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Forecasting difficulties in showers
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The calibration of ERS-1 scatterometer winds

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Summary

The European Remote Sensing satellite, ERS-1, was launched by the European Space Agency (ESA) on 17 July 1991. One of its instruments, the Wind Scatterometer, is a radar system from which measurements of near-surface wind vectors can be derived. During the Autumn of 1991, ESA coordinated a campaign of in situ *wind measurements in order to calibrate this instrument. This paper gives a brief description of the campaign, the data resulting from it, and how the* in situ *measurements have been used to improve the quality of the ERS-1 winds.*

1. Introduction

The scatterometer on ERS-1 measures the returned radar power, σ^0, using three antennae which form a swath 500 km wide to one side of the satellite's ground track. Winds derived from the three values of σ^0 per measurement 'cell' have an accuracy requirement of 2 m s^{-1} or 10% (whichever is higher) in wind speed and 20° in direction. An empirical relationship between surface wind vector and σ^0 ('CMOD2') was established prior to launch (Long 1986) using aircraft scatterometers. This relationship — or 'model' — needed to be validated for the satellite instrument, and if necessary, modified for operational use to meet the stated accuracy. Offiler (1987) gives an overview of the scatterometer operation and the derivation of winds using such a model.

During the period 16 September to 10 December 1991, ESA coordinated a campaign to calibrate the geophysical wind and wave products derived from the ERS-1 satellite (the calibration of 'engineering' quantities, such as σ^0, being a separate issue). The campaign, known as RENE-91, involved making *in situ* measurements off the coast of Norway using a variety of platforms, i.e. buoys, ships and aircraft, with participants from several European countries. For part of the campaign period, the Meteorological Research Flight C-130 (Hercules) aircraft was based in Trondheim — the campaign's operations centre — measuring low-level winds over the campaign area at times when the ERS-1 scatterometer was also operating. A German Dornier Do-228 aircraft similarly measured winds using its normal navigation system; it also carried a radar scatterometer so that the back-scatter measurements could be compared with those from ERS-1.

Data from most of the platforms participating in the campaign, together with NWP analyses made by the Norwegian Meteorological Institute (DNMI) and ERS-1 wind and wave products were delivered to a local database, generally within 24 hours of their measurement time. This database was used to form a 'best-estimate' wind field covering the campaign area which could be used to (a) compare with the ERS-1 winds for day-to-day quality monitoring during the campaign, (b) form a high-quality data set which could be used for calibrating or tuning the scatterometer wind model and retrieval algorithms, and (c) validate such tuning.

2. Wind measurement from the C-130

Depending on the needs of particular experiments, the C-130 can carry a wide range of instruments for measuring various atmospheric parameters, including chemistry, radiation (infrared and microwave) and clouds (Readings

1985). For winds, only the standard sensors are required; principally the Inertial Navigation System (INS), giving the aircraft's position, ground velocity and heading from true north and dynamic pressure for air speed. Other navigation aids (in particular GPS) are used during ground processing to correct the INS in order to obtain the best aircraft ground velocities; the air temperature and static pressure are also used to correct for true air speed. The wind speed and direction is then the vector difference of ground and air velocities, with an expected r.m.s. accuracy of about 0.5 m s^{-1} and 5° (Axford 1968).

The scatterometer-derived wind speeds are specified to be those equivalent to a measurement at a height of 10 metres in a neutrally stable atmosphere (a quantity known as U_{10}). In order to compare and calibrate the scatterometer winds, all the *in situ* measurements need to be to the same standard. The C-130 flight level winds were therefore converted to U_{10} using an agreed boundary layer model, using flight-level wind speed, temperature, humidity and static pressure, radiometric sea-surface temperature, radar altitude and temperature lapse rate (the latter determined by profiling in the lowest 1 km of the atmosphere).

While ERS-1 was in its initial 3-day repeat orbit, scatterometer passes were scheduled to give good coverage of the campaign area three times every three days. The C-130 flew missions on two of these opportunities in each 3-day cycle — the southbound pass at around 1050 UTC on the first day of the cycle, and the 1015 UTC southbound pass on the second day. Each flight pattern covered the width of the swath and about 500 km along it. Fig. 1 gives an example flight track and the derived winds for a 'Day 1' pattern. The nominal flight altitude was 200–250 ft (60–80 m), with a profile between 3000 ft (915 m) and 50 ft (15 m) at each corner of the pattern, and passing over at least two buoys for cross-comparisons. A typical flight duration was around 6 hours, so there is obviously a time difference between

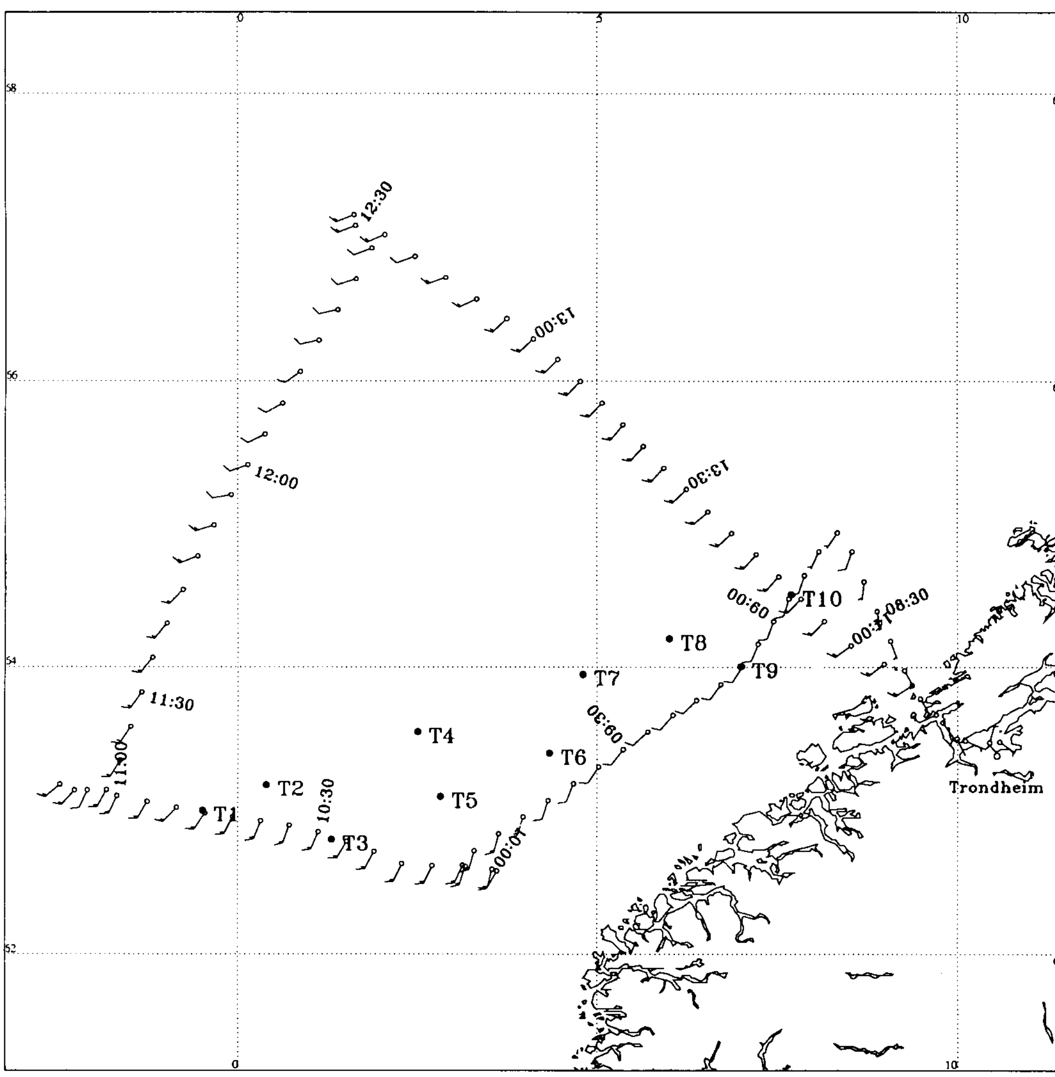

Figure 1. Example C-130 flight track and derived 10 m winds for 0800–1425 UTC on 2 December 1991. The wind symbols are plotted conventionally, with each full feather representing 10 m s^{-1}. The location of the Tobis buoys are labelled T1 to T10.

the some of the aircraft and scatterometer measurements; the flight was planned so that the C-130 would be over the buoy position T1 at the time of the ERS-1 overpass. On the 'day 2' passes, the swath was closer to the coast and further north; on these flights, the rendezvous point was T10, travelling up-swath. All tracks were flown in a clockwise direction.

A total of 18 flights were made when good data were obtained; on two flights, the INS drifted badly and, although the aircraft position could be recovered with the GPS, the aircraft velocities could not be derived with sufficient accuracy to obtain good winds. Only one planned mission was lost, due to an engine problem, and a total of more than 100 hours were flown by the C-130 during the campaign. The final data from each flight were delivered to the local database in Trondheim, in a common format, the day following a flight.

3. Wind analyses

When comparing meteorological satellite data with *in situ* measurements, it has been traditional to use one of two methods:

(a) collocate one *in situ* measurement with one or more nearest satellite points and within some time limit, on an essentially one-for-one basis. This has the disadvantage of introducing collocation errors because of spatial or time differences, and also not comparing like with like, since the *in situ* measurement is usually taken at a point over a time average, and the satellite is an areal average at an instant in time. Such collocations tend to be few in number and rarely cover the whole range of desired parameters.

(b) assimilating the *in situ* data into NWP models and interpolating the required parameter from the analysis grid to the satellite footprint location. However, such models tend to have rather coarse horizontal resolution compared with the satellite, and are generally tuned to the synoptic scale, which tends to smear out or miss small-scale features which might be represented in the satellite swath. The data also need to be available very quickly so they can be used in these operational models.

In the case of the RENE-91 campaign, the *in situ* data, although gathered quickly by campaign standards, could not be delivered to weather centres in time for their numerical models' operational runs. Instead, the RENE-91 winds and DNMI background fields were analysed using a simplified scheme, developed by the Meteorological Office, which could be run on a workstation at the operations centre. A 25 km grid size was chosen as comparable with the scatterometer cell spacing, with the grid covering the campaign area. Because all the RENE-91 data sets were supplied in a common format, wind from all available sources could easily be incorporated into the analysis; the actual sources and quantities varied from day to day, but the following have been used in at least one analysis:

Aircraft — C-130, Do-228,
Radar — Radar Airborne C-band System (RACS) on Do-228,
Buoys — up to 6 of the 10 Tobis-3 buoys,
Ships — Weathership Mike, R/V Gauss, Håkon Mosby,
Platforms — Gullfax,
Models — DNMI wind-field analyses.

All of these contain U_{10} wind speeds or have measurements made close to 10 m; each data source is complementary in that they are made at many different locations over the analysis area and by different sensor and sampling systems. Of course, not all sources were available for every scatterometer pass.

Fig. 2 shows an example of data coverage for one analysis. In this case, the C-130 track from Fig. 1 is plotted, as is the Do-228 track though the centre of the C-130 loop. The latter actually contains RACS-derived winds outbound and Do-228 winds — extracted from their navigation system when flying at low level — on the return. This case also uses data from three Tobis buoys, Weathership Mike (just below the northernmost part of the C-130 track) and the Gullfax platform to the south; the grid of wind symbols is from the midday DNMI NWP analysis. The analysis scheme also calculates a 'quality index', QI; this parameter is related to the local quality, quantity and consistency of the original measurements, and to the time difference from the satellite overpass.

The advantages of this analysis method are that it maximizes the number of collocations, particularly by covering the whole width of the swath and it minimizes the effects of systematic errors in any one platform or poor individual observations. Also, the spatial average is more comparable to a scatterometer measurement, although there will still be a tendency to smooth very-small-scale features or sharp gradients over one or two grid lengths, or when there are rapid changes with time.

The analysed winds then are interpolated from the grid to each of the scatterometer cell locations; Fig. 3 shows the RENE-91 gridded analysis made from the data in Fig. 2, together with the ERS-1 winds. The contour is a threshold QI value, inside which the analysis is almost entirely derived from the *in situ* measurements, and outside which it is influenced only by the DNMI background wind field. Over most of the swath, the scatterometer shows good agreement with the analysis except in the north-west part of the contour, where there are differences in wind direction of 20–30°; this is probably due to an active front passing through the area between the time of the satellite pass and the C-130 track 1–2 hours later. The frontal position can be identified from the wind direction changes in Fig. 1 along the north-east- and south-east-bound C-130 legs.

A total of 81 scatterometer passes were processed, with analyses made using the technique described here, creating nearly 22 000 individual (but not totally independent) collocations within the QI threshold contour. Not all of these passes have good coverage of *in situ* data or have DNMI backgrounds available, but the QI value is a good filter for poorly covered cases. Some passes, like the example shown, have frontal systems which may give rise to 'errors' in the analyses — these may need to be excluded by inspection of the data and by consulting the corresponding synoptic charts before being used for calibration purposes. These collocation files have also been delivered to the ERS-1 database for use in model tuning by other groups.

These analyses cover the wind speed range 1–21 m s^{-1} with directions mainly from the south-west to the north; but as the passes are both northbound and southbound the wind directions relative to the satellite are spread more uniformly. Taken over the whole data set, the r.m.s. differences between the scatterometer winds and analysed winds are 2.7 m s^{-1} in speed and 21° in direction. This shows that against the RENE-91 analyses, the ERS-1 wind directions are generally acceptable, but the wind-speed retrieval from the then operational wind model (CMOD2) required tuning if the scatterometer specification of 2 m s^{-1} was to be met.

4. Wind model tuning

Although the global, near real-time scatterometer winds derived using the prelaunch model, CMOD2, compared favourably with conventional synoptic observations from ships and buoys, some deficiencies were clear, and ESA felt that the product was capable of improvement. Several groups, some involved in the RENE-91 campaign, have used different sources of wind data either to tune the CMOD2 empirical relationship or to define a new one. These groups include ESA themselves, the European Centre for Medium-range Weather Forecasts (ECMWF), the French Meteorological Office (Meteo-France), the French oceanographic institute (IFREMER) and the Universities of Hamburg and Oregon; the wind data used have included the RENE-91 collocations described above, sub-sets of the RENE-91 *in situ* measurements, deep-water NOAA buoys and NWP models. Most of this work is reported in Wooding (1992).

