CURRENT PROBLEMS IN MEDIUM RANGE FORECASTING AT ECMWF: MODEL ASPECTS

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Abstract

Some characteristic model errors revealed by two years of operational forecasting are described. Systematic mean errors are presented, and a brief discussion of errors in the treatment of transient mid-latitudinal disturbances is also given. The performance of the model for the Tropics is mentioned. Some particular questions relating to numerical techniques, resolution and parameterizations are also discussed.

1. INTRODUCTION

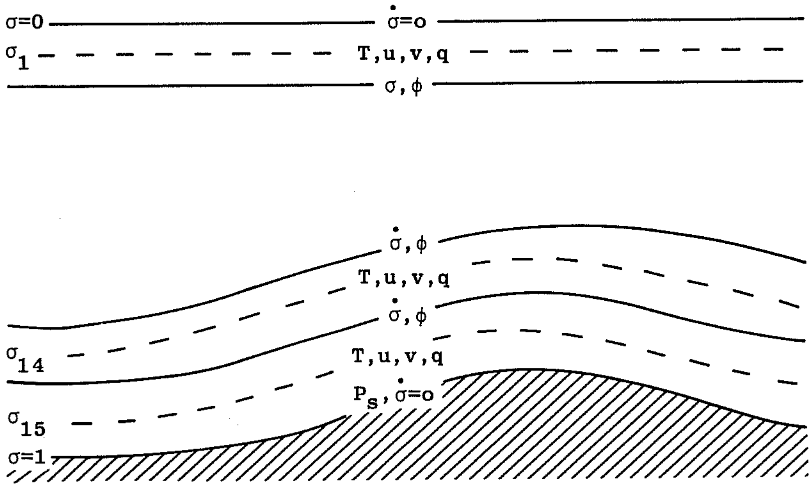
In this contribution we discuss some of the problems in atmospheric modelling of particular current relevance for medium-range weather prediction at ECMWF. The material presented here may be generally divided into two inter-related parts. The first comprises a presentation of some of the systematic deficiencies of the ECMWF forecasting model that have been revealed over the first two years of its operational implementation. The second concerns some of the unanswered questions which have arisen either from the results of research experiments or in the planning of future work.

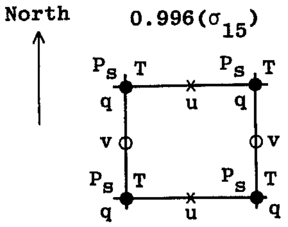
An outline of the operational forecast model is given in Fig. 1. The model uses a finite-difference scheme based on a staggered grid of variables known as the C-grid (Arakawa and Lamb, 1977). Choice of this grid was made mainly because of its low computational noise and the ease of implementation of a semi-implicit time scheme. Following the work of Arakawa (1966) and Sadourny (1975), the finite difference scheme was designed to conserve potential enstrophy during vorticity advection by the horizontal flow. Further detail has been given by Burridge and Haseler (1977), and Burridge (1979).

CHARACTERISTICS OF THE ECMWF OPERATIONAL GLOBAL GRID POINT MODEL AS AT AUGUST 1981

SIGMA LEVELS

0.025 (σ_s)
0.077
0.132
0.193
0.260
0.334
0.415
0.500
0.589
0.678
0.765
0.845
0.914
0.967
0.996(σ_{15})





Vertical and horizontal (latitude-longitude) grids and dispositions of variables in the ECMWF grid-point model. Vertical coordinate: $\sigma = p/p_s$

Independent variables	λ, φ, ϕ, t
Dependent variables	T, u, v, q, p_s
Grid	Staggered in the horizontal (Arakawa C-grid). Uniform horizontal (regular lat/lon). Resolution: $\Delta\lambda = \Delta\phi = 1.875$ degrees lat/lon. Non-uniform vertical spacing of the 15 levels (see above).
Finite difference scheme	Second order accuracy.
Time-integration	Leapfrog, semi-implicit (Δt = 15 min) (time filter $\nu = 0.05$)
Horizontal diffusion	Linear, fourth order (diffusion coefficient = 4.10^{15})
Earth surface	Albedo, roughness, soil moisture, snow and ice specified geographically. Albedo, soil moisture and snow time dependent.
Orography	Averaged from high resolution data set.
Vertical boundary conditions	$\dot{\sigma} = 0$ at $p = p_s$ and $p = 0$.
Physical parameterisation	(i) Boundary eddy fluxes dependent on roughness length and local stability (Monin Obukov) (ii) Free-atmosphere turbulent fluxes dependent on mixing length and Richardson number (iii) Kuo convection scheme (iv) Full interaction between radiation and clouds (v) Full hydrological cycle (vi) Computed land temperature, no diurnal cycle (vii) Climatological sea-surface temperature

Fig. 1

Vertical and horizontal resolutions were selected, within overall computational constraints, to provide a reasonable description of the fundamental large-scale instabilities, some representation of the stratosphere, and an explicit boundary-layer structure. The related parameterization scheme (Tiedtke et al, 1979) describes the interactions thought to be of importance in the medium range, including a full hydrological cycle, a relatively detailed stability-dependent representation of boundary and free-atmospheric turbulent fluxes, and an interaction between the radiation and model-generated clouds.

2. SYSTEMATIC MEAN ERRORS

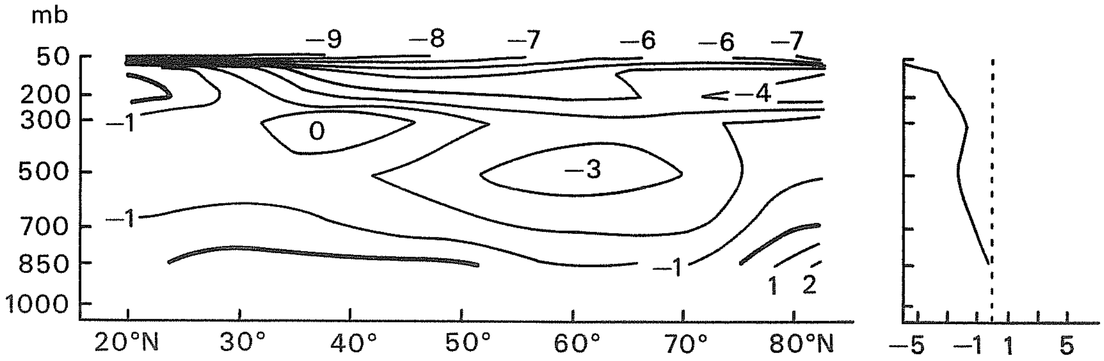
An important part of the total model error is revealed by averaging forecast errors over a number of cases. These "systematic errors" have been calculated routinely using, for convenience, monthly means. They characteristically grow in amplitude throughout the forecast period, and their general similarity towards the end of this period to errors in the model climatology revealed by integration over extended periods indicates that these errors represent a gradual drift from the climate of the atmosphere towards that of the model. The rate of this drift is found to vary from case to case, but the overall error associated with it appears to be independent of the initial data.

The importance of this climatological component of the forecasts was recognized by Miyakoda et al (1972) in their early series of medium-range forecasts. Two particular errors noted by them were a general cooling of the troposphere, and too low values of the 500 mb height, and to a lesser extent the 1000 mb height, over the North-Eastern Pacific and Atlantic Oceans. Similar, though larger, height errors were found in a trial series of forecasts using February cases carried out at ECMWF by Hollingsworth et al (1980). These authors also estimated that correction of model deficiencies leading to this systematic error might directly lead to an increase of some 20% in objective estimates of the period of useful predictability. Related improvements in transient features might also be expected.

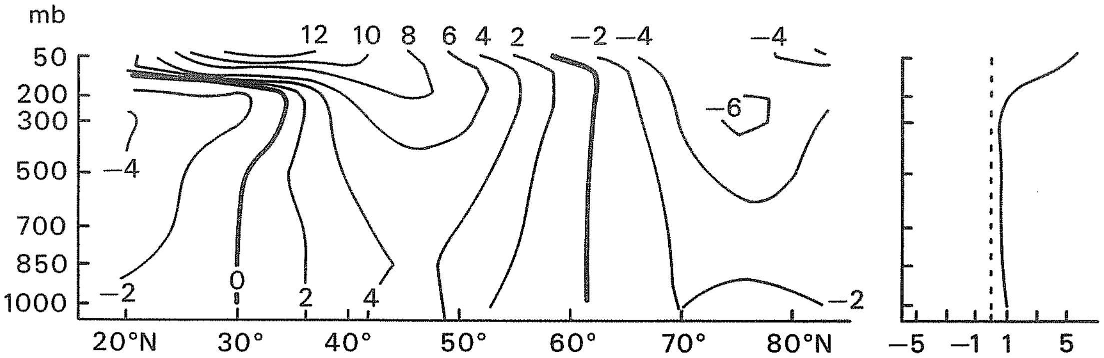
Operational experience has essentially confirmed the findings of Hollingsworth et al. We here restrict attention to the extratropical Northern Hemisphere, and present systematic temperature and height errors towards the end of the forecast period for January 1981. This month was characterized by a persistent, relatively strong circulation, and the systematic error was particularly large.

