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ORGANIZATION OF RESEARCH IN THE METEOROLOGICAL OFFICE

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Early years.—The Meteorological Office has always had an interest in research; the selection or establishment of seven observatories in 1867 by the Meteorological Committee of the Royal Society was one of the early steps towards providing data for exact investigation of weather phenomena. But it was only from about 1906 that the governing body took definite action to offer a career in research to its own staff.

In the *Report of the Meteorological Committee* for the year ending March 31, 1906, we read that two new appointments apart from the Directorship (then held by Mr. W. N., afterwards Sir Napier, Shaw) were created in the Meteorological Office, to be filled by men of " high scientific attainments ", namely the posts of Superintendent of Statistics and Superintendent of Instruments. Mr. R. G. K. Lempfert and Mr. E. Gold were appointed to these posts. In the same report we read also that the Commission had been fortunate in securing the services of Mr. W. H. Dines, F.R.S., for the organization and control of experiments for the investigation of the upper air[1]*. And later we read that Mr. G. C. Simpson (afterwards Sir George Simpson, Director of the Office 1920–1938) who was acting as volunteer assistant to the Director had made arrangements for kite ascents in Derbyshire. In these appointments we see the beginnings of meteorology as a recognised profession offering a career for men " of high scientific attainments ".

In the years that followed, up to the outbreak of the first world war in 1914, a number of well-known names became identified with meteorology—L. F. Richardson, G. I. Taylor, G. M. B. Dobson, F. J. W. Whipple, R. Corless, the Dines brothers, whilst Chree was active in geophysics at Kew. Outside the Office Rayleigh, Schuster, Aitken, Lyons, Chapman and others were active. Within this period the Meteorological Office and its associated workers made a tremendous contribution to the science of meteorology. The office organization developed, but a substantial part of the time of each scientific officer continued to be expended on scientific research and investigation.

*These numbers refer to the list of references on p. 97.

Period 1914–39.—The outbreak of war in 1914 brought new requirements into which a great part of the scientific and technical staff was rapidly absorbed. At the end of the war a greatly increased office was transferred to the Air Ministry, and the services required by aviation imposed henceforth a major demand on the resources available. Research did not die out but it occupied only a slender place in official organization, and the bulk of the research work actually published in the next 20 years came from individuals who had to encroach more or less heavily on their private time to accomplish it. Officially sponsored research included, however, such major items as the expedition to Fort Rae (our main contribution to the International Polar Year 1932–33), part of the effort of the observatories and such investigations as those carried out on wind structure at Cardington in connexion with airship design or at Porton on turbulence.

Period since 1939.—In 1939 plans were in hand to set up a research organization and a Meteorological Research Committee. The outbreak of the second world war interrupted these plans, but in 1941 the Committee came into existence. Its members are appointed by the Secretary of State for Air[2,3].

Within the last year three sub-committees have been set up to deal respectively with instruments, synoptic and dynamical problems, and physical problems. At the same time, within the Meteorological Office, the co-ordination of research and the task of liaison with other bodies have been centralised in a Deputy Directorate of Research, with three Divisions concerned respectively with general research, special investigations and instruments. Comprised in the first of these divisions are the observatories at Kew, Eskdalemuir and Lerwick, the Branch Office at Edinburgh, the Meteorological Research Flight[4], special stations at Cambridge, Rye and East Hill, and a branch at Headquarters concerned with administration and secretarial duties. Research in weather forecasting is provided for separately by a Division under the control of the Deputy Director for Forecasting, whilst research in climatology and marine meteorology is covered by the Divisions concerned with these subjects and controlled by the Deputy Director (Services).

From this it will be seen that research in some degree now pervades all parts of the Office, and indeed the broad intention is that some element of research or original inquiry should enter into the duties of all staff of the scientific officer category; work which has developed to the stage of routine—even a professional and highly specialised routine—should so far as possible be passed to the experimental officer and assistant grades.

Results of recent years.—The difficulties of publishing during and since the war have made it not easy for those outside official circles to appreciate the extent of the advances made in meteorology in the past 10 years. Here it is only possible to present a brief summary of the position.

Upper air.—Investigation of the upper air had been going on for many years before 1939, but from 1939 the tools for the job developed greatly and the general tempo increased rapidly. Within a few years measurements were being obtained four times a day, at several stations in the British Isles, of temperature and pressure by radio methods[5], and of wind by the use of radar[6], to a height of over 50,000 ft. The present aim is to increase the height to 100,000 ft. By radio methods humidity can as yet be measured with reasonable accuracy only up to about 25,000 ft. The Dobson-Brewer frost-point hygrometer, however, developed about 1942–43, enables humidity to be measured accurately to the lowest temperature reached in the atmosphere. The instrument requires an observer to operate it, but it is now in regular use on the high-flying aircraft of the Meteorological Research Flight, and has produced new knowledge about the upper troposphere and lower stratosphere. The air in the stratosphere is found to be intensely dry, at all events when the tropopause is low, the relative humidity then being frequently of the order of only 1 per cent. This peculiarity probably throws light on the circulation of the air in the stratosphere over the globe; there is only one region, namely in the upper troposphere and lower stratosphere within the tropics, where air at high levels is cooled to frost points of the order now being observed in the stratosphere in England. The first inference, therefore, is that the air of the lower stratosphere in temperate latitudes is air which at some time previously has passed through the upper troposphere in the tropics and has not since returned to lower levels.

The accumulated observations of wind have been analysed statistically to obtain the frequencies of winds of different speeds and directions in the different seasons of the year, also the variability of wind with distance and time. Obviously such information is of fundamental importance in estimating the potentialities of aircraft, the possibilities of navigation by dead reckoning, problems of long-range artillery, etc. Methods of using the upper air data in forecasting the weather, and more particularly the upper winds, have been investigated.

Exact measurements of the type described above, exist as yet only for certain regions. Outside western Europe, North America and a few places in India, the observational material is scanty. A few years ago attention was therefore turned to theoretical methods of computing and charting approximately the wind distribution over the globe as a whole for the different seasons of the year. A comparison of the theoretically computed " wind roses " with the actual observations in the regions where observations are available suggests that a useful degree of reliability attaches to these charts, but it is considered of great importance that further observational material be obtained, particularly in the tropics and in high latitudes.

Using the data just mentioned and a special technique, expectations of the frequency with which aircraft would encounter headwinds of various strengths on any desired route up to 40,000 ft. can be derived. Sometimes it has been possible to check the computations against the frequencies experienced by aircraft on regular routes and the checks have proved satisfactory.

For a period of a year, a series of measurements of wind at 100,000 ft. was made in the south of England, using as a pointer the burst of a shell which could be sent to that height by a hyper-velocity gun belonging to the Royal Marine Siege Regiment. The results showed that at these great heights the wind is easterly from about May to August, with speed up to about 30 m.p.h.: during the rest of the year it is westerly, the speed at mid-winter rising to about 100 m.p.h.

By indirect and less positive methods based on observations of the travel of sounds from explosions, the winds and temperatures have been estimated up to about 150,000 ft. These results point for the first time to a substantial variation of temperature throughout the year at this level.

Using the results just described and further theoretical estimates, an approximate cross-section of average winds and air densities for summer, winter, spring and autumn from north pole to equator and up to a height of 150,000 ft. has been computed. Here again, the observational material for very high levels being confined to the British Isles, the obvious next requirement is material for tropical regions and high latitudes.

Wind structure.—Turbulence or the structure of eddies or gustiness of wind enters into questions of the design and strength of aircraft, and into many military problems. With increasing speed of aircraft, the importance of wind structure and information as to how it varies at different heights becomes ever greater. A gust which would not seriously affect an aircraft travelling at 150 m.p.h. could have alarming results at 500 m.p.h. Considerable information has been acquired in the past 35 years about wind structure, diffusion, etc., in the lower layers of the air, but the problem as affecting the higher levels is one of great complexity. Measurements made from aircraft, or indeed from any moving body, have inevitably a bias depending on the dimensions, speed, aerodynamic properties, etc., of the machine itself. The worst conditions are probably experienced in cumulonimbus clouds where visual observation is ruled out.

Cloud physics.—In the early part of the war, the making of a condensation trail constituted a grave risk to aircraft, however high, when flying over enemy territory. A theoretical investigation yielded the useful result that above a certain temperature, which could be computed for each height, there should be immunity from exhaust trails. The meteorological research section of the High Altitude Flight at Boscombe Down confirmed these results in 1941, and established the further result that persistent trails were practically never formed in the stratosphere but only short ephemeral ones[7].

Cloud and fog have always had special interest for the airman by reason of their obstruction to vision. With the need to operate in all weathers, the questions of turbulence in clouds, of icing of airframes and carburettors, and of lightning have become of greater import. Various devices and also theoretical computation have been used by the meteorologist to measure or assess maximum gusts, water content, drop size distribution, etc., in clouds; and a powerful new tool has become available in recent years in the shape of radar.

Co-operation between the Meteorological Office and the Telecommunications Research Establishment of the Ministry of Supply has led to special applications of radar. It was found that some clouds, notably those containing large water drops, interfered greatly with the ordinary use of radar for detecting solid bodies. It is possible, by the use of wave-lengths of 10 cm., to locate all the important precipitation clouds within a range of the order of 70 miles from the investigating radar station. Such a radar station is now used by the Meteorological Office for experimental purposes in co-operation with machines of the Meteorological Research Flight carrying observers and with single-seaters of the Royal Aircraft Establishment. The aircraft are equipped with apparatus for recording gustiness and work, in collaboration with a simple network of ground stations, on the exploration of all aspects of cloud structure.

A series of very valuable experiments on condensation and sublimation of water has been conducted in the Clarendon Laboratory, Oxford, under the direction of Dr. Dobson, the present Chairman of the Meteorological Research Committee. Air tests under natural conditions are made by the Meteorological Research Flight, which conducts observations regularly in clouds of various types with a view to determining their constitution (whether water drops or ice crystals) and the conditions of formation of rain and snow. Experiments in methods of " rain-making " are also being tried, not purely with the idea of causing rain to fall, but rather as a means of studying the physics of rain formation[8,9].

Weather forecasting.—Almost every advance in meteorology is a potential contribution to weather forecasting. Notably is this true of improved means of obtaining upper air observations, of researches on the dynamics of cyclones, the physical processes of weather and so on. Of late years other important aids have been introduced. The " Sferics " equipment[10], for example, a radio receiving and direction-finding apparatus set up with the help of the National Physical Laboratory at four stations in the British Isles, can sweep all regions within some 1,500 miles and locate places where lightning is occurring. In practice, this means that many of the important regions of precipitation and beginning of precipitation can be charted.

During the war various methods of forecasting weather up to a fortnight ahead were tried, but none gave any measure of success substantial enough to justify continuation. Thus, unless in certain specially stable types of weather which may justify extension to a week, it is not yet considered justifiable to issue forecasts for more than about 24 to 48 hours ahead. The advantage to be secured from more accurate weather forecasting and from an extension of the period to a matter of weeks, still more to seasons, would be enormous, not only in military operations but in the general economy of the country. The complexities of weather as shown when it is mapped over a large area, for example the northern hemisphere, are so great that no immediate prospect can be seen of forecasting with accuracy of detail and of time scale for any long way ahead. On the other hand it may be that some method may yet emerge of outlining the broad characteristics of the weather over longer periods or of discovering in advance whether a season is likely to depart conspicuously from normal in temperature, wind distribution or rainfall, for example. Only a better understanding of the general atmospheric circulation and the factors controlling it can tell.

REFERENCES

1. DINES, L. H. G.; Early days of upper air research. *Weather, London*, **2**, 1947, p. 199.
2. JOHNSON, SIR NELSON K.; Meteorological research. *Weather, London*, **1**, 1946, p. 2.
3. London, Meteorological Research Committee. Fundamental problems in meteorology. *Met. Mag., London*, **76**, 1947, p. 269.
4. FRITH, R.; Meteorological Research Flight, *Met. Mag., London*, **77**, 1948, p. 241.
5. LANDER, A. J.; The British radiosonde. *Weather, London*, **1**, 1946, p. 21.
6. SCRASE, F. J.; The application of radar to the measurement of upper winds. *Weather, London*, **3**, 1948, p. 151.
7. BREWER, A. W.; Condensation trails. *Weather, London*, **1**, 1946, p. 34.
8. BANNON, J. K.; Artificial stimulation of rain formation. *Met. Mag., London*, **76**, 1947, p. 169.
9. BANNON, J. K.; Rain making. *Weather, London*, **3**, 1948, p. 261.
10. OCKENDEN, C. V.; Sferics. *Met. Mag., London*, **76**, 1947, p. 78.

ERRATUM

March 1949, PAGE 85, line 12: *for* lower *read* higher; line 13 : *for* higher *read* lower

THE STRATOSPHERE

By J. K. BANNON, B.A., and A. H. R. GOLDIE, D.Sc., F.R.S.E.

The temperature of any part of the atmosphere is, though often indirectly, dependent on the energy radiated by the sun. The qualification " indirectly " is important because the temperature of the air at a particular place and time is not just a result of what is taking place there. It depends also on other factors. The first of these is its recent past history—*i.e.* it may have travelled from a place where conditions promoted higher or lower temperatures than those which it would have assumed had it always been where it is now: this is the " advective " effect. The second factor is the dynamical control of temperature through its pressure changing under more or less adiabatic conditions.

Solar radiation, being largely in the visible part of the spectrum, is but little absorbed by the lower atmosphere and is for the most part passed down through it and warms the surface of the earth. The air is thus warmed only very little by direct sunlight except at very great heights. The outgoing radiation from the earth, however, is mainly in the infra-red part of the spectrum and is strongly absorbed by three minor constituents of the atmosphere, namely water vapour, carbon dioxide and ozone. Apart from possible advectional and adiabatic effects, which will be discussed later, the atmosphere can therefore be divided roughly into three layers:

(i) the lowest, the troposphere, where heating by the earth's surface is spread upwards mainly by convectional processes.

(ii) the lower stratosphere where absorption of the long-wave out-going radiation is the main controlling factor.

