THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

December 1983

Met.O.958 No. 1337 Vol. 112

METEOROLOGICAL OFFICE Met.O.958

THE METEOROLOGICAL MAGAZINE

No. 1337, December 1983, Vol. 112

551.509.313:33:519.7

Predictability in science and society

By Sir John Mason, CB, FRS
(Formerly Director-General, Meteorological Office)
(The Presidential Address to the British Association for the Advancement of Science, Brighton 1983)

The theme of this address is based on the premise that the validity and power of any theory, scientific, economic or social, rests on its ability to make predictions that can be tested by observation or experiment. Such is the power and success of scientific prediction that scientists are almost bound to experience frustration and disappointment when they turn their attention to social and economic problems. The predictability of any system depends largely on its stability and its susceptibility to random disturbances (noise) and on the strength of the underlying theory. In classical astronomy the system is very stable, the noise level is low and the theory is well established, so the predictions are very accurate. In meteorology the atmosphere is inherently unstable to small disturbances, the noise level is higher, and the theory, though firmly based in physics and dynamics, is less complete, so the predictions are less accurate. In economic and social systems the noise level is higher still and there is no adequate underlying theory, so the predictions are very uncertain; moreover man himself is an integral part of these systems and is often a destabilizing influence. This being the case, one may ask whether human judgements are being helped or are in danger of being overwhelmed by modern techniques of data storage, retrieval and processing on ever more powerful and sophisticated computers. The technology advances relentlessly but does it lead to better decisions?

The future of the world, nations and individuals, is being determined to an increasing extent by the predictions or forecasts of enormously complex mathematical models run on giant computers. As scientists we would probably agree that major policy decisions should be based as far as possible on rational analyses of the facts and objective predictions rather than on intuitive and subjective judgements. However, there is a danger that the sheer size and complexity of the numerical models now employed in such diverse fields as war-gaming and the arms race, weather forecasting and economics, with their hundreds of equations and backed by millions of calculations per second, may come to dominate the judgements of governments and corporations without sufficient understanding of the structure, behaviour and limitations of the models and of the degree of uncertainty attached to their predictions.

The nature of prediction

In exploring the nature of the prediction process, we may recall that man has an innate requirement to predict the future course of events, including the consequences of his own actions, as part of his survival mechanism. In performing ordinary tasks, like riding a bicycle or driving a car, he makes a rapid sequence of observations, predictions and reactions, his sensors, brain, nerves and muscles forming the components of an automatic predictor-and-control system which can, however, be overruled by conscious decisions through the exercise of free will. Of course these capabilities are limited by the range of the human sensors and by the capacity and speed of the human computer. Outside this innate, unconscious experience, one has to rely on the recall and extrapolation of past experience or construct for oneself predictive models which may range from purely mental concepts to complex mathematical models programmed for a computer.

The more complex the situation the less likely are past experience and intuition to lead to useful long-term predictions. Whilst an amateur observer may successfully forecast the weather over the next few hours by watching the sky and calling on his past experience, he will be quite unable to predict what will happen a few days ahead. This will be determined by developments far beyond the range of his senses that are not amenable to simple extrapolation and involve data processing and calculation far beyond human powers.

In economics, too, prediction by simple extrapolation of past experience — the technique of the chartists — is an unreliable, ill-founded procedure because the past record almost never contains regular cycles or fluctuations of repeated amplitude and frequency. Of course if it did, and the causes were understood, forecasting would be simple — like forecasting sunset and sunrise. In fact historical records, both of the weather and the economy, are so irregular with so much random variation (noise) that they have little predictive power. No extrapolation of past trends, nor any theory or model based on past experience, could have given warning of the dramatic rise in oil prices in 1973 or, for that matter, of the hot summer of 1976 — the hottest in 250 years.

Weather forecasting

In weather forecasting it had already become apparent, twenty years ago, that the time-honoured empirical methods, based largely on extrapolation of very recent developments and the experience of individual human forecasters, were unlikely to improve significantly or produce reliable forecasts for more than about 24 hours ahead. Fortunately, with the arrival of powerful digital computers, it became possible to replace these highly subjective, empirical methods by objective techniques that treat weather forecasting as a problem in mathematical physics.

This involves the building of very large and complex mathematical models of the atmosphere based on the physical and dynamical laws that govern the birth, growth, decay and movement of the main weather systems. They incorporate the principles of conservation of momentum, mass, energy and water in all its phases, the Newtonian equations of motion applied to an air mass, the laws of thermodynamics and radiation, and the equation of state of a gas. Parameters which are specified in advance include the size, rotation, geography and topography of the Earth, the incoming solar radiation and its diurnal and seasonal variations, the radiative and heat conductive properties of the land surface according to the nature of the soil, vegetation and snow or ice cover, and also the surface temperature of the oceans.

The physical state of the atmosphere itself is updated every 12 hours from observations made simultaneously over the whole globe both at the surface from land stations, ships and buoys and in the upper air from satellites, balloons and aircraft. The model atmosphere is divided into 15 layers between the ground and 25 km (about 80 000 ft) and each level is divided into a network of points about 150 km apart — one-third of a million points in all. Each of these points is assigned new values of temperature, pressure, wind and humidity every 12 hours and the governing differential equations are integrated in 12-minute time steps at each point to provide forecast values for up to six days ahead twice daily. A forecast for 24 hours ahead involves about one hundred thousand million (10^{11}) calculations but with a computer making 400 million calculations per second, these are performed in less than four minutes. The whole operation results in the automatic production of hundreds of different forecast charts of pressure, temperature, wind, humidity, vertical motion and rainfall that form the basis of the weather forecasts issued to the general public and to almost every weather-sensitive industry.

In particular the Meteorological Office provides more than two million forecasts a year for civil and military aviation and will soon provide flight-planning forecasts for all the world's airlines covering the whole of the globe.

This new approach to weather forecasting has extended the range of reliable deterministic forecasts from only one day to 4–5 days ahead and significantly increased their accuracy and detail, the new Meteorological Office model now producing 3-day forecasts that are as accurate as 2-day forecasts were five years ago and 2-day forecasts as accurate as 24-hour forecasts were then. Although the model remains stable for much longer periods the detailed predictions tend to deteriorate rather sharply beyond the fourth or fifth day. Reliable forecasts for a week or more ahead, which would be of great economic value, will require improved models with better representation of the physical processes, improved computational methods and even more powerful computers but, above all, a much better supply of global observations. There are, however, *inherent* limitations to the predictability of atmospheric behaviour which we shall now discuss.

Atmospheric predictability

We now raise the crucial question of whether there is for each scale of motion a time limit beyond which it is not possible to make a deterministic forecast. This question is of great importance for practical weather forecasting because the answer may set ultimate limits to what is achievable and to what is worth aiming at. If we had a physically faithful model of the real atmosphere, were able to specify exactly the initial conditions for all scales of motion, and made no computational errors in integrating the non-linear differential equations, could we expect to predict the atmospheric evolution from an initial state with infinite precision infinitely far ahead? Or, would small random perturbations (noise) develop in the real atmosphere and amplify to a point at which the numerical simulation and the real atmosphere would progressively diverge and ultimately become uncorrelated?

There is evidence that the atmosphere is inherently unstable to small perturbations so that two states, with only slight differences initially, and each evolving according to the same physical laws, may progressively diverge and eventually develop into quite different states. Experiments with complex global weather models indicate that the root-mean-square differences between two initially very similar fields of pressure, temperature or wind double about every 3–5 days so that weather systems on the scale of large depressions, which are well represented in such models, may be predictable up to 2–3 weeks ahead. Beyond this, it is doubtful whether further improvements in the models, the initial conditions (observations), or in computing power would increase predictability for these scales. This is so because even if the larger-scale systems were observed perfectly and represented perfectly in the models their behaviour would eventually be affected by the action of much smaller disturbances such as thunderstorms and tornadoes which cannot be adequately observed or represented and yet may double in amplitude within a few minutes. These may, within a day or two, induce uncertainties in the larger scales comparable to the initial errors resulting from inadequate observations.

This does not mean that models are necessarily incapable of making any useful predictions beyond 2–3 weeks. Although deterministic forecasts of individual mobile weather systems may not be generally feasible beyond this time range, we sometimes observe relatively stable systems embedded in the general turbulent flow which retain their character and predictability for considerably longer periods, an example being the blocking anticyclone that produced the prolonged hot summer in western Europe in 1976. A supreme example is the Great Red Spot on Jupiter, an enormous anticyclonic vortex, larger than the Earth, which has retained its essential character for more than 300 years!

And, even if models cannot predict the evolution of individual depressions several weeks in advance, they may be able to predict the general tracks of such depressions and thereby the general character of the weather over the next month or two even if they fail to capture the day-by-day variations.

Numerical modelling of the economy

From our experience of the behaviour and predictability of complex, non-linear physical systems like the atmosphere, can we infer anything of value about even more complex and variable economic and social systems? To what extent can we apply the techniques of mathematical modelling on powerful computers to simulate, understand, predict and control such systems?

The boldest steps in this direction have been taken by economists, sometimes working with scientists, mathematicians or control engineers, who have built large, complex models in which the working of the economy is described by a system of hundreds of equations in the case of the Treasury and London Business School versions. But apart from their size and complexity, these economic models have little in common with weather forecasting models. They both deal with highly complex, interactive, non-linear and strongly constrained systems but the differences are both fundamental and instructive.

