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The development of the Meteorological Office new operational forecasting system

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Summary

During the ten years since the 10-level model was brought into use for operational weather forecasting there have been considerable advances in automatic and remote sensing techniques as well as in theoretical aspects of numerical weather prediction. With the acquisition of a CYBER 205 computer, the Meteorological Office is now able to update and improve its data analysis and forecasting methods to take advantage of new sources of observational data and to increase the accuracy and scope of the services it provides to customers. An outline is given of the background to new developments in the subject followed by a description of the main features of the forecast system that will replace the present operational 10-level model in the latter part of 1982.

Introduction

It is perhaps surprising that weather forecasting, an apparently inexact skill, was one of the first practical applications of computers. Indeed, the principles underlying their use for such purposes were established during the First World War, and published shortly after it by L. F. Richardson (1922), a remarkable British mathematician who spent several years working in the Meteorological Office.

Richardson's essential contribution was to set down weather forecasting as a problem in classical physics and to indicate how the resulting equations could be solved by numerical techniques. At that time the conventional method of weather forecasting was based on experience and history. Depressions and anticyclones were followed and their movements extrapolated or predicted on the basis of historical precedents, but this was done without a clear conception of what caused the motion or, indeed, why depressions and anticyclones formed in the first place. Richardson's proposal was to change these inexact, qualitative methods for quantitative techniques based on the established laws of physics. The mathematical problem was formidable. The atmosphere was to be represented by the values of variables (i.e. temperature, pressure, wind, humidity) on a three-dimensional mesh of points with a horizontal separation of 400 km and a vertical separation of about 200 mb. The equations of motion, thermodynamics and conservation of matter could then be written in a form that enabled the changes taking place at a particular mesh point to be calculated from the values at surrounding mesh points. The changes could be added to the initial values to find the expected state of the atmosphere a short time later. The calculations then had to be repeated so that the 'forecast' could be stepped forward towards the time for which it was required. The calculations when carried out by hand were so laborious that Richardson was employed for many hours in evaluating a 6-hour forecast for a single point on the earth's surface. The pressure change he calculated (145 mb in 6 hours) was completely unrealistic, and his failure seemed to put paid to attempts to make weather forecasting more quantitative.

Richardson's work on weather forecasting was carried out at least a quarter of a century before electronic computers were developed. When they were, the possibility of using them in weather prediction was recognized by the distinguished American mathematician J. von Neumann. He collected together a group of talented young scientists to work on the problem and so exploit the potential for more accurate weather forecasts which seemed to be opening up. Some of those involved, for example Professors J. G. Charney and J. Smagorinsky, were to be among the most outstanding and influential dynamical meteorologists of our day. From these beginnings stemmed developments which, over the last three decades, have revolutionized the science and practice of weather forecasting.

Within the United Kingdom similar but independent research on the quantitative description of atmospheric changes was going on, the outstanding names being those of Dr E. T. Eady who worked within the Meteorological Office during the Second World War but, after it, left to become a member of the distinguished group of meteorologists who constituted the Meteorological Department at Imperial College, London, and Dr R. C. Sutcliffe whose paper in the *Quarterly Journal of the Royal Meteorological Society* in 1947 was the mainspring of developments in dynamical meteorology within the Office for more than a decade. The first models which were used in the Office for research into forecasting by computer methods owed their derivation directly to Sutcliffe's work.

An important element in the researches of that time, which was crucial to the practical application of computers in forecasting, was the elucidation of the main reason why Richardson's initial attempt at forecasting produced such a poor result. Essentially it was that the meteorological observations on which his forecast was based were used in a 'raw' form. In general, measurements made in the atmosphere are influenced by the effects of motion due to meteorological phenomena of many different scales, for example by the motion created by individual clouds or by narrow frontal systems as well as by the depressions and anticyclones, the larger features which the forecasters were hoping to deal with. The motions associated with the features Richardson was hoping to forecast were being seriously contaminated by those caused by much smaller, short-lived features which could not be represented by grid points 400 km apart. This led to the concept of adjusting the initial analyses so that they represented only that part of the wind and temperature field associated with the large systems, and of 'filtering' the equations which formed the atmospheric model to ensure that they did not give rise to unrealistic small-scale motions. When these new ideas were incorporated into the models, the difficulties experienced by Richardson were removed.

The first model used by the Meteorological Office to produce numerical forecasts operationally was a 'filtered' model which had three levels in the vertical where the calculations were carried out and where results were available to the forecasters, and a horizontal mesh with nodes positioned about 300 km apart. The event which enabled this model to be used in providing information directly to the forecaster quickly enough to influence the forecasts issued to the public, was the replacement of the first Office computer, a Ferranti Mercury, by the faster English Electric Leo KDF9. This operational system provided the guidance for Meteorological Office forecasts for seven years, a period during which the products came to be recognized and regarded as the most important information available for forecasting the weather for 24 hours to 36 hours over the British Isles.

However, even before the system became operational, research was indicating rather clearly that the use of filtered equations to suppress extraneous motions sometimes prevented the models from indicating atmospheric developments realistically. The constraints imposed by the filtering could be harmful, and furthermore they were shown to be not strictly necessary. It was discovered that filtering could be replaced by much less restrictive methods and, in effect, one could return to techniques much closer to those introduced by Richardson, provided care was taken to ensure that the initial conditions were still tailored to eliminate certain types of motion not of meteorological interest. If the initial data for a forecast were of the right kind, then, with reasonable care in the numerical techniques, the representations of atmospheric motion remained realistic when the equations were integrated forward in time to obtain a forecast. The new models which then became possible were termed 'primitive equation' as opposed to 'filtered' models and their power was rapidly demonstrated when they were applied to forecasting real conditions. In particular, they could forecast not only the wind field but the rainfall and cloudiness, features which presented enormous difficulties to the earlier models. Furthermore, since they were more general, they had the potential to represent smaller-scale aspects of the meteorological situation, for example frontal systems which are of such significance in the rainfall of this country.

In the Meteorological Office, research aimed at exploiting 'primitive equation' models, particularly to investigate the processes occurring within fronts, was initiated in the early 1960s by J. S. Sawyer. It led to the development by F. H. Bushby of a new model with 10 levels in the vertical and a horizontal mesh length of 100 km (Bushby and Timpson 1967). The first situation on which it was tested was 1 December 1961, when a shallow trough some 500 km west of Ireland developed rapidly to become an active depression and deposited large amounts of rain on southern England as it ran quickly eastwards. The conventional forecast on this occasion was not particularly successful, but the new model predicted the deepening of the depression, its eastward movement and the rainfall very well. The promise of this model was such that when the opportunity arose in 1972, through the replacement of the KDF9 computer by an IBM 360/195, to improve the Meteorological Office numerical weather forecasting system a version of it was chosen as the basis for future operational guidance. Since that time the basic operational system has been essentially unchanged, though of course minor changes have been made from time to time as investigations indicated them to be desirable. At the present time, the 10-level model with a 300 km horizontal mesh length covering most of the northern hemisphere is used twice a day to provide the forecasts for aviation and the basis for forecasts to the general public. In addition, a 'fine-mesh' version of the model covering Europe and the Atlantic is used very soon after the standard observations are received, to provide preliminary guidance and to give more detailed forecasts for the British Isles, including estimates of precipitation. One of the most significant improvements that has been achieved by using this model is that it has been possible to extend the period over which numerical predictions provide guidance from about 48 hours at most with the 3-level filtered model to more than twice this length of time. The model now provides forecasts to six days regularly, and the results are useful on most occasions. It is as a result of the improved ranges to which numerical predictions can now be pushed that the European Centre for Medium Range Weather Forecasting was established with the aim of extending the period to ten days at least. In the future, therefore, the Meteorological Office will be concentrating on the early part of the range, about one to four days, leaving the later period to be dealt with by the Centre.

Despite the success of the 10-level model, the desirability of changes on a more fundamental scale than have been undertaken in the last decade has become clear. Twenty years since its initial conception and nine years since its introduction into operational use, the model continues to provide forecasts comparable with any produced elsewhere. Indeed, if account is taken of the relatively small amount of computer time it consumes and of the rapidity with which observations are processed and used to provide guidance to weather forecasters, the system as a whole is probably the most effective in the world. Nevertheless, improvements are now desirable, particularly to take account of two new factors. First, forecasts are required for larger areas of the globe and to greater heights in the atmosphere; and second, changes in the meteorological observing network call for different methods of analysis, involving the use of the model itself to derive the best starting point for a numerical forecast. In addition, some aspects of the model need to be redesigned to derive maximum benefit from recent developments in representing atmospheric processes. In the following sections the research on the design of aspects of the new model and the changes in the observing network and analysis techniques are discussed. In the final section the operational system now being developed is described and an example of its performance presented.

Research leading to the design of the next operational model

The atmosphere contains motions on all possible scales. Eddies form downstream of stones, blades of grass, telegraph wires and trees; winds swirl around buildings, sometimes forming intense gusts or vortices; the shimmering seen on hot summer days is caused by hot pockets of air rising from heated surfaces; individual clouds range from the very small to thunderstorms which may be 10 km across and occupy the whole depth of the troposphere. Beyond these systems come the fronts associated with the travelling depressions and anticyclones of middle latitudes which are largely responsible for the variable weather experienced in the British Isles.

The effect of small-scale motions (which are not represented on the model's mesh of points) on the larger-scales (which are) is a very important factor in the improvement of weather forecasts and has been the subject of much research.

In its early stages, numerical forecasting concentrated on the dynamics of the largest scales; the mesh sizes used aimed to deal with features on a scale of 2000 km and upwards adequately, as this included the most commonly observed cyclones and the long waves which tend to control their movement. They were treated almost independently of smaller-scale motions, though it was recognized that on many occasions the latter's influence in modifying the main systems could be significant. This is particularly obvious on some summer days when thunderstorms originating over northern France and moving northwards can transform the large-scale situation; or in winter-time when cold Arctic airstreams reaching Britain from the north are warmed and modified as a result of small-scale heating from the surface by travelling over relatively warm seas. On a slightly longer time-scale, it is necessary to include the effects of small-scale motions in maintaining the vigour of the larger systems because it is generally through them that the energy of the atmosphere is destroyed and replenished. Friction at the earth's surface caused by roughness such as waves on the sea surface, trees and buildings destroys energy at a rate which, it is estimated, would bring the atmosphere to rest in about 10–14 days if it were maintained. That energy has to be replaced by energy created largely as a result of differential heating, and therefore, for consistency, if the terms representing the slowing down of the large-scale motions by friction are to be included (as they must be to forecast, for example, the decaying stage of a depression's life-cycle), then so must also the differential heating between the tropics and higher latitudes, between land and sea, and between cloudy and cloud-free areas. Most of the heat rises from the earth's surface in small-scale turbulence and is then carried through the depth of the troposphere in cumulus clouds. These effects clearly should be represented in numerical forecasting models.

It is of course out of the question to create a general-purpose model capable of representing all the important atmospheric motions at the same time. Two fairly obvious things can be done. Firstly the mesh spacing can be reduced so that a larger span of motions can be described adequately in explicit terms. Thus the spacing in the first numerical models was commonly 400–500 km, and this has been reduced progressively to 250 km or less, with even finer mesh models over restricted areas to try to capture the detail required. However, as the mesh is made finer, the computing time for a forecast increases; if only the horizontal distance between nodes is halved, the time is increased by a factor of eight, and clearly therefore there is a limit to how far it is profitable to go in this direction. Secondly, one can parametrize (i.e. represent statistically) the effects of the smaller-scale motions in terms of the average values which the model can be assumed to represent; for example, the energy extracted from the wind over a given surface by turbulence can be estimated in terms of the average wind speed over the area. Fortunately, investigations of turbulent motions in the atmosphere have indicated that the more important small-scale phenomena are controlled by the structure of the atmosphere on larger scales together with the character of the underlying surface of the earth, and observations of clouds have shown that they can often be related to the buoyancy characteristics of the airstream in which they occur.

Research aimed at providing adequate parametrizations of the effects of small-scale motions has been a major preoccupation of meteorological research since at least the mid-1960s. It remains an area in which understanding is partial and patchy and from which therefore we can expect research to continue to improve numerical forecasting in the future.

Broadly speaking, the parametrization problem can be split into three:

(1) the interaction between the atmosphere and the earth's surface;
(2) the transfer of heat, water and momentum vertically through the depth of the atmosphere, mainly as a result of buoyancy effects; and
(3) the interaction between the atmosphere and radiation, including the effects of clouds on both short- and long-wave radiation.