(iii) the upper stratosphere where absorption of direct solar radiation by ozone, mon-atomic oxygen or other constituents, controls the temperature.

Lower stratosphere.—The tropopause, the dividing surface between troposphere and stratosphere, varies considerably in height, its mean level varying from equator to pole and also from summer to winter. In the tropics it is usually to be found at heights of 16–18 Km. but towards the poles its mean height falls to 10–12 Km. in summer and to 8–10 Km. in winter.[1,2,3*] Over this country the mean tropopause height is about 10½ Km. in winter and 11½ Km. in summer but variations from day to day are often as much as 3–4 Km. In the tropics, the lower stratosphere is cold (−70° to −80°C.) with a progressive warming towards the poles where it has a mean temperature of −50° to −60°C. in winter and −40° to −50°C. in summer.

Above the tropopause, the temperature does not vary greatly with height up to 35 Km. or so[4], but before this height is reached, probably above 20–25 Km., direct solar radiation begins to assume importance.

As stated above, the important factor in the maintenance of the temperature of the lower stratosphere is the absorption of outward long-wave radiation by water vapour, carbon dioxide and ozone. Let us consider each of these in turn:—

Water vapour.—Reliable observations of humidity in the stratosphere are very few. Those reported by Dobson[5] and more recent observations made by the Meteorological Research Flight[6], using the same type of instrument

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*These numbers refer to the list of references on p. 103.

the Dobson-Brewer frost-point hygrometer, have shown that over Great Britain, the air in the lower stratosphere is usually very dry, with a relative humidity of only a few per cent. Because the height attainable by the aircraft of the Meteorological Research Flight is, at present, restricted to about 40,000 ft., these observations were made mainly in air with a polar origin (low tropopause). When stratospheric air has a tropical origin the tropopause will be above the maximum ceiling of the aircraft; it may be found to be moister than polar stratospheric air, but, because of its lower temperature, it cannot hold much water vapour. It seems safe to say that, in general, the air of the lower stratosphere contains very little water vapour—probably the mixing ratio is of the order of 0·01 gm. of water vapour per Kg. of air, or the absolute humidity at the base of the stratosphere is about 3 mg./m.^{3} over this country.

Carbon dioxide.—Dobson, from a review of all available evidence, estimates[5] that the concentration of carbon dioxide in the lower stratosphere is roughly constant and equal to 0·03 per cent. by volume.

Ozone.—The total amount of ozone in the atmosphere above a particular place, varies considerably. Near the equator it is small and fairly constant—equivalent to a layer 2 mm. thick at standard temperature and pressure; in high latitudes, however, there is a large annual variation, the amount of ozone being greatest in spring, when it can be equivalent to 4·5 mm. or more, and least in autumn when it is about 25 per cent. greater than the equator value[5] In temperate latitudes the ozone amount varies greatly from day to day, stratospheric air from a polar source having much larger total amounts in the vertical direction than air from the tropics.

The concentration of ozone increases upwards in the stratosphere, reaching a maximum at a height between 20 and 30 Km. and falling off to zero by about 50 Km.[4,5] There does not appear to be as yet an entirely satisfactory explanation of ozone formation and distribution.

Dobson[5] comes to the conclusion that the above gases are of roughly equal importance in the radiative balance of the lower stratosphere, the relative concentrations explaining the observed differences in temperature. They each absorb the outgoing long-wave radiation. Dobson's argument is very convincing and since the annual variation of temperature in the lower stratosphere shows a maximum in June and not in August, as in the troposphere, it fits with the idea that the warming is caused by the increased absorption in spring by the greater quantities of ozone. Dynamical and advectional effects may also be very important as will be seen later.

Stratosphere at greater heights.—Ozone, of course, absorbs radiation strongly in the short wave-lengths from 2200A to 3200A. It is quite understandable, therefore, that available evidence points to a big increase in temperature in the stratosphere above about 35 Km. where the proportion of ozone to air (by volume) is at a maximum.

Measurements by radio-sonde balloons can at present be made only up to about 30 Km. The results of careful experiments on the audibility of sound at great distances, however, can only be explained on the assumption that temperature increases above about 35 Km. This is confirmed by the fact that meteors (of all sizes) most frequently disappear at heights between 45 and 50 Km. indicating higher temperatures there than at the tropopause[4].

Above 40–50 Km., conditions are more a matter of conjecture. Recent American observations from V-2 rockets[7,8] indicate that the temperature distribution shows the same characteristics as that assumed in the National Advisory Committee of Aeronautics proposed standard atmosphere, up to heights of 400,000 ft., based on theoretical considerations[9], *viz.* a maximum at about 50 Km. of 320°A., a minimum of about 200°A. at 80 Km. and a steady rise above 100 Km. It is not yet clear, however, how much reliance can be put on these measurements.

Chapman[10] suggests that above the ozone levels mon-atomic oxygen, which can absorb some solar radiation, is present in increasing proportions, and this could explain the increasing temperatures at great heights.

Little is known of the variation of temperature in the high stratosphere with place and time. Murgatroyd and Clews[11] have found that the wind at 30 Km. over south-east England is predominantly easterly in summer, rising to some 30 m.p.h., and in winter is generally westerly, with rapid variations in direction between NW. and SW. and averaging about 100 m.p.h. at mid-winter. Murgatroyd[12], from measurements based on the propagation of sound from explosions, has found an important seasonal variation of temperature, the temperature at 45 Km. being some 40°C. warmer in summer than in winter. This kind of seasonal temperature variation is, in fact, necessary to give the pressure field appropriate to the seasonal variation in wind direction at 30 Km.

Since the absorption of solar radiation is probably all-important at great heights, it is to be expected that the position of the sun in the sky will have a great effect on temperature there. Gowan[13] has calculated that even the diurnal variation of temperature at 50 Km. over this country should be of the order of 25–30°C., while Seaton[14] estimates diurnal variations of the order of 100°C. and temperature differences of over 100°C. between polar and equatorial regions at heights above 100 Km.

Advective and dynamical effects.—A great complication is superposed on all that has been said earlier by the advective and adiabatic factors. We know that the air in the stratosphere, at the equator for example, does not stay put in that latitude. Following the Krakatoa eruption of 1883, the dust, and the optical phenomena considered to be due to its presence in the high atmosphere, gradually spread both northwards and southwards in an ever-widening belt from the equator. It crossed the 40 degrees of latitude to Japan, for example, in the stratosphere in about four days[15]. There must therefore be corresponding air movements.

Again, if we compute the density of the air in different latitudes at different heights, we find some interesting results. At the surface at the solstices the density in different latitudes varies by up to 10 per cent.; about 8 Km. it is comparatively constant all over the globe, varying by not more than 2 per cent. At 16 Km. it has become some 20 per cent. greater at the equator than near either the arctic or the antarctic circle. At 24 Km., so far as we can infer from the information available, the variation is again small, up to perhaps 5–8 per cent.; whilst at 40 Km. it seems probable that over the summer pole the density is some 30 per cent. greater than at the equator; and over the winter pole some 30 per cent. less than at the equator[3]. Thus, we must budget for considerable, if slow, circulations of air in the vertical; and as the adiabatic effect on temperature is proportional to $\Delta p/p$ it follows that at great heights where the mean pressure is, say, 50 mb., the adiabatic effects of change of level on the part of the air become many times as important as at the surface.

Fig. 1 shows the average temperatures as deduced from observations, including acoustic experiments, or estimated, up to 40 Km. and the average height of the tropopause from winter pole to summer pole. The tropopause is drawn as a continuous line, but it will be seen that there is a very steep slope between latitudes 20° and 40° in the winter hemisphere and a steep, but less steep, slope between latitudes 35° and 50° in the summer hemisphere. In each of these regions there are, not infrequently, traces of two tropopauses, one at about 12 to 14 Km., the other at about 17 Km. The tropopause can be pictured as a wide lid (to the convectional part of the atmosphere) and it looks as if the tropical part had been burst up by some 3 to 5 Km. The above picture of tropopause variation with latitude was derived from observations in western Europe, combined with those for India and Batavia. Hess[3] has recently

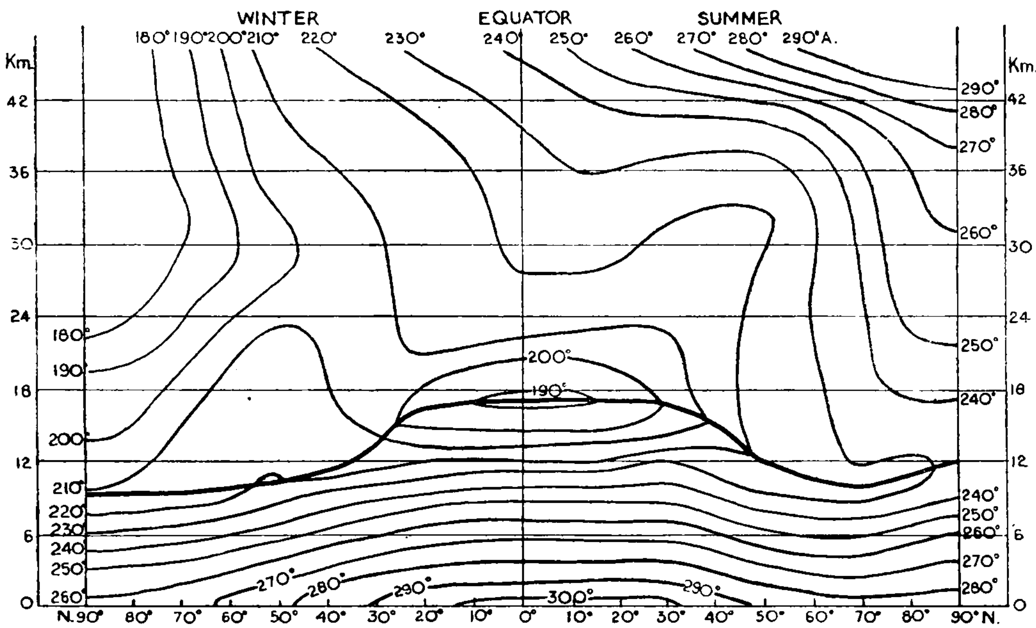

FIG. 1—DISTRIBUTION OF TEMPERATURE WITH HEIGHT AND LATITUDE

Based on data from Abisko, England, India and Batavia. Temperatures are in degrees absolute and the tropopause is the thick line

given a cross-section derived from radio-sonde data roughly along 80°W. and covering latitudes 2°S. to 71°N. in summer and winter. A cross-section derived from his paper is shown in Fig. 2. He finds that the tropopause cross-section is not a continuous line but falls quite definitely into separate arctic and tropic tropopauses, the discontinuities or regions of overlapping tropopause for 80°W lying in about 38°N. in winter and 50°N. in summer. The position of the breaks in the tropopause therefore doubtless varies with longitude.

Several circumstances suggest that, in these latitudes of overlapping tropopause, masses of air from the upper part of the tropical troposphere and from the lower part of the tropical stratosphere are drifting out quasi-horizontally to middle latitudes. The first pointer is a temperature and density distribution which would favour such a circulation. The next pointer is that it is difficult to see how air could be brought to the frost points now being measured in the lower stratosphere over England without having passed at some recent time in its life history through the region of the equatorial tropopause. Note also that in these latitudes of steeply sloping tropopause the isentropic surfaces cut the tropopause.*

If this picture is correct, the air which is found in the lower stratosphere of temperate and higher latitudes is air which has come from the tropics, has subsided—as a rule by some 3 Km.—and has been correspondingly adiabatically warmed by an amount of the order of 25° or 30°C. Its temperature and its frost point are at least broadly consistent with this life history[2].

But if this is correct, there must be a reverse side; in polar regions or, at least near the winter pole, there should also be no continuous tropopause but a cooling and subsidence of stratosphere air into troposphere air to be followed by its eventual return, through the great eddies of depressions, to lower latitudes.

If valid, this picture of stratosphere air as having come at some earlier time, even if slowly, from tropical latitudes and piled up in temperate and higher latitudes according to the height of the tropopause, would also have a bearing on the amount of ozone found at any time in the vertical direction—but that is too complex a matter for discussion here.

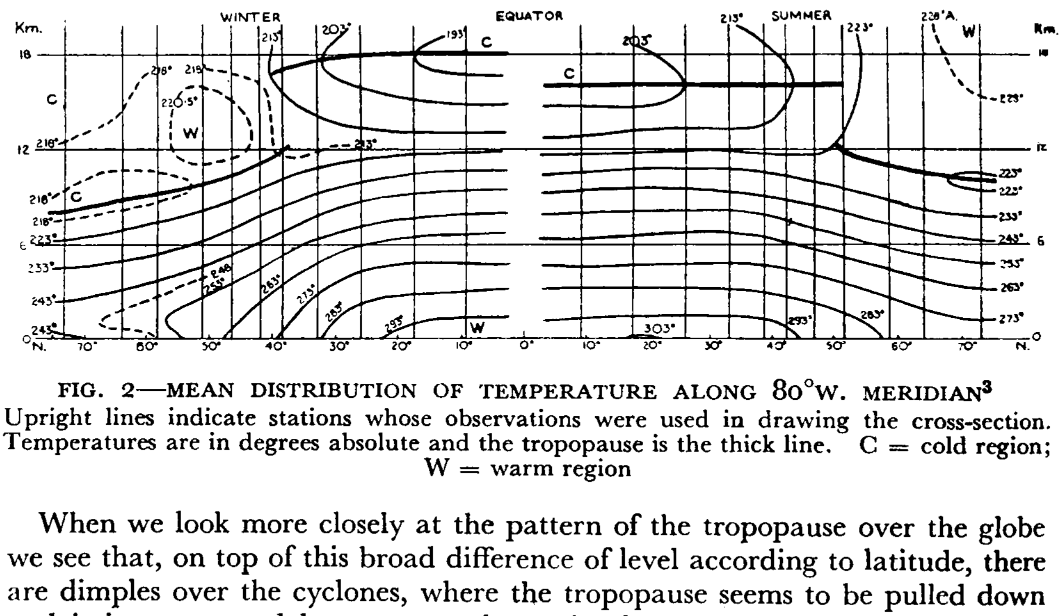

FIG. 2—MEAN DISTRIBUTION OF TEMPERATURE ALONG 80°W. MERIDIAN[3]
Upright lines indicate stations whose observations were used in drawing the cross-section. Temperatures are in degrees absolute and the tropopause is the thick line. C = cold region; W = warm region

When we look more closely at the pattern of the tropopause over the globe we see that, on top of this broad difference of level according to latitude, there are dimples over the cyclones, where the tropopause seems to be pulled down and it is warm, and humps over the anticyclones, where the stratosphere is pushed up and it is cold. To a large extent these local variations can be explained by advection of air masses complete with their stratospheres from higher or lower latitudes[16]. But there is an intimacy of association with surface pressure distribution which suggests a dynamical connexion; and it is possible to show in particular cases that variation of level of tropopause exists over an air mass which is homogeneous as to its origin.