Since launch, the Meteorological Office has reprocessed the near real-time σ^0 values to winds (using our own algorithms) in order to make use of our NWP wind fields in the ambiguity removal processing (Offiler

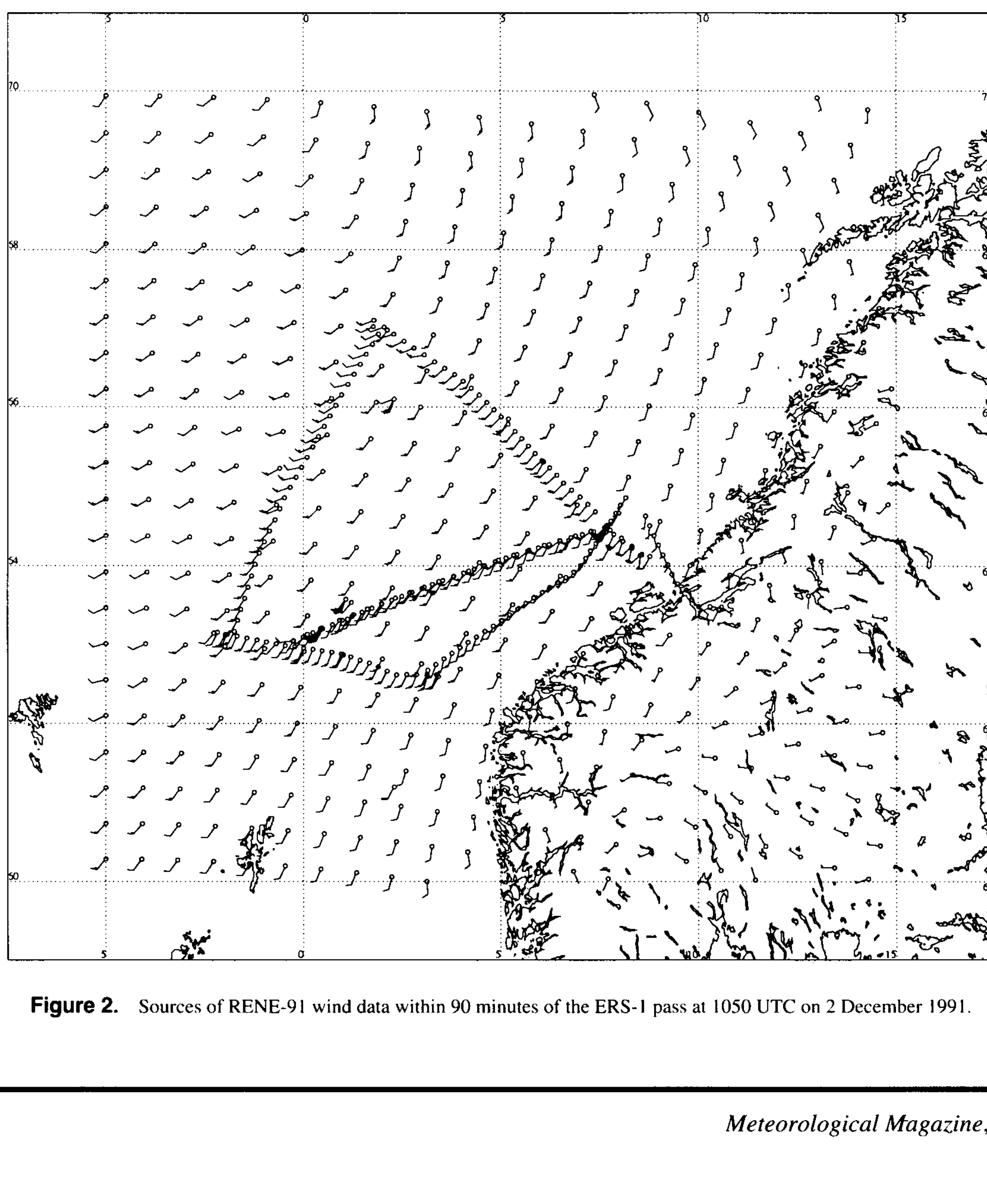

Figure 2. Sources of RENE-91 wind data within 90 minutes of the ERS-1 pass at 1050 UTC on 2 December 1991.

1987). We could therefore use this scheme off-line to reprocess the RENE-91 σ° data, substituting any of the candidate models developed by the other groups. The performances of these models were judged by comparing the quality of the wind vector retrievals against the analysed RENE-91 campaign winds, sub-divided by (for example) wind speed or cell position across the swath. Parameters included the mean and standard deviation of differences in wind speed and direction and r.m.s. vector differences when compared with the RENE-91 analyses. The models were also validated using global, near real-time data, with a comparison against our NWP fields.

ESA were keen to improve their operational wind product, so each group sent their initial candidate model to the Meteorological Office for evaluation during March 1992; results were returned to all participants, including the ESA calibration managers, and were discussed at a geophysical calibration workshop, held in April (Wooding 1992). Most of these candidate models improved upon CMOD2, and a short-list was drawn up; the workshop recommended the model provided by ECMWF, and this was implemented as 'CMOD3' by ESA for operational processing since June 1992.

However, between the model tuning exercise, and the implementation of the new model, ESA had independently updated the engineering calibration of the σ° values — the major effect being the introduction of a 1 m s^{-1} low bias on the retrieved wind speeds. There were still problems in retrieving wind directions on the inner edge of the swath, so the tuning and model validation exercise was repeated using the latest calibration standards. This has recently been completed and we have recommended to ESA that a modified version of the original ECMWF formulation offers the best performance improvement of the latest set of candidates. The bias has now been removed, and wind directions are significantly better on the inner edge. ESA implemented this model as CMOD4 in February 1993, and it is likely that this model will then remain in place for the remaining lifetime of the satellite. Table I summarizes the performances of the old (CMOD2), intermediate (CMOD3) and new (CMOD4) models in terms of differences from the RENE-91 analyses, and Table II similarly for an extended validation against operational NWP fields. These results clearly show the overall improvements obtained by tuning the wind vector–σ° relationship.

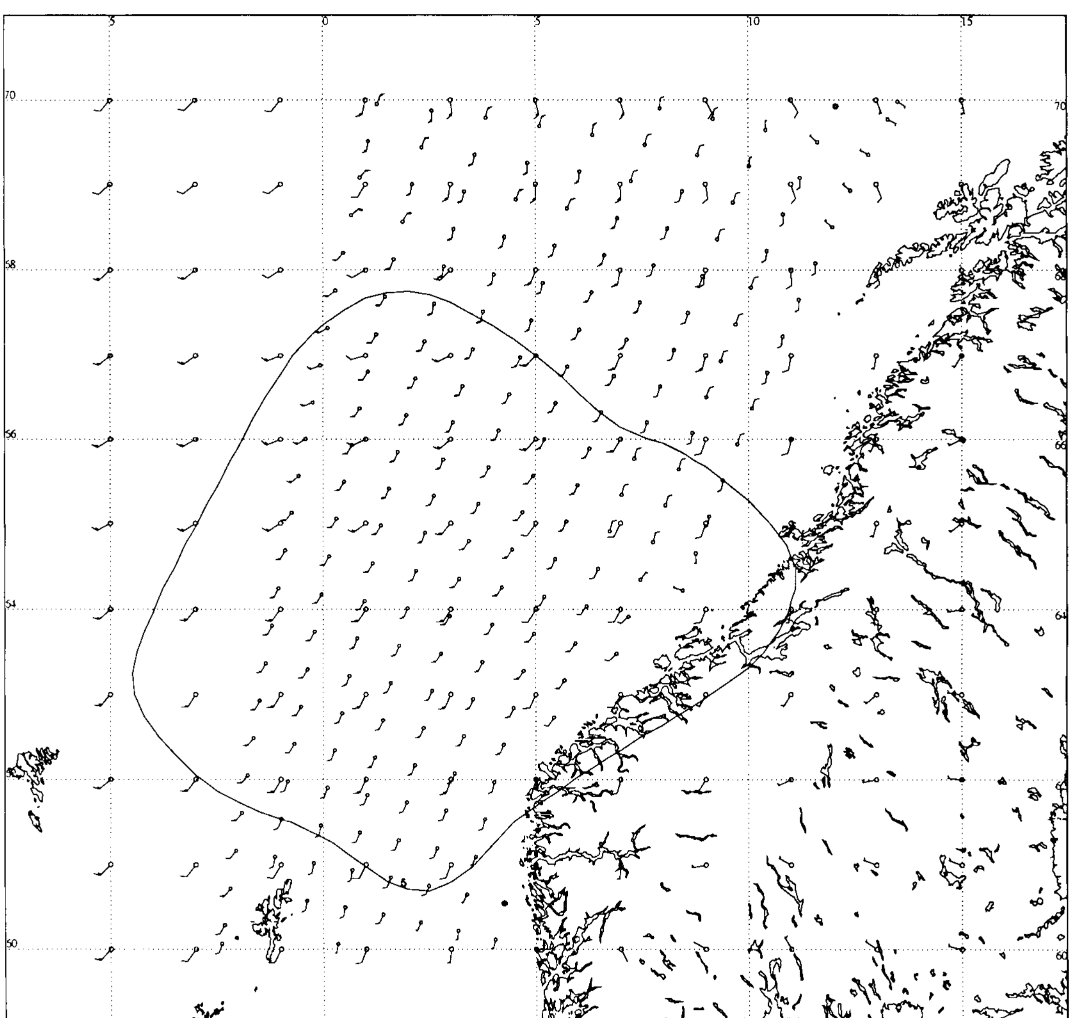

Figure 3. Collocated scatterometer and RENE-91 analysed winds from Fig. 2.

Table I. Summary of a comparison of ERS-1 winds against RENE-91analyses. (These statistics exclude winds < 4 m s^{-1}.)

Model identification	No. of cells	Speed (m s^{-1}) Bias	SD	Direction (°) Bias	SD	Vector (m s^{-1}) R.M.S.
CMOD2	18898	−1.4	2.8	−2.3	20.2	3.9
CMOD3	18898	−1.0	2.0	−1.2	17.5	3.3
CMOD4	18898	0.1	1.9	−1.6	17.2	3.2

Table II. Summary of a comparison of ERS-1 winds against Meteorological Office global NWP analyses 15–30 March 1992 (14 October–4 November 1992 for CMOD4).

Model identification	No. of cells	Speed (m s^{-1}) Bias	SD	Direction (°) Bias	SD	Vector (m s^{-1}) R.M.S.
CMOD2	820374	−1.3	2.6	1.4	22.7	4.1
CMOD3	820374	−0.9	2.2	1.1	21.1	4.0
CMOD4	1437910	0.0	2.1	1.2	20.9	3.6

5. Conclusions

The RENE-91 campaign has provided a high-quality set of wind measurements from aircraft, ships and buoys, which have enabled us to construct analysis fields covering a three-month period. We believe these fields to be the best available estimate of the true wind which can be used to compare with those from the ERS-1 satellite, albeit limited in area and lacking in the higher wind speeds. These and other data sources have been used by other groups to 'tune' the empirical relationship between the near-surface wind vector and satellite radar backscatter measurements.

We have independently evaluated several candidate models by using a common retrieval scheme and on the same data (the RENE-91 collocated scatterometer measurements and analyses). One of the interim models was recommended to ESA, and replaced the prelaunch model in their operational 'fast delivery' products from June 1992. Further tuning by the groups involved has resulted in a new model with significantly better performance, and ESA have been using this model since February 1993.

In the future, small improvements (by modifying the empirical functional form and/or tuning the model's coefficients) may be possible, but these will probably not be worthwhile implementing in ESA's operational system. Effort is now turning to improve the complete wind retrieval scheme and ambiguity removal algorithms — originally developed some years ago — to reflect the characteristics of the new model. For instance, in prelaunch simulations, the CMOD2 model, based on aircraft σ° data, was able to discriminate upwind–down wind ambiguities in most cases. In practice, the differences in the satellite-measured values of σ° are much smaller, making successful ambiguity removal more dependent on some prior knowledge of the general wind direction — as is already the case in the Meteorological Office's scheme. Looking even further into the future, the use of 'neural nets' — which may be able to learn how to relate the σ° measurement directly to a single wind vector — might be able to provide a means of bypassing the need for a fixed, explicit model.

Acknowledgements

My thanks are extended to all the participants in the RENE-91 campaign for providing their data so quickly and allowing it to be used in this validation experiment. Thanks also to my colleagues who supplied their model formulations and updates to coefficients to meet the deadlines placed upon this study.

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Forecasting difficulties in showery situations

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Summary

The problems encountered by forecasters when they use numerical weather forecasts to predict the occurrence of showers are discussed. Forecasts from the Meteorological Office's Limited Area Model for a thundery day in June 1992 are used to illustrate the problems.

1. Introduction

Throughout the evolution of Numerical Weather Prediction models, there has been much emphasis laid on the importance of the 'man–machine mix' in the forecasting process. The numerical models may be expected to provide pointers to the general atmospheric developments and a guide to likely distributions of the various weather elements, whilst the forecaster can use his experiences of the behaviour of the atmosphere and of the numerical models to fine-tune the model forecasts.

Forecasters may take into account errors in the model's analyses (the starting points for the forecasts), which can be identified when the analyses are compared with the human interpretation of the data. These errors could be carried forward into the forecast, thereby reducing the value of the model products. The forecaster may also know about deficiencies in the model's guidance in the given type of weather situation, such deficiencies having been identified over an extended period of use of the model. In addition, forecasters need to use their understanding of the atmospheric processes to assess the overall value of the model's forecasts.

The man–machine mix has a number of steps. The forecaster at the main or central forecast centre evaluates the model products in a broad sense, taking into account likely global developments and their impact on the weather pattern over the country as a whole. He provides overall guidance on the interpretation of the model products for the other forecasters around the country. The forecasters at the regional and local centres use the overall guidelines to interpret the model results for their parts of the country, adding their local knowledge, to provide the detailed forecasts required by their clients. The man–machine mix works well when the forecast model provides a good overview and is an acceptable starting point for the fine-tuning of the output by the forecaster. When, however, the forecaster has only a low confidence in the details, as frequently happens when deep convection is expected, the forecaster makes the major or perhaps the total input to the collective result.

2. The man–machine mix in showery situations

Although the mechanisms that can lead to the development of convection are well known, their scales and complexities have made them difficult to quantify both for the human forecaster and by the numerical models. Small changes in the details of the weather elements involved in the convective processes, such as the humidity through the atmosphere or the shape of the upper-level flow, even in the surface wind such as at sea-breeze fronts, can make large differences to the extent or distribution of the convection. The processes are often on a scale below that of the numerical models. As a result, most numerical models can provide relatively little guidance for the forecaster, beyond perhaps identifying that convection is likely and the more favoured locations or times for it to occur. The forecasters, in turn, appreciating the problems inherent in forecasting convection, have to make subjective judgements about the value of this limited model guidance, and try to add value to the forecast based on their knowledge and experience.

When guidance from the models is consistent, a more confident forecast will result. If, however, the solutions shown by the models vary, either from one model to another or between successive runs of the same model, then decisions on accepting the model guidance are more difficult, and confidence in the forecast is lower than when the model output is consistent. In the example given below, the difficulties of interpreting very variable model forecasts in a convective situation are highlighted. It is not the intention to try to identify general model inadequacies in convective situations.