Whereas weather and climate models are firmly based on the fundamental laws of physics such as Newton's Laws of Motion and the laws of thermodynamics, there are no such fundamental laws in economics but only empirical relationships which may hold for quite long periods in a particular economy but are not sufficiently stable or universal to qualify as laws.

These empirical economic relationships are established by fitting equations to past data, usually from inadequate records going back less than 25 years. It is salutary to recall that this method of using past statistical data to predict future developments has proved unsuccessful in producing reliable weather forecasts for even a few days ahead. Weather forecasting is now treated as an initial value problem using entirely new data every 12 hours.

Since there are no universally accepted economic laws the models are very much creatures of their builders who may introduce relationships that express personal or political judgements. This is one reason why different economic models often give quite different predictions. If they are to be acceptable and not just ignored by the policy-maker, they must be tuned to some extent to his requirements and are not therefore objective in the same sense as the weather forecast.

The weather forecast has no effect on the weather but the economic forecast may well affect the economy!

All forecasts, if they are to be credible, must be capable of verification. Weather forecasts are checked every day against the actual weather so mistakes are quickly recognized and experience and understanding can be built up much more rapidly than in economics where it may take many months to verify a prediction.

Economic prediction is more difficult than weather forecasting for the following reasons:

It is often required to predict the residuals between two large quantities, each of which may be subject to considerable errors: e.g. the balance of payments is the difference between imports and exports and may amount to less than 1% of the gross national product.

The media and markets tend to exaggerate the importance of small movements in the economic indicators and this has a destabilizing effect. Economic calculations and forecasts are made in terms of monetary units which do not have a fixed value. Dealing with currency fluctuations has been likened to running the electricity supply industry with a variable electronic charge!

The economy, unlike the weather, is subject to the quirks of human behaviour. These unquantifiable and unforeseeable disturbances, amplified by speculation, loss of confidence and even panic are liable to induce instability and make the management of an economic crisis much harder.

The stability and predictability of an economic model (and a weather model) will be limited by the cumulative action of a gamut of random fluctuations in the real economy which cannot be properly represented in the model so that the predictions will progressively diverge from reality. Such models are also inherently unlikely to predict an unprecedented situation although one can hope to control the model and the economy in such a way that they will be less vulnerable to sudden shocks.

On the other hand, our thinking should not be entirely dominated by short-term fluctuations but should recognize that, on larger time-scales, economies, like the atmosphere, are remarkably resilient. Given even moderately competent management, total collapse of the system is unlikely because the overall constraints such as the total resources of material and manpower are largely unaffected by temporary fluctuations and the restoring forces eventually assert themselves and bring the system to a new equilibrium. Economic crises, like bad weather, do not last for ever. But, of course, electorates and governments are not prepared to wait for the system to adjust and adapt of its own accord. *Laissez-faire* attitudes are unfashionable and governments, under continual pressure to do something, tend to over-react and to get their timing wrong. So, given our imperfect understanding of how economic systems work, and given the inability of models to produce unique or even consistent solutions, what is the decision-maker to do? What guidance can models offer him in his attempts to manage and control the economy?

Guidance for policy-makers

It does not seem reasonable to expect models to provide accurate predictions either of short-term fluctuations or of very long-term developments far removed from recent experience on which the models are built. Instead we should use them to indicate underlying trends in the medium term, to help educate policy-makers in the workings of the economic system, its external and internal constraints, on what may be feasible and what is unattainable. For example, models can be used to investigate the sensitivity and response time of the economy to various fiscal and monetary controls and to help to decide between alternative ways of achieving a particular set of policy options involving inflation, unemployment, economic growth, balance of payments etc. Alternative strategies may be tested and optimization procedures applied to select one policy from a number of internally consistent options that do not violate the overall constraints of the real world. Models usually make deterministic forecasts but one could test the sensitivity of their outputs and predictions to various uncertainties introduced by deficiencies in the input data or in the model itself.

In their present state of development, economic models should perhaps be used more for experimentation designed to improve understanding of how the economy works, its sensitivity to various uncertainties and the assessment of various controls rather than give too much weight to the forecasts themselves.

One can learn, for example, that in applying a control signal to the economy, it is very important to ensure that it is the correct magnitude and phase otherwise it may destabilize the system. This only serves to confirm what we know from bitter experience that if governments, intent on fine-tuning of the economy, attempt to correct short-period anomalies in a system which takes several months to respond, they will almost certainly get their timing wrong and make matters worse. In attempting to correct for an imbalance in the system, the control signal should be a function of the imbalance averaged over a period comparable to the response time of the system and therefore action should be delayed until this can be assessed.

However, this poses a problem for governments under pressure from articulate electorates and the media for 'instant fixes' which may destabilize the economy and make rational longer-term decisions even more difficult. It is, for example, very difficult to make sensible long-term investment decisions during a period of high inflation and with high and rapidly fluctuating interest rates. A deeper understanding of the dynamical behaviour of economic systems might also help convince governments that it is virtually impossible to react sensibly to short-term fluctuations in a sluggish system and that they should concentrate on longer-term objectives designed to produce a more stable economic and social climate in which transient events will have less impact. This cannot be done effectively without international co-operation to achieve greater stability of exchange rates, interest rates and commodity prices, thereby reducing the scope for speculation and damping down the turbulence which so often obscures the fundamental developments. Above all, governments should avoid introducing sudden major changes. Economic systems are usually sufficiently robust to adjust to gradual changes but not to cope with large shocks that may induce instability and have quite unforeseen consequences.

These propositions may seem obvious, even self-evident, but it is remarkable how often they are ignored by governments who appear to believe that they can circumvent the laws and constraints of the system and gain at least a temporary advantage.

Conclusions

Despite the reservations made earlier, I am convinced that numerical models offer the best means and the greatest promise of improving our understanding of how economic systems work; for simulating past economic situations; for studying the sensitivity of the economy to various perturbations and controls and for predicting the likely outcome of present policies. I also believe that the study of such difficult but crucial problems calls for close collaboration between some of the best minds in both the physical and the social sciences. The physical scientist, by application of his powerful tools of mathematical modelling, computing, systems analysis and control theory, has an important contribution to make provided that he is willing to tackle real problems and not engage in purely technical or academic exercises. However, he is unlikely to be successful unless he has the insight, understanding and humility to realize that social systems are much more complex, less well-defined and constrained and therefore more difficult to simulate than the physical systems which he operates so successfully in the laboratory and factory. By the same token it will not be enough for the social scientist to adopt uncritically the tools of the physical scientist or, worse still, to imitate his symbolism and jargon without understanding what lies behind it. Working together and learning from each other, they stand a better chance of exposing the essential nature and behaviour of economic systems and of educating policy-makers on the dangers of simplistic solutions by setting limits to what may or may not be feasible.

At the same time many important social problems are not amenable to rational scientific analysis and mathematical modelling if only because human motivation and behaviour cannot be formulated in quantitative terms. In these cases little will be gained by discussing the issues in pseudo-scientific terms, obscuring them in a blanket of sociological or systems-analysis jargon, or by forcing them into the straightjacket of an over-simplistic model that has little to do with the real world.

The outputs and predictions of mathematical models are only as good as the theory and thought on which they are based and the facts that are fed into them. Like most powerful tools they are dangerous if used unintelligently and for the wrong job.

551.507.352:551.508.822:621.396.93

The NAVAID dropsonde

By P. Ryder, A. F. Lewis and D. A. Bennetts
(Meteorological Office, Bracknell)

Summary

A NAVAID dropsonde system has recently been developed by the Cloud Physics Branch of the Meteorological Office. The sondes, which measure temperature, humidity, pressure and winds, are designed for ejection from the Meteorological Research Flight C130 aircraft. This paper discusses their performance and illustrates their scientific potential with the results obtained during a pilot study of a weak warm front.

1. Introduction

Following successful attempts to study the fine structure and dynamics of certain weather systems (Hardman *et al.* 1972; Browning *et al.* 1973), the Meteorological Office decided to develop an aircraft dropsonde capable of measuring ambient temperature, humidity, pressure and wind. The sondes were to be used to obtain a sequence of atmospheric soundings on a scale of 20–50 km in a chosen weather system, anywhere within a large operational area over the North Atlantic. The use of sondes was to replace the technique used in the earlier studies which required that suitable systems passed over a specially manned and instrumented, land-based observing site. The design requirements were set by the scientific objectives of the proposed studies, while at the same time achieving an independence of special ground-based facilities.

The design, development and production of a suitable sonde has been achieved in parallel with that of the necessary instrumentation and a safe, effective sonde ejector for the Meteorological Research Flight C130 aircraft. This paper, which reports the development of the sonde, is divided into two parts. The first describes the general characteristics of the sonde and the accuracy with which atmospheric observations can be made, and the second presents the results of an evaluation trial on 29 March 1979.