The interaction between the atmosphere and the earth depends on the characteristics of the surface—its temperature, roughness and wetness, for example—and also on the lowest atmospheric layers, particularly the wind strength, and whether they are stably or unstably stratified. As the boundary layer, in which the effects on the atmosphere due to the proximity of the earth are appreciable, is usually around 1000 m deep ($\approx$ 100 mb near sea level) and the present operational model has levels 100 mb apart, it is clearly not possible in the model to represent the detailed variation of atmospheric properties close to the ground. The scheme now used to calculate the effects of interaction between the earth and atmosphere has been tailored to these constraints. It was devised by A. J. Gadd and J. F. Keers (1970). Over the oceans, which do not respond significantly to the diurnal variation of solar radiation, a number of simplifications are possible, and therefore the problems to be dealt with are best illustrated by considering the situation over a land surface. The surface temperature responds to the receipt of solar radiation, and there are resultant changes in heating rates, frictional drag, evaporation and cloudiness in the boundary layer. The fractional transmission of solar radiation through the atmosphere depends primarily on the cloud that is present, and in order to find its value an estimate of cloudiness is required. It is deduced from the relative humidity values at grid points. Gadd and Keers then estimate the surface radiation loss using published observations relevant to the cloudiness conditions indicated by the model. The net surface radiation resulting from these calculations is partitioned into heat stored in the ground and sensible and latent heat exchanges with the air, taking account of the wetness of the surface as indicated by climatological data. These exchanges are used in determining the resultant atmospheric changes. It is to be noted that, in this process, surface temperature is not determined explicitly, nor does the stability of the lower atmosphere influence the calculation. For these reasons, among others, the method is limited in its accuracy, and not only the facilities available but the basic understanding have now advanced to the point where it is possible to implement procedures which are capable of calculating the exchanges in a more adequate way.

The new model will have a better resolution in the boundary layer so that stability can be taken into account in the calculation, and surface temperature will be found explicitly, enabling the atmospheric structure near the ground to be inferred more precisely. These changes are desirable on scientific grounds, as they will permit a more realistic simulation of the atmosphere by the model, but they are required in a more direct sense to provide the more detailed information about conditions in the boundary layer that are needed to meet many wide-ranging demands for forecasts. The methods to be implemented in the new model are possible because of a large amount of observational and theoretical research carried out at a number of centres over the globe, but depend particularly on parametrization studies in the Dynamical Climatology Branch. The interaction of the atmosphere with the underlying surface is crucial to an understanding of the physical basis of climate, and investigations concerned primarily with setting up climate models have clarified a number of aspects which have direct relevance also to forecast models.

The surface temperature, and conditions in the atmosphere immediately above, control numerous meteorological processes of direct interest to the forecaster. The accumulation and melting of snow, the rate of cooling at night, frost and the formation and dissipation of fog are obvious examples. As already pointed out, such processes eventually influence the behaviour of the atmosphere on large space-scales and there should therefore be an improvement in the general standard of the forecasts from these measures. The use of the new boundary-layer and surface-exchange parametrization will enable more realistic assumptions to be made about other aspects of the boundary layer. The intensity of the low-level turbulence can be expressed in terms of the low-level wind shear and stability, the infra-red radiative loss will be determined with its appropriate temperature and humidity dependence, and snow predicted by the model will be accumulated or melted according to the calculated values of the surface temperature. Evaporation from the earth's surface will be dependent on the surface wetness, determined from the forecast accumulation of rain reaching the surface, with allowance for percolation into the soil. These parametrizations have already been tested in general circulation models where the validity of the schemes can be assessed from the realism of the climatological simulations. Empirical constants which necessarily appear when particular processes are simplified in a fairly gross way can be chosen to give optimum results on the basis of the calculated climatological distributions of relevant parameters.

Turning to levels above the boundary layer, in which vertical transfer of heat, water vapour and momentum is effected mainly by motions on the scale of individual clouds, a different kind of parametrization is required. Surface heating during the day sets off convection currents which carry the heat up through the atmosphere. The depth of the layer through which it is carried grows as the warm air gradually penetrates and mixes with more stable air at higher levels. In some atmospheric conditions the latent heat released when water vapour condenses to form cumulus clouds capping the convective currents is sufficient to increase their buoyancy to such an extent that the currents accelerate upwards to form rain-shower clouds rising to heights comparable with the depth of the troposphere.

The earliest attempts to represent convective processes in numerical models were based on an examination of the vertical profiles of temperature within the model for buoyant instability and readjusting the atmospheric heat distribution to a neutral or stable configuration. A scheme of this kind was used for some time in the 10-level model. However, the procedure takes little or no account of the actual structure of convective motion as observed. For example, it makes no attempt to represent the direct transfer of heat from the surface to high levels on occasions of vigorous convection. It is not possible to build into it an adequate representation of the vertical transfers of heat, water vapour and momentum nor of the formation of convective clouds and rainfall. Other more elaborate conceptual models have been devised and they permit more realistic representations of such processes.

The current operational model makes use of a parametrization scheme which rests on the supposition that deep convective clouds are initiated and sustained by an input of moisture at low levels concentrated by convergence of the large-scale surface wind field (Hayes 1977). Although such a mechanism is important for some forms of convection (for example within frontal zones), it does not appear to account satisfactorily for other types of deep convection. For example, during the summer months, instability at mid-tropospheric levels is responsible for initiating the growths of cumulonimbus clouds over northern France. They then move northwards across England and Wales, sometimes producing intense hail and thunder, and are maintained for several hours by moisture drawn in at low level by ascent within the storms themselves rather than by large-scale convergence. An alternative scheme for representing deep convection in models was developed by W. H. Lyne and P. R. Rowntree (1976), working in the Meteorological Office Tropical Group in connection with the GARP Atlantic Tropical Experiment (GATE). One of the main aims of GATE (see the *Meteorological Office Annual Report 1978* for an account of the Meteorological Office's participation in the Experiment, pages 78–85, but especially page 83) was to provide research scientists working in this area with high-quality observations to test the adequacy of proposed parametrizations. In the parametrizations developed in the Office the column of air above each ground-surface grid point is examined for convective instability by determining whether air with a small amount of excess buoyancy relative to its surroundings would remain buoyant if it rose from one level to the next, thus simulating the observed tendency for convection to be initiated by warm bubbles or plumes of air. In this stability assessment, due account is taken of mixing between the rising parcel of air and the surrounding atmosphere and also of the latent heat released as water vapour condenses into liquid water during cloud formation. The liquid water is assumed to fall to the ground as convective rainfall, though allowance is made for some evaporation of the raindrops to take place at intermediate unsaturated levels before they reach the earth's surface. The heating of the large-scale environmental air within which the convective plumes are forming is assumed to arise mainly from subsidence which compensates for the upward mass transfer of the rising buoyant air parcels. Extensive tests of this scheme in tropical forecasts, made and verified using GATE data, showed that it gave appreciably more accurate indications of the amounts and distributions of convective rainfall than simpler methods.

The third area requiring parametrization is the effect of radiation and cloud. Spatially varying radiative exchanges create horizontal and vertical temperature gradients, and air motions are then generated which redistribute the heat. Potential energy lost through the lowering of the centre of gravity of the atmosphere reappears as the kinetic energy of air motion. Such effects are fundamental to the atmospheric circulation both on planetary and local scales. Changes in the average temperature of the atmosphere as a whole have a less immediate impact on the weather.

Two kinds of radiation need to be considered, namely short-wave radiation reaching the earth from the sun and long-wave heat radiation emitted by the surface and the atmosphere.

Apart from the absorption of ultra-violet radiation by ozone in the stratosphere, atmospheric gases are largely transparent to solar radiation, and the main factor determining the amount reaching the earth's surface is cloudiness. Clouds are generally highly reflective to short-wave radiation and therefore they can reduce the heat input to the earth-atmosphere system very substantially. The main difficulty which arises in introducing this effect realistically into numerical models is that clouds are extremely variable in space and time, and in many circumstances there is no clear relation between the amount of cloud and the large-scale variables. Thus, many extensive cloud sheets which reflect a large proportion of the incoming radiative energy are much thinner than the vertical separation of levels in a model, and in a region of mixed cloudy and clear conditions there may be many individual clouds of varying depth and opacity within a single grid area. In these circumstances the 'best' parametrization cannot be derived directly from observations as it will depend on the structure of the model: for example, on the horizontal and vertical grid-spacing, on the parametrizations of other quantities and on the finite difference approximations used in dealing with water vapour. Methods which have been tested and shown to give reasonable results in other Meteorological Office models enable the amount and the depth of cloud to be related not only to the relative humidity, the obvious parameter, but to the vertical velocity and the vertical gradients of temperature and humidity. Such methods are being tested in the new model, but it seems clear that the best parametrization will only be decided after a period of operational testing.

The interaction of infra-red radiation with clouds is also important; they trap radiation leaving the earth's surface, and the radiative cooling from cloud tops can lead to the intensification of convective motion within the clouds. The passage of infra-red radiation through the clear atmosphere is also a fairly complex process involving the radiatively active gases, viz. water vapour, carbon dioxide and ozone. While the most significant aspects of infra-red radiative interchanges are, broadly, understood and computer programs are available to calculate them accurately, the particular techniques which work best and are most efficient depend upon the characteristics of the numerical forecasting model and on the specific purposes for which it is used. As with solar radiation and the selection of methods to derive cloudiness, the most appropriate techniques will be selected from the wide range of possibilities available as a result of the experience gained during operational trials.

The meteorological observing network

In the 1950s and 1960s when numerical weather forecasting was being developed into a robust dependable technique, giving predictions of large-scale features of the atmosphere at first comparable with, but later superior to, those of skilled forecasters, the network of observations on which the predictions depended was well-established and fairly static. Surface conditions were recorded at many stations on land, and from numerous merchant ships usually plying the main routes across the Atlantic and the Pacific. Observations of upper-air conditions were made at a much smaller number of special upper-air stations which released balloons carrying the necessary instruments twice a day at 00 and 12 GMT, and sometimes at the intermediate hours 06 and 18 GMT.

For many purposes the network of surface observations was probably adequate over most of the northern hemisphere although, not infrequently, small depressions over the oceans escaped detection, and in tropical regions the network was not established on a secure basis. The problem of the oceanic areas could be serious for countries like Britain lying at the ocean boundary; indeed, some of the worst forecast errors were associated with depressions about which detailed information was lacking at a sufficiently early stage of their development. Nevertheless, the surface situation was very much better than that concerning upper-air observations.

For numerical models the conditions in the upper air are crucial. They calculate how the atmosphere will change, not by following the history of the motions but by interpreting the atmospheric situation at a particular instant, and therefore they require the three-dimensional structure of the atmosphere to be defined accurately if the forecasts are to be correct. Over most of the land surface in the northern hemisphere the upper-air network was quite good but there were large gaps with no observations, and over the oceans the handful of weather ships could not provide all the detail that was desirable.

In analysing the upper-air conditions with such a relatively scattered set of observed values it was essential to make the maximum possible use of the information available, including theoretical relationships, forecasts from an earlier time, and climatological values as well as the observations themselves. In addition, the methods used sought to make optimum use of the known characteristics of the network. Thus the geographical positions of the observing stations were known and they did not vary from day to day; the observations were made synchronously and therefore it was not necessary to deal with off-time values; although radiosondes differed from one country to another, they were measuring essentially the same variables in a similar way and such variations in accuracy and response characteristics as existed could be allowed for straightforwardly; instrumented balloon soundings almost always measured pressure, temperature and humidity (from which, given the surface pressure, the altitude can be deduced), and most of them tracked the balloons carrying the instruments to measure the upper winds, so that winds could almost always be associated with pressures at the same location. The analysis system that derived initial conditions for numerical models was therefore geared to deal with a fixed network of stations, providing data that were generally reliable and accurate. Additionally, because the forecast area was almost entirely confined to extratropical latitudes, the geostrophic relation could be used rather freely to convert wind information into information concerning the gradient of upper-level pressure and vice versa. (Where the geostrophic relation holds, winds can be inferred with acceptable accuracy from pressure charts; for example, the low-pressure systems or depressions which affect the British Isles have winds blowing around them in an anticlockwise direction. However, in the tropics the relationship is no longer strong and fields of wind and pressure need not be closely connected.) Though the mathematical problem of analysis was difficult because the maximum amount of information had to be extracted, and there was little redundancy in the system to check the results, it could nevertheless be specified in considerable detail and satisfactory methods for solving the problems were developed fairly quickly.

