# STUDIES OF INCREASED HORIZONTAL AND VERTICAL RESOLUTION

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SUMMARY

A review is given of a number of resolution studies carried out at ECMWF. A comparison of the current operational T106 resolution with lower horizontal resolutions is presented first. Objective and subjective assessments are summarized, and the roles of resolution-related differences in horizontal diffusion, the specification of orography and the representation of pressure-gradient terms are discussed. Results are then presented from studies of horizontal resolutions higher than T106, with emphasis on a run carried out at T213 resolution. The operational change from 16- to 19-level vertical resolution, in which the stratospheric definition of the model was significantly improved, is discussed next. Finally, some results obtained from development of a 31-level version of the model are presented.

## 1. INTRODUCTION

Among the many developments that have taken place in numerical weather prediction over the decades since the pioneering experiments of Charney et al. (1950), the use of higher resolution is one of the major components. The nature of the development of prediction models is such that the introduction of a new model commonly involves a combination of changes in numerical formulation, resolution and parametrization, and it is difficult to quantify just how much higher resolution alone has contributed to the undoubted increase that has occurred in the accuracy of numerical forecasts. Published accounts of the sensitivity of forecasts to resolution tend to be based on detailed examination of one or two cases (e.g. Miyakoda et al., 1971; Williamson, 1978; Atlas et al., 1982), but over the past ten years a quite substantial set of results relating to the impact of resolution increases has been built up at ECMWF. These form the subject matter of this lecture.

The emphasis before and during the first few years of operational forecasting at ECMWF was principally on the development of the basic formulation of the forecasting system, rather than on resolution studies per se. However, as part of the development of the spectral method for medium-range forecasting, Jarraud et al. (1981) compared the performance of T40 and T63 resolutions for a set of 7 cases from February 1976, and concluded that T63 performed noticeably better than T40, particularly near the surface. In comparing the T63 version with the Centre's then-operational grid-point model, Girard and Jarraud (1982) found some cases in which there were clear phase differences which were essentially reproduced when the resolution of the spectral model was reduced to T53 or T40. They also found cases with more substantial synoptic differences for which the grid-point model produced forecasts closer to spectral forecasts from a resolution lower than T63. Early study of vertical resolution was confined to examination of stratospheric resolution (Simmons, 1979; Simmons and Strüfing, 1981).

Much more comprehensive studies of increased horizontal resolution have been carried out since the operational implementation of the spectral model (discussed by Simmons and Jarraud, 1984). The initial motivation for these studies was the development and assessment of the T106 version of the model that was implemented operationally in May 1985. Routine operational verification shows that the change at this time was the most significant in terms of its impact on forecast accuracy that has been made in the decade that operational forecasting has been carried out at the Centre, although it must be recalled that the resolution increase was accompanied by a substantial change to a number of parametrizations (Tiedtke et al., 1988). The comparison of T106 and lower horizontal resolutions is presented in the following section. More recent studies have examined increases in horizontal resolution beyond T106, in preparation for implementation of a higher resolution operational model when computational resources permit. These experiments are discussed in section 3.

Over the period since 1983 there has been a general tendency to place more emphasis on resolution increases in the horizontal than in the vertical. The possibility of an increase in vertical resolution was considered at the same time as the initial phase of experimentation with T106 horizontal resolution (Jarraud et al., 1985). A set of 8 T63 experiments was carried out with a 20-level vertical resolution in which layer thicknesses in the middle and upper troposphere were reduced by a third, the same reduction that would have occurred in horizontal grid-length if T95L20 had replaced the operational T63L16 model, rather than the alternative T106L16. The results of these experiments were disappointing in that objective verification showed little difference between the 16- and 20-level results, with if anything a slight deterioration at the higher vertical resolution. It was then decided to concentrate on the increase in horizontal resolution to T106 for operational implementation, and to return to the study of a general increase in vertical resolution once the related study of the use of the finite-element method for the vertical discretization (Steppeler, 1988) had been brought to a conclusion.

In view of this, it is not possible in this lecture to discuss the topic of vertical resolution and the development of the ECMWF forecast model as fully as in the case of horizontal resolution. However, at around the time of the implementation of the T106 version of the model, evidence arose for a specific further study of an increase in stratospheric resolution, and in May 1986 the current 19-level vertical resolution was introduced operationally. This topic is discussed in section 4. Since then, a programme of experimentation with a 31-level resolution has begun, and some results are presented in section 5.

## 2. COMPARISON OF T106 AND LOWER RESOLUTIONS

### 2.1 Introduction

We present two sets of experiments that have been carried out to provide an extensive comparison between spectral-model forecasts with different horizontal resolutions. The first comprises a group of 24 cases spanning the two years prior to the operational introduction of T106 resolution. Forecasts were produced with T21, T42, T63 and T106 resolutions. The second consists of T63 and T106 forecasts for 48 cases covering the two years since May 1985.

Initial analyses for the first set were derived from the operational (T63) analyses for the 15th of each month from May 1983 to April 1985. Experiments were carried out using two different prescriptions of the orography for each resolution (and a third for T106). Results relating to orography have been discussed by Jarraud et al. (1988); here we present only results produced using an "envelope" orography based on adding $\sqrt{2}$ times the standard deviation of the actual subgridscale orography to the grid-square mean (the operational choice for T63). For each particular initial date the same model parameters, vertical resolutions and parametrizations were used for each horizontal resolution, with the exception of the horizontal diffusion coefficients. The latter took the same values for T21 and T42 as used routinely for T63. The T106 forecasts used the value of $10^{15} m^4 s^{-1}$ for all variables for the first 19 cases, with the ultimate operational value of $2.5 \times 10^{15} m^4 s^{-1}$ adopted for divergence for the final 5 forecasts. The 19 cases were run with the parametrization schemes used operationally up to December 1984 (Tiedtke et al., 1979), and the final 5 used the revised longwave radiation scheme that became operational in December 1984 (Ritter, 1984) and the revised treatments of clouds, convection and condensation that were implemented operationally with the resolution change in May 1985 (Tiedtke and Slingo, 1985).

The second set comprised forecasts run from the 1st and 15th of each month from May 1985 to April 1987. The operational T106 forecasts (with one standard-deviation envelope orography) served as controls, and corresponding T63 forecasts were carried out from truncated T106 analyses, again using the same parametrizations and model settings (including a T63 envelope orography), apart from the coefficients of horizontal diffusion. For the latter, the previously operational T63 values were used for the first 15 cases, after which the coefficient for divergence was reduced to $5 \times 10^{15} m^4 s^{-1}$, 2.5 times larger than that for other fields, as was (and is) the case for T106.

2.2 Objective assessment

Anomaly correlations of 500 hPa height for the extratropical Northern Hemisphere, averaged over the two sets of cases, are presented in Fig. 1. The upper plot shows, not surprisingly, a much larger improvement of T42 over T21 than that of T63 over T42, which in turn is larger than the improvement of T106 over T63. This tendency for convergence at high resolution does not, however, imply that differences between T63 and T106 are small throughout the forecast range, but rather that what can be quite large differences later in the forecast range are not systematically in favour of the higher resolution, as will be seen shortly. The apparently small mean differences in skill are nevertheless larger than the average differences between gridpoint and spectral forecasts discussed by Girard and Jarraud (1982), and larger than average differences between forecasts using mean and envelope orographies (Jarraud et al., 1988). Other objective measures of forecast skill generally confirm the picture shown in Fig. 1, although standard deviations exhibit more favourable results for T42, and to some extent T63, towards the end of the forecast range. This is presumably related to the higher levels of variance that are found in the higher resolution forecasts.

Comparing the two panels in Fig. 1, it can be seen that differences between T63 and T106 are very much the same in the two sets of experiments, despite differences in the parametrizations, envelope orography, and resolution of the assimilating model (T63 or T106) used to produce the initial analyses. Later in the forecast range a more uniform difference between T63 and T106 is seen in the second, larger set of cases. Perhaps more noteworthy is the large overall difference in forecast quality between the two sets of cases, both T63 and T106 forecasts crossing the line denoting 60% correlation about 1 day later in the second set than in the first. Although interannual variability in the inherent predictability of the atmosphere may contribute to this difference, it is likely that it largely reflects advances in data assimilation (including the use of a higher resolution model) and parametrization, and perhaps the improved stratospheric resolution of the forecast model.

Early in the forecast range differences between T63 and T106 for individual cases are almost systematically in favour of the higher resolution. This is seen particularly clearly at the surface, and is illustrated in the left-hand part of Fig. 2, which plots (from the second set of experiments) each case on a scatter diagram for the anomaly correlation of 1000 hPa

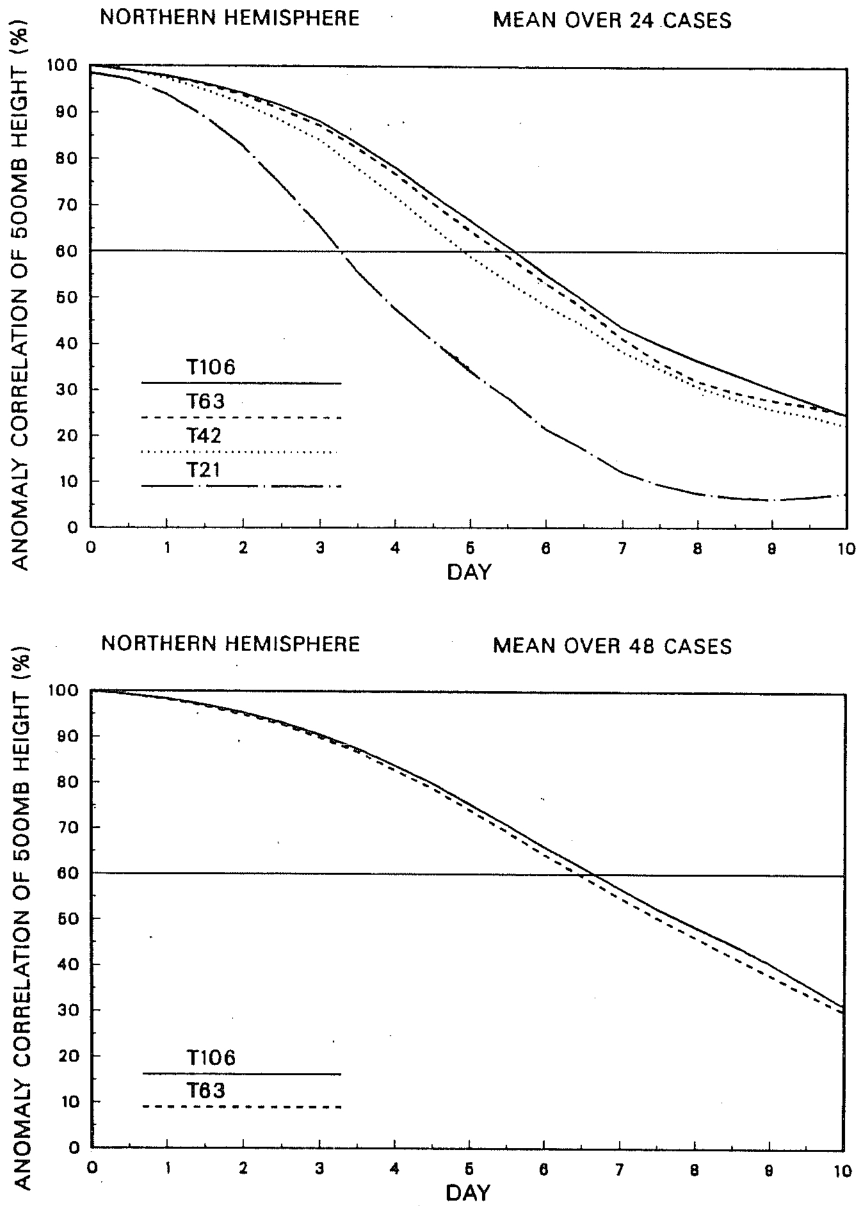



Fig. 1 Anomaly correlations of 500 hPa height for the extratropical Northern Hemisphere averaged over sets of 24 (upper) and 48 (lower) cases, for spectral truncations T21, T42, T63 and T106 as indicated in each panel.

height for 3-day forecasts for the extratropical Northern Hemisphere. Points lying above the diagonal line correspond to cases in which T106 is (according to the measure in question) better than T63, and it can be seen that at day 3 by far the majority of points lie above the line. The plotted points distinguish between "summer" (May to October) and "winter" (November to April) cases, and the advantage of T106 over T63 at day 3 is shown to be particularly clear in summer, only one out of 24 cases failing to yield an improvement. This is related in part to the choice of envelope orography which has been found to have a beneficial impact at both T63 and T106 resolution in winter, whereas in summer it gives poorer average anomaly correlations than does mean orography at T63, with similar correlations for the two orographies at T106 (Jarraud et al., 1988).

The corresponding scatter diagram for day 7 is also shown in Fig. 2. At this range there is evidently more spread, and a less systematic bias in favour of T106. A more beneficial impact of higher resolution in summer than in winter can again be discerned.

Objective verification has been carried out for a number of regions other than the extratropical Northern Hemisphere. Absolute correlations of 850 hPa vector wind for the tropics and anomaly correlations of 500 hPa height for the Southern Hemisphere, averaged over the second set of cases, are presented in Fig. 3. There is a distinct improvement of T106 over T63 in the tropical verification, and a negligible net sensitivity to resolution in the results for the Southern Hemisphere. Similar conclusions are drawn from verification of the first set of cases, although smaller differences are found in the tropical region, with T63 in fact scoring better than T106 out to day 2.5. This may reflect a difference in sensitivity to resolution for the two versions of the convective parametrization used in these experiments, but it could also indicate sensitivity of the shortrange forecast to compatibility between the resolution of the forecast model and that of the assimilating model, which was T63 for the first set of experiments and T106 for the second.

### 2.3 Subjective assessment

An extensive synoptic assessment of results from the first set of horizontal-resolution experiments has been undertaken. It is beyond the scope of this lecture to do much more than briefly summarize the results, and we include in this section just two examples of large sensitivity. Further examples of synoptic impact are discussed in section 3.

Increasing horizontal resolution is found frequently to be beneficial for the prediction of the deepening and tracking of depressions over the first few days of the forecast range. Fig. 4 shows a verifying analysis and day-3 forecasts of mean sea-level pressure over the North Atlantic. The case in question is one in which a low was initially of small amplitude and located off the Florida coast, and subsequently moved rapidly northeastwards and

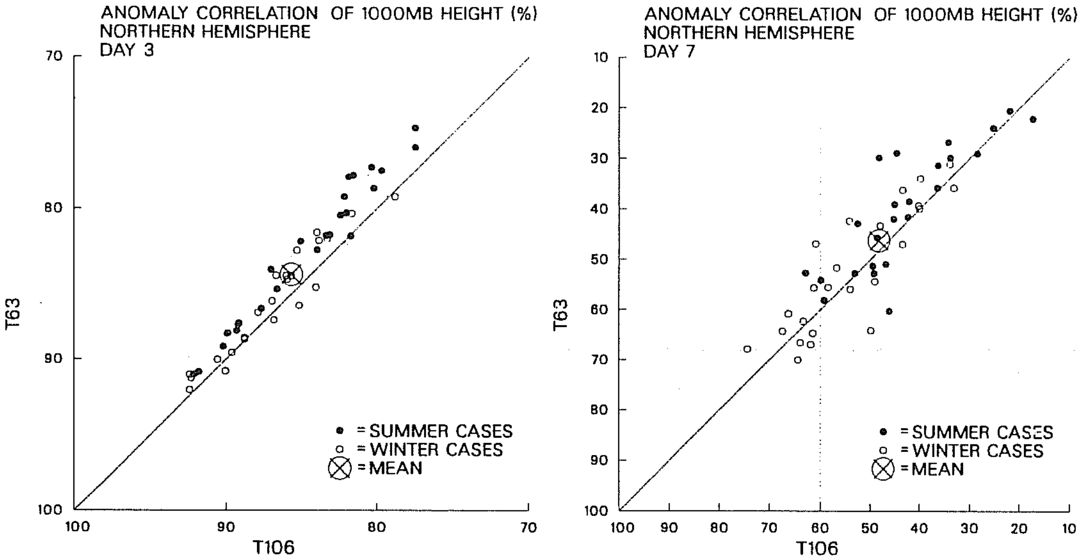



Fig. 2 Scatter diagrams of anomaly correlations of 500 hPa height for the extratropical Northern Hemisphere, comparing T63 and T106 forecasts at day 3 (left) and day 7 (right). Points lying above the diagonal indicate better performance of T106. Solid circles denote summer cases, open circles denote winter cases, and crosses denote the means.

