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THE TETHERED RADIOSONDE

By H. E. PAINTER

History. Since June 1942, observations, at specific heights up to 1200 metres (900 metres since March 1967), of dry-bulb and wet-bulb temperatures and wind speed have been made at Cardington, near Bedford, with instruments attached to the steel cable of a captive balloon.

In the Meteorological Office these observations have been referred to by the name BALTHUM, a word abbreviated from 'BALloon Temperature and HUMidity'. These ascents have been made four times daily (three times daily before 1956) whenever weather conditions permitted the balloon to be flown safely. The observations have been sent by teleprinter to Meteorological Office stations for use in forecasting and have also been used for climatological analyses. Some early results were discussed by Shaw.[1]

Until 1964 the instrument for measuring temperatures was basically that described by Swinbank[2] in which copper-constantan thermocouples were used. The dry-bulb temperature was measured relative to a 'cold' junction in an ice bath and the wet-bulb depression was obtained by measuring the difference between the e.m.f.s (electromotive force) generated by the dry-bulb and wet-bulb thermocouples. The e.m.f.s from the thermocouples were measured by a potentiometer at ground level connected to the thermocouples by means of a multicore cable. A cup-contact anemometer was also attached to the balloon cable and was connected to a ground relay counter by the multicore cable. Height could only be determined by measuring the length of balloon cable paid out. This, of course, was not a very accurate method since the height of the balloon was affected by the wind. In practice the telemetering cable was often the cause of trouble when in light winds it became entangled with the balloon cable; in extreme cases it had to be cut to be disentangled.

A new instrument has been designed in which signals are transmitted to the ground by radio and this radiosonde first came into routine use on 9 November 1964; there have been some changes in the design since then and the latest version is described below. In addition to the previous measurement of dry- and wet-bulb temperatures and wind speed, there is a pressure sensor which permits more accurate determinations of heights than hitherto.

The sonde circuit. Suitable circuits had already been designed by the Meteorological Office for its rocketsonde[3] and these circuits have been adapted for the tethered radiosonde. The transmitter consists of an R/F (radio-frequency) oscillator coupled to a ¼-wave aerial and operates at a pre-set frequency in the meteorological band 27·5–28·0 MHz. This R/F oscillator is modulated by two A/F (audio-frequency) oscillators. One A/F oscillator is used in conjunction with a cup-contact anemometer and oscillates at about 5 kHz when the contacts of the anemometer are closed, but at a much lower frequency when these contacts are opened. The second A/F oscillator is made to vary in frequency by variations in resistive transducers. A switch is energized every 8 seconds and this switch connects in sequence to the A/F circuit two thermistors measuring dry-bulb and wet-bulb temperatures, a variable resistance controlled by an aneroid capsule and a reference resistor of fixed value. The frequencies in this A/F circuit are between 800 and 2000 Hz, and when received at the ground are filtered by a band pass filter to exclude interference from the wind A/F oscillator. The filtered signals are measured on a frequency counter and from these measurements temperatures and pressures, and hence heights, can be deduced.

Temperature sensors. The temperatures are measured by ordinary commercial thermistors; those used have a nominal resistance of 1000 ohms at 20°C. They have a faster response time than is required and their response time is increased by fitting them into hollow brass cylindrical bulbs 30 mm long and 6·5 mm in diameter. The top of each brass bulb is screwed into a tube of poorly conducting material 32 mm long and 6·5 mm in diameter. The leads of the thermistor pass through the centre of the tube and are sealed with epoxy resin to prevent any short-circuiting of the thermistor by moisture. The tube, since it is a poor thermal conductor, serves a double purpose; it is used as a support for the temperature element and also, by fitting the wet-bulb sleeve over the brass bulb and well up the stem of the poorly conducting tube, errors in wet-bulb readings, due to conduction down the stem, are greatly reduced.

Over the range of temperatures (+40° to −30°C) required for the tethered sonde, the stability of the thermistors has proved to be very satisfactory. Laboratory tests were made on the thermistors by measuring their resistance when placed in baths of liquids of known temperature. Resistance measurements were made by the potentiometric method using a standard 1000-ohm resistor. The current through the thermistor in these measurements was never greater than 0·1 mA; at this current the self-heating is quite negligible (<0·01 degC). When used with the sonde the current through the thermistor is much less than 0·1 mA. It was found that a good calibration of the thermistors could be obtained by taking very accurate resistance measurements at two temperatures only and then evaluating the constants in the standard equation for the relation between the resistance and temperature of a thermistor. This equation can be put into the form

$$\log_{10}R = A + B/T,$$

where R is the resistance in ohms, T the absolute temperature, and A and B are constants.

The two fixed temperatures chosen for these calibrations were 0°C and approximately 20°C, both being very easy to obtain and maintain in the laboratory. Repeated tests over 18 months showed that the thermistor calibrations were reproducible to within the equivalent of 0·05 degC, and that there was no discernible drift.

The two thermometer bulbs are mounted in double-walled radiation shields and are aspirated by a fan which draws air over the thermometer elements. Plate I shows the psychrometer unit attached to the box containing the batteries and circuits of the sonde. Both radiation shields have been removed (and are lying below) to show the thermometer elements projecting below the aspirator housing. The wet-bulb sleeving can be seen on the left-hand element and this sleeving passes through a polythene tube to a water bottle. When the radiation shields are screwed into position they project to the same level as the bottom of the sonde container so that the air that is drawn into the shields has not come into contact with the large box housing the sonde circuits. The fan is 70 mm in diameter and delivers about 0·7 m^3 of air a minute at a water pressure of about 8 mm. The fan is of the axial type and operates from 12 volts d.c.

Wind-tunnel tests show that the ventilation over the dry bulb is about 10 m/s. At this rate of ventilation the lag coefficients of the dry bulb and wet bulb are about 40 and 22 seconds respectively. The wet-bulb thermometer with this aspiration is giving the maximum wet-bulb depression as shown by tests in the laboratory.

Attempts were made to assess errors due to radiation by shining a bright light on the psychrometer. A radiation intensity of 50 mW/cm^2 falling on a vertical plane through the radiation shield caused a rise in temperature of 0·15 degC. A radiation intensity of 90 mW/cm^2 falling on a white surface below the thermometer element (to simulate conditions when the radiosonde is above an extensive cloud sheet) caused the thermometer element to warm up by 0·2 degC. The extreme upper limit of errors due to radiation is thus thought to be 0·35 degC.

Pressure transducer. An instrument to measure height to the degree of accuracy desired for low-level soundings is not readily available. A special transducer was made consisting of an aneroid capsule mechanism driving a brush round a silver-palladium potentiometer. The operative range of the transducer is 1050 to 800 mb and the resistance then varies between 0 and 2500 ohms, approximately linearly with pressure changes. Tests were made in a pressure chamber to determine the reproducibility of the calibration. For a given pressure the greatest difference detected in resistance was 7 ohms (equivalent to 0·7 mb). In the majority of cases the readings were reproduced to within 0·5 mb. These differences included errors due to hysteresis, which would not affect an actual sounding when readings are taken on the ascent after a reduction in pressure. The maximum change in calibration for a change in temperature from −20°C to +40°C was 2·5 mb. The pressure transducer is situated in the thermally lagged container of the sonde and under normal conditions the change of temperature of the transducer is not more than 10 degC. If for special measurements it was thought necessary, the temperature of the transducer could be measured and telemetered to the ground.

Construction. The transistorized circuits are wired to three small plug-in boards. The R/F oscillator circuit together with the A/F oscillator circuit for the wind measurements, are on one board. A second board has the A/F circuit for the oscillator measuring temperatures and pressures, and the third board has the switch circuit which operates a rotary switch so that the various transducers are connected in turn to the A/F oscillator. A six-way switch is used, although at present only four different elements are connected to the A/F circuit. The switch is energized every eight seconds and switches in turn into the circuit resistances controlled by the dry bulb, wet bulb, pressure, dry bulb, wet bulb, and reference resistor, and so on. The circuits and pressure transducer are contained in the upper portion of the sonde and the necessary batteries in the lower portion. The whole of this container is thermally lagged with 1-inch thick polyurethane foam. There are five 6-volt accumulators all of the unspillable type. Two of these accumulators are of higher capacity and supply 12 volts to the fan motor, the other three supply 18 volts to the sonde circuits.

Calibration of temperature and pressure oscillator. The A/F oscillator plays a vital part in the measurement of temperature and pressure, and hence the stability of its various components must be very high. The oscillator has been designed to keep to a minimum changes in frequency due to small variations in voltage and variations in the temperature of the components. The small changes in frequency arising from the oscillator circuit, apart from the meteorological transducers, are measured by putting a very high-stability wire-wound resistor of 1800 ohms into the circuit instead of the meteorological transducers. Each A/F oscillator has its own reference resistor and the calibration of the oscillator is made with reference to the frequency appropriate to the standard resistor.

Hitherto the frequency of the A/F oscillator has been mentioned in terms of hertz, but in common with current radiosonde practice in this country readings from the tethered radiosonde are made in terms of periodicity, by timing a fixed number of cycles, the unit employed being microseconds (μs). The calibration of the sonde is carried out in two stages; firstly a resistance/temperature or resistance/pressure relationship for the meteorological transducers is determined, and secondly the relationship between resistance and periodicity for the A/F oscillator is determined. This oscillator is accurately calibrated for resistances between 450 and 12 000 ohms. During this calibration the oscillator circuit is placed in a thermally insulated box at 20°C and the voltage accurately maintained at 18·00 volts. Decade resistance boxes are adjusted to give readings for every 5 μs from 750 μs to 1300 μs. At frequent intervals throughout the calibration the reference resistor is switched into the circuit and the corresponding period noted. The overall change throughout the calibration in the periodicity produced by the reference resistor is about 0·5 μs. These changes are mainly due to small variations in the values of certain components of the oscillator arising from small changes in their temperature. The final calibration table of the oscillator is arranged to give the resistance at every 5 μs allowing for variations deduced from the reference resistor measurements. In practice the period for this reference resistor is rounded off to the nearest whole number. Thus, for example, for a particular A/F oscillator the relationship between resistance and periodicity is known

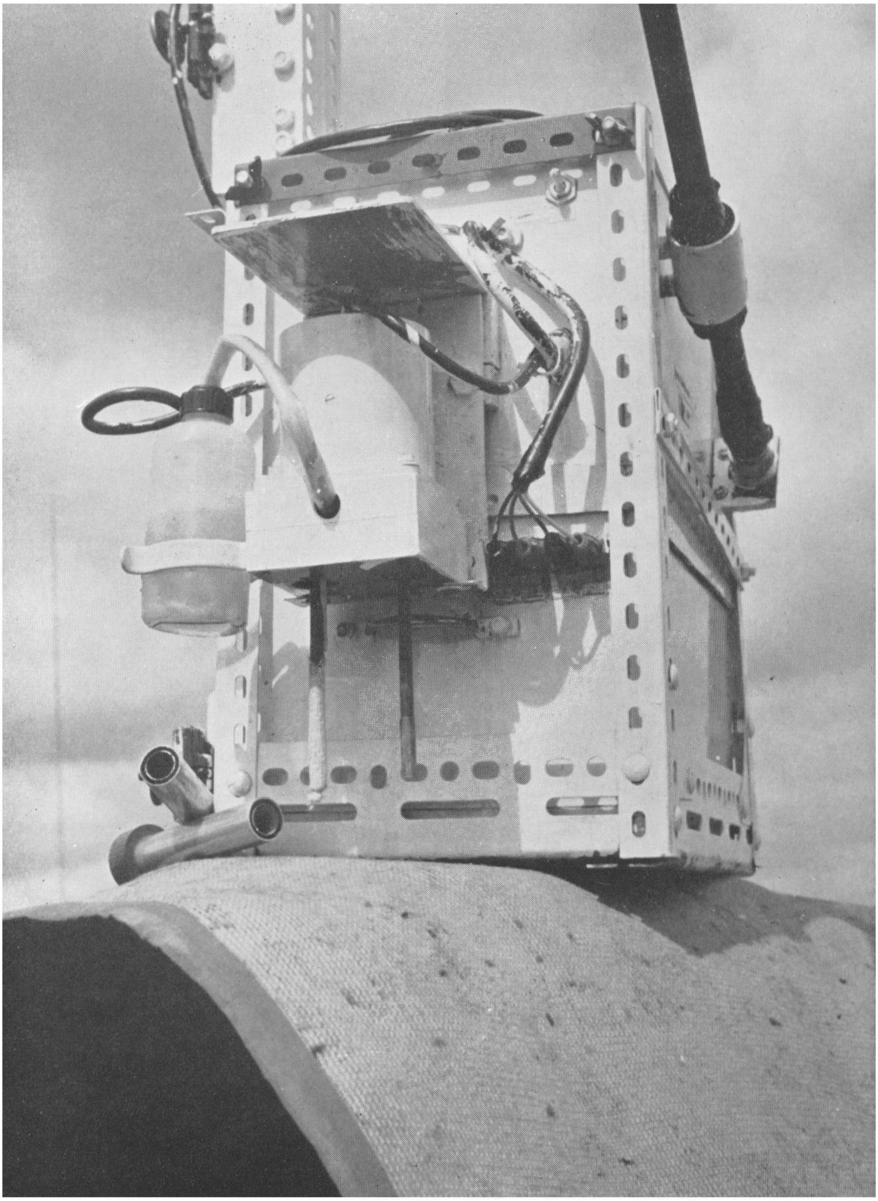

PLATE I—TETHERED RADIOSONDE SHOWING PSYCHROMETER WITH SHIELDS REMOVED FROM TEMPERATURE SENSORS

See page 95.

