LARGE-SCALE WEATHER PROCESSES

A SHORT course of three afternoon lectures on "Large-Scale Weather Processes" was given on November 3, 10 and 17 at the Royal Institution, London, by Dr. R. C. Sutcliffe, deputy director (research) of the Meteorological Office. The broad thesis, concerning those parts of the atmosphere, the troposphere and lower stratosphere, which are of primary interest in weather and climate, was first to consider the mean world distributions of temperature and wind as revealed by direct observations, mainly by the methods of radiosonde and radar wind, during very recent years ; then to discuss the large-scale day-to-day variations upon this mean state ; and finally to review the problem of the general circulation of the atmosphere in the light of these results.

Many serious gaps still remain in the world network of upper-air stations. For climatological purposes the northern hemisphere is tolerably well covered, special credit being due to the combined Canadian–United States efforts in the far Canadian North and to the international Ocean Weather Ship scheme of the Atlantic. The wide stretch of the Pacific is relatively poorly charted, but the tropical land areas have many valuable stations, India being notably progressive, as would be expected from its long tradition in meteorological work. The chains in the southern hemisphere, mainly the efforts of South Africa, Australia and New Zealand, still leave large uncharted areas, and the Antarctic is little known. Much hope is placed upon the coming International Geophysical Year to provide answers to outstanding questions on three-dimensional world climate.

The early ideas on the broad troposphere–stratosphere structure have stood up well to recent observations. The mean level of the tropopause near the equator is at about 100 mb. pressure, about 16 km. high, where the temperature averages about $-80°$ C. with an inversion above continuing to the ozonosphere. In middle latitudes the values are about 250 mb., 10 km. and $-60°$ C., and approach 280 mb., 9 km. and $-50°$ C. towards the northern pole during summer. During winter the north polar tropopause is often ill defined, and temperatures at these levels fall to lower values. The earlier model, with a continuous sloping tropopause, has, however, been generally abandoned during recent years, the data pointing to a rather sudden break and lowering from 100 to 200 mb. near lat. 30°. There is also frequently, although not everywhere and invariably, another discontinuous descent with increasing latitude in the neighbourhood of the polar front, although this is a region of large day-to-day variations, and in the northern winter the polar front discontinuity in the tropopause tends often to merge with that at low latitudes. The picture for the southern hemisphere is similar so far as data go, but the mean state in high latitudes is largely conjectural ; temperatures at equal heights are certainly lower and may average $-60°$ C. in summer and $-70°$ C. in winter at the polar tropopause.

The upper-air pressure field can be derived from the surface pressure and the hydrostatic equation, while the equation for the geostrophic wind suffices to give the general pattern of winds except quite near the equator. The limited amount of upper wind data fits well enough into the geostrophic pattern. The most striking features are the jet streams—the more-or-less strong wind maxima reached below the tropopause—and it is now believed that there are two distinct westerly jet streams in each hemisphere associated with the two zones of rapid change or discontinuity in tropopause height. Again, the absence of adequate data makes the picture uncertain, and it is necessary, especially in middle latitudes, to draw the distinction between the climatological mean and the daily synoptic patterns. In the mean the two maxima seem to merge in some longitudes and seasons, whereas the separation can usually be traced on daily charts. The climatological mean maximum wind strength attains a value of 150 knots in certain longitudes in winter, and there seems no doubt that the jet stream structures can, with varying intensity, be traced through all longitudes.

