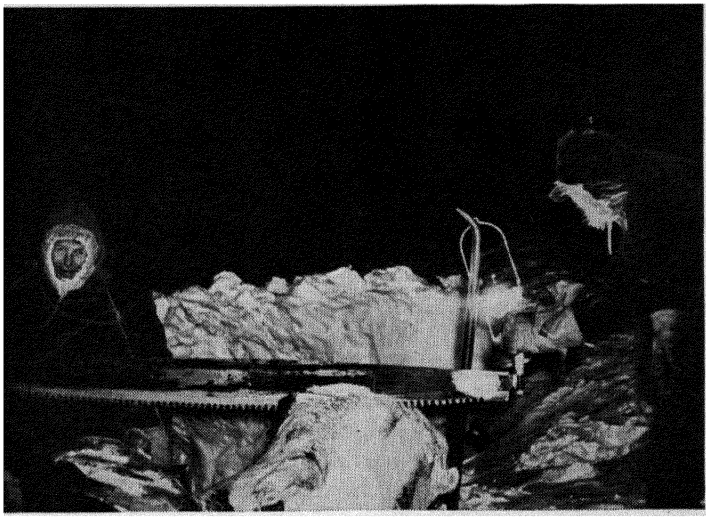
Another problem is to keep vehicles such as "sno-cats" or tractors working in the cold. If ordinary oil is used even at freezing point, engines become more difficult to start, but special oils will give very much better results. However, at very low temperatures ordinary oil becomes solid, and even with special low-temperature oils some kind of pre-heating of engines is necessary before they will start. In the case of instruments which must function in the extreme cold, the oil is cleaned out and dry graphite flakes are used for lubrication.

Condensation also causes difficulties. Instruments such as cameras brought into a warm hut or tent from very cold outside air will immediately become covered with a layer of frost. When this happens it may be an hour or more before the water dries off completely and the camera is usable again.

Expedition members are always having to adjust themselves to meet these low temperatures, even in small ways. Seal meat for the dog teams, for instance, may be frozen so hard that it has to be cut up not with a knife or cleaver, but with a cross-cut saw worked by two men. And these men will probably have ice condensed on their beards and on the fur around the hoods, as may been seen in the illustration on page 109.

Obviously in these conditions great attention must be paid to clothing. A typical cold-weather outfit might consist of a string

vest, which keeps a good layer of warm air around the body; long woollen pants; a flannel shirt; warm woollen trousers; and two or three sweaters. On top of all this woollen clothing must go windproof outer garments to prevent the cold air cutting through the comparatively loose weave of the wool. For the head, a ski-cap with ear flaps, or a woollen balaclava, or a leather motor-cycling helmet with a woollen lining may be used, over which is drawn the fur-edged hood of the outer windproof jacket so that



[*Reproduced by permission of the Trans-Antarctic Expedition.*

FIGURE 5. Sawing frozen seals into blocks of meat for feeding dogs during the Antarctic winter.

as little as possible of the face is exposed. The feet are kept warm by two or three pairs of woollen socks, a pair of felt slippers and over all a pair of leather and canvas boots; or perhaps some Finnish or Lappish finesko, made of reindeer skin. Fingerless mittens, useful for surveyors and others who have to operate delicate instruments, are covered by other pairs of gloves, with windproof canvas, leather or reindeer skin gloves as the outer layer. The advantage of these materials is that they are porous enough to let water vapour pass through. If rubber gloves are used the air inside is completely sealed in, and all the moisture

evaporating off the hands is trapped and forms ice inside the gloves.

This kind of clothing is used for an active outdoor job, such as sledging along with the dog team, but if the job is a sedentary one, such as driving a vehicle, then even heavier clothing is used, for example, reindeer or dog-skin parkas and breeches or, lighter but very warm, eiderdown jackets and trousers.

Housing, like clothing, has to be specially designed for Antarctic use. The most urgent task facing any expedition members, after unloading the stores from the ship which brought them, is the erection of the base buildings. Once winter blizzards start to blow, it is almost impossible to keep the inside of any partly finished huts clear of drifting snow. The Trans-Antarctic Expedition, who were unable to build their main hut completely before the winter came, found during one period near mid-winter's day that by the time they had cleared 80 tons of snow from the east end of their partly erected hut, another 40 tons had filled the west end. Even when the buildings can be finished before winter comes, huts to be sited on snow have to be designed to deal with huge drifts which may well bury the whole structure during the course of the winter. This puts a considerable strain on the roof and walls. Where the base is built on rock, the huts must be very securely fastened down on to the rock by means of heavy wires, so that they will not blow away in high winds. However, once the main hut is built, and the galley, heating system and electric power installed, it is possible to live as comfortably inside the hut as in any similar building anywhere else in the world.