3. An example of a convective situation on 29 June 1992

A good example of the thundery breakdown of a short fine spell, a situation often encountered during the summer months, occurred on 29 June 1992. The surface and upper-air analyses at 1200 UTC on 29 June are shown in Figs 1 and 2. The forecasts were based on the Meteorological Office's Limited Area Model (LAM) which gave a particularly variable sequence of forecasts of the rainfall. By midday the thundery breakdown had started. A cold front across northern Scotland had been slow moving for several days, giving a good deal of rain in that region. Further south, a high centre, which had been over the United Kingdom the day before, had been eroded and displaced to the east, as pressure falls

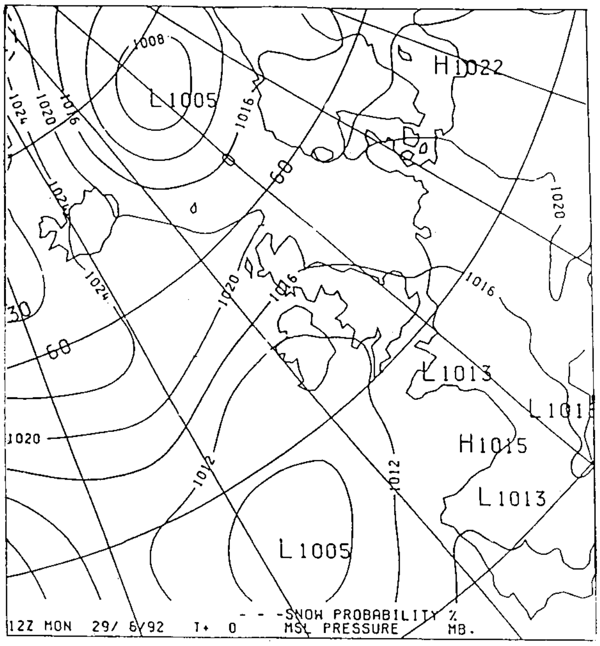

Figure 1. Surface analysis for 1200 UTC on 29 June 1992.

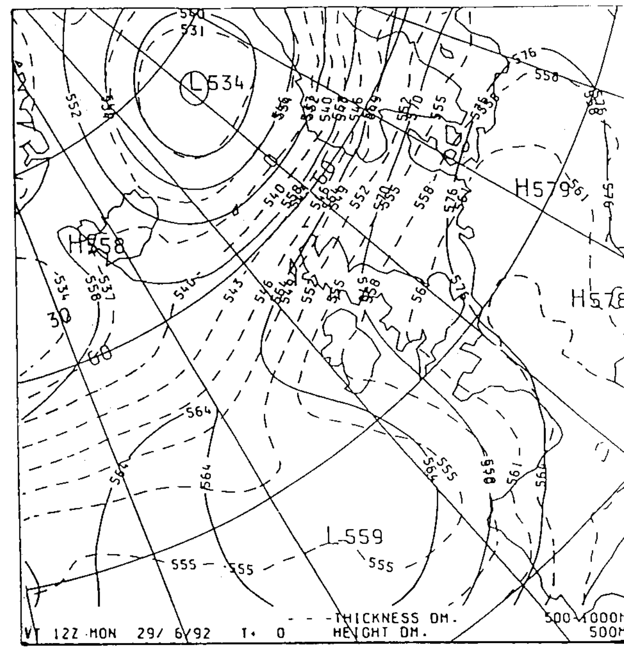

Figure 2. Upper-air analysis for 1200 UTC on 29 June 1992 showing fields of 1000–500 hPa thickness and 500 hPa contours (both measured in dam).

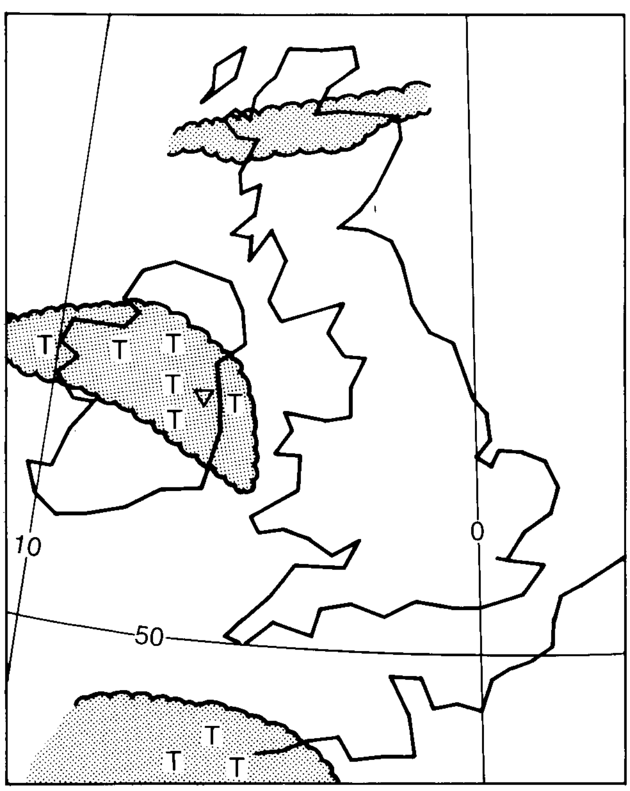

Figure 3. Sketch map showing areas of rain at 1200 UTC on 29 June 1992. T represents reports of thunder.

occurred ahead of the advancing upper vortex to the west of the Bay of Biscay. A preliminary band of thundery showers had moved north from the Biscay area and was over Ireland at that time, whilst a further band of thundery rain was moving north from north-west France. The areas of significant weather over the United Kingdom at 1200 UTC on 29 June are shown in Fig. 3.

It is of interest to review the forecasts from the LAM valid at this time, to show the problem that the model has in ascribing correct details to an overall correct solution, and as a corollory to highlight the problem for the forecaster, who normally would expect to use the model products as the basis for the forecast.

The LAM forecasts of surface pressure and rainfall for 1200 UTC on 29 June 1992, with lead times decreasing from 36 hours to 6 hours, are presented in Fig. 4. It can be seen that the model provided good forecasts of the pressure field over and around the United Kingdom at that time, when compared with the analysis in Fig. 1.

The 36-hour forecast upper-air pattern for 1200 UTC on 29 June, shown in Fig. 5, is also similar to the actual analysis, see Fig. 2. However, some errors in the shape of the trough to the south-west of the United Kingdom may be discerned, whilst the forecast thermal contrast across the United Kingdom is weaker than in reality, especially close to the cold front over Scotland.

A comparison of the T+36 forecast of the 850 hPa wet-bulb potential temperatures close to the United Kingdom valid at 1200 UTC on 29 June (Fig. 6) with the analysis of the same field (Fig. 7) again reveals close agreement in general terms.

The shorter-term forecasts of these parameters were similar. Thus it may be reasonably suggested that the LAM was providing good overall guidance of the likely atmospheric structure, even 36 hours ahead of the event.

In terms of the forecast precipitation patterns (Fig. 4), the result is much less satisfactory, with significant changes in the distribution between successive forecasts

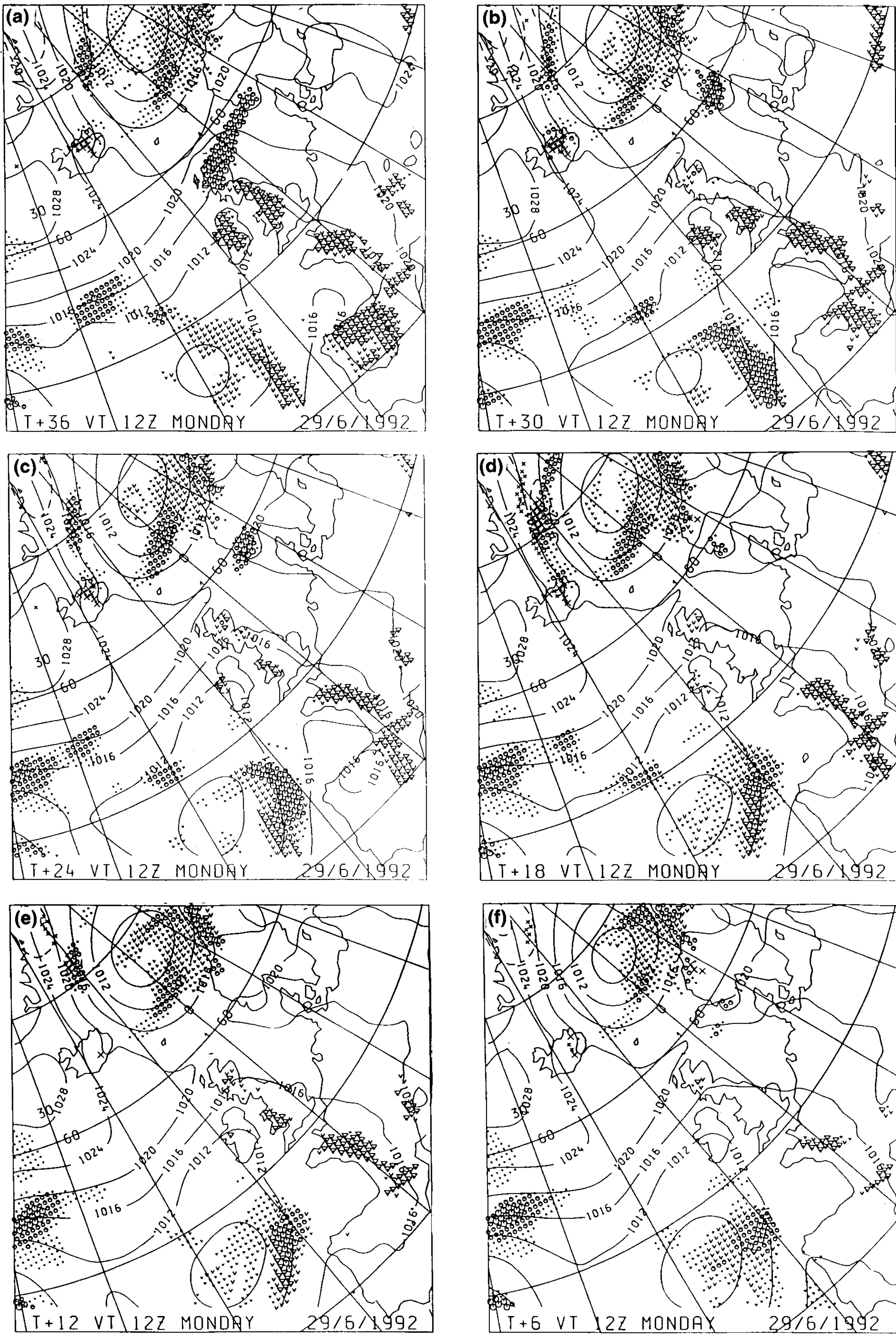

Figure 4. Limited area model forecast of surface pressure and rainfall valid for 1200 UTC on 29 June 1992, with forecast lead-times decreasing from 36 hours (a) to 6 hours (f) in 6-hourly steps.

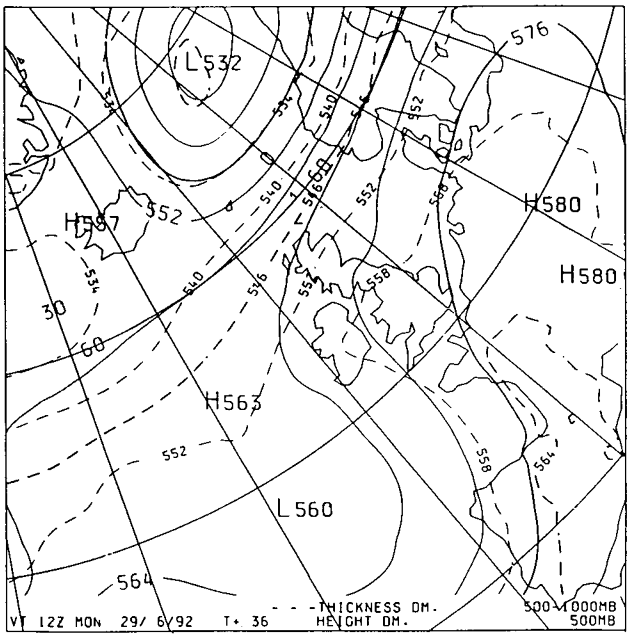

Figure 5. Limited area model 36-hour upper-air forecast valid for 1200 UTC on 29 June 1992.

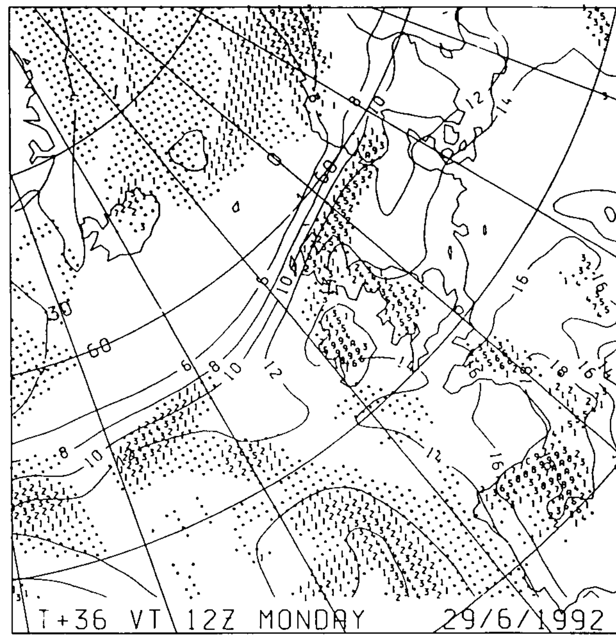

Figure 6. Limited area model 36-hour forecast of field of 850 hPa wet-bulb potential temperatures valid at 1200 UTC on 29 June 1992.

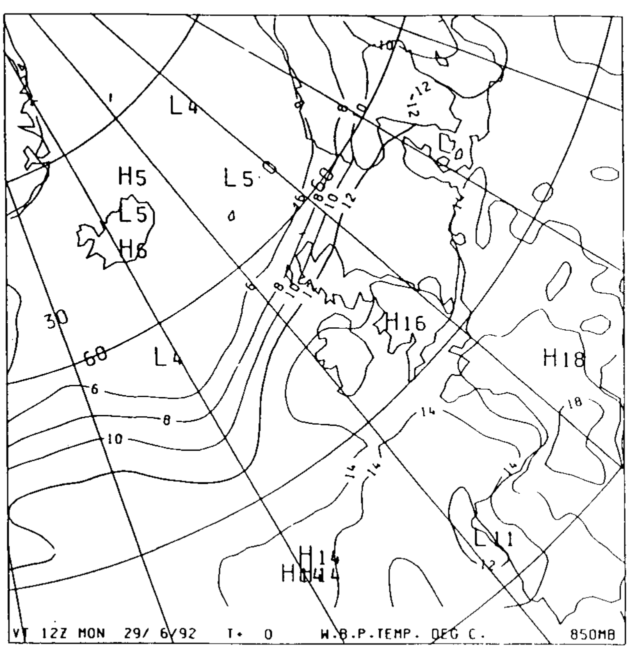

Figure 7. Analysed field of the 850 hPa wet-bulb potential temperature at 1200 UTC on 29 June 1992.

and a low correlation with what actually occurred, as shown in Fig. 3.

