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OPERATIONAL NUMERICAL FORECASTING  
Evaluation and Applications

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## **Operational numerical forecasting: evaluation and applications**

This issue of the *Meteorological Magazine* is devoted to four articles on the evaluation of results from the Meteorological Office's operational numerical prediction models and on applications of the numerical models to forecasting and other services. These articles form a sequel to those on the numerical forecasting system itself which appeared in the previous issue of the *Meteorological Magazine*.

The first article deals with the evaluation of forecasts and demonstrates the improving performance of numerical prediction over the years as well as some characteristics of the errors that remain. The second article shows how the improved numerical guidance is used in a 'man-machine mix' approach to public service forecasting of surface weather in the Central Forecasting Office at Bracknell. Upper-air forecasts for civil aviation, which are the subject of the third article, are very largely based on the direct use of numerical products, though the human forecaster plays an important role in the preparation of significant-weather charts. In the final article attention turns to the application of numerical forecasts of sea surface waves and storm surges to a wide range of marine services.

## **Forecast evaluation**

By C. R. Flood

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### **Summary**

This paper shows results of a number of evaluation statistics produced routinely by the Meteorological Office to monitor the forecasts. Changes in the forecast skill over a period of 20 years or more are examined. The impact and performance of the operational numerical models currently run at Bracknell are discussed, but no attempt is made to compare the results with those from models run at other major centres.

### **Introduction**

Although it is difficult to produce consistent and meaningful evaluations of weather forecasts, there are excellent reasons for attempting to do so. The professional customers, the public and the meteorologists all need to know the capabilities and limitations of weather forecasting since these may well influence decisions taken. On a different level, those involved in producing forecasts need to be able to assess the effects of possible changes to their forecast system (changes to the observing network or to the numerical model, for example).

### **Problem of evaluation**

Evaluation is by no means straightforward even for the numerical forecast fields which are conveniently stored on the computer for analysis. The main difficulty is what to use as the truth. One possibility is to use observations. This is attractive in many ways but there is a danger of biasing the statistics to the areas where observations are concentrated and there is the problem of how to deal with erroneous observations. Some form of quality control is needed to exclude the rogues, which can otherwise have a significant effect (for example on a root-mean-square error), but where should the line be drawn? In addition, long-term statistics may be influenced by changes in the quality of the observations, irrespective of whether the forecasts are thereby improved.

An alternative is to use the numerical analyses as truth. Here the question marks lie over the character of the analysis and there is the danger of a self-fulfilling prophecy. In areas where there are few or no data, the analysis must inevitably rely heavily on the 6- or 12-hour forecast from the previous run of the model. More subtly, such matters as the smoothness of the analysis and the extent to which the observations are fitted by the analysis can affect the figures produced even if the forecast is unchanged.

It can be seen that comparisons may be misleading unless figures are produced in an identical fashion. Nevertheless, when used with care, the forecast evaluation statistics have proved to be generally reliable over the years and extremely useful. For example, a few weeks' figures can on occasion lead to the detection of an unwanted side effect from a change to the numerical forecast suite.

### **Long-term improvements**

One aspect of evaluation is to be able to monitor progress over the years. This can be seen most readily from the numerical model forecast results. Fig. 1 shows the root-mean-square height error of the 500 mb 48-hour forecasts for the area shown in Fig. 2 for each year since 1967. The different symbols

represent the different models in operation, from the limited-area 3-level model (Bull 1966) to the 300 km resolution 10-level hemispheric model (Burridge and Gadd 1977) and the current 150 km resolution 15-level global model. Changes during the lifetime of a model (of varying significance) are not shown.

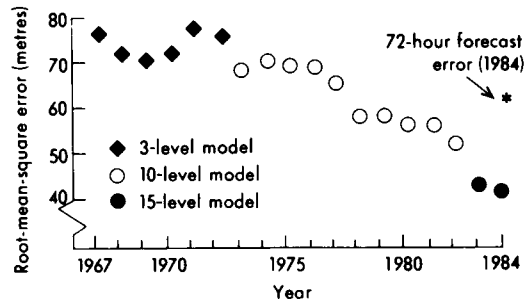


Figure 1. 500 mb height errors for 48-hour forecasts, verified using analyses. (Note that 1972 and 1982 were transition years.)

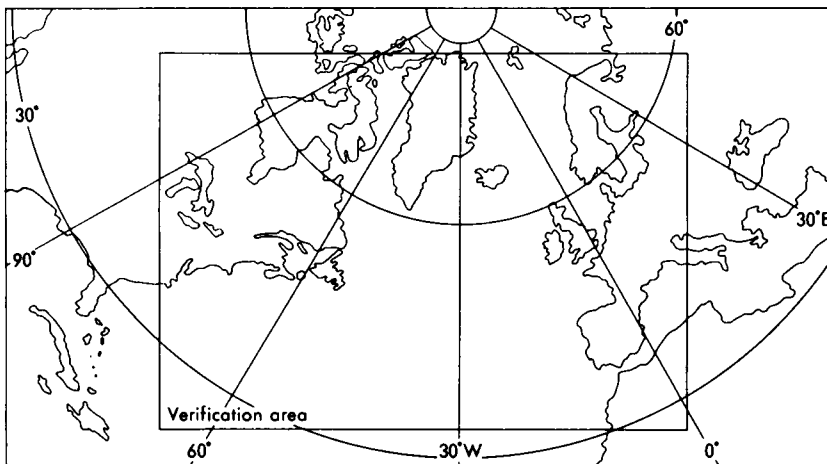


Figure 2. Map showing verification area (inset).

Even the 3-level model in the late 1960s showed distinct skill. This can be judged by comparing the root-mean-square (r.m.s.) error of 70–80 metres with the ‘persistence error’ of about 110 metres (the error which would have been obtained if the 48-hour forecast was simply one of no change from the initial conditions). The improvement in the figures since then is marked and it is interesting to note the current accuracy of the 72-hour forecast, shown by an asterisk on Fig. 1. The value of 62 metres is lower than for any of the 48-hour forecasts before 1978. Similarly the 1976 value of 42 metres for the 24-hour forecast was slightly higher than that for the 1984 48-hour forecast. This improvement in forecasting skill by 1 day out of 2 or 3 within 6 years or so is quite striking and is borne out by a wide range of evaluation statistics. Another example is shown in Fig. 3 which shows the increase in the 1000 mb height change correlation coefficient, i.e. the correlation between the height change from the initial conditions predicted to occur and that actually taking place. This is over the same area (Europe, the Atlantic and part of North America) and there is a separate line for each forecast period.

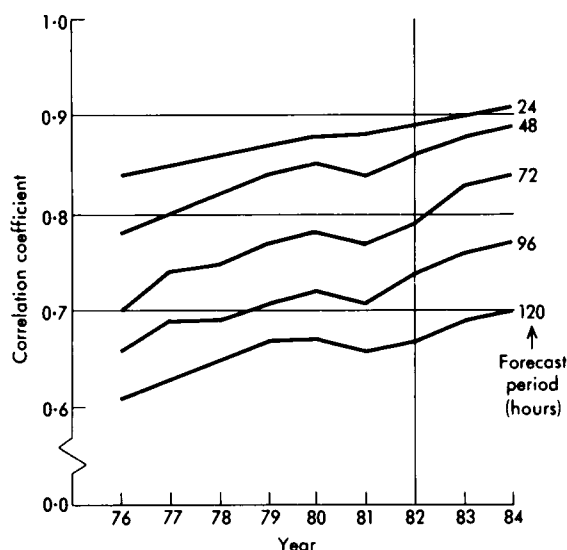


Figure 3. 1000 mb height change correlations for different forecast periods.

Long-term comparisons of a different kind may be made by considering the forecast errors of the position of fronts on 24-hour surface prognoses. In an internal paper by B. C. V. Oddie figures are quoted for each year from 1951 to 1960; these vary somewhat but 110 nautical miles (n mile) is a mean figure. In a similar exercise carried out in the winter of 1983/84, the figure was about 50 n mile, with 84% of cases showing errors less than 100 n mile. This is a substantial improvement. Although the forecast frontal positions continue to be produced subjectively, the positions inferred from the numerical model products now play a major part. The 850 mb wet-bulb potential temperature field is considered the most useful tool and is regarded as very good guidance by the forecasters (Woodroffe 1984).

A contribution to the improvement in all these evaluation figures comes from changes in the observation network (for example the introduction and subsequent improvement of the satellite soundings in the late 1970s) and from a better understanding of the atmosphere. However, the primary influence has been the considerable advances in numerical modelling. Alongside the research effort, the developments in computer technology have been a necessary ingredient. The much faster computers have allowed the use of finer horizontal and vertical resolutions and a more realistic representation of the physical and dynamical processes. The current global model with about a third of a million grid points produces forecasts quicker than the 3-level model did with fewer than six thousand grid points.

### Impact on forecasting

In the case of upper-air forecasts, the numerical products have reached the stage where it is difficult for the forecaster to add very much, at least in terms of forecasting upper winds and temperatures. A study in 1983 showed that when the forecaster made changes to the 12-hour 'spot wind' forecasts for civil aviation (which he attempted for less than 10% of the values), only 51% were for the better. The forecaster had some success with amending the 18-hour numerical forecasts; the corresponding figure was 70%, but this was with the advantage of later data (i.e. the subjective forecast was really only for 12 hours ahead). Although delineation of the significant weather areas remains in the forecaster's domain, most upper-air forecasts for civil aviation are now pure numerical products.

For forecasts of surface weather which are of prime interest to many users, not least the general public, the forecaster has an important contribution to make. While the improvement in forecasting surface fronts has been noted above, this does not always translate into better weather forecasts. After all, even if the forecaster is presented with a perfect surface prognosis, there is still scope for error in terms of the surface weather. For example, in a thundery situation it is difficult to assess even 24 hours ahead the amount of activity, how widespread it will be and so on. Dramatic differences can take place with quite subtle changes in air mass characteristics or air movement, quite apart from the problem of the large variations which occur over small distances in this type of situation.

Although attempted, subjective evaluations of weather forecasts have proved to be rather unreliable. With one method a whole series of forecasts was re-marked several years later; although the same guidelines were used it was apparent that standards had changed meanwhile, perhaps as a result of different expectations of what could be achieved. An objective statistic which bears on the question is shown in Fig. 4. These are the results of a simple question posed to the Senior Forecaster each afternoon: will it rain in the London area (more precisely at either of two specific rain-gauges) between 0600 and 1800 tomorrow? While there is a certain chance element, especially in a showery regime, the marking system has the merit of objectivity and statistics are available back to 1962. Setting aside 1970 (a difficult year?) the general improvement probably results from improved numerical model guidance. In this case the effect of the 'man-machine' mix in forecasting can be seen; the M (74% for 1984) represents the value if the model guidance had been followed literally. The difference from the 83% actually achieved would not be so apparent in other parameters, e.g. surface pressure or wind, and it should also be said that the model was modified in May to reduce the overforecasting of small amounts of rain. The model figure for May to December 1984 is 77%, which is very comparable with the Senior Forecasters' scores using the 10-level model.

A more dramatic improvement can be seen in the longer term-forecasts (2–5 days ahead). Fig. 5 gives an indication of how the forecasts deteriorate as the forecast period lengthens. As with Fig. 1 this uses the r.m.s. 500 mb height error (but again other parameters show the same effect). The errors of a 'persistence forecast' are included as a yardstick. Comparison of the 1974 and 1984 values shows that for the longer-period forecasts there is a gain of about 2 days, i.e. the 1984 5-day forecast is only marginally worse than the 1974 72-hour forecast. This very much bears out the experience of the forecasters. Of

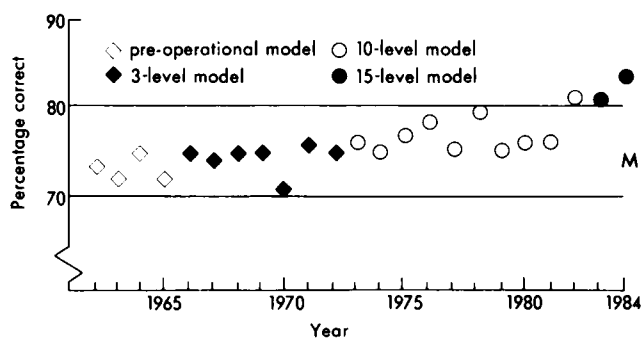


Figure 4. Percentage of correct London precipitation forecasts for the next day. Forecasts produced subjectively; symbol indicates model guidance available. M indicates score directly from the fine-mesh model in 1984.

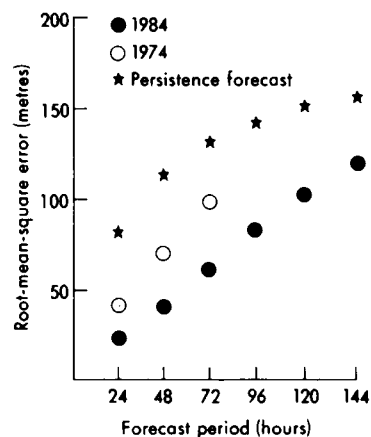


Figure 5. 500 mb height errors for forecasts of different periods (verified using analyses).

course, it depends considerably on what is required by the user (some requirements are very exacting), but there is now good and justifiable confidence in the evolution of the forecast out to day 3 in a way which was not apparent 10 years ago. The 5-day forecasts too have considerable merit, though clearly they need to be used more cautiously. The forecast of the character of the weather is sufficiently good and detailed to be useful to farmers in planning the week's work. The same is true for the offshore industry and in certain situations it is possible to forecast a 'weather window' of several days with winds remaining below a critical threshold, as has been demonstrated in practice during the towing out of some of the very large oil rigs.

### 15-level model performance

The statistics in this section largely relate to 1984 and indicate how the errors vary in space and time.