Meridional cross-sections of errors in the zonal-mean temperature and zonal-mean zonal geostrophic wind, averaged from day 7 to day 10 of the forecasts, are shown in Fig. 2. An overall cooling of the troposphere, by a maximum of 3K at 60°N and 500 mb is evident. The stratosphere was cooled by a substantially larger amount during this month, although this particular error has subsequently been reduced by ensuring an initial pressure-to-sigma interpolation of temperature which is more consistent with the formulation of the model's radiative parameterization. The tropospheric cooling shows little latitudinal variation below 500 mb, and consistent with this the zonal-mean wind error is largely independent of height in this region. The model surface flow is generally stronger than in reality. At upper levels the zonal-mean subtropical jet is displaced poleward, and its strength decreases less rapidly with height than is observed in the stratosphere.

The zonal-mean temperature shows little error at 850 mb, but this disguises a substantially larger error which is revealed by study of the geographical distribution of temperature. Maps of the day 10 temperature error at 500 and 850 mb, and of the 500 and 1000 mb height error, are presented as Fig. 3. Looking first at the height field we see very similar error patterns at 1000 and 500 mb, with distinct centres of low pressure over the North-Eastern

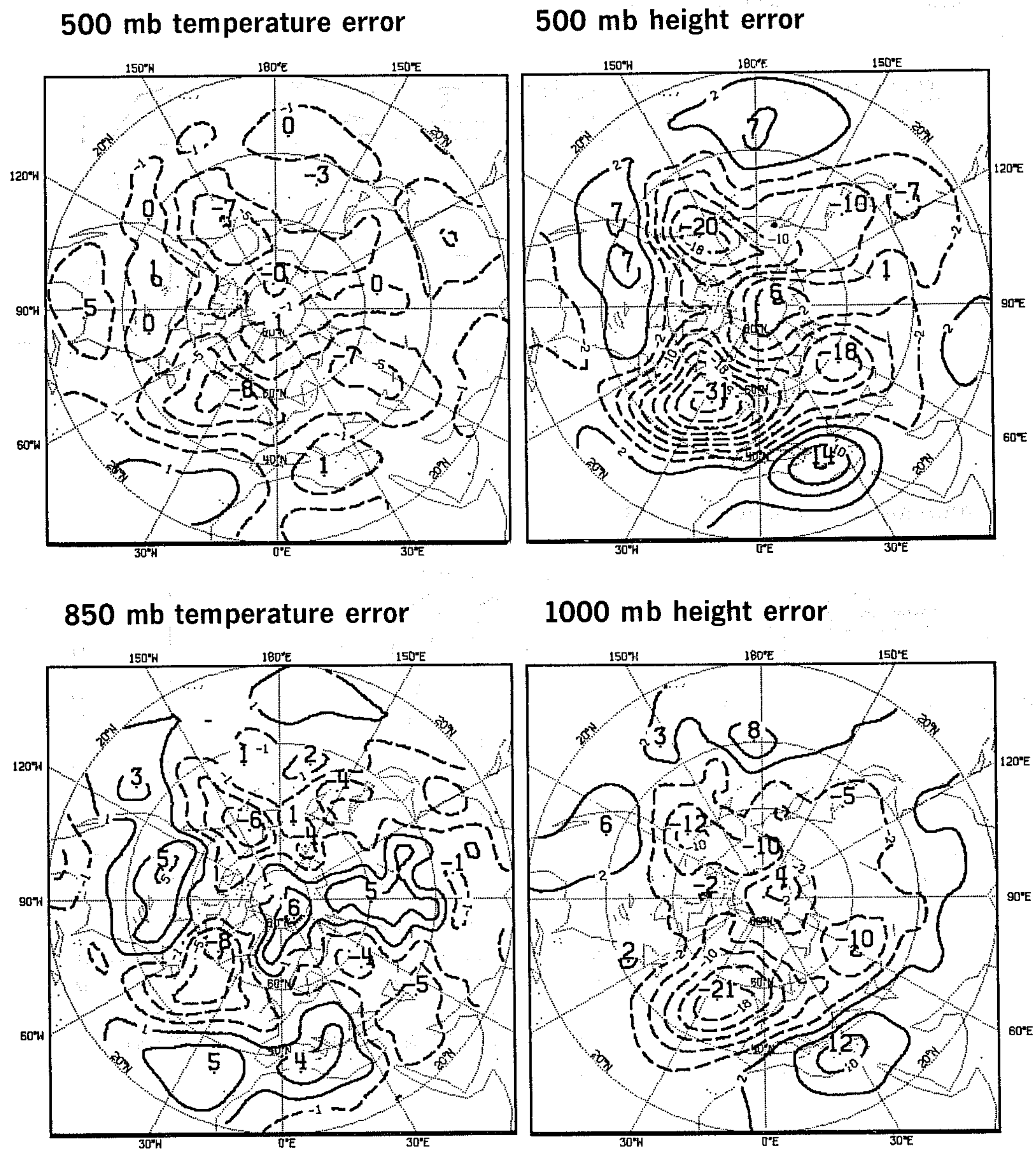


Zonal-mean temperature error



Zonal-mean zonal wind error

Fig. 2 Meridional cross-sections of zonal-mean temperature error (K) and zonal wind error (ms^{-1}) for the Northern Hemisphere calculated as averages from day 7 to day 10 of all forecasts from January 1981. Vertical profiles of the error averaged from 20^{O}N to 82.5^{O}N are shown in the right-hand plots.



500 mb temperature error

500 mb height error

850 mb temperature error

1000 mb height error

Fig. 3 Monthly-mean error maps for day 10 forecasts of temperature at 500 mb (upper left) and 850 mb (lower left), and height of the 500 mb (upper right) and 1000 mb (lower right) pressure surfaces for January 1981. Contour intervals are 2K and 4dam.

Atlantic and Pacific Oceans, and a third centre at 60°E. The amplitude of the error increases with height, and consistent with this, areas of too low temperature tend to coincide with the areas of too low pressure, particularly at 500 mb. Elsewhere the 500 mb temperature error is small, but regions of substantially too warm 850 mb temperature are evident over North America, Siberia and Southern Europe. The temperature error over the latter region is atypical, but warm 850 mb temperatures over the other two areas occur commonly, and become even more pronounced over longer periods of integration. The general distribution of temperature error implies areas of quite erroneous static stability, and a serious impact on transient wave behaviour seems likely. At 850 mb the error may be related to the erroneous horizontal advection implied by the error in the height field.

The error map of the 1000 mb height field shown in Fig. 3 corresponds to erroneously deep Aleutian and Icelandic surface lows. The phase change with height of the atmospheric standing wave pattern is, however, such that the negative centres at 500 mb correspond to an underestimate of the climatological ridges which occur in reality over the North-Eastern Atlantic and Pacific. The model thus exhibits a tendency to predict a too-zonal time-mean flow at upper levels (Fig. 4). Over Europe this is seen in a southward displacement of the jet stream, associated with which is a synoptically-important southward displacement of cyclone tracks.