3. Discussion of the problem

One of the problems for the forecaster is that taken in isolation, each forecast appears to have merit, if the fine points of the upper patterns, the humidity profiles, surface pressure or other fields produced by the model are accepted. Reasons for the distribution of convection shown by the model may be formulated, perhaps in terms of dynamical and local forcing factors. However, when successive model runs giving markedly different rainfall fields are considered, it becomes increasingly difficult to ascribe convincing arguments to support the model solutions, as each run may suggest different forcing mechanisms. These runs are likely to show significant local differences in the details of the key parameters from run to run.

For example, the forecast upper pattern shown in Fig. 5 has some very minor troughs in the flow, such as the one just to the east of Scotland. Later forecasts, despite showing the same overall shape, did not feature the same minor troughs. The presence or otherwise of these is likely to have had an impact on the forecast shower distribution. Until the lead-time is relatively short, perhaps 12 hours or less, when the forecaster may be able to identify such minor troughs from satellite cloud images, it is very difficult to know whether the troughs should be believed.

Another parameter which has a vital impact on the distribution of the showers is the vertical humidity profile. It is well known that this can vary a good deal over small distances and short time-periods when the weather is showery. There are also large spatial variations in the vertical humidity profile in model forecast fields and these appear to vary significantly from one model forecast to another for the same validity time and place. Indeed, differences in the forecast humidity fields for particular locations between the forecast runs probably had the greatest impact of all possible factors, in leading to the differences in the rainfall forecasts in Fig. 4. Given the relative sparseness of reports of the humidity profile, it is difficult to know what the correct spatial or temporal variation of the parameter should be, and hence to know

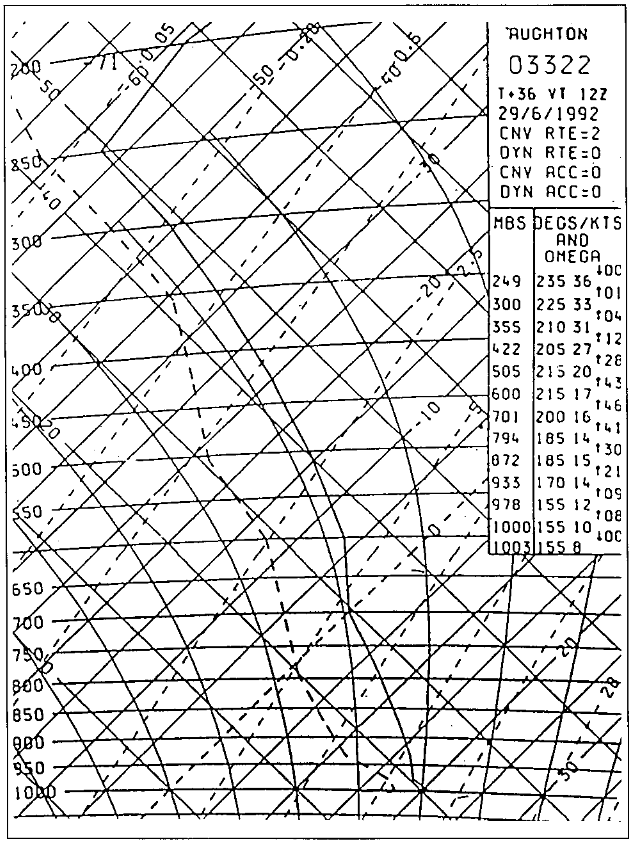

Figure 8. Limited area model forecast tephigram for Aughton, north-west England, valid at 1200 UTC on 29 June 1992.

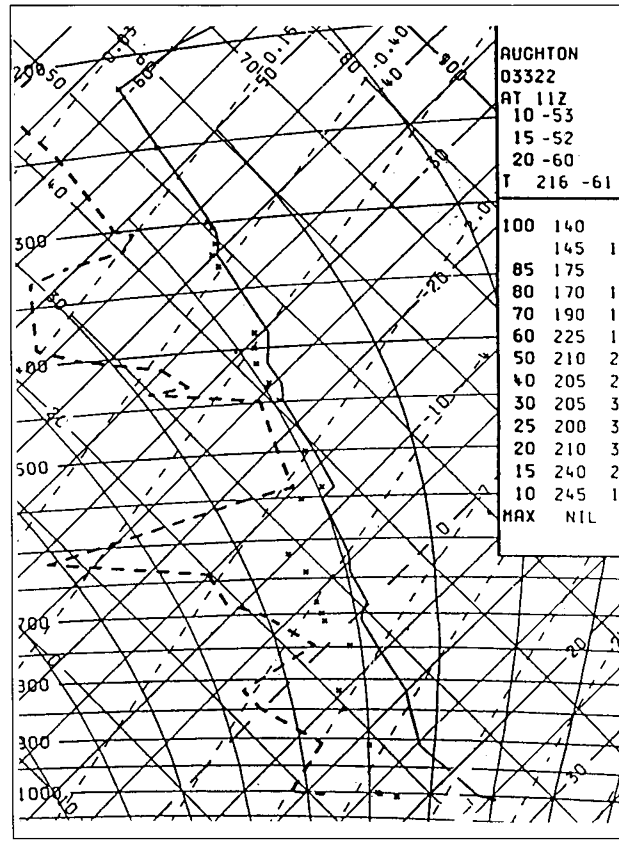

Figure 9. Actual tephigram for Aughton at 1200 UTC on 29 June 1992.

if the model's solution is helpful. Again satellite images can provide useful pointers to the distribution of moisture, but not until close to the time of the event. Radar is also a powerful tool in this respect, but again is only useful for adjusting the forecast at very short lead times.

An example of the importance of errors in the model's forecast vertical fields can be seen by comparing the forecast and actual tephigrams for Aughton, in north-west England, which was in an region of deep convection on the 36-hour forecast rainfall field (Fig. 4(a)). Comparing the 36-hour forecast tephigram for Aughton (Fig. 8), with the actual ascent for Aughton at about 1200 UTC on 29 June 1992, shown in Fig. 9, it may be seen that the model gave a reasonably correct forecast of the degree of instability, but was seriously in error with the vertical moisture profile and hence with the rainfall. Similar errors are likely to be common in forecasts of convective situations, but the dilemma for the forecaster is to try to identify such errors from amongst the correct signals.

4. Conclusions

Forecasters have a daily problem of whether to believe the model products, which are provided to give them a basis for their forecasts. On many occasions the answer is positive, although normally some limited improvements can be envisaged. However, in showery situations, it appears that the numerical models should not be relied upon to too great an extent, particularly on occasions of deep convection moving north into the United Kingdom, as the known or perceived problems inherent in them in this weather type will lead to either significant errors in the forecasts or at least to a lack of confidence in them. The models may be used to give valuable pointers to the broad-scale developments and to the likely occurrence of convection, both spatially and temporally. However, until the lead-time is short enough to allow the forecaster to become more aware of the real smaller-scale features of the atmosphere — for example, the availability of evidence of the structure of the humidity fields or of the development of local convergence zones — the finer details of the convection shown by the numerical forecasts should be treated with a good measure of caution.

The storm of 10 January 1993

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Summary

The evolution of the severe storm of 10 January 1993, has been described elsewhere by Hewson and by McCallum and Graham, who christened it the 'Braer *Storm' because of its unfortunate consequences for the stricken tanker. This article looks at the problems of forecasting such an explosive development and highlights some data problems that arose from the extremely low sea-level pressure.*

Fig. 1 shows the surface analysis for 12 UTC on 10 January when the storm was probably at its deepest. Fortunately for any sailors involved but less so for the meteorological community, there were no ships in the vicinity of the storm centre. The lowest pressure recorded at this time was 926 hPa by a buoy at 61.5° N, 13.4° W, about 120 n mile to the north-east. This near-record low developed during a period of very disturbed conditions. An intense baroclinic zone over the eastern Atlantic between unusually cold air over the Canadian arctic and very warm air pushing north-east from Florida gave rise to a series of depressions forming to the south or south-west of Newfoundland which then deepened rapidly as they tracked north-east to pass close to northern Scotland. Some, like the low that deepened to 940 hPa east of Iceland at 00 UTC on the 8th were, by normal standards, very intense depressions. They were reasonably well forecast by numerical models but without any indication of an extreme event. Then the Bracknell Global Model (GM) forecast from 00 UTC on the 7th showed a dramatic change from the run 12 hours earlier. The earlier forecast gave no hint of any major development. The T+96 forecast for 12 UTC on the 10th (Fig. 2) showed an open wave with a central pressure of 978 hPa just north of Scotland. T+96 forecasts from ECMWF and Germany were very similar. However the GM T+84 forecast (Fig. 3) shows an extremely intense depression only 8 hPa shallower and 50 km east of the actual low. The forecast then took the low north-east between Iceland and the Faeroes, threatening northern

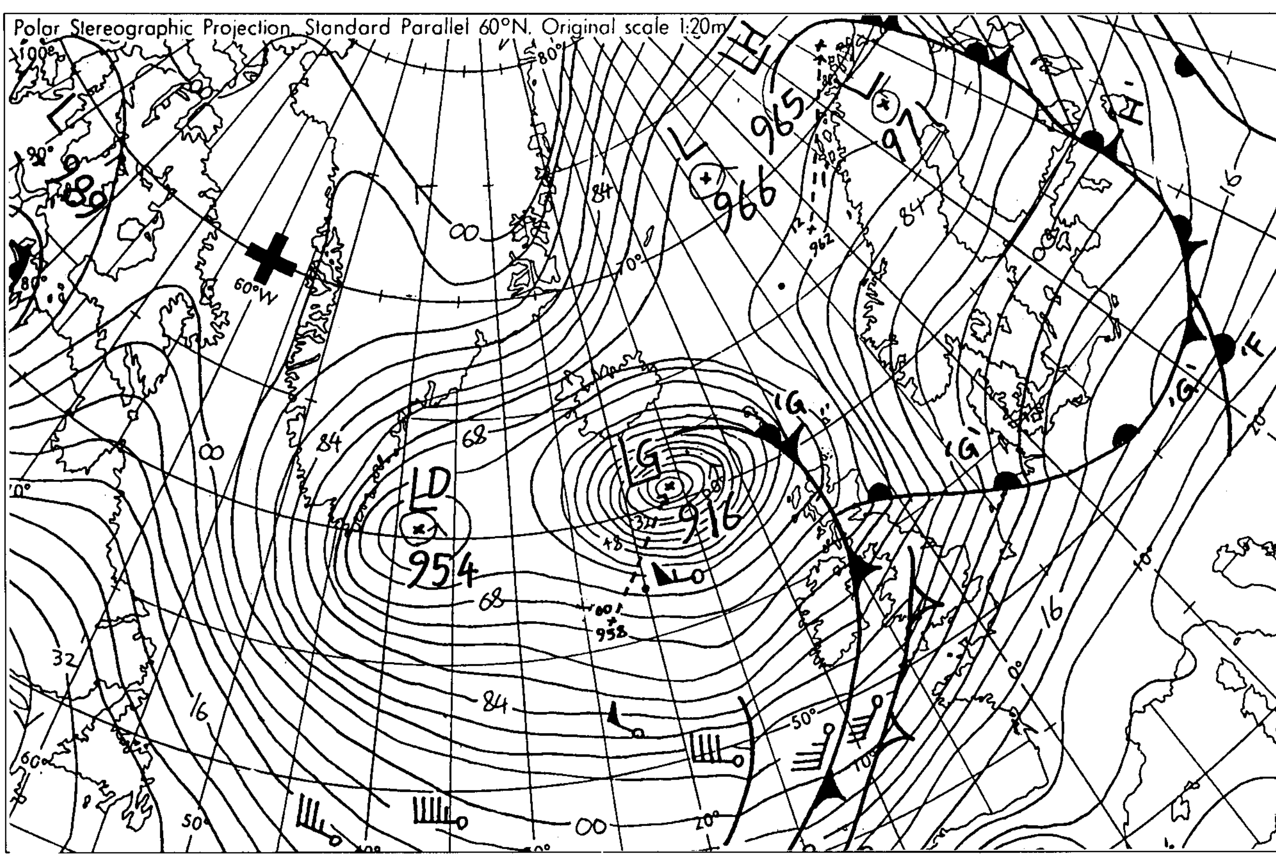


Figure 1. Surface analysis, 12 UTC on 10 January 1993.

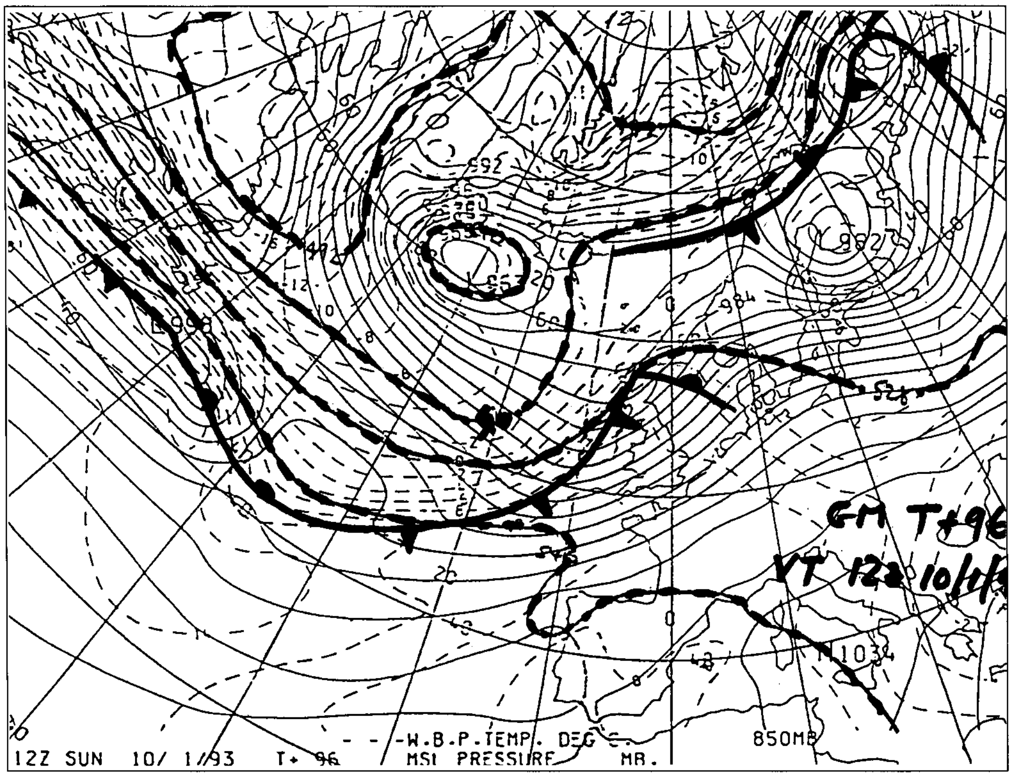


Figure 2. Global model 96-hour forecast MSL pressure verifying at 1200 UTC on 10 January 1993. Frontal positions estimated from model parameters such as 850 hPa wet-bulb potential temperature. Thick pecked lines are 1000–500 hPa thickness.