A number of years ago, V. Bjerknes[17] showed that, if two superposed fluids of different densities with a quasi-horizontal bounding surface are in steady rotation, the boundary surface is pulled down or pushed up according as the

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*See, for example, Fig. 2 of Goldie's paper[2] or Fig. 63 of " Manual of Meteorology ", Vol. II.

kinetic energy of rotation is greater in the lower or the upper fluid. Now recent preliminary investigations[18] using radio-wind measurements suggest that, at least in the later stages of a depression's life, the kinetic energy reaches a maximum in the upper part of the troposphere. The result should thus be to pull down the tropopause and incidentally, by the same reasoning, to pull up the boundary between warm and cold air (*i.e.* to occlude the depression); whether it always works out in accordance with theory and whether it works for anticyclones remains to be investigated. But, if we accept the dynamical explanation for cyclones, may not the same principle determine in a broad way the variation of tropopause height from subtropical latitudes up to the poles? Here we have a belt of more or less strong westerly circulation increasing with height in the troposphere and falling off rapidly again in the lower stratosphere. This general westerly circulation, regarded as a vortex about the poles, thus has as a rule its maximum kinetic energy under the tropopause and the result should be to pull down the tropopause towards high latitudes.

It seems that both the dynamical and the advective effects are essential and fundamental parts of any explanation of the variations of tropopause height with time and place. It is not conceivable that any theory of radiative balance could alone explain the day-to-day changes in tropopause level and stratosphere temperature which take place in temperate latitudes and their continual adjustment to the synoptic situation. The extreme range of these changes is not much short of the whole range of conditions experienced over the whole globe.

Summary.—The picture, finally, of the stratosphere which we are tempted to give is thus one in which the quasi-static conditions at the " boiler " of the atmospheric heat engine are determined by radiation in the tropical zone, and the conditions (probably also quasi-static) at the " condenser " of the engine are determined again by radiation in polar regions—probably mainly in winter polar regions; whilst in the latitudes between, where the air is changing position more rapidly, dynamical and advective processes play a large part in adjusting the shape of the boundary surface between stratosphere and troposphere and in determining (adiabatically) the temperature within the stratosphere itself.

REFERENCES

1. DEWAR, D. and SAWYER, J. S.; Seasonal charts of the mean height of the tropopause. *Met. Res. Pap., London,* No. 334, 1947.
2. GOLDIE, A. H. R.; The upper atmosphere: estimated distribution of temperature, pressure and wind up to the 45 Km. level. *Met. Res. Pap., London,* No. 360, 1947.
3. HESS, S. L.; Some new mean meridional cross-sections of the atmosphere. *J. Met., Lancaster, Pa.,* 5, 1948, p. 293.
4. HAURWITZ, B.; The physical state of the upper atmosphere. *J. R. astr. Soc. Can., Toronto,* **30**, 1936, p. 314 and **31**, February 1937, reprinted with addition, October 1941.
5. DOBSON, G. M. B. with BREWER, A. W. and CWILONG, B. M.; Meteorology of the lower stratosphere. *Proc. roy. Soc., London,* A, **185**, 1946, p. 144.
6. FRITH, R.; Meteorological Research Flight. *Met. Mag., London,* **77**, 1948, p. 241.
7. KRAUSE, E. H.; High altitude research with V-2 rockets. *Proc. Amer. phil. Soc., Philadelphia, Pa.,* **91**, 1947, p. 430.
8. London, Meteorological Office. Meteorological Office Discussion. Rocket-sondes. *Met. Mag., London,* **78**, 1949, p. 69.
9. Anon.; N.A.C.A. standard atmosphere extended to 400,000 feet. *Bull. Amer. met. Soc., Lancaster, Pa.,* **28**, 1947, p. 424.
10. CHAPMAN, S.; On the annual variation of upper-atmospheric ozone. *Phil. Mag., London,* Series 7, **10**, 1930, p. 345.

11. MURGATROYD, R. J. and CLEWS, B. J. B.; Wind at 100,000 ft. over south-east England. *Geophys. Mem., London,* **10**, No. 83, 1949. (in the press)
12. MURGATROYD, R. J.; Anomalous sound reception experiments. *Met. Res. Pap., London,* No. 346, 1947.
13. GOWAN, E. H.; Night cooling of the ozonosphere. *Proc. roy. Soc., London,* A, **190**, 1947, p. 227.
14. SEATON, S. L.; Temperature of the upper atmosphere. *Phys. Rev., Ithaca, N.Y.,* **71**, 1947, p. 557.
15. Royal Society, Krakatoa Committee. The eruption of Krakatoa and subsequent phenomena. London, 1888.
16. GOLDIE, A. H. R.; Circumstances determining the distribution of temperature in the upper air under conditions of high and low barometric pressure. *Quart. J. R. met. Soc., London,* **49**, 1923, p. 6.
17. BJERKNES, V.; On the dynamics of the circular vortex with applications to the atmosphere and atmospheric vortex and wave motions. *Geofys. Publ., Oslo,* **2**, No. 4, 1921.
18. GOLDIE, A. H. R.; The vertical circulation in relation to the momentum and density distribution in cyclones. *Met. Res. Pap., London,* No. 213, 1944.

SCIENTIFIC RESULTS OF THE "BALAENA" EXPEDITION 1946-47
Meteorology

BY H. H. LAMB, M.A.

Two earlier articles have given a general account of the meteorological work on the 1946-47 *Balaena* expedition to the eastern Antarctic whaling grounds in the Southern Ocean[1]*. The present article is intended to give a summary of the scientific results of the expedition in the field of meteorology pending the full report, publication of which may unavoidably take some time.

Surface weather observations were carried on from leaving England in mid October 1946 until the vessel's return to Southampton in May 1947. The observations were made at 6-hr. intervals in the Southern Ocean, for the most part between 80° and 115°E. and between 55° and 65°S. close to the ice margin. A full weather diary covered progressive changes of weather and cloud development in the intermediate hours. 105 pilot-balloon ascents were made at picked times when the 15,000-ton vessel and her course and speed were steady enough to permit the use of theodolite and tripod (see photograph facing p. 108). In 1946 no special marine theodolite was available, but the method used was checked in various ways and found to give satisfactory results. Ninety ascents were made in the Southern Ocean, the remaining fifteen in the South Atlantic and near the equator on the homeward voyage; the highest ascent reached an assumed height of 57,000 ft.; and altogether fourteen balloons were followed to heights above 10,000 ft. over the Southern Ocean. In addition, *Balaena's* aircraft made twelve meteorological ascents in the Far South, using psychrometers supplied by the Meteorological Office (see photograph between pp. 108 and 109); several of these ascents reached 10,000 ft. To send up radio-sondes would have taken more time, labour and accommodation than was available, but even so a valuable amount of observational data was brought back from regions where little meteorological work had been done before.

The quotation of averages and statistics from the observations of one moving ship visiting various regions in the course of a single southern summer and autumn can have little meaning, unless great care is exercised in the manner in which data are grouped and considered. We shall prefer therefore to present

*These numbers refer to the list of references on p. 112.

particular observations of special interest and to point to what appear to be significant trends. This scruple has guided the entire work and will be followed here.

Upper air observations.—A deeper troposphere than has been commonly supposed to occur in the Far South was indicated by a pilot balloon entering cirrus cloud at 43,500 ft. near 59°S. 81°E. on December 28, 1946. Comparable observations have since come to hand in the radio-sondes from the Dutch whaling ship *Willem Barendsz*, mainly south of 60°S. in the Atlantic sector, during the same season, though these would suggest that the tropopause is somewhat lower on most days.

Low cloud limited pilot-balloon work in the stronger easterly winds, hampering efforts to explore the depth of the easterly current. Table I however gives extracts of some *Balaena* ascents which are of interest in this connexion. Although the easterly components generally decrease upwards, this is not so in all cases: the balloon of January 18, 1947 showed increasing south-easterly wind up to 134° 36 kt. at 13,000 ft., the greatest height reached. This was the

TABLE I—SAMPLE PILOT-BALLOON ASCENTS FROM THE *Balaena* IN EASTERLY WINDS

Date	Time	Position		Winds at heights of 2,000 ft.		5,000 ft.		10,000 ft.		20,000 ft.	
	G.M.T.	°S.	°E.	°true	kt.	°true	kt.	°true	kt.	°true	kt.
3.12.46	1600	59·9	66·8	223	5	049	2	068	3	—	
28.12.46	1200	59·2	81·3	036	11	046	19	006	10	274	19
29.12.46	1100	59·5	81·8	069	16	103	15	047	15	—	
18. 1.47	1100	63·3	94·6	171	21	186	20	153	25	—	
27. 1.47	1400	63·3	98·5	098	5	050	4	260	4	195	3
7. 2.47	1000	64·3	105·9	081	14	084	12	030	2	—	
22. 2.47	0500	64·9	109·6	075	15	078	7	142	6	—	
5. 3.47	1100	65·1	112.9	127	21	152	15	089	7	—	
12. 4.47	0800	63·0	43·9	023	17	027	14	259	17	—	

deepest, so-called " solid " easterly current probed. The prevailing westerly currents of the upper levels of the troposphere were however distorted or replaced by southerlies and northerlies on a number of occasions; and it is clear that when the wind in the lowest layers was easterly the currents between 10,000 and 20,000 ft. were commonly light airs from various directions.

The highest-level wind observation of all was 166° 14 kt. at 55,000 ft. on January 24, 1947 in 63½°S. 97½°E. This was in an anticyclonic situation with light southerly and south-westerly winds in the lower levels. There were several progressive changes aloft in this ascent: to 268° 9 kt. at 14,000 ft., to 153° 19 kt. at 28,000 ft. and to 280° 22 kt. at 41,000 ft.

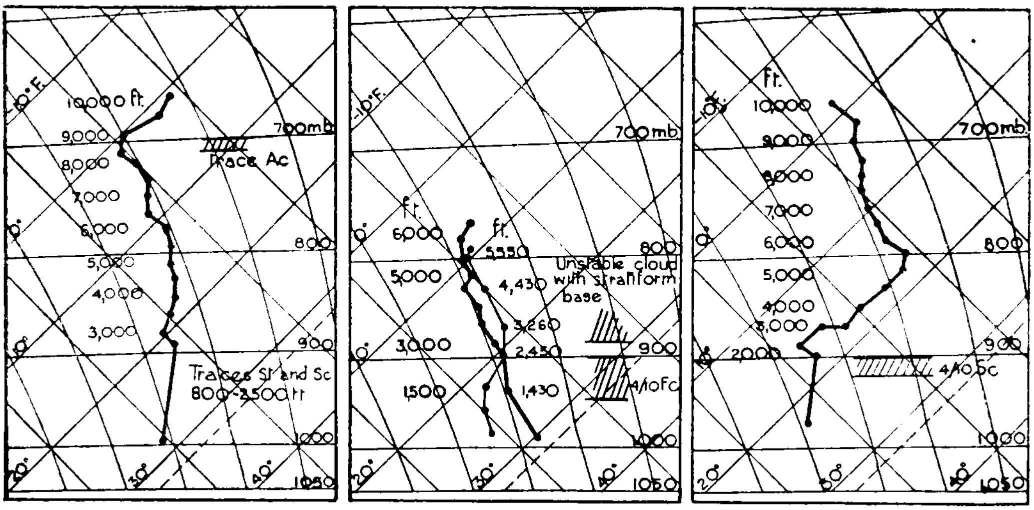
Samples of typical deep westerly currents are given in the ascents listed in Table II, including one in 65°S.

TABLE II—OCCASIONS OF DEEP WESTERLY CURRENTS

Date	Time	Position		Winds at heights of 2,000 ft.		5,000 ft.		10,000 ft.		20,000 ft.	
	G.M.T.	°S.	°E.	°true	kt.	°true	kt.	°true	kt.	°true	kt.
16.12.46	0800	57·1	83·8	223	15	223	16	219	17	—	
7. 1.47	1100	59·4	84·7	290	18	305	21	265	22	—	
7. 3.47	0900	65·0	112·5	264	6	311	9	318	20	321	24

The continuous series of 156 daily weather maps drawn on the *Balaena* during the season suggest how these upper air observations may be related to the synoptic circulation patterns of a great part of the southern hemisphere.

In Fig. 1 sample upper air temperature soundings, made by *Balaena's* Walrus aircraft under the command of John Grierson are shown. The ascent on February 11, 1947 was made in a deep westerly current in high latitudes, the centre of lowest pressure being estimated over Wilkes Land in 65–70°S. 125–130°E.; the lapse rate approaches the saturated adiabatic in the surface air mass up to 8,500 ft. The ascents on March 8, 1947 were made in a stagnant situation with presumed antarctic continental air over open water close to the coast in 114–116°E.; instability was indicated by the growth of towering cumulus and altocumulus castellatus clouds, with tops in sight probably reaching 20,000 ft. over the coastal mountains. The sky looked thundery—this being the only occasion during our sojourn in high southern latitudes—although most of the cloud had a high base and no thunder was heard. Small hail fell in a brief shower over the ship. Another type of situation is represented by the ascent of March 15, 1947, with south-westerly winds and a ridge of high pressure thrusting out from Antarctica ; the stable layer and clear sky above the strato-cumulus top at 2,000 ft. probably indicate subsidence.