2. The dropsonde

A sketch of the sonde is shown in Fig. 1. It is in the form of a cylinder of length 84 cm and diameter 12.5 cm. The total weight is 3.5 kg. The body of the sonde is divided in its mid-section by a polypropylene insulator so that the two halves of the sonde casing act as the elements of a UHF dipole. Release from the aircraft initiates a time delay circuit which, 1 second after ejection, turns on the UHF transmitter and fires an explosive bolt to release the parasheet. A spring loaded drogue is used to pull out the main parasheet before falling away to leave the sonde suspended beneath an aerodynamically clean canopy. The average terminal velocity of the sonde from 30 000 ft to the surface is approximately 12 m s^{-1}. The transducers for measuring temperature and humidity are located at the downward facing end of the sonde within a small, well ventilated duct. Data from these sensors are passed to the aircraft via the sonde's UHF transmitter.

The guide surface parasheet, which supports the sonde during its descent, was chosen as a result of comparative tests to establish wind following characteristics. Unlike some conventional parachutes this type possesses positive stability and is therefore not prone to 'fly' relative to the air. Given that the sonde responds to and moves with the local horizontal component of the air motion, the problem of deriving the horizontal velocity is one of measuring the rate of change of its position. Classically such position. finding has been achieved by radar, or optical tracking. Unfortunately these techniques require a very stable reference platform and are essentially short-range ($<$100 km) methods. These characteristics are not compatible with the desire to carry out self-contained aircraft experiments over the North Atlantic.

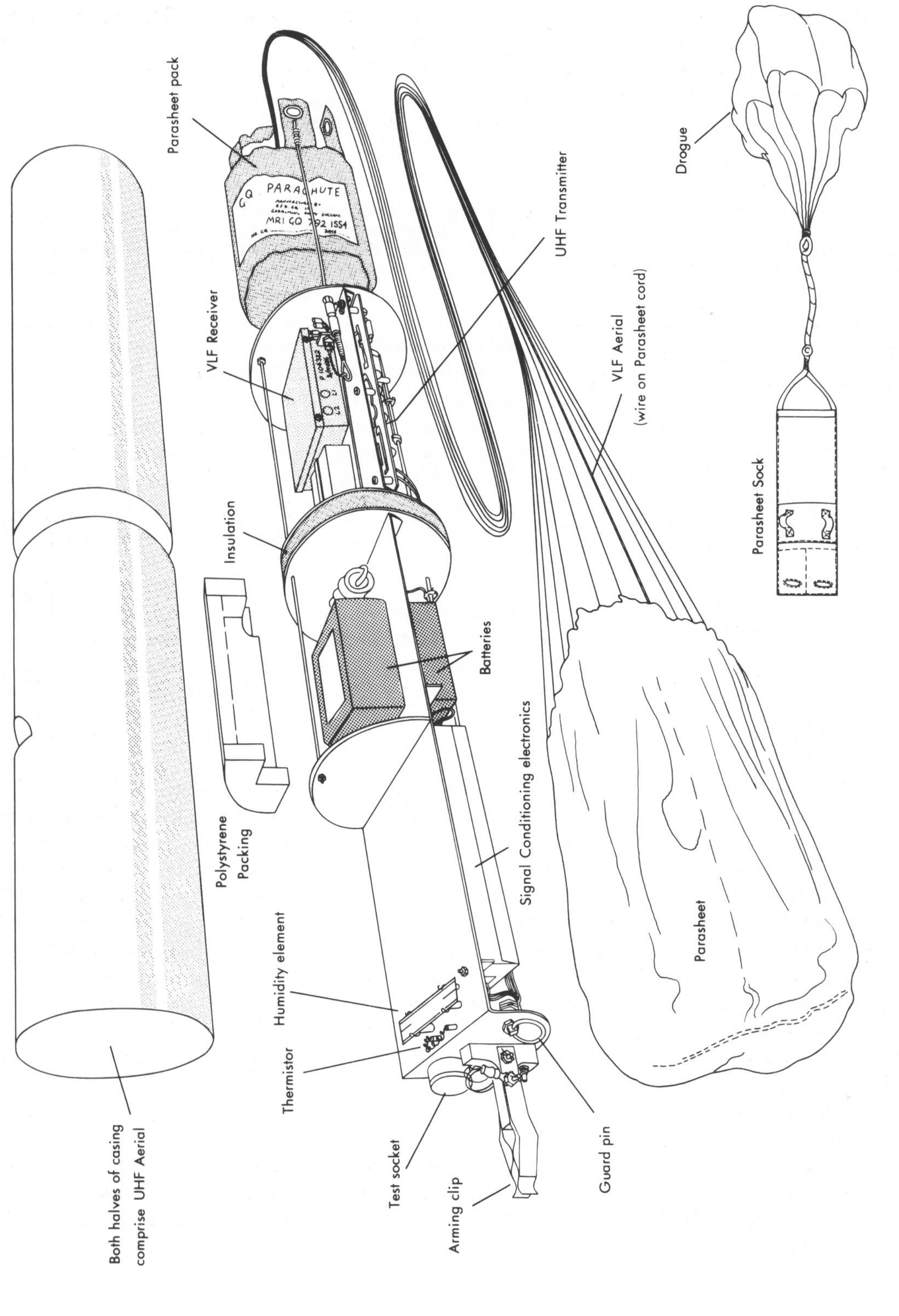

Figure 1. The NAVAID dropsonde.

As a result sonde tracking through the retransmission of the long-range navigation aid, 'Loran C', was chosen after a careful ground-based assessment of its potential accuracy (Ryder *et al.* 1972). The Loran C signal is received by the sonde through a low-frequency aerial located within one of the rigging lines of the parasheet, frequency-multiplexed with data from the meteorological sensors, and retransmitted to the aircraft via the UHF link.

(a) *Wind-finding characteristics*

Loran C consists of a set of powerful transmitters which emit pulses of 100 kHz signal on a common and closely controlled time-base. The difference in time of arrival of signals from two separate but co-herent transmitters defines a 'line of position'. Two such time differences obtained from at least three transmitters create intersecting lines of position and hence effectively define a unique plan position. The advantage of this technique for sonde positioning arises from the fact that position can be inferred provided only that time differences are preserved without distortion, In particular, any common signal path such as when the sonde retransmits received Loran signals to the moving aircraft, preserves time differences.

Loran C is operated by the US Coastguard in co-operation with host nations and has been set up to provide an accurate navigation aid in various parts of the world. The accuracy with which it can be used to define the local wind vector is a function of the relative position of the transmitters and sonde, and upon received signal strength and stability. The predicted wind finding accuracy for the North Atlantic is shown in Fig. 2, taken from Ryder *et al.* (1972). These data are based upon ground based measurements of received signal stability and the known transmitter locations. However, the predictions have been confirmed in trials at Aberporth and Benbecula test ranges when sondes have been tracked by both radar and Loran C (Ryder 1979).

The ability of the sonde to measure the magnitude and direction of the wind during the descent is an important requirement. Such information from a sequence of sondes is necessary to infer regions of vertical motion, and hence those areas likely to produce cloud and precipitation. The expected scale and magnitude of such motion fields demands measurements of horizontal winds, averaged vertically over 600 m or so, to $\pm$ 0.4 m s^{-1} or better. The 0.4 m s^{-1} contour is clearly marked in Fig. 2.

Three sondes were dropped at Aberporth on 18 July 1978 to test the ability of the data acquisition system to accept data from more than one sonde at a time. Near Aberporth the intersecting lines of position (LOPs) created by transmissions from Loran C transmitters at Ejde, Sandur and Sylt form parallelograms as sketched in Fig. 3. The component of motion perpendicular to a given set of LOPs can be inferred from the rate of change of the time difference which defines those lines. Thus the Ejde–Sylt time difference can be used to calculate the wind speed perpendicular to 032°. Similarly the Ejde-Sandur time difference provides an estimate of the component perpendicular to 342°. These components are compared for sonde A001 with their equivalent radar estimates in Figs 4(a) and (b). When viewed in this way the great importance of LOP geometry is isolated and emphasized. Each component is derived from the rate of change of time difference assessed over 60 seconds centred on the time of the estimate. This is calculated by fitting a straight line by the least squares method to the 60 one-second time differences obtained from each source. The error bars, which represent standard error estimates of the time difference gradient, are a measure of the 'goodness of fit' of the straight line to the measured one-second time differences.

Conversion from rate of change of time difference to rate of change of distance (i.e. wind component) is achieved by use of the LOP scale factors. As might be expected from Fig. 3, the small scale factor for the Ejde–Sylt time difference allows a good estimate of the wind component perpendicular to 32° (parallel to 122°); Fig. 4(a) confirms this.