Fig. 6 shows the way the temperature and wind errors vary in the vertical. For wind these are r.m.s. vector errors, i.e. taking into account direction as well as speed errors. The figures relate to the same area as in Fig. 2 but are based on comparisons with observations; r.m.s. errors against analyses are generally a little lower, though there is fair agreement between the two. The wind errors peak noticeably at the main jet-stream levels around 250 mb. Temperatures behave similarly though with a less pronounced maximum. The aviation community is a major user of upper-air forecast information. Improvements of forecast accuracy here have a direct bearing on fuel savings resulting from better flight planning. Fig. 7 shows the change over the last 5 years for the winds and temperatures at 200 mb, again verified against

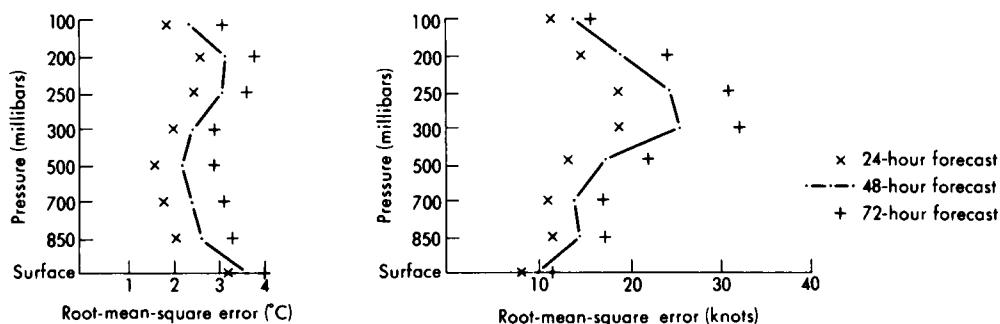


Figure 6. Temperature and wind errors (verified using observations), 1984.

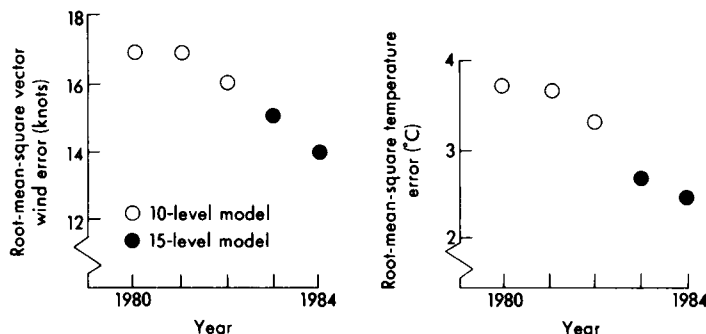


Figure 7. 200 mb wind and temperature errors for 24-hour forecasts (model changed September 1982).



observations. Although 1984 was the best year on record the improvement is maintained into 1985 with r.m.s. errors reduced by a further 1–2 knots in each of the first 3 months of the year compared with the corresponding months in 1984.

Returning to Fig. 6 and looking at the surface, it can be seen that the winds are generally very good. Of course the particular location is important and in the stormy mid-Atlantic r.m.s. vector wind errors at the surface are just over 10 knots for 24-hour forecasts and about 13 knots for 48-hour forecasts. The importance of the wind direction in the vector error can be judged by comparing these with the corresponding r.m.s. wind speed errors of 6 knots at 24 hours and 8 knots at 48 hours for the same stations. The surface winds are used extensively in forecasting for shipping and the offshore industries. They are also the vital input to the numerical wave models, the accuracy of which is quoted elsewhere (Francis 1985). The considerable variations of surface temperature are not so well captured by the model and r.m.s. errors are about 3 °C at 24 hours. Model changes to the radiation scheme and the boundary-layer physics are expected to lead to improvements. A contributory factor is also the significant mean errors, especially for stations whose heights differ from the somewhat smoothed topography in the model.

So far, for convenience, the evaluation statistics have all related to the same area. Fig. 8 shows the latitudinal variation of the errors. These are very much related to the natural variability of the atmosphere and the surface-pressure and 500 mb height errors show a distinct minimum in tropical regions. The smaller atmospheric variability is reflected in much lower errors from a persistence forecast; at 24 hours these vary from 7.2 mb for 30°–90°N, 2.1 mb for 30°N–30°S to 8.1 mb for 30°–90°S.

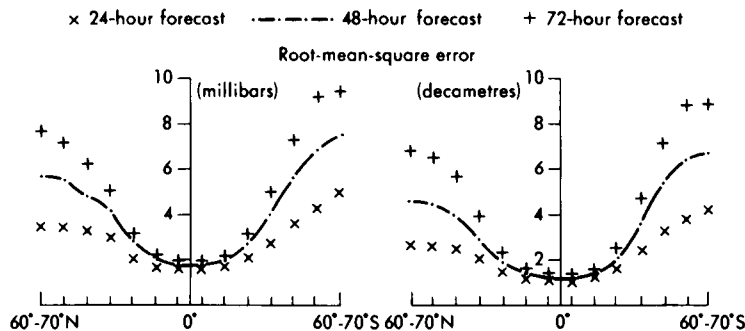


Figure 8. Surface pressure and 500 mb height errors by 10° latitude bands, 1984.

Considered as a percentage of the persistence error, numerical forecasts in tropical areas are poorer than those in higher latitudes; other parameters of more relevance to forecasting in the tropics, e.g. the 850 mb wind, show the same effect. It is interesting to compare the two hemispheres. The persistence errors (measured over a year to avoid seasonal effects) are similar, though a little larger in the southern hemisphere. The observing network, on which the forecasts are based, is much sparser in the southern hemisphere. However, comparing the forecasts in mid-latitudes there is roughly only a 12–24 hours difference in forecast skill. Thus the southern hemisphere 2-day forecast error is smaller than the northern hemisphere 3-day forecast error. Linking this with the conclusion from Fig. 1 it is not unreasonable to suggest that the southern hemisphere forecasts are as good as those in the northern hemisphere were in the late 1970s.

Variations through the year are shown in Fig. 9. Bearing in mind this is for the area in Fig. 2 (mostly north of 30°N) the surface-pressure error changes are not unexpected, reflecting the quieter summertime

conditions. The difference between January and December (both 1984) is a little unreal as a significant model change in December reduced errors by about 0.5 mb at 24 hours and about 1 mb at 72 hours judging from 1985 results. There is much less annual variation in the upper-wind errors and there is some evidence of the rather random month-to-month variability, perhaps dependent on the synoptic situation. The relatively flat curve is a little surprising with the strong jet streams in winter; however, the jets are also more coherent and are generally below 200 mb in the area concerned.

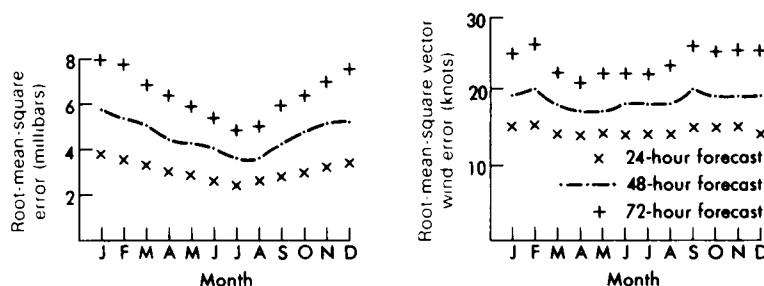


Figure 9. Surface pressure and 200 mb wind errors month by month in 1984.

## Conclusions

It is clear that numerical forecasts have improved markedly since their operational inception in the mid-1960s and have become a major tool in forecasting for all but the shortest forecast periods, up to 6 hours. For the bulk of upper-air forecasting the numerical products are such that they can be issued directly with little reference to the forecaster. For surface weather forecasts, the 'man-machine mix' continues to be very important. Even so, much greater reliance is now placed on the model products and the improved standard of forecasting, particularly for parameters which are well related to the synoptic pattern (e.g. surface wind and frontal rainfall), is apparent. There is clearly scope for further improvement — but the signs are healthy and the positive trend in forecasting is expected to continue.

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## The models in action

By R. D. Hunt

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### Summary

A number of examples of fine-mesh and global model forecasts are shown, covering a wide range of weather situations. The results demonstrate the very good guidance which is given by the models to the forecasters in the Central Forecasting Office.

### Introduction

Other papers in this issue describe the latest weather forecasting models developed by the Meteorological Office and the form in which the output from these models reaches the forecasters. This article gives an indication of how useful the models have been in providing assistance to the forecasters in both the short range (up to 24 hours ahead) and the medium term (up to 6 days ahead) by looking at examples of recent model forecasts in different weather situations.

The Central Forecasting Office (CFO) in Bracknell is responsible for producing forecasts in the form of charts and descriptive texts which are used by the forecasting offices in the United Kingdom as guidance for the preparation of detailed forecasts to the public, the media and many weather-dependent industries. Together with this national role, Bracknell also has a wider, international responsibility. As a Regional Meteorological Centre, Bracknell sends analyses and forecasts produced by CFO to other Meteorological Centres in Europe, while as one of the two World Area Forecast Centres, Bracknell provides forecasts to civil aviation for use in many parts of the world. CFO is therefore a major forecasting centre and it is vital that the products issued are of the highest possible standard. Since the autumn of 1982, the 15-level fine-mesh and global models have been available operationally and the output from the computer in the form of various forecast charts has been of great benefit to the forecasters.

The main fine-mesh model output consists of forecast charts at 6-hourly intervals up to 36 hours ahead; the charts are of surface pressure, rainfall and various other parameters needed to assist with the forecasting of frontal positions, surface temperature, the likelihood of showers and many other features of the weather. The output from the global model consists of a smaller range of products at 12-hourly intervals but going forward to 6 days ahead. Some examples of both are given below.

### Example 1: 15 October 1983

Fig. 1 shows the analysis for midday on 14 October 1983. Most of the United Kingdom lay in a showery south-westerly airstream; parts of the east in particular were quite sunny. In the Atlantic a depression was about 600 miles west of Scotland with associated fronts moving eastwards towards Britain. The forecast for midday on 15 October produced by the fine-mesh model, based on data from midday on the 14th and available to the CFO forecasters during the afternoon of that day, is shown in Fig. 2. (It should be noted that the actual frontal positions as such are not predicted by the model but output is produced, such as the 850 mb wet-bulb potential temperature field, from which positions of fronts can be inferred.) The analysis for midday on the 15th is shown in Fig. 3 taken from London Weather Centre's *Daily Weather Summary*.

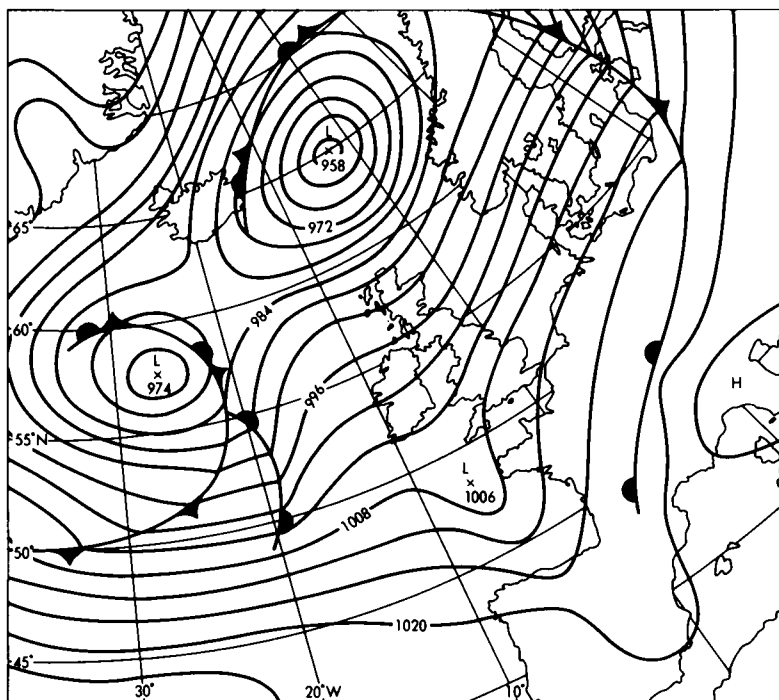


Figure 1. Analysis for 12 GMT on 14 October 1983.

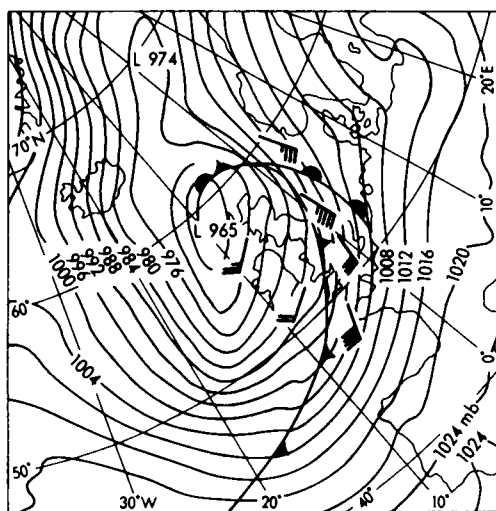


Figure 2. Forecast for 12 GMT on 15 October 1983, produced by the fine-mesh model and based on data from 12 GMT on the 14th.

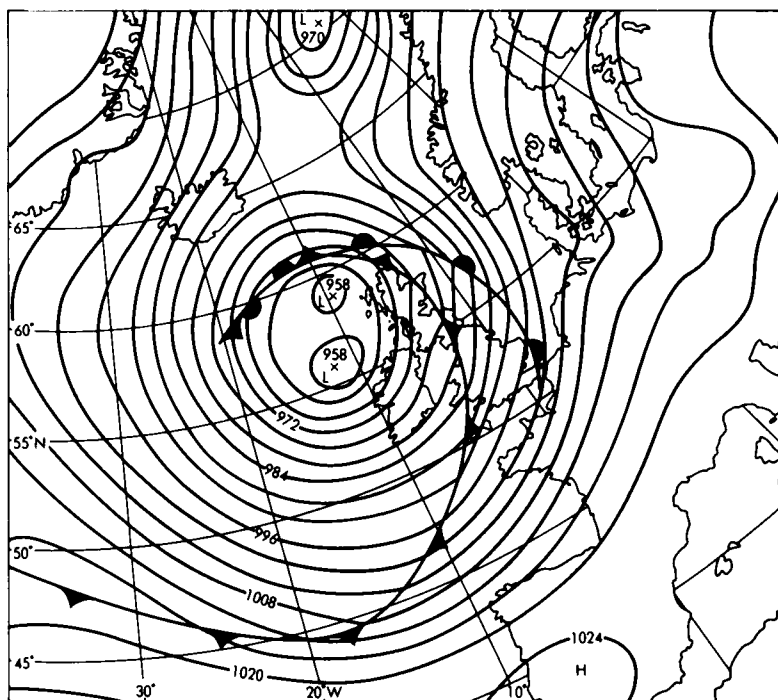


Figure 3. Analysis for 12 GMT on 15 October 1983.