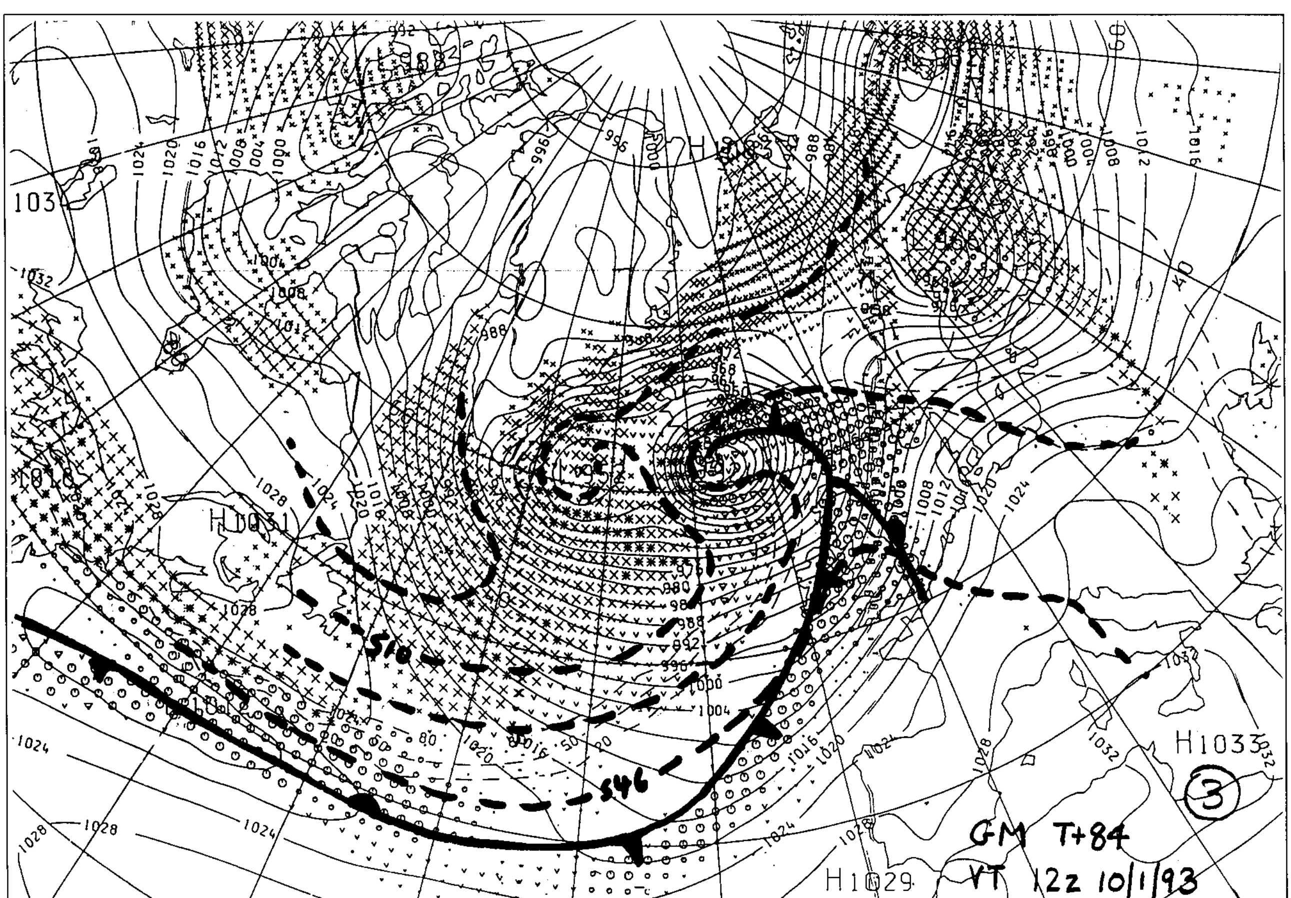


Figure 3. As Fig. 2 but 84-hour forecast.

Scotland with damaging winds. Should this new story be believed? This dilemma was soon resolved as all subsequent runs from all forecast centres predicted an unusually deep low in more or less the correct place (Fig. 4). However, no forecast before the GM T+84 hinted at this (ECMWF forecasts are only made once a day from midday data). The German T+84 forecast went part way towards this solution with a low of about 940 hPa 500 km to the north-east of the actual position. It is interesting that no global model forecast from any of the centres appeared to over deepen the low, though the values used here may be higher than the lowest grid-point pressure since they have been taken from plotted charts which almost certainly have lower resolution than the basic model grids. Later UK limited-area model forecasts did over-deepen the low but only by about 8 hPa at most.

Fig. 5 compares the track and central pressure of the developing depression with the predicted track from the first good forecast. This forecast was remarkably accurate throughout the life-cycle until the mature stage. At no time was the pressure more than 8 hPa out or the position more than 150 km adrift in spite of the explosive deepening and rapid movement. What then was the difference between this forecast and the one 12 hours earlier? The storm can be traced back to a shallow wave over North Carolina at 00 UTC on the 8th. At this stage the surface pressure forecasts for this area were almost identical, both with a wave in the correct position. At 500 hPa some slight differences were discernible. A trough to the north-west of the Great Lakes was slightly sharper and extended further south in the later forecast, but it is doubtful if these differences would been seen as significant without the benefit of hindsight. As the right entrance area to the powerful westerly jet ahead of the upper trough moved east across the Great Lakes, pressure fell generally over the eastern seaboard, but more so in the case of the good forecast where the right entrance region was better defined and slightly further south. This had the effect of increasing the warm advection ahead of the wave and extending it further north which in turn caused the pressure to fall faster and further north than in the previous run, nudging the wave track northwards and into the path of the developing upper trough. This is shown schematically in Fig. 6(a). Up until midday on the 9th, the deepening of the wave was largely due to warm advection, but after this time the vorticity advection ahead of the trough enhanced the ascent due to warm advection ahead of the low; the two became 'phase locked' and the explosive deepening phase began. Fig. 6(b) shows that in the poor forecast the warm advection never extended far enough north to force the wave into the path of the upper trough, which until the feedback from the rapidly deepening low began, was handled in a very similar manner in both forecasts. In the poor forecast the forcing from the upper trough eventually led to the development of a separate wave further north which subsequently passed close to northern Scotland (Fig. 2) but there was no pre-existing low-level circulation to phase in with the upper trough and no exceptional development took place; though in the forecast sequence this low was subsequently deepened to 940 hPa over Finland. Figs 7(a) and 7(b) show the Meteosat infrared images for 1200 and 1800 UTC on the 9th, respectively. Not until the 1800 image is the rapid deepening obvious from the imagery. This could have posed a problem for forecasters

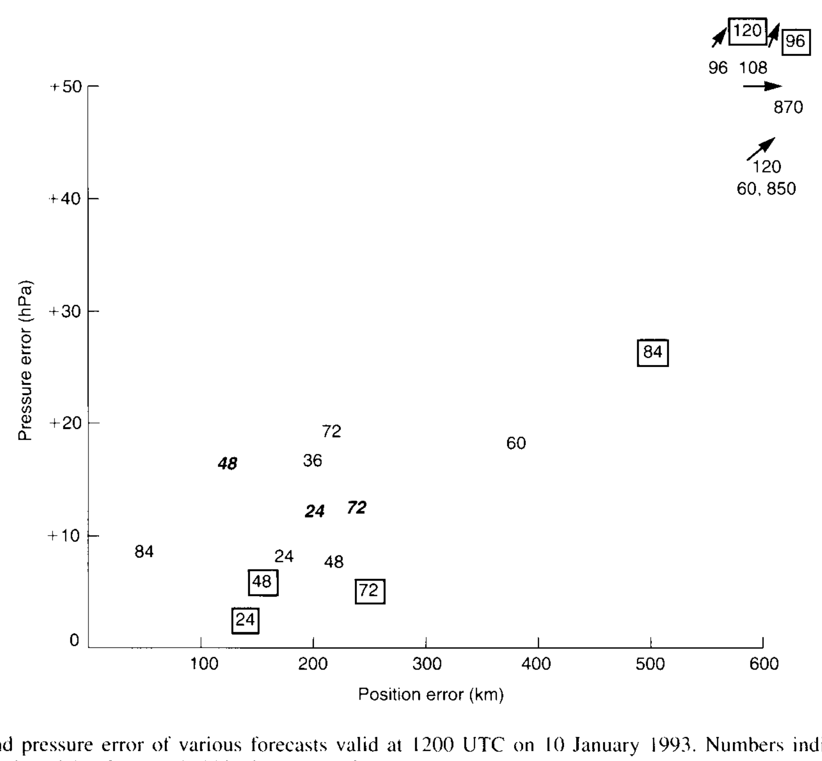


Figure 4. Position and pressure error of various forecasts valid at 1200 UTC on 10 January 1993. Numbers indicate lead time of forecast. Forecasts are the UK global model, ECMWF (bold italic) and the German (boxed).

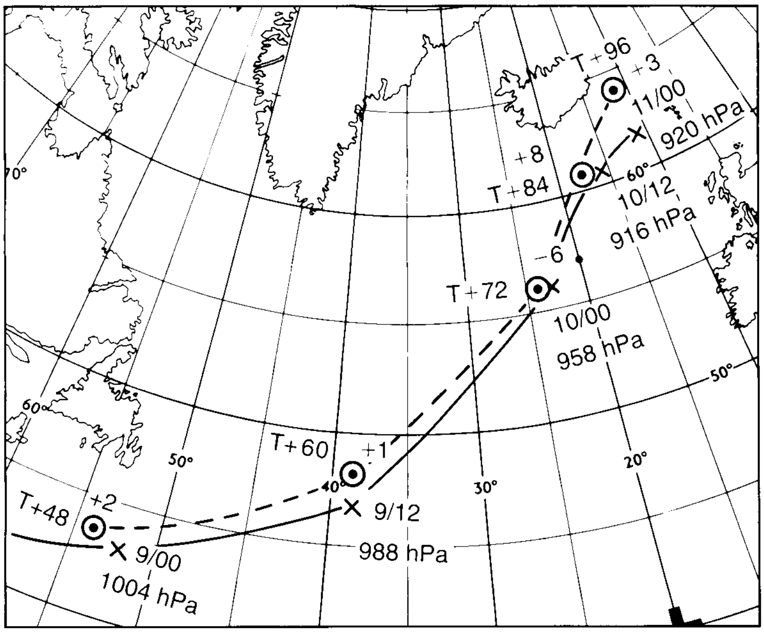


Figure 5. Track of developing storm (solid line) and track from forecast from 0000 UTC on 7 January 1993 (pecked line). Times and estimated central pressure are plotted alongside the observed track. Numbers along forecast track give the forecast lead time at each point and the error in the forecast central pressure at that time.

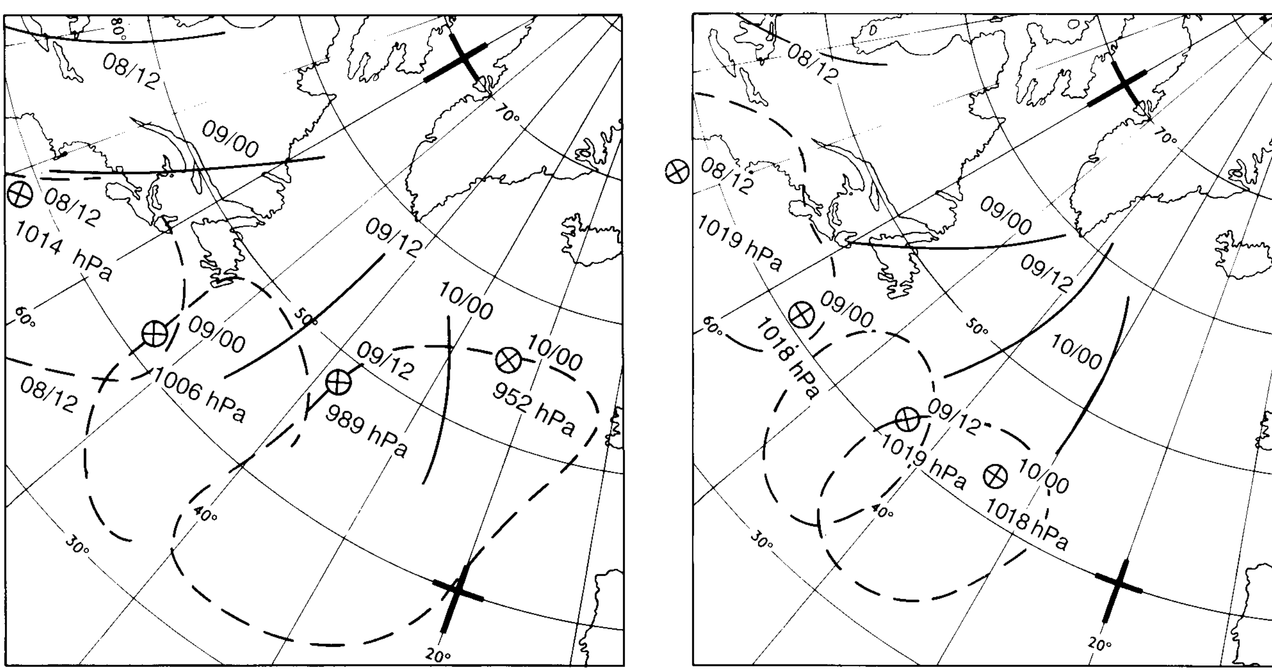
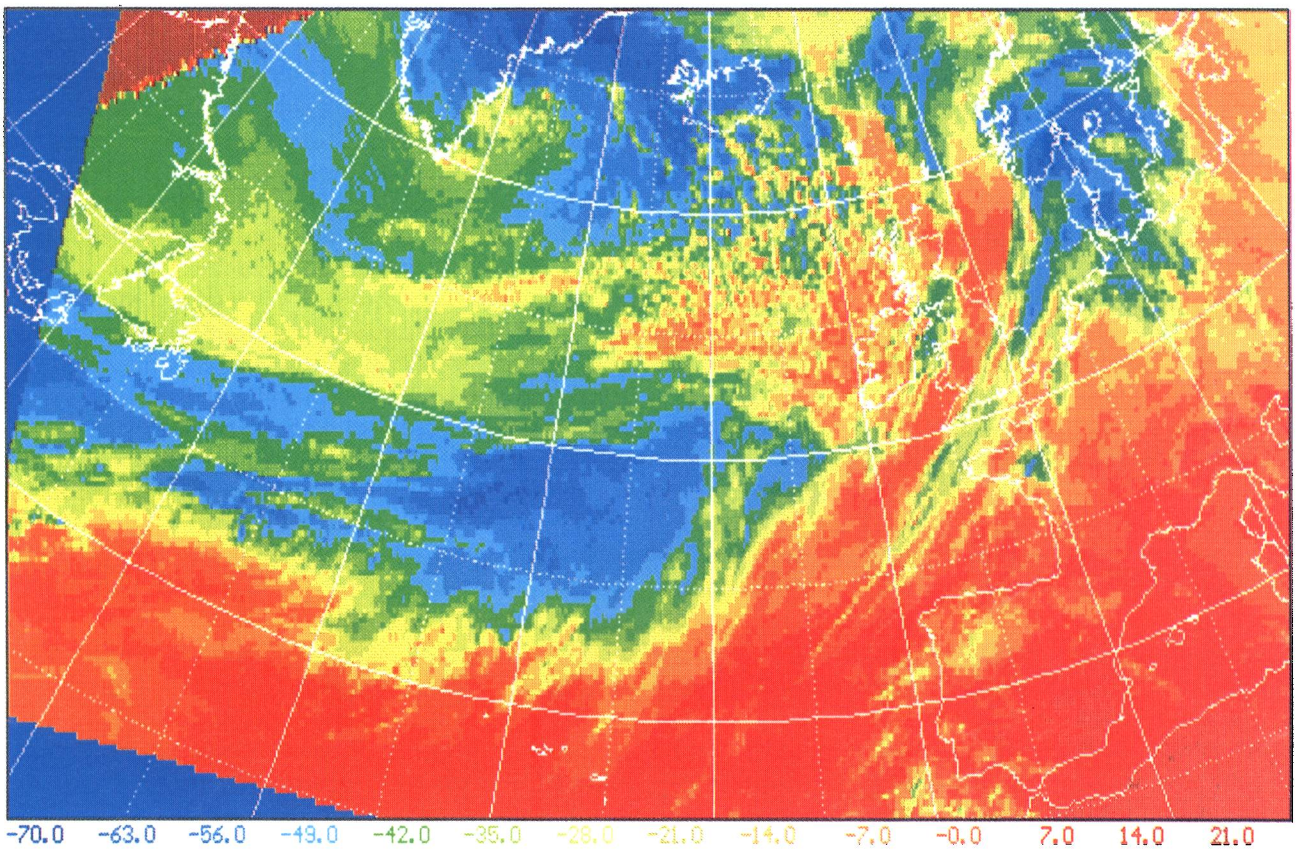