A modern Antarctic base requires some hundreds of tons of stores for its establishment, and those not needed for immediate use must be stowed away so that they are accessible when required. Often a system of tunnels lined by store cases is used, serving the double purpose of stacking away the food and equipment, and providing easy access to other huts without making it necessary to go out into all winds and weathers. With the complex observations to be carried out, it is usually found desirable to erect a number of huts, rather than one very large building. Then if a fire breaks out, only one section of the base will be damaged. In any case, certain huts need to be isolated; for example, the essential electric generators are noisy and need massive foundations, and may therefore be sited away from the living hut; if an extensive

study of weather conditions is being made, a hut will be needed for filling balloons with hydrogen before they are released into the air in order to radio information on the upper atmosphere back to the station; if the magnetism of the earth is being studied, then a special non-magnetic hut must be built away from the others. There may be separate garages for maintenance of tractors. Apart from huts, there will almost certainly be a number of tall masts to be erected for radio aerials, and perhaps special towers and outdoor screens for meteorological observations. The photograph on page 103 of the Americans' South Pole base shows some of these features.

When snow falls in England, within a few days it melts and the resultant water drains away as ordinary rain-water does. But in the Antarctic the air is too cold for the snow to melt, and so it accumulates, the lower layers turning to ice as it does so. Round much of the coastal region, where the highest precipitation occurs, 3 feet or so of snow may fall on the surface during one year. This amount is equivalent roughly to 16 inches of rainfall, or rather less than London's annual average. In the central area of the continent, however, away from the moist air over the sea, precipitation is much lower, and only about 4–8 inches of snow, equivalent to 2 or 3 inches of water, falls on the surface in a year. At this rate, it must have taken a long time for the ice layer on the Antarctic to build up to its present thickness, which is over 2 miles in places.

The diagram on page 112 will help to show how the Antarctic ice cap may have been built up, if the present pattern of a heavy snowfall close to the coast, and a light snowfall well inland, existed in the past. At first a high ridge will be built up round the Antarctic coasts, leaving a lower basin in the middle. At the same time, the ice which has formed beneath the surface snow around the outer edge of the Antarctic will flow out over the sea and break off to form icebergs, which will float away and melt in the warmer waters to the north. Not all the ice from the outer edges will flow outwards, however. A little may flow inwards and help to fill up the central depression, but even without this, the light snowfall inland will finally build up a dome with its highest part near the centre of the continent.

Until 1956, the theory was still current that the building up of such a dome had not yet been achieved, and that the height of the

continent in the centre around the Pole of Inaccessibility might be lower than the height in Queen Maud Land, near the coast, or the height at the south pole, which was known to be over 9,000 feet. The Russians, however, have recently recorded an ice depth of about 12,000 feet or nearly 2½ miles near the centre of the continent, and surface heights of almost 14,000 feet in the same vicinity, which shows that the ice cap has in fact become a dome already. It is not a perfect dome, as the presence of mountains and fjords under the ice affects its shape slightly, but the findings of expeditions from several countries all confirm that the ice rapidly increases in thickness towards the interior. If, as has already been stated,

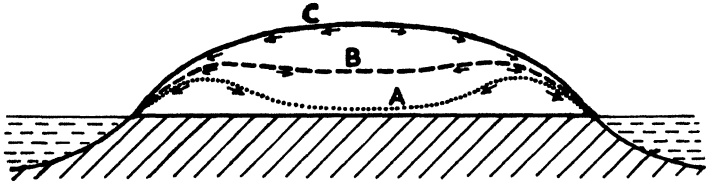


FIGURE 6. Possible stages in the growth of a large ice sheet. Arrows show the direction in which the ice will tend to flow.

Curve A Early stage of formation.
Curve B Intermediate stage.
Curve C Final stage when equilibrium has been established and the loss of ice by outflow around the edge of the continent approximately equals the amount of snowfall over the continent.

only 6 inches of snow, the equivalent of about 3 inches of ice, fall in the central regions in a year it is obvious that it will take a very long time, perhaps 50,000 years, to build up an ice layer of some 12,000 feet. In fact, the Antarctic ice sheet is believed to be a good deal older even than that. According to Dr. Péwé of the U.S.A., while vast ice sheets up to 10,000 feet thick waxed and waned over northern Europe and over the northern part of North America during the last million years, the ice of McMurdo Sound in the Antarctic increased at times up to 1,000 or 2,000 feet above the present level.