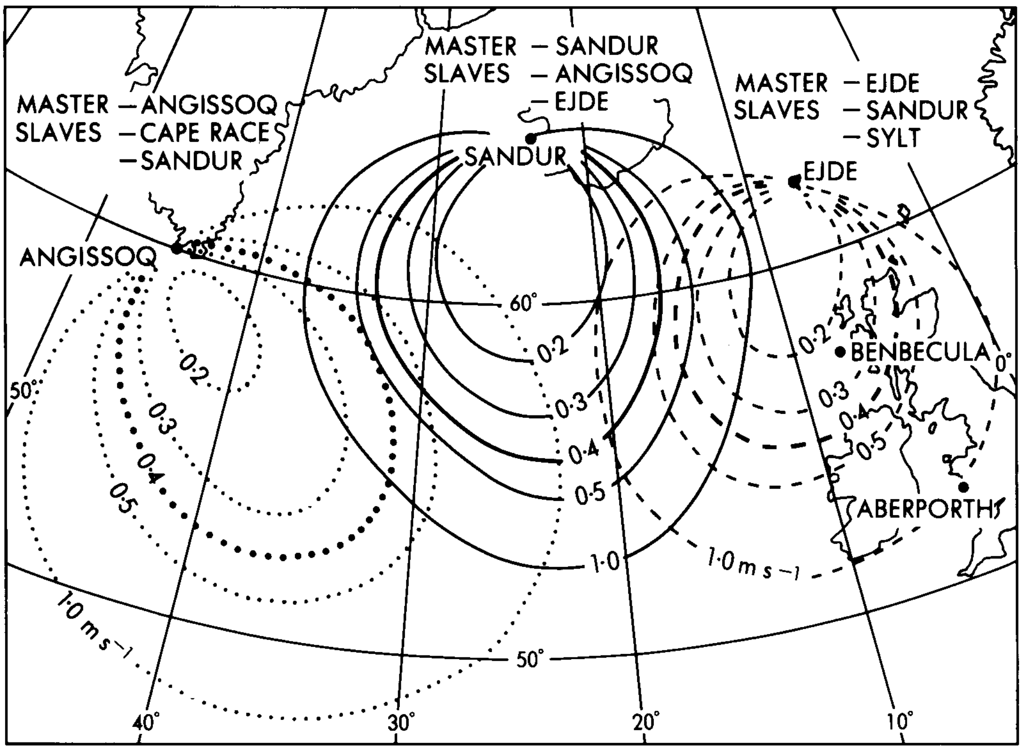

Figure 2. Predicted root-mean-square 1-minute wind errors for daytime using the indicated Loran C transmitters. Data are smoothed by a 15-second running mean.

Note that the root-mean-square (RMS) difference between radar and Loran C estimates of the wind component is 0.3 m s^{-1}, which is in good agreement with the error predicted from goodness of fit (0.2 to 0.3 m s^{-1}). The large scale factor in the Aberporth area, which applies to the Ejde–Sandur time difference, produces much larger differences between radar and Loran C estimates for that wind component (i.e. parallel to 072°), but again the RMS differences are comparable to the goodness of fit estimates (i.e. 1.2 m s^{-1} compared with 0.6 to 1.0 m s^{-1}). Of course this latter error dominates the estimation of the *total* wind vector error, which is close to that predicted in Fig. 2 for the Aberporth area. The results have further significance, however, because they demonstrate that where the geometry and scale factors are favourable, as in the North Atlantic, low total wind errors may be achieved. (The scale factors are important in determining the accuracy of each wind component and the geometry is important for determining the accuracy of the total wind.)

In an analysis of the algorithm which is used to trace the time of the individual Loran C signal zero crossing from which time differences are derived, Ryder (1976) has pointed out that the response of the algorithm can be oscillatory if the algorithm is not correctly matched to the signal-to-noise ratio (SNR). Accordingly the SNR for each transmission is also shown in Fig. 4. There is an obvious correlation between low SNRs at about 1505 GMT and the increased component errors at that time. The oscillatory nature of the departure of the 'Loran' wind from the 'radar' wind is also evident. Unfortunately, there are at present insufficient data to determine the modifications to the algorithm necessary for a better matching in low SNR conditions.

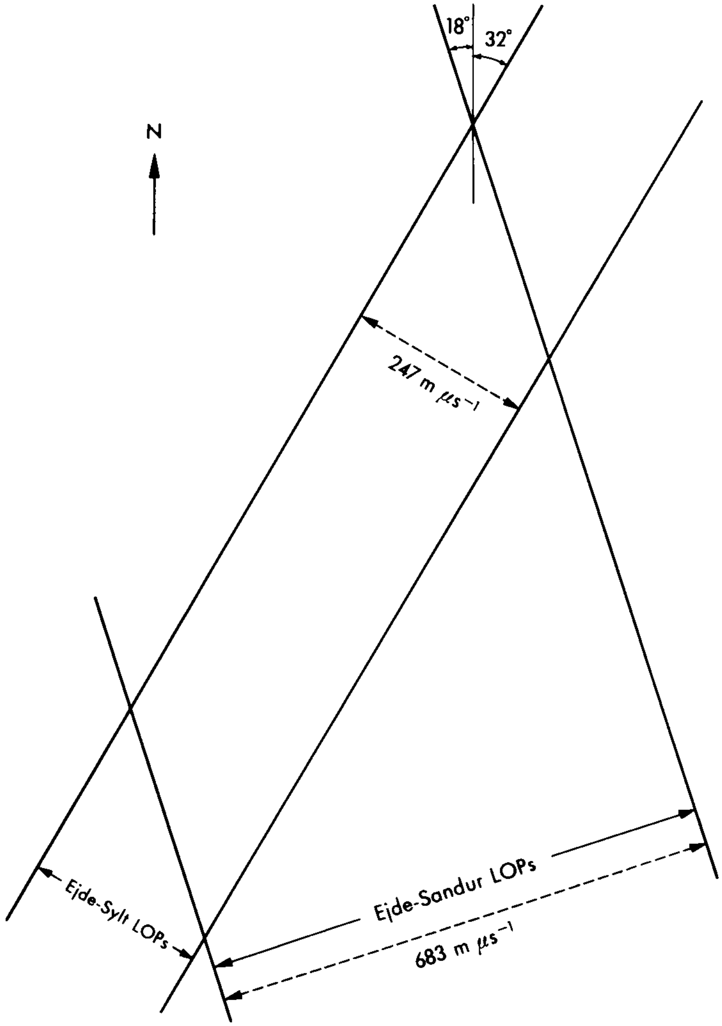

Figure 3. Line of position (LOP) geometry in the vicinity of Aberporth created by transmissions from Loran C transmitters at Ejde, Sandur and Sylt.

(b) *Air temperature and humidity*

A thermistor, with a time-constant of about 1 second at the achieved ventilation rate, is used to sense the air temperature. The sonde can experience a thermal shock of the order of 70 °C when it is ejected at 30 000 ft. Since measurements are required as soon as possible after ejection, when the body of the sonde may be far from thermal equilibrium with its surroundings, great care has been taken to ensure that, in addition to being protected from the heating effects of solar radiation, the sensor experiences ambient atmospheric conditions. For example, it has proved necessary to coil the thermistor leads to reduce the effects of heat conduction along them. The difficulty of providing a comparable measurement in the field does not allow a complete statement of the accuracy to be expected under operational conditions, but absolute errors appear to be generally less than 0.5 °C. Unfortunately this only permits the vertical