Over the last two decades the observing network has been changing in significant ways. At an early stage in the development of satellites it was realized that they were ideal platforms for meteorological observations as all parts of the earth could be looked at, in large areas simultaneously. It was conceivable that they could provide the extra information from the oceans and from the tropics that was needed to achieve a more adequate monitoring of the atmosphere. There was also the possibility that satellites could replace parts of the conventional network. Essentially, however, the only measurements relevant to the atmosphere that can be made from satellites are of the intensity of the radiation reaching them from a part of the earth's disc. If the measurements are in the visible, then a picture of clouds and the earth's surface can be built up; if in the infra-red then it is possible to deduce information about the temperature of the emitting body, and by taking a variety of wavelengths it is possible to estimate temperatures and (as water vapour is one of the important radiating constituents) humidities through the depth of the atmosphere. When geostationary satellites were put into orbit, work started on trying to deduce winds by tracking suitable cloud elements between pictures taken a short period apart. Research on these aspects of using satellites to obtain winds and temperatures has now been going on actively for over a decade, and some of the latest satellites provide reasonable estimates of temperatures and winds in favourable conditions. What is important from the point of view of analysis, however, is that the estimates are no longer easily compatible with conventional measurements. Thus the temperatures are average values over substantial volumes of the atmosphere rather than discrete values at a point, and their accuracy depends a great deal on how much cloud the volume contains. For measurements of winds from geostationary satellites the main difficulty is in attributing them to specific levels. The level has to be decided from radiation measurements from which it is possible to make estimates of the cloud-top temperatures, and therefore of the approximate height of the cloud in the troposphere. Other technological developments, coupled with the increase in the cost in relative terms of the conventional methods of observing the atmosphere, have led to other changes. Mainly these have been towards automation which enables observations to be made without the need for human skill or human intervention. It is now possible to measure winds accurately in aircraft flying commercial routes without the aircrew having to be involved. They can then be transmitted via a geostationary satellite into the meteorological telecommunication system. Such observations are potentially extremely valuable for analysing atmospheric conditions since they provide accurate measurements at well-defined heights. They do, however, present problems of consistency, because in using them to best advantage it is necessary to try to recreate the pressure and temperature fields at levels below the aircraft winds so that the structure throughout the entire depth is reasonable and leads naturally to the observed winds. Other technological developments have made possible automatic observations of quantities which are already observed and where the gain is mainly in the increased numbers that are, or can be made, available. For example, surface pressure can be measured on unmanned drifting buoys and transferred to the telecommunication network by satellites; more complicated automatic systems have been devised for a wider range of measurements.

The analysis method

From the point of view of analysing the atmosphere these new types of observations have complicated the problem enormously. The observations are no longer synchronous, no longer reasonably uniform in type and accuracy, no longer complete at a particular horizontal location. The new conceptual and mathematical problems are formidable and we cannot be sure at this stage that we know how best to deal with all aspects. This is particularly true because the system and methods of interpreting the observations are still changing. We can, however, create an analysis program which gives better results than we have had before and which is sufficiently flexible to cope with changes in the network which will arise in the future. The question of optimizing the results from the method is a longer-term project when the new operational system is working to reasonable satisfaction.

The analysis problem for numerical weather forecasting is that of representing the three-dimensional structure of the large-scale features in the atmosphere as accurately as possible consistent with the meteorological observations at a particular instant, and of presenting the information to the forecasting model in a form that will allow the best simulation of future developments to be produced. As discussed in the introduction, this implies the creation of a set of internally consistent values which describe only the meteorological features and in which extraneous motions are absent or very small. Ideally, the set should be complete and include realistic vertical motions. However, a particular difficulty concerns the vertical motion at the initial time. It is closely related to the divergent component of the wind, which itself constitutes less than 10 per cent of the wind analysed as being representative of the large-scale features. Atmospheric developments, other than those brought about by simple translation, depend on vertical motion which is the means whereby stored potential energy is converted into kinetic energy and motion. Thus the intensification of depressions requires the ascent of relatively warm air with compensating descent of relatively cold air elsewhere. If the distributions of vertical velocities or of temperature are significantly in error the intensification will be predicted incorrectly. Neither the present observational system nor any likely to exist in the foreseeable future provide the information required to diagnose the vertical motion field associated with large-scale systems directly.

The procedure adopted in the present operational model is to analyse the mass (or, equivalently, pressure) distribution in the atmosphere as accurately as possible. Wind observations are used in this process since in extratropical latitudes they are related to the pressure gradient. The wind velocities over the whole area of the forecast are then deduced theoretically from the mass field by a method which automatically eliminates non-meteorological motions. This procedure, known as initialization, ensures that wildly unrealistic developments do not occur in the subsequent forecasts. However, the winds deduced at an observation point may not be precisely the same as those measured and the vertical motions are unlikely to be those required to give the true atmospheric developments in the initial stages of the forecast. Fortunately it is found that the numerical model is generally able to develop more realistic and consistent vertical velocities, so that the developments judged by changes over 12–24 hours are usually correct. The analysis method which has been developed to replace the present operational system is intended to overcome some of these shortcomings. It does so mainly through two significant changes: (1) it deals with observations of different types on the same footing, so that the geopotential will no longer be the prime variable for analysis, and (2) the concept of analysing the observations for a specific instant independently of the numerical model is abandoned in favour of an analysis period within a normal forward run of the model when the observations are allowed to influence and change the model state. Whereas in the present system the vertical velocity is set to zero at the beginning of the analysis and estimated anew from the analysed field of geopotential, in the new system it will be retained and modified like other variables as a result of the gradual assimilation of new information. Such a system is better adapted to circumstances in which many observations apply to times between the main meteorological observing times and are heterogeneous as regards reliability and accuracy. Also it seems to hold out promise for improving the forecast of developments in the first few hours, and could therefore have applications in finer-mesh models designed for short-period forecasting.

Analysis and data-assimilation schemes have been developed over a number of years in the Forecasting Research and the Dynamical Climatology Branches. Techniques developed for analysing tropical data during GATE have been particularly useful. More recently the process of assimilating data into a numerical model has been tested during the Special Observing Periods of the First GARP Global Experiment (FGGE), a world-wide intensive observational program carried out during 1979 to obtain accurate data concerning the entire global atmosphere. In the scheme which has been tested, separate analyses for winds, temperatures and surface pressures are produced. The analysis procedure, known as 'optimum interpolation', uses the observations to calculate corrections to a preliminary estimate of the values of the physical quantities obtained from a forecast from a previous time. The corrections are expressed as weighted averages of the departures of the observed values from this preliminary estimate, the weights themselves being selected so that the statistically expected errors in the analysis are minimized. This assumption enables the weights to be calculated in terms of the expected error distributions of the preliminary estimate, the probable error bounds of each observational technique and, where appropriate, correlations of the error at each observation with those of its neighbours. The procedure takes due account of the differing accuracies of various observing systems (for example, winds inferred from following the movement of clouds viewed from geostationary satellites are likely to be less accurate than those found by tracking balloons with radar).

Two quality-control checks are made to test the validity of the data. Each observation is first checked against the value of the preliminary estimate. It is regarded as possibly erroneous if it departs by more than a pre-set amount, though greater tolerances are allowed for observations made by using techniques assessed as likely to have larger errors. Secondly, a more stringent test is applied by comparing the observed values with values analysed, using all observations except the one being tested.

The corrections calculated by this method are assimilated directly into the forecast model by a method of repeated insertion over a short period of time preceding the observation time. At each time-stage the differences between the forecast and the observed values are multiplied by weights calculated in the way just described to provide values of the adjustments required at each grid point. However, to avoid sudden alterations to the forecast values, only a small fraction of the changes are added into the model as the forecast advances time-step by time-step towards the observation time. This is done because sudden local changes are found to generate spurious non-meteorological motions which rapidly disperse the effect of the alterations implied by the observations. In this way the model is steadily adjusted towards the observed state of the atmosphere and a natural balance is set up between the winds and other physical variables which correctly reflects the evolution in time of the weather systems. Realistic vertical velocity patterns are set up and the subsequent forecast continues on a realistic course. When this system was tested during FGGE it was found to give particularly accurate wind analyses, an aspect which in the current operational analysis and initialization procedure is often unsatisfactory. An example showing the detail that can be achieved by the assimilation technique is illustrated in Fig. 1 which portrays the analysed winds at 300 mb over the Indian Ocean on an occasion during the summer months of FGGE.

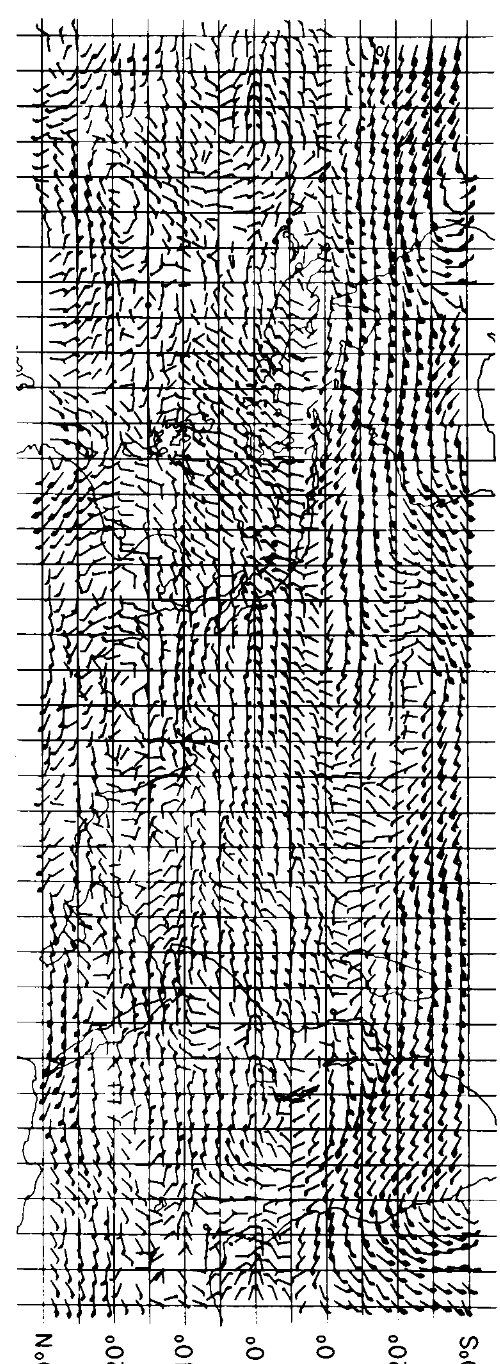

Figure 1. Wind analysis using the FGGE data-assimilation scheme at 300 mb for 12 GMT on 16 June 1979 in an equatorial zone east of the Greenwich meridian to 180° between latitudes 30°S and 30°N.

The next operational model

An operational forecasting system must be geared to strict deadlines determined by the needs of forecast offices. Advice has to be available quickly after the making of the observations, and the best possible advice is required for the main forecasts sent out in the early morning and in the late afternoon. To meet this requirement an acceptable schedule has evolved over the 15 years or so during which numerical forecasts have been used operationally in the Central Forecasting Office. It is based on two forecasting models, the first of which covers a limited geographical region and is run as soon as the observations from Europe and the Atlantic have been received; by this time some American observations are usually also available. Preliminary advice based on this model is presented to the forecaster within 3½ hours of the observing time. Before this, the whole sequence of operations to produce a forecast has to be gone through: this involves receiving, sorting and checking the observations; using them in an analysis scheme, with human intervention as necessary, to produce a representation of the three-dimensional state of the atmosphere at the time of the observations; adjusting the initial state to suit the forecasting model, and to be free of non-meteorological motions; integrating the forecast model for the required length of time; and, finally, obtaining the output quantities in their required formats, which involves drawing charts and the interpretation of model data to determine quantities which are not treated explicitly. It is a tight schedule, which can only be achieved consistently by ensuring that the computer programs and the personnel involved work efficiently with close attention to the deadlines and the alternative routes to be followed should any link in the chain of operations fail. A similar schedule is followed for the large-area model when observations from further afield have been received. In this case results are presented to the forecasters 4½ hours after the observing time.