One current problem is to try to find out whether the Antarctic ice sheet is increasing or decreasing in size at the present time, but the experts have not yet agreed on the answer. Some glaciologists

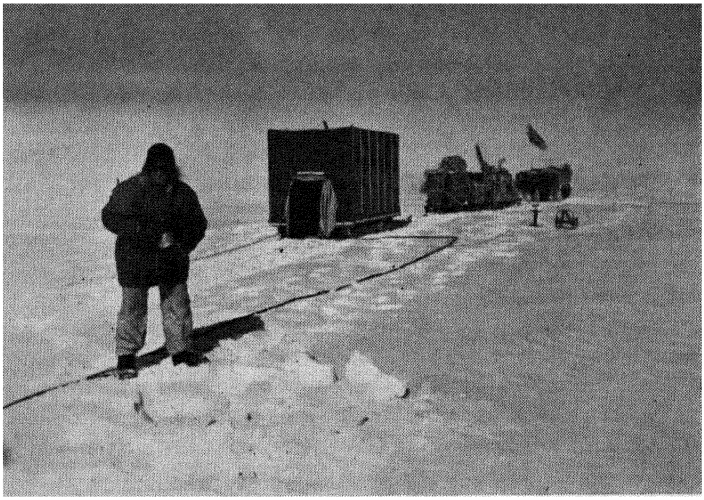
have found evidence in certain coastal areas of Antarctica of a recent retreat of the ice which has uncovered more rock, while in other areas the ice has not retreated during the past fifty or one hundred years. Similar studies near the centre of Antarctica have not been made, as there are no exposed rocks against which recent changes can be measured. A second approach is to estimate the total weight of snow falling on the continent in one year, and to see if this exceeds the loss of ice by calving of icebergs, by melting of ice in the sea, by wind-blown snow and by evaporation during the same period. Several such estimates make it appear likely that the Antarctic ice sheet is at present gaining in mass, but this does not agree with the evidence of mean sea-level. Since the Antarctic continent is about one-thirtieth of the area of the oceans of the world, for every yard of ice which is deposited on the continent, the average sea-level over the world should fall by about 1 inch. However, at present the average sea-level appears to be rising by some 4 inches or so per century, a fact which may be partly explained by melting of smaller northern hemisphere glaciers. This does not encourage one to believe that the Antarctic ice sheet is increasing. We will probably have to wait for some years until repeated measurements of ice thickness at stations well inland on the continent tell us whether the ice is increasing in depth or not.

It has been seen from the diagram on page 112 that the ice on the Antarctic continent is constantly flowing outwards and at the coasts breaking off as icebergs. A few hundred miles in from the coast line the ice is probably only moving at an average speed of 3 or 4 inches a day, though its flow quickens towards the coast. This slow movement inland is continuous, so that a party travelling to the centre of the continent which stops for one day to overhaul vehicles will have an extra 3 inches to go when it starts again twenty-four hours later. On the other hand, when travelling away from the centre the ice flow will help by pushing the traveller along at the rate of 3 inches a day.

It has already been said that the ice depth near the centre of the continent is about 12,000 feet, and it may be asked how ice depths as great as this can be measured. The most reliable method is known as seismic shooting, a technique which has grown out of two sciences. The first is the study of earthquake waves by sensitive seismographs which can record very small movements of the earth's surface; the second is the principle of echo sounding. To

make an ice-depth sounding, an explosion is fired on or under the surface, and from that explosion sound waves travel down through the ice until they reach the underlying rock. From the rock they are reflected up again through the ice to the surface, where seismometers pick up the echo. The seismometers are very sensitive and can measure movements of about a millionth of an inch.

The photograph below, and that on page 115, help to explain



[*From the Collection of the Scott Polar Research Institute.*

FIGURE 7. Placing a seismometer in the snow to record echoes from an explosion set off in the ice. Six seismometers were connected by electrical cables to recording instruments in the caravan.

this system in more detail. Figure 7 shows a seismic sounding party doing field work in Queen Maud Land in 1951. The caravan was used to sleep in, and was also a minature laboratory, containing amplifiers and various electrical supplies. Six seismometers were normally laid out in a line on the surface, each connected to an amplifier in the caravan. A hole about 40 feet was bored by hand in the ice, and a charge of half a pound of T.N.T. was placed in the hole. When all was ready, the explosive was fired electrically from the caravan, and the movement of the surface of the ground after the explosion went off was recorded.