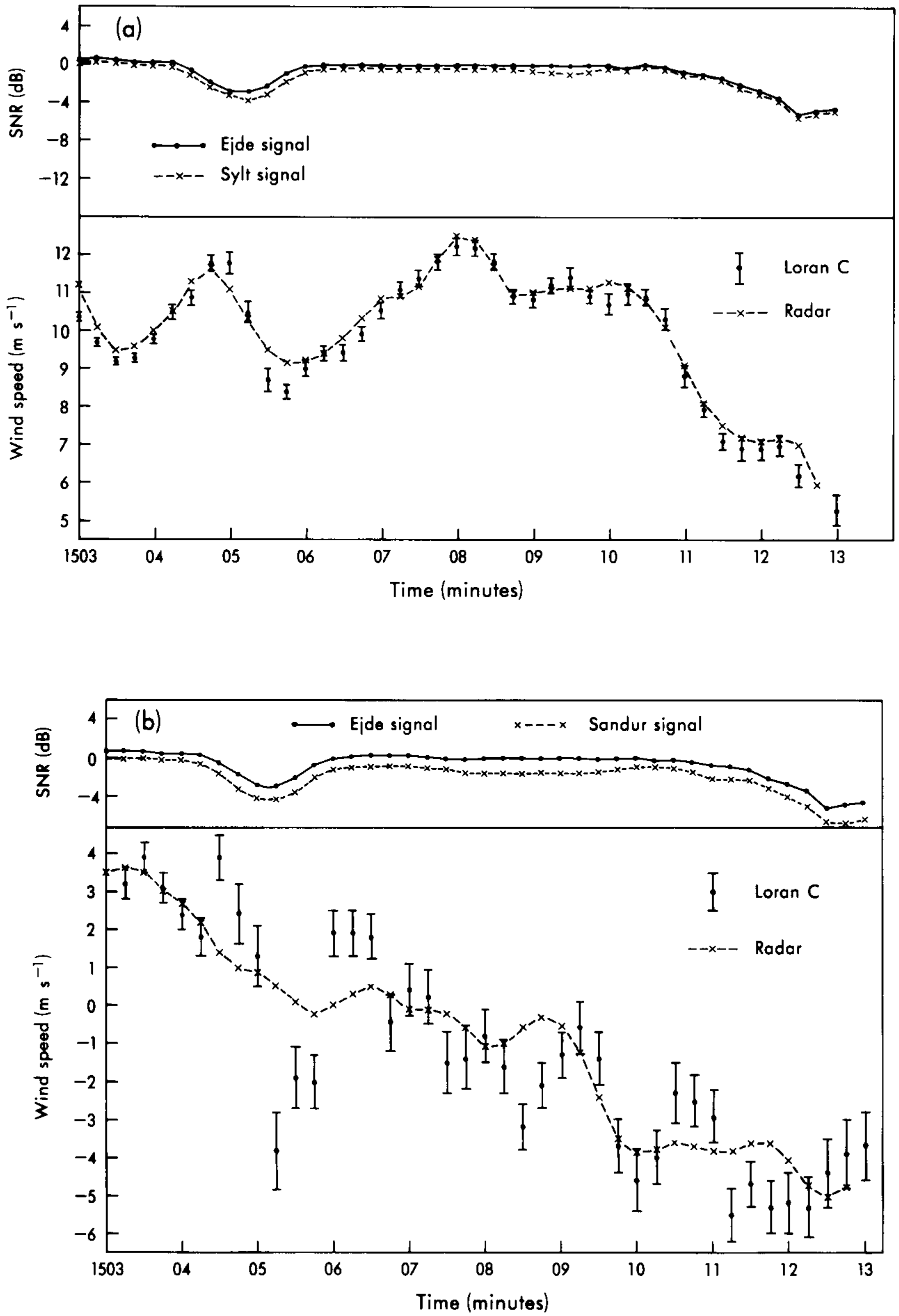

Figure 4. Wind components measured by Loran C and radar tracking at Aberporth on 18 July 1978 (a) parallel to 122° and (b) parallel to 072°.

wind shear to be evaluated from the thermal wind equation to an accuracy of about 5×10^{-3} s^{-1}, which is insufficient for many meteorological purposes.

The humidity element is a carbon hygristor of the type used in the VIZ radiosonde (VIZ Manufacturing Co., Philadelphia, PA, USA). The device was chosen after careful evaluation in the laboratory and in field trials (see Gibbs *et al.* 1975). Again exposure is most important; speed of response is a function of ventilation rate, humidity and temperature. Trials suggest that accuracy in the range 30% to 95% relative humidity is better than ±5%.

Fig. 5 shows a comparison between the temperature and humidity profiles measured by sonde A021 at Benbecula at 1400 GMT and the midday Stornoway radiosonde ascent on 28 February 1979. On this occasion the aircraft was flying above the tropopause, but despite the temperature difference of some 70 °C between the aircraft cabin and the external environment it is clear that the sonde's temperature transducer rapidly responded to the environmental conditions. Lower in the atmosphere many small-scale features can be detected in the humidity profile. On close inspection many of these are seen to be linked to small changes in temperature lapse rate. Transit through at least one layer of cloud in the vicinity of 840 to 900 mb demonstrates the ability of the humidity element to dry out below cloud, although in other tests it has been found that after a long passage through wet, icing cloud, drying out may be delayed by up to 30 mb. When this occurs a significant wet-bulb effect can be seen in the temperature profile. On future sondes it is hoped to incorporate a fast response cloud detector.

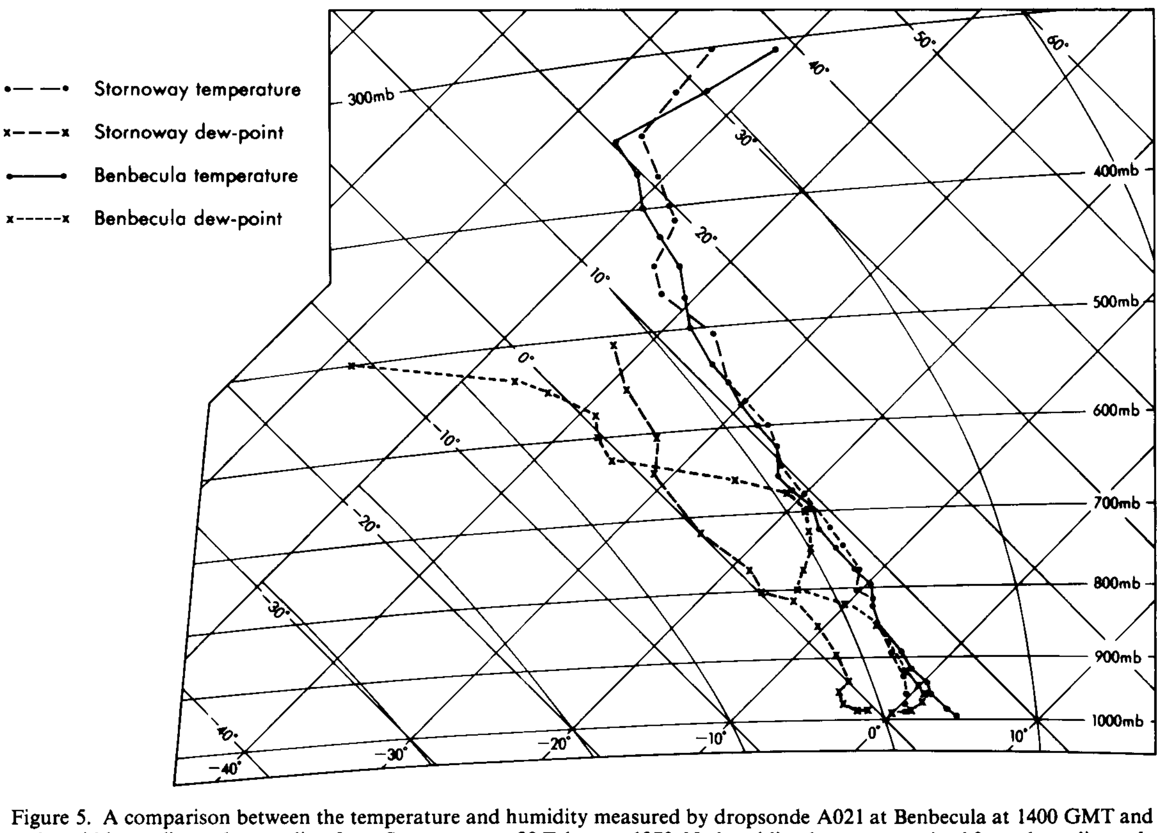

Figure 5. A comparison between the temperature and humidity measured by dropsonde A021 at Benbecula at 1400 GMT and the midday radiosonde sounding from Stornoway on 28 February 1979. No humidity data were received from the radiosonde above 500 mb.

(c) *Pressure*

The pressure transducer (Ryder and Lewis 1979) is a proprietary integrated circuit device (National Semiconductor LX 1602A). A vacuum reference cell is created by etching a silicon chip. This is sealed by a diaphragm on which are diffused four piezo-resistors. These form a strain gauge bridge on the diaphragm which, together with signal conditioning electronics and temperature sensing elements, generate high level voltages which are functions of pressure and diaphragm temperature. Trials have shown that the transfer characteristics of the devices, including their temperature coefficients, are stable except for an offset error which varies slowly with time. The sensors are not sensitive to shocks of the type experienced at ejection.

The accuracy of the pressure element was investigated by comparing its output with the sonde height derived from simultaneous ground based radar observations. The radar height data were converted to a pressure altitude by use of the hydrostatic equations, the necessary constants being provided by an estimate of the surface pressure and the sonde measurements of temperature. The result of one such comparison is summarized in Table I. Most of the differences are less than 2 mb, well within the expected accuracy of the pressure transducer, and their systematic nature reflects the tolerances permitted in the initial calibration. (The sonde was dropped close to the radar and errors in radar height are negligible.) Similar results have been obtained from several other comparisons, except for one which was unusual in that a constant difference of about 6 mb was observed. The reason for this is unknown. It was always expected that the absolute measurement of pressure would be difficult and it is for this reason that each sonde undergoes a single pressure calibration before ejection. Fortunately experience suggests that a further check may be possible. The loss of signal indicates entry of the sonde into the sea with a resolution of ± 0.2 s, allowing estimation of the surface pressure to ± 0.2 mb. Provided that the surface pressure can be inferred from some other source, gross errors at least can be avoided.

(d) *The aircraft instrumentation*

Equipment on the aircraft is required for three purposes: firstly, to test and perform simple calibration checks on the sondes before use; secondly, to store sondes and to eject them safely when required; and thirdly, to receive, process and store data from the sondes. Hardware and software for this last purpose were purchased from Beukers Labs Inc., Philadelphia, PA, USA.

The testing of sondes is carried out on a purpose-built rig through the sonde test socket (Fig. 1). All data are displayed during a test and are also stored on magnetic tape for subsequent analysis. The rig is used in the laboratory for the calibration of all the sensors and their signal conditioning electronics, over a range of temperature and pressure, before their incorporation into the sondes, and on the aircraft to allow a single-point calibration at cabin pressure shortly before use. If this calibration has drifted too far from the laboratory calibration the sonde is rejected.

The dropsonde ejector is a hydraulically operated, spring-loaded device in the rear loading ramp of the C130 aircraft. Sondes are ejected with their long axes parallel to the aircraft wings. A seal is provided to allow use when the cabin is pressurized. A nearby storage rack allows up to 80 sondes to be carried on a sortie. The ejector has been tested extensively and the facility incorporates several monitoring features including a rearward-facing television camera to verify satisfactory ejection.