The basic forecast pattern is clearly very good, although there are some differences between the forecast and the analysis. The positions of the fronts over the United Kingdom show good agreement although the forecast cold front is a little too far advanced, particularly in the North. Fig. 2 shows that the main depression near north-west Scotland was forecast to have only one centre of depth 965 mb whereas in reality there were two centres each about 7 mb deeper. Also the forecast has marked troughing in the isobars to the south-west of the main centre which Fig. 3 shows to be exaggerated.

The closeness of the isobars on the forecast chart indicates the model's prediction of winds of severe gale force in many places, but especially ahead of the cold front with a noticeable decrease in wind strength behind it. Fine-mesh surface wind forecasts at some locations are shown on the forecast chart. Fig. 3 shows that these important general features were correct; gusts of over 60 kn were reported widely during the day with a gust of 80 kn on the Isle of Wight. After the cold front passed the winds did decrease markedly, which is also evident from Fig. 3.

Looking at some other products, it can be seen that Fig. 4 shows the expected rainfall pattern at the verifying time. In this diagram, the circles represent dynamic rain of a continuous nature with the size of the circle being proportional to the intensity of the rain, while the convective rain, or showers, is represented by 'V's, again with appropriate size variation. This figure shows a large area of rain, quite heavy in places, associated with the cold front, and showers coming into Ireland and much of Scotland behind it. Smaller amounts of rain are associated with the warm front and the warm air. Fig. 5 shows where the rain was actually occurring at the time. Essentially the agreement is very good although there are some differences, the most notable being the spread of heavy rain across southern counties of England which actually occurred well ahead of the cold front. Rainfall totals predicted by the fine-mesh

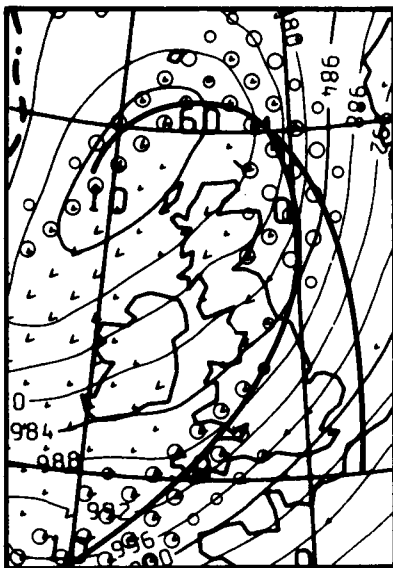


Figure 4. Expected rainfall at the verifying time of 12 GMT on 15 October 1983. Data time is 12 GMT on the 14th.

model for 15 October were widely in excess of 10 mm and over 20 mm in parts of the south and south-west; these totals were well representative of what actually occurred (although the rainfall distribution on that day showed large local variations due to topography which are inevitably smoothed out somewhat by the 75 km horizontal resolution of the model).

The forecast for 15 October then, based on the fine-mesh products from the previous day, successfully predicted widespread severe gales with heavy rain moving from west to east across the United Kingdom, followed by showers.

### **Example 2: 22 January 1984**

Fig. 6 shows the analysis for 00 GMT on 21 January with a cold south-easterly airstream over most parts of Britain and with a depression well to the west moving north-eastwards. Figs 7 and 8 show the 18-hour and 30-hour fine-mesh forecasts from that time. The depression was expected to move northwards to the west of the United Kingdom, the associated frontal system bringing precipitation and strong winds across many parts overnight. These figures also include the 'snow probability lines' from the model based on the 1000–850 mb thickness field, indicating 20%, 50% and 80% probabilities that any precipitation falling will be snow. These probabilities require considerable interpretation, the chance of snow increasing not only on higher ground but also as the precipitation becomes heavier and more continuous. On this occasion the model was suggesting that much of the frontal precipitation would be sleet or snow at first with only south-west Wales and south-west England being outside the 20% line at 18 GMT on 21 January and much of the precipitation in the north falling within the 50%

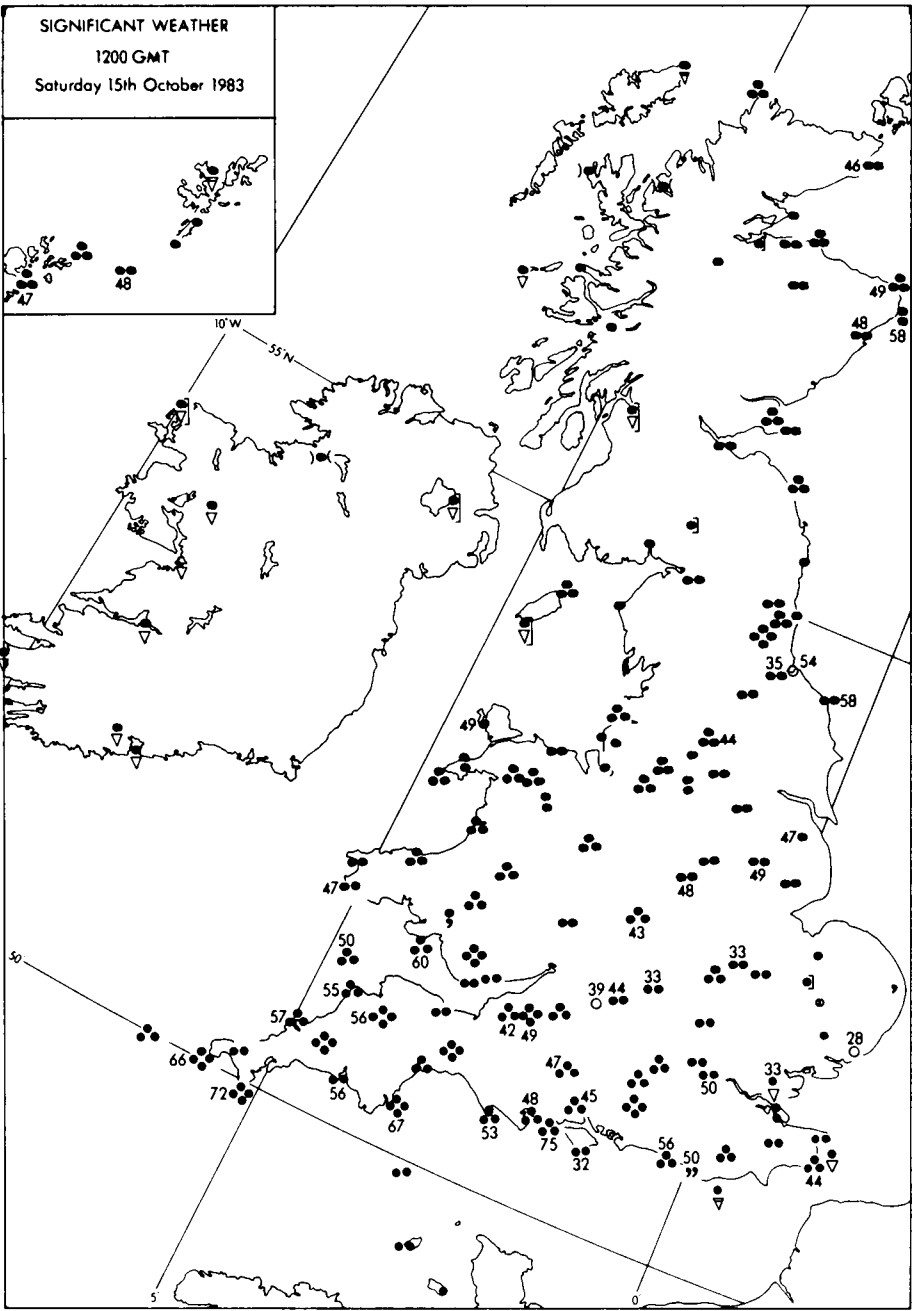


Figure 5. Actual distribution of rain at 12 GMT on 15 October 1983, the verification time of the forecast chart shown in Fig. 4. The figures on the chart are maximum gusts (kn).

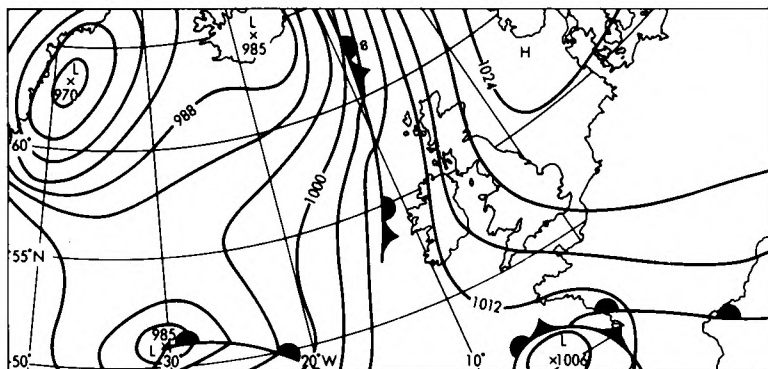


Figure 6. Analysis for 00 GMT on 21 January 1984.

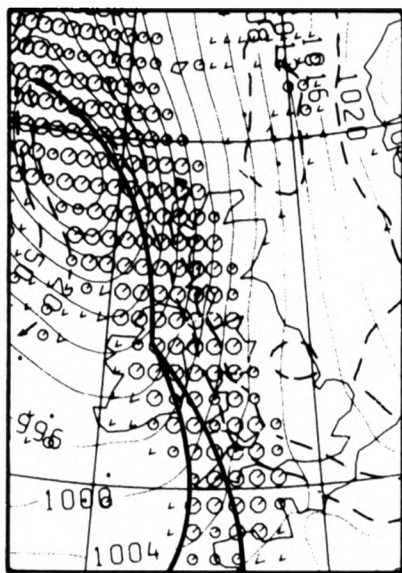


Figure 7. 18-hour fine-mesh forecast from 00 GMT on 21 January 1984.

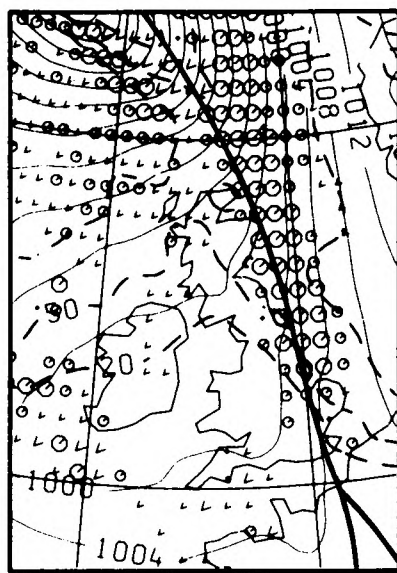


Figure 8. 30-hour fine-mesh forecast from 00 GMT on 21 January 1984.

line. During the night, however, the model was warming up the low-level air in central and south-western areas and the retreat eastwards of the 20% line suggested that the sleet or snow would turn to rain before dying out.

Fig. 9 shows the analysis at 06 GMT on 22 January, corresponding to the forecast shown in Fig. 8. The front is somewhat further west than the model had implied and the area experiencing precipitation was consequently slightly misplaced. However, precipitation fell as sleet or snow in many areas and with accompanying strong winds, considerable drifting of snow had taken place in the east and north leading to considerable disruption of transport. In more southern counties early snow had turned to rain while in some western areas the precipitation had died out to be followed by showers, wintry in the north-west, much along the lines of the fine-mesh forecast. The model forecast gave very good guidance in a critical situation of great importance to the public and sections of industry.



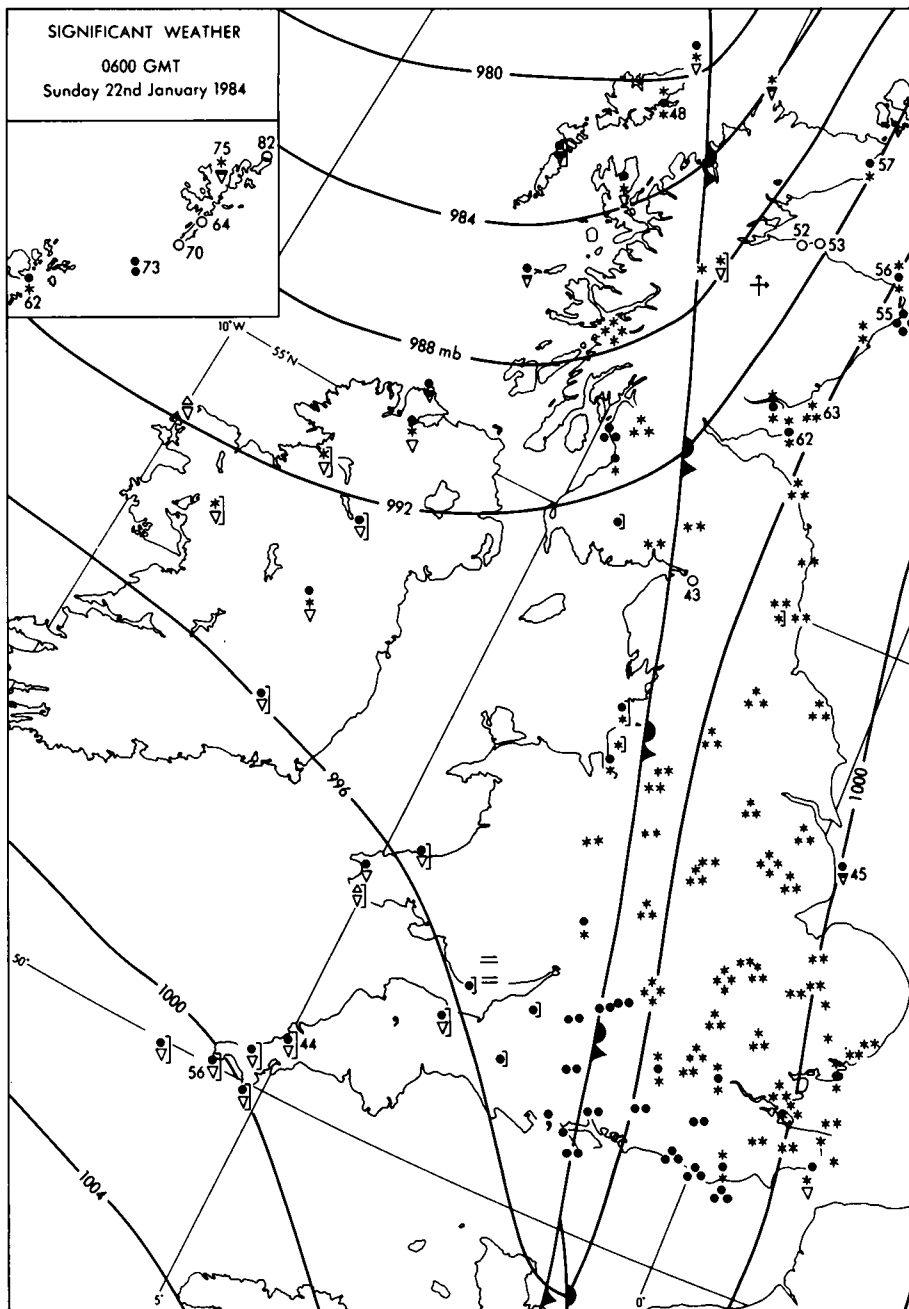


Figure 9. Analysis for 06 GMT on 22 January 1984, the verification time of the forecast shown in Fig. 8. The figures are maximum gusts (kn).