To face page 97

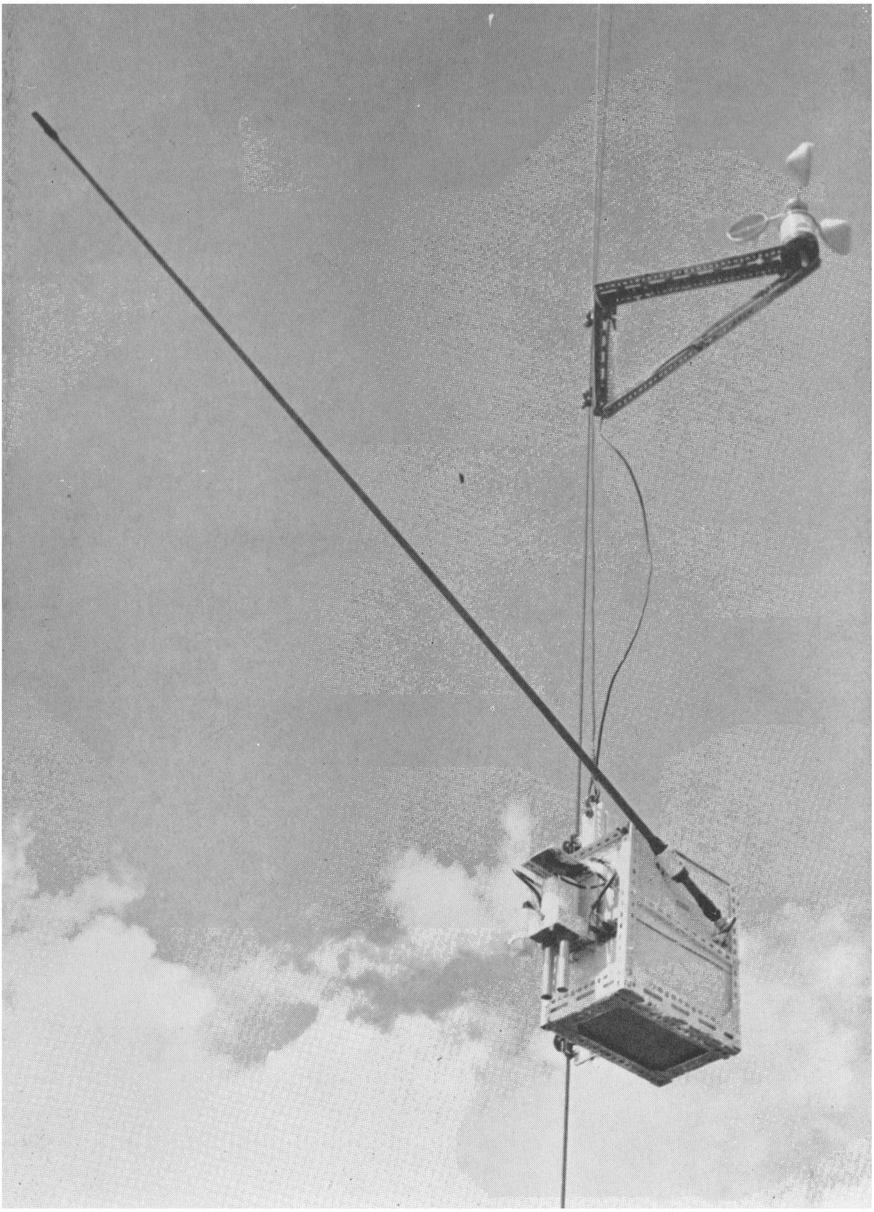

PLATE II—COMPLETE TETHERED RADIOSONDE ATTACHED TO THE BALLOON CABLE

See page 95.

when the period for the reference resistor is, say, 1047 μs. This period must be known and used whenever measurements are being made with the particular A/F oscillator.

From the resistance calibrations of the meteorological transducers and the resistance calibration of the A/F oscillator, calibrations of the meteorological transducers are evaluated in terms of periodicity. This process is done on a computer and tables are produced to give the temperature to 0·1 degC and the pressure to 0·1 mb. The final temperature calibration against periodicity is almost linear, being about 8 μs per degC. This is convenient although fortuitous and occurs because the resistance/temperature calibration of the thermistor and the resistance/periodicity calibration of the oscillator are combined to give a linear relationship between temperature and periodicity. The pressure calibration ranges from 0·3 mb/μs at 800 mb to 1·8 mb/μs at 1050 mb.

In routine use, small changes in the stability of the oscillator are observed by measuring the periodicity corresponding to the reference resistor. The difference between this periodicity and that for which the calibration of the oscillator was evaluated is applied as a displacement correction to all periodicity readings obtained with the meteorological transducers. To estimate errors likely to be introduced by this method, readings were taken with the A/F oscillator under standard conditions and again with the voltage reduced by 0·1 volt and the temperature increased by 10 degC, under which conditions the errors are cumulative. Under these conditions, by assuming a constant periodicity correction as given by the reference resistor, the errors in temperature were found to be no greater than 0·03 degC and the errors in pressure no greater than 0·2 mb. During routine operation of the sonde the stability of the calibration of the thermistors is checked weekly by taking a periodicity reading when the thermistor is in a bath of ice. The pressure sensor is checked at the beginning of each ascent by taking a periodicity reading and comparing this reading with a value from the calibration corresponding to a pressure reading from a standard barometer. Laboratory tests showed that, provided the transducers did not produce a difference of more than 1·5 μs from their original calibrations, a constant periodicity correction could be applied to all readings with a maximum error of 0·04 degC for temperature and 0·2 mb for pressure. In operation, the corrections from all sources are less than 1 μs so that the application of constant periodicity corrections over the whole range of temperature or pressure is well justified.

Wind speed. For the tethered radiosonde no change has been made to the wind speed sensor. For very light winds a sensitive cup-contact anemometer is used and for higher wind speeds a standard Meteorological Office cup-contact anemometer is used. The signals from the wind oscillator are filtered at the ground, the pulses are automatically recorded, and the mean wind speed is obtained for five minutes at each level at which measurements are made.

Ground equipment. The ground equipment is very simple, consisting of a short-wave radio receiver, two filters to discriminate the signals from the two A/F oscillators, a counter to measure the anemometer pulses, and a digital frequency counter which displays the periodicities from the pressure and temperature oscillator. At present the pressure and temperature readings are written down but there are plans for automatic recording.

Soundings. Soundings are made daily when conditions are suitable at the standard times of 00, 06, 12 and 18 hours GMT. Plate II shows the instrument connected to the balloon cable. The cup anemometer is fixed to a bracket on this cable about 2 m above the main sonde to which it is wired; the main sonde contains the pressure sensor, the various circuits and accumulators and the psychrometer, which can be seen projecting from the container. The long rod is the ¼-wave aerial which consists of a piece of wire inside a glass-fibre fishing rod. Since the transmitter is for the most part over the receiving station, the best attitude of the aerial has been found to be at about 30° to the horizontal. The main container of the sonde is approximately 50 cm by 22 cm by 38 cm and its weight including accumulators and psychrometer is about 16 kg. Readings of all elements are taken at nominal heights of 2, 36, 75, 150, 300, 450, 600, 750 and 900 metres, these heights being determined by the length of the balloon cable paid out. On the midnight sounding readings are also taken at 225 m. The sonde is held at each height for six minutes. Temperature and pressure readings are taken after five minutes. A continuous count of the wind speed is made from the end of the first minute to the end of the sixth minute and the mean wind speed over five minutes is determined. The reported message for the soundings of the tethered radiosonde consists of a reading of pressure, dry-bulb and dew-point temperatures and wind speed at the nominal heights listed above.

Acknowledgements. Thanks are due to the staff at Kew Observatory, where the laboratory tests, calibration and constructional work were done, and the staff at the Meteorological Office Research Units at Cambridge and Cardington who were concerned with the field trials.

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OBJECTIVE ANALYSIS OF UPPER AIR HEIGHT AND HUMIDITY DATA ON A FINE MESH

By MARGARET J. ATKINS

Summary. This paper describes an objective analysis system which has been developed in the Forecasting Research Branch of the Meteorological Office to produce initial fields of height and relative humidity for the fine grid of the Bushby-Timpson 10-level model. The method of height analysis is based on that of Bushby and Huckle, and Corby, and is similar to the current operational analysis of the Meteorological Office. The humidity analysis has been devised specifically for the 10-level model. The possible use of these and other methods in a future operational system is discussed.

Introduction. The widespread use of numerical models in weather prediction has led to the development of several methods of objective analysis. Numerical models need as initial data certain meteorological variables to be specified at points of a regular grid or mesh. The variable most often required is geopotential height, and methods of objective analysis have been devised to produce values of geopotential height, at a regular grid of points at about 300-km intervals, by using reported height and wind data from radiosonde ascents, aircraft reports and, more recently, satellite data. Among these are Cressman's[1] correction method, Gandin's[2] method of optimal interpolation, and methods of polynomial interpolation such as that of quadric fitting, described by Bushby and Huckle[3] and Corby,[4] which is currently used in the British Meteorological Office. Although mainly used for analysing height fields, some of these methods have been used to analyse other variables such as wind.

With the development of more sophisticated numerical models such as the Bushby-Timpson[5] 10-level model, some thought needs to be given to the most suitable method of objective analysis which should be used with the new models in an operational system. The 10-level model requires initial values of heights, winds and relative humidities; the heights and winds are required at all levels, and the relative humidities at the mid-points of the 7 lowest layers of the model. The heights and relative humidities are obtained from analyses of observed data, and the winds are obtained from the height fields by means of the balance, omega and continuity equations, as described by White.[6] There are two versions of the model. One is on a hemispheric scale and has a grid length of about 300 km in middle latitudes; established methods of objective analysis may be used for the height fields in this case. The other, on a finer scale, has a grid length of about 100 km, and it is this version with which the work described in this paper is concerned.

An experimental analysis system for the fine-scale version of the 10-level model has been developed in the Forecasting Research Branch of the Meteorological Office. This has shown up some problems in the analysis of heights on a fine grid and some improvements and other possible methods of analysis are suggested. It has also necessitated the development of a completely new system to analyse relative humidity.

Contour height. Upper air data are analysed at the seven standard levels 100, 200, 300, 400, 500, 700 and 850 mb. The 1000–500-mb thickness is also analysed and used in conjunction with the 500-mb field to obtain a 1000-mb field. The 900, 800 and 600-mb fields are obtained by vertical linear interpolation using formulae given by White.[6] A more realistic 1000-mb field obtained from surface data is compared with the 1000-mb field obtained from upper air data. The upper levels are adjusted according to the formulae

$$h_n' = h_n + \frac{(n-1)}{9} \cdot \Delta h \qquad \ldots (1)$$

where n is an integer and $1 \leqslant n \leqslant 10$, h_n' is the corrected height at $n \times 100$ mb, h_n is the original height at $n \times 100$ mb and Δh is given by

$$\Delta h = h_s - h_{1000} \qquad \ldots (2)$$

where h_s is the 1000-mb height obtained from surface data and h_{1000} is the 1000-mb height obtained from upper air data. The surface data are currently analysed subjectively, but a computer programme is being developed for the objective analysis of surface data for the fine mesh. The fields are then ready for the initialization procedure.