The aircraft is fitted with a downward-facing broad-band UHF receiving antenna, which feeds a suitable preamplifier with the meteorological and Loran data. Each sonde transmits at one of five separate, crystal controlled frequencies in the 400 MHz band. By using receivers each tuned to one of these frequencies, data from up to five sondes can be processed simultaneously. This is a very valuable capability when frequent soundings are required; to study features on the scale 20 to 30 km for example. The audio frequency signals from each of these five sources are separately detected, decommutated, digitized and provided as input to a 32K memory computer.

Table I. *Comparison of output from dropsonde pressure element with pressures derived from ground-based radar observations. Sonde No. A003, launched at 13.54:21 GMT on 28 April 1978.*

Time (s)	Sonde Pressure (mb)	Radar Pressure (mb)	Difference (mb)	Time (s)	Sonde Pressure (mb)	Radar Pressure (mb)	Difference (mb)
488.4	1006.7	1008.8	-2.1	238.6	712.4	712.0	0.4
458.6	971.1	973.9	-2.8	228.6	701.4	700.7	0.7
448.6	958.9	961.3	-2.4	218.6	690.4	689.7	0.7
438.6	946.6	949.1	-2.5	208.6	679.4	678.4	1.0
428.6	934.2	936.7	-2.5	198.6	668.7	667.6	1.1
418.6	922.0	924.8	-2.8	188.6	657.7	656.5	1.2
408.6	909.8	912.0	-2.2	178.6	647.0	645.5	1.5
398.6	897.6	900.1	-2.5	168.6	636.0	634.6	1.4
388.6	885.6	887.1	-1.5	158.6	625.2	623.6	1.6
378.6	873.5	875.1	-1.6	148.6	614.6	612.7	1.9
368.6	861.7	863.2	-1.5	138.6	604.0	602.2	1.8
358.6	849.9	851.2	-1.3	128.6	593.4	591.3	2.1
348.6	838.1	839.8	-1.7	118.6	583.0	580.9	2.1
338.6	826.3	827.8	-1.5	108.6	572.5	570.4	2.1
328.6	814.7	815.7	-1.0	98.6	562.2	559.9	2.3
318.6	803.2	804.1	-0.9	88.6	552.0	549.5	2.5
308.6	791.7	792.3	-0.6	78.6	541.7	539.1	2.6
298.6	780.0	780.8	-0.8	68.6	531.6	528.8	2.8
288.6	768.7	769.1	-0.4	58.6	521.4	518.6	2.8
278.6	757.3	757.6	-0.3	48.6	511.4	508.5	2.9
268.6	745.9	746.0	-0.1	38.6	501.5	498.5	3.0
258.6	734.7	734.5	0.2	28.6	492.0	488.0	4.0
248.6	723.5	723.2	0.3	18.6	482.0	477.9	4.1

The aircraft receives Loran C transmissions directly as a so-called 'local' signal as well as from the five 'remote' sonde sources. In each case the signals are amplified and shaped to provide an in-phase square wave. The time of arrival (TOA) of one zero crossing in each of the eight repetitive Loran C pulses is measured against a stable internal clock. Each such group of zero crossings is effectively tracked by a second-order error detection algorithm in the computer to provide a continually updated assessment of the TOA. The characteristics and optimization of this technique have been discussed by Ryder (1976). Time differences are formed by straightforward subtraction of the relevant TOAs. The 'local' source provides a suitable first estimate of the times of arrival of the 'remote' source immediately after sonde ejection. This ensures that stable tracking and hence useful information is available as soon as possible after a sonde is released. Acquisition of the optimum zero crossing of the 'local' signal is obtained at leisure under a combination of automatic and manual control before the sonde dropping sequence is entered. Individual time of arrival estimates are formed from each of the tracked signals from each of the sondes once per second, and are stored with the digitized audio frequency data on magnetic tape for subsequent analysis. Various analogue signals are produced by a digital-to-analogue converter for real-time display on chart recorders. The data are subsequently processed in the laboratory to give profiles of wind components. It is hoped that in due course a real-time analysis facility will be available to allow the temperature and humidity to be displayed in the aircraft. The 'local' source also provides a valuable means of tracking the aircraft. A post-flight record of the C130 ground position is produced as a matter of routine by this method.

The C130 aircraft is also fully equipped with other instruments for meteorological research. Of particular interest to the study to be described later is the Ekco E290 3 cm weather radar. The antenna, which has a beam width of 3°, is programmed to scan the 180° sector ahead of the aircraft at one of a number of angles of tilt to the horizontal. This facility combined with the forward motion of the aircraft allows a three-dimensional view of the precipitation echo to be constructed. The radar has range compensation and an experimentally determined threshold equivalent to a rainfall rate of about 0.25 to 0.5 mm h^{-1} out to ranges of 40 km. The radar display is photographed at regular intervals to allow detection of areas of rainfall exceeding this threshold.

3. A pilot study of an Atlantic front

The surface analysis for 1200 GMT on 29 March 1979 is shown in Fig. 6. Although rather a weak feature with little thermal contrast and producing only light rain and drizzle, the occlusion/warm front S was chosen as the subject of a pilot study. The objectives were primarily to test some operational procedures for locating and studying such fronts, but a number of results were obtained which augur well for future investigations.

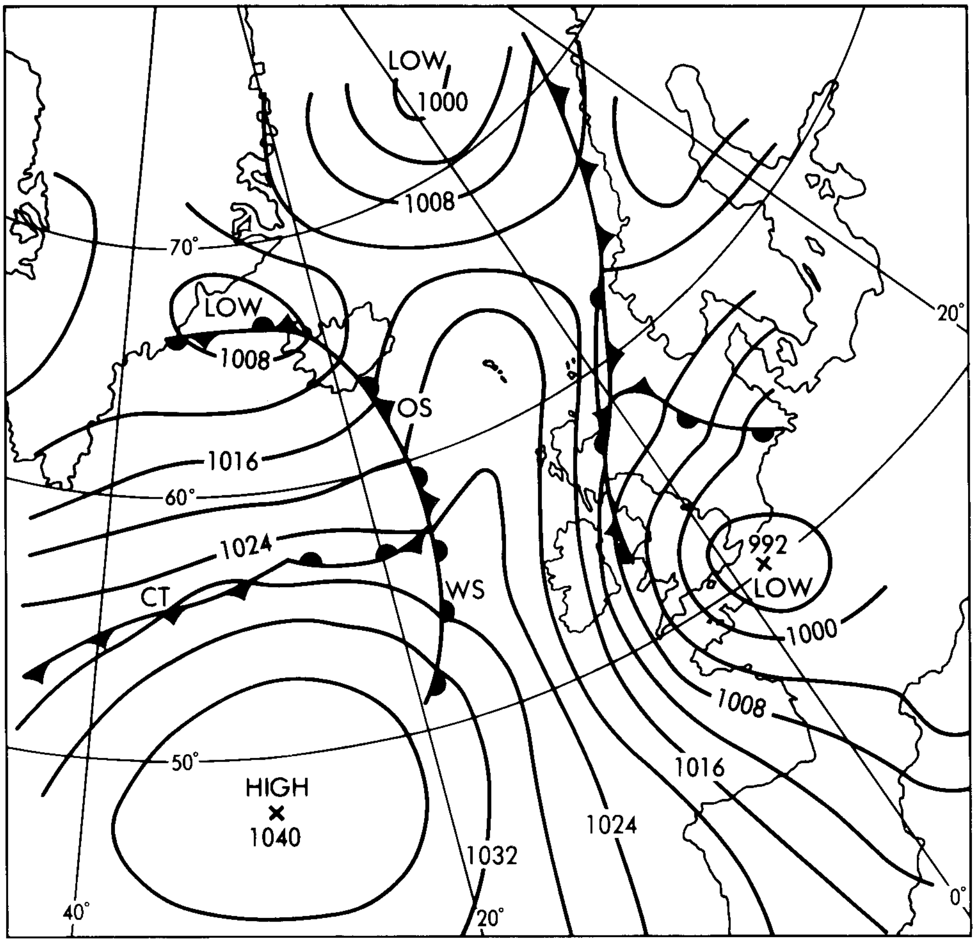

Figure 6. Surface analysis for 1200 GMT on 29 March 1979.

Measurements were made between 1100 and 1300 GMT by sondes dropped along an east-west line centred at 57°50′N, 17°W. Nine sondes were released in two groups from an altitude of 7.3 km in the vicinity of the front. Although wind data were obtained from only five of these and one parachute failed to deploy correctly so that temperature and humidity data from that sonde are suspect, a number of east-west cross-sections of interest have been derived.

Data are presented in a (p, x–st) frame of reference where p is pressure, s is the component of the system velocity vector in the x direction — west to east in this case — and t is time. Normally a sequence of sondes would be dropped both to test the validity of the system velocity concept (which assumes a non-developing system being advected at some constant velocity s) and where appropriate to define the vector. This was not done on 29 March. However, the synoptic-scale observations suggest that the front was moving eastwards at between 10 and 15 m s^{-1} and the 700 mb westerly wind measured by all the sondes was close to 12.5 m s^{-1}. Accordingly a value of 12.5 m s^{-1} from 270° has been assumed to be the system velocity; because the time between sonde ejections is short the resulting fields are not very sensitive to the choice of system velocity. The origin of the x-coordinate is arbitrarily set to the west of the observations.