With the new operational model and analysis schemes, the schedule, again based on two models, will be maintained essentially unaltered. However, the great power of the new CYBER 205 computer will enable many features to be introduced that have been identified by research over the past few years as contributing to improved forecasts; some of these have been described in previous sections.

As now, the large-area model will use a coarser mesh than the limited-area model, and the distinction between the two will remain, namely that the limited-area model aims to provide relatively short-range forecasts over the British Isles while the large-scale model produces forecasts up to several days ahead for a wider area and is used directly for aviation route forecasts. The new area for the large-area model will be the part of the globe north of 30°S, thus placing the southern boundary in a relatively quiet zone from a meteorological point of view. It has been demonstrated in the past that a boundary at or near the equator distorts the active circulation associated with the Intertropical Convergence Zone and the south-east Asian monsoon, and the errors soon spread to higher latitudes. The new area is sufficiently large to cover the major shipping and aircraft routes in the world, and will enable the increasing number of requests for forecasts for longer routes to be met. The limited area will be defined by lines of latitude and longitude (at present it is a rectangle on a polar stereographic map) and this will permit the eastern part of America to be included and its observations used in defining the initial state. It is hoped that this will lead to improved forecasts of the generation of depressions over the western Atlantic; they often move and deepen very quickly and soon affect weather conditions over much of the Atlantic.

The horizontal grid lengths of the two models will be made as small as is compatible with the forecasting schedules and the speed of the computer, since there is ample evidence that a smaller grid length will give more accurate forecasts. It is hoped that the large-area model will have a mesh length of about 150 km; for the limited-area model half or a third of this value is aimed for. The finer resolution will improve a number of features of the forecasts. Areas of rainfall will be more clearly defined, and amounts on average will be nearer those observed (average values now tend to be less than observed, for reasons that are broadly understood); jet streams and frontal systems will be delineated in greater detail; rates of deepening of depressions will, in general, be more accurate. In the vertical, the number of levels will be increased from 10 to 15, with greater concentrations in the boundary layer and near the usual jet-stream levels. As described above, the concentration in the boundary layer will enable the structure of the layer and surface exchanges to be represented more adequately and this should lead to improved forecasts at the earth's surface. Better definition at upper-tropospheric levels should lead to improvements in aircraft wind forecasts, and particularly in the probability of clear-air turbulence, as well as in more general forecasts up to several days ahead.

The models will use a terrain-following vertical co-ordinate rather than pressure as now. This will allow the effects of orography to be calculated more accurately and will dispense with the special mathematical conditions which, in the past, have had to be invoked whenever mountains were intersected by a pressure surface on which values of variables used by the model were specified. Better forecasts of orographic rainfall, and of conditions in mountainous regions generally, will be possible. The numerical technique used for solving the equations will be essentially the same as in the current operational model since it has been shown to be the most efficient (in terms of computer usage) that has yet been devised.

Tests of a version of the new model have already been carried out for several occasions. However, because of limitations in the computing time available before the new computer was delivered, the experimental version had a lower resolution and a smaller forecast area than are to be used in practice. Also, it has not yet been possible to test fully the combined system including the new data-assimilation technique to provide the initial data analyses. However, despite these limitations, it has become clear that the quality of the forecasts from the new model is distinctly better than from those currently available, particularly for three days or more ahead.

An example of a test forecast is illustrated in Figs 2–5. The initial data were for 12 GMT on 16 June 1980. During the subsequent three days the depression near Iceland moved away and became less active while the pair of small depressions near Newfoundland moved across the Atlantic and combined into a single intense depression which, by 12 GMT on 19 June, was situated north of Scotland (Figs 2 and 3). North-westerly surface winds of 40–45 knots were reported from several merchant ships sailing north of Ireland at this time. The three-day forecasts from the new model (Fig. 4) indicated this deep depression only slightly displaced from the observed position. Although the central pressure was slightly too shallow, the model correctly forecast strong north-westerly winds in about the right areas. The forecast produced by the current operational model (Fig. 5) moved the depression too far north to a position west of Iceland with a central pressure some 17 mb too high. As a result, the wind forecasts off the coasts of Scotland and Ireland were too weak. In general, it has been noted that the present operational model often forecasts insufficiently strong pressure gradients. The new model appears to offer the prospect of overcoming this defect.

The development of the Meteorological Office operational weather prediction system has been an evolutionary process over many years. In the early stages of numerical weather forecasting research the main problems were those of a mathematical nature. However, it is clear that the design and maintenance of a forecasting system with as wide a range of applications as is proposed for the new system depends heavily on a broadly based research program covering many different facets of meteorology. It is expected that the new operational weather forecasting system will produce more accurate forecasts than is at present possible and will extend the ability of the Meteorological Office to provide the service required by its customers, while the flexibility of its design will allow future improvements and modifications to be made to suit changing needs.

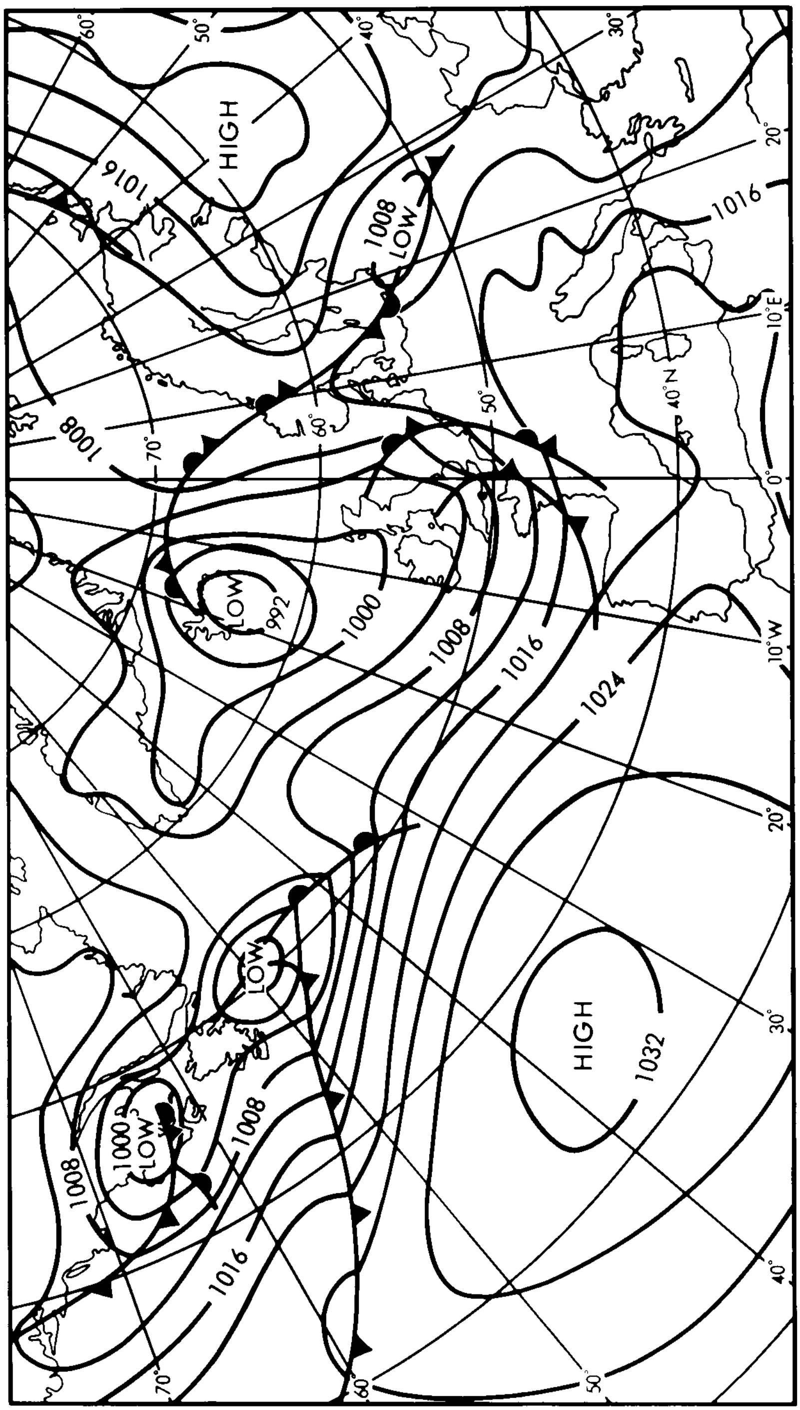

Figure 2. Synoptic chart for 12 GMT on 16 June 1980, as analysed by hand at the Central Forecasting Office, Bracknell.

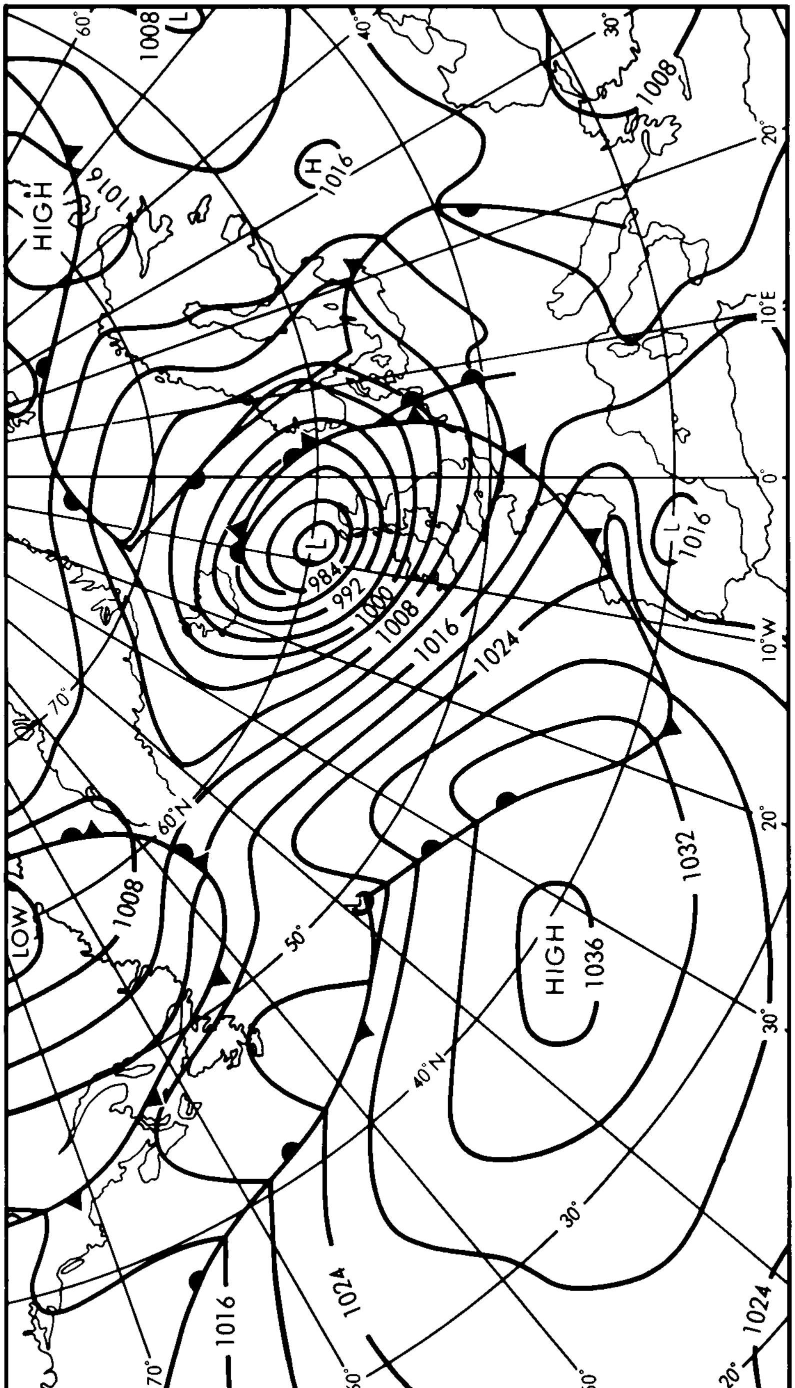

Figure 3. Synoptic chart for 12 GMT on 19 June 1980, as analysed by hand at the Central Forecasting Office, Bracknell.