Figure 6. Positions of upper trough (thick solid line), surface low (circled cross) and area of warm advection (pecked line), for various times from (left) the forecast from 0000 UTC on 7 January 1993, and (right) 1200 UTC on 6 January 1993. The warm advection has been omitted for 0000 UTC on 10 January 1993. At this time warm advection covers a very large area ahead of the low in (a) and an area had developed in (b) ahead of the upper trough independent of the original wave.

had it not been for the complete coherence of all forecast runs at this stage and the fact that several ships in the area at midday confirmed the models' forecast of a rapidly developing system.

Once the forecast of an exceptionally deep low passing close to the Faeroes was accepted, the problem remained of predicting the wind strength. Limited-area model level 3 winds (roughly 2000 ft or gradient wind level) of up to 110 kn were predicted close to northern Scotland, with 60–70 kn over much of the rest of the United Kingdom at some stage during the passage of the low to the north. These winds turned out to be good guidance in general



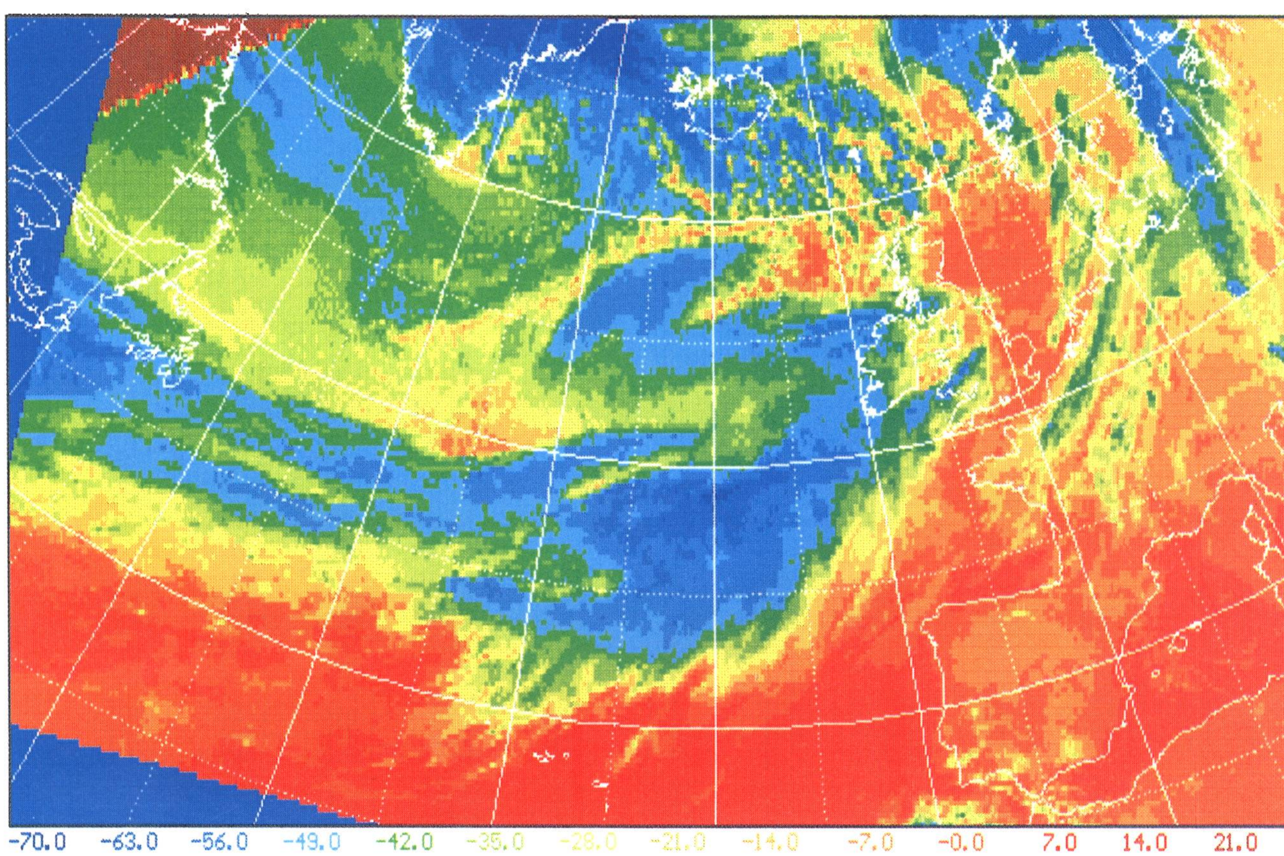


Figure 7. Meteosat infrared images for (top) 1200 UTC on 9 January and (bottom) 1800 UTC on 9 January 1993.

but care is needed when assessing the likely mean surface wind and gust strength. The pressure trace for OWS *Cumulus* along with selected surface wind observations is shown in Fig. 8. At 2300 on the 9th with strong warm advection taking place ahead of the warm front the ascent was stable, though only just so, with a 925 hPa wind of 180° 59 kn and a surface wind of 40 kn and no significant gusts. By 0400 on the 10th the mean wind had increased to 53 kn with gusts to 78 kn. However, at 0500 a temporary lull to the rear of the cold front came at a convenient time for the launch of the morning ascent, before the wind increased even further. Nevertheless the crew and observers must be congratulated on completing a full series of ascents during this extremely stormy period. The 1100 ascent is shown in Fig. 9. By this time the air was highly unstable with a surface temperature of only 0.6 °C, more than 8° colder than the sea surface temperature, and with convection up to about 550 hPa. The surface wind had moderated a little to a mean of 60 kn, but this was only 7 kn less than the 925 hPa wind and the gust speed of 91 kn, greater than the wind at any level within the troposphere, must have been enhanced by a cumulonimbus downdraught. By way of contrast, overland in the warm sector at Hemsby, the surface wind was only 21 kn even though the 925 hPa wind of 70 kn was slightly stronger than at the weather ship. However, when the gradient wind increases beyond 70–80 kn, even in the warm sector the stability may not be enough to prevent the stronger winds mixing down to the surface as happened in the October 1987 storm and to a lesser extent over southern England, only three days after the *Braer* storm.

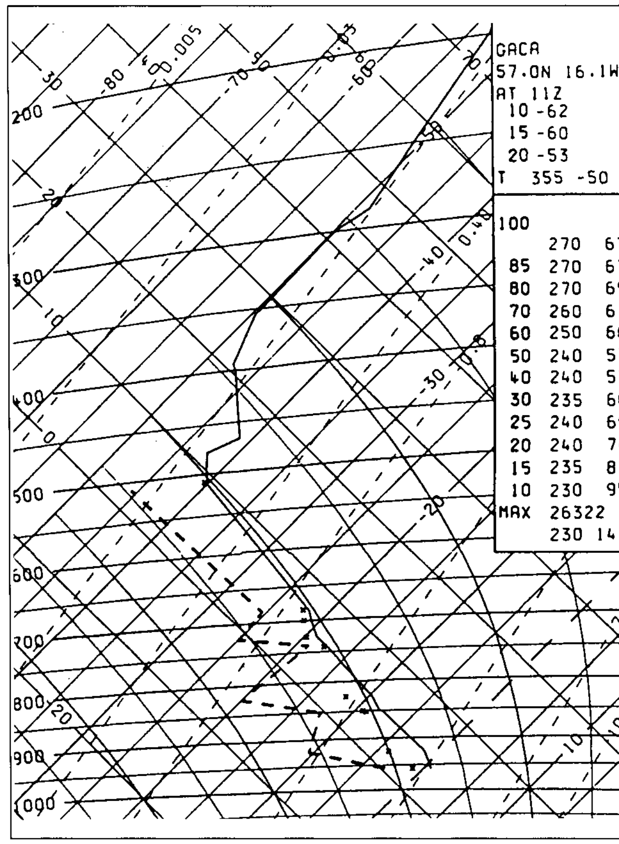


Figure 9. Ascent for 1100 UTC on 10 January 1993 from OWS *Cumulus*. Winds at standard heights are given in the inset.

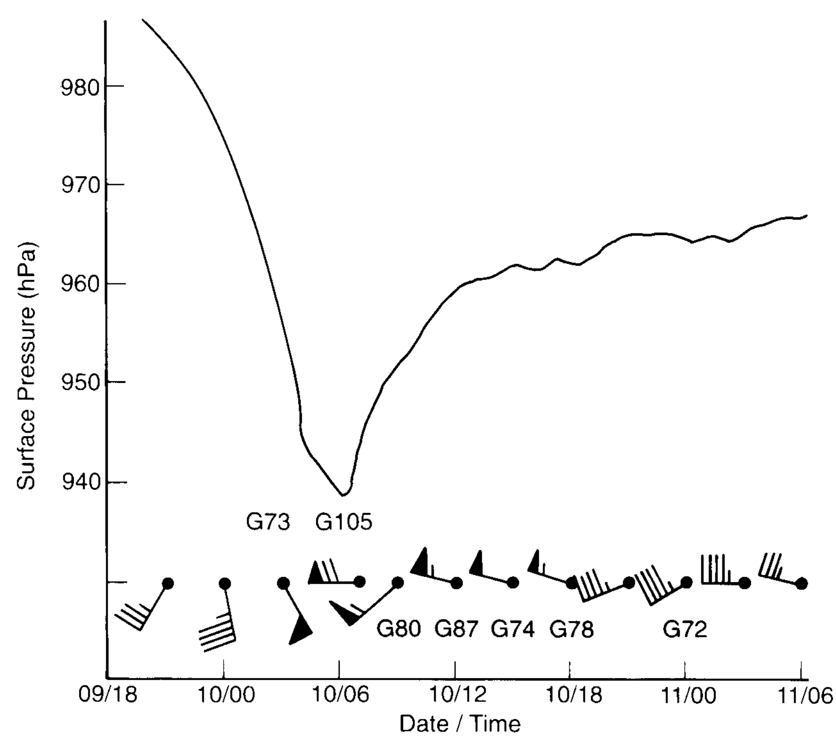


Figure 8. Surface pressure at OWS *Cumulus* (approximately 56° N, 16° W) from 1800 UTC on 9 January to 0600 UTC on 11 January 1993, with selected surface wind observations.

The extreme low pressures associated with the storm brought to light two problems associated with data collection and dissemination. The buoy already mentioned above as recording the lowest pressure on the midday chart, reported a pressure of 924 hPa at 1300 UTC. Thereafter no pressures were reported until about 0300 on the 11th, when the pressure was again given as 924 hPa, though wind observations continued throughout. After this time pressures were again reported as normal, but all values were above 924 hPa as the pressure rose quickly to the rear of the low. It appears that an internal quality control check rejected pressures below 924 hPa. At the time the pressure fell to 924 hPa, the 3-hourly tendency was −22 hPa. Extrapolating the pressure curve to the time at which the winds veered from south-east to south-west gives a lowest pressure of about 913 hPa. This is consistent with the extrapolation of the rising trend backwards to the time when the wind veered further from south-west to west and the pressure could be expected to begin to rise. As the storm centre passed very close to the buoy at about the time of maximum development, this lowest pressure is probably the best estimate of the lowest central pressure of the low. The other data problem thrown up by the low pressure concerns the TEMP code for upper-air ascents. When the surface pressure is below 1000 hPa the height of the 1000 hPa surface below the station is estimated to enable 1000 hPa height fields to be drawn and thicknesses to be calculated. To show that the height is negative 500 is added to the 3-figure code. Since the value is given in metres a minimum of −499 m is allowed for. At Thorshaven in the Faeroes at 2300 UTC on the 10th the surface pressure was 932 hPa giving a 100 hPa height of −564 m, which could not be coded correctly. The observation gave a code of 000 which lead to a reported thickness of 473 dam instead of 529 dam. Fortunately the numerical models analyse temperatures and not thicknesses.

In this article an attempt has been made to show some of the difficulties faced by the forecaster when an extreme event is predicted by the numerical models. In this case confidence was high and timely warnings issued because all model runs were in agreement. It would have been quite a different proposition if the good forecast run had not been supported by the other models. It would have been very difficult to assess which forecast was correct from the small differences apparent as the low began to develop over the eastern seaboard of the USA. It was not until the afternoon of the 9th, only 18 hours before the maximum development that the explosive cyclogenesis became apparent from the satellite imagery.