In the study of variability Dr. Sutcliffe confined his attention to middle latitudes. The salient place in theory taken by horizontal wind divergence (in the normal hydrodynamical sense) was stressed by showing its relation with pressure change through the hydrostatic equation ; with vertical motion and adiabatic changes through the equation of continuity ; and with the development of circulations, cyclonic and anticyclonic, through the vorticity equation applied to quasi-horizontal motions on a rotating Earth. This key part played by divergence would indicate an approach to theory through its direct study ; but it is one of the peculiarities of dynamical meteorology that this most interesting quantity is not determinable either from measured winds or geostrophic estimates. A significant divergence for hydrostatic pressure change is less than 1 per cent per day and for vertical motions less than 10 per cent per day. Since winds can be measured, even granted the network, with an accuracy little better than within 10 knots, the divergence over areas of dimensions 100 miles may be directly estimated only within some 10 per cent per hour. The use of the geostrophic wind has long been known to be useless in this respect, as the divergence of momentum vanishes identically, apart from a term due to variation of latitude which is a minor term in dynamical development.

The direct approach through divergence has therefore to be abandoned, at least in extra-tropical latitudes, but the problem has yielded much to an attack resting on the vorticity equation. Vorticity and its changes can be estimated approximately from the geostrophic equation (more recent work aims at using a less-restricted stream function), and the dynamics can be built up from this approach. The simplest, yet still fruitful, attack has come by studying the dynamics of a barotropic atmosphere, virtually non-divergent flow. The justification for meteorological application rests on the smallness of the vertical integral of divergence compared with rates of change of vorticity by advection. In a broad sense the whole troposphere may thus be regarded as moving with a mean field of motion which is almost non-divergent. From this first approximation Rossby derived his now classical barotropic wave equation for idealized zonal flow, which is almost certainly related with the observed long waves of continental dimensions in the circumpolar westerlies.

The two-dimensional solution of the barotropic equation carried out numerically with electronic computing aids and starting with the known initial conditions provides a forecast of the mean flow for twenty-four hours ahead which stands comparison with both the facts and the best efforts of trained forecasters using established methods. Dr. Sutcliffe went on to describe more elaborate dynamical models which take account of divergence and vertical motion and which can therefore handle not only the mean motion but also vertical variations with cyclones and anti-cyclones. It may now be said that a deductive theory of the behaviour of large-scale systems in extra-tropical latitudes can be presented as a straightforward, if still only approximate, development from the hydrodynamical equations. This branch of meteorology has therefore, within the past decade, rather suddenly become almost a matter for formal text-book treatment in the tradition of applied mathematics, and the application of the theory is at present going rapidly ahead towards a new system of forecasting using electronic aids, with the research division of the Meteorological Office at Dunstable making a major contribution. Results so far are definitely encouraging, although in the nature of the physical problem no revolutionary increase in forecasting accuracy can confidently be predicted.

The theory applied to the complex large-amplitude oscillations in the wind flow, coupled with other studies based on perturbation theory, lead to the conception of large-scale instabilities and exponential growth-rates of disturbances as the normal state of the atmosphere, and numerous slides shown by Dr. Sutcliffe, illustrating the surface and upper-air weather maps, made this interpretation seem eminently realistic. The atmosphere is essentially in turbulent motion on the scale of many hundreds of miles, and the evolution of individual turbulent elements is likely to present tremendous, perhaps insuperable, difficulties when the prediction period is extended beyond the time-scale of growth or decay, of the order of one day.