(*a*) (*b*) (*c*)

FIG. 1—TEPHIGRAMS OF AIRCRAFT OBSERVATIONS IN THE SOUTHERN OCEAN

Observations were usually made at 500-ft. intervals

(*a*) in 64·5–65°S. 109°E. at 0430 G.M.T., February 11, 1947;
(*b*) in 65·3°S. 113·8°E. at 0540 G.M.T., March 8, 1947 (thick line) and in 65·7°S. 116·2°E. at 0650 G.M.T., March 8, 1947, in clear patch with towering cumulus further east (thin line); and
(*c*) in 64·3°S. 106·3°E. at 0830 G.M.T., March 15, 1947.

These ascents dispel the idea that we can speak of a prevalent surface inversion over the cold waters of the Far South, at any rate in the sector visited, even in summer. Subsidence inversions between 2,000 and 4,000 ft. were usually indicated in fine weather ; at other times unstable air masses often separated by thin, stable layers were common.

Surface weather observations.—Cumulonimbus and large cumulus cloud, already referred to, were observed on 35 out of 150 days south of 50°S.

Altocumulus castellatus was very rare. Stratocumulus clouds prevailed, often with small cumulus penetrating the base. Normal frontal altostratus, altocumulus and cirrostratus were often seen. In the "fifties" these systems advanced mainly from west and south-west, but farther south frontal cloud systems advancing from other quarters, notably from east and south as well as north, became frequent.

The mean of all *Balaena's* pressure observations in five months south of 50°S. was 982·2 mb. This is consistent with the generally low level of pressure represented by all available annual mean pressures south of 50°S., though rather lower than any of the known annual means (the lowest being 986·5 at Mawson's Queen Mary Land base, near the coast in the same sector in 66°S. 95°E.*). During the 1946-47 season another whaler *Empire Victory*, operating around 63°S. 84°E. over a more restricted area than *Balaena*, had a mean pressure of 985 mb. for 4 months. Now all the available reports during the same period in other sectors, including some from whaling ships in the Weddell Sea, show values close to the known annual means (*i.e.* within 2 mb.). These figures suggest therefore that our annual mean pressure maps should show a centre of lowest pressure in the Indian Ocean sector. Fig. 2 shows a suggested scheme of annual mean pressures covering the southern hemisphere, using all the previously existing data and amplified in the light of these indications.† The pattern over Antarctica follows Meinardus[3] with slight adjustments suggested by the *Balaena* daily weather maps.

It is interesting to note that pressures observed even in good weather in extensions or offshoots of the antarctic anticyclones over the surrounding ocean were low by comparison with northern hemisphere experience, ranging from 988 mb. to about 1010 mb.—the latter figure coming from the Weddell Sea region. *Balaena* only once had pressure over 1000 mb. south of 60°S., 1002·4 being observed near 63°S. 96°E. on January 24, 1947.

These figures hint at an unequal division of atmospheric pressure between the northern and southern hemispheres as a whole. The explanation probably lies in the recurrent strong westerly currents blowing over the main width of the Southern Ocean and always ready to break down any tendency to establish a large-scale meridional transport of air. Nevertheless we have seen that meridional transport does sometimes occur even at great heights, and it is suspected that the anticyclones over the south polar plateau depend upon occasional instances of such transport for their formation. The composite picture of atmospheric circulation which this implies suggests that the manner of formation of the antarctic continental anticyclones is similar to that of anticyclones in high northern latitudes and yet explains why they seldom reach the intensity of their northern counterparts.

The surface air temperatures observed by *Balaena* require little comment. The average of all observations south of 50°S. was +28·7°F., extremes being +37·8°F. and +12·1°F.

Relative humidities varied from 100 to 55 per cent., values of 65–70 per cent. being typical in fine weather. Fog was not common, and occurred at only 15 out of 600 observations south of 50°S.; in this respect it is thought that the

*The German expedition ship, *Gauss*, had a mean pressure of 986 mb. over 11 months, when she was icebound near 66°S. 90°E., also in the same sector.

† *cf.* Maps in Shaw's "Manual of Meteorology".[2]

eastern longitudes visited by *Balaena* differed from certain other sectors. For instance, fogs are believed to be commoner in the South Atlantic sector east of the Weddell Sea. In the Indian Ocean sector, according to certain indications, fogs are relatively commoner in longitudes 80–90°E. than farther east.

Air-mass advection fogs are noticeably associated with winds with northerly components—even slight northerly components—bringing warmer air streams over the cold water. This generalization seems to apply to widespread fogs in all sectors in high latitudes in the Southern Ocean and is familiar to the whalers.

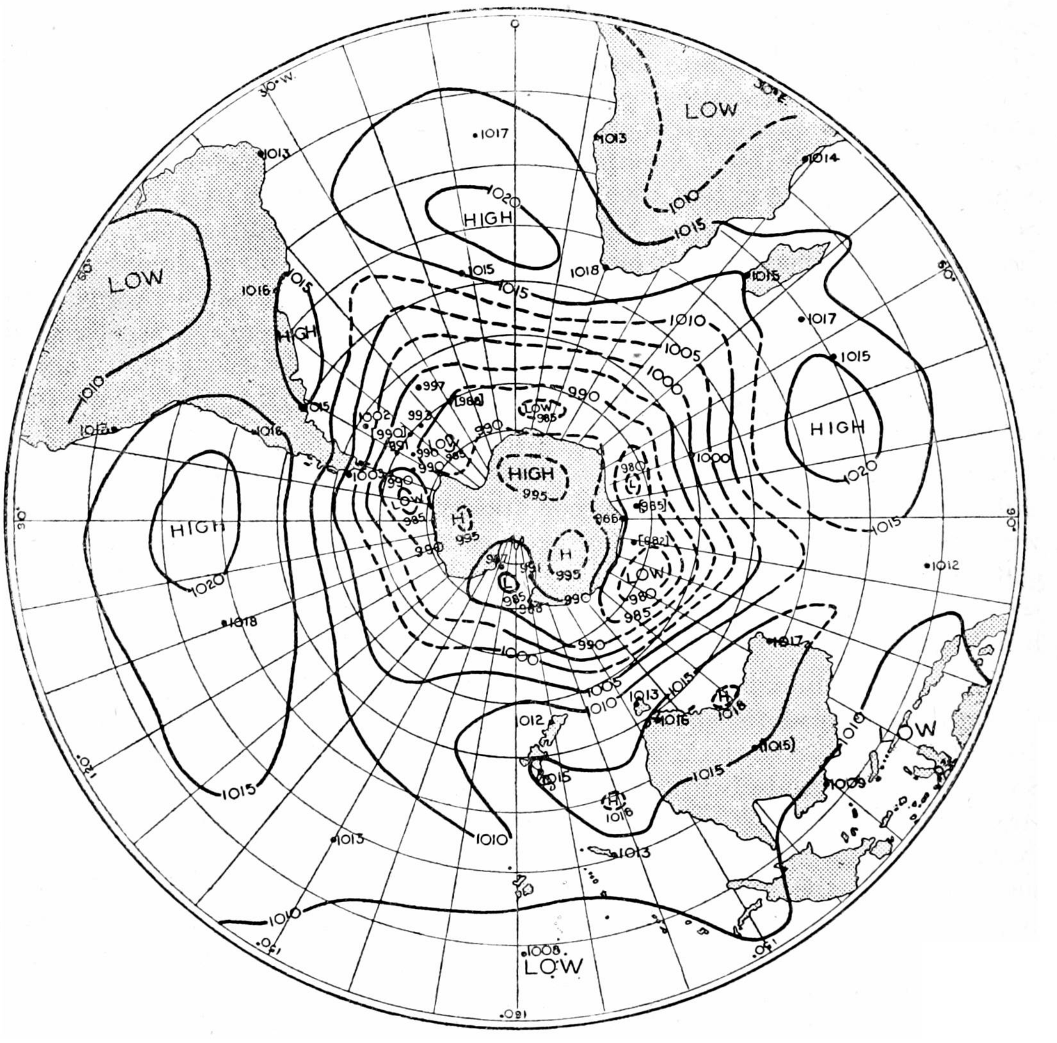


FIG. 2—SUGGESTED ANNUAL MEAN PRESSURE PATTERN

Figures in square brackets taken from the 1946–47 whaling vessels' observations, using these figures as indicative of the probable yearly values over the same parts of the Southern Ocean.

Most of the fogs experienced in the *Balaena* voyage in the Far South were however frontal fogs, in narrow and very isolated belts, and these might persist for some time even when drifting slowly from south to north. These frontal fogs, believed to be associated with increased humidity in the lowest layers where precipitation was, or had been, falling, were accompanied by residual frontal cloud sheets, attributed in most cases to old, decaying occlusions drifting about in, or driven forward by, the circulations of newer systems.

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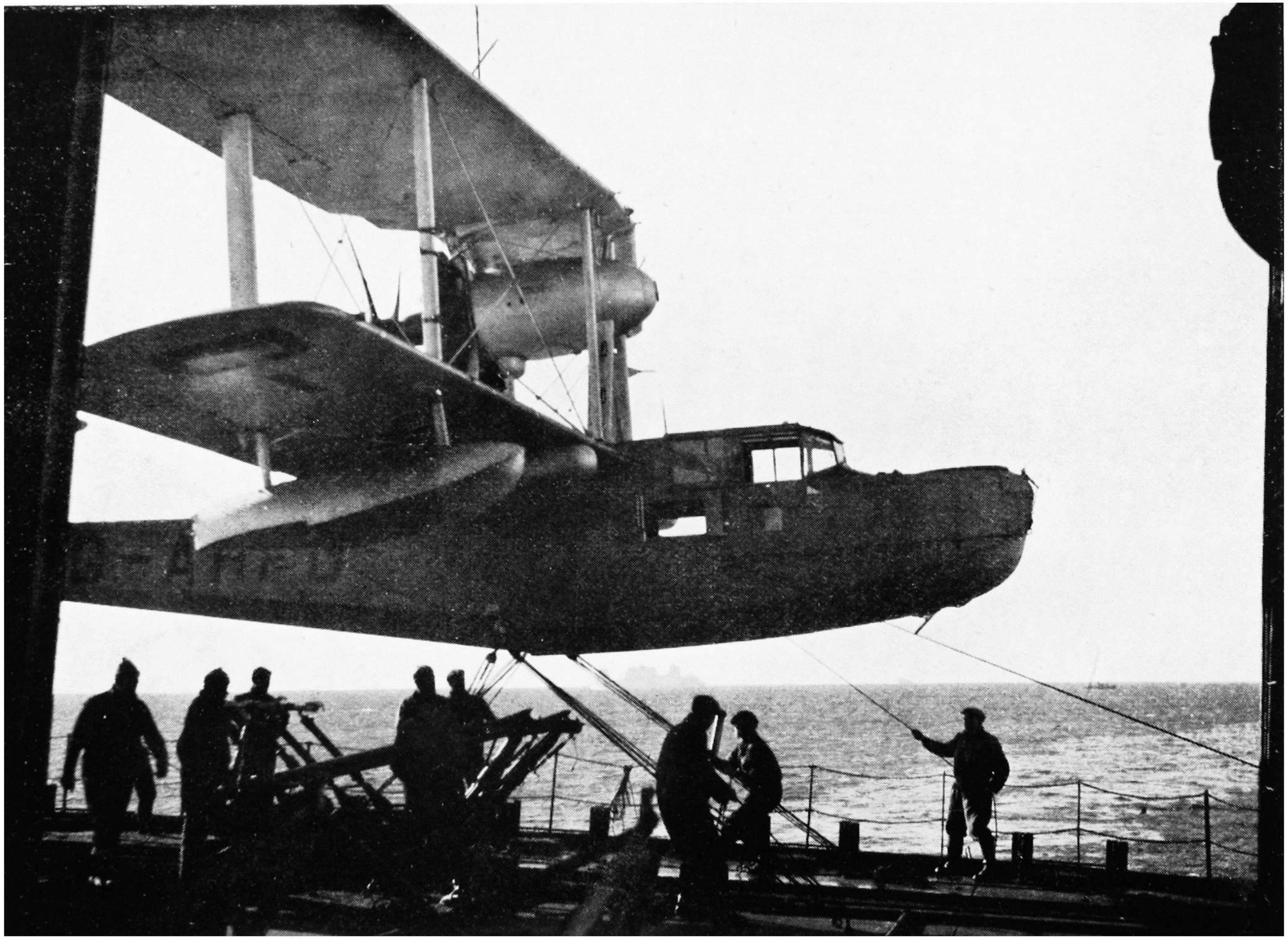
THEODOLITE SET UP FOR A PILOT-BALLOON ASCENT ON THE FLIGHT DECK AT *Balaena's* STERN

Such a large balloon (rising at 1,000 ft./min.) was used in exceptionally good conditions. The flight deck is 45 ft. above the water line. Two small icebergs can be seen near the horizon at the left. (see p. 104)



