Ozone in the Upper Atmosphere and its Relation to Meteorology.*

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UNTIL nearly the close of the nineteenth century, meteorologists—with but a few exceptions—had been content to confine their attention to studying the atmosphere near the ground. When Teisserenc de Bort and W. H. Dines began to study the conditions up to a height of 20 km. or more by means of small balloons carrying light self-recording instruments, it immediately became clear that a knowledge of the free atmosphere is essential to an understanding of the physical processes which we include in the term meteorology. Since, however, observations have shown that while pressure gradients associated with cyclones or anticyclones, after continuing without great change throughout the troposphere in most cases, fall off rapidly within the stratosphere, and become very small at about 20 km., we have come to regard the domain of physical meteorology as being roughly confined to that part of the atmosphere below about 20 km. I wish now to describe some observations that seem to show that there are effects of cyclones and anticyclones which extend up to something like three times that height.

About ten years ago, MM. Fabry and Buisson first showed that there is a very small amount of ozone situated at a great height in the atmosphere, and they also developed methods by which the amount could be measured with considerable accuracy. The actual amount is very small, but, as will be shown, it has very important effects. If the various gases of the atmosphere were all separated from each other and brought to a layer uniform in density at normal temperature and pressure, the thicknesses of the layers of different gases would be as given below:

Gas.	Nitrogen.	Oxygen.	Argon.	Carbon dioxide.	Neon.	Helium.	Ozone.
Thickness	6·2 km.	1·7 km.	76 m.	2·4 m.	10 cm.	3·2 cm.	3 mm.

This shows how very little ozone there is compared with the other gases, but the effect of even this small amount is by no means unimportant; thus, it prevents excessively strong ultra-violet radiation from the sun, which would cause intense sunburn and other effects, from reaching the earth, and it is further responsible for raising the temperature of the atmosphere at great heights to values far above those of the stratosphere and probably nearly up to the normal boiling-point of water.

Turning now to the methods used for measuring the amount of ozone in the atmosphere, this is always done by spectroscopic means. Ozone has an exceedingly strong absorption band in the ultra-violet region between about 3200 A. and 2200 A., so that if we measure the absorption of light of a suitable wave-length while passing through the atmosphere, we can deduce the amount of ozone through which the light has passed. In practice it is not convenient to measure the absolute intensity of one wave-length, but we measure the ratio of the intensities of two adjacent wave-lengths, chosen so that one is strongly absorbed by ozone while the other is but little absorbed. By this means we largely eliminate changes due to haziness in the lower atmosphere and also changes in the energy emitted by the sun.

For most of the work so far accomplished, photographic instruments have been used, and spectrograms of sunlight are taken under carefully controlled conditions so that the energies in the different wave-lengths can be accurately determined. With these instruments there is naturally a most inconvenient delay due to developing and measuring the plates before the ozone content can be deduced; further, the labour is very great. Photoelectric methods are now available which allow exceedingly small amounts of light to be measured, and these, when used in conjunction with a suitable double spectroscope, allow the ozone to be easily measured within a total time of about five minutes at all times when the sun is more than about 10° above the horizon, whether the sky be cloudy or not. If the sky be clear, measurements can be made even when the sun is much nearer the horizon. Indeed, we may say that, provided the sun is sufficiently above the horizon, we can measure the amount of ozone in the upper atmosphere nearly as easily as we can measure the barometric pressure and with an accuracy approaching that of barometric readings, when we take into account the 'correction to sea-level' to be applied when comparing barometer readings at different places, which is often rather uncertain for stations at some little height above sea-level.

The height of the ozone in the atmosphere can be deduced by taking measurements when the sun is rising or setting, since in these conditions the calculation of the amount of ozone involves both the height of the ozone and the curvature of the earth. The method is not very accurate, but a large number of measurements show that the average height of the ozone layer is about 50 km. above sea-level. We do not yet know how far above or below this height the ozone layer extends.