Examining maps corresponding to that shown in Fig. 3 shows the detailed pattern to vary from month to month, but centres of erroneously low pressure are almost invariably seen over the two ocean regions during the winter months. Maxima are generally less than the 31 dam illustrated for January 1981, but typically reach vaues around 20 dam at 500 mb. Error patterns appear more variable in summer and amplitudes are some 50% lower. 500 mb error maxima greater than 20 dam, and a general weakening of the monthly-mean

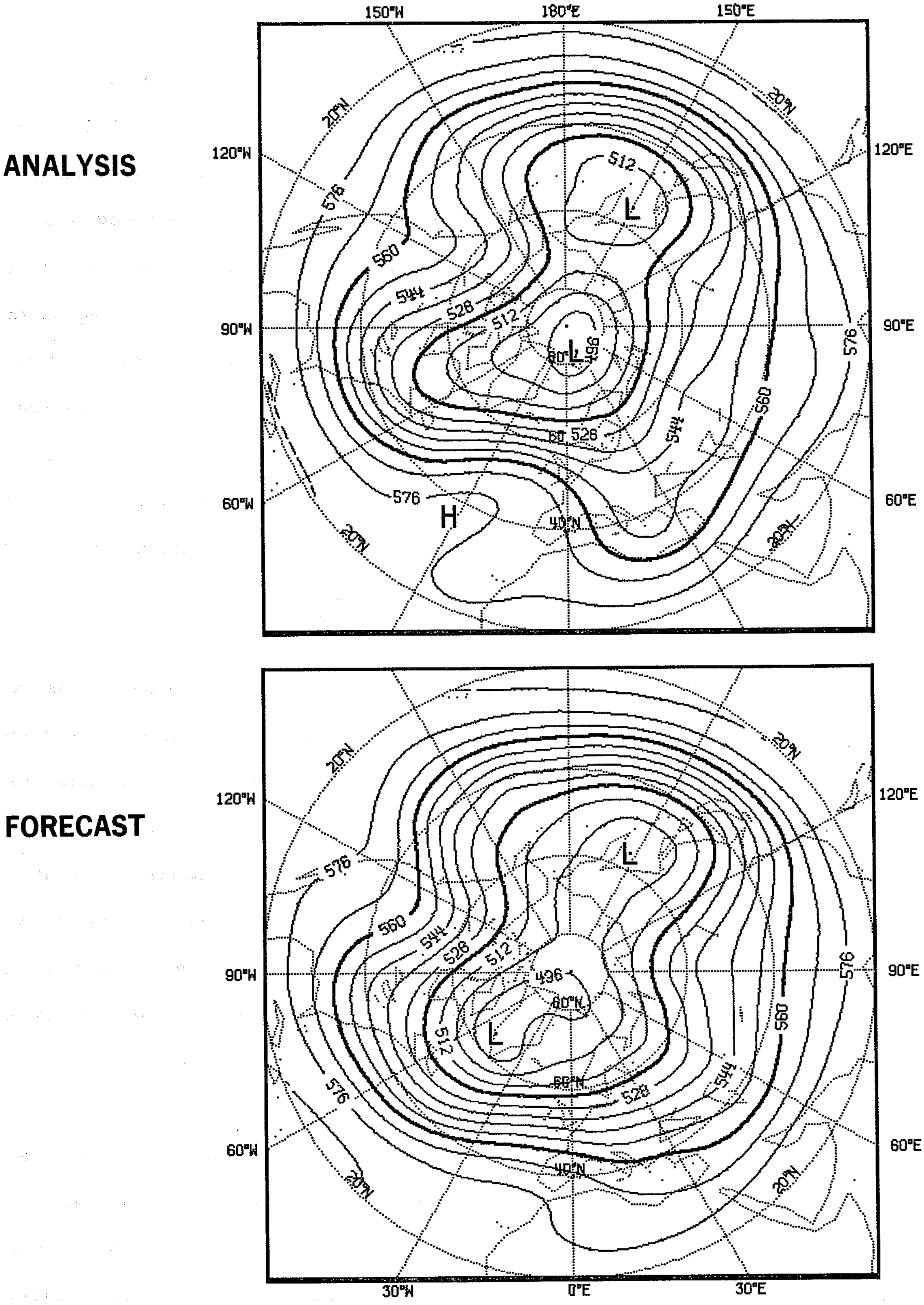


Fig. 4 Monthly-mean 500 mb height maps for the period 11 January to 10 February 1981. The upper map shows the mean of analyses and the lower map the mean of the day 10 forecasts verifying in this period. The contour interval is 8 dam.

standing wave pattern, may also be seen in day 10 forecasts for the Southern Hemisphere.

There are other points of interest concerning the systematic height error. In its equivalent-barotropic structure and location of amplitude maxima it tends to resemble actual anomalies of the atmospheric circulation such as discussed by Wallace and Gutzler (1981). In many respects it is by no means unique to the forecast model discussed here (Bengtsson and Lange, 1981, Wallace and Woessner, 1982), and experience at ECMWF confirms that of Manabe et al (1979) who found this error to increase with increasing horizontal resolution in climate simulations. Solution of this particular model problem is thus of importance both for medium-range prediction and for the numerical simulation of climate. Some sensitivity of the error to the parameterization of turbulent fluxes has been found, and further investigations are being actively pursued. (Recent diagnosis by J.M.Wallace has shown that the pattern of the mean short-range forecast error is apparently closely linked to the distribution of orography.)

3. ERRORS IN THE FORECAST OF TRANSIENT MID-LATITUDE DISTURBANCES

A substantial amount of information concerning the treatment of transient mid-latitude disturbances by the ECMWF forecasting system is contained in the synoptic assessments received from Member States. It is not within the scope of this paper to review these, but reference may be made to a forthcoming article in the Centre's Meteorological Bulletin series, No.2.1/1. Here, by way of example, we use anomaly correlations of height averaged over the extratropical Northern Hemisphere for the forecasts of May 1981, to select examples of relatively good and bad forecasts at days 4 and 7. Figure 5 presents maps of the 1000 mb height field for the 4-day forecasts from 12th and 19th May, together with the verifying analyses. Corresponding 7-day forecasts for 500 mb are shown in Fig. 6. The forecast from the 12th is, according to our chosen objective measure, the best of the month at both day

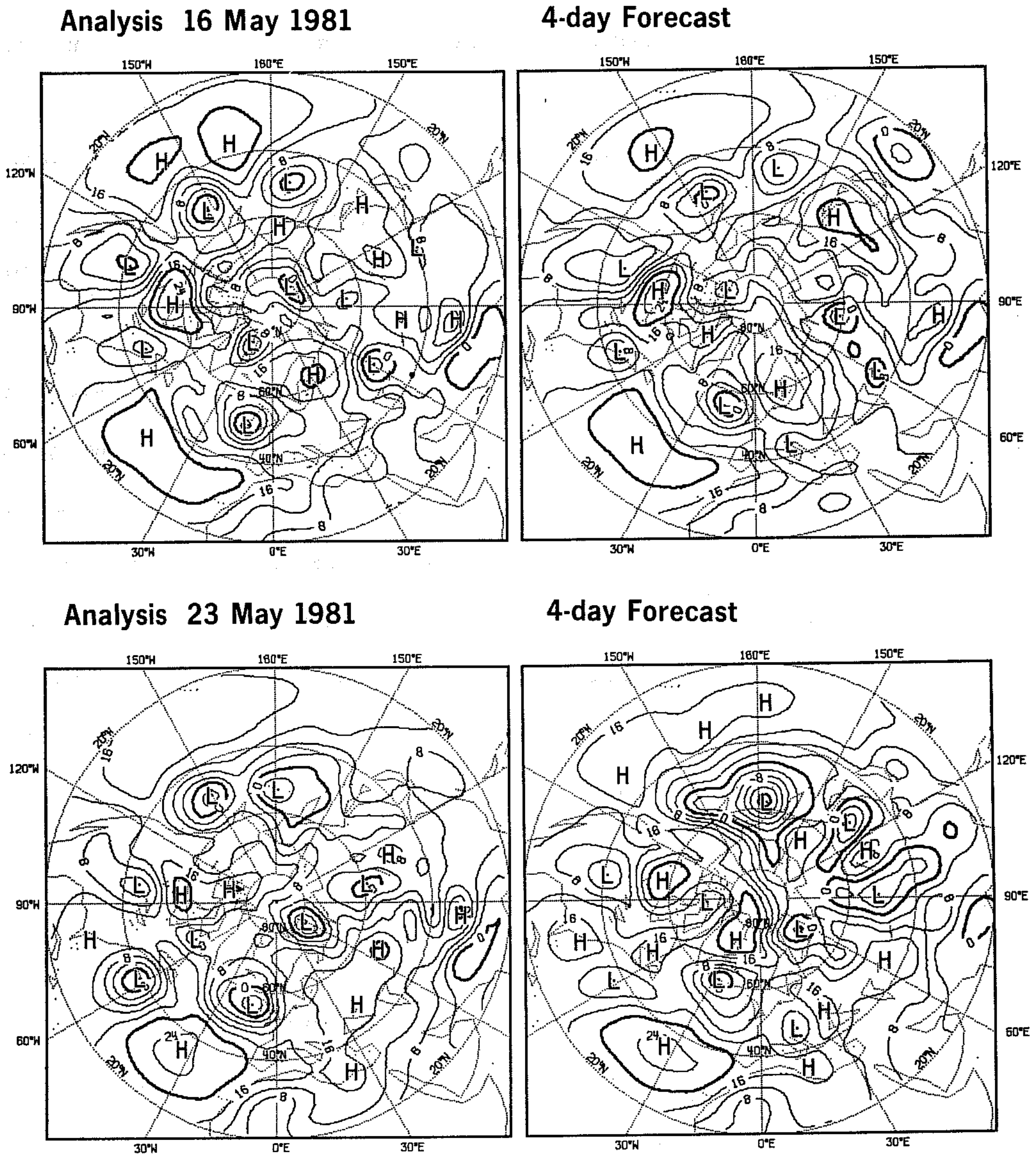
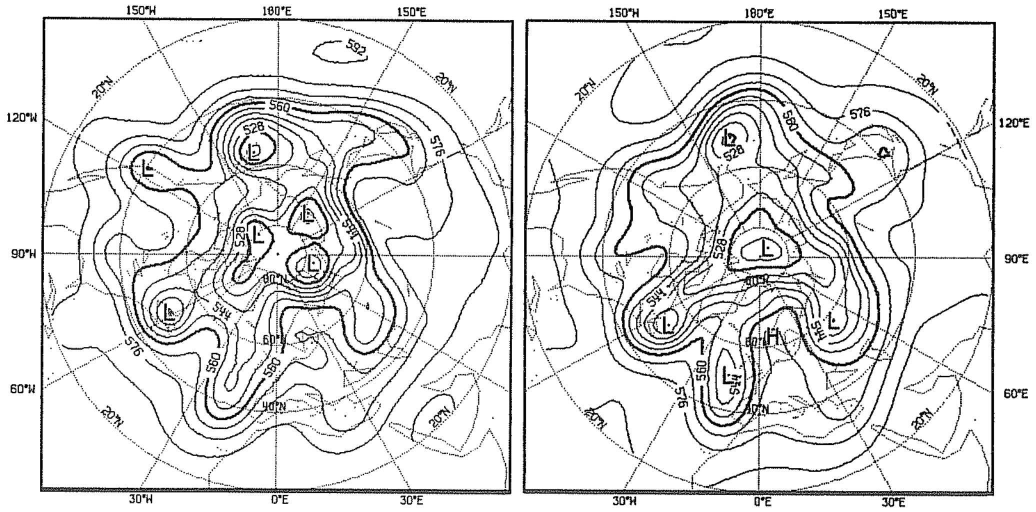