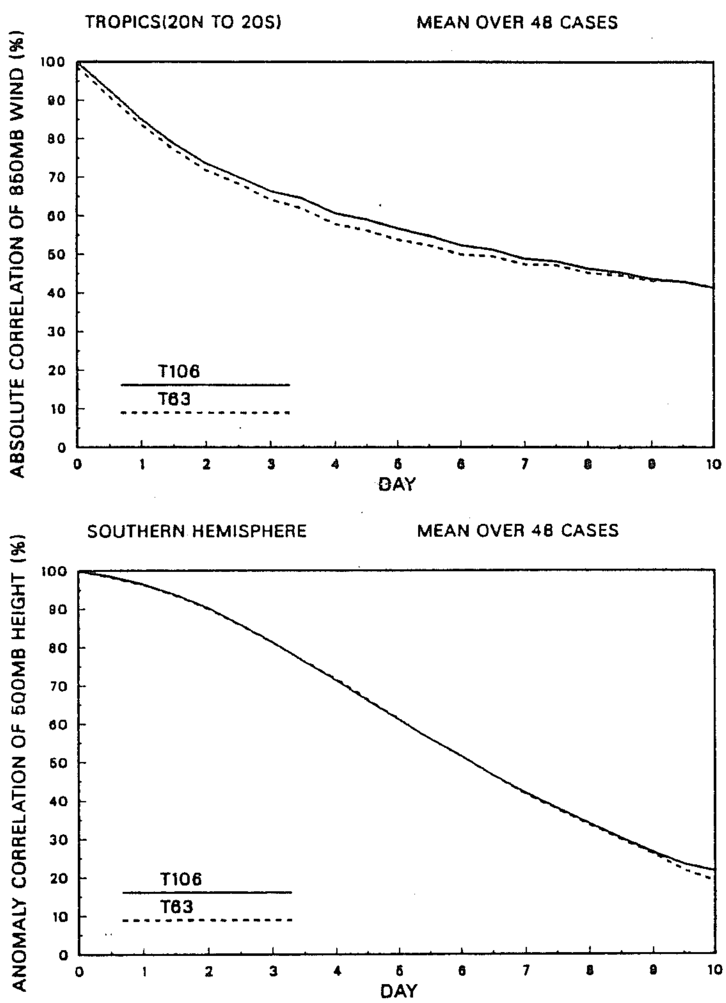



Fig. 3 Absolute correlations of 850 hPa vector wind for the tropics (upper) and anomaly correlations of 500 hPa height for the extratropical Southern Hemisphere (lower), averaged over 48 cases for T106 (solid) and T63 (dashed) forecasts.

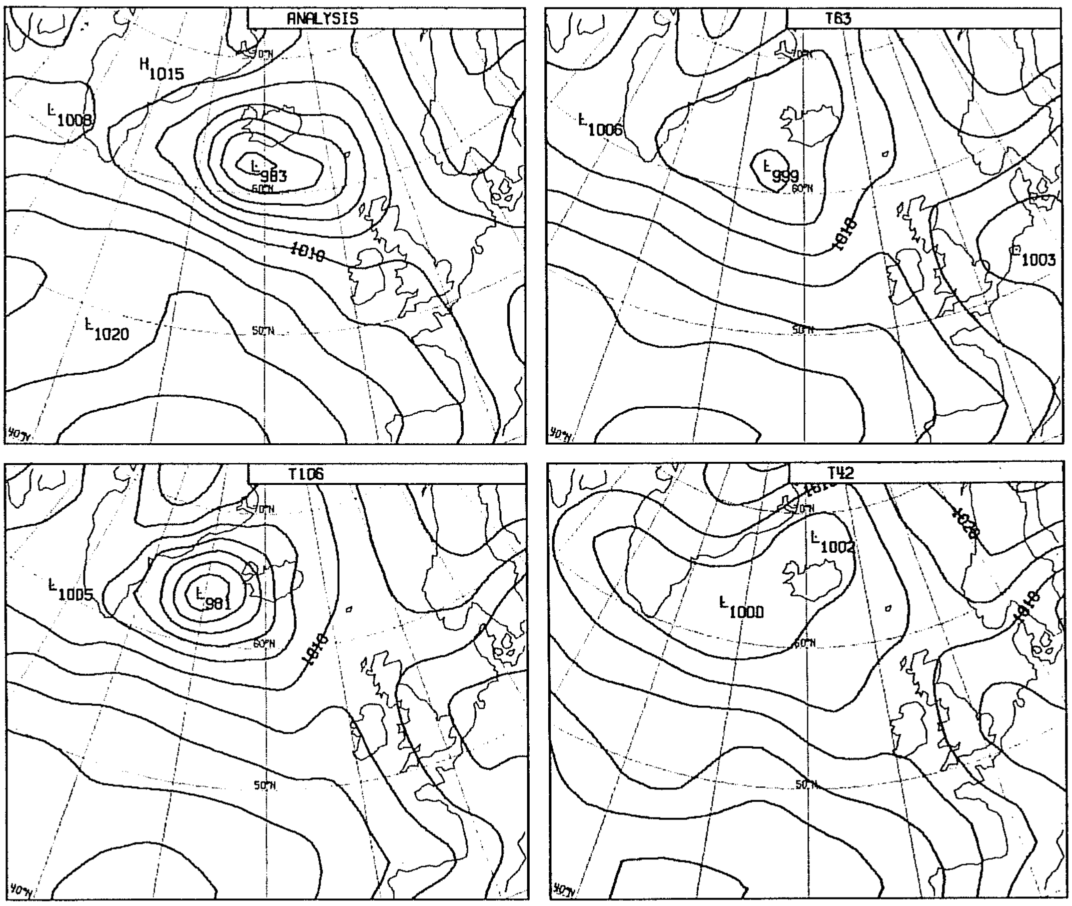



Fig. 4 Comparison of 3-day forecasts for 12UTC, 18 September 1984 of the mean sea-level pressure (contour interval 5 hPa) made with T42 (lower right), T63 (upper right) and T106 (lower left) models; the upper left panel shows the verifying analysis.

amplified significantly. By day 3, it was located south of Iceland. Only at T106 resolution was the intensity of the development captured, although the low was in this case placed too far to the west and in a position rather worse than that of the weak low present in the T63 forecast. It is also noteworthy that the erroneous predicted circulation centred over the Low Countries is common to all three resolutions shown; increased resolution cannot be expected to rectify the effect of a major deficiency in some other component of the forecasting system.

Beyond four or five days ahead, small-scale lows are generally more poorly positioned than in shorter-range forecasts, and the prediction of deeper systems at T106 resolution can then lead to worse objective scores. This was in particular found to be the case in the two situations which were picked out by objective verification as exhibiting the poorest performance of T106 relative to T63 for the extratropical Northern Hemisphere. As other sources of forecast error are reduced, a more clear benefit of high resolution can be expected.

Bengtsson (1981) and Tibaldi and Ji (1983) have discussed examples of sensitivity in the prediction of blocking for resolutions up to T63, and here we present an example of strong dependence on resolution beyond T63 truncation. Fig. 5 presents 500 hPa height maps averaged from day 5 to day 10 for a number of forecasts from 15 March 1984, together with the verifying analysis. The blocking structure which in reality prevails over Europe and the North Atlantic is quite accurately captured at T106 resolution. Although there is some indication of blocking at the other resolutions, there is a substantial deterioration in the realism of the pattern and phase of the field as resolution is decreased. By day 10 in this extreme case, objective verification of the 500 hPa height over the extratropical Northern Hemisphere showed that the standard deviation of differences between the T63 and T106 forecasts was larger than that of the error in the T106 forecast.

This case was found to be also highly sensitive to the representation of orography, with a much poorer T106 forecast when mean orography was used. The modelling of the orography over northeast Canada and Greenland was shown to be crucial (Jarraud et al., 1988). It was thus decided to rerun the T106 forecast using the same orography as used for the T63 prediction, to see the extent to which the forecast would be degraded. The result is included in Fig. 5 (middle right), and in fact shows very little deterioration compared with the full T106 forecast. In this particular case, the improved prediction by T106 does not arise principally from a finer resolution of the orographic forcing, despite the important impact of use of envelope orography.

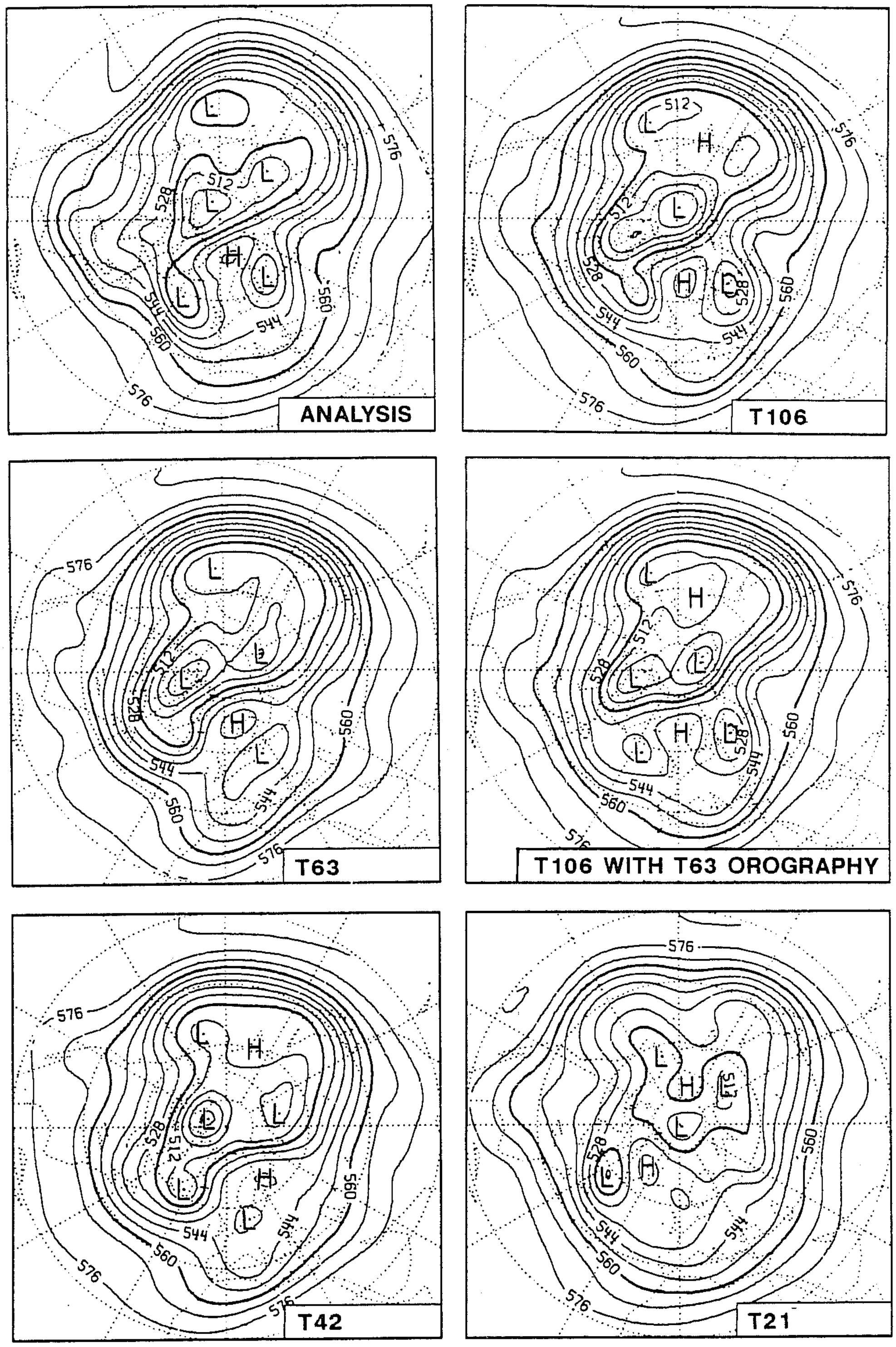



Fig. 5 Five-day mean charts for 500 hPa heights (contour interval 8 dam). The panel labelled analysis is the mean for 20 to 25 March 1984. The remaining five panels are means for day 5 to day 10 of a number of forecasts from 12UTC 15 March 1984 (as labelled).

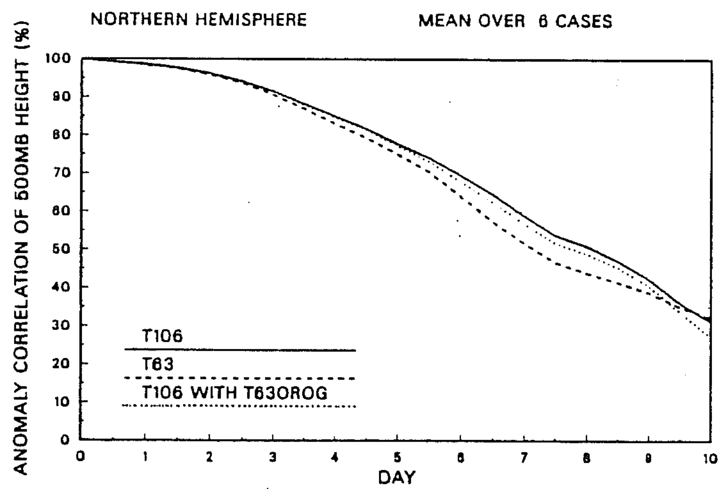
Beneficial synoptic impact of higher resolution has been found in a range of other situations. Alpine lee cyclogenesis is one example which will be illustrated shortly. Improvements in predicting the formation, movement and filling of cut-off lows are found with increasing resolution, as is a better definition of secondary features embedded within complex quasi-stationary low-pressure systems. A better treatment of lows at high latitudes is also found in the higher resolution forecasts.

## 2.4 Orography, horizontal diffusion and the representation of pressure-gradient terms

The T106 forecasts entail use of a finer-resolution orography and use of lower coefficients for horizontal diffusion. In addition to the case shown in Fig. 5, and the case study to be discussed in the following section, sensitivity to orography and horizontal diffusion has been examined for six cases particularly sensitive to resolution. A set of T106 forecasts was carried out using a T63 representation of the orography, and a second set used T106 orography, but the diffusion coefficients used for T63. The cases were chosen from the 24 forecasts carried out in the second year of the second experiment, selecting out of the 4 available for each two-month period the case which gave the largest difference between T63 and T106.

Results are shown in Fig. 6 in terms of anomaly correlation of 500 hPa height for the extratropical Northern Hemisphere. Both finer-resolution orography and smaller diffusion coefficients evidently contribute to the improvement of T106 over T63. Perhaps surprisingly, a somewhat larger impact from diffusion than from orography is seen in Fig. 6, but the reverse is found to be the case for anomaly correlations of 1000 hPa height and for standard deviations of the height field errors. The small number of cases must also be borne in mind. It should also be noted that reduced horizontal diffusion is not universally beneficial. Simmons and Miller (1988) present an example in which the poorer performance of T106 compared to T63 in the latter part of the 10-day forecast period is associated with the lower horizontal diffusion used by T106 in the early stages of the forecast, a result thought to be connected to an unusually strong initial "spin-up" of vertical velocity in the tropics.

A study of mean errors has been carried out for the first set of cases. Tropical height biases were very similar in T42 and T63 forecasts, but substantially smaller for T106. Overall, the global-mean 500 hPa temperature, averaged over days 8-10 for the 12 "winter" cases of the sample, was 0.7 K higher for T106 than for T42 and T63. Experiments with different diffusion coefficients were carried out for a limited number of cases, and these indicated that the temperature change could be largely accounted for by the reduction in horizontal diffusion for T106, particularly the diffusion of the divergence field. Seven of the 12 cases included in the sample were carried out with the former operational



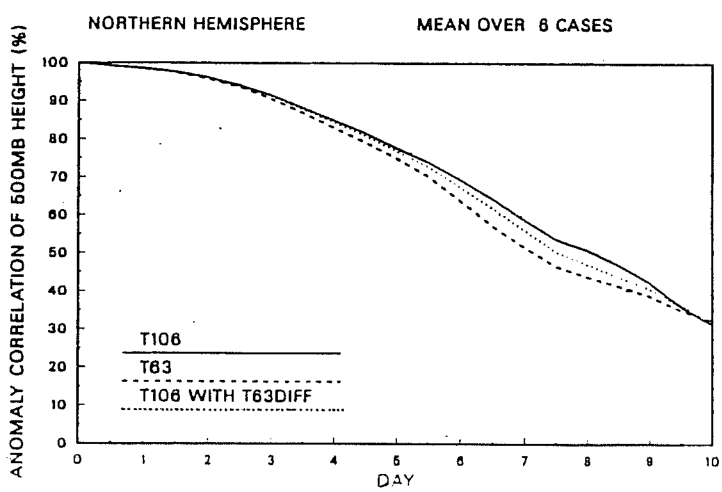




Fig. 6 Mean anomaly correlations of 500 hPa height for the extratropical Northern Hemisphere, for 6 cases carried out at T106 (solid) and T63 (dashed) resolution, and for T106 forecasts carried out with T63 orography (dotted, upper panel), and with T63 diffusion coefficients (dotted, lower panel).

parametrization schemes, for which the reduced cooling with T106 was clearly beneficial. With the new parametrization schemes, which were developed at T63 resolution, T106 tended to enhance a small general warming of the middle troposphere. The net impact of the parametrization and resolution changes on mean tropical structures is much more fully discussed by Tiedtke et al. (1988).

A sensitivity of forecasts with lower horizontal resolution to the representation of the pressure-gradient terms has recently been found, and explains at least some of the particular sensitivity of forecasts to horizontal resolution at polar latitudes. A version of the spectral model was developed in which the spectrally represented thermodynamic variable was not temperature, but the deviation of temperature from a reference atmosphere. This atmosphere was defined by a particular function of pressure for which there was a rather simple change to the governing equations. Tested at T42 (19-level) resolution, the new scheme gave a significant improvement in forecast skill scores for the Southern Hemisphere. The effect was substantial over Antarctica, and a small improvement was found over the Arctic. The new scheme was such as to make the T42 forecasts closer to T106 forecasts, and exhibited a tendency at longer forecast ranges to reduce erroneously high pressures which have been identified as a systematic error in lower resolution simulations in the vicinity of the Antarctic coastline east of the Ross Ice Shelf.