Analysis methods: quadric fitting, 'single-scan'. In the first experiments the operational objective analysis system used in the Meteorological Office at that time was adapted to the fine grid of the 10-level model, the grid length being one-third of that of the operational model. This method, for all levels except 100 mb is described by Bull[7] and is based on that of Bushby and Huckle[3] and Corby.[4] In the analysis of each grid point on the fine grid, the observations used were the same as if the point were one of a larger grid and the distance weighting factor for each observation remained the same in terms of distance on the surface of the earth (Figure 1). The relative weight of winds to heights and the relative weight of observations to background field also remained the same. The background fields were derived by three-dimensional linear interpolation from the operational

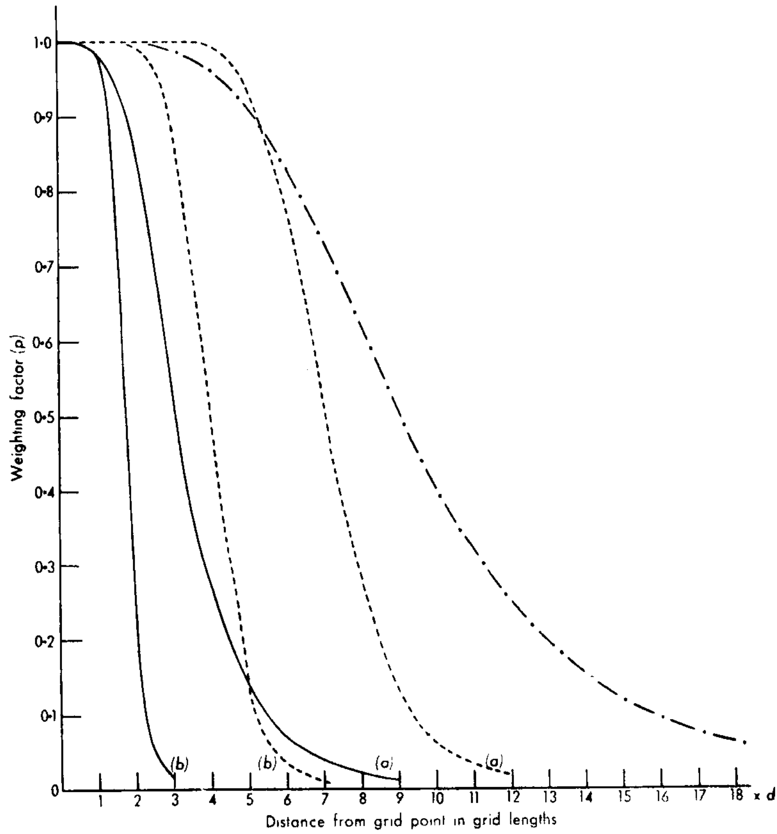

FIGURE 1—DISTANCE WEIGHTING FACTORS

——— Humidity (*a*) 1st scan $\dfrac{1}{1+0{\cdot}01d^4}$ (*b*) 2nd scan $\dfrac{1}{1+0{\cdot}01d^8}$

– – – – 2-scan height (*a*) 1st scan $\dfrac{1}{1+1{\cdot}5\times10^{-7}d^8}$ (*b*) 2nd scan $\dfrac{1}{1+1{\cdot}5\times10^{-5}d^8}$

— · — 1-scan height $\dfrac{1}{1+1{\cdot}4371794\times10^{-4}d^4}$

where d = grid length

analyses at 1000, 500, 200 and 100 mb. The nine background points used were as shown in Figure 2.

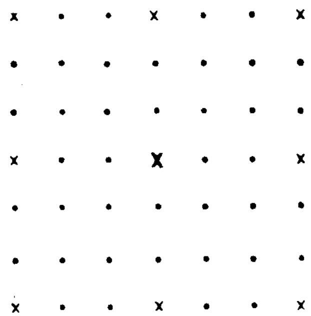

FIGURE 2—BACKGROUND FIELD POINTS USED IN ANALYSIS OF ONE GRID POINT

X Grid point being analysed
x Grid points used
Distance between **x** and **x** is 300 km.

The 100-mb analysis was essentially that devised by Woodroffe,[8] with similar modifications to those described above. The background field was obtained by horizontal interpolation from the operational 100-mb analysis.

The results on the whole tended to be rather rough, particularly at upper levels in regions of strong winds. The data check after the first analysis was found to be unsatisfactory. In the first analysis erroneous heights tended to be fitted in favour of correct winds. During the data check these heights were not rejected but some correct winds were rejected, resulting in an even poorer second analysis.

Since the object of this work was to produce analyses for research purposes rather than operational use, it was decided to leave out the automatic data check at all levels except 100 mb, where it is an essential part of the method, and examine the data subjectively before the analysis was begun. The data were extracted from archival magnetic tapes containing synoptic upper air observations and a facility was put into the programme for rejecting or inserting data. It was found that owing to a lack of data in the Atlantic the insertion of artificial data to produce a more realistic analysis was necessary on some occasions.

This procedure, however, did not remove all roughnesses and further investigation of some of the actual quadric surfaces in one of the worst cases showed that there was some difficulty in fitting winds. Winds at a distance of more than about six grid lengths from the basic grid point were very badly fitted and their exclusion from the data caused the nearer winds to be fitted better. This was because a quadric surface necessarily has a constant rate of change of slope in any direction and the combined height and wind data suggested a surface whose slope first increased and then decreased on crossing the area surrounding the grid point. This suggests that a better analysis could be obtained by only including winds within, say, six grid lengths, or by letting the distance weighting factor for winds fall off more sharply with distance from the grid point.

The roughnesses in the field, therefore, are caused not merely by over-fitting of bad observations with the use of an interpolated analysis as a background field, although this may be a contributory factor, but by the inadequacy of the quadric surface to fit the data. This inadequacy may cause a considerable change in the form of the surface, if there is a change in the data when the analysis passes from one grid point to the next, and on a fine grid these changes show up as roughnesses in the field. However, with the judicious rejection and insertion of data in bad cases, it was thought that the smoothing of the analysis in the initialization process would be sufficient to remove these roughnesses so as not to upset the forecast. Both objective analyses that have so far been used for forecasts, that is those for 12 GMT, 9 July 1968 and 00 GMT, 6 February 1969, have been done in this way.

One objective method of improving the data is to use the differences between the observations and the analysis at 100 mb to correct the data at lower levels (Hawson and Caton[9]). A proportion of these differences, or random errors, is removed from the data at each of the levels from 500 to 200 mb. Although the 100-mb analysis on the 10-level grid is not perfect, it seems good enough to improve the analyses of lower levels by this method.

Analysis methods : quadric fitting, 'double-scan'. About the time that this work was being done, problems concerning the fitting of winds in the operational analysis were noticed. Some work by Spackman, of the Central Forecasting Office of the Meteorological Office, concerning the distance weighting factors has led to an improved scheme, here referred to as the 'double' or '2-scan' method, being introduced into operational use. The main features are :

(i) the first analysis is used as a background field for the second,
(ii) a distance weighting factor which gives less weight to more distant observations is used in the second analysis, and
(iii) the values of T^2, the factor weighting winds relative to heights, is increased in the second analysis.

This has now been adapted to the analysis scheme for the 10-level grid in a similar way to the 'single-scan' system and is summarized in Table I, where p is the distance weighting factor (see Figure 1) for an observation at d grid lengths from the grid point being analysed.

TABLE I—WEIGHTING FACTORS USED IN 2-SCAN METHOD FOR HEIGHT FIELD

Scan No.	p	T	Background field
1	$\frac{1}{1+1{\cdot}5\times 10^{-7}d^8}$	4	Interpolation from operational analysis
2	$\frac{1}{1+1{\cdot}5\times 10^{-5}d^8}$	8	Result of 1st scan

The double-scan method has been run a few times only, but results so far indicate a smoother analysis and a closer fit to observations than has been obtained with the single-scan method.

Other possible analysis methods.

(i) *Linear interpolation from a larger grid.* An acceptable analysis might be obtained by direct linear interpolation from a larger grid, as has been used to obtain background fields. However, current evidence suggests that this is unlikely to give as good results as the above scheme, although improvements in the coarse grid analysis would result in corresponding improvements in the interpolated fine-scale analysis.

(ii) *Two-dimensional orthogonal polynomials.* A pilot experiment has been done using Dixon's[10] method of orthogonal polynomials on a small area of the 10-level grid. The results are good but more work needs to be done.

(iii) *Three-dimensional analysis in the orthogonal system.* Experimental work done in the Central Forecasting Office of the Meteorological Office has shown that it may be possible to use Dixon's method in three dimensions and to fit the whole volume of the 10-level model in four or two blocks, or even only one block, thus ensuring both horizontal and vertical consistency.

Relative humidity. In the analysis system which is being developed in the Forecasting Research Branch of the Meteorological Office, objective analyses of relative humidity are used for the layers centred at 850, 750, 650, 550, 450 and 350 mb. It is thought that surface data should be used in the 950-mb analysis and since surface humidity data are only just becoming available in digital form, the 950-mb layer is at present analysed subjectively.

Relative-humidity data are available at standard levels, and the relative humidity at the mid-points of the layers is obtained by vertical interpolation at each observing station.

Method of analysis. Since fields of relative humidity are characterized by sharp gradients and by features on the scale of fronts, it was decided that each observation should influence the analysis over a small area only. As there is no analogue to the wind used in the height analysis, there is only a small amount of information available for analysing the humidity at a particular grid point, and therefore it was decided to use a simple weighted mean of the data.

As there are large areas over the sea with no data, a background field is necessary. In an operational system it might be possible to use a forecast humidity field but for research purposes this is unpractical. Instead a background field based on initial vertical velocities derived from the omega equation as described by White[6] is used. It proved difficult to derive a formula for relative humidity in terms of vertical velocity by statistical methods, probably because of the large areas of slow upward and downward motion. The following empirical formula was devised :

$$R = \begin{cases} 70 - 5\omega & \text{for } -6 \leqslant \omega \leqslant 14, \\ 100 & \text{for } \omega < -6, \\ 0 & \text{for } \omega > 14, \end{cases} \qquad \ldots (3)$$

where R is relative humidity and ω is vertical velocity in millibars per hour. This gives a reasonable range of relative humidity. Equation (3) has been tried on two cases which were very different from each other. The first (12 GMT, 9 July 1968) gave fairly smooth fields, but at upper levels the general value was too high. The second (00 GMT, 6 February 1969) was characterized by strong upward and downward motion and the resulting background field was rather rough. It may be necessary to alter this formula in the light of experience.

The formula used in the analysis for each grid point is of the form

$$R = \frac{\sum_{i=1}^{n} (p_i R_i + b R_b)}{\sum_{i=1}^{n} p_i + (b)} \qquad \ldots (4)$$

where R_i is an observation of relative humidity at a nearby station, R_b is the value of the background field of relative humidity at the grid point concerned, b is the relative weight of the background field to the observations and p_i is a distance weighting factor for observations of the form

$$p_i = \frac{1}{1 + \lambda d_i^{\gamma}} \qquad \ldots (5)$$

where d_i is the distance in grid lengths from the station to the grid point, and λ and γ are parameters which determine the shape of the curve. The summation of (4) is taken over the n nearest stations. In practice n was limited to six. When there are no observations, equation (4) is replaced by the value of the background field.

At first it was decided that only stations within three grid lengths of the grid point should be used; for most grid points this implied fewer than four stations. The distance weighting factor was

$$p = \frac{1}{1 + 0{\cdot}01 d^8}. \qquad \ldots (6)$$

This was found to be unsatisfactory as in places the background field differed markedly from the observations and this resulted in 'pools' around isolated observations.

The system which has been adopted is one which consists of two scans through the field. The first uses the background field derived from vertical velocities, and up to six stations within a distance of nine grid lengths from the grid point. The second scan uses the results of the first scan as background field, and stations up to three grid lengths from the grid point. This second scan is intended to bring out the smaller-scale features.