Fig. 5 Maps of 1000 mb height for the extratropical Northern Hemisphere. The left-hand plots are analyses for 16 May, 1981 (upper) and 23 May, 1981 (lower), while the right-hand plots are 4-day forecasts verifying on these two dates. The contour interval is 4 dam.

Analysis 19 May 1981 7-day Forecast



Analysis 26 May 1981 7-day Forecast

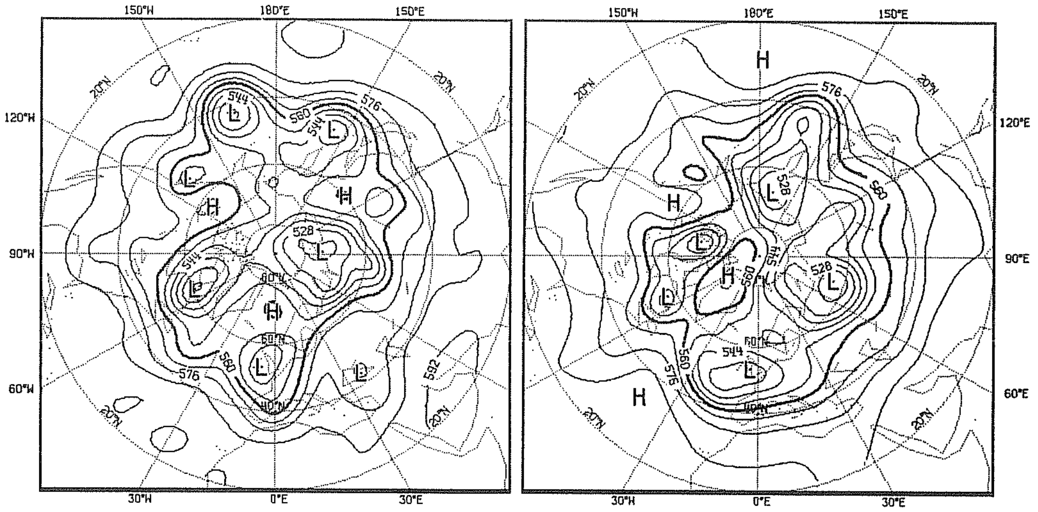


Fig. 6 As Fig. 5, but for 7-day forecasts and the 500 mb height. The contour interval is 8 dam.

4 and day 7, whereas that from the 19th is close to the worst of the month at both days. Anomaly correlations averaged over the extratropical Northern Hemisphere are 79% and 62% respectively for the day 4 forecasts at 1000 mb, and 62% and 32% for the two day 7 forecasts at 500 mb.

The surface synoptic situations were very similar on the 16th and 23rd May. Particular common features to note are the two lows in the Central and Eastern Pacific, the low to the west of Ireland and the developing low near the eastern coast of North America, although the latter is of different amplitude on the two days. Despite this similarity, the two day 4 forecasts are quite different. Although the better of the two has errors of detail, it has clearly forecast with reasonable accuracy the positions and intensities of the four lows in question.

The forecast from 19th May, however, exhibits at day 4 a number of errors which may commonly be seen at later stages of the ECMWF forecasts. Particularly worthy of note is the Pacific sector, where the forecast has produced not two distinct lows but what appears closer to one, large-scale and large-amplitude depression. Conversely, the development of the low near 60°W has been substantially underestimated, while the phase of the low to the west of Northern Europe has also been poorly forecast.

Overdevelopment of depressions, such as illustrated near 180°E in the above example, tends to occur most commonly over the Central and Eastern Pacific, and over the Eastern Atlantic and Northern Europe. In the mean this appears as the intensification and eastward shift of the Aleutian and Icelandic lows discussed in the preceding section. In contrast, late or inadequate development of new disturbances over the Western Atlantic occurs in a number of cases, and an underestimation of the phase speed of rapidly-moving lows is frequently observed, although in the forecast from 19th May the low centred near 30°W had an origin significantly different from that of the analyzed low centred further towards the east.

In view of the deficiencies of the 4-day forecast from 19th May it is not surprising that the 7-day forecast exhibits little skill. Figure 6 shows that while the analyzed and forecast charts bear some overall resemblance (corresponding to the anomaly correlation of 32%) there is substantial error at most longitudes. In contrast, all main troughs exhibit a reasonably accurate position and amplitude in the 7-day forecast from a week earlier, although some detail is lost over the Pacific and the west of North America.

4. TROPICAL FORECASTS

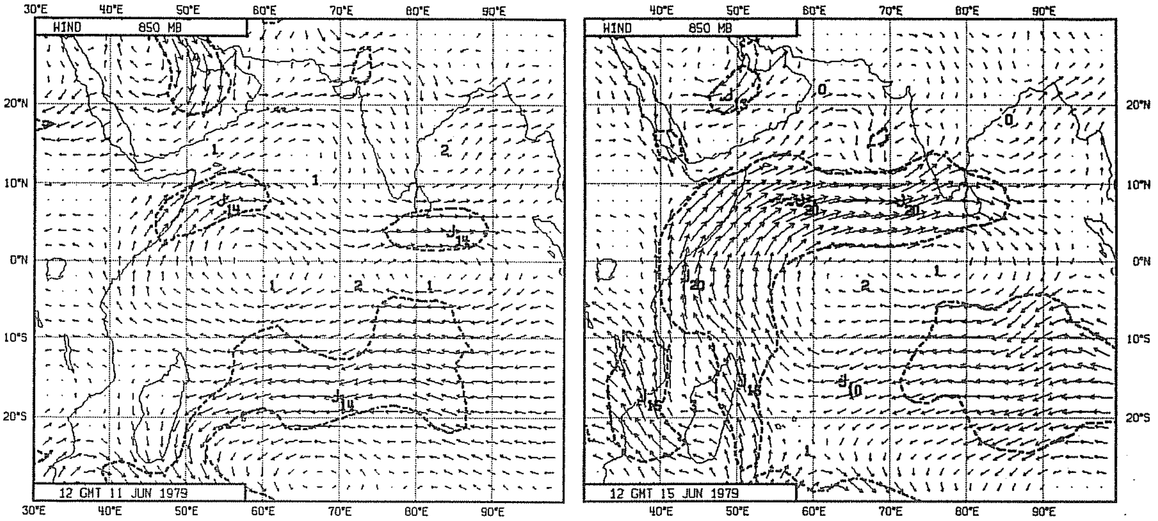
Although the forecasts for the Tropics have not been evaluated in as extensive an objective and subjective way as those for the extratropical Northern Hemisphere, there is no doubt that at present their accuracy and usefulness is very substantially less. Indeed, standard deviations of forecast winds show, in the mean, no improvement over persistence in the lower troposphere, while synoptic assessment reveals that some distinct errors in the low-level flow develop quite systematically in the earliest stages of the forecast. Maintenance of the quasi-stationary regional circulations of the tropical atmosphere is evidently a distinct modelling problem, and in the zonal-mean there is a partial suppression of the Hadley circulation and an underestimation of tropical precipitation by some 20%.