World weather news — March 1993

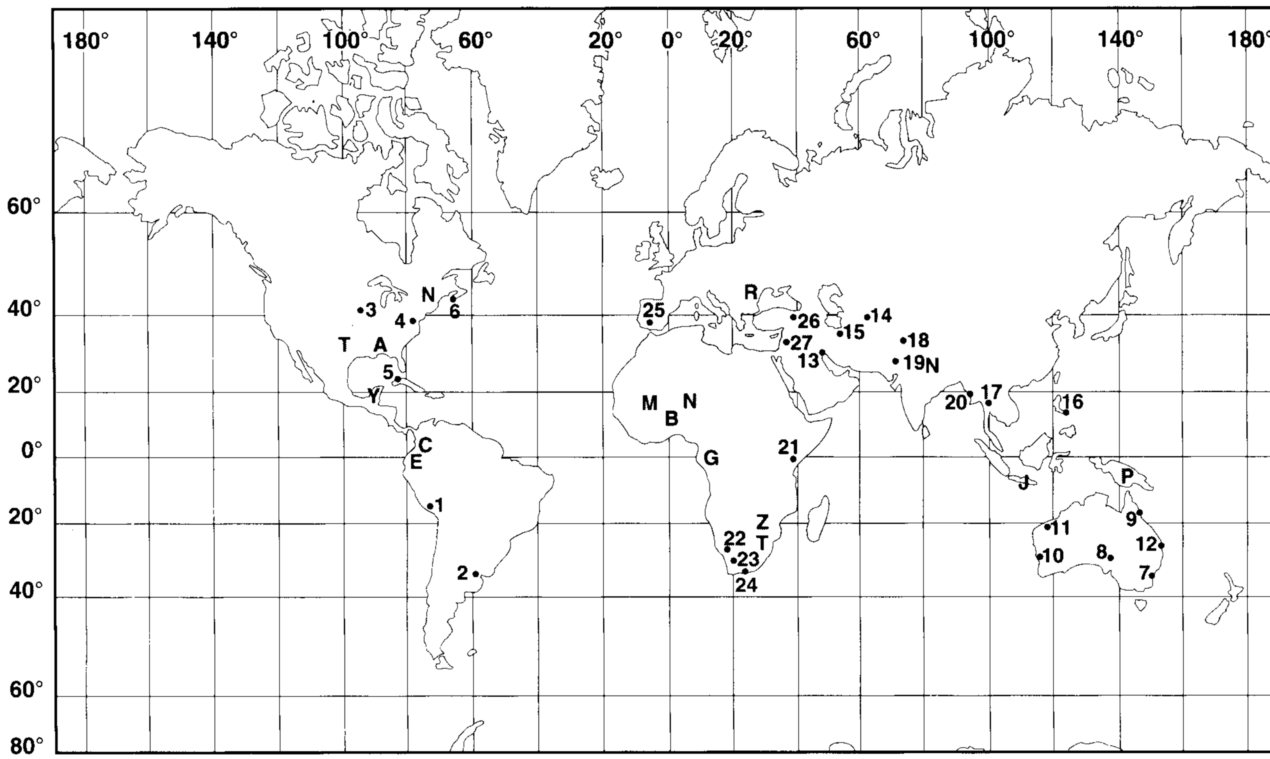
This is a monthly round-up of some of the more outstanding weather events the month, three preceding the cover month. If any of you, our readers, has first hand experience of any of the events mentioned below or its like (and survived!), I am sure all the other readers would be interested in the background to the event, how it was forecast and the local population warned.

These notes are based on information provided by the International Forecast Unit in the Central Forecasting Office of the Meteorological Office, Bracknell and press reports. Naturally they are heavily biased towards areas with a good cover of reliable surface observations. Places followed by bracketed numbers, or areas followed by letters, in the text are identified on the accompanying map. Spellings are those used in The Times Atlas.

South America

On the 12th there were reports of heavy rain in the northern highlands of Peru which has caused an artificial lake to overflow in Marka, 400 kilometres north-east of the capital Lima (1): 80 are reported missing. Later in the month, in Columbia (C), the volcano Mount Galeras was in the news again, it killed 9 vulcanologists on 14 January. This time on the 23rd mild tremors preceded showers of flaming rocks which destroyed the monitoring stations near the crater. However, there are no indications at this time that a significant amount of ash had been injected into the atmosphere.

Late in the month in Ecuador (E), heavy rain caused widespread flooding and mudslides in an area about 300 miles south of Quito in the Andes: some 300 were killed or missing, 1500 were made homeless. Additionally 40 km of paved roadway were lost, 43 km of railway and 5 bridges were washed away. By the 21st the flood water was threatening two Andean towns and was held back by a single earth dyke which was expected to fail soon. Interestingly this earth dyke was made of 5 million cubic metres of landslide that made a 330-foot dam, and a lake 12 miles long. This eventually grew to



Location of places mentioned in text.

submerge 6 towns. On 2 May this dam was breached in a relatively controlled manner and a violent discharge of water went down a previously prepared channel. Though a lot of damage was done there were no casualties as the area had been evacuated in preparation.

Buenos Aires (2) was having maxima up to 33 °C mid month, though this eventually triggered thunderstorms which gave 59 mm on the 14th. Two days later Bolivar, 200 miles to the south-west, got 132 mm (monthly average is 87 mm).

North and Central America

On the 5th there were reports that the St Lawrence Seaway had been freed of their worst ice jams in about 20 years. Then on the 8th came reports from Nebraska of the worst flooding in 15 years as the thaw set in and ice jams drifted down rivers causing them to overflow. By the 11th the floods were still rising and the rivers Platte and Loup were particularly mentioned. The former was 5 to 8 miles wide in places and it was forcing the river Missouri to back-up and the flooding was worst nearest Omaha (3).

A big storm affected much of the north-eastern USA on the 4th and 5th with heavy snow around the Great Lakes giving depths of around 20 cm. Near the coast the wind gusted to 65 kn on Long Island and Washington's (4) 48 kn gust equalled their March record gust.

It was on the 13th that the 'Storm of the Century' developed in the Gulf of Mexico. The first to suffer badly was Cuba when the cold front swept across the island, five were killed and 100 were injured. Winds gusted to over 60 kn; heavy rains and high seas caused flooding on north coast and in Havana (5). Some 40 000 homes were reported to have been damaged and 1500 destroyed. Many western provinces were without electricity for some hours and six aircraft were damaged at the airport. A lot of damage was done to crops and livestock on the island — so much so, that international aid was being sought. The storm then swept up the east coast of United States causing havoc from Florida to the Canadian border. The death toll on land was about 40. Very high seas driven by near-hurricane force onshore winds caused a lot of beach erosion, as bad as the storms earlier this year. Snowfalls were up to a metre in some places and there were reports of as much as a foot of snow as far south as Alabama (A) and Tennessee, places which did not have snowploughs because snow does not normally fall at all. In Florida there were reports of about 50 tornadoes which caused 26 deaths and cut electricity supplies to around 2 million. A significant number of the deaths were due to heart attacks as people struggled to push stuck cars and dig away the effects of a foot of wet snow blown by strong winds. Some of the worst conditions were experienced in New England (N) where a lot of the precipitation fell as rain or sleet which turned to large sheets of ice as the temperature fell below freezing. At sea, 10 m waves and hurricane-force winds caused a predictable amount of havoc to shipping. The worst instance seems to have been the loss of the 26 000-ton gypsum carrier, *Gold Bond Conveyor*, which capsized and sank with the loss of 33 lives off Cape Sable Island (6). Just before sinking they reported 50 to 70 knot winds and 30 m waves. In total the damage due to the storm seems to be in the order of $1.6 billion. (The meteorological details of this interesting storm will appear in our next issue.)

High temperatures around the Gulf of Mexico, consistently above 35 °C on the Mexico/Guatemala border, and a March record of 38 °C at Merida on the Yucatan (Y) on the 29th helped provide the moisture for some hefty storms and tornadoes in the southern USA. Texas was visited by damaging hailstorms and high winds on 25th and 26th with golf-ball-size hail in Austin which broke a lot of glass and damaged cars, the total damage was estimated at $125m. A couple of days later in Kansas rather less damage was done by another hailstorm and high winds. This time the hailstones were reported as being marble to baseball size around Wichita; they did a lot of damage to sheet metal roofs: never to be outdone, Langtry, Texas (T) managed tennis-ball-size hail on the 29th. Top rainfall may have been 89 mm in a day at Mobile, Alabama on the last day of the month.

Australasia

First an apology: in the notes for December 1992 I reported rainfalls of 410 mm at Croydon and 350 mm at Moranbah. A coding or transmission error made these too high by a factor of 10. I am grateful to the Australian Bureau of Meteorology for bringing this to our attention and providing the material below.

There were some notable thunderstorms this month. In New South Wales flash flooding occurred in some suburbs of Sydney (7) on the 7th, also affected by fierce storms on 20th and 26th. Hailstones reached 4.2 cm diameter in a storm near Kempsey on the 9th. The 26th also brought severe thunderstorms to South Australia. In one near Marree (8) gale-force winds blew away some sheds while 36 mm of rain fell — 27 mm of these in a mere eight minutes! In Western Australia the storms on the 19th in the south covered one road with 30 cm of hail, flash flooding burst some dams and drowned sheep. Rainfall totals of around 90 mm in 24 hours set new daily records for March in several places. In contrast the far north of Queensland had the driest March on record.

North Queensland was also hot. New March records of nearly 38 °C were set at Townsville and Cairns (9) on the 15th and 18th respectively while some other places had record mean maxima. In Western Australia persistent southerly winds led to record low mean maximum temperature at Geraldton (10) of 28.1 °C (onshore winds) and a record highest mean maximum of 38.7 °C at Port Hedland (11) (offshore winds).

Further afield a tropical depression gave Jinjo in Papua New Guinea (P) 99 mm on the 10th. This low became tropical storm Roger. From the 16th to 18th Roger passed well offshore of the Sunshine Coast but the Port of Brisbane (12) was closed for a time by the very high seas and strong winds.

Asia

From Iran there came reports on the 8th of 750 villages in the south and west being cut off by floods: these were in provinces affected by February's catastrophic floods. The Karun river burst its banks in near Khorramshahr and damaged the town of Abadan (13). A few days later there was a report from Uzbekistan that five had been killed and several bridges had been washed away when 'two months rain fell in one day' in the mountains near Samarkand (14). The report added that 50 km of irrigation channels were blocked by silt washed into them. Heavy rain returned to Iran towards the end of the month. On the 26th there were reports that heavy rain had led to landslides: five had been killed in the south in one incident where a hillside had collapsed into a river and diverted it. Deep erosion channels are beginning to appear around Ardad, 400 km south of Tehran (15).

In the Philippines, Mount Mayon near Legaspi (16) was still being potentially dangerous: there was a considerable number of eruptions, six on the 21st which ejected ash to a height of about 6.5 km; on the 24th there were 26 big blasts and the mountain was still going strong at the end of the month.

No report in this section would be complete without some mention of heavy rains in the islands, though I have not seen any reports of life-threatening events. Tasikmalaya on Jawa (J) managed 141 mm on the 4th (about half the month's average). Luang-Prabang in northern Laos outdid this with 160 mm in 12 hours on the 11th and followed this with a near gale and more rain. Yogyakarta, on Jawa, used to have a record March 24-hour record of 56 mm, 96 mm fell on the 21st. To prove it is not all rain at this time of year, Tak (17) in Thailand managed a maximum temperature of 41.5 °C on the 29th, 1.5 °C above the previous record.

Indian sub continent

The second half of this month seems to have been very disturbed. In Pakistan, westerly disturbances were causing substantial amounts of rain in the higher provinces with 5 to 45 mm falling in 24 hours ending on the 14th with snow on the hills. Starting about the 10th there was heavy rain in the Northwest Frontier which caused waterlogging and there are reports that 20 people had been killed by collapsing buildings. Peshawar (18) got 86 mm of thundery rain in 24 hours to the morning of the 11th (the average March total is 62 mm). The train service between Quetta (19) in Pakistan and Zahedan in Iran was suspended because long sections of the track had been undermined. On the 20th in Bangladesh, Cox's Bazaar on the coast of the Bay of Bengal had 20 injured and 15 000 made homeless by a violent hailstorm which battered the Kutubdia Islands 45 km offshore: hailstones were reported to have weighed 1 kg. Later the storms affected Chittagong (20) but no serious injuries were reported there. There was a similar event on the 23rd, this time there was 55 mm of rain with winds gusting to 48 kn in a 90-minute storm; fifty were injured and thousands made homeless. A further violent storm arrived on the 27th and swept the area around Chittagong; about 300 were reported to have drowned in one squall with gusts of over 50 kn and 91 mm of rain in 6 hours. Some 22 small vessels vanished and a ferry carrying 250 capsized. In all 25 000 were made homeless. It was said that 2500 houses were destroyed in three minutes in one district. About the same time storms were affecting India and Nepal. On the 24th and 25th in the Indian foothills of the Himalayas 30 are reported to have been killed by flash floods north of Jamu as water washed away houses during the night. Two are reported to have been killed by lightning: and the Punjab may have lost 10% of its winter wheat. Dehra Dunn, 120 miles north-east of New Delhi, and the surrounding area, had over 50 mm on the 24th, about twice the average for the whole of March. In Nepal (N) over the 26th to 28th two days of thunderstorms killed two and injured 37. There were 200 gm hailstones near Janakpur in south-east Nepal and 100 gm hailstones in the Chitwan district. The winter wheat is reported to have been severely damaged here as well. In Calcutta 39 mm fell in thundery showers on the 30th.

Africa (except the Mediterranean coast)

The approach of Summer became apparent in western Niger (N) early in the month with temperatures well above 40 °C, Dori in neighbouring Burkina Faso (B) reached 44.2 °C on the 6th. A bit further south in Cameroon thunderstorms on the 7th gave more than 100 mm in overnight storms; Bafia's report of 190 mm was about the average for the whole of March. At Koundja the morning reading on the 10th of 108 mm would have been a new March record if it had not been reset at 134 mm on the 6th! In Mali (M) temperatures reached 43.2 °C on the 17th then a breeze from the Sahara kept the night minimum to 31.2 °C (cf. mid-March average 19 °C). At Mayumba on the Gabon (G) coast heavy thunderstorms on the 23rd/24th dropped 222 mm for a new March daily record: then on the 25th there was a further 82 mm; the week's grand total was 312 mm, 62 mm more than the monthly average.

On the other side of the continent, Makindu (21) near Nairobi had some weather which struck us as atypical on the 23rd when thundery showers produced 16 mm of rain but with winds that started easterly/30 kn and later veered southerly/34 kn before slowly dying down overnight.

My thanks go to the South African Weather Service for providing information on their part of the continent.

Autumn brought some startling extremes to South Africa with a maximum of 42.7 °C at Vioolsdrif (22) on the 16th and a minimum of 0.8 °C at Sutherland (23) on the 30th. The rainfall varied from a record low of 0.5 mm at Cape St Francis (24) to 379.6 mm in 24 hours at Graskop in Eastern Transvaal (T) (out of a monthly total of 688 mm). However, the emphasis seems to have been on continuing dryness with less than 75% of normal over a wide area. Fortunately rainfall was about normal in the main agricultural areas of Transvaal and Natal.

There seems to have been three periods with rain. Over the first few days of the month an easterly trough caused widespread rain from Zimbabwe (Z) to south-east Transvaal: local flooding caused two deaths. An unseasonal cold front brought needed rain to southern Natal between 11th and 15th though the tornadoes near Dundee on the 15th were probably less welcome. Another cold front affected the same area on the 21st to 23rd which is probably when Graskop got its rain. At the end of the month a deep low developed in the interior bringing more rain to Natal where Mkuze got 104 mm.