The system is summarized in the Table II.

TABLE II—WEIGHTING FACTORS FOR 2-SCAN METHOD FOR HUMIDITY FIELD

Scan No.	p	r	Background field	b
1	$\frac{1}{1 + 0{\cdot}01 d^4}$	9	$70 - 5\omega$	0·05
2	$\frac{1}{1 + 0{\cdot}01 d^8}$	3	Result of 1st scan	0·2

where r is the radius of influence in grid lengths. The distance weighting factors are shown in Figure 1. In the first scan the weight of the background field is the same as that of an observation at about six and a half grid lengths, and in the second scan it is the same as that of an observation at about two grid lengths.

Results for an occasion in February 1969. Figures 3 and 4 show

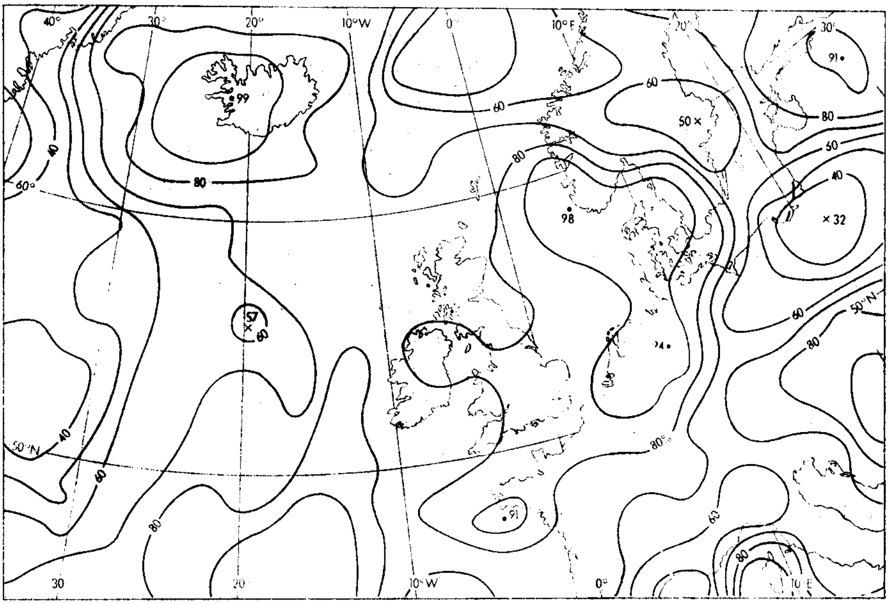

FIGURE 3—OBJECTIVE ANALYSIS OF 850-mb RELATIVE HUMIDITY FIELD, 00 GMT, 6 FEBRUARY 1969

Isopleths at intervals of 10 per cent.

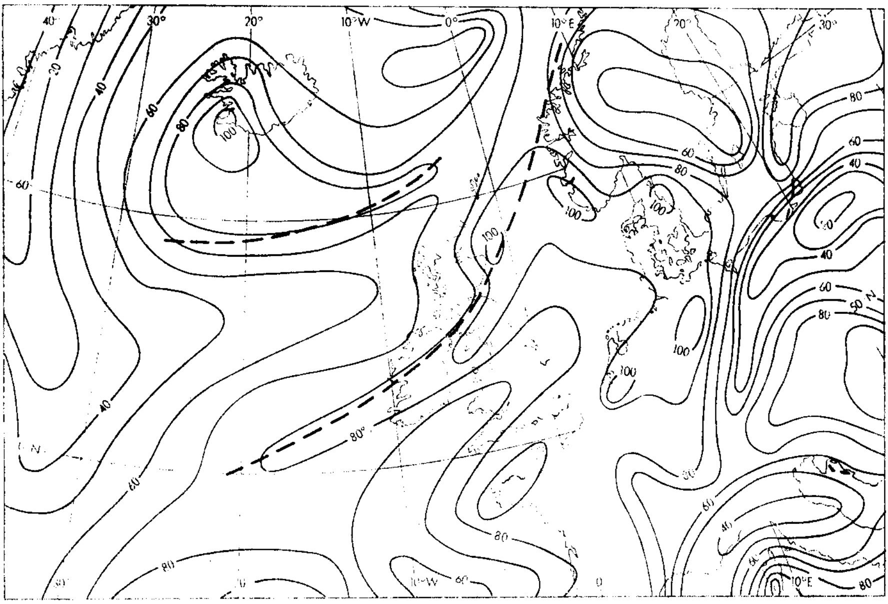

FIGURE 4—SUBJECTIVE ANALYSIS OF 850-mb RELATIVE HUMIDITY FIELD, 00 GMT, 6 FEBRUARY 1969

— — — Surface fronts

Isopleths at intervals of 10 per cent.

objective and subjective analyses of relative humidity at 850 mb for 00 GMT on 6 February 1969. The values at the corresponding grid points are reasonably close to each other, although the shapes of the features are different. The shape is not quite so important here as in a height analysis, because it does not imply anything analogous to a wind. However, in sparse data areas it is difficult to identify such features as fronts. In this case there was a surface front from western Norway, through Shanwell and Long Kesh, to just south of ocean weather station 'J'.

An objective analysis of humidity for this date, for all levels from 850 to 350 mb with a subjective 950-mb analysis, has been successfully used in conjunction with an objective height analysis to produce a 24-hour forecast. Figures 5 and 6 show the actual synoptic situation for 00 GMT on 6 and 7 February 1969 respectively. Figure 7 shows the forecast surface and 500-mb patterns valid for 00 GMT on the 7th. The surface trough has been forecast to move from a position south-east of Iceland across the British Isles into the North Sea, although it has not been deepened sufficiently. The region of high pressure in the Atlantic has been intensified and that over Europe weakened. The 500-mb trough has been moved eastward but it is still 5° of longitude too far west and not sufficiently deep. Figure 8 shows the present weather for 00 GMT on the 7th. There are scattered showers over most of the British Isles except south-east England; they are more frequent on exposed coasts but there are some inland, mostly carried in from the sea by strong winds. Figure 9 shows the forecast precipitation for the same time. The main area of rain has been forecast to the east of the British Isles but in the southern North Sea is west of its actual position; the area indicated in the Atlantic is purely convective. There is an absence of showers over the British

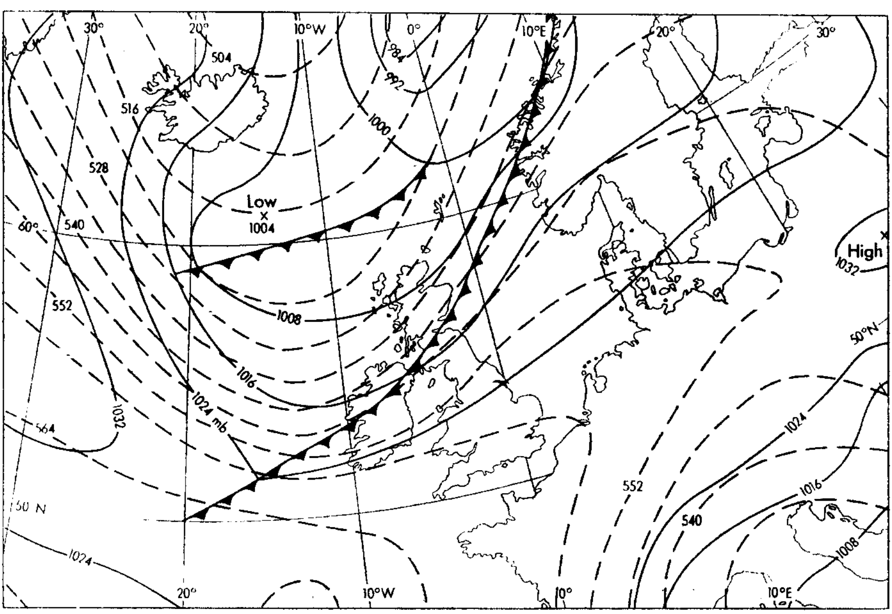

FIGURE 5—ACTUAL SYNOPTIC SITUATION, 00 GMT, 6 FEBRUARY 1969
——— Surface isobars at intervals of 8 mb
— — — 500-mb contours at intervals of 6 geopotential decametres

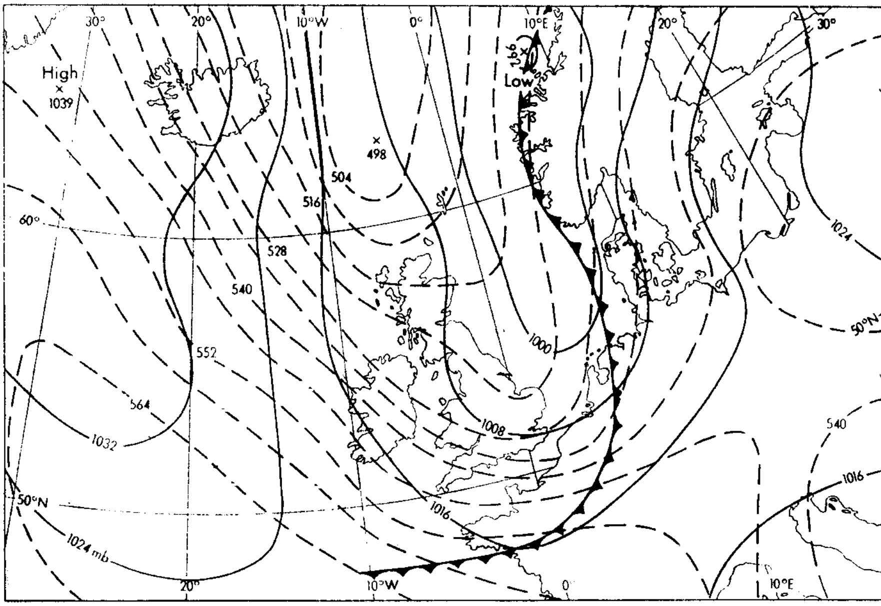

FIGURE 6—ACTUAL SYNOPTIC SITUATION, 00 GMT, 7 FEBRUARY 1969

——— Surface isobars at intervals of 8 mb
— — — 500-mb contours at intervals of 6 geopotential decametres

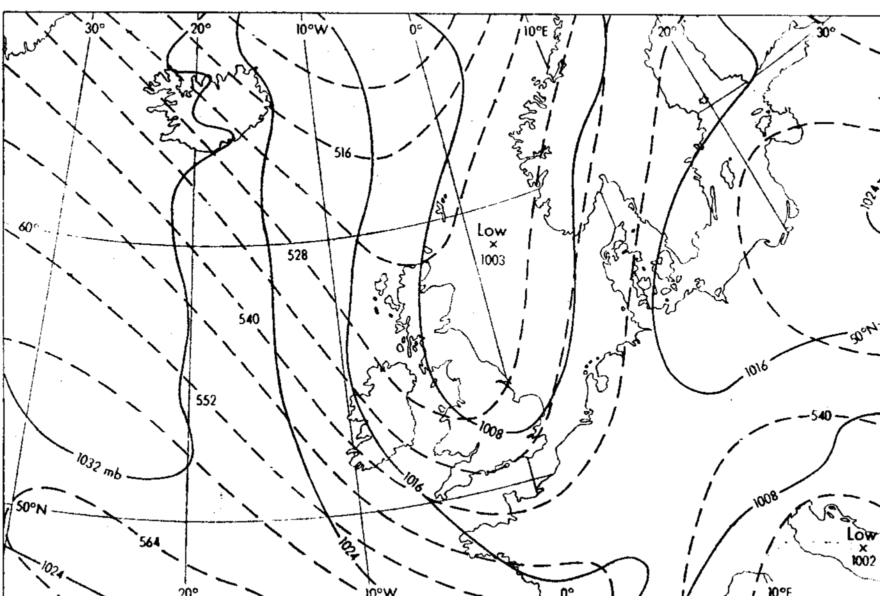

FIGURE 7—24-HOUR FORECAST OF SYNOPTIC SITUATION, 00 GMT, 7 FEBRUARY 1969

——— Surface isobars at intervals of 8 mb
— — — 500-mb contours at intervals of 6 geopotential decametres