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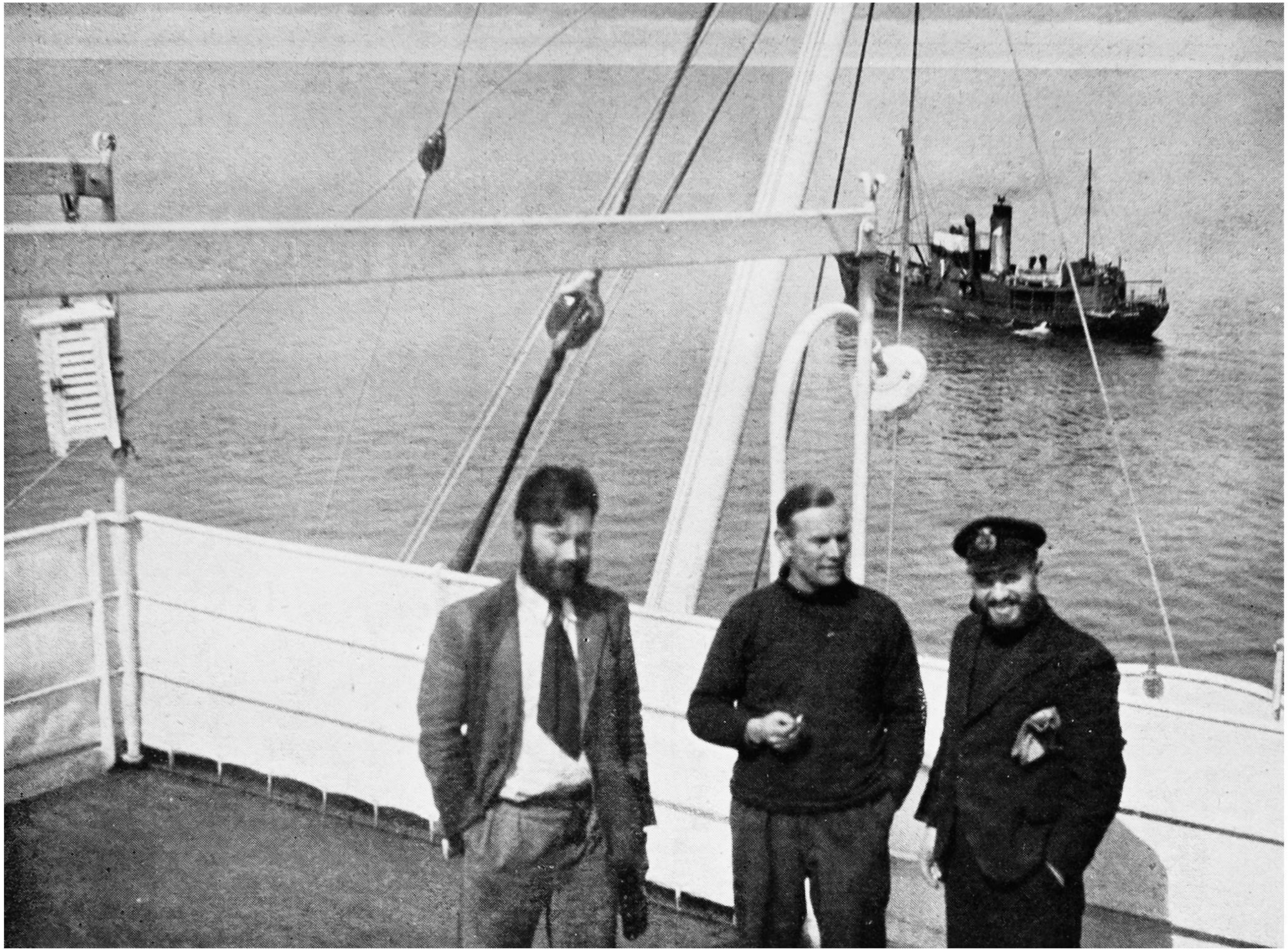
MANŒUVERING THE WALRUS AIRCRAFT ON TO THE CATAPULT TROLLEY AT *Balaena's* STERN

The catapult was fired so that the aircraft was sent out abeam. The psychrometer can be seen close to the fuselage just at the afterside of the lower window which was used by the observer. Two icebergs can be seen on the sky-line.

(see p. 104)



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EXPOSURE OF THE THERMOMETER SCREEN 60 FT. ABOVE THE WATER LINE

Screens were suspended above the forward rail of the Monkey's Island, on either side of W/F *Balaena*, and the windward screen used for readings. The whale-boat in the background is towing a whale alongside.

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RAIN-GAUGE AND ROPE CRADLE USED FOR HOISTING TO THE YARD-ARM

One gauge was suspended on either side of the foremast. This thick deposit of rime occurred during 24 hours exposure to fog and had to be chipped off the suspension before the gauge was hoisted again. (Fog was not common, but the occasional instances produced deposits of ice in quantities of similar order to the precipitation received in the form of snow, drizzle, etc. in high southern latitudes.)

Cloud amounts averaged over 9 tenths in most sections of *Balaena's* voyage south of 50°S., but fell to 7·4 tenths in the narrow sector between 105° and 110°E. where the ship was fairly close to the coast of Antarctica and had more off-shore winds. Yearly averages of 5–6 tenths are typical for cloudiness reported at expedition stations on the Antarctic coast in eastern longitudes. In the "fifties" in the Indian Ocean away from the pack-ice appreciable amounts of clear sky seemed only to occur in regions of strong subsidence between frontal systems; even so, totally clear sky was never observed, the next advancing cloud system always coming into view before the last had disappeared. In those regions sunshine was therefore confined to periods of 3 or 4 hours once in 4 or 5 days. Cloudless skies did occur however in off-shore winds sufficiently near the ice-margin or coast of Antarctica.

The instrumental equipment on *Balaena* included two Snowdon rain-gauges, which were not however found suitable for measuring precipitation in the Far South without considerable adaptation. Measurements were fairly successful, using modified gauges in different exposures for purposes of comparison from November until mid February, but thereafter (when the season became stormier) had to be eked out by estimations. During the 5 months spent south of 50°S. the estimated total equivalent rainfall was only 43·6 mm., roughly equivalent to 105 mm. or 4 in. of rain a year. Comparable figures have been obtained from stations in the Australian desert, the Sahara and near the coast of northern Greenland. This low rainfall total represented slight, though frequent, precipitation; only one day in five was free from rain or snow. Moisture precipitated by the comparatively rare fogs on the vertical rigging and sides of the ship added up to a similar figure (53 mm. in 5 months), whilst a total of 4·7 mm. of glazed ice was deposited in this way even on level objects—these figures are not included in the ordinary rainfall measurements.

Wind was measured by a cup anemometer exposed above the hangar roof astern, 70 ft. above the water line. A highest gust of 56 kt. was noted, on February 25, 1947 near 65°S. 113°E. At the same time the wind was averaging 48–50 kt. and SE. force 11 was reported. The steadiness, or relative freedom from gusts, of this south-easterly storm near the coast of Antarctica was remarkable, and the ocean swell was not great owing to the short fetch of open water. Vessels at sea are of course less liable to extreme winds than stations on land exposed to katabatic gales, especially in valleys. Points close to a mountainous coast seem most favourable for extreme winds at sea; this generalization fits the *Balaena* observations and the experience of other vessels, particularly in the Ross and Weddell Seas.

Storms were not very frequent, Beaufort force 8 or over being reported at only 16 out of 600 observations south of 50°S. on *Balaena's* voyage. The mean wind force observed over the same waters was only 3·9. It is interesting to compare the annual means given by the *Gauss* station in 65°S. 90°E. in the belt of easterlies (3·5) and by Kerguelen island in the zone of Brave West Winds near 50°S. 70°E. (5·0), each taken from one year's observations. It appears that the easterlies near the coast of Antarctica in this sector are on the average less strong than the westerlies over the ocean farther north, although occasional extremes may be experienced near mountainous stretches of the coast.

An attempted geographical analysis of *Balaena* and *Empire Victory's* statistics of wind observations south of 62½°S. between November 1946 and April 1947 suggests that the pressure patterns prevailing may also favour stronger winds and rather different mean directions in different longitudes. Table III summarises the evidence. It will be noticed that the prevalent wind directions follow the broad configuration of the coast and become more variable west of 90°E., where the vessels were farther from land owing to the great bight in the coast of Antarctica between 55° and 90°E. Westerly and north-westerly winds made up over 10 per cent. of the observations in these longitudes and were distinctly less frequent though never entirely absent east of 90°E. Northerly and north-easterly winds were almost lacking in the observations east of 100°E.

These observations agree with other indications that near the coast of Antarctica, longitudes east of 110°E. as far as 120° or 130°E. and east of the point of Enderby Land between 55° and 75°E. are particularly associated with strong south-easterly winds and frequent storms, whilst the sector between 80° and 105°E. gets more quiet weather.

These considerations, based partly on the experience of the whalers in other seasons, have been taken into account in drawing the suggested mean isobars in Fig. 2.

TABLE III—WINDS OBSERVED SOUTH OF 62° 30′S.

Limits of longitude	Mean Beaufort Force	Percentage of occasions from direction									No. of obser-vations
		N.	NE.	E.	SE.	S.	SW.	W.	NW.	Calm	
°E.											
115–110	5·0	3	4	24	**51**	7	3	4	3	3	74
110–105	4·1	0	1	21	**27**	14	21	12	4	0	79
105–100	3·2	3	6	**25**	**25**	3	19	9	6	3	33
100– 95	3·6	2	8	24	**37**	19	12	0	0	0	67
95– 90	3·4	0	12	**38**	26	11	11	3	0	0	86
90– 85	3·7	10	14	**19**	15	11	14	8	8	1	73
85– 80	3·5	9	15	**24**	12	11	12	12	5	0	102
80– 75	3·7	3	5	**21**	16	11	**21**	8	14	0	37
75– 70	(5·5)	0	6	12	**29**	18	24	12	0	0	(17)

Other observations.—Fig. 3 presents the sea temperatures observed on the outward and homeward voyages across the Southern Ocean between Cape Town and the whaling grounds. Identification of the classical temperature discontinuities known as the subtropical and antarctic convergences from these observations would be difficult; the curves suggest rather a variable situation with three well marked discontinuities passed on the southward voyage in November and no major but several minor discontinuities on the return voyage in April.

Between March 3, 1947 and April 12, 1947 *Balaena* travelled rather quickly west along the ice margin, giving some approach to a synoptic view of the course of the limit of open water at the end of the warm season in the Indian Ocean and Australian sectors. Open water extended to the coast of Antarctica in 116°E.; from there the ice margin ran approximately north-west as far as a great ice headland in 62½°S. 101–102°E. West of this open water extended gradually farther south again, reaching south of 64°S. between 60° and 80°E. It is clear that open water extended farthest south in the stormiest regions; and it is thought that the accumulation of ice near the 100th meridian marked a transition or boundary region in both air and water circulations between the broadly cyclonic, clockwise systems of the southern Indian Ocean and those farther east.

Space forbids comment here on the other oceanographical observations.

Land was observed on a number of occasions, and observed cloud-height was used to gain an approximate idea of the heights of the uncharted mountains. Speculations about the geography of the coast and interior based upon reasoning from the meteorological observations have been discussed elsewhere.[4]

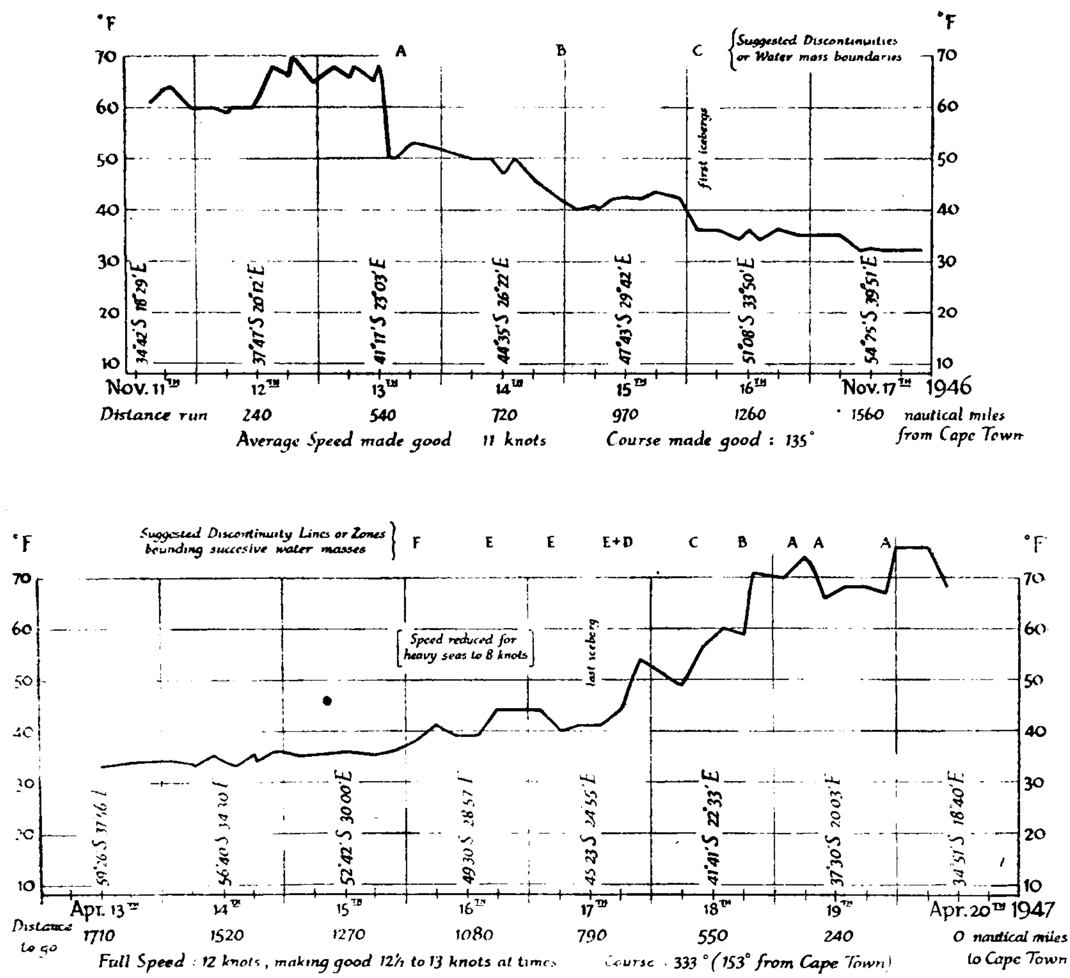

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FIG 3. SEA TEMPERATURES RECORDED WHILE CROSSING THE SOUTHERN OCEAN

Another by-product of the immediate meteorological work of the expedition has been a consistent series of daily synoptic weather maps covering a very wide area of the southern hemisphere for over 5 months. Verification of the charts in the light of observations in high latitudes in the Southern Ocean received later gave a probable error of ±6·8 mb. in pressure and 150–190 miles in the positions of major systems. In the South Atlantic a probable error of under 3 mb. was obtained. These charts have been used as the basis of a more precise re-analysis study of an Antarctic anticyclone, for a preliminary investigation of the formation of easterly storms over the southernmost parts of the Southern Ocean, and to derive a tentative frequency distribution map of the occurrence of fronts in the southern hemisphere.