The combination of steeply sloping orography and strong temperature gradients found near the Antarctic coastline suggested that a changed representation of pressure-gradient terms could have been responsible for the model improvement. The general topic of the representation of these terms has been discussed by Mesinger and Janjic (1984, 1987) at previous ECMWF Seminars, and these authors in particular point out the possibility of "hydrostatic inconsistency" if horizontal and vertical resolutions do not match. Tests were thus carried out of a scheme in which a reference profile was used only in the pressure-gradient calculation (as suggested earlier by Gary (1973) and Phillips (1973)), changes being made only to the calculations carried out in grid-point space. The pressure-gradient terms

$$\nabla\varphi + R_d T\, \nabla \ell np \tag{1}$$

where

$$\varphi = \varphi_s + \int_p^{p_s} \frac{R_d T}{p}\, dp$$

were rewritten as

$$\nabla\tilde{\varphi} + R_d \tilde{T} \, \nabla \ell n p \qquad (2)$$

where

$$\tilde{T} = T - T_o \left(\frac{p}{p_s}\right)^{\alpha}$$

$$\tilde{\varphi} = \varphi_s + \frac{RT_o}{\alpha} \left(\frac{p_s}{p_o}\right)^{\alpha} + \int_p^{p_s} \frac{R_d \tilde{T}}{p} \, dp$$

$$T_o = 288 \text{ K}$$

$$p_o = 101320 \text{ Pa}$$

$$\alpha = 0.0065 \, R_d/g$$

and the notation is otherwise standard. Equation (2) was discretized in the same way as (1) is in the usual ECMWF scheme (Simmons and Burridge, 1981).

This change was indeed sufficient to capture the improvements found with the full scheme in which the spectrally-represented variable was changed. As an example of the impact of the revised pressure-gradient calculation, maps of forecast errors and differences for day 1 and day 7 of a case exhibiting large differences around Antarctica are presented in Figure 7. Tests of the revised pressure-gradient calculation at T106 resolution reveal a very much smaller impact than found for T42.

## 3 STUDIES AT RESOLUTIONS BEYOND T106

### 3.1 A case study at T213 resolution

It has been possible to date to run one forecast with the global spectral model at a resolution of T213, on a computer remote from ECMWF. The case chosen for study had an initial time and date of 12 UTC, 20 March 1986. It was selected because the subsequent weather situation was one in which the improved mountain description possible at T213

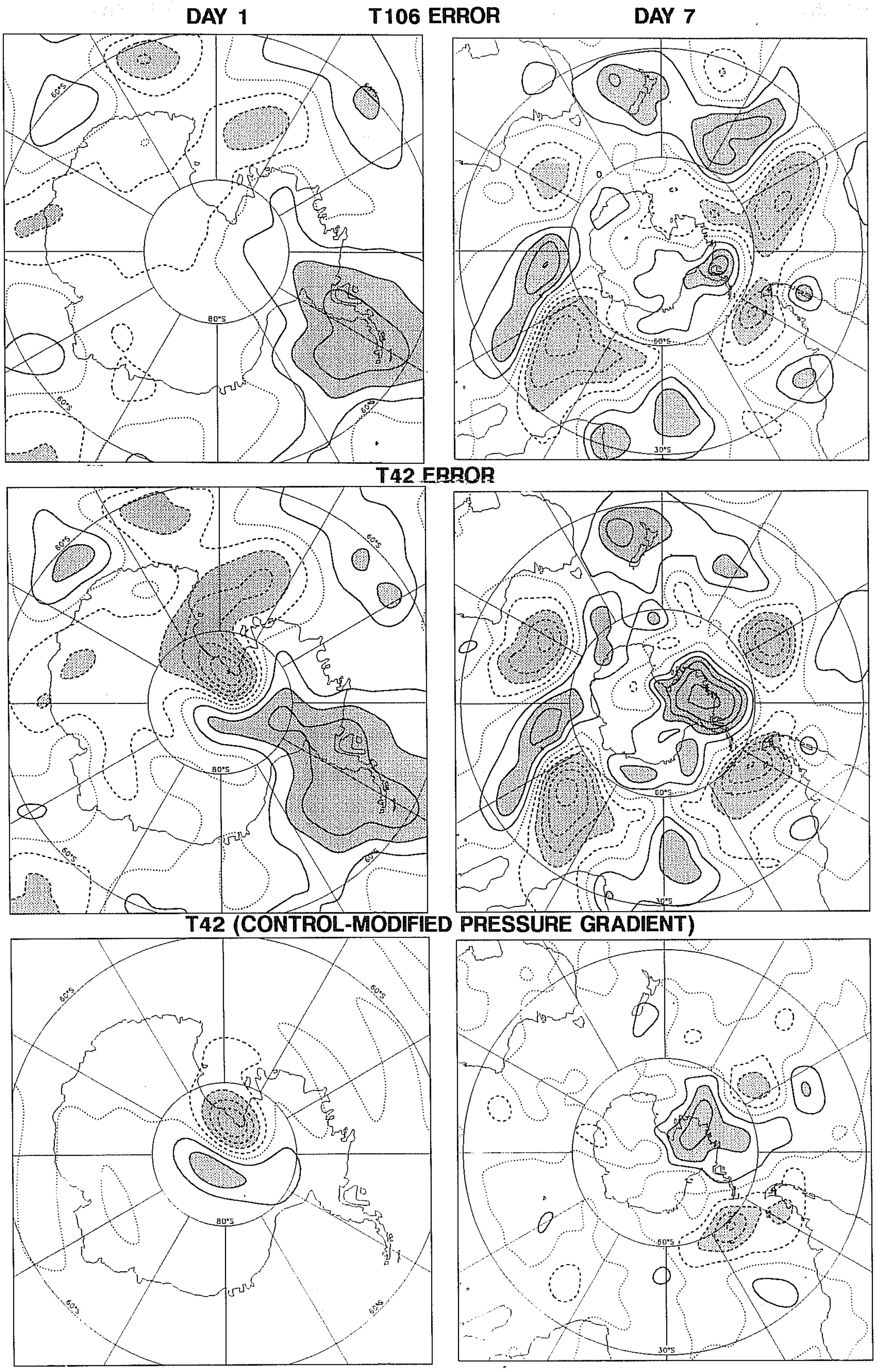



Fig. 7 Maps of 500 hPa height errors and differences of forecasts at day 1 (left, contour interval 40 m) and day 7 (right, contour interval 80 m). The upper and middle panels show forecast errors from standard T106 and T42 forecasts respectively, and the lower panels show differences between the standard T42 forecast and the T42 forecast with modified pressure-gradient calculation. The initial time and date are 12UTC 15 September 1987.

resolution was expected to influence significantly the quality of the forecast. Fig. 8 shows a set of surface pressure maps from lower resolution forecasts at one-day range, together with the analysed, actual maps for the starting time of the forecast and one day later. The actual maps (upper panels) indicate a marked change in pattern over the Mediterranean during the one-day period, with the development of a lee cyclone south of the Alps. This development is clearly underestimated and misplaced at T42 and T63 resolutions (middle panels), and is still underestimated for T106 (lower left panel), although its position is much improved. That this improvement is due to the better definition of terrain heights possible with T106 is demonstrated by the forecast shown in the lower right panel; rerunning the forecast with T106 resolution but with terrain heights smoothed to their T63 representation produces a forecast of the lee cyclone which is very close to that produced using T63 resolution.

The T213 forecast was run using 19-level vertical resolution and the version of the model code that was operational at the time of its execution, which differed from the 16-level vertical resolution and model code used to produce the forecasts shown in Fig. 8. The differences had little impact when tested at lower resolutions in this case. One-day T63, T106 and T213 forecasts with the newer version are shown in Fig. 9. The T63 and T106 forecasts are much as shown in Fig. 8, and the increased intensity of the lee cyclone in the T213 prediction is evident. The T213 forecast in fact shows a degree of detail not present in the analyzed map. The latter was produced as a result of using the T106 resolution model in the data assimilation, and its resolution is thus limited. The small-scale features seen in the T213 map are characteristic of those drawn in manual analyses of similar situations (e.g. Radinovic, 1986), and detailed comparison with observations of low-level wind, cloud and rainfall (not shown) for the present case confirm the correctness of much of the detail produced by the high-resolution run.

Over the following two days, the lee cyclone moved southeastwards, and weakened somewhat in intensity. The analysed observations indicate a low-level circulation centred just south of Italy. This is shown, together with the corresponding T106 and T213 forecasts in Fig. 10. Winds are plotted at model grid-points (the grid of the T106 data-assimilation model in the case of the analysed winds). The T213 plot clearly shows a circulation to be present in the high-resolution forecast, albeit a little weaker and farther to the west than analysed. There is only the faintest indication of such a circulation in the T106 forecast, and in the corresponding T63 forecast (not shown) there is westerly or northwesterly flow over the whole of the region in question.

The better performance of the T213 version of the model shows up clearly in other parameters at this time range. Maps of cloud as diagnosed in the 3-day T106 and T213 forecasts are shown in the upper and middle panels of Fig. 11, and the corresponding satellite picture is presented below. The increase in resolution is of substantial benefit in producing less cloud over the bulk of the Iberian Peninsula and to the immediate east. The T213 forecast is also successful in its depiction of cloud over Yugoslavia and southern Greece that was not captured using T106. A better impression is also given of the banded structure of the cloud field over the Mediterranean south of Italy.

One of the output fields most sensitive to horizontal resolution is precipitation. This depends sensitively on details both of the prevailing weather pattern and of the distribution of orography. In the case in question improvement due to use of T213 resolution is seen well into the forecast range. Fig. 12 shows predicted precipitation for the period from 4 to 5 days beyond the starting time, for T213 and T106 resolutions, together with the corresponding observations. Inspection of these shows that the increased detail of the T213 forecast is essentially realistic.

Perhaps the most interesting mountain effect occurring outside Europe for the period in question was seen in the early part of the forecast range over Central America. The distribution of terrain heights for this region is shown in Fig. 13. The weather situation during the early part of the forecast was one of strong northerly flow over the Gulf of Mexico. Under such circumstances, the mountains of southern Mexico present a major barrier to the low level flow, which is typically channelled through a gap (seen in the upper left quadrants of the maps shown in Fig. 13) to reach the Pacific Ocean as a narrow belt of high winds over the Gulf of Tehuantepec. Fig. 14 shows T213 and T106 forecasts at 60-hour range. The increase in resolution brings about a significant increase in wind strength where the flow emerges over the Pacific, and T213 evidently produces a more pronounced reversal to either side. Observations from ships support the T213 forecast as the more accurate.

An example of a forecast improvement unrelated to mountains is shown in Fig. 15. Surface maps for day 5 are presented over northern Europe. The analysed actual map (upper left) shows a depression over southern Sweden which is quite well captured, though a little to the west, in the T213 forecast (upper right). There is also a low to the northwest, which is less well positioned in the high-resolution forecast. The standard T106 forecast (lower left) produces a single, weaker depression at an intermediate location. However, in this case a result much closer to the T213 forecast is obtained (lower right) by using T106 resolution, but with the weaker horizontal diffusion coefficients ($3x10^{15}m^4s^{-1}$) employed in the T213 run. Reducing the damping on the scales resolved in the T106 truncation is evidently beneficial for predicting the weather system in question, although objective

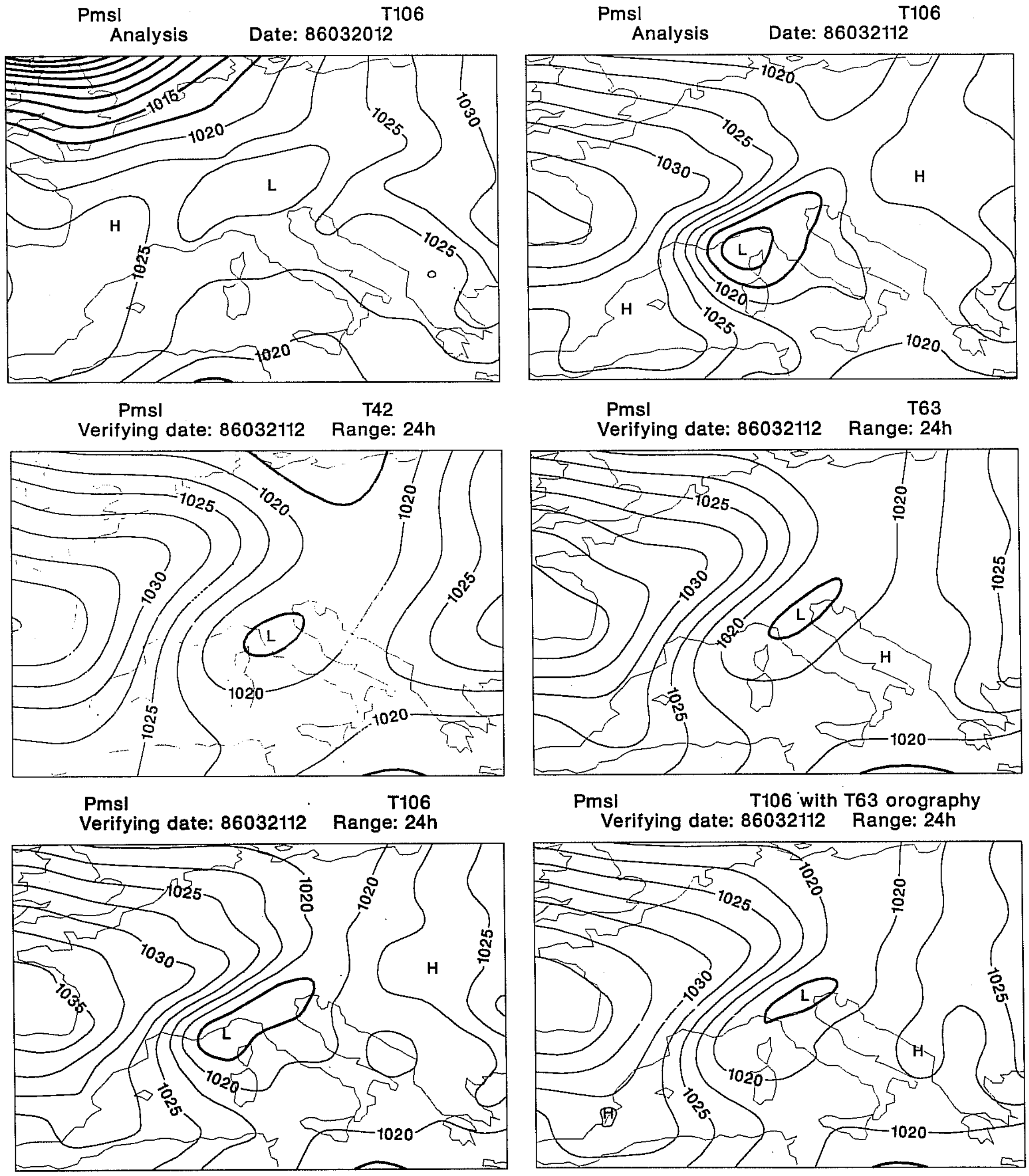



Fig. 8 The analysed map of mean sea-level pressure for 12UTC 20 March 1986 (upper left) and 21 March 1986 (upper right). The other maps show 24-hour forecasts from the earlier date and time using T42 (middle left), T63 (middle right) and T106 (lower left) resolutions, and also a T106 forecast in which terrain heights with T63 resolution were used (lower right). The contour interval is 2.5hPa.

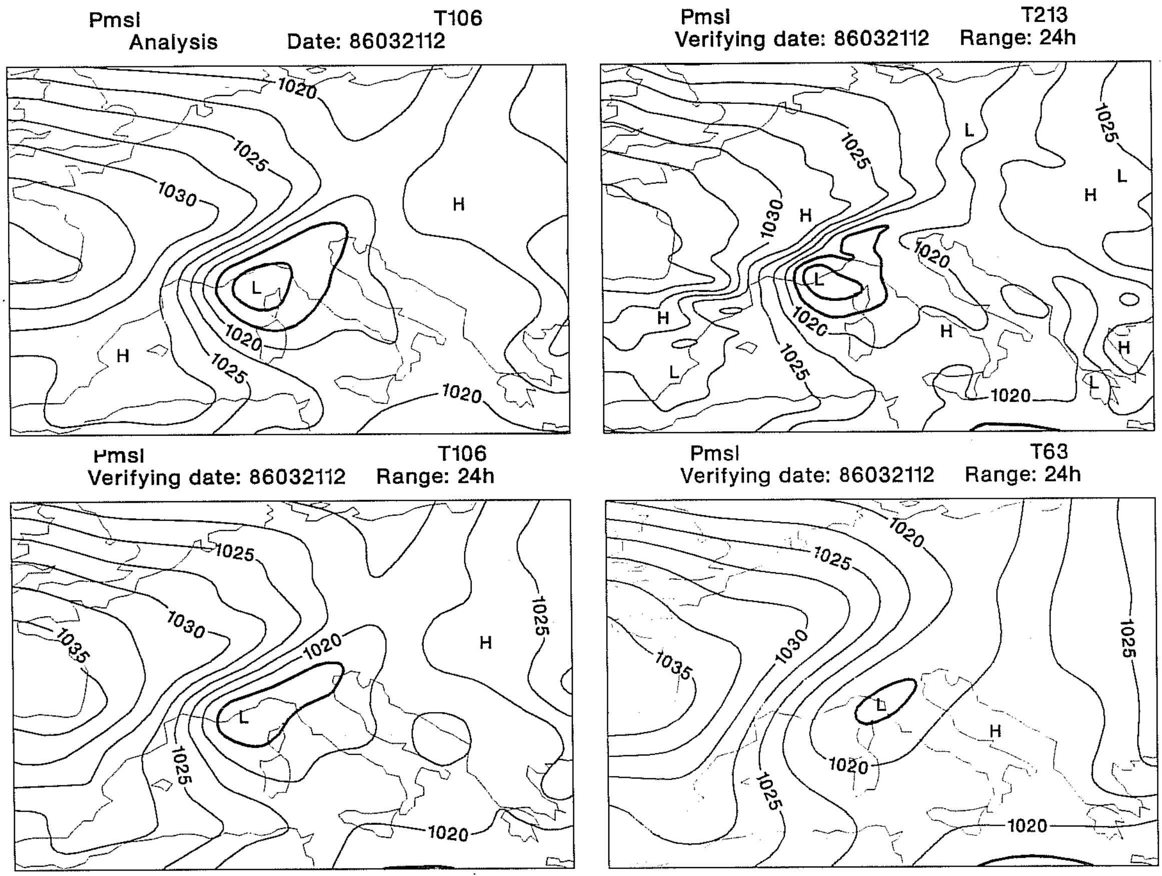



Fig. 9 The analysed map of mean sea-level pressure for 12UTC 21 March 1986 (upper left) and 24-hour T213 (upper right), T106 (lower left) and T63 (lower right) forecasts for this date and time.