**Example 3: 17 June 1984**

At midnight on 16 June 1984 an anticyclone was centred over Northern Ireland and covered most of the United Kingdom, with a weak warm front having just crossed Scotland moving into the North Sea. The analysis is shown in Fig. 10. The fine-mesh forecast run at that time, however, showed that, despite the high surface pressure, showers were expected to develop in central and northern areas on the 16th and in the south-east on the 17th. The 36-hour forecast verifying at 12 GMT on 17 June is shown in Fig. 11. As well as indicating the approach of another warm front towards north-western areas, it also shows a number of shower symbols over England, particularly in the south-eastern quarter, with some large symbols indicating heavy showers. With high daytime temperatures in a summer month, forecasters interpreted this as a likelihood of thunderstorms, taking into account the other model output relating to atmospheric stability.

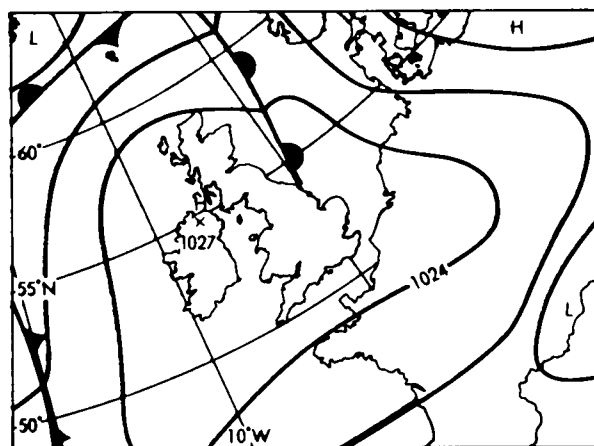


Figure 10. Analysis for 00 GMT on 16 June 1984.

By midday on the 17th scattered thunderstorms were developing over south-east England and by 18 GMT widespread storms were occurring in an area very similar to that shown by the model forecast for 6 hours earlier. Fig. 12 shows the distribution of thunderstorms between 12 and 18 GMT; some very large rainfall totals were reported, up to 60 mm locally, with some flooding and several lightning casualties. Once more there were errors in detail in the fine-mesh forecast. The model had developed the showers too early and produced some showers over northern England shown in Fig. 11 which failed to materialize. Also the light rain in Ireland ahead of the warm front is a little too far advanced. Nevertheless, the model had again given good guidance of the most significant weather event in the forecast period.

**Global model example 1: 12 GMT on 18 May 1984**

On 19 May 1984 a depression was forming over north Africa which developed as it moved northwards across Italy and central Europe during the following 2 days. It then developed a rather complex structure with one part turning westwards towards the United Kingdom and another section moving east and filling. The analysis for 12 GMT on 22 May is shown in Fig. 13; the centre of the depression was close to London with the associated warm front having crossed England from the east bringing rainfall in excess of 20 mm to many central and southern parts of the country. The low-pressure area subsequently turned

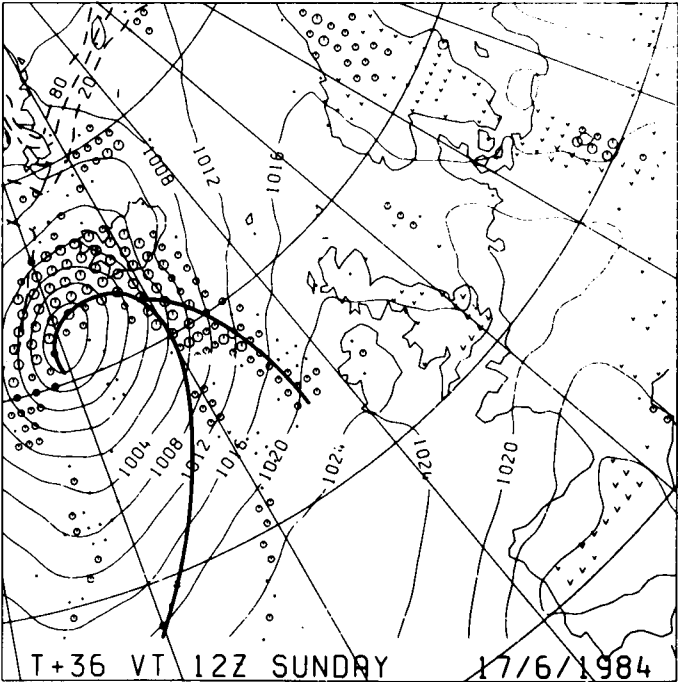


Figure 11. 36-hour forecast verifying at 12 GMT on 17 June 1984.

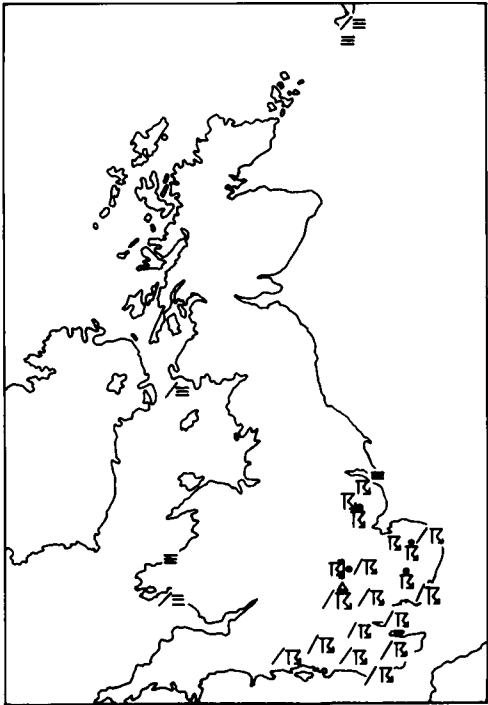


Figure 12. Significant weather at 18 GMT on 17 June 1984. Solidus denotes weather in previous 6 hours.

south-westwards towards Biscay. The track of the depression and the amount of rain associated with it made this a very unusual and particularly difficult situation to forecast.

Fig. 14 is the 96-hour forecast run at 12 GMT on 18 May and verifying at 12 GMT on 22 May. The global model had correctly predicted the development of the depression over north Africa, its track across Europe and its approach towards the British Isles from the east. In fact the forecast centre was rather too deep and its position a little too far to the north-east. Nevertheless, the forecast was considered to be remarkably accurate, particularly if the unusual nature of the development is borne in mind. Incidentally, the fine-mesh forecast runs from 21 May (not shown) were very successful in predicting the timing, areal distribution and quantity of rain on the following day.

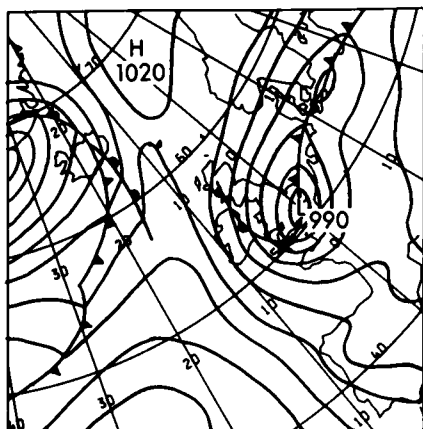


Figure 13. Analysis for 12 GMT on 22 May 1984.

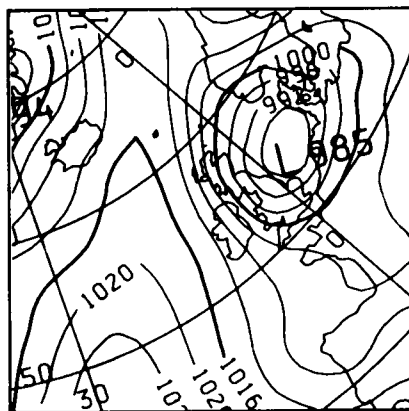


Figure 14. 96-hour forecast run at 12 GMT on 18 May and verifying at 12 GMT on 22 May 1984.

### Global model example 2: 12 GMT on 30 August 1984

One of the most important aspects of forecasting several days ahead is to be able to predict significant changes in weather type. It is vital for forecasters to give as much advance notice as possible of, say, a change from dry, settled weather to changeable, wet weather or from warm to cold conditions. One such change of type occurred on 4 September 1984 when a prolonged spell of dry, warm weather over the southern half of England and Wales with mainly southerly winds gave way to a much cooler, northerly airstream, following the passage of an area of low pressure across northern England. Maximum temperatures over much of England and Wales were up to 9 °C lower than on the previous day giving the coolest day generally there since the end of June.

Fig. 15 gives the analysis for 12 GMT on 4 September showing the depression which brought about the change in weather approaching Denmark. The 5-day forecast verifying at that time, run at 12 GMT on 30 August is shown in Fig. 16. The general agreement is good, with the model showing the much cooler airstream established over the British Isles behind the cold front then over France. The position of the model's cold front, inferred from the 850 mb wet-bulb potential temperature field, is spectacularly accurate for 120 hours ahead. There are differences between the forecast and the verifying analysis of course. The model had taken the depression responsible for the change in weather across Scotland to southern Norway, the track being somewhat further north than was actually the case. The ridge of high pressure in the Atlantic had built more than the model had predicted allowing a stronger northerly gradient to be established over the United Kingdom. But these are essentially differences in detail which

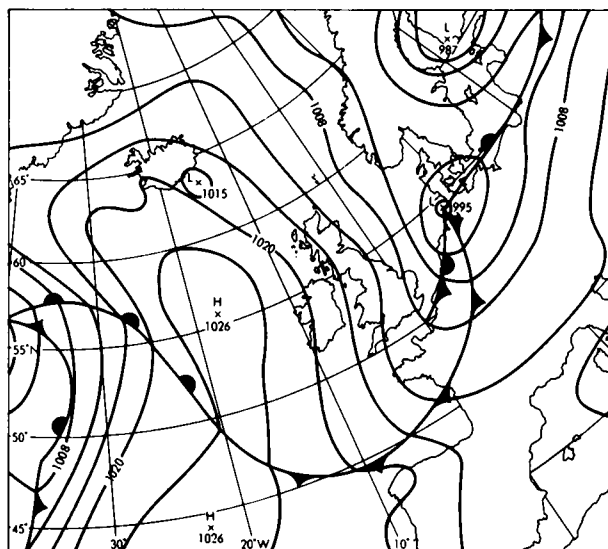


Figure 15. Analysis for 12 GMT on 4 September 1984.

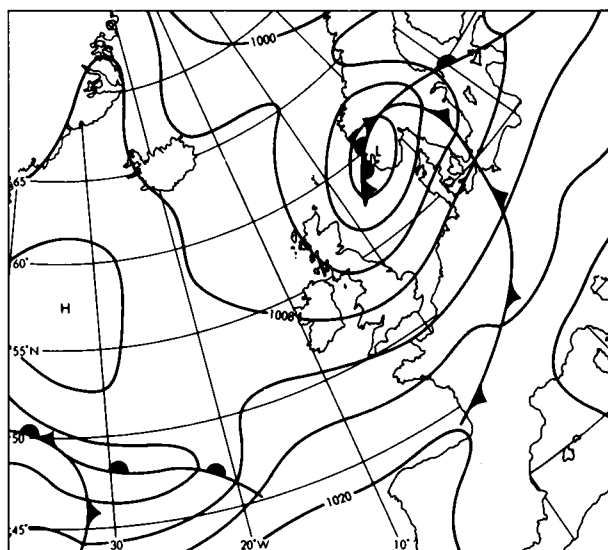


Figure 16. 5-day forecast run at 12 GMT on 30 August and verifying at 12 GMT on 4 September 1984.

can only be expected in a forecast for 5 days ahead. On this occasion it was the change in basic weather type which was by far the most significant aspect of the forecast and in this respect the forecast was very good. Using it as guidance, the medium-range forecasters in CFO were able to predict 5 days ahead the end of the long summery spell of weather over southern Britain.

### **Interpretation of forecasts**

An assessment of the performance of the Meteorological Office's weather prediction models in general terms is given elsewhere in this issue. The examples given here demonstrate how effective they have been in some difficult and important situations. In the light of these the temptation might be to underestimate the role of the human forecaster in CFO or elsewhere. This would be a mistake, as there is little doubt that his contribution is still vital. Firstly, the success of a particular forecast depends crucially on the model's analysis. Forecasters must thoroughly investigate as much of the data received at Bracknell as possible, including satellite pictures, to ensure that the analysis is as accurate as possible. They must also assess the effect any shortcomings in the analysis may have on the subsequent forecast. Secondly, the forecaster is able to adjust the model forecast using his knowledge of the model formulation, his experience of model behaviour and in the light of actual developments. This is often important when considering forecast rainfall patterns, but also applies more generally, for example in the development of a small-scale but intense depression.