When measurements of the quantity of ozone are made in temperate latitudes, it is found that there are large variations in the amount present from day to day, amounting to nearly 50 per cent of the mean value. There is also found to be a well-marked annual variation, having a maximum in spring and minimum in autumn. The day-to-day variations show a close connexion with the meteorological conditions in the upper troposphere and lower stratosphere, the amount of ozone being high when the temperature of the troposphere is low, when the pressure near the base of the stratosphere is low, and when the height of the base of the stratosphere is low, and vice versa. The number of meteorological observations reaching a height of more than 15 km. is not very large, but such observations as there are indicate that the amount of ozone is closely related to the pressure up to the

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greatest height where observations are available. It has also been shown by Dr. Duckert that the amount of ozone is closely related to the density of the air about 15 km. and above, but not with that at a lower level. Considering that the comparison has necessarily to be made between ozone measurements made at one place and meteorological observations made 100 km. or more away and often some hours different in time, it is remarkable that correlation coefficients so high as 0·80 have been found.

When the distribution of ozone is compared with the distribution of barometric pressure, a close relationship is again found. Unfortunately, the meteorological observations are not available from which maps showing the distribution of pressure and temperature at various heights in the atmosphere can be drawn, but even the surface distribution shows that the two are closely associated. Observations were made at seven places in north-west Europe in order to study this relationship during 1926 and 1927, and the distribution of ozone in the different regions of a typical cyclone or anticyclone are shown in Figs. 1 and 2.* At the time when these measurements were made, only the older photographic spectrographs were available, and these could not be used when the sun was low or when the sky was cloudy, so that measurements had to be stopped during the winter, and even in the summer a large number of days were missed owing to cloudy skies. Thus the information at present available is very meagre, but there is no doubt whatever that in practically all cyclones the distribution of ozone is roughly as indicated in the accompanying figures, and there are indications that cyclones only form when there are large differences of ozone in adjacent regions. It was seen that the relation between the amount of ozone and the meteorological conditions at any one given place is very much closer if the conditions in the upper air are taken than if surface conditions are considered, and there is reason to think that if we were able to draw pressure and temperature maps for a height of, say, 10 km., we should find that the distribution of ozone

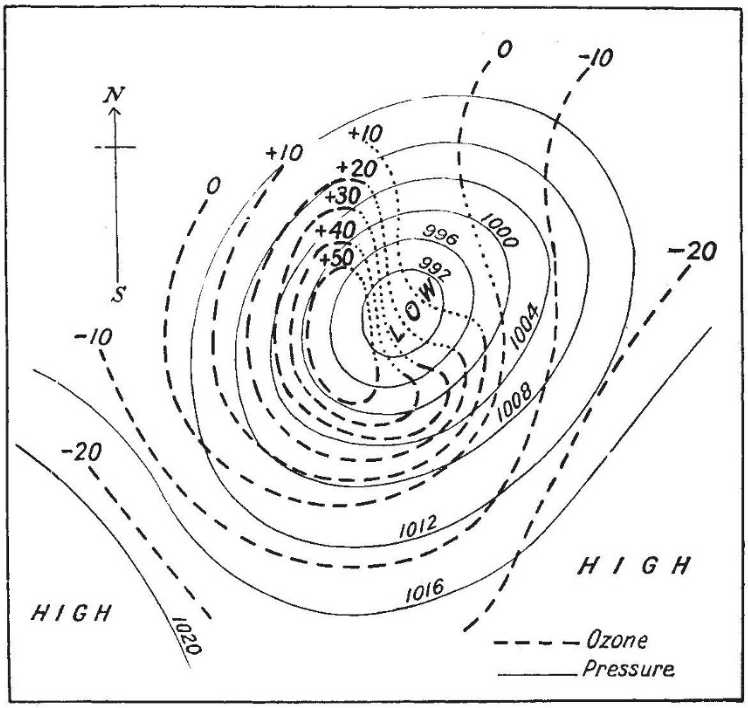

FIG. 1.