Despite these deficiencies, individual cases of quite accurate forecasts of transient behaviour may also be found. For the longer range there are arguments to suggest that the predictability of temporal and spatial means of the tropical atmosphere may be higher than that of middle latitudes (Shukla, in this Volume) but such studies have not as yet been carried out at ECMWF.

The indication from both subjective and objective assessments of the tropical forecasts is that there are serious deficiencies in the parameterization of convection, and a substantial effort to understand and correct these deficiencies is currently being made. As an example of the sensitivity that can be found, we show in Fig. 7 two 4-day forecasts of the 850 mb wind over the Indian Ocean and bordering areas. These forecasts (which used FGGE rather than operational data) cover a period starting from 11 June 1979 which was marked by the onset, rather later than normal, of the south- west monsoon. The two differ only in their parameterization of convection, one using the scheme of Kuo (1974) adopted for operational forecasting and the other the Arakawa-Schubert (1974) scheme. The latter evidently produces a quite different forecast, and in fact a very much better representation of the development of the strong monsoon flow over the Arabian Sea. Just one experiment cannot of course be used to draw firm conclusions as to which of the convection schemes is the better (and indeed, the extratropical forecasts in this case were slightly the better using the Kuo scheme), but the sensitivity of the forecast is worth noting. Other studies have in addition shown sensitivity to the prescription of soil moisture and orography, results in general agreement with those found elsewhere (Rowntree, 1978). Overall, it seems that the tropical forecasts respond more quickly and acutely to defects in the model than do forecasts at middle and high latitudes.

5. COMPARISONS OF GRID-POINT AND SPECTRAL TECHNIQUES FOR THE HORIZONTAL REPRESENTATION

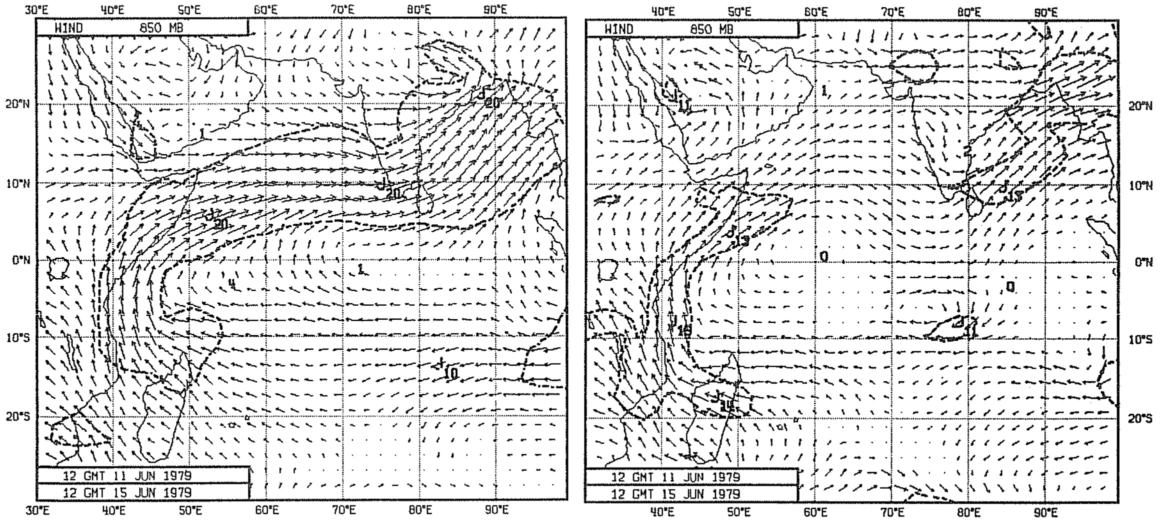
In designing a new forecasting system, a choice has to be made concerning the discretization techniques to be adopted in normal use of the system. Research on this topic at ECMWF has initially concentrated on a comparison of finite-difference and spectral methods for the horizontal representation. Detailed results of an extended experiment comparing forecasts performed once per week for a complete year have been given by Girard and Jarraud (1982). In this experiment, the operational grid-point model forecasts (which used a



Analysis 11 June

Analysis 15 June

Forecasts 15 June



Arakawa-Schubert

Kuo

Fig. 7 Analyses of 850 mb wind for 11 June (upper left) and 15 June (upper right), and corresponding 4-day forecasts for 15 June using the Arakawa-Schubert (lower left) and Kuo (lower right) convection schemes. Flow maxima and minima are marked in ms^{-1}.

1.875°, or "N48" resolution) were compared with spectral forecasts using triangular truncation at total wavenumber 63 (T63), these two models requiring a similar amount of computing resources.

Although the models often gave a very similar forecast, some clear differences in overall performance were found. An indication of this is given by Fig. 8, while Fig. 9 presents one example (out of by no means few) of a markedly better local forecast by the spectral model. The occurrence of such differences in the medium range raises the question as to the extent of any future improvement that might be obtained by refinements in numerical technique or resolution.

Although many of the systematic errors noted in previous sections occur for the T63 spectral model as well as for the operational finite-difference model, some reduction in a number of these errors has been found. One example is the overall cooling, which has been found to be less in the series of spectral forecasts. A second, for which statistics are presented in Table 1, is the tendency to underestimate the phase-speed of rapidly-moving lows. Table 1 shows phase speeds to be generally better represented by the spectral model, at least in the short-range (for which an unambiguous identification of analyzed and forecast lows was possible).

6. HIGHER RESOLUTION

A question which naturally arises during the course of work at a numerical forecasting centre is that of the extent to which forecasts might be improved by increases in horizontal or vertical resolution. One approach to answering this question is to extrapolate using results from the current resolution and those obtained using lower resolution. In this respect, experiments with the ECMWF spectral model show a clear improvement to result from increasing horizontal resolution from T40 to T63 (Jarraud, Girard and Cubasch, 1981). A