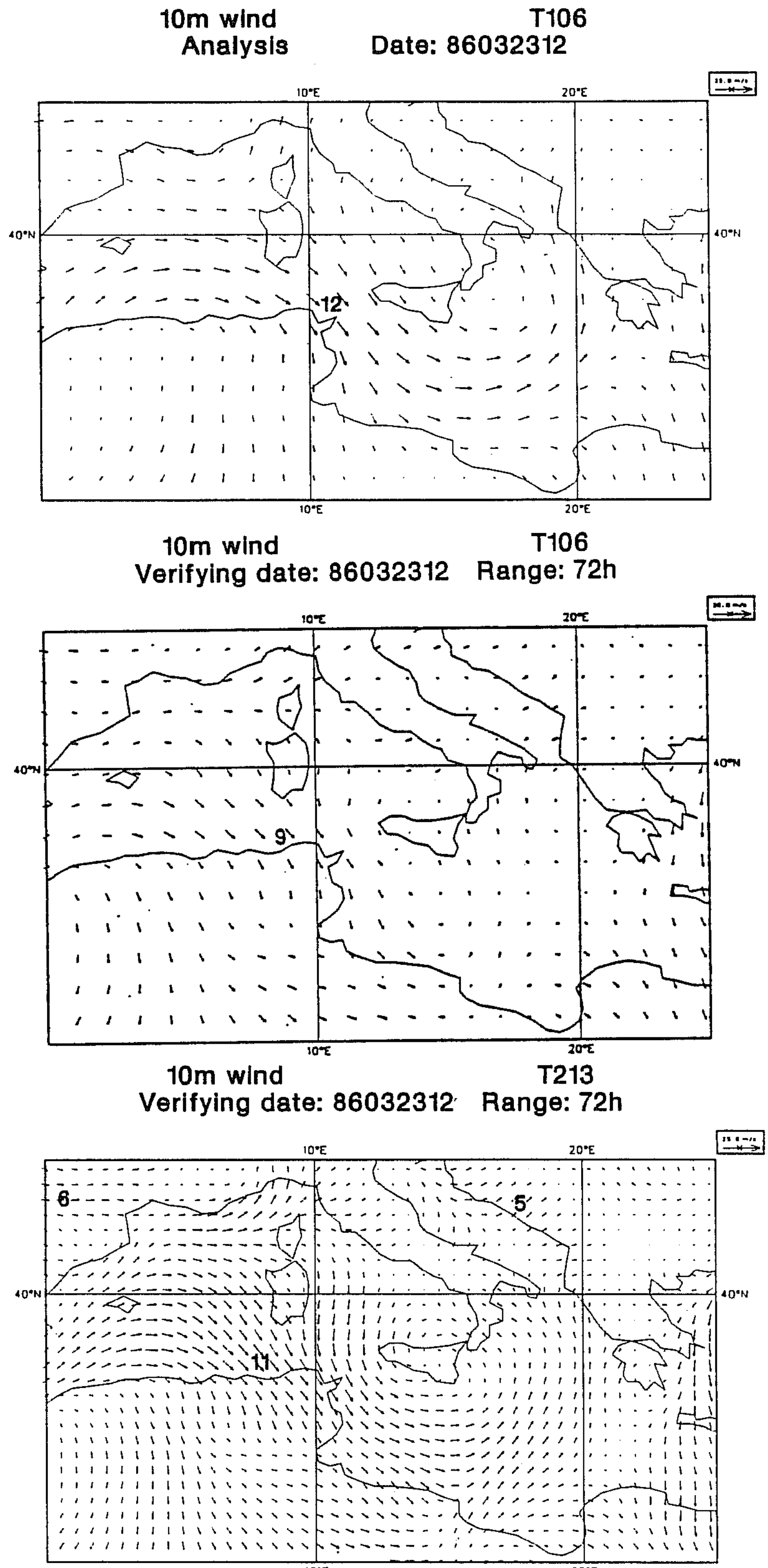



Fig. 10 Wind at 10m as analyzed for 12UTC 23 March 1986 (upper) and the corresponding 3-day forecasts with T106 (middle) and T213 (lower) resolutions. The length of each arrow is proportional to the wind speed, and maxima are marked in $ms^{-1}$.

forecasts for one of the cases studied. Each cross-section cut through the Cascade and Rocky Mountain chains of western North America, although only T106 and to a greater extent T159 resolutions are capable of distinguishing between the two ranges. Over this area, the large-scale forecasts were rather insensitive to horizontal resolution in this case, with a predominantly westerly incident flow. Small-scale wave motion over and immediately downstream of the Rockies ridge was evident in the T159 forecast, but not at lower resolutions.

These forecasts were carried out prior to the introduction of a parametrization of gravity-wave drag. There is an evident possibility (ECMWF, 1987) that as resolution increases, effects of gravity waves which in reality occur on scales close to the truncation limit may appear twice in the model, once through parametrization and once explicitly. Quite apart from this problem, the explicit appearance of vertically-propagating gravity waves brings the question of the upper boundary condition to the fore. Cross-sections presented by Simmons (1987) for the case referenced above show a divergence field with a westward phase tilt with increasing height in the troposphere over the Rockies at T159 and T106 resolutions. However, there is an absence of tilt in the stratosphere which is suggestive of an erroneous wave reflection due to the inadequate treatment of upward propagating waves in the topmost layers of the model.

### 3.3 Use of limited-area models

Limited-area models provide an economical way of investigating specific local aspects of the performance of a forecasting system as resolution is increased, and there is much experience within the Member States of ECMWF and elsewhere of using high-resolution limited-area models for short-range numerical prediction. At ECMWF, a number of such studies were carried out using a derivative of the original operational grid-point model. A prime example is the study by Dell'Osso (1984) showing the impact of increased horizontal resolution on the prediction of a lee cyclogenesis from the ALPEX period, and examining the behaviour of different orographic representations as a function of resolution. Development of a limited-area version of the Centre's global spectral model has now reached the point where this version can begin to be used for experimentation at resolutions equivalent to the global T213 and beyond. An early study showed a marked sensitivity to horizontal resolution in the prediction of the severe storm which struck northern France and southern England on the night of 15/16 October 1987. Part of this sensitivity was accounted for by the lower horizontal diffusion employed at T213 resolution. Recent studies of hurricane "Gilbert" from the summer of 1988, of another case of intense extratropical cyclogenesis and of the development of a polar low have yielded further results of interest.

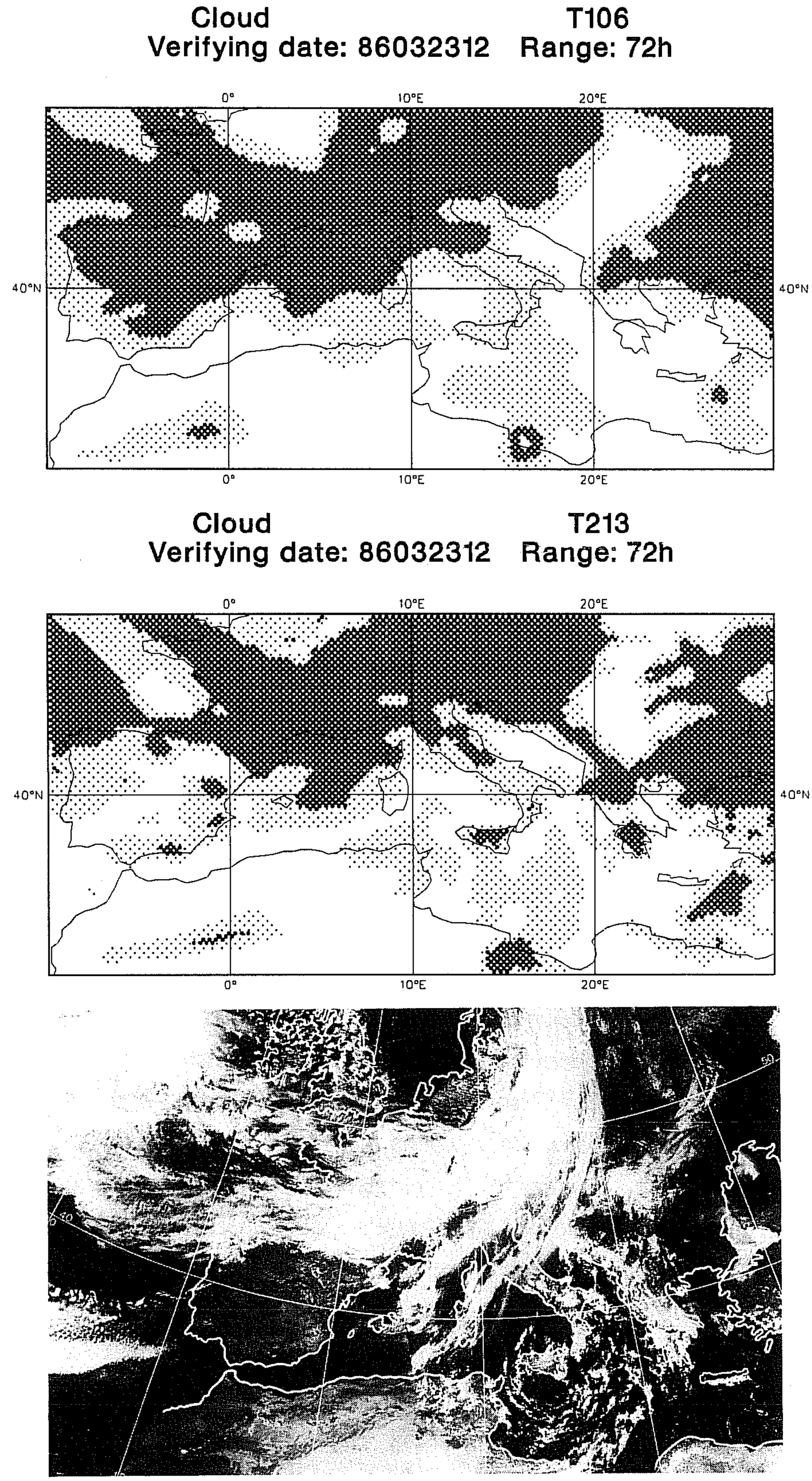



Fig. 11 Day-3 forecasts of cloud cover from T106 (upper) and T213 (middle). The heavier shading denotes cloud cover in excess of 80%, and the light shading shows cover in the range from 20 to 80%. The lower panel shows a composite satellite picture in the visible range valid for about the time in question, published by the Freie Universität Berlin, and reproduced here courtesy of the Meteorological Institute.

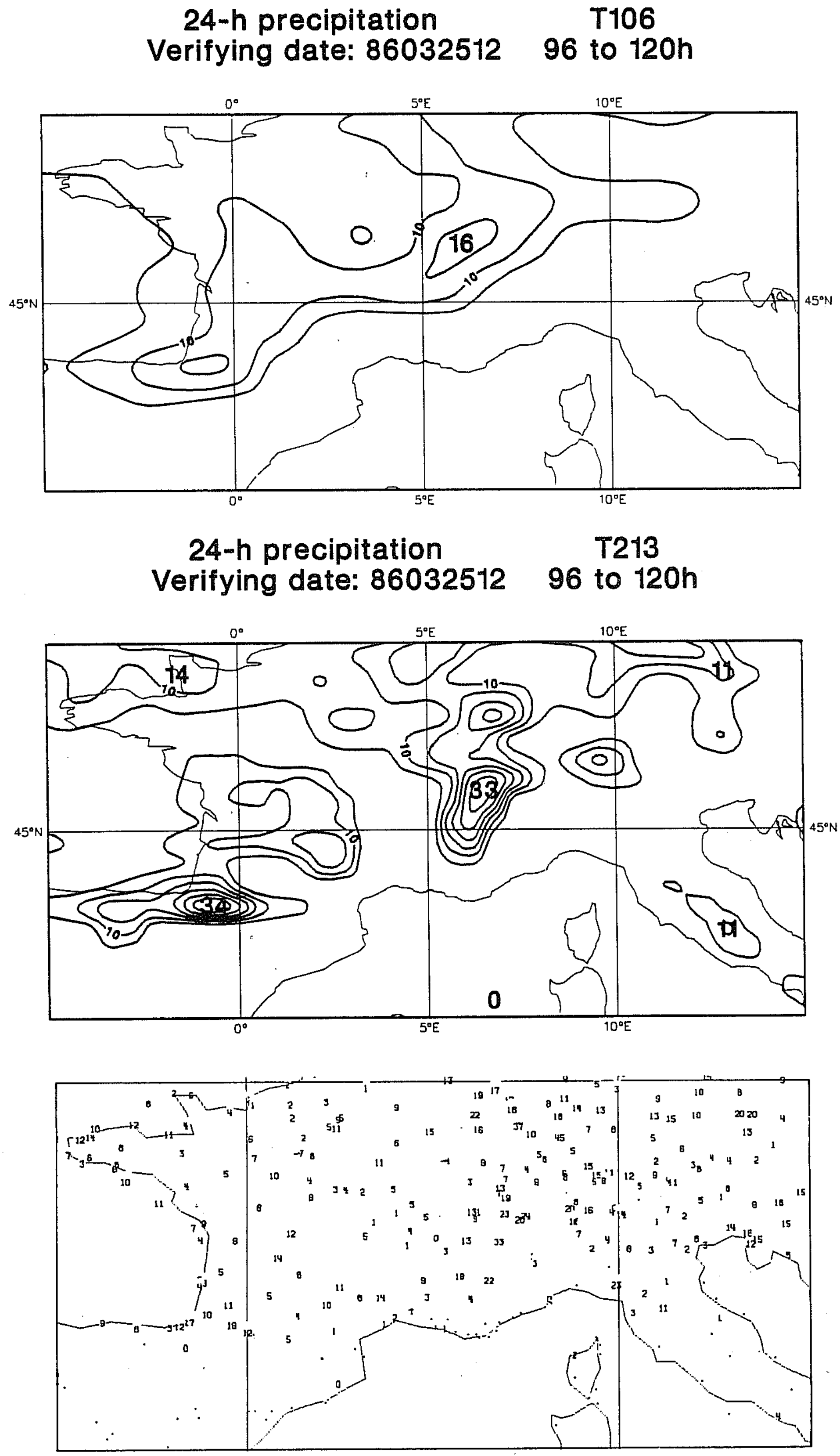



Fig. 12 Values of precipitation (mm) for the period 12UTC 24 March to 12UTC 25 March 1986. Forecasts from 12UTC 20 March are shown for this time range using T106 (upper) and T213 (middle) resolutions. Observed values are plotted in the lower map.

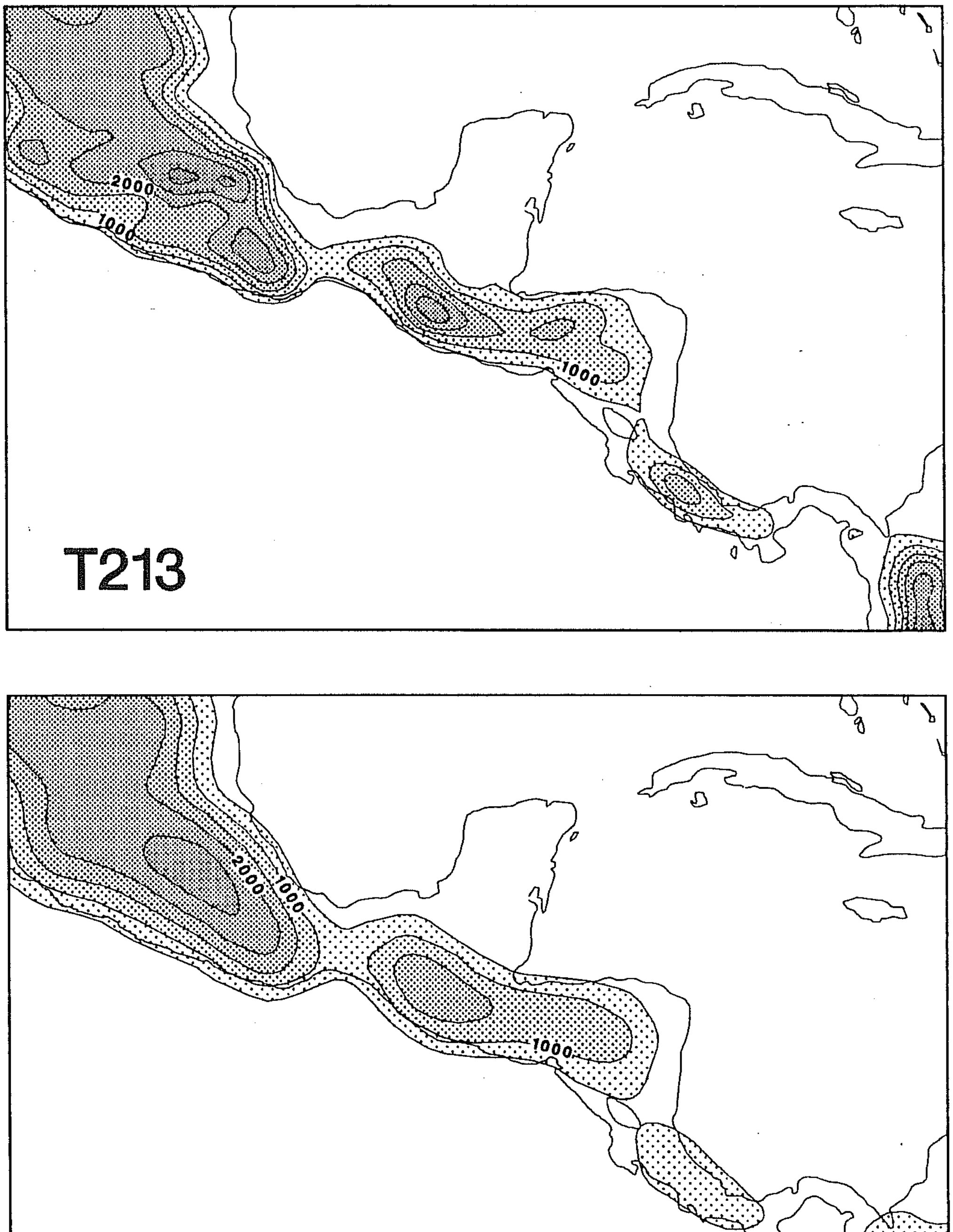



Fig. 13 Contours of model terrain height over Central America for T213 (upper) and T106 (lower) resolutions. The contour interval is 500m.