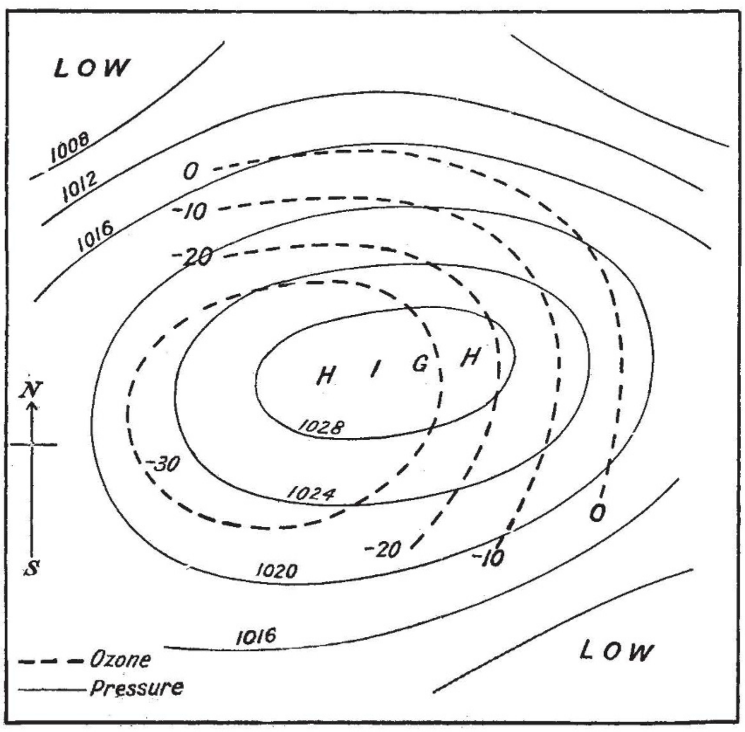

FIG. 2.

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showed an even closer connexion than that found using maps for the surface.

When we turn to the distribution of ozone over the whole world, we find that the relatively few measurements so far made give a fairly definite picture of the main outlines. These are best seen from Figs. 3 and 4, which both show the same results but presented in a different manner. It will be seen that at all latitudes outside the tropics there is a definite annual variation, with maximum in spring and minimum in autumn both in the north and south hemisphere. Within the tropics the amount of ozone is small at all seasons, and it is noteworthy that even such big changes as the Asiatic monsoon appear to have no effect on it, presumably because the ozone is at a much greater height than is reached by the monsoon. In the spring there is a very rapid rise in the amount of ozone from the equator to the pole, the amount at the pole being more than double, and possibly treble, that at the equator. On the other hand, in autumn there is but little change in the amount of ozone over the whole hemisphere. These results seem to be true for both north and south hemispheres, and though there have been only about one year's observations at most of the stations, it is thought that while another year may give slightly different values, the general conclusions are not likely to be changed.