Figure 8 shows some of these records. Each record of a shot shows the movement of six seismometers, and the seventh line on top records the time of the explosion. The vertical lines are projected on to the moving paper at intervals of one-hundredth of a second, so that the time between the shot and the arrival of a sudden impulse at a seismometer can be measured to one-thousandth of a second. After the sharp break recording the shot instant, the seismometers remain still for several hundredths of a second until the noise from the explosion reaches them. It is possible to see the way this noise passes each seismometer in turn, and on some records it is clear that this noise consists of three

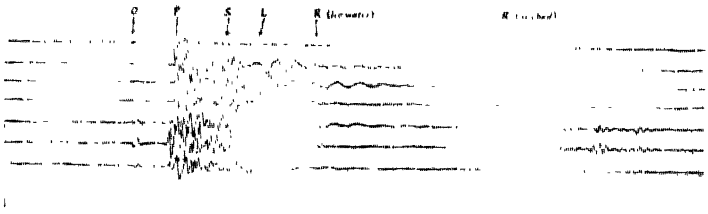


FIGURE 8. The record of an explosion made on a floating ice shelf. The first waves, P, S and L, are the waves which travel directly from the explosion to the seismometers while R (ice-water), R (sea-bed) are echoes from the bottom of the floating ice and the bottom of the sea.

distinct waves, all travelling through the ice. Finally, the echo reaches the seismometer after the noise of the explosion has passed the instruments. The reason why the six seismometers are laid out in a line can now be seen. If an echo is coming up almost vertically from up to a mile and a half below, it will reach all the six seismometers at the same time, and so is easily distinguishable from the noise from the explosion passing by the instruments in turn.

Figure 9 shows the sort of profile found under the ice as a result of seismic shooting. It shows, from left to right, thick ice floating on the surface of the sea; then a peninsula where the ice rests on solid rock and has formed into a small dome; another area of ice floating on sea-water; and finally, the land mass of the continent showing a very rugged, mountainous topography hidden

under the ice except in two places where the mountain peaks actually pierce through the ice cap and are exposed as nunataks or rock outcrops.

Seismic shooting can be a laborious and time-consuming method of measurement, particularly when holes to contain the explosive have to be bored by hand. The farther inland the shots are fired, the deeper the holes have to be, or the noise from the explosion on the cold ice lasts too long after the explosion and blots out the echoes. There is, however, one method which is much quicker, although not sufficiently accurate to replace seismic shooting entirely, and that is to measure the force of gravity.

Newton's well-known law of gravitation states that every body attracts every other body with a force equal to the product of their masses and inversely proportional to the square of their distance



FIGURE 9. Seismic shooting profile of ice thickness along a section of the Antarctic Ice Sheet in Dronning Maud Land.

apart. So, at given points on the ice cap, the varying amounts of ice in relation to underlying rock will affect the value of gravity. To give a small example, a block of metal held at a height of 3 feet off the ground weighs about one part in three million less than it does when weighed at ground level, since the force between the metal and the earth depends on the square of the distance between it and the centre of the earth. An instrument, known as a gravimeter, has been made which is delicate enough to measure even this minute difference in gravity. Such instruments have been used in the Antarctic to measure gravity changes when travelling over the ice sheet in order to get an indication of the changes of depth of the ice sheet over the underlying rock.

A further use for a gravimeter was found at the Shackleton base of the Trans-Antarctic Expedition, which was located on a thick, floating ice shelf which moves up and down with the tide. There were no rocks or shoreline against which the height of the tide could be measured, but by measuring the changes of gravity by a

gravimeter it was calculated that the tidal rise and fall varied from 2 to 10 feet in a day.

When travelling over the continent, the value of gravity will vary with changes of height above sea-level, with changing distance from the pole and with any general changes in the type of rock under the ice. Corrections for height and position have to be

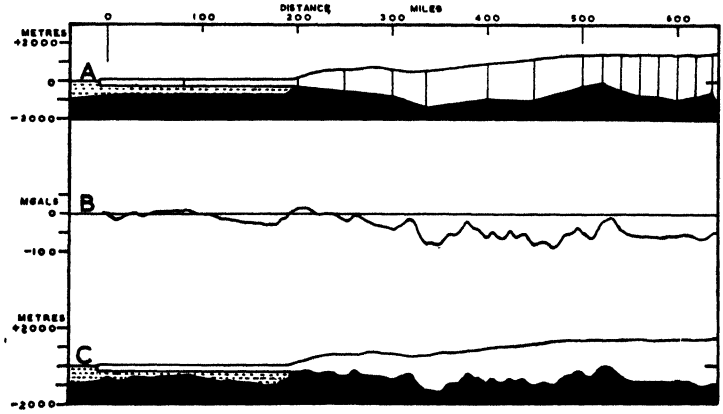


FIGURE 10. Profile of ice thickness from the U.S. Little America V station to Byrd station in Marie Byrd Land obtained by combined seismic shooting and gravity methods.