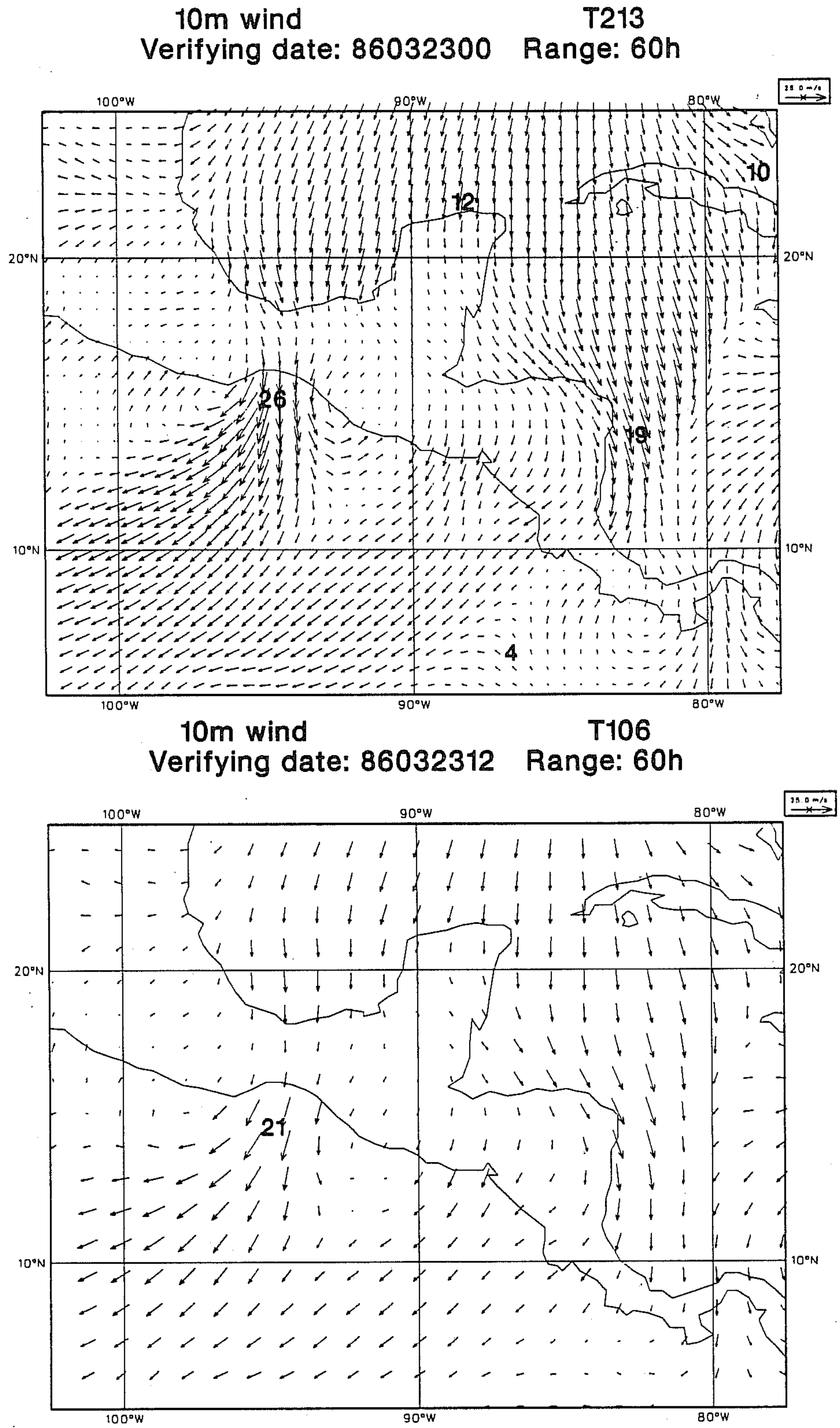



Fig. 14 Wind at 10m from 60-hour T213 (upper) and T106 (lower) forecasts. Maxima are marked in $ms^{-1}$.

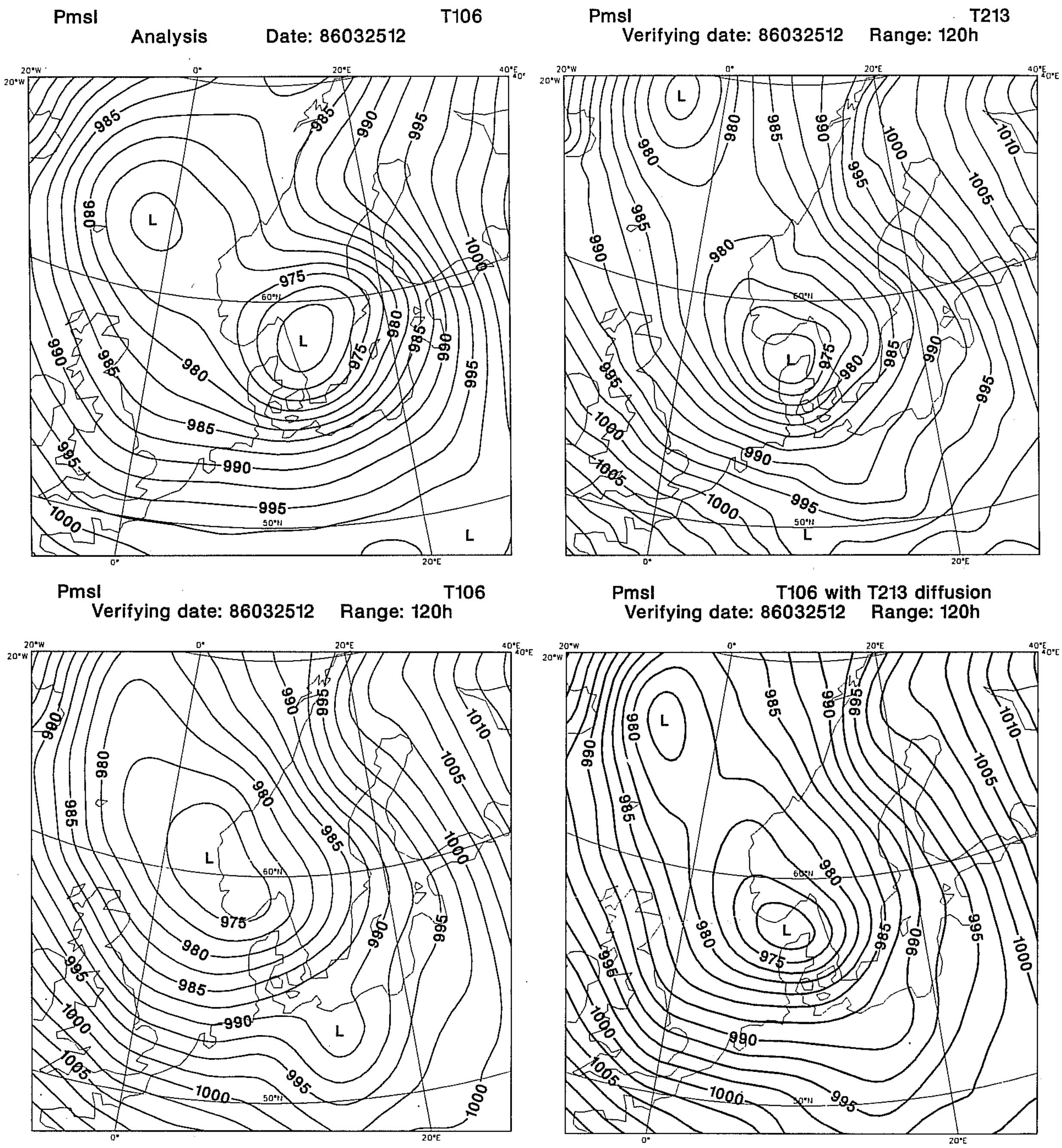



Fig 15 Mean sea-level pressure (hPa) as analyzed for 12UTC 25 March 1986 (upper left), and 5-day forecasts for this time using T213 (upper right) and T106 (lower left) resolutions. The corresponding map obtained when the T106 forecast uses the lower horizontal diffusion of the T213 forecast is shown in the lower right panel.

verification (not presented) shows the T106 forecast as a whole to be worsened by the reduction in diffusion.

### 3.2 T159 experiments

In addition to the T213 forecast, the impact of resolution increases beyond T106 has been studied in a set of 7 10-day forecasts, and a number of shorter-range forecasts, at T159 resolution. Here we give a brief summary of results, and discuss two items in a little more detail. Further findings are presented by Simmons et al. (1987).

An overall advantage of the resolution increase to T159 was found. In terms of objective assessment, the net improvement of T159 over T106 was about half the improvement of T106 over T63 in the medium range. Several of the cases were chosen because of the occurrence in the short range of a weather event for which some aspect of the forecast was expected to be sensitive to the horizontal resolution of the prediction model. Improvements in the representation of rapid cyclogenesis, frontal structure, orographic effects and the evolution of a polar low were indeed found. A tendency for a somewhat higher amplitude of the large-scale wave pattern was seen in the T159 forecasts, as indeed was the case in the T213 forecast discussed in the preceding section.

One of the cases studied was the evolution of hurricane "Gloria" as it moved towards and then along the eastern seaboard of the USA. As illustrated at the 1987 ECMWF Seminar (Simmons and Miller, 1988), the T159 forecast produced a track of the storm which was significantly closer to the analysed track than that produced by the T106 forecast. The better track, coupled with a greater (and more realistic) intensity of the system, resulted in a substantial difference in the amount of rainfall forecast over the East Coast. The T159 forecast was clearly the better, and its precipitation patterns over and to the north of the Great Lakes were also the more correct.

Deficiencies in models can be highlighted by changes in resolution. The T159 experiments have revealed a more pronounced overshoot (or "spin-up") of tropical convective heating in the early forecast period than occurs with T106 resolution, and the occasional occurrence of "noise" in the planetary boundary layer indicates the need to investigate further the parametrization of vertical diffusion, work that was necessary for the change from T63 to T106 (Jarraud et al., 1985). We conclude this section with brief discussion of one other problem.

As horizontal resolution increases, models can be expected to represent a larger degree of explicit orographically-induced gravity wave activity. Simmons (1987) presented cross-sections of wind and potential temperature at day 6 of T42, T63, T106 and T159

## 4. THE INCREASE FROM 16 TO 19 LEVELS

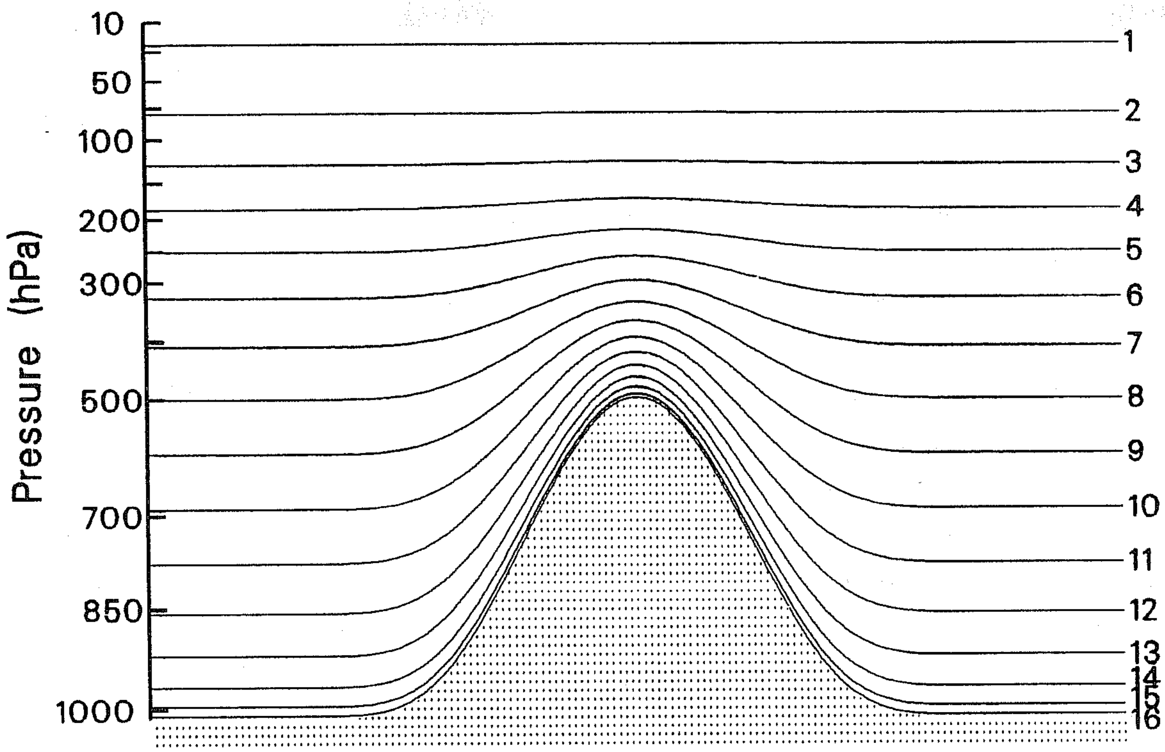
Figure 16 shows the original operational 16-level vertical resolution and the 19-level resolution currently used. The principal motivation for investigating the change from 16 to 19 levels came from problems experienced with the stratospheric analyses produced operationally with the 16-level model. Because of the limited stratospheric resolution of this model, it was used in data assimilation to provide first-guess information only up to 50 hPa. For analysis at 30, 20 and 10 hPa, the differences of first-guess fields from model-generated values at 50 hPa were taken to be a blend of the differences for the preceding analysis and climatology. The preceding analysis was smoothed by representing it as a truncated series of Hough functions.

These procedures proved, however, to have some serious drawbacks. The use of the preceding analysis to provide the first-guess resulted in a tendency for incorrect structures (introduced by bad data) to persist through many data assimilation cycles. In addition, the vertical coherence of the model first-guess was disturbed, resulting in large initialization changes in the model stratosphere. Tidal signals were also mishandled. The Hough filtering gave rise to further problems, among them the removal of Kelvin waves, the weakening of strong gradients and bias towards the acceptance of wind rather than height information.

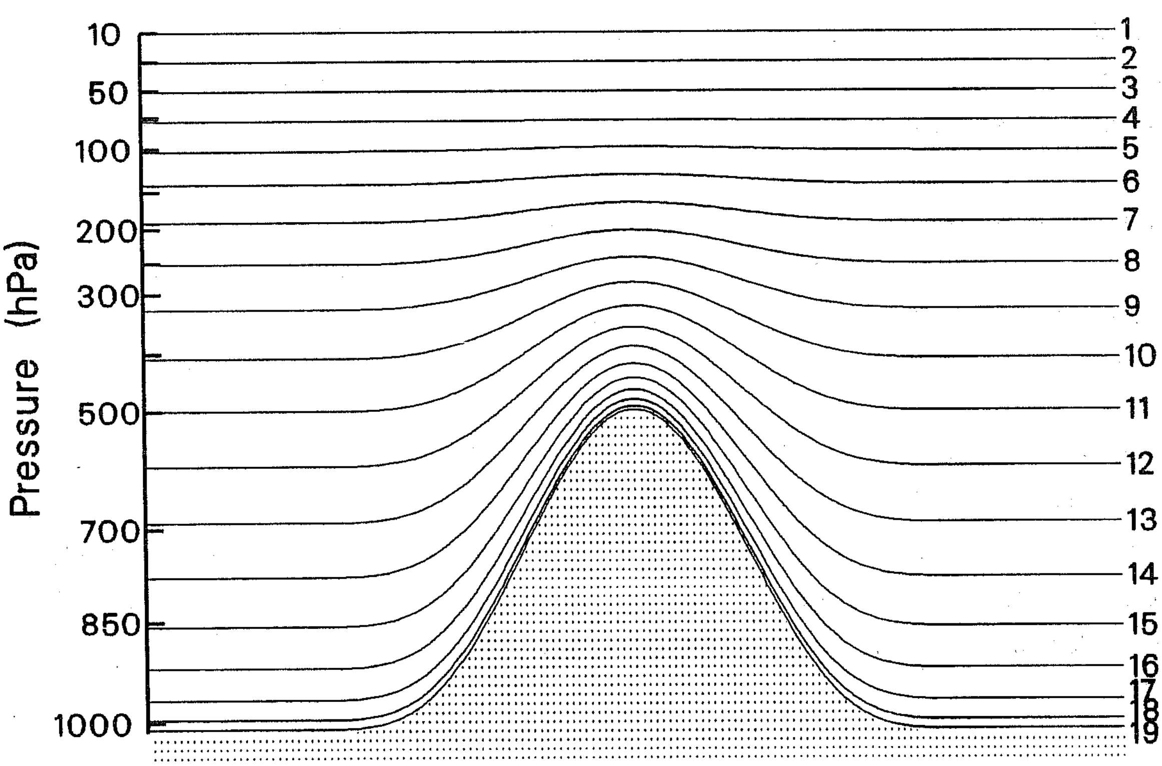
The 19-level resolution was designed to remedy these problems by providing a model first-guess that could be used at all analysis levels. For this resolution, no use of persistence and climatology is made in the formation of the first-guess, and no Hough filtering is applied.