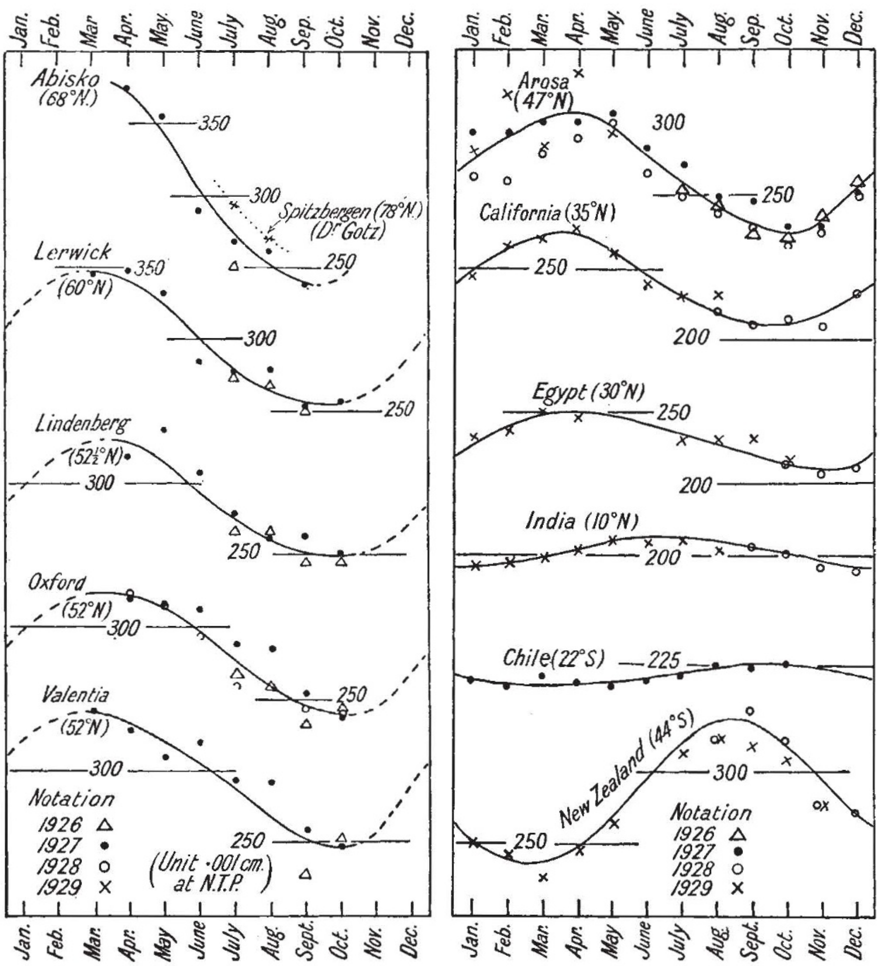

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FIG. 3.

We come now to the obvious questions: What forms the ozone in the upper atmosphere, and why is the amount so closely associated with the other meteorological conditions if the ozone is really at a height of some 50 km.? It was at first supposed that the shorter wavelengths of the sun's radiation, by breaking up oxygen molecules into atoms which combined to form ozone, was the chief cause. This view is difficult to reconcile with the high value found in polar regions in the spring and the steady low value within the tropics. It has been thought that this difficulty can be overcome, but we believe that it is fatal to the view that solar ultra-violet radiation is the chief cause. Since there have never yet been more than seven stations measuring the amount of ozone in Europe at one time, it is not possible to say for certain whether the amount of ozone is ever increased locally by formation over a limited area, but it is probable that this may happen. If so, it would be quite fatal to the hypothesis of ultra-violet light, since it would seem that this must affect a large area of the earth's surface alike. The only other suggestion is that it is formed by some action connected with the aurora. This would account for the high values at the poles, and in this case there is no reason why ozone should not be formed in small local areas. The annual variation is also easily accounted for on this view, since Dr. Gowan has shown that owing to the absorption of about six per cent of the sun's radiation by the ozone, its temperature will be relatively high and the higher its temperature the faster will it decompose. Hence we should expect the amount of ozone to be small after the sun has been strongest and large when the sun has been cut off, as at the poles at the end of the winter. There is, however, at present, no certainty in this matter.

The relation between the amount of ozone and the meteorological conditions presents even greater difficulties. There are good reasons for thinking that the average height of the ozone layer is appreciably the same at all times of the year and whether the amount of ozone present be large or small. This seems to rule out any suggestion that in polar regions there is ozone in the lower stratosphere and that this is carried to lower latitudes by the polar currents which are well known to be associated with cyclones. Even if we suppose that the great polar and equatorial currents extend up to 50 km. and so transport ozone at this height, there are difficulties, for, as shown above, while there is a great difference between the amount of ozone at the pole and the equator in spring, there is but little difference in autumn, so that on this hypothesis the rear of cyclones should have much ozone in spring but there should be a nearly uniform distribution in autumn. This is far from being the case.

Again, so far as we can tell at present, the amount of ozone in the rear of a cyclone in Europe during the autumn seems to be greater than the normal amount anywhere within that hemisphere at that season. Thus, there is nowhere from which the ozone might have been transported, and we are almost driven to supposing that it is formed in the area where it is found. If this is so, there are three possibilities: either the presence of a cyclone causes ozone to be formed in the atmosphere above it, or a local increase in the amount of ozone leads to the formation of a cyclone in the atmosphere below it, or thirdly, both cyclones and ozone are formed by some common agency. At present it does not seem possible to settle this question without further and fuller observational material, and for this reason it is hoped to organise ozone observations at at least a dozen stations in Europe with the new photoelectric instruments, which have none of the disadvantages of the older photographic ones, and one may hope that results of great meteorological interest will be obtained.