REFERENCES

1. LAMB, H. H.; A meteorologist in the Antarctic. *Met. Mag., London*, **76**, 1947, pp. 231 and 247.
2. SHAW, SIR NAPIER; Manual of meteorology. Vol. II: Comparative meteorology. Cambridge, 2nd edn., 1936.
3. KÖPPEN, W. and GEIGER, R.; Handbuch der Klimatologie. Band IV, Teil U.: Klimakunde der Antarktis, by W. Meinardus. Berlin, 1938.
4. LAMB, H. H.; Topography and weather in the Antarctic. *Geogr. J., London*, **111**, 1948, p. 48.

METEOROLOGICAL OFFICE DISCUSSION

Turbulence in clear air and in cloud

The Discussion on Monday, January 31, 1949 was devoted to a symposium on turbulence in cloud and in clear air. The opening speakers were Mr. J. K. Bannon and Mr. R. F. Jones.

Mr. Bannon, in introducing the subject " Turbulence in clear air ", said that for several years now it had been known that aircraft may encounter bumps in clear air even in the stratosphere. With the possibility of future aircraft flying well above 20,000 ft. and at high speed, the occurrence of turbulence at these heights is of importance both in the design of aircraft and also to planners who have to consider the comfort of passengers, a very important aspect. He intended, however, to talk mainly about the meteorological conditions associated with the occurrence of aircraft bumps at heights greater than 20,000 ft.

Regarding the severity of the clear air bumps experienced above 20,000 ft., the largest acceleration recorded was about 0·7*g* (the aircraft was flying at about 230 kt. equivalent airspeed) but usually the accelerations on an aircraft flying at about 180 kt. were 0·1 to 0·2*g* (bumps of 0·25*g* would be uncomfortable if they persisted and of 0·5*g* would be very uncomfortable indeed).

Many pilots have commented on the contrast between these bumps and those experienced near the ground on a warm afternoon; the clear-air bumps are more regular in character—almost periodic, about 2 to 3 a second—though they often occur in patches with quiet conditions between.

This high-level bumpiness has been noted above practically all kinds of weather as experienced on the ground. It has been observed in the stratosphere though it appears to occur less frequently there than in the troposphere. The highest observation of turbulence was at 42,000 ft. over Derby—6,000 ft. above the tropopause.

The bumpy layer is frequently very shallow, an important consideration for the aviator, for it means that if bumpiness is encountered it usually requires only a small change of height to get out of the turbulence.

Attempts have been made to correlate the occurrence of turbulence above 20,000 ft. with the shear of wind with height, the lapse rate of temperature with height (or static stability) and the Richardson number, but so far without success. One of the British European Airways (B.E.A.) investigational flights suggested wind shear in the horizontal as a possible factor and this has been explored further. Fig. 1* shows the ratio of the frequency of occurrence of various horizontal shears in bumpy conditions (for bumpy layers of more than 4,000 ft.

*Taken from *Met. Res. Pap., London*, No. 436.

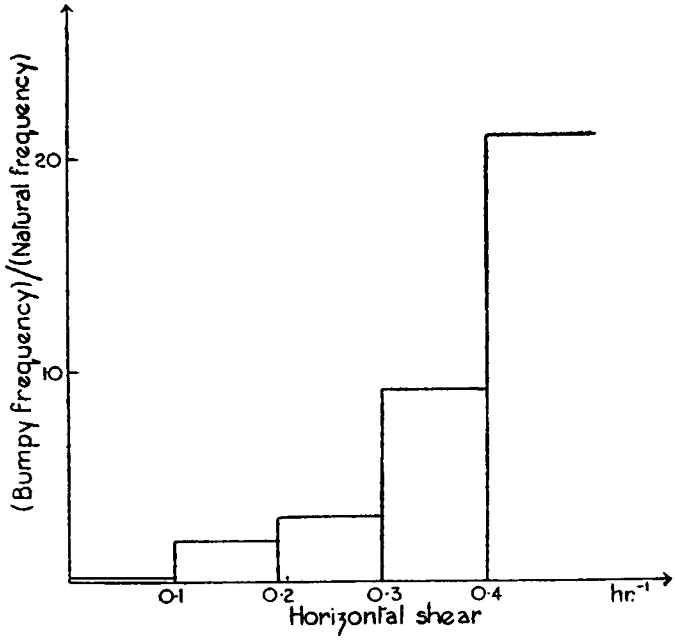

FIG. 1—FREQUENCY OF OCCURRENCE OF VARIOUS HORIZONTAL SHEARS IN BUMPY CONDITIONS
(for bumpy layers more than 4,000 ft. deep)

in depth) to the average frequency of these horizontal shears for all occasions, *i.e.* the normal frequency. The fact that this ratio is not unity but increases rapidly with increasing shear, indicates that bumpiness and horizontal shear are related. A similar but less well marked relationship is found if all bumpy layers, including shallow layers, are considered.

It was also found that wind speed is related to the occurrence of high-level turbulence. Since large horizontal shear of wind is usually found on occasions of strong wind, this is not surprising. It is not certain which is the active factor, shear or wind speed, but it is much easier to visualise a physical connexion between turbulence and shear than between turbulence and wind strength.

Tentatively, therefore, it is to be expected that bumpiness will be a possibility in regions of large horizontal shear. Very strong horizontal shear is found on the boundaries of well marked jet streams, and the same characteristics of a marked maximum of wind speed at a height usually between 30,000 and 40,000 ft. are to be found in connexion with any well marked front in temperate latitudes and moving, to a certain extent, with the front. The axis of the jet or wind maximum is usually some 400 to 700 miles ahead of a warm front and somewhat less than this behind a cold front. These considerations might be used in a first tentative attempt to forecast bumps at high altitude.

An important point which seems quite well established from the data so far analysed is that bumpiness frequently occurs at or just above the tropopause. Usually it is very slight in magnitude, but not always so (the Meteorological Research Flight has on two occasions encountered quite rough conditions there). Turbulence has also been observed at and in temperature inversions in the upper troposphere. It is puzzling to find this turbulence in conditions which are very stable statically and it is difficult to conceive of vertical turbulent currents in such stable layers. The suggestion is therefore made that the bumps experienced by an aircraft in such turbulence are not caused by vertical eddy currents, but by turbulent variations in the horizontal wind. Mr. Morris of the Royal Aircraft Establishment (R.A.E.), however, says that other evidence indicates that variations in the horizontal wind are unlikely to cause anything more than very slight bumps, and that the effect of such turbulence would decrease with increasing speed of the aircraft.

In conclusion, horizontal shear of wind is so far the only physical quantity which shows a direct connexion with the occurrence of bumps. It is likely, however, that the complete answer to the problem will be found to depend on wind shear in the vertical and in the horizontal, linked with the thermal stratification of the atmosphere, both in the vertical and in the horizontal. With the British European Airways' experimental flights continuing and valuable data being collected from R.A.F. flights, it is hoped that much more progress can be made towards the solution of the problem.

Mr. R. F. Jones opened the section of the discussion dealing with turbulence in cloud by emphasising that the investigations into this subject so far made had been confined to turbulence in cumulus and cumulonimbus clouds.

He then indicated how the work being done at the Meteorological Office radar station at East Hill was being used to investigate the problem. It is possible to distinguish, on the radar display tubes, the weather echoes from shower clouds and thunderstorms from those caused by other types of precipitation and it was therefore worth-while to investigate the possibility of using the radar characteristics of a cloud in relation to turbulence as a substitute for the visual characteristics which have been used in the past. The radar has the advantage over visual aids that it is unaffected by darkness or the presence of intervening clouds.

The radar echo from a cumulonimbus cloud does not come from the whole cloud but only from that part of the cloud which contains drops in sufficient numbers and of a large enough size. The radar echo from one raindrop is equivalent to that from millions of cloud particles. It was necessary therefore to attempt to establish whether the radar echo was the most turbulent portion of the cloud and, if so, whether there were any characteristics of the weather echo which would give an indication of the degree of turbulence to be expected and the places within the echo where the turbulence would be expected to be most marked.

Arrangements were made for a Spitfire aircraft to investigate weather echoes under direction by radio-telephone from East Hill. The Spitfire carried a recording accelerometer and was so directed that it flew always along the line of the radar beam from East Hill, with the result that a vertical cross section of the weather echo was obtained at the same time as the aircraft flew through the echo. Photographs of the radar echo were taken and accurate notes of the time of entry into and departure from cloud and weather echo were made. The readings and photographs taken at East Hill are being compared with the analysed accelerometer records. This analysis is still going on and any results given are to be regarded as tentative only and subject to revision or modification.

A total of 136 separate flights through cumulus and cumulonimbus clouds had been made involving a distance flown in cloud of some 700 miles. The magnitude and frequency of bumps encountered on each of these flights have been measured and provide a large amount of interesting data.

In dealing with these data two approaches are being made: (i) statistical, and (ii) a detailed examination of particular flights through an echo.

Mr. Jones dealt first with the statistical approach. A slide was shown which indicated that, in general terms, the higher the echo extended above the freezing level the greater was the value of the maximum up-gust likely to be recorded on flying through the cloud containing the echo. A similar analysis for down-gusts, however, showed that, for a large range of vertical extent of the echo, the maximum down-gust appeared to be independent of the vertical extent and only in clouds containing the very biggest echoes was a down-gust experienced greater than those experienced in cumulus clouds giving no echo at all.

A second statistical investigation showed the frequency with which gusts of specified magnitude were likely to occur, and a significant increase in frequency was shown to occur when the flights were made through clouds containing echoes which extended 9,000 ft. or more above the freezing level.

Although the Americans, working on a much greater volume of data, had indicated a zone of maximum turbulence at the freezing level it had not been possible to discover any such zone in the data provided by the Spitfire flights. The American flights, however, had never exceeded the freezing level by more than about 9,000 ft., while the biggest gust during all flights by the Spitfire was experienced at 30,000 ft., almost 20,000 ft. above the freezing level. There was no obvious evidence of a zone of minimum turbulence, although in the level 2,000 to 4,000 ft. above the freezing level no gust greater than $\pm 0{\cdot}7g$ had been encountered, this value having been exceeded at all other height intervals.

Mr. Jones then turned to a discussion of the detailed examinations made of individual flights through a weather echo. He again stressed the fact that examination was by no means complete but indicated a few tentative conclusions reached.

(i) A large bump was usually associated with entry into the sharp vertical edge of a column of weather echo. This was interpreted by the suggestion that a column of echo represents the occurrence within the cloud of a strong upward current.

(ii) The places of maximum turbulence within an echo are associated with the edges of marked columns within the echo and with the troughs between them.

(iii) Even the most turbulent clouds contained quite calm patches which extended at times over 3,000–4,000 yd.

(iv) Echoes with a diffuse or level top frequently give a fairly smooth flight even though marked bumps may occur on entry and departure.

(v) An echo which is showing signs of decay and particularly if it is developing a bright band near the freezing level is generally smooth.

(vi) A column of echo which is still growing is turbulent with a preponderance of up-gusts.

(vii) Large gusts, especially down-gusts, do occur outside the weather echo, but it is probable that the very large gusts, greater than $1g$, occur only in clouds which give echo columns extending to great heights and probably in the edges of those columns or the troughs between them.

Mr. Jones indicated the possibility of the application of his results to the detection of cumulonimbus embedded in frontal layer clouds and concluded with a tribute to the pilots of the Spitfires from the Aero Flight, Farnborough, who had been engaged on this work.

The Director welcomed the visitors from the Ministry of Supply, British European Airways, and other places, and invited them to take part in the general discussion which would follow. He expressed the appreciation of all meteorologists for the R.A.E. pilots who flew into cumulonimbus.

Dr. Hislop (B.E.A.) said that the special flights which B.E.A. were making were to investigate high-level bumps from the point of view of passenger comfort. In their investigation they did not make a special analysis unless the accelerations exceeded $0{\cdot}2g$. He pointed out that, according to a diagram shown earlier, wind shear in the vertical was large beneath a jet stream and asked if this was not as important as the strong horizontal shear at the sides of the jet. He suggested that waves on the tropopause " breaking " and becoming turbulent, might explain observed bumps there.

Mr. D. E. Morris (R.A.E.), in thanking the Director for the appreciation of the work of R.A.E. pilots, said the hazards of hail had been found greater than those of turbulence in this work. Hail, though infrequent, had seriously damaged the aircraft. He did not think the character of bumps changed from high to low altitudes; clear-air turbulence occurred even below 10,000 ft. He had not noticed any great regularity in the bumps. Regarding " horizontal eddies " he did not think they would be important as a cause of bumps ; observations of indicated air speed at low altitude had shown that the turbulent variations were of the same order of magnitude as the vertical turbulent velocities, deduced from accelerometer recordings, and these variations in the horizontal wind were quite incapable of causing the bumps observed. R.A.E. pilots had not noticed any large fluctuations in air speed in the turbulence experienced at high altitude.

More recent flights from R.A.E. have shown a higher frequency of occurrence of turbulence in the stratosphere than the early flights but again no significant maximum at the tropopause. Though they had recently been seeking conditions in the upper air associated with well marked fronts, they had not found such conditions particularly bumpy. He asked if there was any evidence that the turbulence noted persisted, or did it soon die away.

Dr. Goldie thought that perhaps our observations were incapable of detecting large wind shear in the vertical. When there is shear in the horizontal there must also be shear in the vertical. He said that when the product of density and wind speed is plotted against height, a very sharp decrease is found just above the tropopause, on the average, indicating unusually large shear there and this may explain the turbulence often noted at the tropopause.