After successful preliminary investigations, two periods of extended data assimilation were carried out to test the longer-term stability of assimilations using the 19-level model, and to provide initial datasets for examining the impact of the resolution change on medium-range forecasts. The first comprised a 19-level test from 14 to 26 February 1985 using T63 horizontal resolution. The versions of the model and analysis codes operational in early 1986 were used, and a parallel 16-level assimilation was run to provide a strict control.

Because of large initial interpolation and extrapolation errors it took about 2 days for the 19-level assimilations to become well established. Results thereafter showed no sign of a systematic drift of the assimilation. The fits of first guesses and analyses to data in the stratosphere (see Simmons et al., 1989) were significantly improved by use of the 19-level model, particularly in the tropics, where some benefit was found almost down to the surface.




16-LEVEL MODEL




19-LEVEL MODEL

Fig. 16 Distributions of the "full" model levels where winds, temperature and humidity are represented for the original 16-level operational resolution and the current 19-level operational resolution.

The second spell of data assimilation was run in parallel to operations at T106 resolution, from 24 to 30 March 1986. Results were qualitatively similar to those discussed above, but the fit to tropical height data was even better, because a special handling of the tides in the initialization used for this series (Wergen, 1987) responded to a vertically more coherent tidal signal from the 19-level model. Synoptic assessment showed the 19-level assimilation to be free from spurious tropical stratospheric vortices, the persistence of which was a particularly detrimental feature of the 16-level analyses.

Forecasts from both spells of extended data assimilation were run at two-day intervals starting from the second day of each assimilation. This gave 9 pairs comprising 16-level forecasts from 16-level assimilations and 19-level forecasts from 19-level assimilations. Six 16-level forecasts were also run using initial fields derived by vertical interpolation from the first set of 19level analyses. These sets of forecasts have been verified objectively, and some averaged results are shown in Figs. 17 and 18. The upper plot of Fig. 17 presents anomaly correlations for the extratropical 500 hPa height field of the Northern Hemisphere for the 19-level forecasts from the 19-level assimilations and the 16-level forecasts from the 16-level assimilations. It shows little impact of the resolution increase in the first half of the forecast range, but a quite substantial improvement beyond day 6. Examining results for individual forecasts reveals improvement in all but one case beyond day 7. Corresponding scores but with the 16-level forecasts carried out from initial conditions derived from the 19-level assimilation are shown in the lower plot of Fig. 17. This shows that much, though not all, of the improvement comes from the improved initial state, rather than from improved stratospheric resolution during the execution of the 10-day forecast.

Initial analyses were improved more substantially in the tropics than in the extratropics by the use of the 19-level model, and this is reflected in the forecast verification. The upper plot of Fig. 18 shows mean absolute correlations of 850 hPa vector wind. These clearly favour the 19-level system, despite a penalty from using (operational) 16-level analyses for verification, which results in spuriously higher initial scores for the 16-level forecasts. Improvement is seen earlier in the forecast range than for the Northern Hemisphere, a result consistent with the noticeably improved fit of the 19-level analysis to wind observations at as low a level as 850 hPa in the tropics. Some improvement in objective scores for the Southern Hemisphere is seen later in the forecast range (lower plot of Fig. 18), although the overall forecast quality is much poorer in this hemisphere for the cases studied.

Subjective assessment of the forecasts reveals a distinct improvement over Europe in the latter half of the 10-day range. This is found in many individual cases, and shows clearly in ensemble-averaged maps. Fig. 19 presents, from the first period of data assimilation, 6-case average 500 hPa heights for 3 sets of day-10 forecasts and for the corresponding

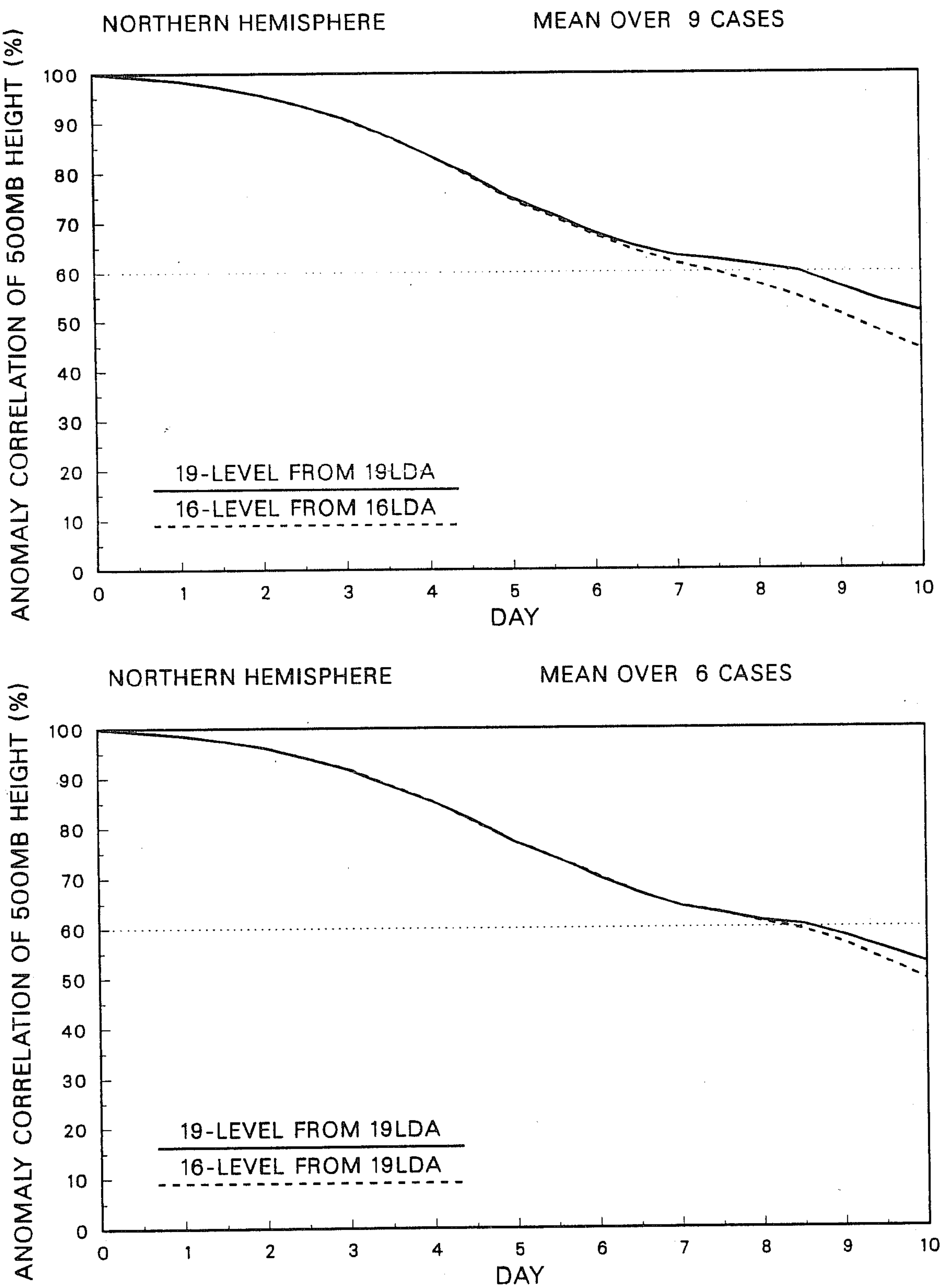



Fig. 17 Ensemble-means of anomaly correlations of 500 hPa height for the extratropical Northern Hemisphere. The solid lines denote 19-level results and the dashed lines those for 16 levels. In the upper panel, the 16-level forecasts were run from 16-level assimilations, and in the lower panel they were run from interpolated data from the 19-level assimilations.

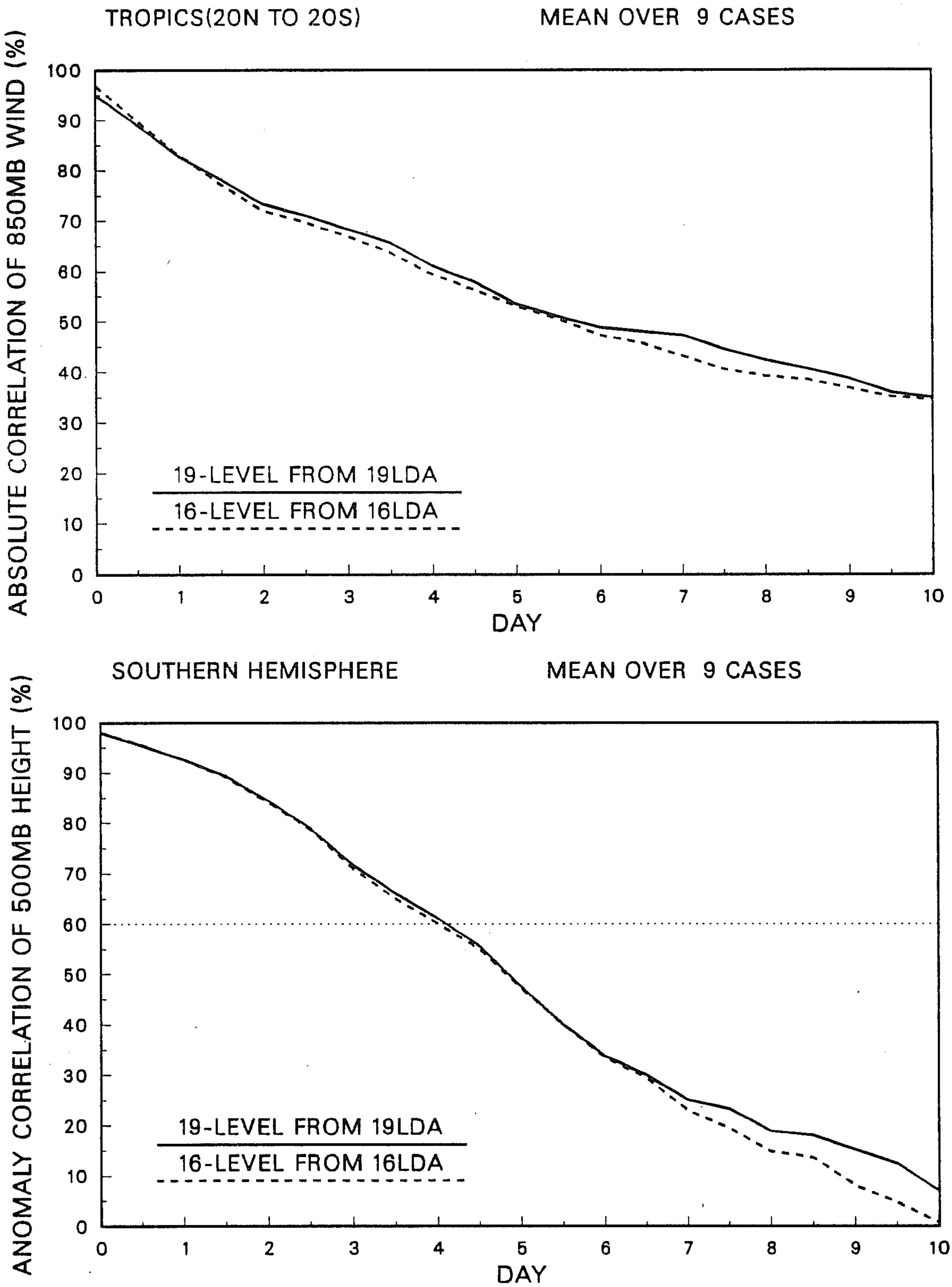



Fig. 18 Ensemble-means of absolute correlations of 850 hPa vector wind for the tropics (upper) and of anomaly correlations of 500 hPa height for the extratropical Southern Hemisphere (lower). The solid lines denote 19-level results and the dashed lines those for 16 levels (from 16-level assimilations). Operational analyses produced using 16 levels are used for verification.

verifying analyses. The mean analysis is shown in the upper left panel. Upper right is the mean 19-level forecast from the 19-level assimilation, and lower left the mean 16-level forecast from the 16-level assimilation. Improvements in the Atlantic jet, the jet split and the downstream ridge and trough are evident. The lower right panel shows the corresponding mean D+10 forecast using the 16-level model from the 19-level analyses. This captures much of the improvement, in agreement with the result of objective assessment.

It is difficult to quantify reliably the impact of a model change which has a significant effect on data assimilation, because of the impracticality of carrying out the necessary periods of data assimilation across a wide range of synoptic situations. In particular, it should be remembered that the experiments that have been discussed here were carried out for just two late-winter periods, and that the impact on forecast accuracy almost certainly would vary with synoptic situation and season. However, it is worth noting that running 16-level forecasts from 19-level operational analyses for cases from the Northern Hemisphere winter of 1986/87, when the stratospheric vortex was substantially disturbed, showed a larger impact of enhanced stratospheric resolution in the second half of the forecast range than in the cases reported above. This can be seen by comparing the plot in Fig. 20 with the lower plot in Fig. 17.

A further benefit of the resolution increase to 19 levels was a distinct improvement in the winter tropospheric climate of the model, as determined by a series of 90-day integrations at T42 resolution. This is in agreement with results of Boville (1984) concerning sensitivity of tropospheric simulations to the representation of the stratosphere. Increased stratospheric resolution acts particularly to reduce erroneously high westerly flow over northwestern Europe. An example has been presented by Simmons (1987). This example shows also how a change in numerical scheme, use of envelope rather than mean orography, and introduction of a parametrization of gravity-wave drag can bring about changes in model climate which are, qualitatively at least, of a similar nature. The example is an indicator of the caution that has to be exercised in the development of climate models, for example in fine-tuning an orographic representation to improve the climate of a model with inadequate stratospheric resolution.

Comment on one further aspect of increased stratospheric resolution is appropriate. During testing of the 19-level version, gravity-wave cases were examined which were more extreme than that illustrated by Simmons (1987) and discussed in the preceding section. Strong mountain waves appeared explicitly at T106 and T63 truncations. These showed a severe stratospheric problem at higher vertical resolution, with the occurrence at small horizontal scales of pronounced two-grid waves in the vertical at upper model levels. This led to the use of higher horizontal diffusion in the stratosphere of the operational 19-level

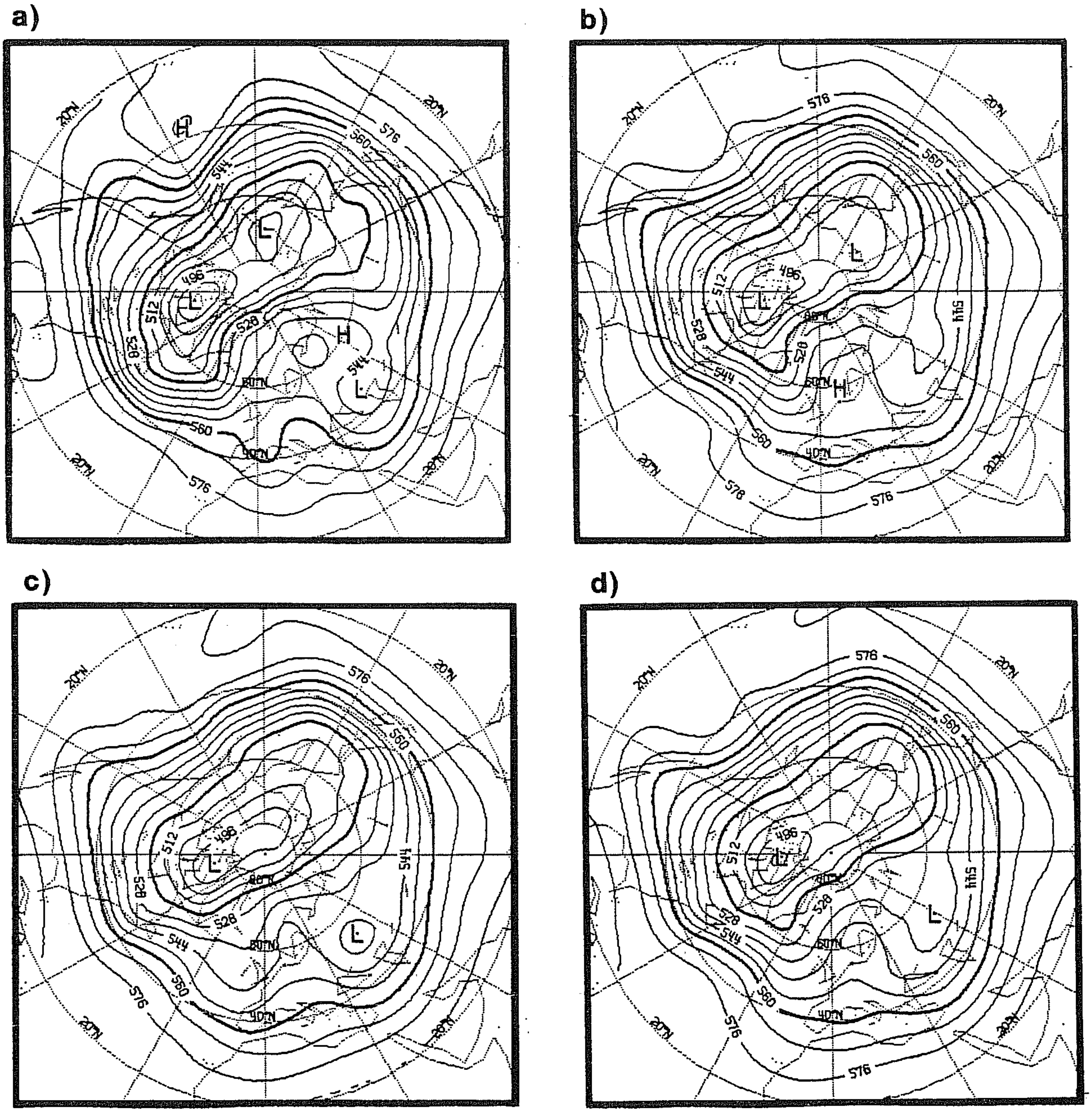



Fig. 19 Ensemble-mean 500 hPa heights (contour interval 8 dam) for a) verifying analyses, b) 19-level D+10 forecasts from the 19-level assimilation, c) 16-level forecasts from the 16-level assimilation, d) 16-level forecasts from the 19-level assimilation.