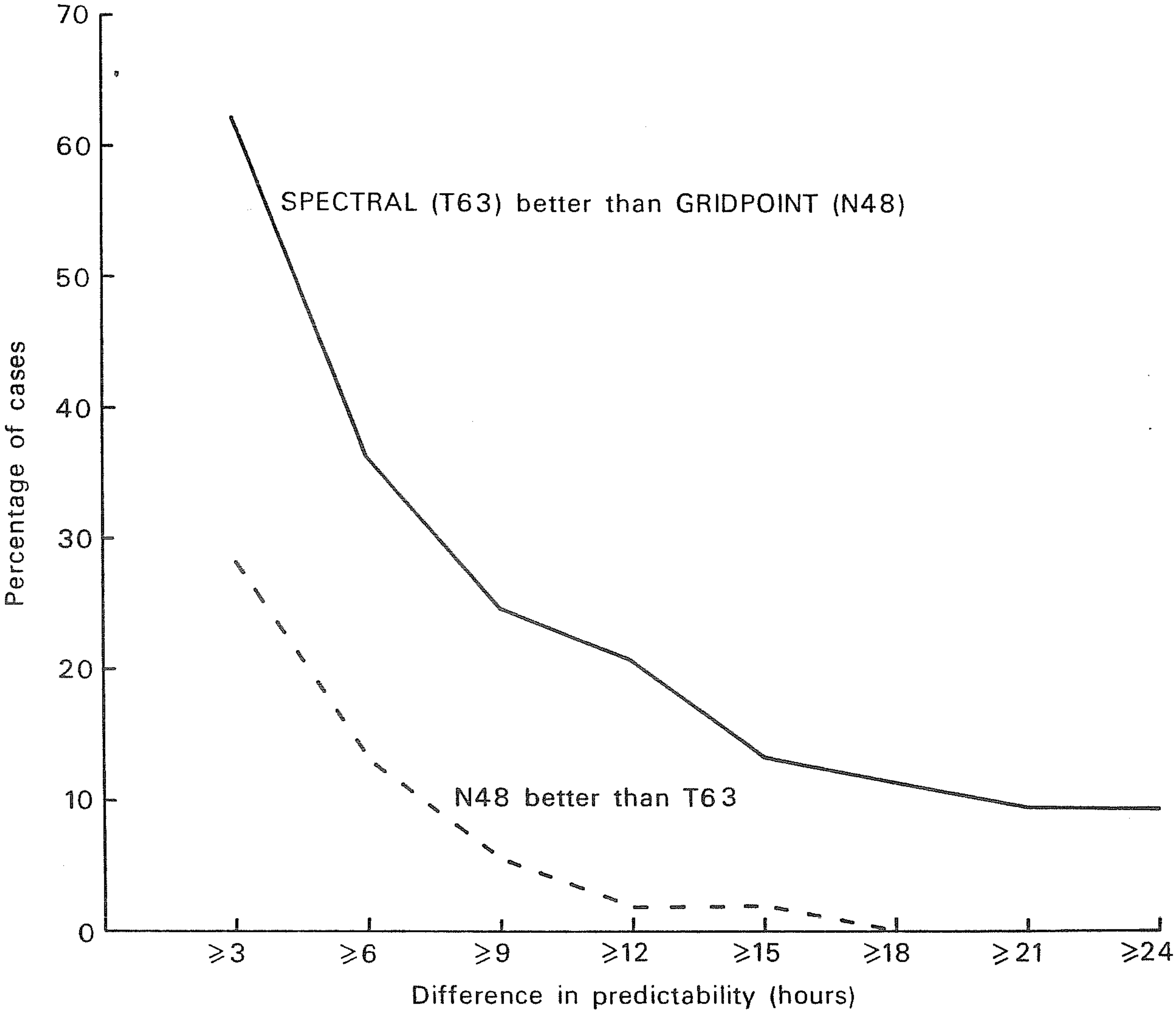


Fig. 8 The difference in predictability (measured by the length of the forecast period for which the anomaly correlation of the 1000 mb height over the extratropical Northern Hemisphere remains above 60%) between spectral (T63) and grid-point (N48) models. Results are expressed in terms of the percentage of cases for which one or other model gave better results.

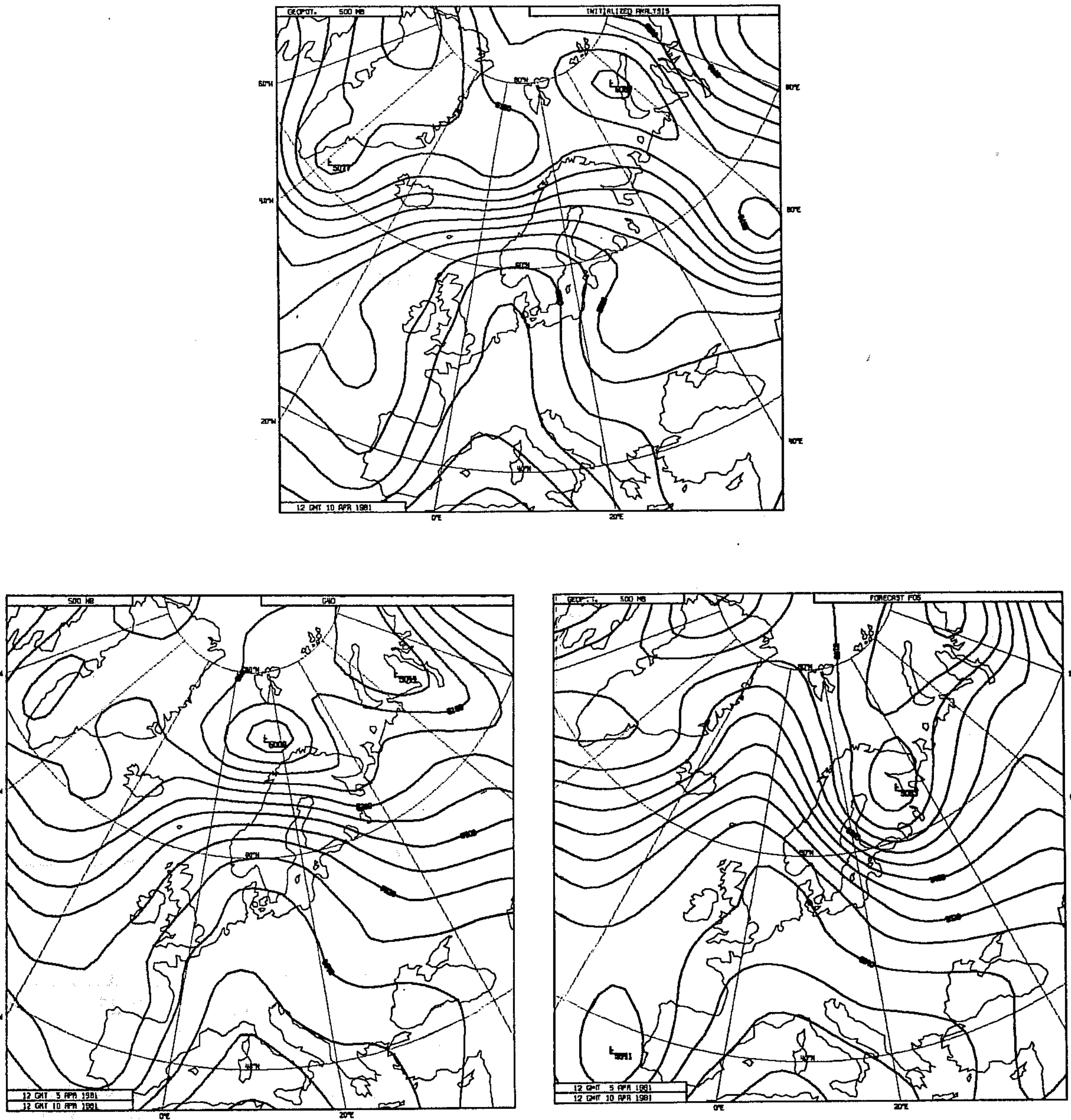


Fig. 9 The analyzed 500 mb height for 10 April, 1981 (upper) and 5-day forecasts for this date by the T63 spectral model (lower left) and the N48 grid-point model (lower right).

Table 1 Errors in the displacement (in degrees longitude) of surface lows between day 1 and day 2 of the forecasts for spectral (T63) and grid-point (N48) model forecasts.

Displacement (D)	Cases	Error (Degrees) T63	Error (Degrees) N48
$D < 5^\circ$	64	+.6	+1.0
$5^\circ \leqslant D < 10^\circ$	39	+.3	+.2
$10^\circ \leqslant D$	89	-1.8	-2.6
$15^\circ \leqslant D$	44	-1.8	-3.3
$20^\circ \leqslant D$	16	-2.9	-4.5

more convincing approach is actually to carry out higher resolution forecasts, although computational limitations often inhibit a comprehensive experimental programme.

Only very limited evidence of the influence of higher resolution is currrently available for the ECMWF forecasting models, and it would be unwise to attempt to draw any firm conclusions at this stage. Figure 10 illustrates how the intensity of a rapid, initially small-scale, development is captured better with increasing horizontal resolution, while Fig. 11 shows, from the same forecast, a much-improved indication of the flow over the North Eastern Atlantic from the highest resolution (T96) forecast. It should be noted that all forecasts shown in Figs. 10 and 11 were performed from an analysis produced using the N48 grid-point model in the data assimilation. The sensitivity of forecasts of relatively small-scale developments such as shown in Fig. 11 is emphasized by Fig. 12, which compares two (grid-point model) forecasts from analyses which differed not in the content of the data sets used, but rather by the refinements in analysis technique made over the course of a year or so's development of the ECMWF system. It appears that in view of results such as these, due attention should be paid to the data assimilation in the planning of higher resolution experiments. In particular, use of the higher resolution model in the data assimilation cycles is probably necessary for a reliable indication of any benefits of higher resolution.