Dr. Frith also said that high-level bumps were no different from those at low levels and compared the former to those experienced on a windy day flying at 2,000 ft. He suggested that though bumps are often found in a shallow layer, this layer may be found to vary quite rapidly within a much deeper layer. He drew attention to three sizes of turbulent eddies noticeable in an aircraft; first those some 100 ft. across which give bumps, then those some 2–3 miles in diameter and finally those about 20–30 miles in size, the latter two showing up in the fluctuations of temperature and humidity. He had observed bumpiness to persist for two hours though the bumpy patch appeared to move slightly relative to the air. Mr. Goody of Cambridge had suggested to him that the bumpiness associated with the tropopause might be linked with the radiational heating of the stratosphere spreading downwards and gradually lowering the tropopause surface. He thought that horizontal eddies could not be ruled out as an explanation of some of the bumpiness experienced. He asked if hail was encountered in cloud giving an echo at a height well above the freezing level.

Dr. Stagg pointed out that the extreme conditions found in connexion with marked jet streams made them suitable for meteorological research. Outstanding characteristics, *e.g.* clear-air bumpiness, could be studied in the exaggerated conditions of a jet and general results applied to less extreme cases.

Mr. Sawyer suggested that a study of air movements by means of smoke trails would be of help in determining the nature of eddies which cause bumps. He found great difficulty in understanding how a temperature inversion was not broken down rapidly if vertical eddy velocities were occurring in it and for that reason preferred the idea of horizontal eddy velocities in such circumstances.

Mr. Rowe (B.E.A.) pointed out that bumpy layers were not always shallow. B.E.A. observations indicated that clear-air bumps were of a different nature from those usually found near the ground. Their pilot had described them as giving the sensation of driving a car across a ploughed field. He commented that periodic bumpiness was more serious for aircraft design than irregular shocks.

Mr. Cumming emphasised the magnification of bumps by increased speed of the aircraft, and suggested that meteorologists might soon be asked to forecast bumpy conditions even at high altitude. He also asked if free-air turbulence could cause high-speed aircraft to stall but Mr. Morris replied that this was unlikely.

Mr. Mathewman reminded the meeting of Parr's principle in oceanography, that great stability in the vertical was conducive of turbulence in the horizontal, and suggested that the turbulence in the clear air occurred mainly along isentropic surfaces.

Mr. N. E. Davies, suggested investigating turbulence with a fast and a slow aircraft simultaneously to determine whether the eddy velocities were in the vertical or the horizontal.

Mr. F. E. Coles asked what relation there was between the top of the radar echo and actual cloud top and what was the greatest echo height observed at East Hill, mentioning American reports of echo tops at 65,000 ft. Mr. Coles also drew attention to American reports of a zone of maximum turbulence at the freezing level, and asked if there was any height to be recommended to pilots for flying through a thunderstorm.

Mr. E. Gold thought that probably the effects on an aircraft of horizontal and vertical gusts were indistinguishable and inquired if any relation has been found between high-altitude gusts and the topography beneath.

The Director said that one of the most interesting points was " From where does the supply of energy come to maintain these bumps? " Regarding Mr. Sawyer's query, he understood that the Ministry of Supply proposed to investigate the nature of clear air eddies by means of smoke trails.

Mr. Bannon, in reply, said that there was a large shear of wind in the vertical below a jet stream as well as shear in the horizontal on its sides and suggested this was an additional reason for expecting turbulence near such jets.

Regarding the character of these high-level bumps, he had tried to emphasise the contrast between them and the type of bumps found near the ground on a warm afternoon—dynamic or frictional turbulence as opposed to convectional turbulence. Several R.A.F. pilots had confirmed the impressions of the B.E.A. investigators that this dynamic turbulence gave bumps of some regularity. The persistence of bumpy conditions has been observed for 12–24 hr., in fact, for as long as the particular weather type continued. Whether the turbulence is continuous or takes place as frequent sporadic outbreaks is not known. Regarding the sharp fall off in wind velocity with height above the tropopause, the measurements showing this (radar or radio winds) are of the same type as those used in the analysis of bumpy occasions, so that the same order of magnitude of shear should be detectable in the latter cases, if present.

In reply to Dr. Frith, he found it difficult to understood how heating from above, as suggested by Mr. Goody, could cause turbulence, as this process should be one of stabilization. Regarding Mr. Gold's query, there were insufficient observations as yet, to say whether mountains or other surface effects could be connected with high-level bumpiness. The B.E.A. research flight had found turbulence over Turin, on one occasion, when a N. wind was blowing over the Alps, but wind strength at mountain-top level was only 15–20 kt. as far as could be judged. B.E.A. had also found turbulence over the Scottish Highlands on another occasion.

In reply to Mr. Coles, the highest observed bumpiness (42,000 ft.) occurred above a tropopause at 36,000 ft., about the average height over this country. There is no evidence that bumpiness in the stratosphere is associated with a low tropopause though there are indications that bumpiness in the tropopause region often occurs with a double tropopause.

Mr. Jones, in answer to Dr. Frith, said that hail was reported surprisingly infrequently by the pilots, the most frequent reports of type of precipitation in the echo being rain, even at considerable heights above the freezing level. In reply to Mr. Coles, the greatest echo height observed at East Hill was over 40,000 ft. and there was no doubt that thunderstorm echoes could extend right up to the tropopause. As regards the height to fly through a cumulonimbus, the evidence so far did not warrant recommending any height to a pilot, and the point was strongly emphasised that the successful navigation of a cumulonimbus cloud depended very much on the confidence of the pilot and his handling of the aircraft.

NEWS IN BRIEF

The wedding took place on December 18, 1948, at the Presbyterian Church, Edgware Road, London, of Mr Vander Elst, Director of the Meteorological Service of the Belgian Congo and Miss Patricia Jordan, lately of the International Meteorological Organization Secretariat, Lausanne.

Mr. Vander Elst is well known to many British meteorologists, apart from his present work and international activities, since he served as a Flight Lieutenant in the Meteorological Section, R.A.F.V.R., during the war.

ROYAL METEOROLOGICAL SOCIETY

The Annual General Meeting of the Royal Meteorological Society was held on January 26, 1949, with the President, Dr. G. M. B. Dobson, F.R.S., in the Chair.

The Symons Medal was presented to the eminent Swedish meteorologist Prof. Tor Bergeron, of the University of Uppsala, the first Darton Prize to Mr. F. H. Ludlam for his paper on ice clouds*, and the second Darton Prize to Mr. C. A. Wood for his paper on the meteorology of Borneo†. Sir Robert Watson-Watt, F.R.S., was elected President of the Society for the coming year.

Dr. Dobson delivered his Presidential address on " Ice in the atmosphere ". The address was a comprehensive review of the present state of knowledge of the process of condensation of water vapour at temperatures below freezing point as gained by laboratory experiments followed by an indication of the problems concerned with the application of that knowledge to the atmosphere. Prof. Dobson remarked that our laboratory information was large and concordant but our knowledge on its atmospheric applications was very limited.

After giving some facts on the ratio of and difference between the saturation vapour pressures over plane surfaces of ice and water, Dr. Dobson pointed out that surface tension made an appreciable difference to the vapour pressure over small water drops, and asked what difference there was between the vapour pressure over a large piece of ice and over a small crystal. This question he could not answer, but referred to the recent Guthrie lecture by Sir G. P. Thomson to the Physical Society in which it was shown that the growth of a crystal was an extremely complicated affair with molecules moving about in a concentrated semi-liquid semi-vapour layer till they dropped into their proper niche in the structure.

Dr. Dobson then gave a survey of the historical development of the subject and summed up present knowledge on condensation below freezing point:—

Condensation temperature °A.	
273–263	All nuclei produce water droplets.
263–241	A very few nuclei (the so-called " Findeisen " sublimation nuclei) produce ice crystals at 263°A. and the proportion of nuclei effective in producing ice crystals steadily increases as temperature falls. The crystals form at supersaturation over water. In this range many more water droplets are formed than ice crystals.
241–232	At 241°A. large numbers of nuclei become able to form ice crystals and at 232°A. all form ice suddenly, still at supersaturation over a water surface. Below 210°A. all nuclei become less active in forming ice.

The nuclei which form ice crystals at temperatures above 241°A. appeared to be present only at low levels over land. They were absent over the central oceans, at great heights in the atmosphere, and on high mountains.

*LUDLAM, F. H.; The form of ice clouds. *Quart. J. R. met. Soc., London,* **74**, 1948, p. 39.
†WOOD, C. A.; Report on the weather of the Borneo-Celebes region. *Quart. J. R. met. Soc., London,* **74**, 1948, p. 144.

Other important facts referred to were, that though natural nuclei, except ice crystals themselves, always required supersaturation over a water surface to give condensation, either solid or liquid, ice formed on cadmium-iodide particles at ice saturation, and that no supercooled water droplet has been seen to freeze spontaneously in the laboratory.

Turning to the atmosphere, the lecturer pointed out that Findeisen had found ice particles in cumulus clouds at 259°A. and in stratus at 267°A. while Frith had encountered a pure ice cloud at 253°A. It certainly seemed that ice could form in the atmosphere at a higher temperature than in the laboratory unless we were to suppose that supercooled water droplets in the atmosphere could freeze.

On the question of artificial nucleation of clouds Prof. Dobson thought that it was not very likely to be of importance for rain making, but that it might be possible to transform the droplets of winter anticyclonic stratus into ice particles which would settle out. This would give a bright sunny day instead of a dull one and save electricity and gas.

METEOROLOGICAL OFFICE PUBLICATIONS

The following publication has recently been issued:—

METEOROLOGICAL REPORTS

No. 1. Aviation meteorology of South America

A new series of publications is being made by the Meteorological Office under the general title of Meteorological Reports. The series is designed to make available to the public or special users information which otherwise would exist only in manuscript, or in undigested statistics, but there will be included in this series, a number of papers of this type which would in the past have found a place in Meteorological Office Professional Notes.

The first of these reports deals with the aviation meteorology of South America. Prior to and during the war a number of reports on the meteorology of various countries and air routes were compiled and issued in manifolded form for limited distribution. They were designed to give information on climate and weather in a form which would serve as a book of reference to the aviator and the meteorologist, and the report on South America is no exception. It deals primarily with the air route from Montevideo to Santiago but discusses as a background the general climate of South America and the characteristics of the air masses to which the continent is subject. As appendices general climatological summaries are given for places on the air route as well as tables of the frequencies of visibility and of the height of cloud base.

LETTER TO THE EDITOR

Jet streams

It appears to me that the jet-stream concept is valuable in providing an explanation for the abnormal movements of depressions towards south-south-east which occur in severe winters such as that of 1947. It was a brave fore-caster in those days who predicted that the first of a series of depressions would change its course, as owing to the smoothing of upper air charts there was no rational explanation. The jet stream does, however, stress a known fact, that the isotherms crowd together aloft near a front giving strong winds, and the idea of a narrow but intensely strong air stream quickly transforming the whole pressure field is less crude than that of a depression being diverted by a wall of cold air with which I used to justify my intuition. With upper air data so sparse, isentropic charts, thickness patterns, etc., do on occasions yield real information, but often sympathetic treatment of the data gives these techniques credit actually inherent in the surface chart, the fact being revealed only when the prebaratic breaks down. Given more observations, existing upper air techniques might be as effective as the jet-stream concept, in which I doubt if there is anything new except terminology.

J. W. THOMPSON

Chivenor, February 2, 1949.

NOTES AND NEWS

Navigation through the ages

At the exhibition "Navigation through the Ages" held at the Royal Geographical Society there were a number of meteorological exhibits shown by the Meteorological Office and by British Overseas Airways Corporation.

The Meteorological Office exhibit consisted of a model of an ocean weather ship with photographs showing the purpose of the weather-ship scheme and the work carried out on board and, to show the seaman's voluntary contribution to meteorological knowledge, two logbooks, the first kept in 1857 by Captain Toynbee (a former Marine Superintendent of the Office) and the second a recent one kept on a British "selected" ship. The importance of meteorology to the air navigator was directly illustrated by a specimen flight forecast compiled for a transoceanic flight and exhibited by British Overseas Airways Corporation.

OBITUARY

Mr. Samuel F. Hurnard, who died on January 13, made a noteworthy contribution to British meteorology by maintaining an unbroken record of rainfall at Lexden, near Colchester, over a period of 60 years. Some time ago he wrote: "The observations have been an interesting pastime, the value and enjoyment of which deepen with the passing of decades of years. There are always surprises in store for the rainfall recorder."

WEATHER OF FEBRUARY 1949

An anticyclone which was centred over Scotland on the 1st crossed the North Sea on the 2nd, and was nearly stationary over central Europe until the 8th. Next morning a vigorous depression moved north-eastwards across England. Later in the day a wedge of high pressure began to extend north-eastwards from an anticyclone near the Azores, and by the 15th this had developed into a large anticyclone centred over southern and central Europe. After the 20th a ridge of high pressure lay over the Azores, France and central Europe for several days, and from the 24th to the 28th there was a well developed anticyclone westward of France. As a result of all these anticyclones the tracks of depressions, except on the 9th, lay far to the north-west of the British Isles.

Mean pressure for the month was above 1030 mb. over most of France, and above 1020 mb. over an area which included central and southern Europe, the Mediterranean, the Azores, Bermuda and the western half of the U.S.A. It was above the average from south-west Russia across to the central part of

North America, with an excess of 13 mb. in central and north-west France, and from 10 to 15 mb. below the average from Iceland across to Spitsbergen and Bear Island.

The weather in the British Isles was distinguished by a large excess of sunshine, particularly in England and Wales. It was mild generally, and dry in England and Wales and east Scotland, but wet in the west and north of Scotland.

During the opening days an anticyclone, centred over Scotland on the 1st, moved south-east to Germany. This system maintained mainly fair, sunny weather apart from local fog until the 6th, when some rain fell in western districts.