Lastly, the model forecast requires considerable interpretation. Even with a very good sequence of surface-pressure charts, skill and judgement are required to forecast the many aspects of weather which are of importance to customers. For example, forecasts of maximum and minimum temperatures, the possibility of frost, the amount of cloud and the likelihood of fog are essential. Some of the model output is of indirect assistance to the forecasters in these respects (e.g. the 1000–850 mb thickness charts are a useful aid to surface temperature forecasting), but sometimes contradictory factors need to be taken into account. Even those aspects such as rainfall amount and distribution which form part of the direct output from the models require careful interpretation. Limitations in the vertical resolution can lead to incorrect predictions of convective rainfall for instance; the forecasters need to judge when this is likely to be the case.

Nevertheless, the latest weather forecast models in operational use in the Meteorological Office have proved to be an invaluable aid to the forecasters, and the increasing confidence the customers have shown to possess in the forecast products stems largely from the improved accuracy of these tools not only for the British Isles, to which all of the examples apply, but over the whole world.

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## **The use of 15-level model products in the Central Forecasting Office for forecasts for civil aviation**

By M. E. Hardman

(Meteorological Office, Bracknell)

### **Summary**

The use of the 15-level global prediction model as a basis for Bracknell's role in the World Area Forecast System for civil aviation is described. Some further developments are mentioned which are expected to lead to further increases in the accuracy of the forecasts and the effectiveness of the service.

### **1. Introduction**

A number of features of the design of the 15-level model, when compared with its predecessor the 10-level model, enable it to provide an improved representation of the atmosphere near those levels of most importance for modern commercial airliner operations. These include greater horizontal and vertical resolution, improved output modelling of tropopause and maximum-wind data, and the use of winds and temperatures as primary model variables.

In recognition of these features and the capability of global coverage from the model, Bracknell was designated by the International Civil Aviation Organization as one of two World Area Forecast Centres (WAFCs) within the framework of the new World Area Forecast System (WAFS) for civil aviation. The role of the World Centres in Bracknell and Washington is to provide numerical forecasts of winds and temperatures (primarily in coded bulletins of grid-point values) with a global coverage. These are distributed to a network of Regional Area Forecast Centres (RAFCs) with responsibility for providing planning information and flight documentation for the user airlines. The Central Forecasting Office (CFO) assumed the role of an RAFC, one of three in Europe, on 1 February 1984.

This paper describes the products available from WAFC Bracknell and their use, with other model data, by RAFC Bracknell.

### **2. World Area Forecast Centre products**

Using a data cut-off time of  $T+3$  hours 20 minutes, global forecast fields of grid-point values of wind and temperature at standard flight levels from FL 050 (850 mb) to FL 530 (100 mb) and for verification times  $T+12$ , 18, 24, and 30 are transmitted using WMO GRID code (FM 47-V) typically commencing at  $T+4$  hours 30 minutes. The GRID resolution for bulletins, (compared to a model grid of  $1\frac{1}{2}^\circ$  latitude by  $1\frac{7}{8}^\circ$  longitude) is  $2\frac{1}{2}^\circ$  latitude by  $5^\circ$  longitude between  $20^\circ$  and  $70^\circ$  north or south and  $5^\circ$  by  $5^\circ$  in the tropical belt. A lower resolution is used over polar regions. Additional bulletins containing maximum winds and tropopause data are also transmitted. Back-up for the data, to cover a failure or delay of the subsequent forecast run, is provided by bulletins for  $T+36$ , 42 and 48. In the event of unavailability of the global model for two consecutive runs, grid-point data from WAFC Washington, using a data time 12 hours earlier, are transmitted. Full details are given by Francis (1985).

### 3. CFO as a Regional Area Forecast Centre

Regional Centres are tasked with the processing of WAFC products to provide flight documentation. Charts are required for transmission by facsimile to users. In the United Kingdom these are made available through the CAMFAX circuits which serve the larger aerodromes throughout the country. They are sent by landline to a number of international centres including Paris and Frankfurt — the other European RAFCs — and are also broadcast by radio facsimile (GFE).

Charts may be divided into two categories: (a) those constructed directly from the model products and depicting wind and temperature at standard flight levels (Fig. 1); and (b) those constructed by a combination of subjective methods and data from the model such as significant-weather charts (Fig. 2). Figs 1 and 2 also show the primary area of responsibility of RAFC London (Bracknell), the so-called 'NAT' area, extending from the Persian Gulf to the west coast of North America. Both charts are transmitted at A2 size to users — a scale of approximately 1:36 million. Output (a) also includes charts covering the 'MID' area from Europe to south-east Asia, the 'AFI' area covering routes to Africa and South America, and on a larger scale a 'EUR' chart covering Europe and the Mediterranean. Charts are issued on a 6-hourly sequence of verification times, normally at 18 and 24 hours from the corresponding model data times. Transmission sequences commence at 5½ and 11 hours respectively for charts (a). Corresponding significant-weather charts are available to users by T+9 and T+15 hours.

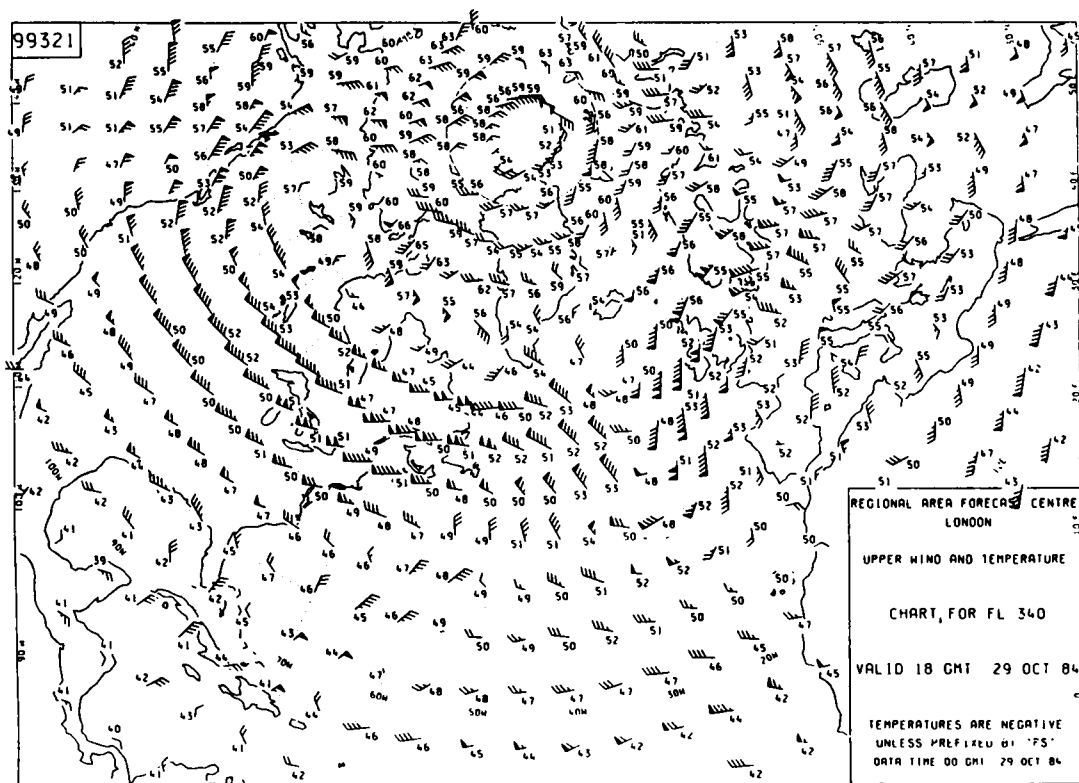
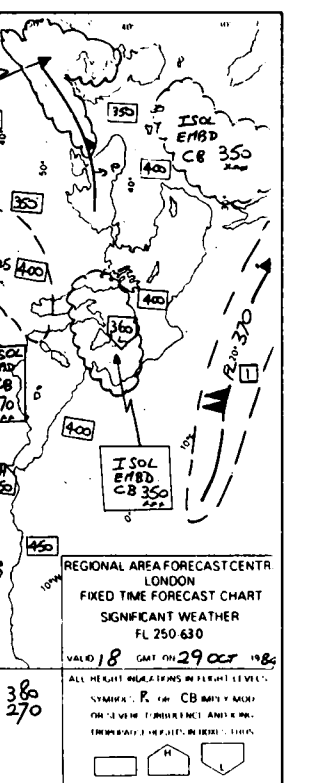


Figure 1. Flight documentation chart of winds and temperatures at flight level 340 (250 mb), 'NAT' area 18-hour forecast from data time 00 GMT on 29 October 1984, as issued by Central Forecasting Office (Regional Area Forecast Centre, London).



regions, i.e. surface to 10 000 mb). Routine significant. On this chart (Fig. 2) are axes, areas of moderate or widespread thunderstorm associated with frontal zones or

ded. The construction of the  
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630 (400 to 70 mb). Time and area

Numerical fields of significant-weather parameters are available as guidance (Fig. 3):

- |                        |   |
|------------------------|---|
| (a) maximum wind speed | } — derived by curve fitting to the data at the 15 model levels |
| (b) maximum wind level |   |
| (c) tropopause height, |   |
- and

(d) probability of clear-air turbulence — based on statistical and physical relationships between model variables and CAT.

In addition, forecast vertical temperature profiles available on a visual display unit give an indication of deep convection. To this model information the forecaster adds a considerable amount of subjective experience both of the relationship between the synoptic features and significant-weather parameters and of the model's ability to handle these features in different situations. Later observations, both from pilot balloons and aircraft, together with satellite imagery, are also useful.

## 5. Model accuracy

Elsewhere in this issue is an historical account of the accuracy of forecasts from the Meteorological Office operational models. This shows the marked improvement as a result of the introduction of the current global model. The recent performance of this model in forecasting winds at the levels of commercial airline operations is illustrated in more detail in Fig. 4. This shows analysed and 24-hour forecast values of mean wind-speed error (a) and root-mean-square (r.m.s.) vector wind errors (b) at 250 mb, as verified against observations over an area covering Europe, the North Atlantic and eastern parts of North America. Monthly values are plotted from August 1983 to December 1984. The r.m.s. 24-hour forecast values show only a small seasonal variation, highest in early winter, between 16 and 20 kn, and r.m.s. analysis values show a slight growth from 7 kn to a peak of about 10 kn in October 1984. A small underestimate of generally less than 2 kn is seen in the mean errors at this level.

All winds at 250 mb are taken into account in these figures giving a general indication of the accuracy of wind forecasts for civil aviation. A more selective approach is required to assess the ability of the model to predict such features as the position and strength of jet streams, and their associated horizontal and vertical shears which are important for the forecasting of CAT. One such approach is to verify model forecasts of maximum wind speed against radiosonde observations. A severe test is to select only cases where the observed value is greater than 90 kn (Fig. 5). It is seen that there is a considerably larger mean error, with these stronger winds underestimated by between 12 kn in winter and 25 kn in summer for 24-hour forecasts (Fig. 5(a)). The explanation lies partly in the statistical treatment since winds greater than 90 kn comprise a much smaller fraction of the population in summer than in winter. Subjective examination of maxima depicted on model output (e.g. Fig. 3(a)), however, confirms that part of the variation is real. Indeed, while forecasters in CFO had reported jet maxima 'well handled' by the model during its first winter (1982/83), as summer 1983 approached an increasing number of seriously underestimated maxima were observed in model output, leading to the setting up of a subjective investigation to study the problem. This showed that for all jets over a 6-week period in July and August 1983 the mean bias in the model's 24-hour forecast of jet strength was -19.5 kn, in broad agreement with the results in Fig. 5(a), when compared to subjectively analysed jet cores. Positional errors were ignored. Subjectively amended 24-hour forecasts issued by CFO reduced this bias to 5.6 kn. While such improvements are possible with jet cores, investigations have shown that subjective amendment of general wind forecasts is more difficult.