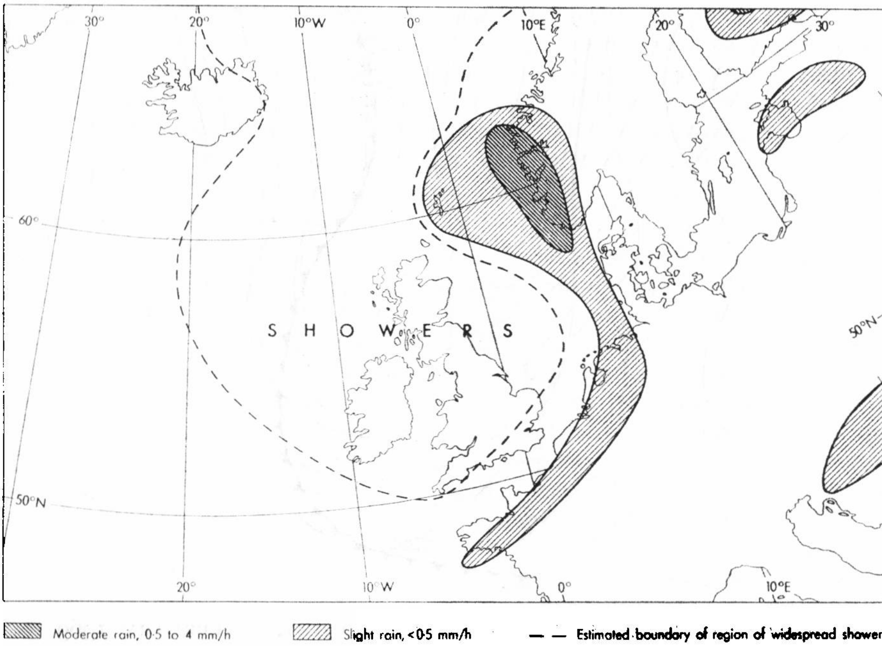

FIGURE 8—PRESENT WEATHER, 00 GMT, 7 FEBRUARY 1969

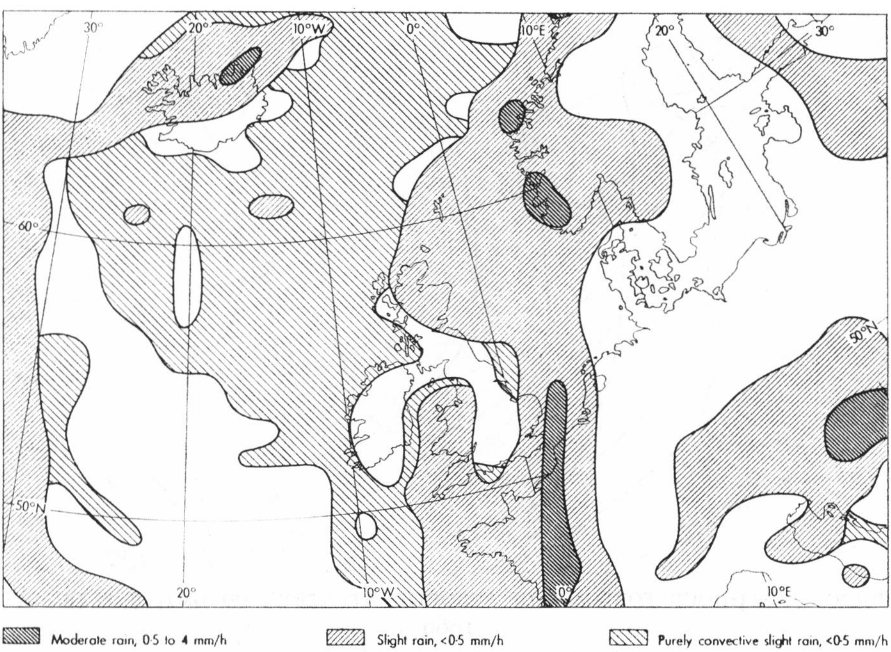

FIGURE 9—24-HOUR FORECAST OF TOTAL RATE OF RAINFALL, 00 GMT, 7 FEBRUARY 1969

Isles in the forecast because the surface heating, which is used in the model for land surfaces in February, is naturally insufficient to induce convection and the model does not allow for showers being advected inland from over the sea.

A 6-hour forecast was also computed using the same objectively analysed heights but subjectively analysed humidities. There are some small differences between the 6-hour forecast in the 1000-mb height and rainfall. However, these are probably the result of the way the 950-mb humidity field was obtained and mask effects due to the difference between subjective and objective analyses at higher levels. In the subjective case, a subjective analysis of surface humidity was used as a 1000-mb humidity field and the 950-mb field was obtained by vertical interpolation. In the objective case this same subjective analysis was used directly as the 950-mb humidity field. This resulted in the 950-mb field being moister in the objective analysis in some areas, and at 6 hours the forecast from objective data appeared better.

Discussion. The system of analysis of heights and humidities described above is adequate for research purposes but would not be suitable for operational use in its present form. Both the height and humidity data are examined subjectively before the analyses commence, and those used in the analyses are assumed correct. At present the 1000-mb height and 950-mb humidity fields are analysed subjectively. It should be relatively easy to develop a 1000-mb height analysis from surface data using established methods, but some research needs to be done on the use of surface humidity data in the analysis of the 950-mb relative humidity field.

A probable method of improving the height analyses is the use of orthogonal polynomials in two dimensions and it may be possible to fit the whole area of the 10-level model with one surface. It is not thought likely that linear interpolation from a larger grid would improve the height analyses very much.

The humidity analysis is good over areas of good data coverage but could be improved over areas of sparse data. Some possible methods are as follows :

(i) The use of forecast humidity fields as background fields.

(ii) A better background field obtained by an improved relationship with vertical velocity.

(iii) The use of surface cloud and present weather data. Chisholm *et alii*[11] and Ball and Veigas[12] have done some work relating dew-point depression at 850, 700, 500 and 400 mb with surface observations.

(iv) The use of satellite cloud data.

(v) The use of significant-level data. This could be particularly valuable in analysing the 950-mb layer.

However, the method of objective humidity analysis for upper levels described above compares well with a subjective analysis and it has been used to obtain a reasonable forecast. It should be possible to use it operationally if no better method is meanwhile developed.

Acknowledgements. I wish to thank members of the staff of the objective analysis section of the Central Forecasting Office of the Meteorological Office for the use of some of their programmes and for their general help and advice, and also Mrs V. D. McDougall for her assistance in the programming for this work.

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551.558.21

MOUNTAIN LEE-WAVE INCIDENTS IN SCOTLAND

By M. BAILEY

Summary. Three cases of mountain lee waves are described. In each case the aircrew reports are related to the values of wavelength and maximum vertical velocity determined by the method due to Casswell. It is suggested that this technique can provide a useful guide when assessing the aviation hazards in a particular wave situation.

Introduction. Recent work by Casswell[1] and Foldvik[2] has given forecasters a simple graphical method whereby maximum vertical velocities, wavelength and level of maximum amplitude of mountain lee waves can be assessed using simple quantities obtained from a representative tephigram.

The vertical motions, wind variations and turbulence involved in well-developed wave systems can each present a major hazard for aircraft. When an aircraft in level flight encounters a wave updraught it will tend to rise, but its angle of attack may be reduced by the pilot so the aircraft will enter a shallow dive relative to the rising air and its airspeed will increase. If altitude is maintained in a downdraught, airspeed will decrease unless power is increased. A stall might result from this loss in airspeed.

When an aircraft is climbing through a wave system, for example on take-off, the actual rate of climb will vary, being greater in the updraughts. This variation is not directly related to the strength of the draughts, because the actual rate of climb will depend upon how the aircraft is flown, and its type, since entry into a draught will alter the incidence of air on the wing and hence the lift. This is illustrated in the first case described (Figure 4). Units used are in accordance with the usual aviation units.*

*Conversion factors to Système International (SI) units: 1 kt ≈ 0·5 m/s, 1000 ft/min ≈ 5 m/s 1000 ft ≈ 300 m, and 1 n. mile ≈ 2 km.

29 April 1966. At 0550 GMT on 29 April 1966 a British European Airways Herald aircraft flying from Aberdeen to Edinburgh reported marked standing waves. Writing several days after the event the pilot described the incident.

> 'I recall that the rate of climb was varying between 600–800 ft/min and 1500–1700 ft/min and the airspeed was varying between 160 and 210 kt in sympathy. As I recall there was no noticeable turbulence. In consequence of aircraft weight, altitude and power in use, rate of climb should have been approximately 1000–1200 ft/min and airspeed constant at 204 kt. Airspeed in the updraughts would have been in excess of the 210 kt stated, but power was reduced to keep speed within the aircraft limits.'

The route flown lies on a bearing of 226° (true) from Aberdeen/Dyce to Perth. This airway (shown on Figure 1) crosses the eastern flank of the Grampians where there are several ridges and valleys approximately at right angles to the route.

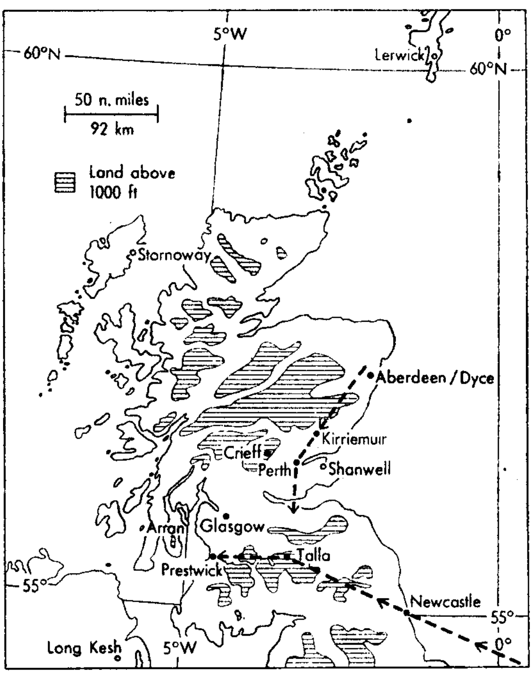


FIGURE 1—ROUTES FLOWN BY AIRCRAFT REPORTING TURBULENCE
o Upper air stations

The 06 GMT surface chart showed a weak warm front to the west of the British Isles and a strong south-westerly gradient over Scotland. Similarly, the 500-mb chart showed a strong south-westerly flow, mainly to the west of Scotland (Figure 2). This strong wind belt moved slowly eastwards during the day. The 00 GMT upper air sounding from Shanwell had a marked inversion at 850 mb, with instability above and below. This inversion was probably due to subsidence but there was evidence of the warm frontal air at 500 mb. At 06 GMT the wind at the inversion level was 42 kt, increasing above the 400-mb level to reach 69 kt at the tropopause. Figure 3 shows

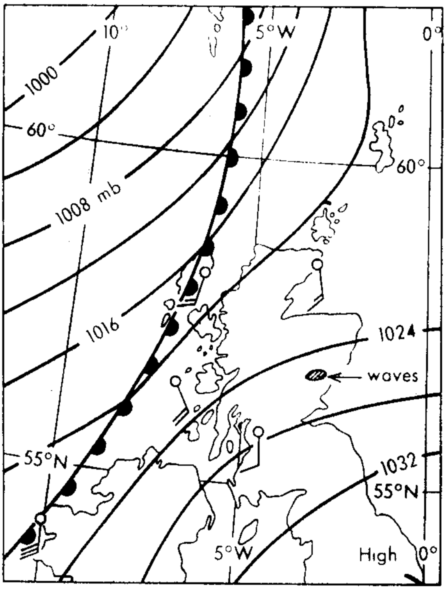


FIGURE 2—SYNOPTIC SITUATION AT 06 GMT ON 29 APRIL 1966, AND SHOWING LOCATION OF WAVES

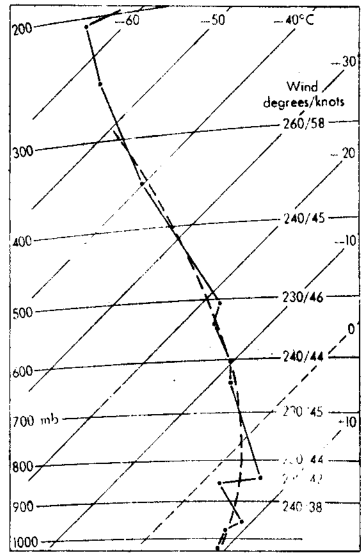


FIGURE 3—UPPER AIR SOUNDING FOR SHANWELL AT 00 GMT ON 29 APRIL 1966, WITH WINDS AT 06 GMT

·———· Temperature
— — — Smoothed curve used in Casswell calculation

the 00 GMT sounding from Shanwell and the 06 GMT winds with the smoothed curve used in the Casswell calculation. The results appear in Table I.