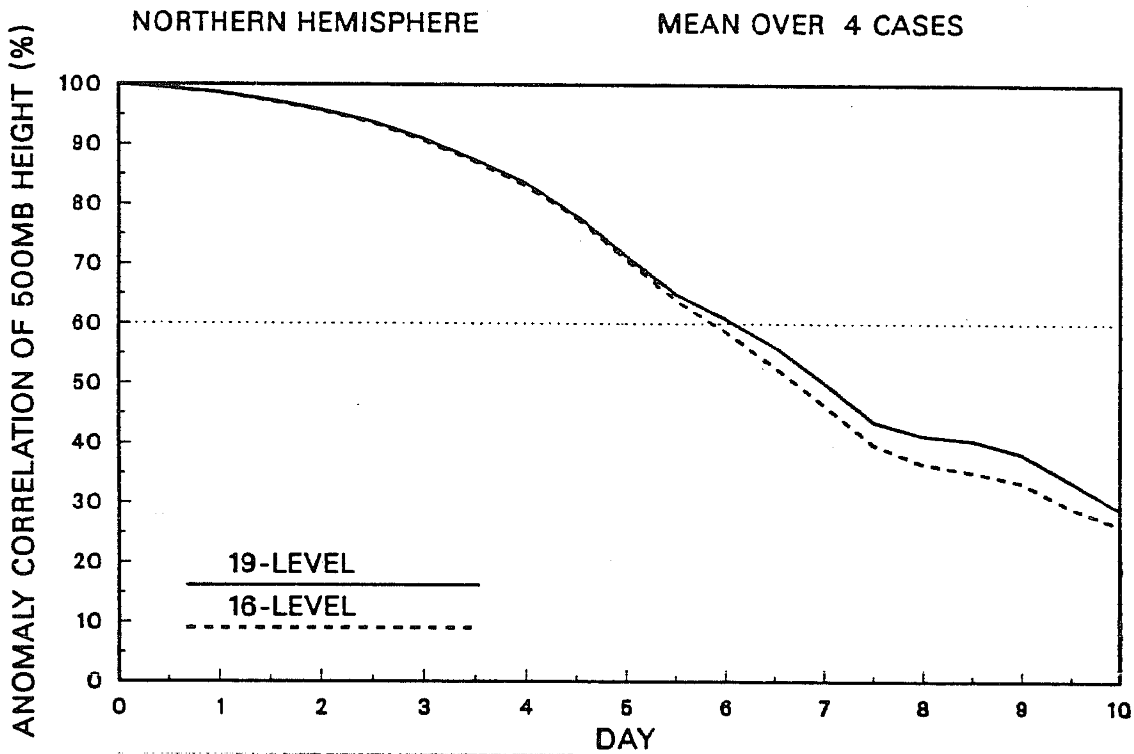



Fig. 20 Anomaly correlations of 500 hPa height for the extratropical Northern Hemisphere, averaged over four cases from the winter of 1986/87. The solid lines denote 19-level results and the dashed lines those from 16-level forecasts run from interpolated 19-level initial data.

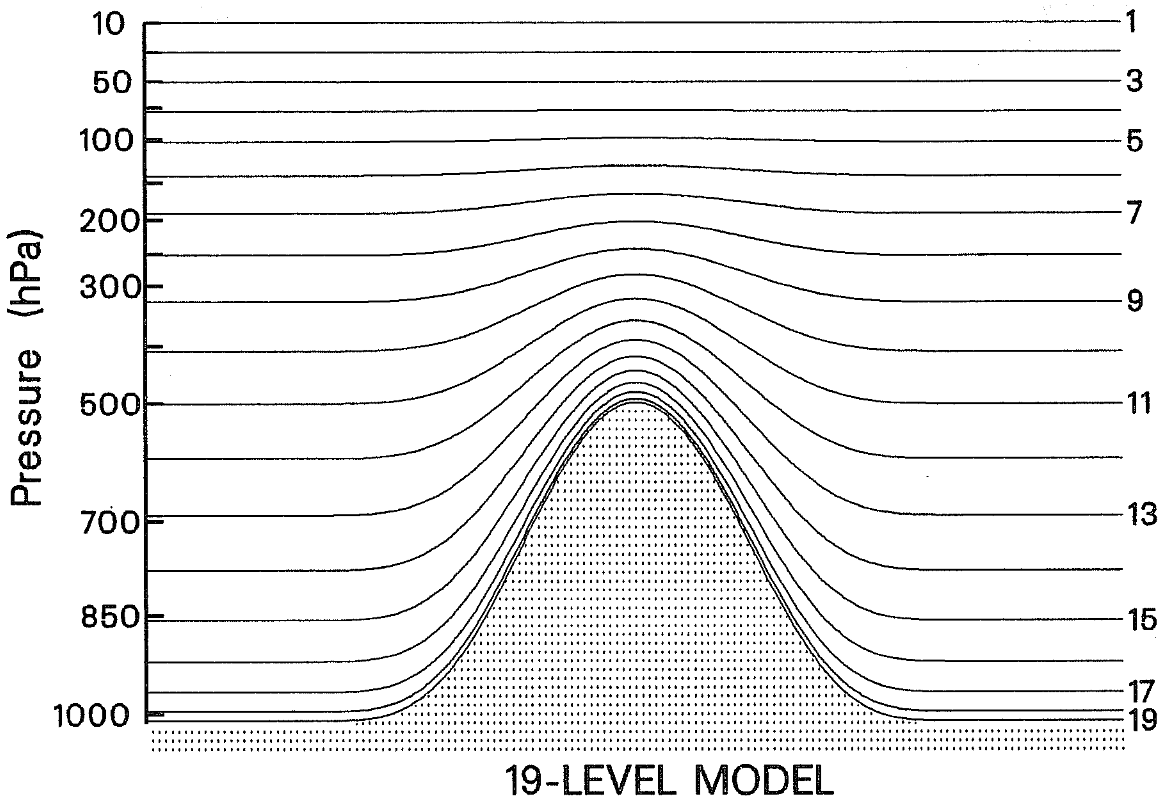
model, an apparently effective remedy, at least for the short term, but one which does not obviate the need for a much more thorough study of the representation of stratospheric gravity-wave propagation as horizontal and vertical resolution increase further.

## 5. STUDIES OF A 31-LEVEL RESOLUTION

Work on a general increase in vertical resolution is currently being carried out in preparation for the future implementation of a higher (horizontal and vertical) resolution model. The vertical resolution that has been most extensively tested has 31 levels distributed such that layer thicknesses are approximately halved over most of the free troposphere and lower stratosphere, with resolution unchanged close to the ground (where it is determined principally by the requirements of boundary-layer parametrization) and near the top of the model. This 31-level resolution is shown schematically in Fig. 21.

T63 horizontal resolution has been used for the bulk of the experimentation to date. This was in order to reduce computational demands, but it should be noted that if one takes a ratio of around 100 to 1 as representative of the ratio of horizontal to vertical scales in mid-latitude weather systems, then this suggests that finer horizontal resolution should be used to measure the full benefit of the increase to 31 levels. Also in the context of the consistency between horizontal and vertical resolution, it is found that at both T63 and T106 horizontal resolutions the timestep of the model has to be reduced when changing from the 19- to the 31-level vertical resolution. The usual timesteps for these horizontal resolutions are not small enough to lie within the CFL stability limit for vertical advection when the vertical resolution is increased.

A first set of experiments was carried out using interpolated operational (T106L19) analyses to provide initial conditions. Thirteen experiments were carried out in all. The first case, starting from a special FGGE analysis for 16 January 1979, had shown sensitivity to vertical resolution in much earlier tests using the grid-point model, and the new experiment again demonstrated a better representation of a blocking high in the second half of the forecast range. The remaining cases were simply chosen at monthly intervals from 15 June 1986 to 15 May 1987. Objective verification did not reveal a substantial overall sensitivity, but there was an indication of a small net improvement of the 31-level forecasts over the 19-level forecasts in both the extratropics and tropics. Such mean results must however be treated with caution, as examples of pronounced sensitivity have been found later in the forecast range. Results indicate that the Atlantic is a region particularly sensitive to vertical resolution, and comparing the evolution of the height field in a number of cases points to the Rockies and Greenland as sources of differences. This suggests a relationship between vertical resolution and the treatment of orography,



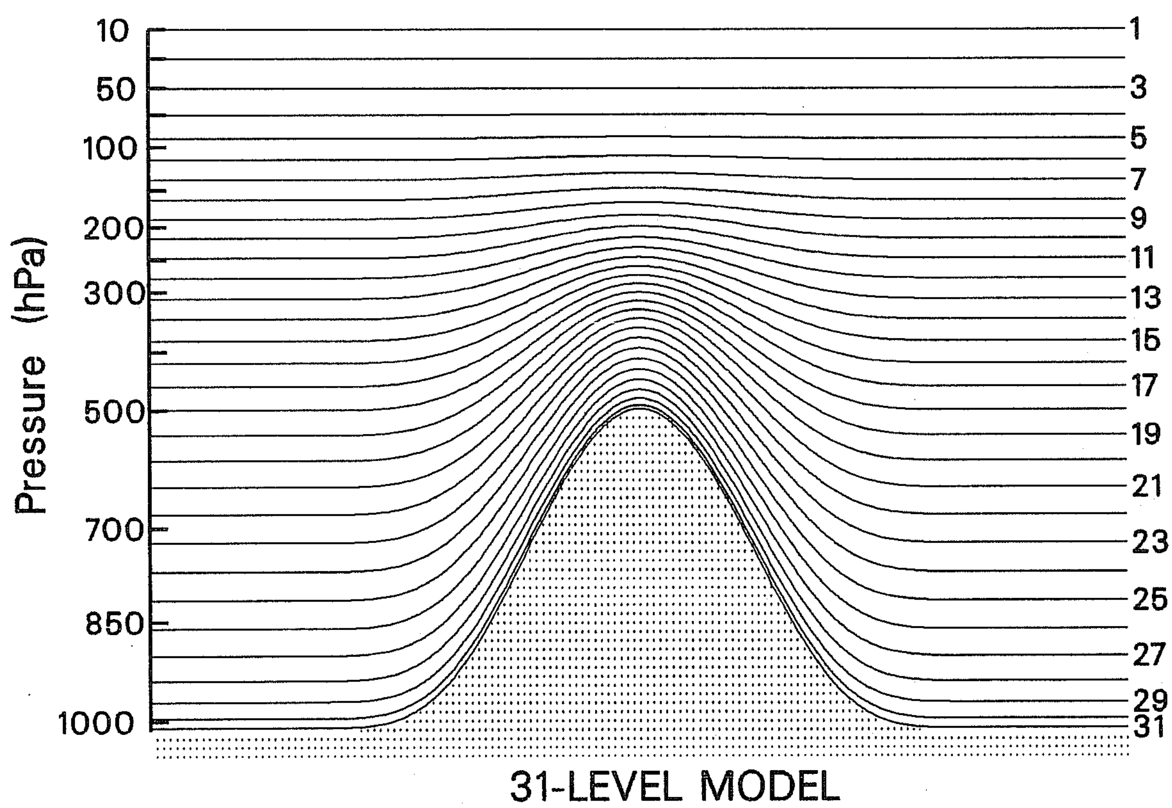




Fig. 21 Distributions of the "full" model levels for the 19-level operational resolution and the experimental 31-level resolution.

associated either with the representation of actual meteorological effects or with the numerical problems of steeply-sloping coordinate surfaces.

As an example of synoptic impact in the short range we look at the one case that has been run with T106 horizontal resolution. This is a second case from the FGGE year: the "Presidents' Day Storm". Diagnosis of this event has indicated the importance of a pronounced tropopause fold which developed upstream prior to the surface cyclogenesis (e.g. Uccellini et al., 1985). The upper panels of Fig. 22 show analyses for 12UTC 20 February 1979. Cyclogenesis has already taken place near the eastern seaboard of North America, and the low has moved out over the Atlantic, with a sharp trough at 500 hPa. This trough is well captured in amplitude and position in the 31-level forecast (middle panels), and is treated less accurately in the 19-level forecast. The surface low is also better positioned in the 31-level forecast. Its depth appears to be overestimated, although note should be taken of a tendency for the objective analysis to underestimate actual depths in cases of rapid cyclogenesis.

Examination of a series of vertical cross-sections reveals a number of local improvements in vertical structure in this and other cases. The expected sharpening of features in the vertical is found, notably at the tropopause and at the top of the planetary boundary layer. An indication of somewhat lower relative humidities in the boundary layer has also been found.

A start has recently been made on examining the performance of the 31-level resolution in data assimilation. Three short spells of assimilation have been carried out using T63 horizontal resolution and 19- and 31-level versions of the model. Six forecasts have been carried out, from the 14th and 15th of January, February and July, 1988. 31-level forecasts were run both from the 31-level analyses, and from data interpolated from the 19-level analyses.

Mean anomaly correlations of 500 hPa height for the extratropical Northern Hemisphere are presented in Fig. 23. The upper panel compares 19- and 31-level forecasts from 19- and 31-level assimilations respectively, and a positive impact of the increase in vertical resolution shows up clearly in the medium range. The lower panel shows the 19- and 31-level forecasts when both are run from the 19-level assimilations. Here the positive impact around days 5 to 7 is much smaller, and for this sample of cases, the 19-level resolution gives better mean results towards the end of the forecast range. Corresponding results for the Southern Hemisphere are given in Fig. 24, and a synoptic example from the Northern Hemisphere is presented in Fig. 25. It is evident that as with the increase in stratospheric resolution discussed in the preceding section, much of the benefit of the

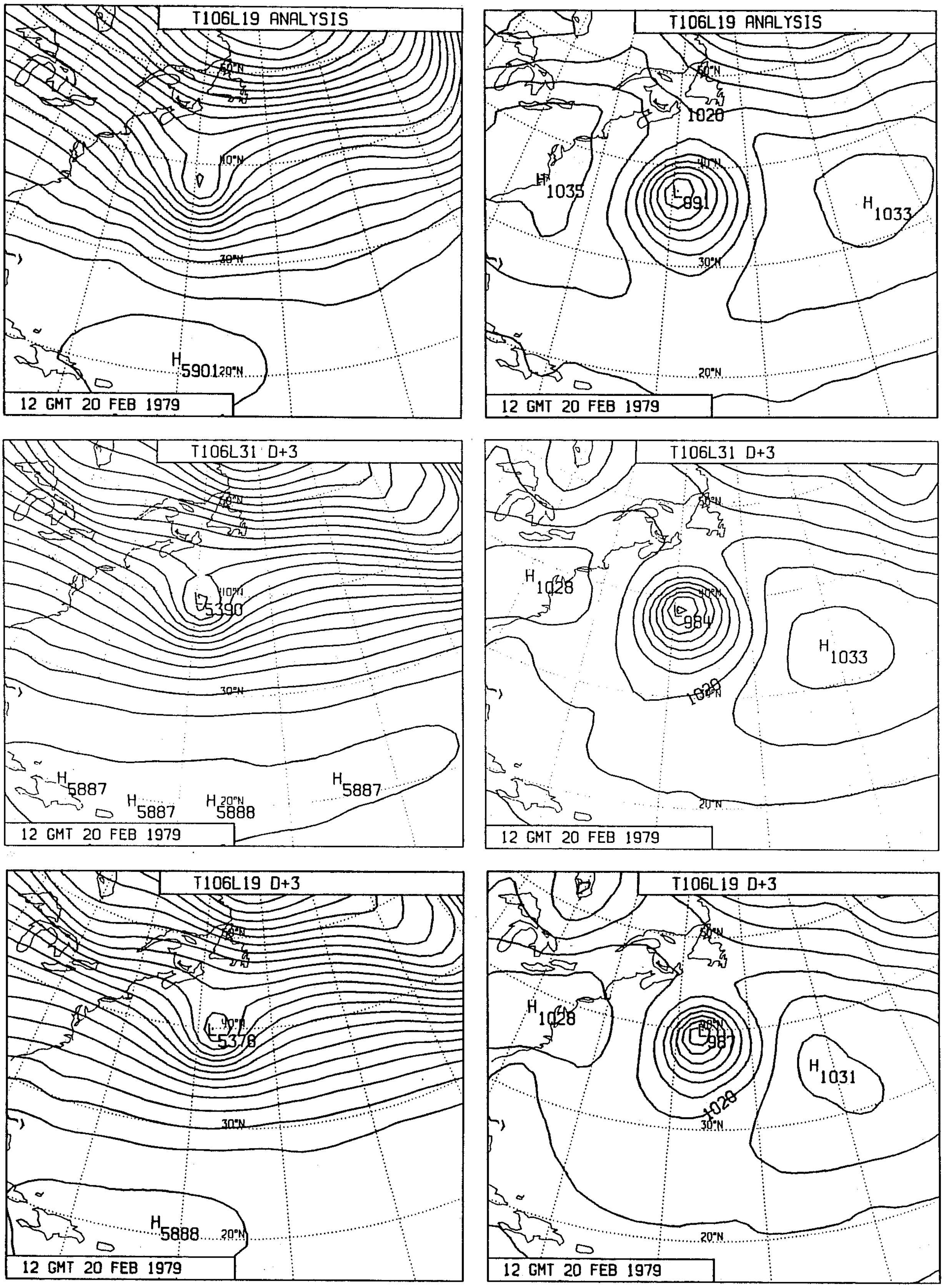



Fig. 22 500 hPa height (left, contour interval 4 dam) and mean sea-level pressure (right, contour interval 5 hPa) for 12UTC 20 February 1979.
Upper: Analysis
Middle: 3-day 31-level forecast
Lower: 3-day 19-level forecast