In the final lecture the problem of the general circulation was formulated as that of deriving the mean state and motion of the atmosphere from the basic assumptions of an atmosphere of known composition on the rotating Earth, with land and sea surfaces, subject to solar radiation. At the present time there is no fundamental deductive theory available. Attention was directed to the summer and winter averages of mean-sea-level pressure and the radical differences between them, especially in the northern hemisphere, differences evidently linked with the land and sea distribution and broadly monsoonal in character. This complication is something superposed on a symmetrical planetary circulation, and the first step in a basic theory is naturally to derive the circulation as it would appear on a symmetrical ocean-covered Earth. Evidence, especially from the southern hemisphere, indicates fairly conclusively that the solution must provide for a mean low-pressure belt around the equator, sub-tropical high-pressure belts bounding the easterly trade winds of lower latitudes, broad belts of prevailing unsettled westerlies bounded at high middle latitudes by low mean pressure with relatively high pressure again at the poles, presumably also much disturbed by synoptic systems. Some sort of zonal mean organization is inevitable on a symmetrical Earth, but Dr. Sutcliffe was not prepared to prove that either a smaller or larger number of zones is fundamentally impossible. One must bear in mind that in certain tropical oceans intense cyclones are rather common in low latitudes, and that under rather different conditions the Earth might well have these features regularly, giving two belts of low mean pressure with prevailing westerlies and relatively high pressure at the equator. There is also a frequent, but passing, tendency for a double cyclonic zonal structure to appear in middle and high latitudes. A basic theory should show that the assumed zonal organization is necessary, but perhaps also that an essentially different organization would be found if the values of the fundamental quantities, in particular radiation, were different perhaps only by a little from their present values. Facile qualitative arguments which purport to explain the general circulation are of little value ; quantitative treatment is essential.

Pending the development of such basic theory, meteorologists are devoting their attention to the mechanism of the circulation as it is observed and attempting, with some success, to show by what processes the long-term average state is maintained as a balance between losses and gains. Brief attention was given by Dr. Sutcliffe to the water, energy and zonal momentum accounts. Evaporation and precipitation must balance over a relatively short period of time, for the mean world value is about 90 cm. a year, whereas the air contains no more than the equivalent of about 2·5 cm. of water. The patterns are, however, very dissimilar, with precipitation maxima in low and middle latitudes separated by a precipitation minimum which, over the oceans, is an evaporation maximum. The evidence is that the relatively steady trade winds are the vehicle carrying moisture to the equatorial rains, but that the transport to the middle latitude rain areas comes mainly in bursts of moist tropical air (the warm sectors of depressions), separated by bursts of cold dry air moving towards the equator ; the transport is then a turbulence phenomenon and not a steady flow in a mean meridional current.

Time prevented a detailed consideration of energy balance during the lecture, but attention was directed to the large amount of energy transported as latent heat and to the less well-known contribution from gravitational potential energy. An inflow of air at high levels coupled with an outflow at low levels could have a major effect in increasing the total energy over an area ; the high values of thermal or internal energy over warm anticyclones are really derived from such overturning. The evidence is that a large part of the poleward flux of energy in tropical latitudes which redresses the lack of balance in radiation is carried as gravitational potential energy.

Considerations of zonal angular momentum have received much attention. The long-period balance requires a zero total couple around the polar axis as the result of friction between ground and atmosphere, and this requires a degree of balance between westerly and easterly winds. But taking zones separately, the trade-wind belt with a westward frictional couple exerted on the atmosphere must export westward angular momentum to be returned to the Earth through the friction of the prevailing westerlies. The different zones are thus very closely linked, and one wonders how far forecasting in middle latitudes, which at present takes no explicit account of the trade-wind belt, can be expected to go.

At the present time it is believed that a steady overturning in low latitudes—a meridional convective circulation with ascent near the equator and subsidence towards and in the sub-tropical anticyclones—is an essential link, but that farther northwards the momentum transport (as the moisture transport) is mainly the effect of the unsteady motions, with mean meridional motions playing a minor and perhaps negligible part.

The study of mechanisms, and especially of the relative importance of steady mean circulations and irregular motions, is important if the basic problem is to be formulated in a manner suitable for mathematical attack. It is now thoroughly established that the mean state of the atmosphere cannot be maintained by the mean motions and that the two together do not provide the solution to any real problem. Thus the nature of the turbulence, which is physically different in different zones, must be introduced into the theory at a very early stage: it is not a mere embroidery on a general circulation existing in its own right. It seems probable that the wave-length or scale of unstable synoptic systems which theory shows must develop in the baroclinic atmosphere sets a scale to the zonal mean organization.