TABLE I—MOUNTAIN LEE WAVES OBSERVED AND PREDICTED, 29 APRIL 1966

Location	Time GMT	Wind at 900 m *deg/kt*	Wind components* 850 mb *knots*	500 mb *knots*	Wavelength (Observed) *n. miles*	Vertical speed (Observed) *ft/min*	Height (Observed) *ft*
Observations							
Banchory	0550					400	6 000
Calculations					(Computed)	(Computed)	(Computed)†
Long Kesh	00	220/29	34	33	5·8	290	8 500
	06	230/38	40	44	7·8	456	11 000
Shanwell	00	230/35	34	33	6·2	420	9 000
	06	240/38	41	45	9·0	494	11 000

*Components at right angles to ridge.
†Level of maximum amplitude from Casswell's graph.

When Casswell's method was used the 06 GMT winds at Shanwell gave a maximum vertical velocity of 494 ft/min with a maximum amplitude at 11 000 ft and a wavelength of 9 n. miles, whereas the aircrew reported changes in the rate of climb equivalent to 400 ft/min at a level 5000 ft below this. Figure 4 shows the aircraft flight path from Aberdeen, based on an estimated ground speed and expected rate of climb. The updraughts and downdraughts were encountered while climbing through the 6000-ft level in the region 15 to 20 n. miles south of Aberdeen. Simplified streamlines have been drawn to show the wave motion downstream of the final lee slopes of the Grampians.

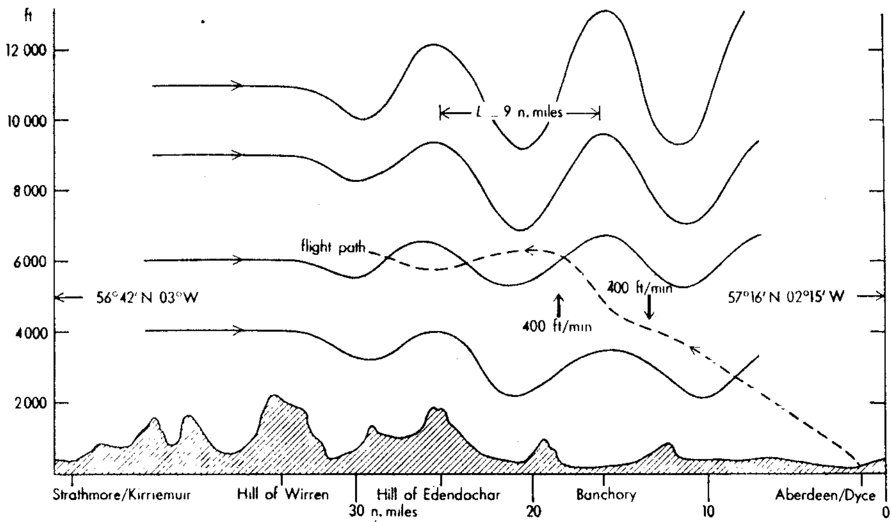


FIGURE 4—SIMPLIFIED CROSS-SECTION FROM ABERDEEN/DYCE TO KIRRIEMUIR, 29 APRIL 1969

L = wavelength

Theory indicates that the first wave-crest will occur three-quarters of a wavelength downstream of the initiating ridge. It is usually accepted that the final lee slope of a mountain system determines the wave form over the downstream lowlands, although Bérenger and Gerbier[3] suggest that consecutive mountain ridges may cause resonance and affect the wave amplitude. The wave amplitude could be increased if ridges are in phase with the wave form and the distance between ridges is close to the wavelength. Examination of the relief profile showed that the Hill of Edendochar was the final marked lee slope below the airway but approximately 7 n. miles upstream a sharp lee slope lies on the north side of the Hill of Wirren. In composing the diagram it was assumed that the latter slope generated the final wave motion with resonance over the Hill of Edendochar, which lies three-quarters of a wavelength downstream. The greatly simplified wave train shown in Figure 4 had a trough about 21 n. miles south of Aberdeen and a crest about 16 n. miles south of Aberdeen. The diagram shows how the aircraft penetrated the updraughts and downdraughts in this region and the flight path has been adjusted in accordance with the modified rates of climb reported. Rough values for the wave amplitudes were obtained using the formula

$$w_{(\mathrm{max})} = \frac{2\pi U a}{L}$$

(where w is the vertical component of wind, U the horizontal component of wind, a the semi-amplitude and L the wavelength) quoted by Corby.[4] In this case there is fair agreement between computed values and those observed.

13 January 1967. On this occasion four reports of mountain lee waves or associated phenomena were received at Prestwick. At 0330 GMT a pilot flying between Amsterdam and Prestwick reported wave activity over the Southern Uplands with vertical velocities of 300 ft/min at 8500 ft. At 0915 GMT severe turbulence was reported between 1000 and 1500 ft near Glasgow Airport, and during the afternoon reports of downdraughts with vertical speeds 1500 ft/min were received. These occurred in the vicinity of Crieff between 4500 and 6000 ft and south of Shanwell at 3000 ft.

At 00 GMT an anticyclone was situated between ocean weather station 'J' and the Brest peninsula. The centre drifted slowly south-east and a strong west to north-west surface flow was maintained throughout the day over Scotland and Northern Ireland (Figure 5). The upper air pattern was similar

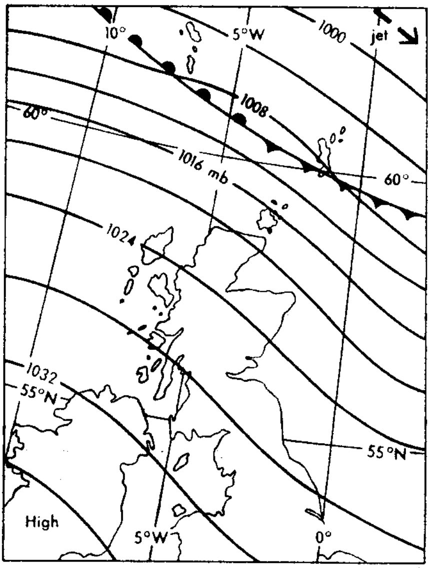
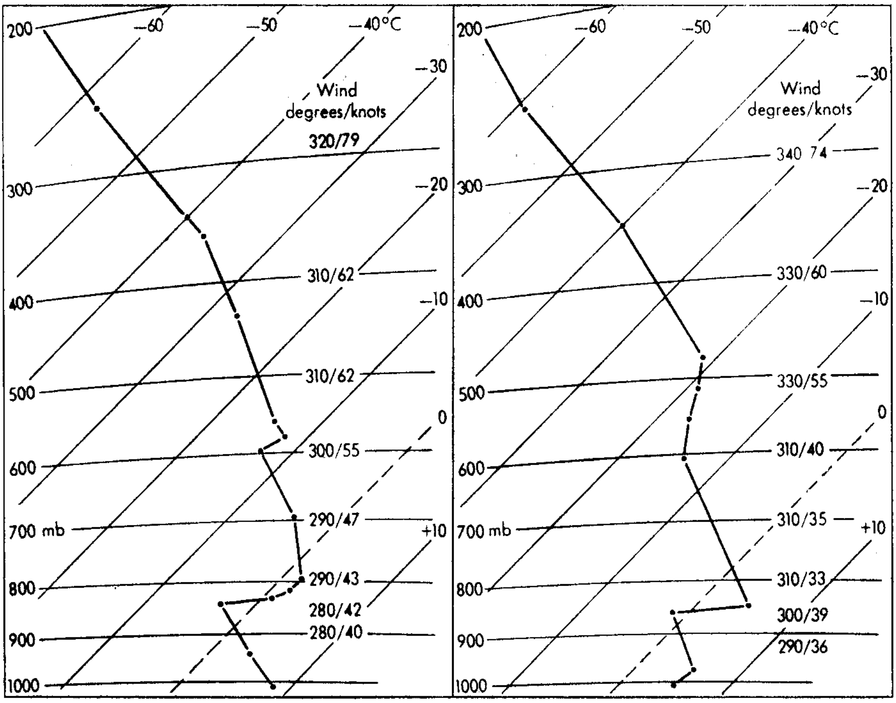


FIGURE 5—SYNOPTIC SITUATION AT 06 GMT ON 13 JANUARY 1967

with a strong flow around the high centre south-west of Ireland. The strongest wind belt lay to the north of the British Isles with a jet stream from Iceland to Oslo. The upper air soundings at Long Kesh, Stornoway and Shanwell (Figure 6) all show typical subsidence inversions close to 850 mb. At Stornoway the steady increase of wind with height was particularly favourable to wave development, but winds at Shanwell and Long Kesh were barely strong enough for well-developed waves.

Calculations based on Casswell's method gave the results in Table II. The wavelengths and vertical speeds increase from the south to north, i.e. towards the strong wind zone. The calculated levels of maximum amplitude were also higher in the north. The highest calculated vertical velocity was 560 ft/min based on the 00 GMT data. At Long Kesh a value of 300 ft/min at 6000 ft was obtained at 00 GMT but the method failed to give results at 06 GMT and 12 GMT.

Examining the four reports one finds fair agreement between the 00 GMT values at Long Kesh or Shanwell and the report from the Southern Uplands. It is probable that these waves were due to the coastal hills of Ayrshire, or possibly the island of Arran. The Glasgow report may be due to a downdraught in the lee of the Kilpatrick Hills but marked wind shear above the Clyde Valley could also be a contributory factor. At 0920 GMT Glasgow



(*a*) Stornoway (*b*) Shanwell

FIGURE 6—UPPER AIR SOUNDING AND WINDS FOR STORNOWAY AND SHANWELL AT 00 GMT ON 13 JANUARY 1967

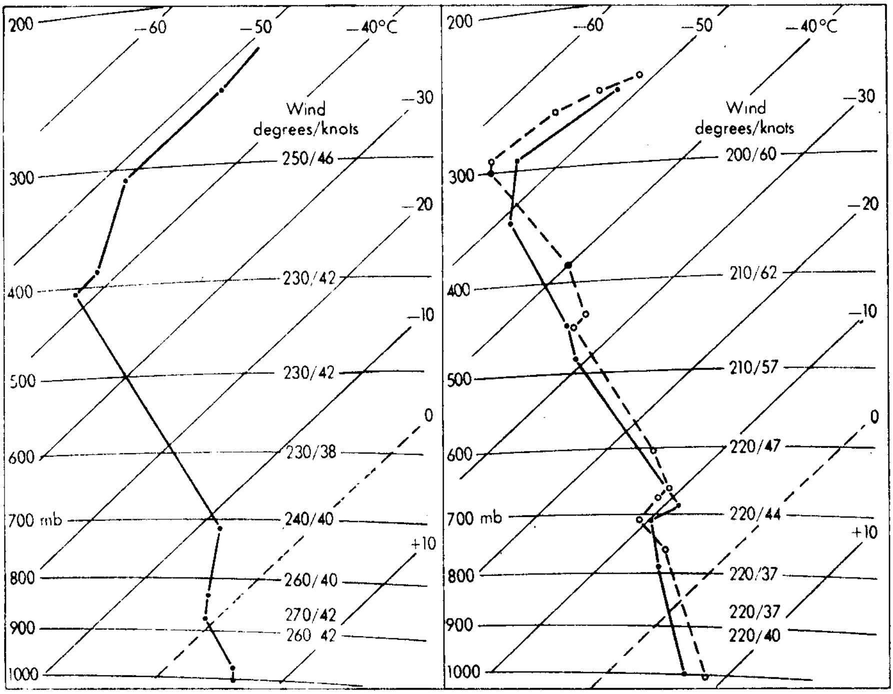
TABLE II—MOUNTAIN LEE WAVES OBSERVED AND PREDICTED, 13 JANUARY 1967

Location	Time	Wind at 900 m	Wind components* 850 mb	Wind components* 500 mb	Wavelength (Observed)	Vertical speed (Observed)	Height (Observed)
	GMT	*deg/kt*	*knots*	*knots*	*n. miles*	*ft/min*	*ft*
Observations							
Southern Uplands	0230					300	8 500
Crieff and Shanwell						1500	3 000 6 500
Calculations					(Computed)	(Computed)	(Computed)†
Long Kesh	00	310/25	27	27	4·0	300	6 500
	06	300/29	37	24	no result	—	—
	12	310/29	39	26	no result	—	—
Shanwell	00	290/36	38	42	7·0	360	10 500
	06	300/43	44	43	7·8	344	11 500
	12	290/39	43	45	8·0	312	12 000
Stornoway	00	280/40	42	53	9·0	560	11 500
	06	280/46	43	42	7·7	414	11 000
	12	290/42	40	49	9·5	504	13 000

*Components at right angles to ridge.
†Level of maximum amplitude from Casswell's graph.