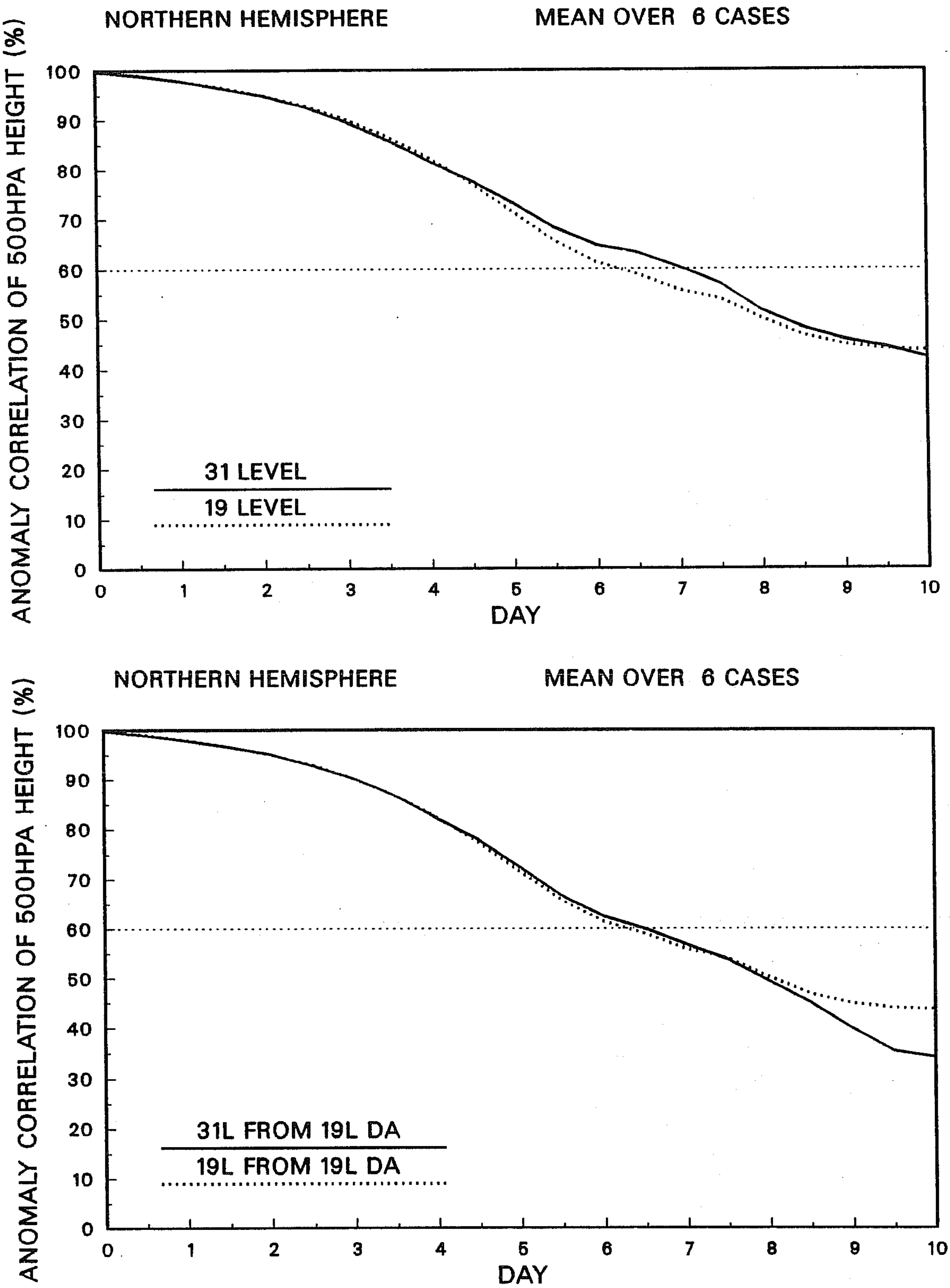
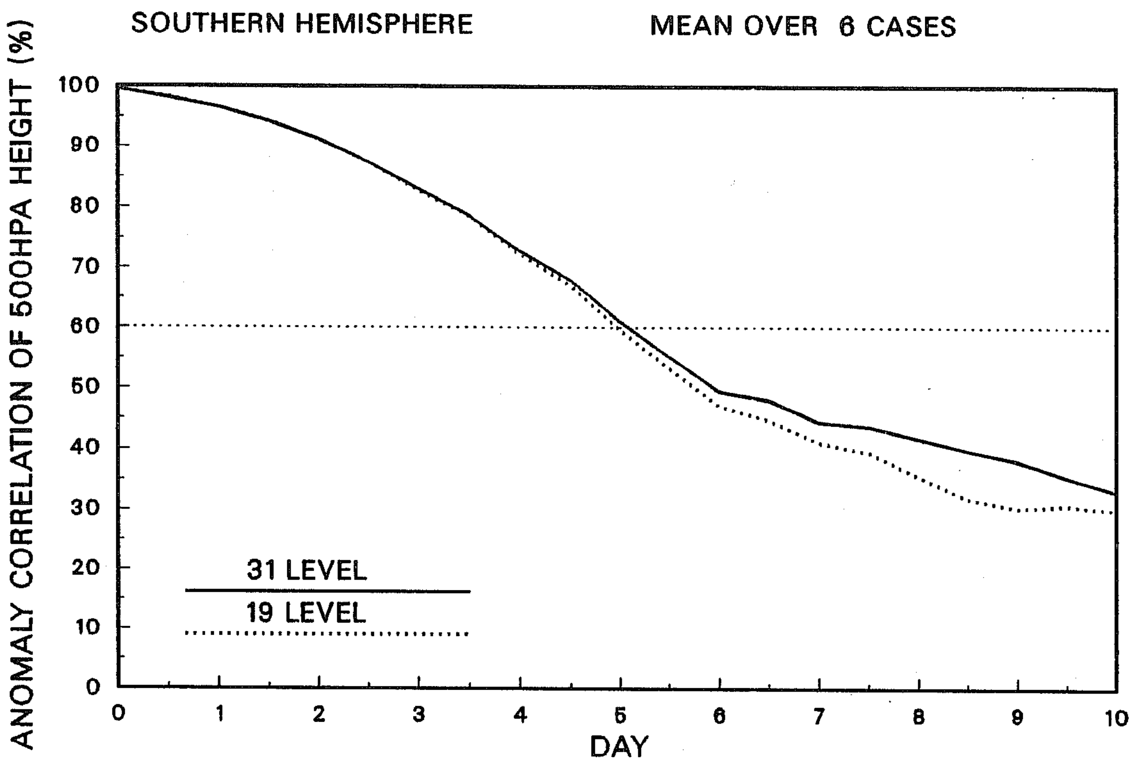



Fig. 23 Ensemble-means of anomaly correlations of 500 hPa height for the extratropical Northern Hemisphere. The solid lines denote 31-level results and the dashed lines those for 19 levels. In the upper panel, the 31-level forecasts were run from 31-level assimilations, and in the lower panel they were run using interpolated initial data from the 19-level assimilations.



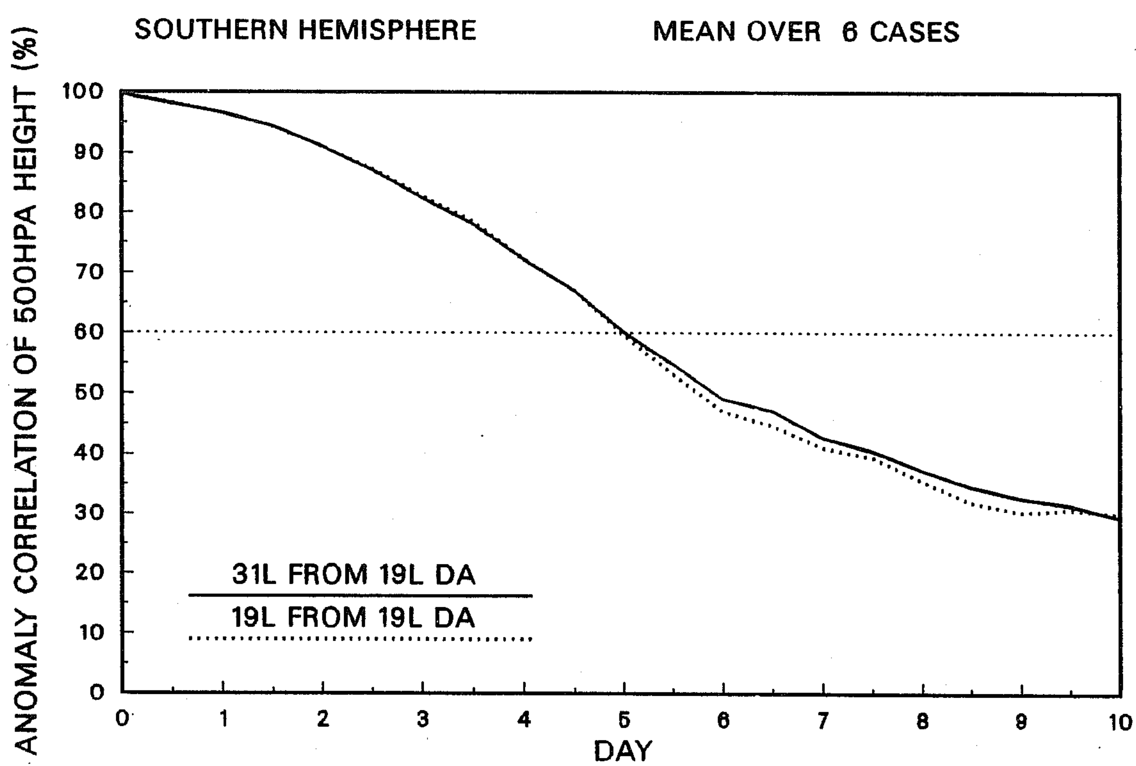




Fig. 24 Ensemble-means of anomaly correlations of 500 hPa height for the extratropical Southern Hemisphere. The solid lines denote 31-level results and the dashed lines those for 19 levels. In the upper panel, the 31-level forecasts were run from 31-level assimilations, and in the lower panel they were run using interpolated initial data from the 19-level assimilations.

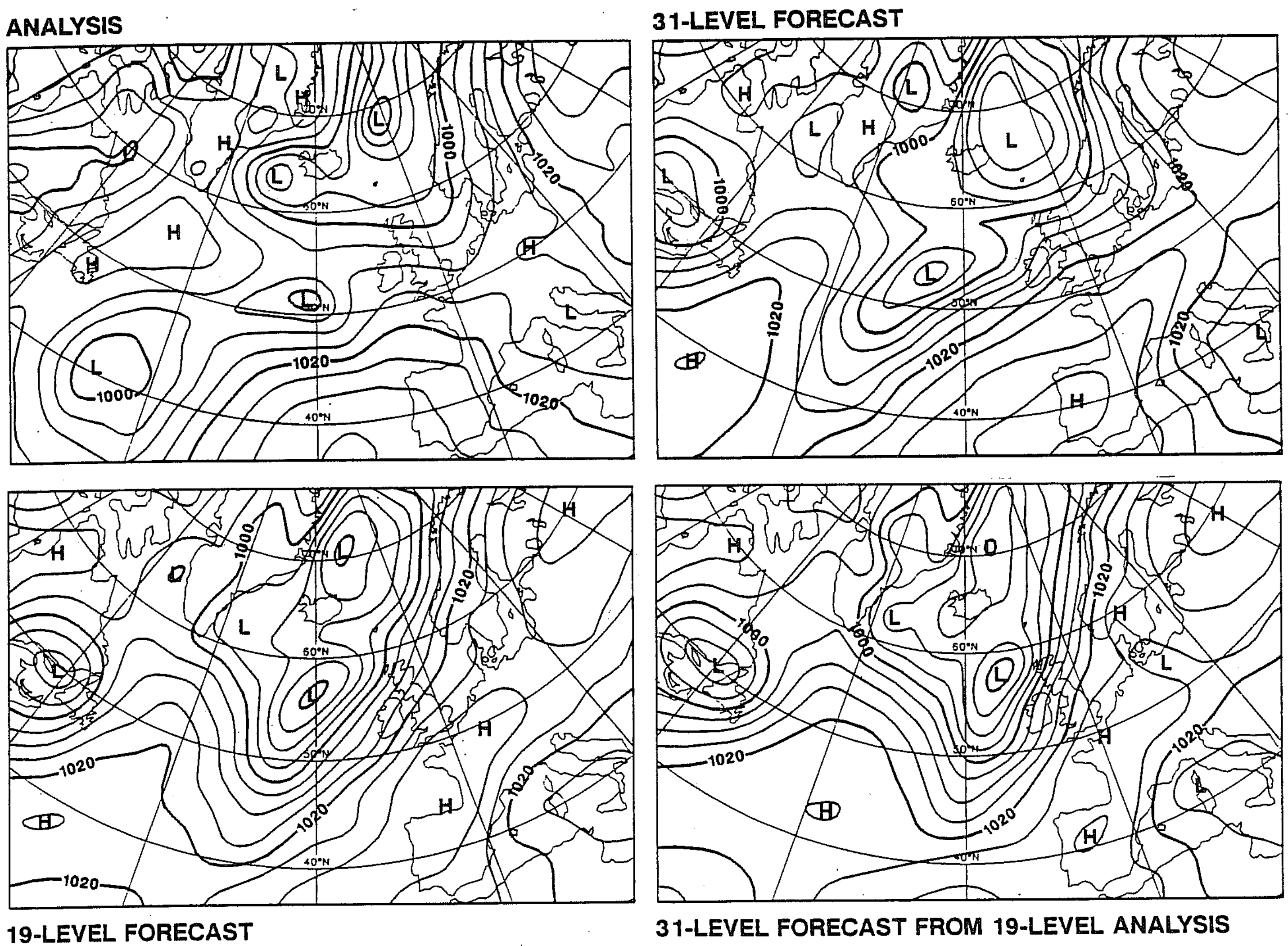



Fig. 25 Mean sea-level pressure (contour interval 5 hPa) for 12UTC 21 January 1988.
Upper left: Analysis
Upper right: 6-day 31-level forecast from 31-level assimilation
Lower left: 6-day 19-level forecast from 19-level assimilation
Lower right: 6-day 31-level forecast from 19-level assimilation

increase in vertical resolution in these six cases comes from the improved definition of the initial state when the higher vertical resolution is used in the data assimilation.

## 6. CONCLUDING COMMENTS

Objective verification of spectral-model forecasts reveals a clear increase in skill as horizontal resolution is refined. Although the mean improvement of T106 over T63 is distinctly smaller than that of T63 over T42, it is nevertheless quite systematic early in the forecast range, particularly at the surface. The impression from subjective synoptic assessment is one of a more decisive advantage of T106 over T63, with quite regular improvements in detail in the first few days of the forecasts, and occasionally substantial impact later in the medium range. More intense and highly structured systems are found at higher resolution, and this tends to bias objective scores towards favouring lower resolution once other sources of error have caused a serious degradation in the synoptic-scale evolution of the forecast. Given a broadly correct prediction of the synoptic pattern, increased horizontal resolution (to T106 and beyond) can result in some very clear improvements in local forecasts of weather elements such as precipitation, and low-level wind and temperature.

It must be stressed that the results relating to the 31-level vertical resolution do not represent a completed study, but rather a progress report on work which is ongoing. Coming as they do from the first sets of experiments in which the vertical resolution of the model has been comprehensively enhanced, they provide some encouraging indications of the gains in accuracy that might be attained from operational introduction of higher vertical resolution, and justify the continuing work on this topic that is being undertaken as part of the preparation of an improved version of the spectral model (including higher horizontal resolution) for implementation on the computer that replaces the Centre's CRAY X-MP/48. Effort is currently being devoted to further study of the 31-level resolution in data assimilation, including investigation of the use of observational data at levels in addition to the standard pressure levels currently used. A further increase of resolution in the middle stratosphere and a raising of the top full level above 10 hPa are also being considered.

Notwithstanding the undoubted benefits of increased resolution, the mean differences in skill of T63 and T106 forecasts, or between 19- and 31-level forecasts, remain small compared with the large variations in mean skill that are found to occur between one month and another (see, e.g. Simmons, 1986), or indeed compared with shorter-term variations in forecast skill. Looking at the future one may foresee the use of higher resolution as providing worthwhile increases in synoptic-scale accuracy and local detail in the first part of the medium range. There may well, however, be a point in the forecast range beyond which increased computational power is better used to run some form of ensemble of lower resolution forecasts to provide indications of expected reliability. Quite where this point will lie will depend on the extent to which forecasts are improved by the development of better parametrizations and numerical techniques, and by better data assimilation (which itself is in part dependent on model resolution), since as other sources of forecast error are reduced, a more pronounced impact of higher resolution may occur.

ACKNOWLEDGEMENTS

Many people have contributed to the work discussed here. M. Jarraud worked extensively on the first set of T63/T106 comparisons and W. Wergen on the change from 16 to 19 levels. Technical work to enable the T213 forecast to be run was carried out by D. Dent. The work of J. Chen relating to the pressure-gradient calculation, and of P. Unden and T. Davies with the 31-level model is also gratefully acknowledged.

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