A breakdown of the mean speed error against jet orientation showed that the largest values occurred with flow from due north or south. Jets with an easterly component were also less well handled, though

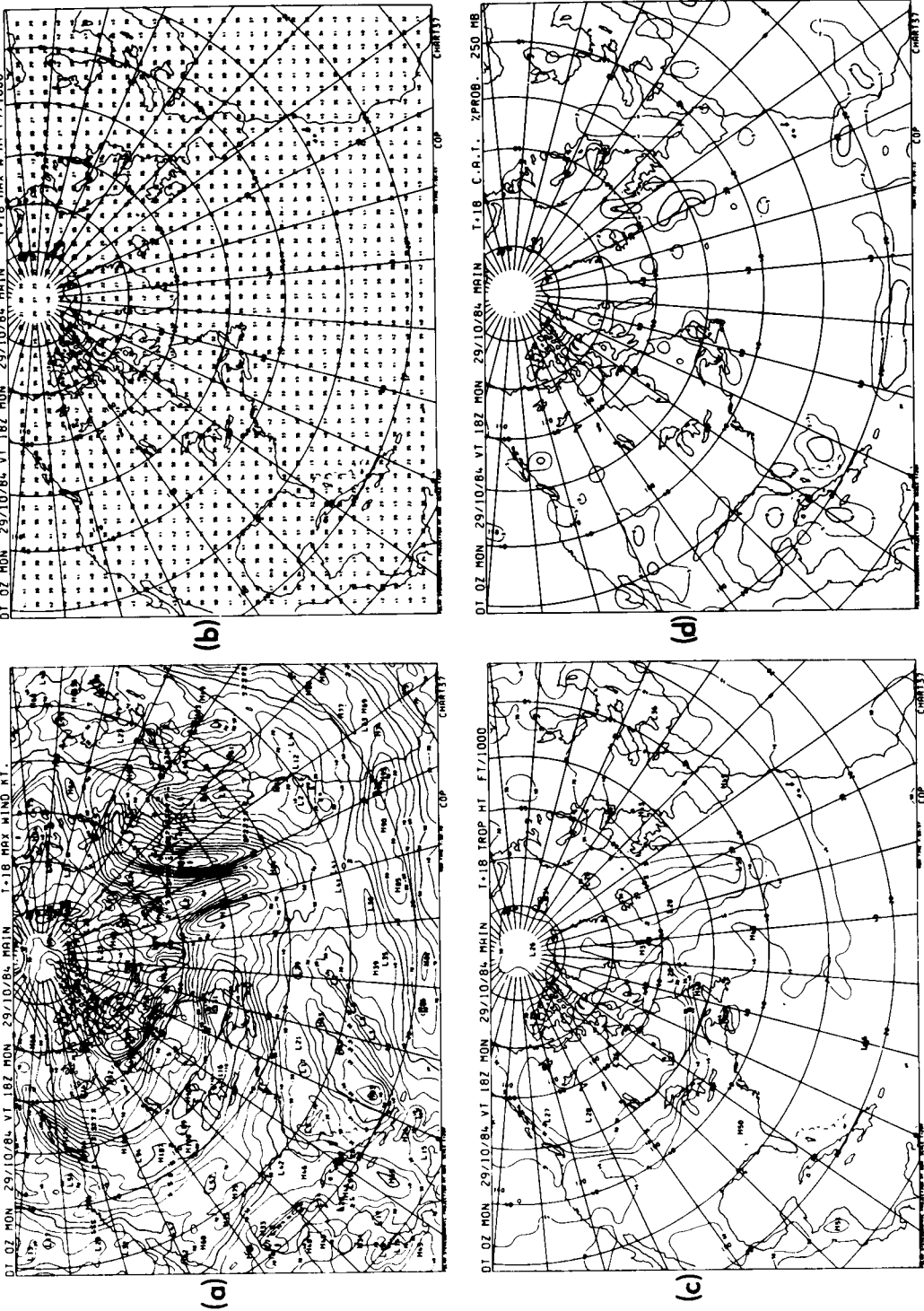


Figure 3. Model output charts from the global model. These are 18-hour forecasts from the same data time as Figs 1 and 2. (a) Maximum wind speed. (b) Maximum wind speed. (c) Tropopause level (ft x 1000). (d) Probability (%) of moderate or severe clear-air turbulence at 250 mb.

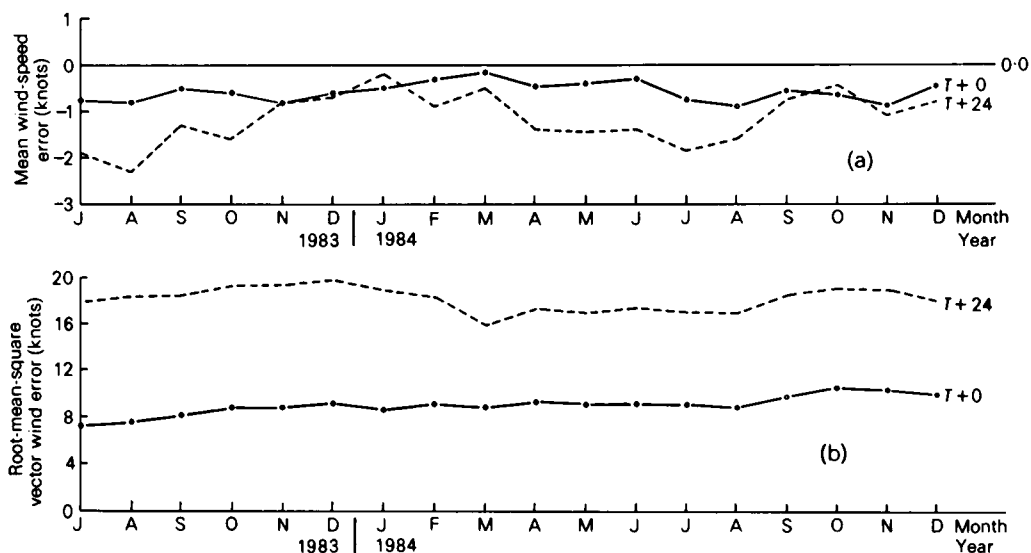


Figure 4. Errors in global model wind analyses and 24-hour forecasts at 250 mb by months from July 1983 to December 1984, as verified against radiosonde observations, for an area covering Europe, the North Atlantic and the easternmost parts of North America. (a) Mean wind-speed error. (b) Root-mean-square vector wind error.

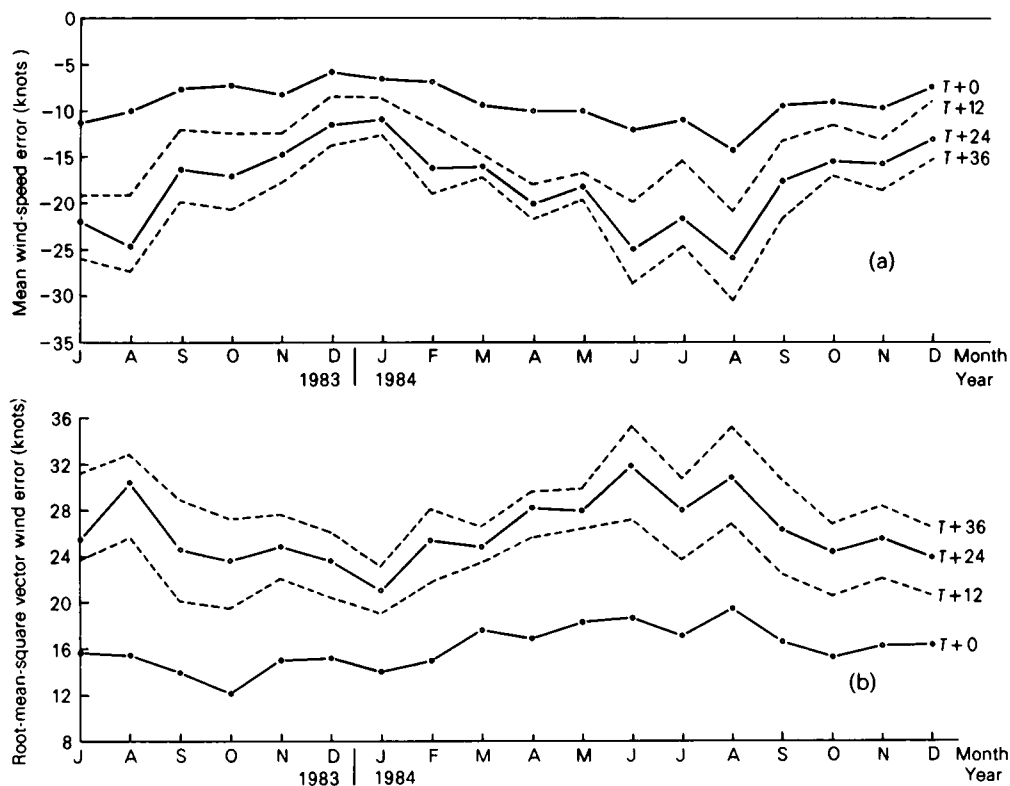


Figure 5. As Fig. 4 but for model maximum wind data verified only when observed value was greater than 90 kn. (a) Mean wind-speed error. (b) Root-mean-square vector wind error.

relatively few in number. However, recent modifications to the model designed to improve the handling of blocked and meridional synoptic patterns with which many of these jets are associated shows encouraging signs of success with January 1985 verifications of upper winds the lowest yet.

#### **6. A 6-hourly forecast cycle?**

Data assimilation in the global model is currently carried out on a 6-hourly cycle while forecasts are run only from the main upper-air observation times of 00 and 12 GMT. The large amount of asynoptic data within 3 hours of 06 and 18 GMT (e.g. aircraft reports and satellite temperature soundings) suggests that it might be profitable to make use of a 6-hourly cycle of forecast runs so that, for example, the 24-hour aviation forecasts from 00 and 12 GMT could be replaced by more accurate 18-hour forecasts from 06 and 18 GMT. This was tested during December 1983 when extra runs were made at 18 GMT and comparison of forecasts, both subjective and objective, carried out. The results have been discussed in detail by Hardman and Day (1984). In summary, while 12-hour forecasts from 00 GMT were clearly better than 24-hour forecasts from 12 GMT, the expectation that perhaps half of this improvement might be demonstrated with 18-hour forecasts from 18 GMT was not realized. Fig. 6 shows r.m.s. mean errors for wind and temperature data verified against radiosonde observations. A similar picture was gained in subjective comparisons of model forecast jet maxima (i.e. ignoring position errors) where, on balance, the 24-hour forecasts were marginally but not significantly superior. The reasons for this lack of improvement are not clear but probably relate to the differing ratios of data types and their assimilation using the current analysis system. It may well be that revised methods of assimilation could change the situation in the future.

#### **7. Flight planning data**

Aviation data are also supplied directly from the numerical model to the airlines in grid-point form using aviation digital code — a vertically stacked format. Full details are given in the paper by Francis (1985). Recipients include British Airways, Scandinavian Airlines System, Japan Air Lines, and SITA (Société Internationale de Télécommunications Aéronautiques) which represents a substantial group of airlines. These data are supplied on direct computer-to-computer links with no subjective input or formal amendment procedure.

#### **8. The role of the Principal Forecasting Office at London (Heathrow) Airport**

While CFO at Bracknell has assumed the role of an RAFC under the new system, Heathrow remains the Principal Forecasting Office in the network of UK civil aviation stations, with primary responsibilities for flights in and around the United Kingdom. Using data in grid-point form, directly transmitted to its OASYS computer, Heathrow provides a comprehensive service at national level for civil and general aviation. It is not the purpose of this article to describe in detail these activities. Examples cited below give brief indications of more specialized uses of 15-level model output. A primary task is the production of significant-weather and grid-point ('spot') wind and temperature charts for an area covering the United Kingdom, North Sea and near continent. The 'spot wind' chart is produced by subjective modification of direct computer output (Fig. 7) which provides considerable detail at lower levels. In contrast to higher-level forecast output using pressure altitudes, flight rules require information on this chart to be computed relative to a mean-sea-level datum. While freezing-level data may also be numerically produced, it has proved more effective to add this subjectively. Beneficial subjective amendment of winds at low level takes advantage of more recent surface observations.

Wind and temperature forecasts for Concorde operations are also based directly on NAT area model output, in this case for 150 and 100 mb. Before the advent of the 15-level model, the temperature forecasts for Concorde had been derived largely subjectively as significant model errors were found at these levels. The extension of model levels to around 30 mb provides a greatly improved product from the 15-level model (Atkins 1983) and it has proved possible to extend use of direct model output to the levels at which Concorde operates.

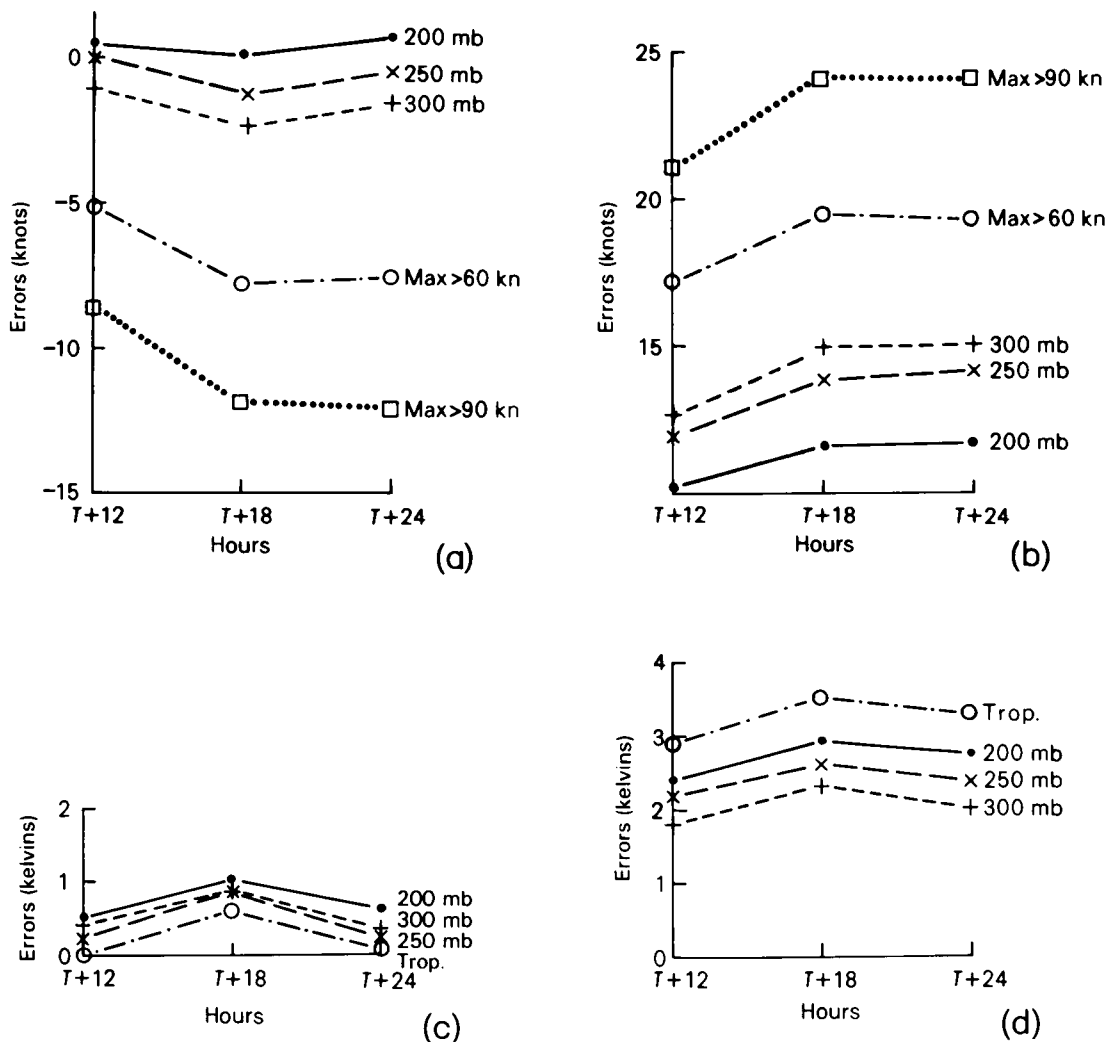
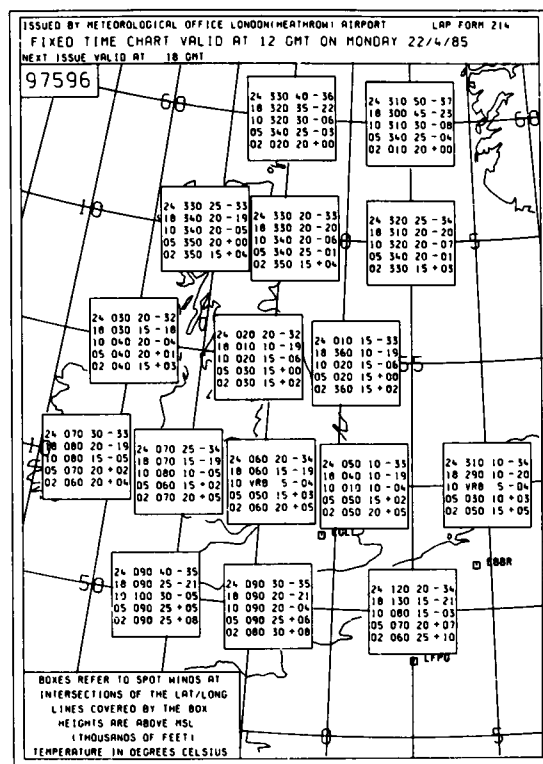