Airport reported surface wind 270° 24 kt, varying between 15 and 37 kt. At 0950 GMT the wind direction was varying between 230 and 290°. Marked vertical wind shear and turbulence are often encountered in this area, particularly when inversions exist near to the surface. Similarly, the Crieff and Shanwell cases might be associated with downdraughts to the lee of major ridges.

18 January 1967. In the third caseconsidered, mountain lee waves were encountered over the Southern Uplands. On this occasion examination of the wind and stability profiles for Long Kesh, Aughton and Shanwell (Figure 7) suggested that waves were unlikely to be a major hazard, although the strong surface winds to the south-east of the depression would produce turbulence in the lower levels. The high level of the inversions, the unstable air at



(a) Long Kesh *(b)* ·——· Shanwell o– – –o Aughton

FIGURE 7—UPPER AIR SOUNDING AND WINDS FOR LONG KESH, SHANWELL AND AUGHTON AT 00 GMT ON 18 JANUARY 1967

Long Kesh and the veering winds were the main factors in this decision. The occurrence of significant waves was demonstrated by the following report.

The crew of an aircraft flying from Amsterdam to Prestwick observed mountain waves over the Southern Uplands. The waves were encountered '20 minutes flying time from the east coast', i.e. 40 n. miles out to sea south-eastwards from Newcastle, 'continuing as far as the west coast at Prestwick'. Vertical speeds in the waves were estimated at 300–400 ft/min with the wave-length 'equivalent to 10 minutes flying time'. The flight path was overhead Newcastle to Talla at 8500 ft followed by descent to arrive at Prestwick at 0250 GMT.

At 00 GMT on 18 January 1967 a depression was situated in the Hebrides with a small wave near the Moray Firth running north-east. By 06 GMT this wave had developed into a separate centre near Shetland with the old low filling. At 00 GMT a cold front lay from Inverness through Newcastle to Southampton, moving steadily eastwards during the night (Figure 8). The

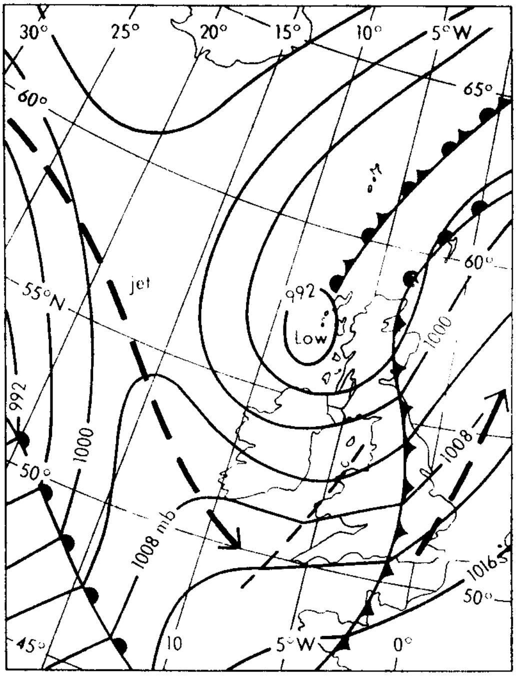


FIGURE 8—SYNOPTIC SITUATION AT 00 GMT ON 18 JANUARY 1967
Broad pecked arrow marks jet stream.

500-mb chart showed a broad trough over the Irish Sea with a south-westerly flow over England and the North Sea at 00 GMT. Over Scotland the winds at 500 mb were relatively light; the pattern at 300 mb was similar.

The upper air soundings from Aughton and Shanwell showed weak inversions at about 700 mb but the Long Kesh ascent clearly showed the cold air below the upper trough to the rear of the cold front. Wind structures were not typical of a strong wave situation but Shanwell did show a change through the inversion with a steady increase of wind above this, to reach a maximum of 65 kt at 400 mb. This had decreased considerably by 06 GMT. Winds at Aughton showed a similar pattern but were lighter. At Long Kesh the light winds veered to north-westerly by 06 GMT.

Table III shows the results obtained from Casswell's method using the 00 GMT data. It is interesting to note that results were obtained for Shanwell

TABLE III—MOUNTAIN LEE WAVES OBSERVED AND PREDICTED, 18 JANUARY 1967

Location	Time	Wind at 900 m	Wind components* 850 mb	500 mb	Wavelength (Observed)	Vertical speed (Observed)	Height (Observed)
	GMT	*deg/kt*	*knots*		*n. miles*	*ft/min*	*ft*
Observations							
Newcastle to Prestwick	0215				13·0	300–400	8 500
Calculations					(Computed)	(Computed)	(Computed)†
Long Kesh	00	260/42	41	37	no result	—	—
Shanwell	00	230/40	37	56	11·0	680	12 000
Aughton	00	230/23	23	42	5·4	506	6 700

*Components at right angles to ridge.
†Level of maximum amplitude from Casswell's graph.

and Aughton but not for Long Kesh which lay in the colder air mass. Taking Shanwell as typical of the Southern Uplands, a vertical speed of 680 ft/min was obtained with a wavelength of 11 n. miles. Estimated level of maximum amplitude was 12 000 ft. Because of the lighter low-level winds, waves calculated for Aughton were of a lower magnitude.

A mean wind of 250° 40 kt at 8500 ft on the aircraft flight path with an aircraft heading of 300° gave a resultant headwind of 26 kt. The airspeed of this type of aircraft is normally 145 kt, so in this case ground speed would be about 120 kt. In 10 minutes flying time a distance of 20 n. miles would be covered. An actual wavelength of 13 n. miles could be deduced from this report, allowing for the divergence of the track from a route parallel to the airflow. This agrees well with the computed value using Casswell's method and a value of 14 n. miles using the equation (based on Figure 12 of Corby[4]) in the World Meteorological Organization *Technical Note* No. 34[5]

$$\lambda = 0{\cdot}585\bar{u} - 2{\cdot}8,$$

where λ is the lee wavelength in kilometres and $\bar{u}$ is the wind speed (metres/second) meaned over the layers contributing to the wavelength assessment.

The interest of this case lies not only in the verification of the wavelength but in the occurrence of waves in the apparently unfavourable conditions on the cold side of a weak jet stream. The wind profile was not ideal and the inversions were weak; however, Casswell's method does yield useful results.

Conclusion. The three cases selected from several aircrew reports collected show that a quantitative method of assessing mountain lee-wave situations can be of use to forecasters.

Acknowledgement. The writer is indebted to Captain Read of the Civil Aviation Flying Unit for advice on the aviation aspects of mountain lee waves, and to the numerous aircrew providing reports.

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551.515.33

A NOTE ON OBSERVED DUST—WHIRL DAMAGE AT NICOSIA, CYPRUS

By J. B. McGINNIGLE

At 1315 GMT, on 31 July 1969, damage to the roof of a house (Plates III, IV) in Nicosia was caused when a dust whirl of considerable intensity passed north-eastwards as shown in Figure 1. About 40 roof tiles each weighing

3 to 4 pounds (nearly 2 kg), were torn from the roof and some landed in the garden on the east side of the house. Damage occurred only on the north-east side of the roof.

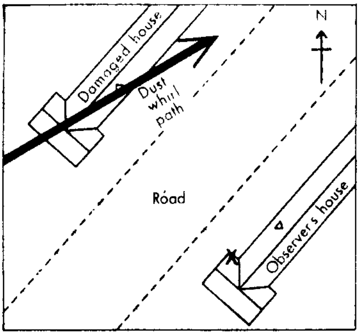

FIGURE 1—POSITION OF HOUSES
X Point of observation

During the incident, light items (papers, etc.), which lay well inside the house, were blown through open french windows on the east side of the house by a strong through draught from open windows in other rooms on the west side of the house. Most articles were lodged at the walls of surrounding houses 30 to 40 ft (about 10 m) away, mainly east and north-eastwards. Chairs were blown from the covered verandah in front of the french windows into the front garden.

At the observer's house (Figure 1), a very strong and sudden wind was experienced for about 10 seconds and windows, shutters and other loose items were blown about violently. Quantities of earth, twigs, etc., were blown from the front garden into the house and all items adjacent to windows at the front of the house, the west side, were covered by a thick layer of grit which had been blown through window-frame cracks.

The dust whirl was thereafter seen to be moving north-eastwards at an estimated speed of 20 kt (1 kt ≈ 0·5 m/s), rotating cyclonically. The estimated vertical development was 300 ft (100 m) and the diameter of the circulation top appeared to be around 150 ft (50 m).

Observational data. The nearest meteorological observing station is at Nicosia Airport, 35°09′N 33°17′E, 219 m (719 ft) above mean sea level and this is situated about 1 n. mile (2 km) south-west of the site of the dust-whirl damage.

Figure 2 shows, diagrammatically, the record of wind speed and direction made by the anemograph at Nicosia Airport and Table I shows the sequence of routine observations of temperature and humidity from 1158 GMT to

TABLE I—OBSERVATIONS AT NICOSIA AIRPORT, 31 JULY 1969

Time	Surface wind		Temperature	Dew-point	Relative humidity
GMT	*degrees*	*kt*	*degrees Celsius*		*per cent*
1158	360	07	36·0	9·3	20
1237	360	08	36·0	8·4	19
1337	280	15	35·5	14·6	29
1437	280	14	34·0	15·2	33

Anemogram shows onset of sea-breeze at 1310–1315 GMT.

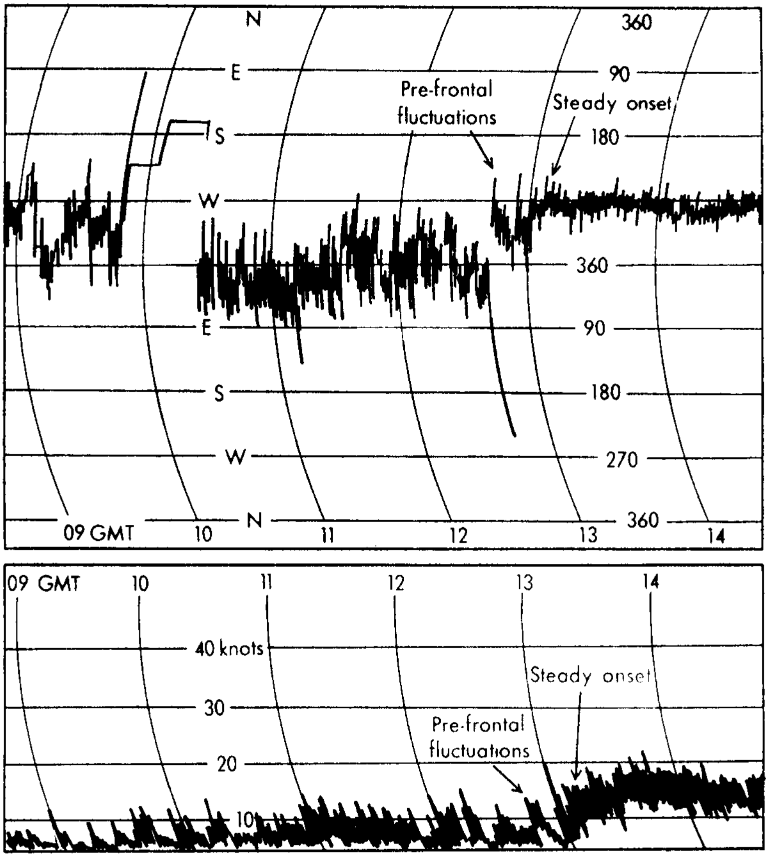

FIGURE 2—DIAGRAMMATIC REPRESENTATION OF ANEMOGRAM AT NICOSIA AIRPORT ON 31 JULY 1969

1437 GMT. Little pressure change was recorded during these times and there were no clouds except small amounts of cumulus, base 7000 ft, over the Troodos mountain range.