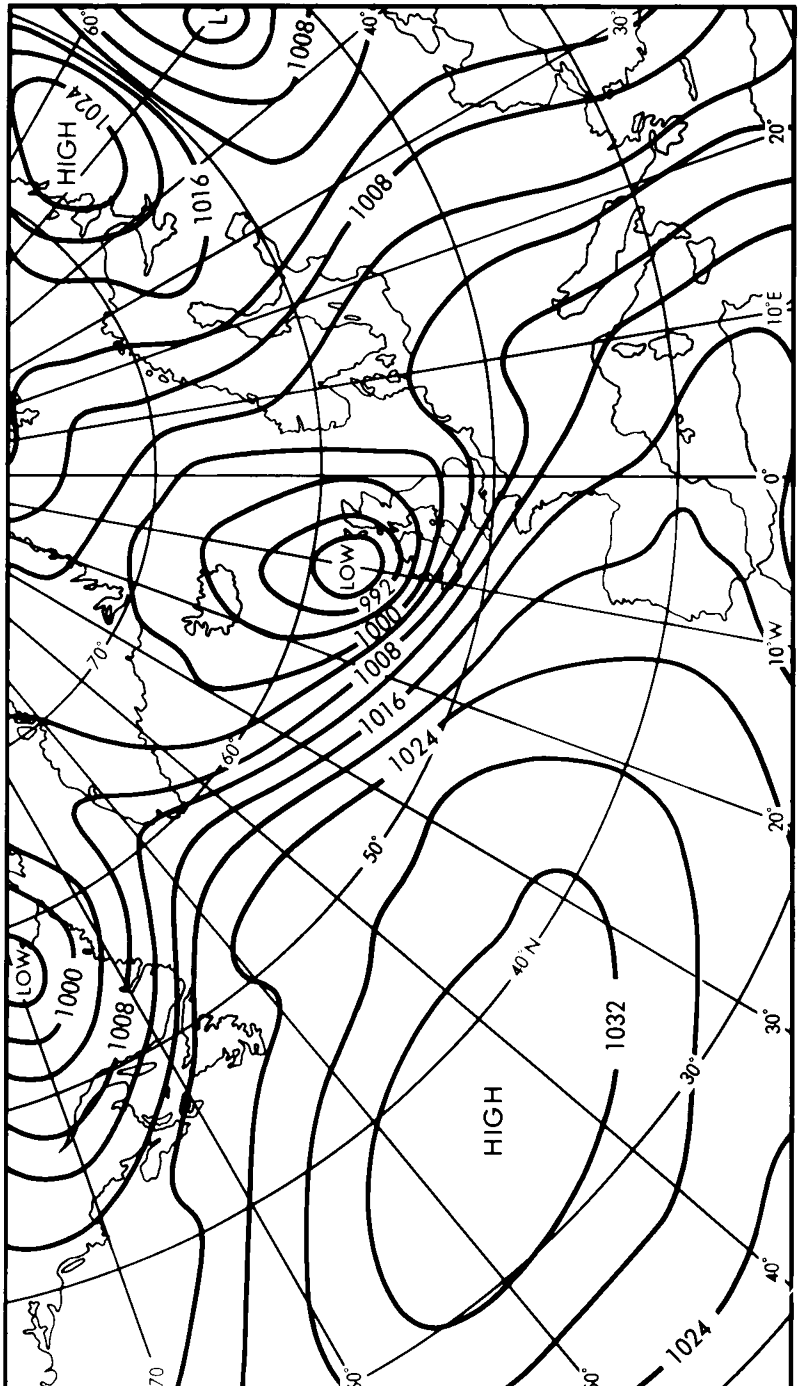

Figure 4. Surface **pressure** forecast for 72 hours after the data time (**12** GMT on 16 June **1980**) as produced by **the new model.**

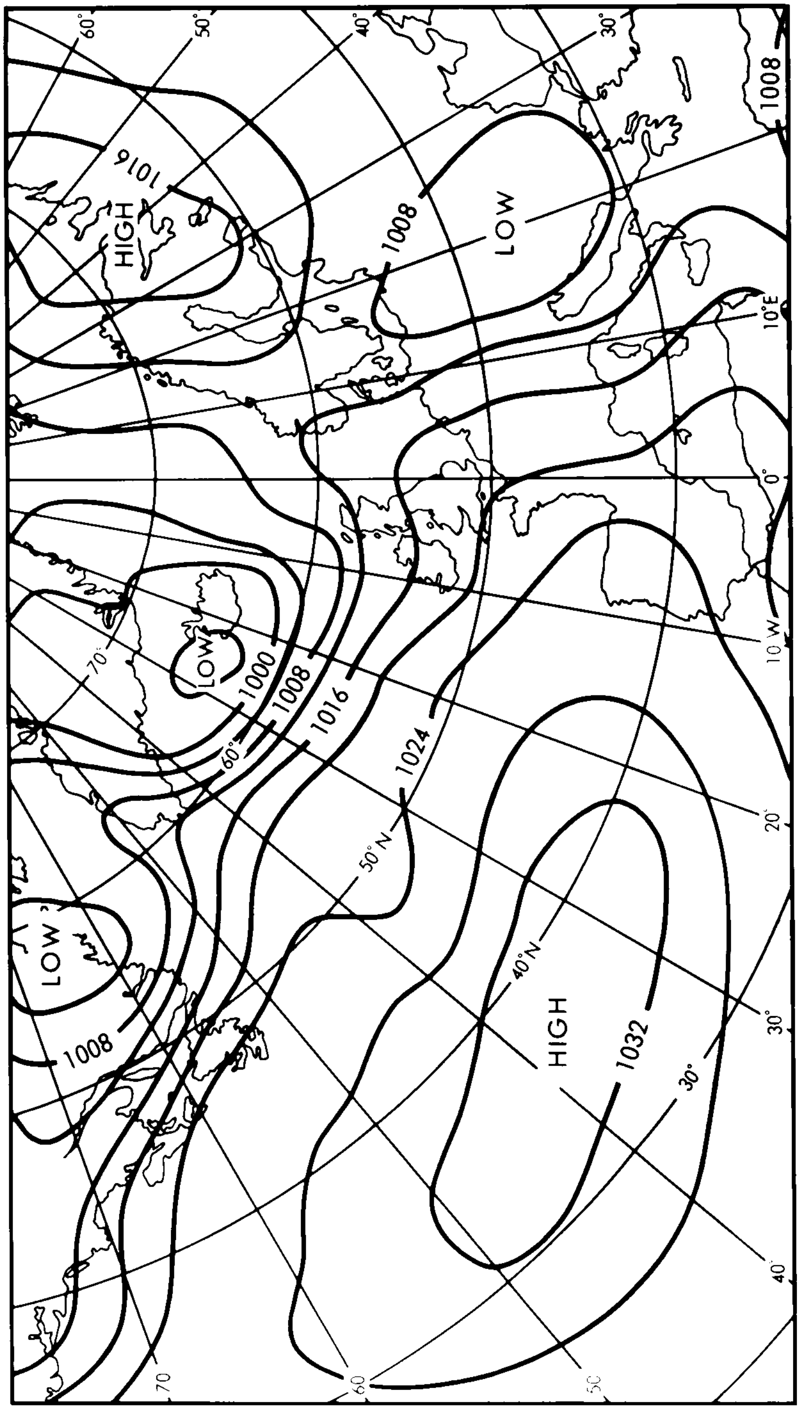

Figure 5. Surface pressure forecast for 72 hours after the data time (12 GMT on 16 June 1980) as produced by the current operational model.

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551.510.52:551.555(5-011):551.557.2(5-011)

The July lower troposphere over the Middle East

By K. Grant

(Meteorological Office, Bracknell)

Summary

Maps of July vector mean winds for six levels from 900 to 500 mb, also July mean wet-bulb potential temperatures and relative humidities at 850, 700 and 500 mb, have been prepared for the area 10–40°N, 30–75°E. In this paper the 850 mb winds and a vertical cross-section are depicted, and features of the flow such as the 'shamal' and the 'wind of 120 days' are discussed.

Great improvements have been made over the past decade in the network of upper-air stations in several countries in south-west Asia, notably Saudi Arabia, Iran and Afghanistan. In the years up to and during the Second World War, and for some time afterwards, the Meteorological Office maintained a network of pilot-balloon stations in this area in support of the Royal Air Force and the Army. Palestine, Iraq, the Persian Gulf and southern Arabia all had their stations, while Cyprus, Egypt and the Sudan to the west, and Pakistan and India to the east supported a relatively dense network. Eventually radiosonde stations were set up, those in the Arabian area being Habbaniya near Baghdad (1949-58), Bahrain (1956-70) and Aden (1956-66), also Masirah in Oman (1967-76).

Though several stations have now closed, the network of stations with data available is remarkably close for a desert area, only the Rub' al Khali in south-eastern Arabia and the Nafud desert of northern Arabia being devoid of data. This suggested the possibility of detailed climatological maps of the upper air in the Middle East, using the data in the Meteorological Office's Technical Archives and Archive of Machinable Data, also summaries published by the individual countries. For many stations monthly data are available, but the number of stations where manual averaging of daily values was necessary meant that detailed coverage could only be attempted for one month. July was chosen as being the standard summer month, and one when the Asian south-west monsoon is fully developed. In winter the flow over Arabia is stronger and mainly westerly, showing less interesting features. The levels 900, 850, 800, 700, 600 and 500 mb were analysed. Above the 500 mb level, pilot-balloon data were unreliable, and the flow was less affected by orography (except near the Himalayas).

The horizontal vector mean winds were evaluated and analysed using major streamlines and isotachs at $2\,m\,s^{-1}$ intervals. A simplified version of the 850 mb map is shown in Fig. 1. A vertical cross-section (Fig. 2) along 240°–060° through the northern Persian Gulf shows the mean wind component from 330° from 900 to 500 mb. For radiosonde stations, mean temperatures, dew-points, relative humidities and wet-bulb potential temperatures were charted at 850, 700 and 500 mb.

The main findings of the analysis are as follows:

(1) The shape of the 'shamal' north-westerlies over Iraq, Kuwait and the western Persian Gulf is seen to be a result of deflection of the airflow by the Zagros mountains of Iran. The core of the stream slopes westwards with height and is still evident in the mid-troposphere near Riyadh. At 600 mb there is a definite, though weak, south-easterly flow along the length of the Zagros mountains. Here the wet-bulb potential temperature is 20 °C compared with 18 °C in the 'shamal'.

(2) There is a marked northerly flow in western Afghanistan. Upper winds from Herat help to define this stream, with maximum mean wind 050° 12 $m\ s^{-1}$ at 800 mb flowing through a gap in the mountain ranges. This mean wind appears to be anomalously veered from the general flow, possibly because of some orographic influence. This is the upper wind which must cause the 'wind of 120 days' in the Seistan depression. The flow is similar to the 'shamal' though on a rather smaller scale.

(3) Over southern Arabia, pilot-balloon winds and July 1980 radiosonde data for cloudy Salalah have been examined. Above the moist air at stratus and stratocumulus levels they show a strong inversion at about 850 mb and frequent north-north-westerly winds at about 600 mb, much further backed than the north-easterlies usually analysed. This is evidence for a summer mid-tropospheric mean trough over south-eastern Arabia.

(4) A considerable area of south-westerly flow is present at 700 and 600 mb over north-western Saudi Arabia and eastern Egypt.

(5) The low-level moist south-westerlies of the southern Sudan and the persistent north-westerlies in the southern Red Sea gradually change to north-easterlies at higher levels. More detail than usual is seen, but little new insight is gained into the exact three-dimensional boundary between the dry and moist air masses. The dry north-westerlies are bounded in the south by the strong winds of the south-west monsoon (Findlater 1971).

The detailed maps of vector mean winds at six levels and humidities at three levels, together with tables of the winds and steadiness (vector mean speed as a percentage of scalar mean wind) at each station, are given in Special Investigations Memorandum No. 111 (Grant 1982).

References

Findlater, J. 1971 Mean monthly airflow at low levels over the western Indian Ocean. *Geophys Mem, Meteorol Off,* No. 115.

Grant, K. 1982 Vector mean winds and humidities in the lower troposphere over Arabia and environs in July. Special Investigations Memorandum, *Meteorol Off,* No. 111, to be published.