The time now seems to be ripe for an attack on the basic problem, and experience with electronic computing for dynamical forecasting in middle latitudes has given to the mere complications of calculating a less formidable appearance. Much progress is almost certain to come during the next decade, and it is urgently required. When one compares the two summers of 1954 and 1955, as experienced in Europe, one is forcibly struck with the fact that the general circulation averaged over a matter of months may run quite differently from one year to the next and so far with no explanation whatever. It seems unlikely that such differences will be understood unless we have a basic theory of the planetary circulation on which to build, and the physical nature of the problem of seasonal weather prediction must for the present remain a mystery.

POPULATION OF BRITISH UNIVERSITIES IN THE 1960's

THE AGE-GROUP BULGE

AT the final session, on the afternoon of December 17, of the 1955 Conference of the Universities of Great Britain and Northern Ireland, the problem of "The Age-group Bulge and its Possible Effect on University Policy" was discussed, with Dr. D. W. Logan (principal, University of London) in the chair. In the opening address, Dr. G. E. F. Chilver (Queen's College, Oxford) defined the problem: at the peak of the bulge (1964–67) there will be at least 7,500 more applicants for university places each year; afterwards there will be a plateau, when the number of applicants will be at least 2,500 more than at present. This is calculated simply on the basis of the extra births in the years from 1944. In addition, there has been a trend towards more pupils aged seventeen years and more remaining at school, the increase since 1951 being 30 per cent in England and Wales and 15 per cent in Scotland. If this trend continues, then the numbers of applicants will be larger than the figures given. However, there are good reasons for believing that the trend is unlikely to operate during the peak of the bulge, though it may well be resumed in the later years.

The more important and tractable problem is that of the plateau. The universities should plan for an expansion of the order of 10–15 per cent in the 1960's, concentrated largely in science and technology. The Ministry of Education has provided places in secondary grammar schools to accommodate the extra children during the bulge, and there are signs that enough specialist teachers are coming forward for sixth-form work. The provision of additional university teachers is not so easily envisaged, since they must be found before the extra graduates are forthcoming; this is particularly so in science faculties, where the teachers will need to be withdrawn from other jobs. Capital development, to be in time to make the expansion possible, must take place earlier; it must be provided in the next quinquennium (1957–62). As regards the peak of the bulge, it may be unprofitable to speculate now, provided that planning proceeds for dealing adequately with the level of the plateau.

Exceptional difficulties are to be expected at Oxford and Cambridge, where it is unlikely that the expansion can be large, whatever may be desirable. This is a matter of fact, based on current views in the older universities, and is not a personal opinion. A major factor here is the existing system of college (as opposed to university) finance, the colleges not being directly in receipt of grants from the University Grants Committee. In any event, expansion in a city like Oxford is difficult, population growth being limited and college sites being too small for much further building. It is generally felt that, in view of their structure, colleges are reaching their maximum size. At the peak of the bulge, it is unlikely that Oxford and Cambridge will dilute their tutorial system to the extent tolerated after the Second World War; they are almost bound to raise their entrance standards.

In the second address, Prof. R. G. D. Allen (London School of Economics and Political Science) supported the contention that the problems of the plateau are more important than those of the peak of the bulge. He thought that 2,500 is a low estimate of the extra numbers the universities must soon absorb each year. Certainly a smaller figure would only arise if universities were to impose higher entrance standards or the economic climate in Great Britain deteriorate. The appropriate employment of 2,500 or so extra graduates a year raises special problems, but there can be no doubts about a ready market for scientists and technologists; for arts graduates also, even those with pass or general degrees, there are clear signs that there is an expanding market for their services, for example, in the Civil Service and local government, in banks and insurance offices. The likely recurrent cost of the expansion is not great—£3 million added to grants by the University Grants Committee and £2 million to maintenance awards—but the cost in capital grants is likely to be high and needs to be incurred early, particularly since much of the expansion must be in science and technology.

As regards the peak of the bulge (1964–67), the university population may well rise to more than