7. PARAMETERIZATION

In our preceding discussion of model deficiencies a number of references has been made to aspects of the parameterization. Thus we have noted some sensitivity of the systematic height error to the parameterization of turbulent fluxes, sensitivity of the tropical forecasts to the parameterization of convection, and sensitivity of the stratospheric temperature error to the parameterization of radiation. A detailed

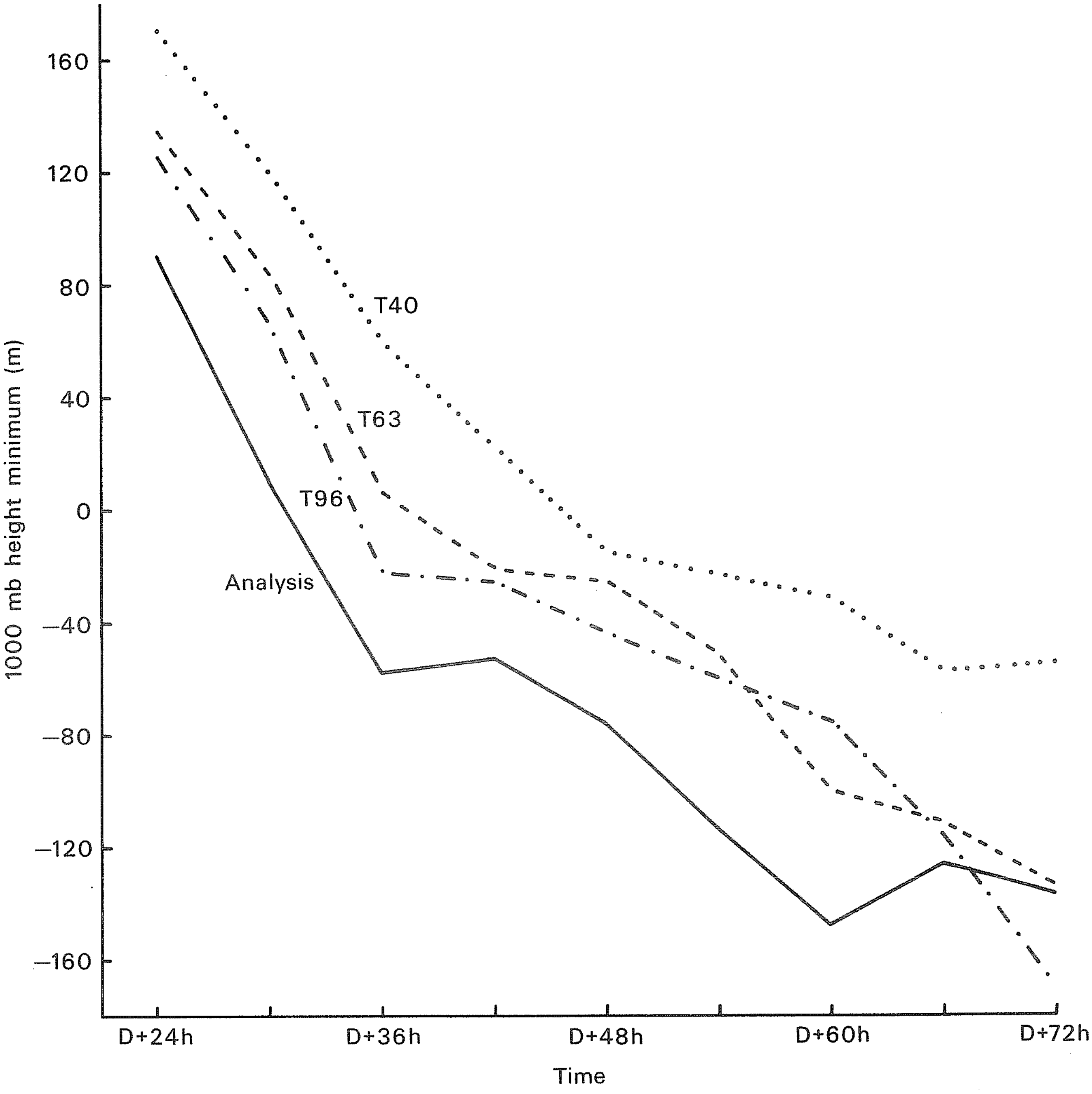


Fig. 10 Forecasts (from 12GMT, 18 Feb 1979) of the rapid development of the "President's Day Storm" using three different spectral resolutions.

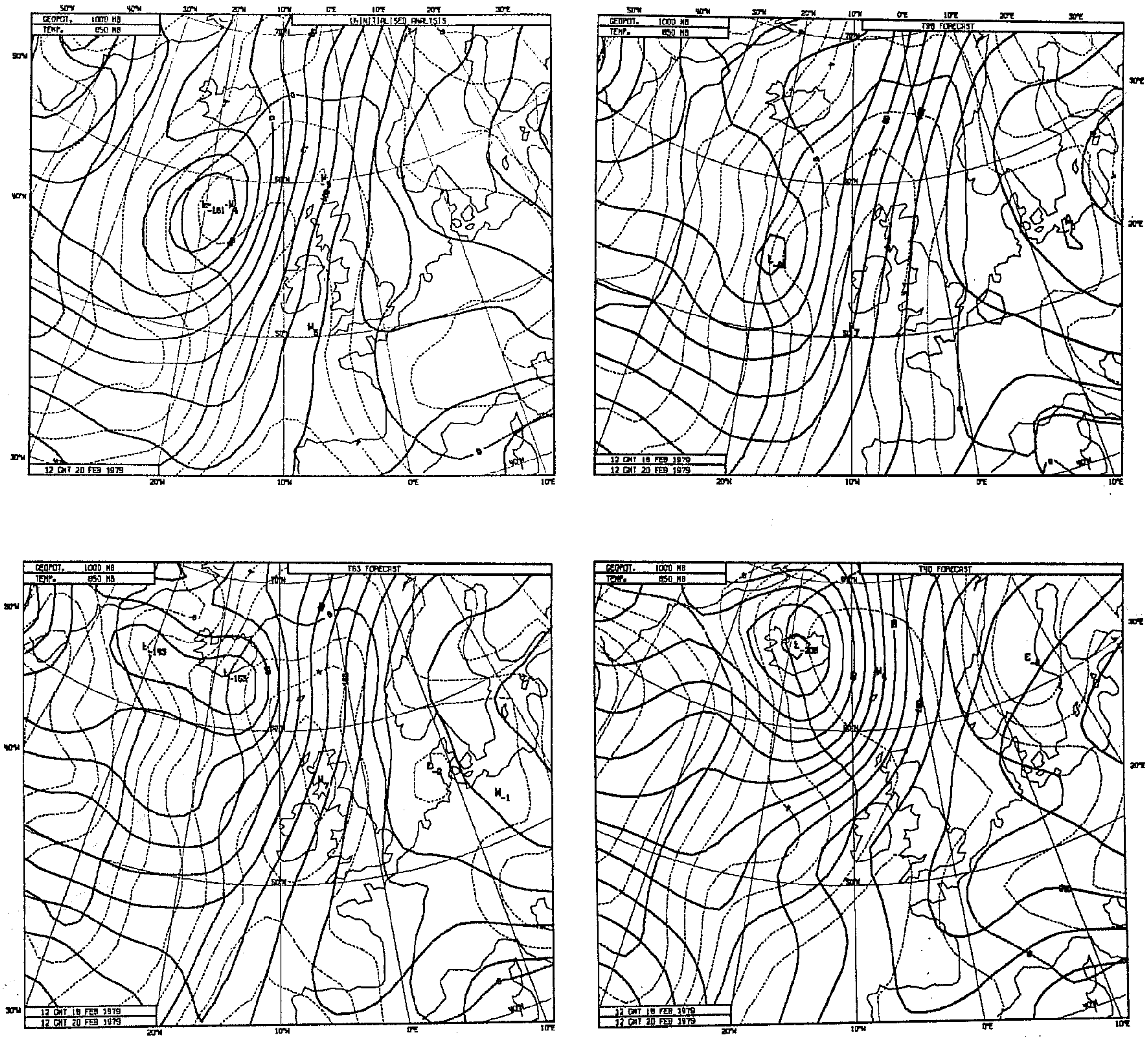


Fig. 11 Maps of 1000 mb height (contour interval 4 dam) and 850 mb temperature (contour interval 2 K) for 12GMT, 20 February 1079.
Upper left: analysis. Upper right: T96 forecast.
Lower left: T63. Lower right: T40.