In addition to the connexion between the amount of ozone and the meteorological conditions in the lower atmosphere, there are also other notable effects produced by it. Although the amount of ozone is so small, its absorption band in the ultra-violet region is so strong that it absorbs practically all the solar radiation of wave-length shorter than about 3000 A. reaching the outer atmosphere. Altogether, it absorbs about six per cent of the incoming solar energy. Thus, one effect of the ozone is to reduce enormously the power of the sun to produce sunburn, and it would be impossible to stay long in the sun without serious effects if it were not for the atmospheric ozone.

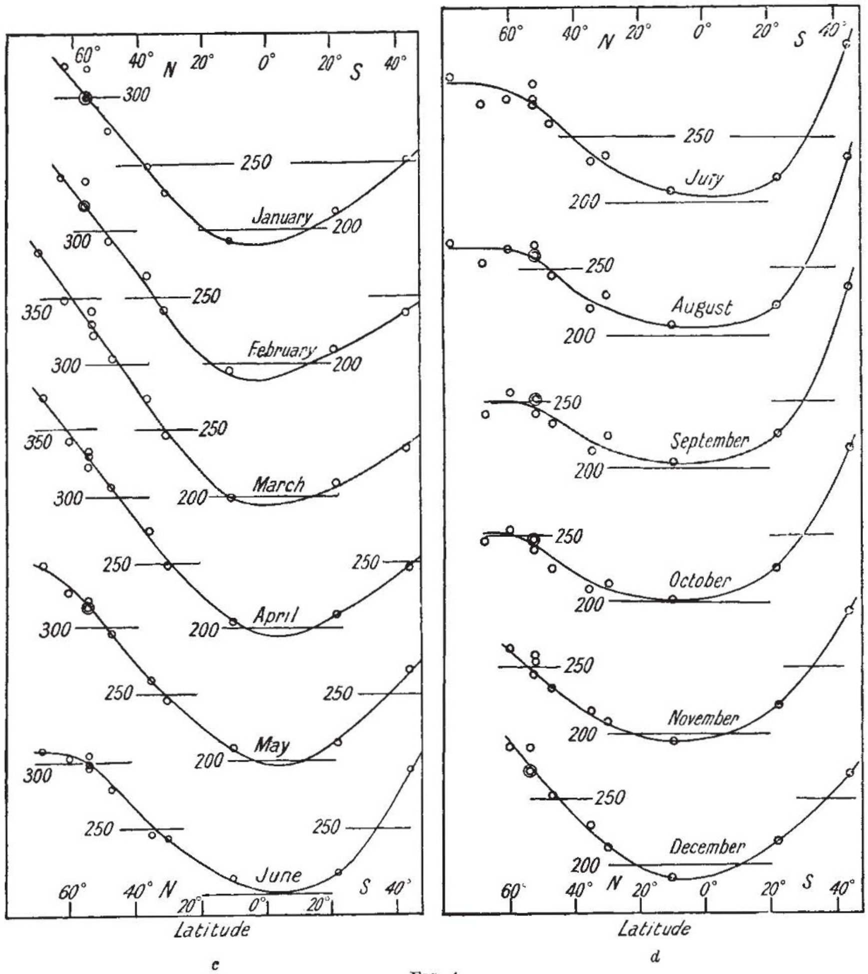

FIG. 4.

Another effect of the absorption of so much solar energy in the high atmosphere is that the temperature at these heights is raised much above that lower down. Since the ozone has only a weak emission band in the infra-red, it cannot easily lose energy by radiation, and most of the heat absorbed in the high layers is probably radiated by the small amount of water vapour there. Estimates made by Dr. Gowan of the temperature show that at a height of 50 km. a value of 400° A. is not unlikely. Dr. Whipple has shown that the high temperature at heights of about 50 km. is responsible for the abnormal audibility of sound from great explosions at distances of 200 km. or more from the source. Measurements made by

Dr. Whipple on the sound waves from artillery fire in Great Britain indicate temperatures up to nearly 400° A. at a height of some 45 km., agreeing well with Dr. Gowan's estimates.