Fig. 7 shows the variation of relative humidity in this frame of reference. The major feature is the layer of saturated air in the lower half of the figure with a long sloping tongue of dry air overlying it. Above the dry zone is another layer of moist air. The location of the radar echo above the threshold (i.e. the location of precipitation) is superimposed on the diagram. The same echo structure was observed throughout the area 20 km to the north and south of the section shown, but the extent to which the echoes represent bands of precipitation beyond that range is unknown.

The field of wet-bulb potential temperature calculated from the sonde data, Fig. 8, exhibits the expected strong gradient in what is assumed to be the frontal zone extending from the surface at 150 km, to 850 mb at 300 km, and weaker gradients elsewhere. Of special interest are the hatched regions denoting air which is potentially unstable. Three of the zones (centred at 25 km, 950 mb; 250 km, 950 mb; 250 km, 700 mb) are both saturated with respect to water and have a lapse rate at, or greater than, the moist adiabatic. Precipitation echoes were observed in the vicinity of all three regions, possibly indicative of the release of the instability. The band of potentially unstable air above the frontal surface (extending from 150 km, 775 mb to 300 km, 550 mb) correlates well with the dry tongue of air identified in Fig. 7. It is conceivable that the implied instability there may have been realized subsequently, following saturation of the air by moistening or lifting. Overall, the precipitation zones exhibit an interesting mesoscale structure, if not periodicity, which is readily resolved by the pattern of sondes. In this context, it is particularly unfortunate that further data were not obtained between 50 and 150 km; the observations at 75 km were made from the sonde with a failed parasheet.

Fig. 9 shows the u-component of velocity relative to the system (positive values indicate motion from west to east). Although perhaps distorted by the choice of system velocity, air above the front is, as expected, moving to the east and overrunning that beneath the front. The v-component (not shown) is consistent with the thermal wind equation and exhibited an upper-level jet parallel to the front. Because the divergence is unknown owing to the lack of data parallel to the surface front, it is not possible to derive the vertical motion rigorously from the equation of continuity. However, within a frontal zone it is reasonable to expect that locally $|\partial u/\partial x| \gg |\partial v/\partial y|$ (the y-axis is parallel to the front) and that changes in vertical motion occur where $|\partial u/\partial x|$ is a maximum. In particular ascent is likely where $\partial u/\partial x$ is large and negative, implying convergence, and descent is probable where $\partial u/\partial x$ is large and positive. The field of $\partial u/\partial x$ shown in Fig. 10 is compatible with ascent near 250 km, 600 mb just below the moistest part of the dry zone (Fig. 7), and descent at the same level at 175 and 275 km, which correlate well with the two humidity minima. Ascent is also predicted at 150 km, 700 mb and 250 km, 975 mb, coinciding well with the regions of potential instability (Fig. 8) and precipitation (Fig. 7). The region of implied descent at 220 km, 925 mb is closely related to the break in the radar echo (Fig. 7).

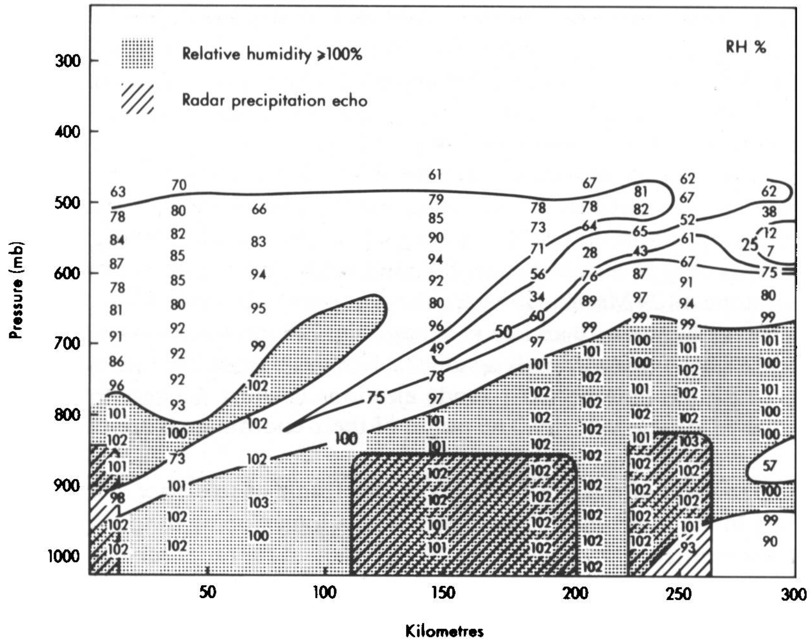

Figure 7. East-west cross-section centred on 57°50′N, 17°00′W of relative humidity with respect to water between 1100 and 1300 GMT on 29 March 1979. The location of radar precipitation echo is superimposed.

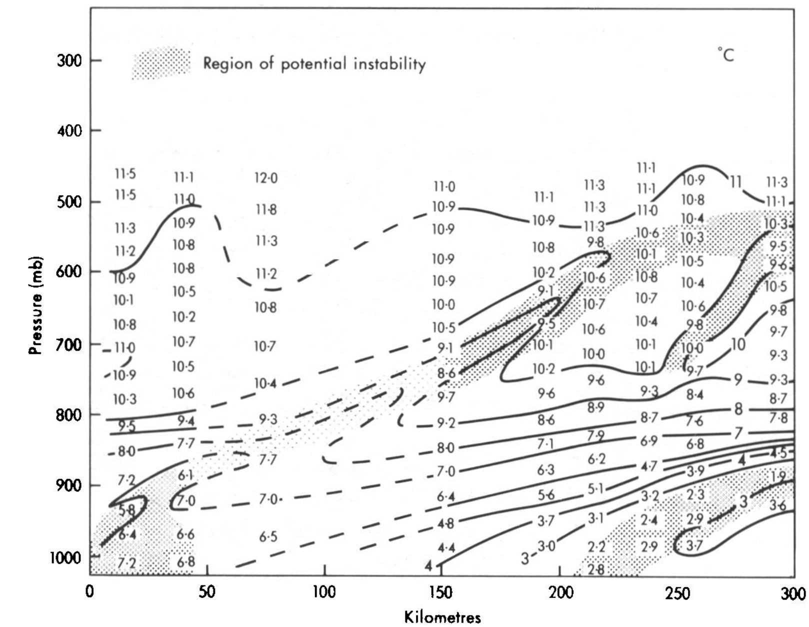

Figure 8. East-west cross-section of wet-bulb potential temperature.

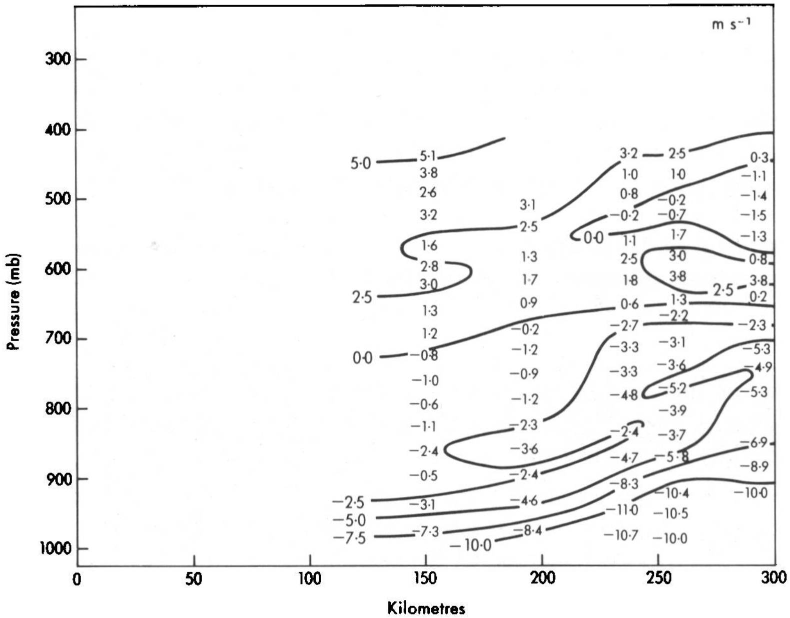

Figure 9. East-west cross-section of the westerly component of wind relative to the system, assumed to be moving from 270°, 12.5 m s^{-1}. Positive values imply motion from west to east.

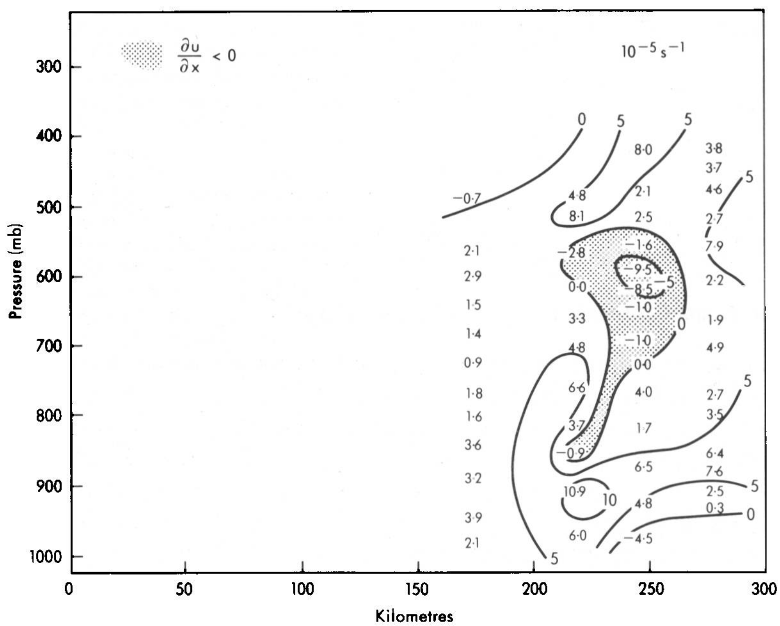

Figure 10. East-west cross-section of $\partial u/\partial x$.