Figure 6. Assessment of forecasts based on 18 GMT data time, December 1983, as verified against radiosondes. (a) Mean wind-speed errors, including maximum-wind forecasts. (b) Root-mean-square wind-speed errors, including maximum-wind forecasts. (c) Mean temperature errors, including tropopause. (d) Root-mean-square temperature errors, including tropopause.



DT 00Z 22/4/85 T+12

Figure 7. Spot-winds chart as produced numerically. Temperatures and winds are represented at heights of 2000, 5000, 10 000, 18 000 and 24 000 feet above mean sea level.

## Acknowledgement

The assistance of Mr B. A. Hall in the analysis of data from the Jet Stream investigation is acknowledged.

## References

- |                               |      |  |
|-------------------------------|------|--|
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| Francis, P. E.                | 1985 | Output products of the Bracknell numerical weather prediction models. <i>Meteorol Mag</i> , <b>114</b> , 242-251.  |
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## Applications of wave and surge models

By J. J. Ephraums

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### Summary

Applications of numerical sea surface models range from the routing of cargo vessels across the North Pacific to predicting flooding by waves and surges along the east coast of England. In the former case, model output is one of the many tools available to the forecaster, whereas in the latter it is possible to send numerical output directly from the computer to the customer for rapid and reliable warnings. In this paper the operational applications and distribution of wave and surge model forecasts are briefly described. Of almost equal importance is the archive of wave model hindcast data which provides vital information to outside customers when measured data are unavailable in their area of interest. There are also many occasions when it is cost effective to hindcast historical storm events using reconstructed wind fields, and on some occasions the model may be judiciously used with idealized wind fields to simulate extreme wave conditions.

### 1. Applications using real-time operational data

#### (a) Introduction

Some of the operational characteristics of the wave and surge models have already been outlined in the companion paper by Francis (1985); in Table I are the details of the products at present available from the Meteorological Office computer system, COSMOS. The way in which the various real-time recipients of wave and surge model forecasts make use of these products is described below.

**Table I.** *Operational products from wave and surge models*

Model	Run time <i>minutes</i>	Output time GMT	Forecast quantities available	Output format
Fine-mesh wave model	4¼	0230 1430	Wind speed/direction Total wave height/period	Charts Grid code
Mediterranean wave model	2¼	0240 1440	Wind sea height/period Swell height/period/direction	Tables
Coarse-mesh wave model	4¼	0430 1630	(Wave spectra)	
Surge model	1¼	0240 1440	Tidal residuals (Currents)	Tables

Notes: Output quantities shown in brackets could be provided but are not produced operationally at the time of writing. The model run times include the hindcast run required for the forecast starting state.

#### (b) Offshore industry forecasts

Forecasts for the offshore industry in the North Sea are produced by a specialized team of forecasters at London Weather Centre (LWC). Because of the sensitive nature of most operations and the differing requirements of each customer it is necessary to provide a tailored service of forecasts with the option of direct and immediate contact between the operators and the forecast bench in rapidly changing weather.

The need for accurate wind and wave forecasts is paramount in all routine and one-off operations. As

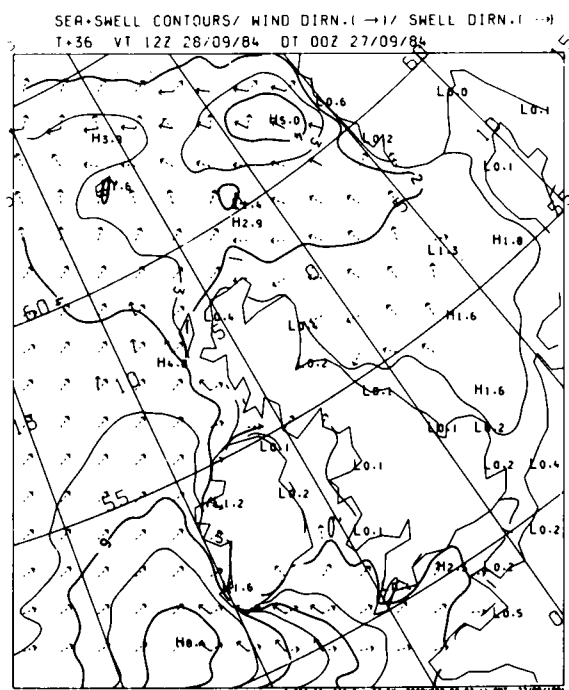


winds and waves increase it may become necessary to curtail drilling and to disconnect the riser pipe through which oil is pumped to production platforms. These processes take several hours to complete, and in the oil business every hour of idle time is costly. There are now guidelines for the evacuation of crews from accommodation platforms in extreme storms — early and accurate warning is essential to avoid disaster or unnecessary effort. In less severe weather there is a hidden danger when large barges are being used to transport and lift large loads to and from platforms. The presence of low-amplitude swell at the resonant frequency of the barge can cause pronounced oscillations which would be more than inconvenient in the middle of a lifting operation! Many of these towing and construction jobs have to be planned well in advance, so here it is the forecast of a wave and weather window of strictly defined limits which is required.

Although forecasts of visibility, precipitation and temperature, for instance, are all required by the offshore industry, the most important operating parameters are wind speed and wave activity.

Some numerical model data are transmitted to LWC via GRID code but the most popular format is a selection of high-resolution charts showing forecast fields of winds or waves. These are now transmitted from Bracknell in digital form to the Outstation Automation System (OASYS) computer where charts can be plotted locally, thus saving almost half-an-hour over the old analogue transmissions of facsimile charts. The wave charts cover the North Sea and coastal waters surrounding the British Isles (see Fig. 1), and are provided in contours of total sea or spot values of swell height and period.

Because the wave model analysis incorporates no measured wave data it is important that the forecaster is aware of the potential errors in the numerical product even at this stage, and this is possible to achieve by comparison with reports. However, these data themselves are subject to errors and



subjective bias, and their spatial distribution does not immediately favour a subjective analysis. In the forecast there may be errors in the forecast winds which the forecaster can anticipate; in these circumstances it may be necessary to perform a graphical wave forecast by hand to estimate the error in the model prediction.

The forecasters have built up a good knowledge of the present wave prediction model and are able to take into consideration all these problems to produce a forecast blended by a man-machine mix which surpasses the accuracy of either the man or the machine alone (Morris 1981). The accuracy of these tailored forecasts, together with the personal contact available through the Weather Centre or on location, places LWC in the premier position for forecasts to the offshore industry.

One forecast which we hope will never be required entails the supply of forecast surface winds to oil companies for use with the oil spill dispersion program SLIKFORCAST developed by the Continental Shelf Institute in Norway for predicting the drift and spread of oil slicks. These winds are extracted from the fine-mesh numerical weather prediction (NWP) model in the event of such as emergency, and sent to subscribers in the affected areas.

#### *(c) Shipping forecasts*

Forecasts for shipping take the form of general broadcasts via the media or dedicated routing advice through the Meteorological Office Ship Routing Service (Metroute) based in the Central Forecasting Office (CFO) (Mackie 1982). As the WMO Regional Meteorological Centre, CFO has the responsibility for transmitting wave analyses and forecasts for the north-eastern Atlantic area in the form of radio-facsimile charts. These are produced in CFO by forecasters who rely greatly on the output from the coarse-mesh wave model since real-time wave data from the open oceans are nearly all in the form of visual observations of sparse distribution.

As is the case at LWC the production of wave forecast charts for users is based on the combined talents of the model and the forecaster. The model is able to produce an excellent basic forecast to which the forecaster is able to add extra detail and information based on his assessment of the NWP model forecast winds and the actual wave conditions at the time. Fig. 2 shows an example of the wave model output available to forecasters from which the transmitted chart shown below it was produced.

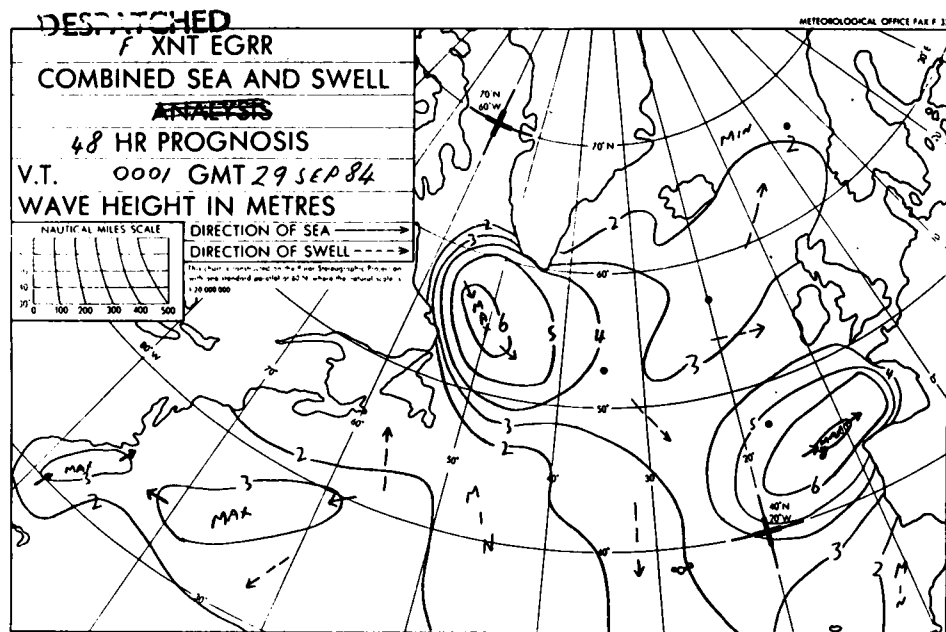
These forecast charts are handed to the Ship Routing bench whose job it is to select the most favourable route for individual ships given the predicted conditions of the sea. Although the calculation of least-time routes has traditionally been by manual techniques, there is now a numerical program being tested which uses the wave model forecasts directly to arrive at a detailed route; again this facility is designed to produce speedy and reliable guidance to the forecasters who will modify the product to the best advantage.

Note that although wave forecasts for the Atlantic are produced by CFO forecasters for Metroute there are no specific forecast charts compiled manually for the North Pacific. In this case the Ship Routing bench must use the unmodified wave model predictions for this area, but nevertheless the model is found to be reliable and accurate.

The numerical surge prediction model has applications in shipping and navigation, through its ability to forecast negative surges at ports. Warnings of particularly low tides due to this effect are sent by the Storm Tide Warning Service (STWS) to Port Meteorological Offices and to the Navy's Radio Navigational Warnings Unit for relaying to coastal radio stations which broadcast to shipping.

#### *(d) Flood warning forecasts*

Much of the British coastline in winter is under threat of flooding owing to storm tides or high waves, and this is especially so in the low-lying regions of the east coast of England. The most notable storm



**Figure 2.** The production of North Atlantic wave forecast charts. The upper chart shows the model guidance and the lower chart is the forecaster's final product. Note that he has enhanced the high waves in the Biscay area.

surge in recent times was the disastrous flood on the night of 31 January 1953 when 300 people drowned and London experienced its last major flood (Grieve 1959). On 13 February 1979, with no imminent large tides and no severe weather present, Portland Isle was severely damaged by exceptionally high swell waves originating from an Atlantic storm several days earlier (Draper and Bownass 1983). Both these events prompted the formation of separate services to warn of such occurrences. In the first case, numerical models were not available for guidance until 1978, but in the second there was already an operational model in use which could be used immediately for warnings of such events after it had been shown that the model was capable of predicting the arrival of distant swell as well as local wind-sea (Golding 1981).

For the prediction of storm surges the STWS uses output from the storm surge prediction model presented in the format of a table of hourly residuals for specific ports (Fig. 3 (upper)). They also have at their command instantaneous readings from the tide recorders situated at 11 ports, empirical prediction techniques using a microcomputer, and up-to-the-minute guidance from CFO.