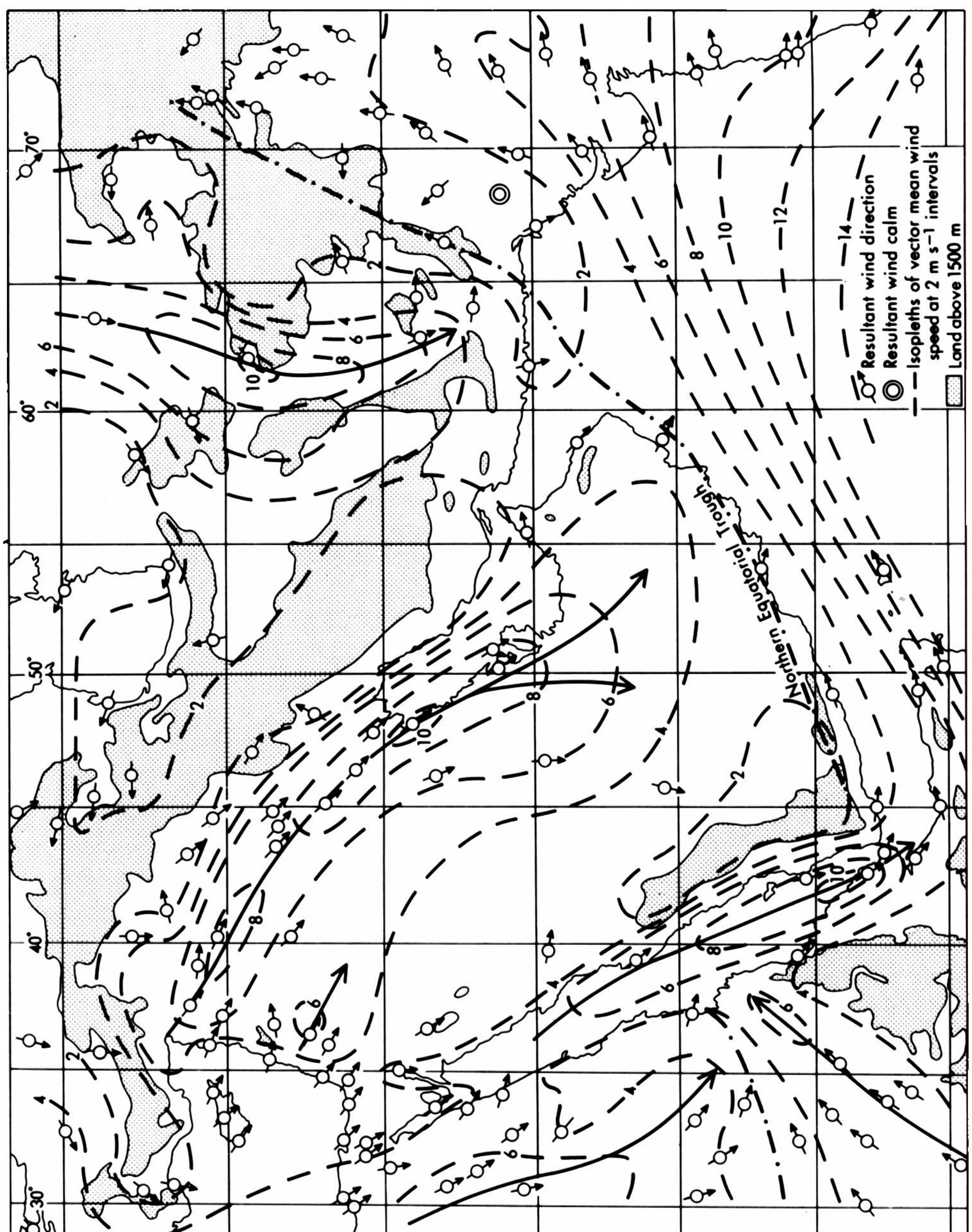

Figure 1. July mean monthly airflow at 850 mb.

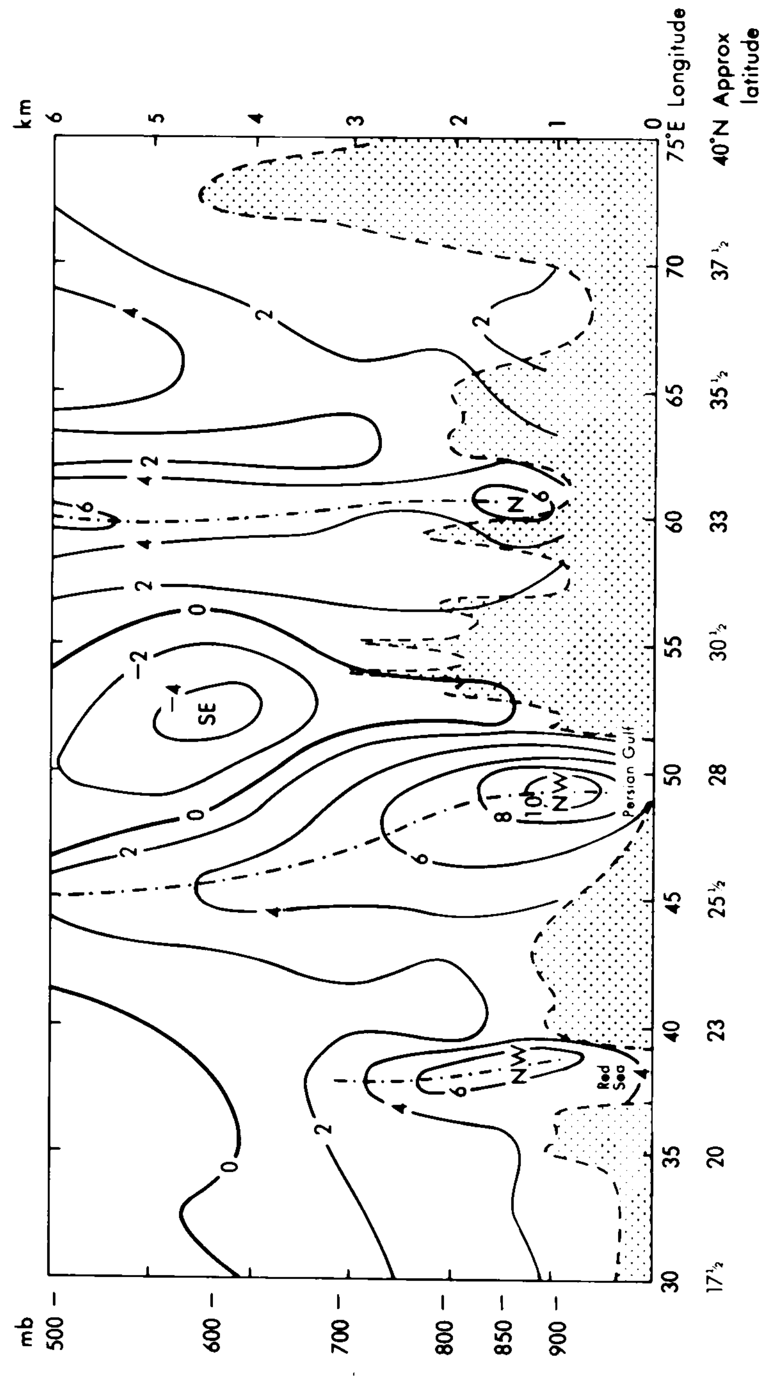

Figure 2. 240°–060° cross-section through the northern Persian Gulf showing mean July wind component from 330° (m s^{-1}). The land surface is shown schematically.

551.574.42

The curious case of the horizontal icicles

By S. D. Burt

(Meteorological Office, Bracknell)

The two photographs here reproduced (Figs 1 and 2) illustrate a fairly unusual meteorological phenomenon: horizontal icicles. They were taken from the first floor of the Meteorological Office Headquarters building at about 1115 GMT on Friday 8 January 1982. Along with many other parts of England and Wales, Bracknell had suffered from a night and morning of fine, powdery snow (falling at a temperature of between −2 and − 3 °C), whipped by a fresh to strong easterly wind into huge drifts. Upon

Figure 1. Horizontal and vertical icicle in close proximity.

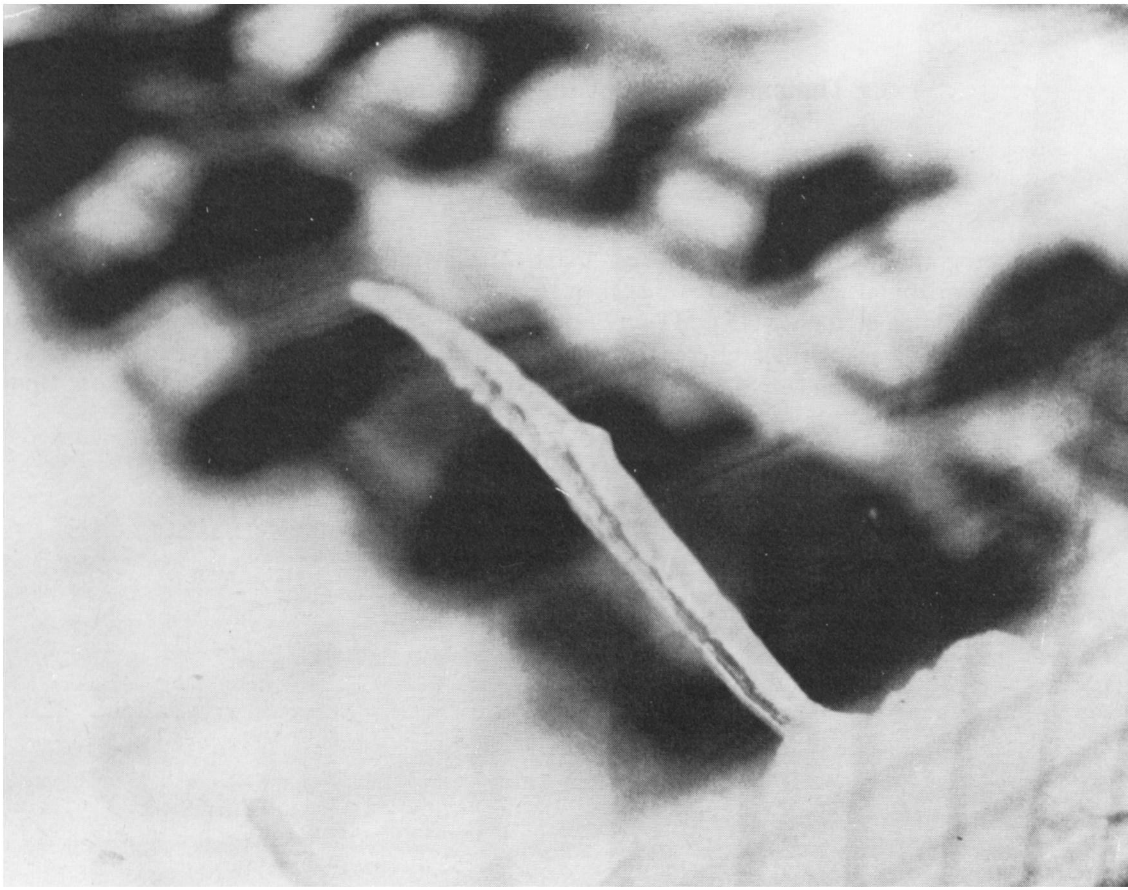

Figure 2. Close-up of horizontal icicle shown in Fig. 1.

contact with the relatively warm surface of the (single-glazed) windows of the building the snow melted briefly into pools of liquid water which then froze rapidly in the harsh ambient conditions into a series of impressive icicles. Most of these were vertical, or nearly so, but in a surprising number of places, on the north and east side of the building, the eddying of the wind obviously favoured sufficiently stable 'updraughts' to permit the anomalous horizontal growth. The icicle shown in Fig. 1, and close-up through the window upon whose sill it had formed in Fig. 2, was 11–12 cm long, the largest of a good many horizontal icicles observed that morning, and is all the more remarkable for existing within a short distance of 'normal' icicles also visible in Fig. 1.

Acknowledgements

I am grateful to Mr F. Singleton and his staff in the Climatological Services Branch for drawing my attention to the icicle that morning.

551.501.9

Synoptic reports from the Isles of Scilly

By C. S. Broomfield

(Meteorological Office, Bracknell)

The closure of the auxiliary reporting station Scilly/St Mary's (03804) on 1 January 1982 brought to an end a series of synoptic reports covering 111 years.

A telegraphic reporting station was established on St Mary's on 1 January 1871. Mr W. Thomas, a signalman, was the observer and he reported twice a day. The reports were included in the Daily Weather Chart which was first issued in 1872. A third daily observation was added to the program in 1878. During the early years there were numerous breaks in the cable to the mainland; some of these were not repaired for several months.