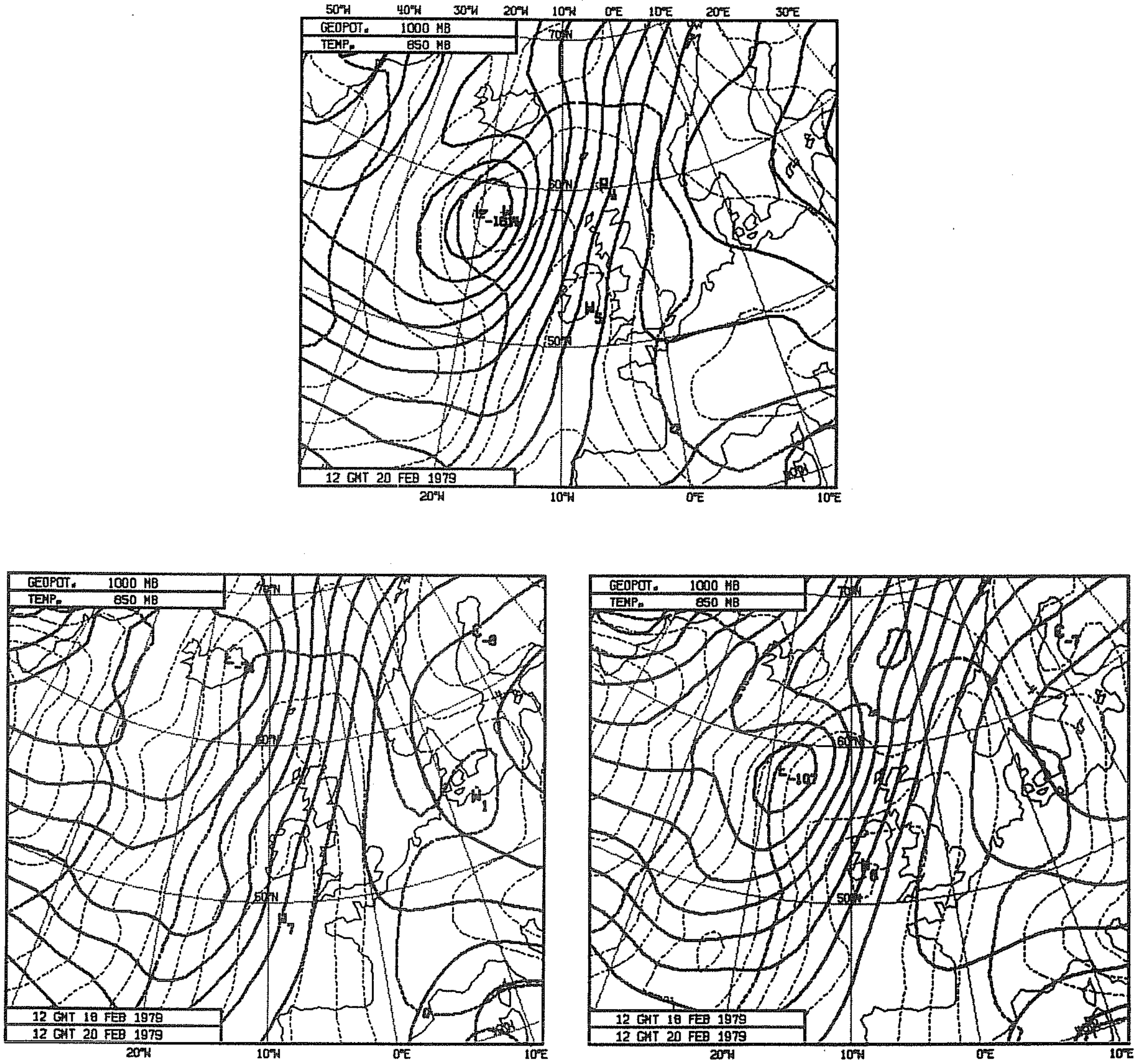


Fig. 12 As Fig. 11, but for the verifying analysis (upper), and for 2-day forecasts from two different initial analyses.

presentation of these and other such results is beyond the scope of this contribution, but we mention very briefly below some work on parameterization currently being carried out at ECMWF, and discuss also problems which have recently arisen relating to the interface between the parameterization and the dynamical model.

Concerning first the parameterization itself, effort is being made to evaluate the performance of a variety of representations of convection. These include the previously mentioned schemes proposed by Kuo (1974) and Arakawa and Schubert (1974), a scheme based on some ideas of Lindzen (1981), a scheme developed at ECMWF by Miller and Moncrieff, and the simpler moist convective adjustment (Manabe et al 1965). The major effort in the parameterization of radiation is directed towards inclusion of a diurnal cycle in the model. Preliminary results indicate a quite small impact on forecasts, and further experimentation is continuing. A project to evaluate the use of a higher-order closure scheme in the parameterization of turbulent fluxes has begun following the successful first results obtained by Miyakoda at GFDL.

More generally, evidence appears to point towards a need to pay greater attention to the interaction between the parameterization and the resolved motion of the forecast model. Traditionally, parameterization schemes take input data at discrete levels for a particular atmospheric column, or grid-point, and produce tendencies of the prognostic variables at these discrete levels for the column in question. Such an approach may, however, yield problems.

One example may be found in the parameterization of radiative cooling. For certain distributions of temperature and humidity, increasing the vertical resolution is found to give rise to increasingly large cooling rates at just

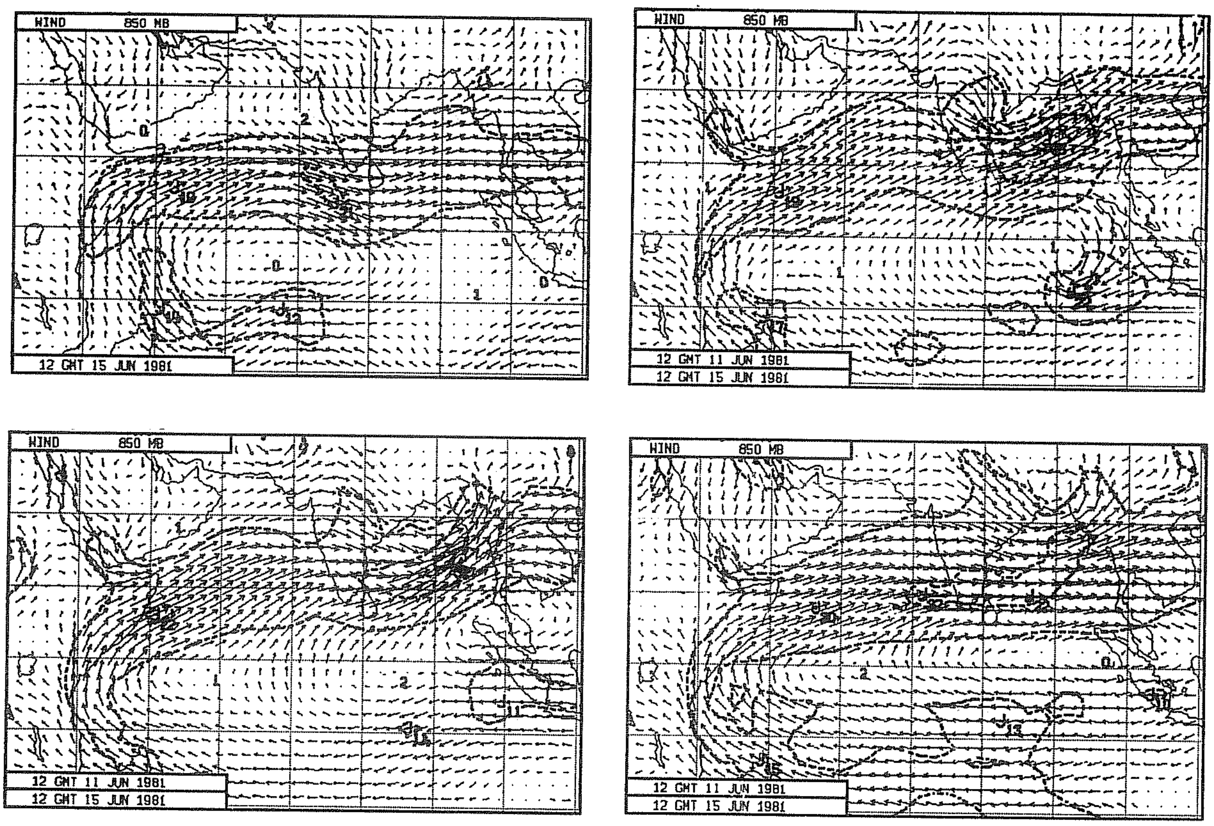


Fig. 13 850 mb wind analysis for 15 June, 1981 (upper left) and day 4 forecasts for this date using moist convective adjustment (upper right), the operational Kuo convection scheme (lower left), and the Arakawa-Schubert convection scheme (lower right).

one model level. These are not by themselves physically unreasonable, representing as they do a substantial cooling of cloud tops, but the response of the (vertical finite-difference) model to such a distribution of cooling is far from clear.

A second example concerns the current parameterizations of convection. In these schemes, an unstable atmosphere leads to parameterized heating profiles being introduced into the model, but with no associated (dynamical-balancing) change to the wind field. This can result in the convective heating being balanced by adiabatic cooling due to excessive vertical motion, rather than by a stabilizing temperature change. Thus regions of convections may persist unrealistically, with unrealistic related circulation patterns. An example is shown in Fig. 13 in which a too-strong monsoon flow is found (apparently driven by excess convection in the vicinity of Burma) over the Bay of Bengal for three different parameterizations of convection.

8. CONCLUSIONS

In this paper we have presented some model-related aspects of current problems in medium-range forecasting at ECMWF. It must be stressed that the discussion has been by no means comprehensive. We have not, for example, touched upon the problems related to the representation of orography or to related problems of the prediction of precipitation. A number of distinct modelling problems have, however, been illustrated. It is difficult to estimate the exact impact that solution of these problems would have on the accuracy of the Centre's forecasts, but there nevertheless appears to be substantial scope for extending the period for which these forecasts are of practical use.

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