A. Profile by seismic shooting. The vertical lines show the position of soundings.

B. Variation of gravitational "anomalies" along the profile. These anomalies show the difference between the calculated values of gravity and the measured value reduced to sea level. The difference is approximately proportional to the ice thickness.

C. Detailed profile obtained by combining accurate measurements of ice thickness shown in A, with the variations shown by B.

calculated, but changes of density of the rocks under the ice can be reliably identified only when the ice thickness is known by seismic sounding, although magnetic measurements may also indicate that such changes of rock may be taking place. Therefore the system now used on most Antarctic traverses is to measure the value of gravity every 5 miles or so, which can be done in a few minutes, and then to take seismic soundings not more than once a day at distances apart of 30–50 miles. Figure 10 shows the way in

which the gravity and seismic measurements were combined for one such traverse. The top profile shows the ice-thickness profile obtained by seismic sounding at a number of points between the

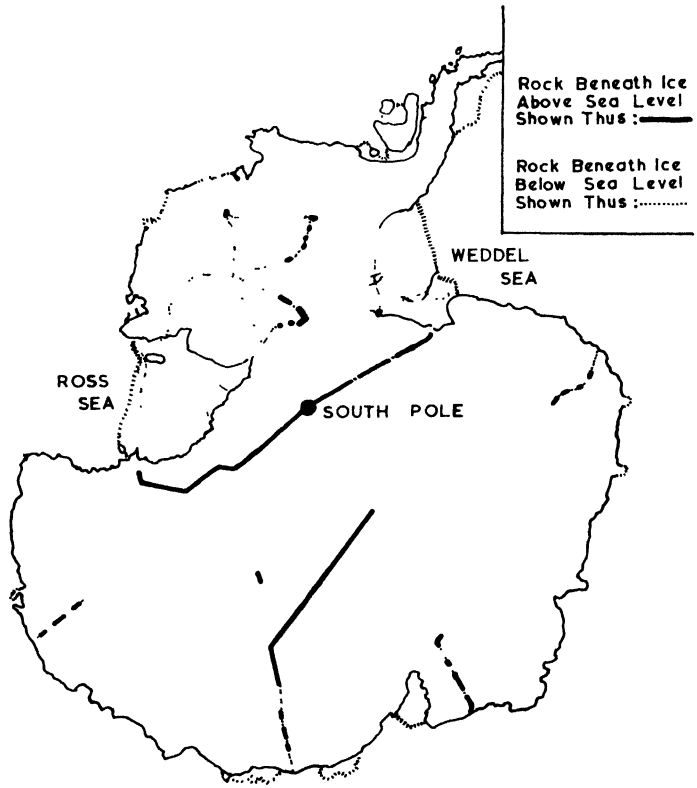


FIGURE 11. The Antarctic continent, showing lines along which ice-thickness profiles are known. The information has been compiled from press and other reports and shows preliminary results only, which may be changed in minor details after a fuller study has been made.

U.S. Little America station and their Byrd station in Marie Byrd Land. The centre graph shows the values of gravity after certain corrections have been applied, and the bottom profile shows the detailed profile obtained when the gravity and seismic soundings are combined.

Now that some 10,000 miles of traverses over the Antarctic continent have been completed, compared with some hundreds of miles before the I.G.Y. expeditions reached the continent, a clearer picture of the basic outline of Antarctica may be seen. The map in Figure 11 attempts to outline the main results at the present time, as far as they can be collected from scientific reports, press reports and other sources. The dotted lines show where the rock surface beneath the ice is at present below sea-level, and the heavy black line shows where it is above sea-level. At first glance it appears that much of the continent is split up into islands, but really many of the parts below sea-level must be joined to the sea by deep fjords filled with ice. Underneath the ice much of the Antarctic must be similar to the coast-line of Norway or Eastern Greenland. However, the section south of the Pacific which has been studied by the U.S. traverse parties shows that much more rock is below sea-level in this area. It is possible that some of this area may be cut off from the rest of the continent by a deep trench, and it may be split up into islands much more than the part of Antarctica facing the Indian and Atlantic Oceans.

This chapter has told you something about the Antarctic ice and the problems which have had to be overcome, not only by glaciologists, but also by scientists carrying out studies described in some of the earlier chapters. More Antarctic workers will be needed in the coming years, and for those who may wish to work there when they are older, it is possible to say that the most interesting time will be had by those who are well qualified and interested in particular scientific studies. People with degrees in physics, geology, physiology and other biological subjects will be wanted, as well as surveyors, mechanics, aircraft pilots and others.

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