If the ozone is formed by some action connected with the aurora, we should expect that the amount of ozone would show a connexion with the intensity of the visible aurora. Unfortunately, with the instruments which were used until recently, it was not possible to make measurements of the amount of ozone in the higher latitudes in winter, and as the aurora cannot be seen in summer, there are too few suitable observations to determine with certainty whether the effect is shown or not. There is, however, a small but definite connexion between the amount of ozone and terrestrial magnetic conditions, days of high magnetic character tending to have much ozone, and vice versa. This is what we should expect if the ozone were associated with the aurora. It is also significant that a large amount of ozone seems to be associated with magnetic disturbance but not with a large amplitude of the normal diurnal variation on magnetically quiet days, which we may suppose to be due to increased ionisation caused by ultra-violet radiation.

This is, briefly, the state of our knowledge of atmospheric ozone at the present time, which is due to researches by several workers during the past five or six years. When the whole story of the part played by ozone in the extreme upper atmosphere has been unravelled, it seems likely to afford material of great interest.

The Centenary of the British Association.

IN 1831, when the British Association was founded, the opinion was freely expressed that there was no useful work for it to do. At the very successful jubilee meeting at York in 1881, fears were felt for the future: the view was held in some quarters that the Association's work was done.

> "At York they thought she was sure to die,
> For she didn't seem to enjoy age . . ."

So roared the Red Lions of the day, rather mysteriously feminising the 'British Ass.'. An interesting historical parallel has already been encountered in the present centenary year—an expression of precisely the same opinion by more than one person unconnected with the Association. There is therefore every reason to hope that at least another century of useful work lies before it.

Certainly the preliminary programme of the meeting shows promise of exceptional interest for scientific workers and laymen alike. The programmes of the Association can never be accused of pandering to the public interest. It is not necessary that they should. If a discussion with an arresting headline happens to appear (such as "The Evolution of the Universe", which is found in the present programme), it may be taken that men of science have something to say on this subject to each other; not that they merely wish to tickle the curiosity of the public. Actually they can do both, and in the present year, what with the Faraday centenary immediately preceding, and the Clerk Maxwell celebration, and the jubilee of the Natural History Museum immediately following the Association's week, there ought to be a gathering of the 'cultivators of science' (to revive the phrase of 1831) such as has never been seen before, in Great Britain or elsewhere. The Association, at any rate, is doing what it can to give the occasion an imperial and, indeed, a world-wide significance by inviting representatives from all the places where it has met in the past, both at home and in the dominions, and also a notable list of foreign guests. Already there is a welcome response to these invitations. Fairfield Osborn, Gregory, and Cattell; Adamson, Torry, Kerr Grant, and McLennan; Ehrenfest, Zeeman, Thilenius, Sergi, Hevesy, Debye, Matschoss —these are names taken almost at hazard from the list.

The mechanism of the Association is adapted by experience to a meeting in any large town except London. Anywhere else than in London the civic and the cultural spirit of the place forms a unit which never fails to co-operate in receiving the Association, powerfully aiding its organisation in all that appertains to local arrangements, and providing a quota of local members to take the opportunity of participating in its transactions. In London there is no such unit: it is too big. Not that there can be suggested any lack of co-operation, when the City through its Court of Common Council first expressed the hope that the centenary meeting would be in London, and the Lord Mayor recently presided over a meeting held in Guildhall to hear the Association's aims; when H.M. Government has promised a reception; when the London County Council, the City of Westminster, and the Royal Borough of Kensington through their principal officers have shown active interest in the arrangements; and when all the great institutions in South Kensington have freely lent their splendid accommodation for the meeting and promised other facilities. Moreover, members attending the meeting will have a unique opportunity of visiting, again with the generous co-operation of the authorities concerned, a selection of the places of scientific interest in London at large, of which places the number is immense; and members will not fail to realise that this opportunity, so far as concerns the Association, will presumably not recur until 2031. Accepting these good gifts, but knowing that it has not on this occasion a local organising unit with which to deal, the Association has set itself to undertake a good deal of the 'local' side of the arrangements, and has backed its luck in respect of their cost. The unknown factor at present is the response of the London public to the stimulus of an Association meeting; the support by way of membership and financial contribution which may be looked for in London.

John Perry, the former general treasurer of the