After a morning of variable winds, marked fluctuations in both direction and speed began to occur at 1245 GMT, when the wind veered from north-east to north-west (through south) thereafter varying in the range 230° to 010°, with a speed range of 3 to 20 kt. After 1310 GMT, the direction became much steadier at around 280° and the mean wind speed increased to 13–16 kt with gusts to 22 kt. From the temperature/humidity records (Table I), the passage of the sea-breeze front occurred between the 1237 GMT and the 1337 GMT reports. The temperature decreased and the relative humidity rose sharply. These records therefore show that the sea-breeze front passed through Nicosia Airport at 1310–1315 GMT, after a 25-minute period of pre-frontal wind fluctuation.

In summer, the sea-breeze at Nicosia sets in normally from west to north-west in the late morning or early afternoon, penetrating from Morphou Bay between mountain ranges to both north and south (Figure 3). Wind speeds

PLATE III—DAMAGE TO ROOF OF HOUSE IN NICOSIA, CAUSED BY DUST WHIRL ON 31 JULY 1969

See page 118.

PLATE IV—DAMAGE TO ROOF OF HOUSE IN NICOSIA, CAUSED BY DUST WHIRL ON 31 JULY 1969

See page 118.

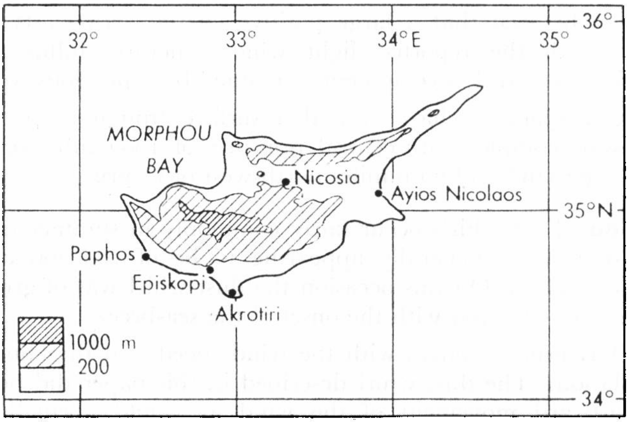

FIGURE 3—MAP OF CYPRUS

are generally 12 to 18 kt with gusts to 25 kt. On this occasion, with a sea-breeze direction of 280°, the frontal orientation is assumed to be 010–190°, at right angles to the wind direction and parallel to the coastline of that part of Morphou Bay nearest to Nicosia.

Pilot-balloon ascents are made at Paphos and Ayios Nicolaos on a routine basis, as well as at the radiosonde station at Episkopi. Unfortunately, none of these reporting stations are in a geographical position to assist with the low-level wind structure on this occasion, except to demonstrate that at 06 GMT, the low-level winds over Cyprus were generally light and variable. At Nicosia Airport, pilot-balloon ascents are made on a non-routine basis and, on 31 July, an ascent at 08 GMT also showed that the low-level winds were light.

Surface	030°	03 kt
3000 ft	335°	07 kt
5000 ft	270°	05 kt
7000 ft	290°	16 kt

The 12 GMT radiosonde ascent for Episkopi is shown as Figure 4. When the Nicosia surface temperature/dew-point convection path is plotted as

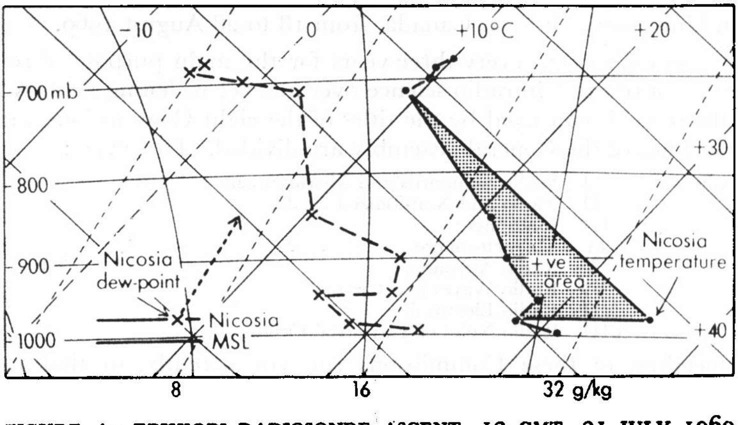

FIGURE 4—EPISKOPI RADIOSONDE ASCENT, 12 GMT, 31 JULY 1969
x – – – x Dew-point · ——— · Temperature

shown, it can be seen that a large positive energy area exists and this, in combination with the reported light wind structure, fulfils the required conditions for dust-whirl development as defined by a previous work.[1]

The 12 GMT synoptic chart showed a surface trough from Turkey to a small depression complex with central pressures of 1002 mb over the north-east part of the island and 60 n.miles north-west of Cyprus.

Discussion. Dust whirls occur fairly commonly in summer in the central plain area of Cyprus, generally appearing to be of 100–200 ft (30–60 m) vertical development. On this occasion the dust whirl was of greater vertical development and occurred with the onset of the sea-breeze.

A dust whirl usually moves with the wind speed and direction at the top of the circulation. The dust whirl described in this paper did not follow the east-south-eastward movement of the wind as would normally occur but moved across the flow at an angle of 40–50°, clearly in association with the sea-breeze front.

A previous paper[2] has described a similar occasion in Libya, where the dust whirl passed directly over the meteorological office at Idris Airport; all the evidence suggests that the dust whirl reported in this note was generated and maintained in a similar manner.

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1. MCGINNIGLE, J. B.; Dust whirls in north-west Libya. *Weather, London*, **21**, 1966, pp. 272–276.
2. MCGINNIGLE, J. B.; Dust whirls at Idris Airport on 31 May and 1 June 1964. *Met. Mag., London*, **93**, 1964, pp. 313–316.

551.501.8:061.3

XVITH GENERAL ASSEMBLY OF THE INTERNATIONAL UNION OF RADIO SCIENCE, OTTAWA, AUGUST 1969

By W. T. ROACH

Introduction. The International Union of Radio Science (or Union Radio Scientifique Internationale (URSI)) held its XVIth General Assembly at Carleton University, Ottawa, Canada, from 18 to 28 August 1969.

These assemblies occur every three years for the main purpose of reviewing the progress of research in radio science over an ever widening field. A general idea of the scope is conveyed by the titles of the eight Commissions into which the proceedings of the General Assembly are divided. These are :

Commission	I	Radio Standards and Measurements
	II	Radio and Non-ionized Media
	III	Ionosphere
	IV	Magnetosphere
	V	Radio Astronomy
	VI	Radio Waves and Circuits
	VII	Radio Electronics
	VIII	Radio Noise of Terrestrial Origin

The meetings of these Commissions run concurrently, so that it is not generally practicable to attend the meeting of more than one Commission, although some meetings were shared by two or more Commissions. The writer attended Commission II meetings.

Historically, the main area of overlap between meteorology and radio science has been in the study of electromagnetic propagation through the atmosphere, and its practical applications to communication links over a very wide range of operating frequencies and distances. The communications engineer, in common with the aeronautical engineer, is not interested in the atmosphere for its own sake, but only as rather a nuisance which often interferes with his interests, and has therefore to be accounted for. There is a long history of liaison between radio interests and the Meteorological Office in a field common to both called radio-meteorology. This subject formed the main business of Commission II. It should, however, be noted that URSI (by definition) is at least as much concerned with the use of radio as a tool in scientific research as with its practical communications applications.

Commission II meetings. Proceedings of the scientific meetings of the XVIth Assembly will be published in due course, so this account will be confined to a brief outline of the main features of scientific interest discussed in Commission II.

During the past five years or so, the dominant research interest has been in theoretical and experimental studies of the electromagnetic scattering properties of the atmosphere, not only from the communications point of view, but also for the information on the structure of the atmosphere that can be inferred from such studies. Readers will recall Professor Atlas's lecture to the Meteorological Office on his analysis of radar echoes from clear-air turbulence.* Since then, other (more powerful) radars have been used to study clear-air echoes, which have now been detected at heights of up to 25 km at ranges in excess of 100 km. The writer has made a plea for a more systematic study of these echoes for the information they might yield on the evolution of clear-air turbulence patches and movement relative to their environmental wind fields.

Also of interest was a discussion of the main features of the Inter Union Commission on Radio Meteorology (IUCRM) Colloquium on the 'Spectra of atmospheric variables' held in Stockholm in July 1969. Evidence of the widespread occurrence of Kelvin-Helmholtz instability (KHI) in the atmosphere was combined with observations of KHI in the ocean thermocline and in laboratory investigations to give a reasonably consistent picture (with good support from theory) of this particular mechanism of transition from laminar to turbulent flow. This led to further discussion of the physical differences between gravity waves and turbulence, and their roles in the scattering of radio waves.

The current importance of this general field of investigation was recognized by URSI by devoting one afternoon to a session on 'Electromagnetic probing of the atmosphere' at a joint meeting of all the Commissions. At this session, the word 'atmosphere' covered the total depth from the troposphere, stratosphere, mesosphere, ionosphere out to the magnetosphere.

Leaving the atmosphere altogether, it is clear that space science (and the reverberations of Apollo 11) is perhaps displacing the atmosphere as the dominant research interest of URSI. Space science leaked into the proceedings of most, if not all, the commissions. At the opening scientific session of

* ROACH, W. T.; Lecture by Professor David Atlas. *Met. Mag.,London*, **95**, 1966, pp. 379–381.

Commission II, observational results of radio and radar studies of the lunar surface and of the planetary atmospheres were discussed. As a result of this, new terms of reference of Commission II were proposed as follows :

> 'Commission II is concerned with the phenomena associated with the propagation of radio waves through the media on the earth, the moon and the other planets, including the effect of boundaries, but excluding the effects of ionization.'

The current title of Commission II (Radio and Non-ionized Media) is perhaps slightly misleading, as ionization is present in some degree throughout the earth's atmosphere, but below the ionosphere the level of ionization has no significant effect on radio propagation.

Turning now to research of a more applied nature, it was clear that there had been an increase in studies of the effect of the atmosphere on line-of-sight links in optical, infra-red and micro-wave frequencies.

The effect of heavy precipitation on micro-wave communication links received considerable discussion. A loss of communication of only a few hours per year due to heavy rain is undesirable; but this loss can be considerably reduced by the use of path diversity, i.e. simultaneous transmission over two or more links spaced far enough apart (≈ 1 km) to make it unlikely for all paths to be seriously affected by rain at the same time. The related subject of rainfall measurement by means of radar received some discussion, with particular reference to problems arising in the comparison of rainfall rates obtained from radar echoes with those obtained from rain-gauges, e.g. fluctuations in precipitation on scales less than the rain-gauge spacing, and the fall velocity of raindrops as a function of their size.

The main item of interest emerging from infra-red and optical attenuation studies was the suggestion that water vapour might exist in polymer form in the atmosphere, and that the diamer of H_2O would be expected to produce discrete lines in the 30–300 μm region plus a continuous absorption over a wide range of wavelengths.

Other topics touched on included radio-glaciology — the use of radar for probing ice sheets in Greenland and the Antarctic — and the possible use of radio techniques from earth satellites for earth resources studies. This, however, was the only time earth satellites were referred to in Commission II.

At the final meeting, it was suggested that IUCRM should consider holding symposia on the following subjects :

(i) Planetary atmospheres and the lunar surface.
(ii) Atmospheric spectroscopy and its uses.
(iii) Electromagnetic techniques in earth resources studies.

In conclusion, it appears that future growth points which may involve Commission II interests should be :

(i) Radar studies of clear-air turbulence with adequate meteorological support.
(ii) Studies of planetary atmospheres, etc.
(iii) Studies of polymer forms of H_2O in the atmosphere.
(iv) Applied research on measurement of rainfall by means of radar and path diversity systems.

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