A small Robinson anemograph was installed about 1881. The pillar on which the anemograph was placed rocked in gales so that the pendulum struck the wall of the case and stopped the clock. Wooden stays were fitted (see Fig 1) and a portion of the iron case filed away to give clearance. The observer asked for a shelter to attend to the anemograph in gales and rain but this was refused as it was thought it would seriously affect the air flow.

The station's data were included in the Monthly Weather Report from 1884. Mr Thomas died in 1890 and Mr A. Hicks, a Lloyds signalman, was appointed observer. In that year arrangements were made for the 8 am and 2 pm observations to be displayed, together with those of 5 other coastal stations, on a board outside the Office at 63 Victoria Street, London.

The Revd W. C. Ley, who inspected the station regularly, commented after his visits in 1890 and 1891 that Mr Hicks was probably the only person on St Mary's who could undertake the work so well.

Mr R. H. Curtis visited the station in 1895 and found the Robinson anemograph working well. He took it entirely to pieces, cleaned and reassembled it, and erected a Dines pressure tube anemograph by the side of the Robinson (see Fig 1). The Dines vane was on a stayed mast 32 feet 6 inches (10 m) above ground.

In 1898 the site of the thermometer screen and anemometers, which was at Garrison Hill, was taken over by the War Office, and the Meteorological Council was charged five shillings (25p) per year site rental. The instruments were resited in 1901. (See Fig. 2.)

Following the retirement of Mr Hicks in 1910 the observing routine was taken over by the coastguards at Lloyds Signal Station.

In 1926 the station moved to Telegraph. A Dines pressure tube anemograph was erected on top of the coastguard lookout tower, access to which was by a number of vertical iron ladders inside the brick tower. The vane was 20 metres above ground. Overlap readings continued at Garrison Hill. The equipment at Garrison Hill was eventually dismantled by the Meteorological Office, with the help of a local man at one shilling (5p) per hour, and the site given up in 1931.

The first inspection during World War II was made in March 1942, by which time hourly reports were being made and cloud-base balloon equipment had been supplied. A new Dines mast which was installed in 1943 caused so many leaks in the roof that it was impossible to use the instrument in wet weather. Lightning struck the building in 1947 throwing the duty coastguard off his chair; a lightning conductor was immediately requested for the Dines mast.

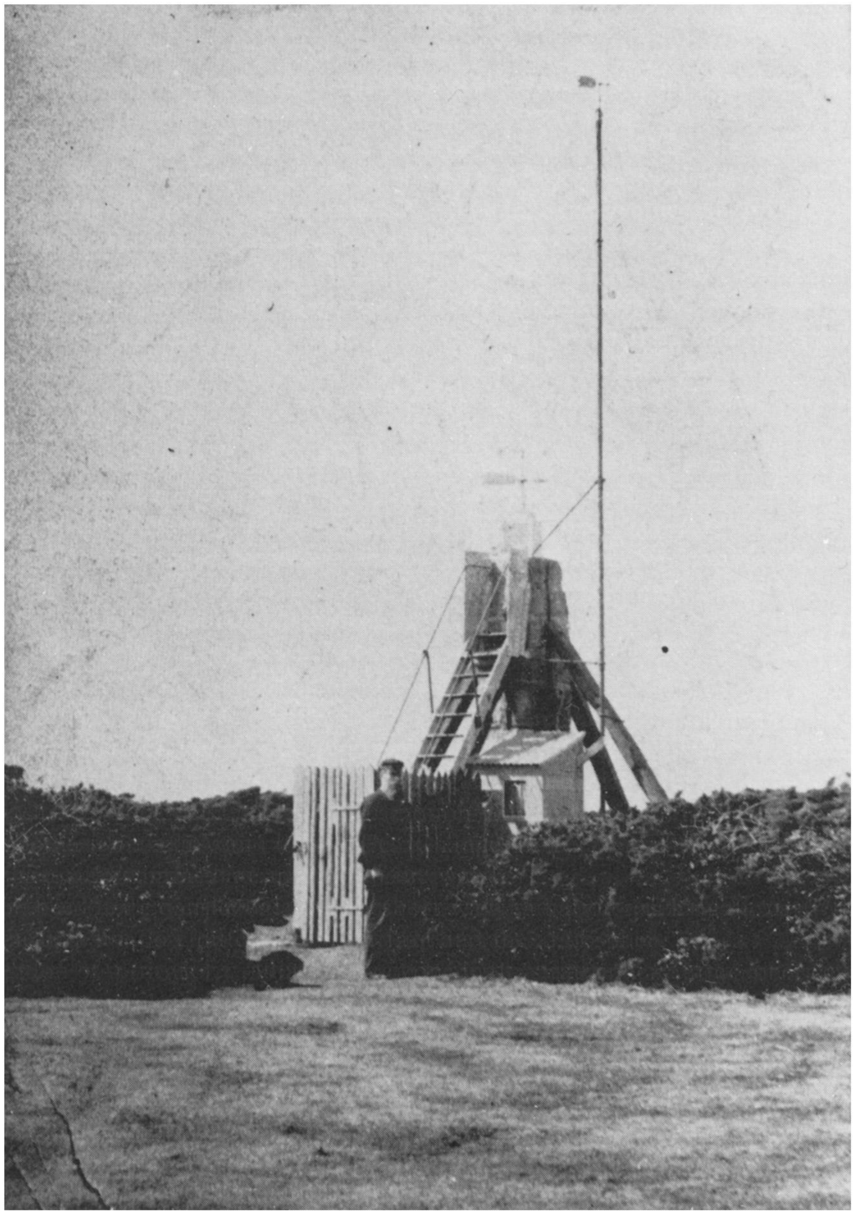

Figure 1. Early site at Garrison Hill.

A cloud searchlight was installed in 1957; siting difficulties restricted the base line to only 399 feet—probably the shortest in the country. The site was used until the station closed.

Temperatures were added to each hourly report from 1958. The coastguards were unable to leave the look-out to visit the screen every hour, so a small screen with dry- and wet-bulb thermometers was fixed to the parapet of the tower (see Fig. 3). This was used at other than main and intermediate synoptic hours.

In January 1962 flying debris damaged the wind vane in gusts of up to 90 miles per hour, in the gales of January 1969 the alidade was torn from its mounting, and the parapet screen and thermometers were smashed when gales blew the screen from its mounting in February 1972.

In September 1976 the parapet thermometers were replaced by electrical resistance sensors in the enclosure screen. The observers had previously noted differences on occasion of over 2°C between the readings from the parapet screen and the screen in the enclosure.

With the installation of remote surveillance equipment, monitored at HM Coastguard centre at Falmouth, there was no longer a need for continuous manual watch at St Mary's and from 1 January 1982 the station was manned only during an emergency or in a special situation. The opportunity to obtain regular weather observations was therefore lost.

With the kind permission of Trinity House the Keepers at Round Island Lighthouse (03802 49°59'N 6° 19'W) (Fig. 4), at short notice, afforded their co-operation by supplying eight reports a day. The Meteorological Office has initiated the installation of an automatic weather station on St Mary's. Abbreviated reports from the Air Traffic Controller at St Mary's Airport (03801) are also broadcast when available.

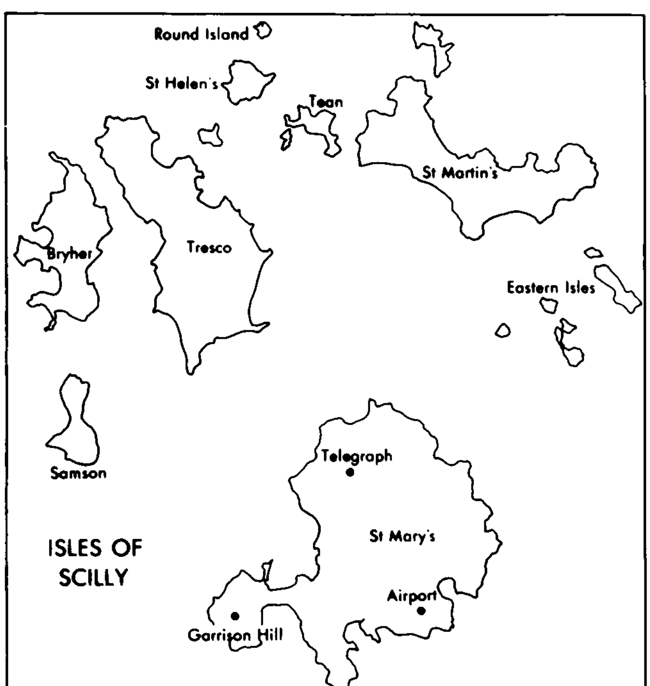

Figure 2. Map showing location of places mentioned in the text.

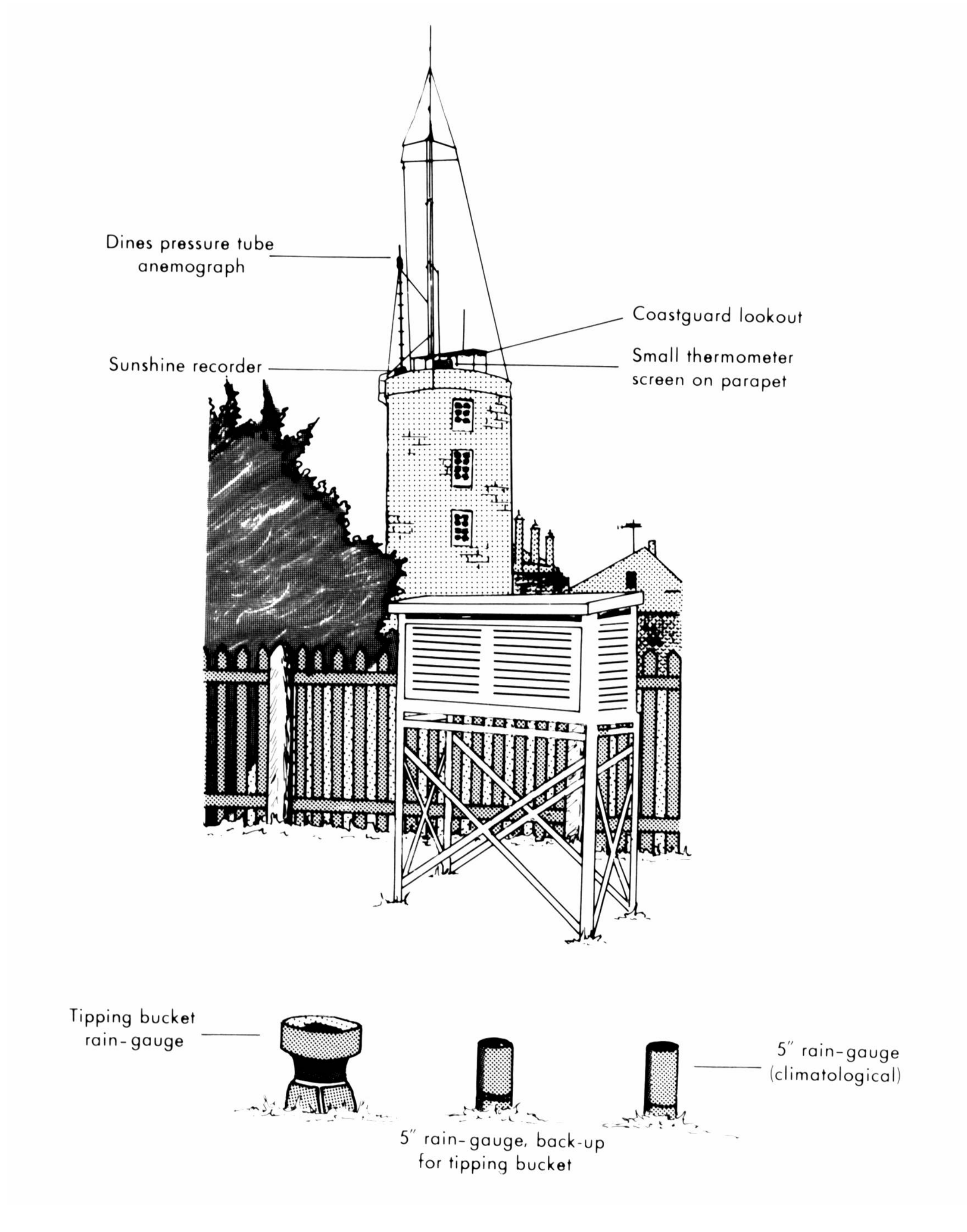

Figure 3. Pen and ink sketch of site at Telegraph.