The model is relied on for prompt and detailed guidance for many locations, but since it lacks the inclusion of measured tidal data it is also necessary for the STWS staff to use the empirical equations

STORM SURGE FORECAST. RESIDUAL ELEVATIONS IN METRES. DATA STARTS AT 0 HRS GMT 27/ 9/1984															
GMT	1687 NLYN	1513 ILFR	1471 AVON	1467 MILF	1380 FISH	1293 BARN	1248 HOLY	1207 HILB	1119 HEYS	1074 WORK	1608 PMTH	1604 PLND	1645 PLYM	1610 NWHN	1524 OVER
0	.02	.02	.03	.04	.04	.06	.06	.05	.06	.05	.01	.02	.02	.01	.01
100	.01	.05L	.01	.05L	.04	.06	.06	.06	.06	.06	.01	.01L	.01L	.01	.01H
200	.01	.03	.01	.04	.04	.03	.06	.05	.06	.07	.01	.01	.02	.01	.00
300	-.01	.02	.02L	.05	.05L	.05	.06	.05	.06	.08	.01	.02	.01	.00	-.01
400	.02	.04	.03	.04	.06	.07	.08	.06	.07	.09	.01	.01	-.01	.00	-.02
500	.04	.02	.03	.06	.08	.08L	.10L	.08	.08	.09	.01	-.01	.03	.00	-.03
600	.05H	.07	.03	.09	.09	.10	.10	.09	.10	.10	-.01L	.01	.04	-.01L	-.04
700	.04	.10H	.05	.12H	.11	.12	.12	.11L	.11L	.11L	-.02	.02	.03H	-.02	-.03
800	.05	.12	.09	.12	.13	.12	.13	.11	.12	.13	.01	.03H	.04	-.02	-.03L
900	.06	.11	.13H	.12	.12H	.14H	.14	.12	.13	.14	-.02	.03	.04	-.02	-.04
1000	.06	.09	.13	.12	.14	.15	.15	.12	.14	.16	-.01	.04	.06	-.02	-.04
1100	.09	.11	.11	.14	.14	.15	.17H	.14	.15	.16	.01H	.05	.07	-.01	-.04
1200	.09L	.13	.09	.14	.15	.18	.18	.15H	.16H	.18	.01	.06	.08	-.01	-.05

FOR TRANSMISSION TO SOUTHERN WATER AUTHORITY VIA MET.0.5

PAGE 1

INITIAL DATA TIME 02 27/ 9/84

LOCATION 50.6N 0.8E

HOURS AFTER DATA TIME	WIND SPEED KTS	WIND DIRECTION DEG(FROM)	TOTAL HEIGHT M	WAVES PERIOD SECS	WIND HEIGHT M	SEA PERIOD SECS	SWELL HEIGHT M	SWELL PERIOD SECS	DIRECTION DEG(FROM)
0.0	4.7	159.	0.5	4.9	0.0	0.0	0.5	4.9	244.
3.0	8.5	198.	0.5	4.3	0.0	0.0	0.5	4.3	234.
6.0	7.9	189.	0.5	4.0	0.4	3.2	0.4	5.8	252.
9.0	5.4	189.	0.4	5.2	0.0	0.0	0.4	5.2	249.
12.0	5.6	185.	0.5	5.1	0.0	0.0	0.5	5.1	245.
15.0	13.3	187.	0.8	3.9	0.6	3.2	0.5	5.6	242.
18.0	11.9	177.	0.9	4.0	0.7	3.6	0.5	7.1	256.
21.0	11.6	182.	0.9	4.1	0.7	3.6	0.5	6.9	256.
24.0	12.7	193.	1.0	4.2	0.8	3.7	0.5	6.9	255.
27.0	11.2	185.	0.9	4.1	0.8	3.7	0.5	7.2	250.
30.0	9.5	174.	1.0	4.3	0.7	3.5	0.7	6.4	237.
33.0	8.4	181.	1.0	4.6	0.6	3.3	0.8	5.9	239.
36.0	13.1	175.	1.1	4.5	0.8	3.7	0.7	7.5	250.

Figure 3. Forecasts for flood warning. The upper print-out shows hourly forecast data from the surge model reference port points. High (H) and low (L) water times are marked for convenience. The lower print-out shows 3-hourly forecast data from the fine-mesh wave model for a point in the Channel.

developed during the years before models were generally available. These equations are based on the behaviour of some 200 historical surges, the most common of which travel southwards along the eastern coast, growing or decaying according to the local winds. Their strength is in the use of real-time measured tidal data from northern ports, and the ease with which they can be recomputed with updated wind forecasts during rapidly changing situations when the model may contain timing errors. The forecasters also consider physical processes not included in the model, in particular the effect known as set-up which is the raising of the water level at a beach subjected to large breaking waves. This mechanism can sometimes account for an extra metre in the recorded level. More details of the work of the STWS can be found in Townsend (1981).

Warnings of storm surges are sent to the police authorities in the affected areas who are then responsible for alerting the local flood organization and issuing public warnings. A special arrangement exists with the controllers of the Thames Barrier who receive advice on whether water levels in the Thames estuary will require the barrier to be raised. They also have access to unmodified surge model data, and fine-mesh NWP model wind and pressure forecasts via a computer-to-computer link so that they can run their own limited-area surge model which is being currently developed.

The warnings of wave-induced flooding are distributed by another means since it is believed that the fine-mesh wave model is capable of predicting with accuracy the near-shore values of waves and swell without the requirement for manual intervention. Tables of 3-hourly wind, wave and swell forecasts up to  $T+36$  are printed out by the computer for selected locations and these are sent immediately by document-facsimile (DOCFAX) to subscribers, notably water authorities on the east, south and north-west coasts (see Fig. 3(b) for example). Although the fine-mesh wave model is a shallow-water model it was not designed for use in coastal regions where small-scale processes such as tides and local refraction can dominate. It is therefore surprising and encouraging that verification of the model against measured data in several coastal positions has revealed an impressive accuracy in the magnitude and timing of high-wave events (Francis 1985). The importance of good timing is crucial since the relative occurrence of high waves and tide may dictate whether flooding occurs or not.

## 2. Applications using archived operational data

### (a) *Introduction*

Diagnoses of state of sea produced every 12 hours by the operational wave-model hindcast cycle have been archived operationally since 1977 (see Table II) and will be kept permanently both for internal use in verification and development work and for access by external customers. Some of the applications of this archive are described below.

**Table II.** *Details of the Meteorological Office wave model archive*

Period	Data time GMT	Models	Archive form
Dec. 1977–Sept. 1982	00, 12	Fine-mesh	Grid-point wave spectra
		Coarse-mesh	Grid-point wave spectra
Feb. 1983–present date	00, 12	Fine-mesh	Grid-point wave spectra
		Mediterranean	Grid-point wave heights, etc.
		Coarse-mesh	Grid-point wave heights, etc.

Notes: The integrated quantities of wave height etc. can be derived from the wave spectra by the archive extraction programs. The archive prior to September 1982 comprises the lower-resolution models run from the 10-level models on the IBM computer at that time.

(b) *Wave energy research*

In the late 1970s and until fairly recently there was an enormous interest in the potential use of wave power as an alternative energy source. During this time the requirements for reliable wave data around the British coast proved the necessity of maintaining a permanent archive of wave-model hindcast fields for use when measured data were absent from the sites of investigation.

In 1981 a detailed joint study by the Meteorological Office, the Institute of Oceanographic Sciences and the Hydraulics Research Station compared the performances of the Meteorological Office wave model and the NORSWAM wave model against measured data during March 1980 (Ewing *et al.* 1981). It was found that both models (which used identical forcing winds and boundary conditions supplied by the Meteorological Office) produced accurate hindcasts of wave height and power, thus justifying their use to estimate wave power levels for design purposes. Winter (1980) found that the archive data from the Meteorological Office model agreed with measured wave data from Ocean Weather Ship 'I' to give an agreement of mean wave power levels to within 6%. He then proceeded to use the model archive, on the basis of this verification, to estimate the mean power levels for various locations round the west and north of the British Isles. Mollison (1980, 1982) performed a similar exercise and found that the wave model archive could be confidently used to map the wave power resource off the Irish coast.

The success of the wave model in providing an accurate climatology of wave power lies in its strength at modelling the frequently occurring medium-height waves which contribute most to the mean wave power. Errors in the frequently occurring but insignificant low waves, and the infrequent large waves, do not have an impact on this quantity.

(c) *Design studies*

The fine-mesh wave model archive data base covering the continental shelf over a period of 7 years is often the only alternative to conventional data bases of measured or observed data when trying to construct a wave climatology. Reliable measurements of waves have been made at only a handful of locations, and even then for a limited time-span which is usually less than that required to extract useful information. For many customers there is insufficient time to start wave measuring programs when the results are required immediately for the design or development of a new or existing platform at a given location. As well as being a complete source of data in itself the model archive is frequently used to fill in missing data gaps when wave recorders have been out of operation.

The ability of the model to reproduce the wave climate at a given site has been shown by Houghton (1984) who verified some early wave-model data against measurements and found little bias in the mean errors of wave height. It is therefore possible to use wave-model archive data for determining some climatological wave values on which to base design criteria for offshore structures.

(d) *Environmental studies*

In a similar manner the wave-model archive has been used as a substitute for measured data in environmental studies and, in particular, near-shore data from the model have been used in projects to calculate coastal erosion and beach sediment transport rates.

(e) *First-order verification of remote-sensing data*

With the rapid proliferation of remote-sensing devices and projects there is a growing need for ground-truth data against which to validate the various devices, whether they are ground or satellite based. At the University of Birmingham there is a group developing a ground-based radar which is capable of measuring the ocean-wave spectra over an area of several hundreds of square kilometres.

As well as deploying waverider buoys they have used archived wave spectra and wind data from the fine-mesh model as a first-order approximation on which to base their verification.

Satellite-based measuring devices, such as synthetic-aperture radars, altimeters and scatterometers, require the same information for verification. By the nature of their operation it is necessary to have reference data available for a very large area so that results from each separate pass can be used. A mission of the Space Shuttle in October 1984 deployed synthetic-aperture radar to image the sea surface, and several ground tracks covered the southern waters of the British Isles. The Meteorological Office contributed archived model wave and wind data to a joint wave measuring program co-ordinated by the Institute of Oceanographic Sciences.

Active participation in remote-sensing experiments such as these is becoming more important if we are to fully realize the benefits of state of sea measurements which will be produced in real time by such vehicles as the European Space Agency Earth Resource Satellite (ERS-1) which is due to be launched in 1989.

#### *(f) Insurance enquiries*

Another occasional use of the wave-model archive is in instances of loss or damage to ships or their cargo caused by severe waves. In some cases the insurance enquiry may request an independent estimate of sea conditions to uphold a claim by the insured party. In the absence of neighbouring ships against which to corroborate reports it has been necessary in the past to refer to archive data from the Meteorological Office wave model.

### **3. Applications using non-operational models**

#### *(a) Introduction*

The powerful computational facilities of the Meteorological Office are ideally suited to running non-operational wave models for hindcasts or experiments. There is usually no shortage of synoptic data from which wind fields may be derived. Wave models may be run with these winds to produce a reasonable alternative to traditional forms of measured or observed wave data which are in scarce supply. Some of the uses of non-operational models are mentioned below.

#### *(b) Hindcast studies*

There are many requirements for high-quality wave data which require a data time-span greater than that covered by the model archive. A case in point is the derivation of 50-year return values of maximum waves or, more generally, the qualification of wave climate severity. For these applications it has been necessary in the past to use the model to hindcast waves for specific historical extreme storm events using reconstructed wind fields.

A good example of this type of project is a hindcast of 17 North Sea storms by the Meteorological Office wave model which was commissioned by the United Kingdom Offshore Operators' Association and completed in 1980. The wind fields for these storms were painstakingly re-created by hand from synoptic charts (Harding and Binding 1978) and used as input to the wave model in order to see how effective it would be at simulating the maximum wave conditions in past severe storms. One of the problems in this sort of study is how to judge the model's performance — the very fact that the exercise was required stemmed from the shortage of reliable measured data!

Such hindcast studies are useful for our own needs in research and development of the model formulation. Recent work has been done to look at the model's accuracy in shallow water using two storms from November 1981 for which the winds could be re-created and good measured spectral data

could be obtained. As an extra source of information we exchanged the wind data with the Royal Netherlands Meteorological Institute and the Max-Planck Institute in Hamburg so that they could run their models in parallel for comparison (Bouws *et al.* 1985).

Similar hindcast experiments using the storm surge prediction model based on grid areas of different resolutions have been performed by the Institute of Oceanographic Sciences who are responsible for its scientific development (Flather 1981).

#### (c) *Artificial idealized experiments*

One advantage that wave prediction models have over atmospheric models is that they are dependent on the input of forcing fields and not completely dependent on the initial state. Operationally this is of course a nuisance — there is a constant need for better and more detailed wind fields, and considerable uncertainty in the validity of the starting analysis. When it comes to examining the model physics, however, this is a welcome property for much information can be gained by discarding the complicated varying structure of synoptic wind fields and adopting idealized wind patterns instead. Models can be retained on their geographical grids, reduced to one-dimensional arrays for fetch-limited studies or even pared to a single point.

In the first case, for which there has been a commercial application, the fine-mesh model was used to estimate the maximum possible wave height at locations in the North Sea by specifying values of constant wind from different directions. The advantage of this technique is its simplicity and cheapness in providing spatial variations in extreme waves due to geographical and sea-bottom effects only. The disadvantage is that it is not so easy to relate the artificial results to real-life storms and their probability of occurrence.

The more idealized cases involving simple grids have been much used by wave modellers to compare their scientific assumptions in the parametrization of the poorly understood processes. The SWAMP experiment was the first such large-scale use of this idea. Ten wave models were run under identical simple wind geometries to highlight the different physical mechanisms (Allender *et al.* 1982, 1984). The same concept was employed for shallow-water wave models to specifically isolate the depth dependency in each (Bouws *et al.* 1984). In all cases it has been found that the differences of behaviour of each model are much more apparent than in their results from real situations.

## 4. Conclusions

It has been shown how operational wave and surge model data can be used, both in real-time forecasting and in applications using the operational archive of hindcasts. These models can also be run with non-operational wind fields to produce reconstructions of historical events or to simulate extreme situations. In all cases the model is a reliable substitute for measured wave data which is in very poor supply, and it provides detailed forecasts which would be unobtainable through traditional manual prediction techniques within the tight schedule of a forecaster's timetable.

There is no doubt that wave and surge models now form an integral part of the forecast and consultancy service provided by the Meteorological Office.



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