4. Conclusion

This first use of a new facility has highlighted its potential for the study of the mesoscale structure and dynamics of the atmosphere. In particular, the ability to define thermal and moisture fields together with the coexisting air motions has been shown to provide a self-consistent and mutually supportive data set.

Although the data are limited in extent in the example described above, a number of interesting features have been identified and a coherent description of the airflow, cloud and precipitation has emerged.

More recently the dropsonde facility has been used to investigate the banded structure of convective rainfall behind a cold front (Bennetts and Ryder 1984).

Acknowledgements

The development of this facility represents the combined efforts of numerous members of the Meteorological Office Cloud Physics Branch and the Meteorological Research Flight. Their contribution is gratefully acknowledged.

References

Bennetts, D. A. and Ryder, P.	(1984)	A study of post cold-frontal mesoscale convective bands: Part I, Mesoscale organisation. (Submitted to *Q J R Meteorol Soc.*)
Browning, K. A., Hardman, M. E., Harrold, T. W. and Pardoe, C. W.	1973	The structure of rainbands within a mid-latitude depression. *Q J R Meteorol Soc*, **99**, 215–231.
Gibbs, J., Lewis, A. F. and Ryder, P.	1975	Evaluation of the carbon hygristor as a humidity element for the NAVAID dropsonde. (Unpublished, copy available in the National Meteorological Library, Bracknell.)
Hardman, M. E., James, D. G. and Goldsmith, P.	1972	The measurement of mesoscale vertical motions in the atmosphere. *Q J R Meteorol Soc*, **98**, 38–47.
Ryder, P.	1976	Description and optimisation of the LOCATE tracking algorithm for use with Loran C. (Unpublished, copy available in the National Meteorological Library, Bracknell.)
	1979	An assessment of the performance of the NAVAID dropsonde. (Unpublished, copy available in the National Meteorological Library, Bracknell.)
Ryder, P. and Lewis, A. F.	1979	An assessment of the pressure transducer of the NAVAID dropsonde. (Unpublished, copy available in the National Meteorological Library, Bracknell.)
Ryder, P., Hardman, M. E. and Goldsmith, P.	1972	The development and use of dropsondes for meteorological research. (Unpublished, copy available in the National Meteorological Library, Bracknell.)

Notes and news

Sir John Mason appointed Scientific Director of acid rain project

Immediately after his retirement as Director-General on 30 September, Sir John Mason took up a new appointment as Scientific Director of a major new research project on acid rain to be conducted over several years by the Royal Society in association with the Norwegian Academy of Science and Letters and the Royal Swedish Academy of Sciences. The project is being funded by the Central Electricity Generating Board and the National Coal Board to make a completely independent investigation of the acidification of surface waters in Norway and Sweden and of the extent to which this is responsible for the reduction of fish populations in some Scandinavian lakes. This investigation will be conducted in parallel with researches already being undertaken by the Central Electricity Research Laboratories and the Meteorological Office to determine to what extent the acidification of precipitation falling in Norway and Sweden may be attributed to the emission of sulphur and nitrogen oxides from UK power stations and to what extent this might be reduced by the partial or total removal of sulphur dioxide from the effluents.

Sir John's main tasks will be to review the current status of recent research in this complex field, to identify important gaps in knowledge and understanding, to formulate key questions and to commission research on at least a five-year time scale in the United Kingdom, Norway and Sweden as appropriate. Sir John's base for this task, which he expects to occupy half his time, will be at Imperial College where he is an Honorary Fellow and former Professor of Cloud Physics.

He will also retain his interest in numerical weather prediction and climate studies by joining the Joint WMO/ICSU Scientific Committee which plans and co-ordinates the World Climate Research Programme and by becoming Scientific Director of the WMO World Conference on the First Global Weather Experiment to be held in Geneva in 1985. These assignments will keep him in close touch with the Meteorological Office.

Sir John has also been appointed by the Secretary of State for Education and Science to the Advisory Board for the Research Councils which funds and determines the broad programs of all the Research Councils covering more than half the scientific research conducted in the universities.

He will continue with his duties as Treasurer and Senior Vice-President of the Royal Society and as Pro-Chancellor of the University of Surrey.

50 years ago

The following letter was published in the *Meteorological Magazine*, December 1933, **68**, 258–259.

Where is the Rainbow?

The elementary theory of the rainbow explains how the phenomenon is produced by reflection and refraction of the sun's rays falling on raindrops, and that the bright coloured arch that we see is actually a multitude of drops which are momentarily in the right position to transmit the refracted and reflected light into the eyes of the observer. This is all quite simple and straightforward, but if we pursue the matter a little further we arrive at a curious and paradoxical result.

Suppose we attempt to locate the position of the rainbow in space by using one of the ordinary methods depending on parallax. We might, for example, use a range-finder, or take the bearings of a point on the bow, *e.g.*, the apex, from two points at the ends of a measured base line. If that be done, the distance so determined is not the distance of the raindrops but "infinity," for the simple reason that it is impossible to observe the same rainbow from two different positions. When the observer moves from one position to the other, the rainbow moves too. The bearings measured from the two ends of the base line will identical. It does not matter whether the bow is formed by a shower a mile away or by the spray from a garden hose-pipe a few yards away, the result must always be the same.

Now our own normal optical equipment consists of a pair of eyes which enable us to judge distances and to see things in their proper spatial relationship by observing simultaneously from two view points, about two and a-half inches apart. Speaking for myself, I feel positive that when I look at a rainbow formed by the spray of a garden hose, I judge it to be close at hand among the falling drops. The theory given in the preceding paragraph indicates, however, that I should judge it to be far behind the drops, at an infinite distance (or to be more accurate, at the distance of the sun). Possibly the explanation is that parallax due to binocular vision is only one of the factors entering into our judgement of distance, other factors being brightness, contrast and apparent relative position. In the case of the rainbow the eyes see a bright translucent object associated with the water drops, and interfering with the visibility of objects beyond the spray. The illusory evidence arising from binocular vision is rejected and the brain judges the bow to be where it really is — among the water drops.

Has anyone ever taken a stereoscopic photograph of the rainbow formed in spray a few yards from the camera? It would be very interesting to see what it looks like in the stereoscope.

E. G. BILHAM

*** Mr Bilham's letter elicited no response. The point he makes does not seem to be dealt with specifically in subsequently written treatises on atmospheric optics such as Minnaert's *Light and colour in the open air*, Tricker's *Introduction to meteorological optics*, or Boyer's *The rainbow*. We have certainly seen, from the seventh floor of the Meteorological Office Headquarters building, a rainbow one end of which clearly arose from the garden of a house adjacent to the main car park.

Oceanology International Conference and Exhibition

Oceanology International 84, sponsored by the Society for Underwater Technology, will take place at the Hotel Metropole, Brighton, from 6 to 9 March 1984.

Forty-nine papers will be given under four main session headings: navigation and position fixing; geophysics, geology and geotechnics; environmental data; and hydrography and seabed surveys. The environmental data sessions will have papers grouped under the headings of user emphasis, ocean climate, measuring systems, wind and remote sensing. There will be poster presentations on a further dozen topics.

Further information may be obtained from the organizers, Spearhead Exhibitions Ltd, Rowe House, 55/59 Fife Road, Kingston upon Thames, Surrey KT1 1TA. Telephone: 01-549 5831. Telex: 928042.

Correction

'Global solar radiation measurements on 6 August 1981. A day of midday darkness' by R. J. Armstrong, *Meteorol Mag,* **112,** 1983, 200–209.

The graph showing the hourly irradiation for East Malling in Fig. 2 on page 203 (broken line) should have its ordinate values multiplied by 2.5. The corresponding daily total in Table II of 2679 W h m^{-2} is correct.

THE METEOROLOGICAL MAGAZINE

No. 1337 December 1983 Vol. 112

CONTENTS

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For Meteorological Magazine'.

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Applications for postal subscriptions should be made to HMSO, PO Box 276, London SW8 5DT.

Complete volumes of 'Meteorological Magazine' beginning with Volume 54 are now available in microfilm form from University Microfilms International, 18 Bedford Row, London WC1R 4EJ, England.

Full-size reprints of out-of-print issues are obtainable from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX, England.

Please write to Kraus Microfiche, Rte 100, Millwood, NY 10546, USA, for information concerning microfiche issues.

Printed in England by Robendene Ltd, Amersham, Bucks.
and published by
HER MAJESTY'S STATIONERY OFFICE

£2 monthly
Dd. 736047 C15 12/83

Annual subscription £26.50 including postage
ISBN 0 11 726941 7
ISSN 0026–1149