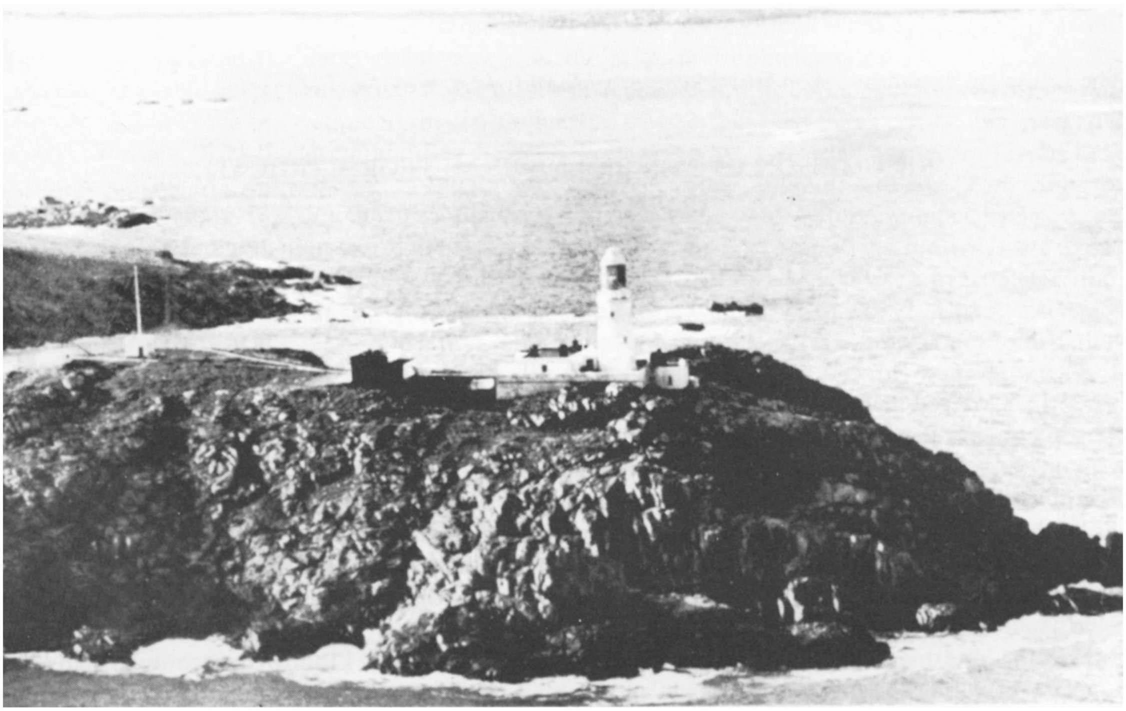

Figure 4. Round Island Lighthouse from the north-east.

Addendum

After the above article was submitted Scilly/St Mary's was reopened temporarily by the Directorate of Naval Oceanography and Meteorology on 20 March 1982.

100 years ago

The following extract is taken from *Symons's Monthly Meteorological Magazine,* July 1882, **17**, 81.

RESUMPTION OF THE BEN NEVIS METEOROLOGICAL OBSERVATIONS, 1882.

By Clement L. Wragge, F.R.G.S., F.M.S.

Under the auspices of the Scottish Meteorological Society.

May 25th.—Arrived at Fort William from Edinburgh.

May 26th.—Engaged making arrangements for workmen, &c. In evening erected Stevenson's thermometer screen, at Achintore, in the same field as last year, by the Loch beach, and about 28 ft above the sea.

Subsequently hung the low level barometer, a fine Board of Trade by Adie, London, its greatest error being but 0.003 in., and compared with it the mercurial barometer that is to be used at a new fixed and fully equipped station I had arranged with the Scottish Meteorological Society to establish at the Lake (1840 ft.)

May 27th.—Started off four men and a mason betimes for the Lake. I followed, accompanied by Mr. Livingston of Public Schools, Fort William, and Mr. J. B. Simpson of Edinburgh University. Away nine hours, and engaged with the men building a cairn for the barometer near the water's edge, 1,840 ft. above sea. Had great trouble in getting the stone, collected granite from the quagmire adjacent and the water's side, where it lies and "crops up" in some quantity. Had to battle with pitiless hail squalls and heavy weather in the afternoon; men could not make rapid progress, and cairn not completed, by some 4 ft. However, fixed the box to contain the barometer inside.

May 28th.—Sunday's rest—engaged, however, examining instruments, and fixing those at Achintore, Fort William.

May 29th.—A heavy day's work. Men left Fort William at 7 a.m., returning about 9 p.m. Two men and mason engaged at the Lake, I superintending. The barometer cairn there finished, and the Stevenson's thermometer screen fixed. These are situated by the edge of the tarn, at the N.E. end. Twelve men and joiner engaged on summit of Ben Nevis, I superintending there in afternoon. Snow covered the entire plateau of the summit to a depth of from 3 to 5 ft. Engaged "digging out" the barometer cairn, which was surrounded by snow 3 ft. 6 in. deep, thermometer cage and hut, and in excavating an area, 18 ft. in diameter, where another thermometer screen was fixed (some ten paces E. from the other). This is to contain a self-recording hygrometer, acting by clockwork, to record the temperature of the air, and that of evaporation at 9 p.m. on the Ben. Messrs. Negretti and Zambra are the makers of this invaluable apparatus, and have most kindly placed it at my disposal, for use on Ben Nevis. The snow walls of this area averaged $3\frac{1}{2}$ ft. high, and presented a most singular appearance. It will be remembered that the barometer was securely built-up last October in its cairn. Great labour was expended to-day, before the north side of the cairn was reopened; the stones were so hard frozen that a crowbar had to be used to remove them. To my delight, I found the instrument in excellent order—nothing the worse for its winter's "rest." Snow had deeply accumulated inside thermometer cage. The reading of the minimum thermometer that has been on the Ben all winter was 11·0, and this occurred since January, when Mr. Livingston, of the Public Schools, Fort William, made an ascent.

May 30th.—Engaged at Achintore Observatory on sundry matters—sowing grass-seed around thermometer box, and placing post for new solar radiation thermometer.

May 31st.—A most important day. Fixed all the instruments for the commencement of my work on the morrow. Up at 5 a.m.; examined the thermometers, to ascertain their index errors; then packed up those for the new "Lake" station and Ben Nevis. Set out at 8 a.m., I carrying barometer for the Lake, accompanied by Mr. Mackenzie, of the Inland Revenue, Fort William, and Mr. J. B. Simpson, Edinburgh University, carrying the thermometers. The Lake Observatory, fully equipped by 3 p.m., and barometer safely hanging in its cairn; then set out for the Ben. By 8.15 p.m. all instruments were fixed in position on the summit of Ben Nevis, including Negretti and Zambra's clockwork hygrometer, and a new tarpaulin was placed over the hut. Arrived at Achintore, Fort William, about 11 p.m.; afterwards re-fixed instruments at the sea level station, and being satisfied that all was correct got to bed about 1 a.m., very tired. Up again by 5 a.m., June 1st, and commenced work, taking observations on the outward and homeward journeys, and five sets of readings on Ben Nevis.

The work this year is much heavier than that of last season, and the following is the plan that has hitherto been, is being, and will be, adhered to till the end of the season:—Outward to Ben Nevis (fixed stations), observations at Achintore, Fort William, are taken at 5 a.m.; on the Peat Moss, about 30 ft. above sea, and two miles N.N.E. from Fort William at 5.30; at "The Boulder," about 840 ft. above sea, 6.15 a.m.; at the new fully-equipped observatory at "The Lake," 1,840 ft., at 7 a.m. (Here are barometer, and dry and wet bulbs, maximum and minimum thermometers in cairn and Stevenson's screen respectively; rain gauge; tubes for earth temperature and ozone tests); at Brown's Well, about 2,200 ft., at 7.30; at the Red Burn Crossing, about 2,700 ft., at 7.55 to 8 a.m.; and at Buchan's Well, about 3,575 ft., at 8.30. On the summit of Ben Nevis, 4,406 ft., the observations are taken at 9, 9.30, 10, 10.30, and 11 a.m.; and consist of atmospheric pressure, by mercurial standard and aneroid barometers, temperature and extremes of ditto, hygrometrical conditions, ozone, rainfall, solar and terrestrial radiation, wind, force, cloud, amount of ditto, movements of the various strata, hydrometeors, &c., and temperature of "Wragge's Well," about 25 ft. from summit; Negretti & Zambra's clockwork hygrometer, registers at 9 p.m.

From June 15th ozone observations are taken half-hourly, and three more rain gauges will be examined at 9 a.m. at different points, from the centre of the plateau to the precipice, to ascertain if, and to what extent, the rainfall varies with different winds. Dr. Angus Smith, F.R.S., of Manchester, has kindly undertaken to supply apparatus for the measurement of the actinism of the sun's rays and of daylight. Browning's Rainband spectroscope is also used.

Homewards from Ben Nevis, the observations are at Buchan's Well at 11.30, at the Red Burn Crossing at noon, at Brown's Well at 0.30, at "The Lake" at 1, at "The Boulder" at 1.45, on the Peat Moss at 2.30, and at Fort William at 3 p.m.

At all intermediate stations a "travelling" hygrometer is used (dry and wet bulbs), and the observations consist of pressure by aneroid, temperature of air (of Lake), wells, and burns, moisture, wind, force, cloud and amount, &c.

Simultaneous observations are taken in direct connection with the foregoing at the low-level observatory at Achintore, Fort William, about 28 ft. above sea, and the hours of observation there are 5 a.m., 5.30, 6.15, 7, 7.30, 8, 8.30, 9, 9.30, 10, 10.30, 11, 11.30, and noon, also 0.30 p.m., 1, 1.45, 2.30, 3, and at 6 and 9 p.m., and the elements of observation are precisely the same. Lest reading half-hourly at the low-level station should, by the heat of the observer's person, cause vitiation of readings of the self-registering thermometers, these instruments have been placed at 30 ft. distant from the hygrometer and other thermometer screen, in a new special screen. I am fortunate in having an able assistant, whom I have myself trained, and who relieves me when occasion requires in the ascent of Ben Nevis, and who takes the low-level observations. Mr. J. B. Simpson has also assisted, and my best thanks are due to him. I have also other assistants in training, so that any emergency may be met. The work is very heavy, but well under control, and punctuality and method will carry it through. The weather during the last few days on the Ben has been bitterly cold, and much new snow has fallen. The barometer cairn and thermometer cages on the 15th instant, were entirely frozen up, and great difficulty was experienced in opening them. A supply of fuel is very necessary, for one's hands get so dead with the cold that writing and handling keys, instruments, &c., are difficult matters—hence the necessity for an observatory house. Temperature has been between 23° and 30°, with biting N.E. winds, and maximum below 32° Fah.

One of the greatest difficulties I have to contend with is the getting the horse (on which I ride to and from the Lake) over the ruts and swamps. The latter are so very treacherous and deep, that the poor animal has a trying time of it. By keeping the work well in hand, I can keep time punctually at the intermediate stations, and so secure the simultaneous, or nearly simultaneous, observations, that I trust will be of the greatest value. The hardest climb is from Buchan's Well to the summit in the half-hour. Earth temperature will be added to the observations on July 1st, and systematic observations of the rainband by Browning's spectroscope will be by then an important feature in the work. CLEMENT L. WRAGGE. *Fort William, N.B., June 16th,* 1882.

P.S. The great value of the intermediate observations is, that they enable disturbances in the varied stratum of atmosphere between Ben Nevis and Fort William to be localised and examined in discussion. We hope largely to increase the value of forecasts.

SUBSEQUENT NOTE. *July 1st,* 1882.

Stevenson's screens, somewhat smaller than the usual size, are now fixed at all intermediate stations (from July 1st) between Fort William and Ben Nevis (at the Lake the large "Stevenson" is used), and in these are exposed neat and small "sling" thermometers with small bulbs fitted as "dry" and "wet." The labour of swinging is thus done away with, punctuality ensured, and accuracy also. The entire observing system goes like clockwork.

There are now 4 rain gauges, 15 paces apart on the plateau of the summit of Ben Nevis, read daily 9 a.m.—*viz.*, A in centre of plateau, D on edge of great precipice, and B and C intermediate. There is a gauge at the Lake 1840 ft. (also on Peat Moss at base of mountain) read weekly; and gauge at Achintore, Fort William, read 9 a.m. 9 p.m.

CLEMENT L. WRAGGE.

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