Europe (plus North Africa and Arabia)

The month opened with cold air over much of the continent and a deep low over the western Mediterranean (980 hPa near Sardinia). Sevilla (25), Spain awoke with a temperature of −2 °C, two degrees below the previous March record; further east Barcelona collected 37 mm of rain and snow. Gibraltar's snow was the first since February 1954. During this time Bulgaria and Romania (R) experienced some of their heaviest snow storms for several years with communications largely paralysed by blizzards. In Bucharest many buildings lost their water supplies for the second time this year. Many Bulgarian towns were cut off by drifts and some were without electricity. Conditions were particularly bad near the Black Sea. There were rumours that the Bucharest meteorologists were on strike at this time. On the 8th severe blizzards continued, in Bucharest there was a metre of packed snow with 65 cm of fresh snow on top. Danube Locks were closed and the port of Constanza was blocked with some 70 vessels. These were advised to put to sea, but gales and 6 to 7 m waves deterred them. Romanian air traffic was diverted to Timisoara and Arrad near the borders of Hungary and Yugoslavia. However, there were no international flights because the passengers could not reach the airports. By the 10th traffic was starting to move again in Bulgaria, and the Danube ports reopened.

Mid-month brought renewed reports of cold weather in the south. Erzurum (26) in central Turkey managed to continue is record-breaking streak with a new record March minimum of −25 °C on the14th. Near freezing conditions occurred elsewhere in the eastern Mediterranean with a new record minimum of 3.8 °C on the 18th in Asyut, Egypt and a near record −3.2 °C in Dimashq (formerly Damascus) (27) on the 20th.

Near the end of the month there was yet another big wind storm in the North Sea which forced the empty tanker *Freja Svea* aground near Redcar in high winds of around 50 kn and huge seas of about 10 m. The ship broke its mooring chains; the main engines were started but it could not hold position as the anchor dragged.

Tailpiece

Vostok in the Antarctic had a maximum of −60 °C on the 23rd, this was followed by a minimum of −69 °C. This is cold even by their standards!

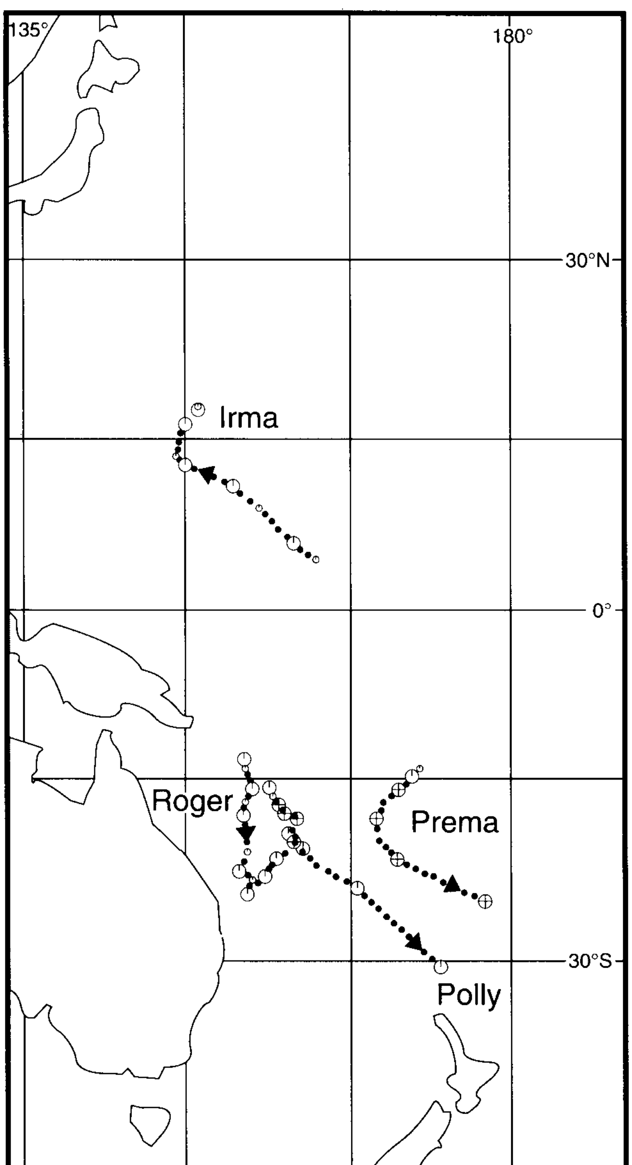
March tropical storms

This is a list of tropical storms, cyclones, typhoons and hurricanes active during March 1993. The dates are those of first detection and date of falling out of the category through dissipation or becoming extratropical. The last column gives the maximum sustained wind in the storm during this month. The maps show 0000 UTC positions: for these I must thank Julian Heming and Susan Coulter of the Data Monitoring group of the Central Forecasting Office.

No	Name	Basin	Start	End	Max. (kn)
1	Polly	AUS	25/02	03/03	100
2	Irma	NWP	10/03	17/03	55
3	Roger	AUS	12/03	21/03	50
4	Prema	AUS	27/03		120

Basin code: N — northern hemisphere; S — southern hemisphere; A — Atlantic; EP — east Pacific; WP — west Pacific; I — Indian Ocean; WI — west Indian Ocean; AUS — Australasia.

Notes: Roger never reached full cyclone status and followed a very erratic track. Polly followed a nearly straight path and was a full cyclone. Prema was still active at the end of the month.



Review

Exploration of the solar system by infrared remote sensing, by R.A. Hanel, B.J. Conrath, D.E. Jennings and R.E. Samuelson. 175 mm × 254 mm, pp. xvi + 458, *illus.* Cambridge University Press, 1992. Price £75.00, $125.00. ISBN 0 521 32699 0.

The title is a little misleading: the book is mainly about the physics of remote sensing of atmospheres, only fairly incidentally about its application to the detailed study of solar system atmospheres, and not very much at all about what one would normally call exploration, although that certainly comes in to it. This minor observation is hardly a criticism of a really superb and very useful and timely book, by accomplished authors who know their material thoroughly.

Dr Rudy Hanel was one of the pioneers in the business of remote sensing of atmospheres from space. At a time when most other instruments were fairly simple low-spectral-resolution radiometers, he was developing the Michelson interferometer as a tool for remote temperature sounding and ozone monitoring. The detailed spectral coverage which results from the measurement of continuous spectra gives a lot of additional, though notionally redundant, information, which can be priceless when unknown or unexpected factors enter the data interpretation problem. This was a not uncommon state of affairs in the early days of weather satellites and is an unavoidable one when it comes to extending similar studies to the mysterious atmospheres of the outer planets. Building successful experiments around such complex and often temperamental instruments as interferometers has been an outstanding achievement by Hanel's team from NASA's Goddard Space Flight Center, three of whom are his co-authors in this book.

Their treatment is quite quantitative and detailed. It begins with the relevant atmospheric physics: radiation theory, radiative transfer, molecular spectroscopy, and multiple scattering by clouds and aerosols. These are the tools by which one solves the direct problem, i.e. computes the radiation field which emerges from an atmosphere whose structure and composition is known. The next third of this fairly long book deals with the theory of space hardware for infrared measurements, and includes examples of real instruments (mostly from the direct experience of the authors — others tend to get rather shorter shrift). Finally, the inverse problem, where the measurements of outgoing radiation are converted back into atmospheric quantities such as vertical temperature profiles, is expertly covered, as we would expect since Dr Conrath in particular is an acknowledged leader in this field. The results which are obtained from this process are generously illustrated with examples of the investigation of atmospheric composition, structure, dynamics and energy balance on the planets, especially Mars, Jupiter and the large Saturnian moon Titan. Again, much of this is drawn from the authors' own work on the overwhelmingly successful Mariner and Voyager missions in which they participated.

Along with non-interferometric instruments there is another significant near-omission, and it is a major one — the Earth. All of the chapters on theory and instrumentation, constituting two thirds of the book, are just as relevant to our own planet as to the others, and even the results on Mars and the rest are relevant to understanding the equivalent processes on Earth and can usefully be compared. The authors are experienced terrestrial remote sounders. Most of their potential readers and buyers are focused on the Earth, for obvious practical reasons including gathering data for weather forecasting and other applications, which are much bigger business than solar system science. The Earth is a planet and a member of the Solar System. Why doesn't it get at least equal time with, say, Titan? It is not ignored altogether by any means, and in a way it is refreshing to see the usual bias reversed — but it seems a little curious, like the title.

An appreciation of the new understanding of the atmospheres of the Solar System which is coming, in part, from remote sensing from spacecraft requires work on the part of the reader as he or she works through the detail in each of the chapters. This is a book for the specialist, or the student wanting to get deeply into the field, rather than the interested amateur or bystander. It is very well done, nearly error-free (if the complete garbling of the name of an unimportant British researcher, near the beginning of the book, is overlooked), nicely produced, and highly recommended.

F.W. Taylor

Retirement of Raymond Hide

In September 1992, Raymond Hide retired from the Meteorological Office, 25 years after he joined in 1967. Raymond was born and brought up in Doncaster and his interest in science led to a first class honours degree in Physics at the University of Manchester. He then undertook a PhD at Cambridge with Keith Runcorn as supervisor and pioneered experimental studies of convection in a rotating fluid annulus. These highly original studies with novel experimental techniques and critical analyses of the results paved the way for some 40 years of continuing work into that, and related systems. They also started Raymond in a multi-disciplinary career being as familiar with fluid dynamics and meteorology as with geophysics.

From his PhD, Raymond's national service led to research at Harwell on shock tubes and magneto-hydrodynamics followed by a brief foray into astrophysical problems with Professor Chandrasekhar at Chicago. From 1957 to 1961 he was a lecturer in the Physics Department, University of Durham, Kings College (at Newcastle-upon-Tyne) and progressively established a research group concerned with what was to be called geophysical fluid dynamics. With students he continued studies of convection in a rotating fluid annulus and started new work involving other rotating fluid phenomena, including Taylor columns. In 1959 he married Anne and, we are advised, somewhat changed his lifestyle.

His great scientific insight was recognized by his appointment in 1961 as a full Professor at MIT A number of his existing students at Newcastle accompanied him to MIT and he established a very active and productive laboratory concerned with wide ranging laboratory experiments, mainly concerned with rotating fluid dynamics. Raymond was recruited into the Met. Office in 1967 by Sir John Mason, who was at that time the recently appointed Director General with the expressed intention of enhancing training and research in fluid dynamics. This recruitment as a Deputy Chief Scientific

Officer was exceptional, and reflected Raymond's distinguished track record for scientific productivity. Raymond brought with him from MIT a considerable amount of experimental equipment, which was crucial to the rapid establishment of his new group. The transport was not however, without problems, bringing Raymond into the first of many clashes with what he saw as excessive bureaucracy in the Civil Service.

From the moment Raymond arrived, the Office benefited from a dynamic source of new energy. Extra lecture series were organized and challenging questions emerged from the back of the room even in existing lectures and colloquia. Within a year Raymond had established a new Met. Office Branch, then Met O 21, known as the Geophysical Fluid Dynamics Laboratory. Most of Raymond's staff were new entrants to the Office and were quickly infected with his energy, and enthusiasm to challenge and learn with sharp scientific methods. One of the first problems encountered by a new member of the group was to attempt to work systematically through the wide range of suggestions and ideas which he put forward; their number far exceeded the capacity of a group much larger than this. However, having embarked on a task, Raymond was always interested in its progress and would willingly discuss it with the most junior member of staff. This was an eye-opener to those who had served in other parts of the Office where even PSOs (now Grade 7) were regarded an unapproachable by young Scientific Assistants. Whilst he always liked a written and well planned approach, most Met. Office correspondence was judged not to apply to him and was conveyed to the rubbish bin. This was not well accepted by the management but support from his secretary gradually enabled satisfaction of most demands.

Raymond always saw one of the main functions of his new group as providing training, beyond that which might be provided by the Training School, and specifically to give wider insight to that subset of Geophysical Fluid Dynamics which comes under the heading of Meteorology. This need for a small number of staff to have more advanced scientific training perhaps foreshadowed the current participation of the SO course in the University of Reading MSc courses.

The staff of Met O 21 grew to about 9 by the mid 1970s and the programme of work developed steadily as Raymond continued to develop new ideas. He pioneered training interactions with universities by hosting the Office's first CASE research student. This small branch and Raymond himself were very productive with over 200 publications being produced by the branch. Impressive as this is, Raymond's personal publication list comprises a large fraction of the total.

Much of the work of the staff concerned laboratory studies of rotating fluid dynamics. These experiments presented a technical challenge demanding precise engineering and the advancement of electronic measurements. These were not without incident however, one member of the group attempting to extinguish a small fire with the aid of a beaker of ether, with spectacular results! In spite of the sophisticated instrumentation which worked reliably, the plumbing of various apparatus proved less reliable giving rise to the occasional flood! Those working for Raymond found him a stimulating fund of ideas and a great enthusiast for the introduction of automation and computers. As well as guiding his group at the Office, Raymond also became increasingly interested in planetary atmospheres as well as maintaining his long-standing involvement in magnetohydrodynamics. Early in the 1970s, the branch also diversified into numerical methods and sought to use precise numerical simulations to complement the laboratory studies. Although these studies made it possible to obtain more detailed information than would have been possible in the laboratory, they were of equal value in providing a test bed for numerical methods.

Raymond received honours too numerous to list fully here but in 1971 was elected Fellow of the Royal Society. In 1974–76 he was President of the Royal Meteorological Society and in 1983–85 he was elected President of the Royal Astronomical Society. In 1985 he was appointed a Commander of the British Empire (CBE).

From the early 1970s until the mid 1980s, Met O 21 continued to develop its laboratory and numerical experiments to increasing sophistication and precision. Raymond continued to be very productive and one of the new foci of his attention became atmospheric angular momentum fluctuations and the associated tiny changes in the length of the day. The latter providing an integral check on the whole atmospheric circulation.

In the 1980s in the face of increasing pressure from the resource challenges of satellites, and the Office's growing range of numerical models, the decision was taken to wind down Met O 21, and by mutual agreement, for Raymond to establish a new laboratory at the University of Oxford in the Hooke Institute.

Raymond put a great deal of effort into transferring his laboratory to Oxford and also helping to run the other collaborative activities in the Hooke Institute. He was understandably very disappointed when, at the time of his retirement, this formal Met. Office collaboration with NERC and the University of Oxford Hooke Institute ceased. In his retirement from the Office, he now remains active at Oxford where the leadership of his laboratory has passed to Peter Read.

During his uniquely rich career in the Office, Raymond provided training, advice and encouragement to all around him and those who passed through his branch. His sound and friendly advice was always sought after and willingly given. He has left a lasting impact in the Office and we look forward to continuing interactions with him at Oxford.

Peter Jonas
Paul Mason
Peter Read

GUIDE TO AUTHORS

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