A change to unsettled conditions occurred on the 7th when a trough associated with a depression west of Ireland moved across England giving general rain. On the 8th a depression near the Azores approached south-west Ireland and on the 9th it moved rapidly north-east across England to Denmark. Rain fell generally on the 8th and showers, wintry locally, on the 9th, while widespread gales prevailed in England and Wales on the 9th. On the 11th and 12th shallow troughs moving east over the country caused rain in most areas. Meanwhile the Azores anticyclone spread north-east and from the 13th to 17th pressure was high in a belt from west of Spain to south-east Europe and mild fair weather prevailed in England. At the same time pressure was low in the far north and troughs of low pressure moving east caused rain in the north; for example, on the 15th, 2·57 in. fell at Ardgour and 2·38 in. at Fort William. From the 18th to 21st troughs of low pressure, associated with deep Atlantic depressions moving north-east, caused some rain, while gales were registered at a few exposed stations in Scotland and north-west Ireland. On the 22nd a vigorous depression approached north-west Scotland from the Atlantic and moved rapidly away east-north-east; widespread gales occurred in Scotland and Ireland and heavy rain in the Lake District, in Teesdale and the Southern Uplands of Scotland (3·20 in. at Borrowdale, 2·46 in. at Thirlmere, 2·46 in. at Hawes Water and 2·23 in. at Middleton-in-Teesdale).

Subsequently high pressure was re-established from the Azores across France to Austria, while pressure continued low to the north of the British Isles. Mild, mainly fair weather occurred over England except in the north-west but unsettled conditions continued further north. On the 28th a deepening depression south-west of Iceland moving south-east to Denmark caused widespread gales.

The duration of bright sunshine in England was very remarkable; at numerous stations scattered over the country it was the sunniest February on record.

The general character of the weather is shown by the following provisional figures:—

	Air Temperature			Rainfall		Sunshine	
	Highest	Lowest	Difference from average daily mean	Percentage of average	No. of days difference from average	Percentage of average	Percentage of possible duration
	°F.	°F.	°F.	%		%	%
England and Wales	59	12	+2·6	60	−5	159	42
Scotland	59	13	+2·4	112	0	119	29
Northern Ireland..	55	24	+2·5	102	0	129	30

RAINFALL OF FEBRUARY 1949

Great Britain and Northern Ireland

County	Station	In.	Per cent of Av.	County	Station	In.	Per cent of Av.
London	Camden Square . .	·93	56	*Glam.*	Cardiff, Penylan . .	2·37	81
Kent	Folkestone, Cherry Gdn.	1·07	53	*Pemb.*	St. Ann's Head . .	1·87	67
,,	Edenbridge, Falconhurst	1·36	62	*Card.*	Aberystwyth	1·40	56
Sussex	Compton, Compton Ho.	1·79	68	*Radnor*	Tyrmynydd	2·92	56
,,	Worthing, Beach Ho.Pk.	1·00	51	*Mont.*	Lake Vyrnwy	3·87	87
Hants	Ventnor, Roy. Nat. Hos.	·96	46	*Mer.*	Blaenau Festiniog . .	5·79	71
,,	Bournemouth	1·28	54	*Carn.*	Llandudno	1·26	65
,,	Sherborne St. John . .	1·35	62	*Angl.*	Llanerchymedd . .	1·49	59
Herts.	Royston, Therfield Rec.	1·28	83	*I. Man.*	Douglas, Borough Cem.	1·81	57
Bucks.	Slough, Upton	1·03	61	*Wigtown*	Port William, Monreith	2·03	66
Oxford	Oxford, Radcliffe . .	1·01	62	*Dumf.*	Dumfries, Crichton R.I.	3·37	103
N'hant.	Wellingboro', Swanspool	·90	56	,,	Eskdalemuir Obsy. . .	6·49	131
Essex	Shoeburyness	·48	39	*Roxb.*	Kelso, Floors	·64	38
Suffolk	Campsea Ashe, High Ho.	1·09	79	*Peebles*	Stobo Castle	3·61	131
,,	Lowestoft Sec. School . .	·95	68	*Berwick*	Marchmont House . .	·92	44
,,	Bury St. Ed., Westley H.	·91	61	*E. Loth.*	North Berwick Res. . .	·54	35
Norfolk	Sandringham Ho. Gdns.	·97	59	*Midl'n.*	Edinburgh, Blackf'd. H.	1·67	101
Wilts.	Bishops Cannings . .	1·41	67	*Lanark*	Hamilton W. W., T'nhill	5·23	180
Dorset	Creech Grange	1·50	52	*Ayr*	Colmonell, Knockdolian	3·55	92
,,	Beaminster, East St. . .	1·80	60	,,	Glen Afton, Ayr San . .	6·77	154
Devon	Teignmouth, Den Gdns.	1·49	56	*Bute*	Rothesay, Ardencraig	5·55	139
,,	Cullompton	1·57	56	*Argyll*	L. Sunart, Glenborrodale	6·44	107
,,	Barnstaple, N. Dev. Ath.	1·26	46	,,	Poltalloch	5·44	126
,,	Okehampton, Uplands	2·58	59	,,	Inveraray Castle . .	10·66	157
Cornwall	Bude School House . .	1·03	41	,,	Islay, Eallabus . .	3·93	94
,,	Penzance, Morrab Gdns.	1·38	41	,,	Tiree	3·44	100
,,	St. Austell, Trevarna . .	2·42	63	*Kinross*	Loch Leven Sluice . .	2·94	104
,,	Scilly, Tresco Abbey . .	1·31	47	*Fife*	Leuchars Airfield . .	1·19	68
Glos.	Cirencester	1·56	69	*Perth*	Loch Dhu	9·83	132
Salop.	Church Stretton . .	1·22	52	,,	Crieff, Strathearn Hyd.	3·41	97
,,	Cheswardine Hall . .	·67	38	,,	Pitlochry, Fincastle . .	2·92	99
Staffs.	Leek, Wall Grange P.S.	1·00	42	*Angus*	Montrose, Sunnyside . .	1·21	66
Worcs.	Malvern, Free Library	·93	52	*Aberd.*	Balmoral Castle Gdns. . .	1·40	54
Warwick	Birmingham, Edgbaston	·77	46	,,	Dyce, Craibstone . .	1·10	48
Leics.	Thornton Reservoir . .	·78	47	,,	Fyvie Castle	1·56	70
Lincs.	Boston, Skirbeck . .	·72	49	*Moray*	Gordon Castle	1·18	61
,,	Skegness, Marine Gdns.	·59	39	*Nairn*	Nairn, Achareidh . .	1·26	78
Notts.	Mansfield, Carr Bank . .	·87	45	*Inv's*	Loch Ness, Foyers . .	5·55	171
Ches.	Bidston Observatory . .	1·10	65	,,	Glenquoich	17·35	168
Lancs.	Manchester, Whit. Park	1·68	87	,,	Fort William, Teviot . .	14·11	188
,,	Stonyhurst College . .	3·26	97	,,	Skye, Duntuilm . .	5·70	124
,,	Blackpool	1·38	62	*R. & C.*	Ullapool	4·97	120
Yorks.	Wakefield, Clarence Pk.	1·05	61	,,	Applecross Gardens . .	6·79	135
,,	Hull, Pearson Park . .	·54	32	,,	Achnashellach	12·19	177
,,	Felixkirk, Mt. St. John	·61	36	,,	Stornoway Airfield . .	5·56	131
,,	York Museum	·62	41	*Suth.*	Lairg	4·68	151
,,	Scarborough	·59	35	,,	Loch More, Achfary . .	9·06	137
,,	Middlesbrough	·44	34	*Caith.*	Wick Airfield	2·09	92
,,	Baldersdale, Hury Res.	3·56	118	*Shetland*	Lerwick Observatory . .	3·53	112
Norl'd.	Newcastle, Leazes Pk. . .	·52	34	*Ferm.*	Crom Castle	3·59	122
,,	Bellingham, High Green	2·30	91	*Armagh*	Armagh Observatory . .	2·51	113
,,	Lilburn Tower Gdns. . .	·74	37	*Down*	Seaforde	1·45	48
Cumb.	Geltsdale	2·47	95	*Antrim*	Aldergrove Airfield . .	1·74	72
,,	Keswick, High Hill . .	5·12	104	,,	Ballymena, Harryville . .	3·04	94
,,	Ravenglass, The Grove	2·39	78	*L'derry*	Garvagh, Moneydig . .	3·02	96
Mon.	Abergavenny Larchfield	1·77	55	,,	Londonderry, Creggan	4·17	131
Glam.	Ystalyfera, Wern House	3·02	59	*Tyrone*	Omagh, Edenfel . .	4·09	137

CLIMATOLOGICAL TABLE FOR THE BRITISH COMMONWEALTH, OCTOBER 1948

Stations	Pressure: Mean of day M.S.L.	Pressure: Diff. from normal	Temperatures: Absolute Max.	Temperatures: Absolute Min.	Temperatures: Mean values Max.	Temperatures: Mean values Min.	Temperatures: Mean values ½ Max. and Min.	Temperatures: Mean values Diff. from normal	Temperatures: Mean values Wet bulb	Relative humidity	Mean cloud amount	Precipitation: Total	Precipitation: Diff. from normal	Precipitation: Days	Bright Sunshine: Daily mean	Bright Sunshine: Percentage of possible
	mb.	mb.	°F.	°F.	°F.	°F.	°F.	°F.	°F.	%	tenths	in.	in.		hr.	%
London, Kew Observatory	1017·9	+3·5	68	27	57·2	43·3	50·3	−0·7	47·8	87	7·8	1·83	−0·87	10	2·9	27
Gibraltar	1017·5	+0·3	83	53	74·3	62·8	68·5	+2·1	64·6	84	5·3	3·20	—	8	7·3	65
Malta	1017·8	+1·8	89	58	78·1	65·7	71·9	+1·0	70·0	80	6·1	5·96	—	6	7·1	63
St. Helena	1017·7	−0·1	67	52	61·8	53·6	57·7	+0·1	54·1	98	9·7	3·42	+1·71	20	—	—
Lungi, Sierra Leone	1012·7	—	89	69	85·8	72·5	79·1	—	74·8	89	7·7	8·89	—	21	—	—
Lagos, Nigeria ..	1012·5	+1·5	92	68	87·8	70·3	79·1	−0·6	76·6	83	8·8	2·18	—	15	6·1	51
Kaduna, Nigeria ..																
Chileka, Nyasaland	1014·6	−0·5	95	62	89·6	67·8	78·7	+0·6	65·9	51	3·0	1·36	+0·30	4	8·3	67
Lusaka, Rhodesia ..	1011·0	−0·1	97	59	88·2	64·1	76·1	−0·2	62·2	50	4·0	5·42	+4·91	7	8·5	69
Salisbury, Rhodesia	1013·8	−0·3	91	52	81·6	59·6	70·6	+0·3	59·1	54	3·4	1·85	+0·70	6	7·8	62
Cape Town	—	—	86	43	69·5	54·2	61·9	+0·7	53·4	63	5·0	1·60	−0·05	10	—	—
Germiston, South Africa	1014·8	−0·2	88	44	76·6	54·5	65·5	0·0	53·3	55	3·5	2·58	+0·91	9	8·8	70
Mauritius																
Calcutta, Alipore Obsy.	1009·5	0·0	94	66	89·7	74·7	82·2	+2·9	76·1	90	3·4	7·00	+2·10	10	7·4	64
Bombay ..	1010·1	+0·3	95	75	88·7	77·2	82·9	+0·5	76·9	86	4·2	2·11	+0·44	6	8·1	69
Madras	1009·8	+0·9	95	72	89·7	75·8	82·7	+0·4	76·5	85	6·3	9·21	−1·94	11	7·5	64
Colombo, Ceylon ..	1010·7	+0·7	88	70	86·4	74·3	80·3	−0·2	74·7	88	6·6	8·97	−4·39	22	7·1	59
Singapore	1009·9	+0·2	91	72	88·7	74·7	81·7	+0·6	76·8	80	7·0	2·63	−5·44	11	—	—
Hongkong	1014·9	+1·2	89	63	81·7	72·5	77·1	+0·2	71·2	76	—	3·13	−1·81	12	6·9	59
Sydney, N.S.W. ..	**1010·8**	**−4·0**	**97**	**47**	**74·4**	**54·7**	**64·5**	**+0·9**	**55·8**	**49**	**3·9**	**0·65**	**−2·20**	**9**	**9·6**	**75**
Melbourne	1010·7	−4·1	86	39	65·3	46·7	56·0	−1·7	50·7	61	7·8	3·58	+0·95	20	4·8	37
Adelaide	1014·8	−1·2	91	42	67·7	49·3	58·5	−3·4	52·6	56	7·0	4·38	+2·64	12	6·8	53
Perth, W. Australia	1018·1	+1·3	89	45	71·1	53·2	62·1	+1·3	57·0	61	5·0	1·84	−0·38	13	8·0	63
Coolgardie	1016·4	+1·5	96	35	79·5	51·1	65·3	+1·6	53·7	45	2·4	0·24	−0·42	2	—	—
Brisbane	1014·5	−1·7	96	53	81·3	60·2	70·7	+0·9	61·5	59	2·4	0·03	−2·50	2	10·2	80
Hobart, Tasmania	1004·6	−5·7	77	36	58·5	43·6	51·1	−3·0	46·8	64	8·1	4·11	+1·85	22	5·1	39
Wellington, N.Z. ..	1008·4	−4·7	67	37	58·6	46·0	52·3	−0·7	49·5	75	8·1	4·43	+0·35	17	5·5	42
Suva, Fiji	1013·3	+0·1	85	70	80·6	73·1	76·9	+1·1	72·6	80	8·2	3·22	−5·07	19	3·6	29
Apia, Samoa ..	1011·4	+0·4	89	71	86·4	73·5	79·9	+0·4	77·0	79	7·1	15·97	+8·80	22	6·9	56
Kingston, Jamaica	1011·9	+0·4	91	72	88·8	74·0	81·4	+0·9	76·1	80	4·8	4·34	−3·12	10	8·6	73
Grenada, W. Indies	—	—	89	71	86·8	75·8	81·3	+1·2	77·7	80	7·8	2·84	−4·92	22	—	—
Toronto																
Winnipeg																
St. John, N.B. ..																
Victoria, B.C. ..																