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Some results from studies of increased horizontal and vertical resolution

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1. INTRODUCTION

The Scientific Advisory Committee, in formulating its overall view on the Four-Year Plan presented to it at its 1986 Session, considered it important to specify the following questions[1], whose answers would lead to a rational evolution of the Centre's forecasting system, bearing in mind the need of the Council to balance expected forecast improvements with the scientific and technical efforts required to obtain them:

(i) What improvements are found as resolution is increased? To what extent are these due to

- improved representation of orography?
- improved advection?
- improved performance of parameterizations?
- improved data assimilation?
- increased separation of important synoptic scales from scales where horizontal dissipation acts?

(ii) What initial data are required and attainable to support a forecasting model with increased resolution?

(iii) What are the problems associated with partly resolving mesoscale features?

(iv) What is the best way of extracting information from the forecasting system? Is an ensemble of forecasts carried out at less than the maximum resolution possible for an individual forecast, the best approach?

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[1]Report of the Fourteenth Session of the Scientific Advisory Committee Section 7.4, Paragraph (b).

During the past year, resolution studies have continued to form a part of the Centre's research programme, and the results obtained from them may be used to provide at least partial answers to the above questions. In this paper we present a selection of these results.

The material we draw on is primarily from an extensive set of forecasts carried out using both T63 and T106 horizontal resolutions, from a limited number of forecasts with T159 horizontal resolution, and from a small set of T63 forecasts comparing the performance of standard (19- or 16-level) vertical resolutions with that of a 31-level resolution in which layer thicknesses are approximately halved in the free troposphere and around the tropopause. Some additional experiments aimed at indicating sensitivity to the resolution of the orography and magnitude of horizontal diffusion have been carried out, and first result of utilizing the spectral limited-area model are also available.

The following section is concerned specifically with the comparison of results from T63 and T106 resolutions, with attention concentrated on objective verification. Included are results of running a number of the T106 forecasts with either T63 orography or with the diffusion coefficients used for the T63 forecasts. Section 3 presents the first set of results obtained comparing T159 forecasts with forecasts of lower horizontal resolution. Examples are given both of improvement in synoptic-scale and local predictions and of some emergent modelling problems. A second small group of T159 forecasts has recently been completed, and some results are presented in Section 4, including one comparison with higher-resolution limited-area forecasts. Increased vertical resolution is discussed in Section 5, which is followed by some concluding remarks.

2. SENSITIVITY TO HORIZONTAL RESOLUTION: COMPARISONS OF T63 AND T106

Two series of experiments 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 in May 1985. 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. In this section we summarize results, principally in terms of objective verification. Synoptic examples of sensitivity to horizontal resolution are presented in Sections 3 and 4.

Initial analyses for the first series 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). A number of results have already been presented to the Scientific Advisory Committee (ECMWF/SAC(85)4); here we present only one set of 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).

The second series 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, using the same parameterizations and model settings 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 from 20 to 5×10^{15} m^4 s^{-1}, 2.5 times larger than that for other fields. All T106 forecasts used diffusion coefficients half those used latterly for T63.

Anomaly correlations of 500 mb 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 clear favour of the higher resolution, as will be seen shortly. The apparently small mean differences in skill are nevertheless larger than differences found earlier between the Centre's N48 grid-point and T63 spectral forecasts, and larger than differences between forecasts using mean and envelope orographies. Other objective measures of forecast skill for the Northern Hemisphere 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, a finding which is presumably related to the higher level of variance that is 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 parameterizations, 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 parameterization, 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 mb 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 particularly evident in summer, only one out of 24 cases failing to show an improvement. This is related in part to the choice of envelope orography, since it has been found (Jarraud et al., 1986) that the impact of envelope orography is beneficial at both T63 and T106 resolution in winter, whereas in summer the envelope orography gave poorer mean anomaly correlations than did mean orography for T63, with similar correlations for the two orographies for T106.

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 cases can again be discerned. It is noteworthy, however, that at both days 3 and 7 there is considerably more spread along the diagonal than across it; differences in forecast accuracy from case to case are generally much larger than differences resulting from the resolution change.

Objective verification has been carried out for a number of regions other than the extratropical Northern Hemisphere. Absolute correlations of 850 mb vector wind for the Tropics and anomaly correlations of 500 mb 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 were 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 parameterization used in these experiments, but it could also indicate sensitivity of the short-range 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.

Some corresponding verifications for regions within the extratropical Northern Hemisphere are shown in Fig. 4. The upper two plots show anomaly correlations for two areas exhibiting quite different degrees of impact, with a relatively large mean sensitivity to resolution around day 5 over North Asia, and very little over the North Pacific. It is tempting to speculate as to model factors which might contribute to such a result, for example a better resolution of the complex terrain over North Asia, but it must be recognized that despite having a sample as large as 48 cases, doubt exists as to the representivity of results for such limited domains. For example, forecasts for the European area during the first year of the sample reveal a distinct improvement of T106 over T63, whereas the converse is the case for the second year. This is seen not only in anomaly correlations, which can be sensitive to the nature of the prevailing anomaly, but also in standard deviations. The latter (for 500 mb height) are shown separately for the two years in the lower plots of Fig. 4. In view of such differences, it is difficult to know what reliance can be placed on the two-year mean for limited areas.

In response to two of the questions raised by the Scientific Advisory Committee at its 1986 Session, sensitivity to orography and horizontal diffusion has been examined in a subset of six cases particularly sensitive to the change in resolution. The cases were chosen from among the 24 of the second year of the 48-case series, on the basis of one per two months, choosing out of the four available for each period that for which differences between T63 and T106 forecasts were largest. Six T106 forecasts were carried out using a T63 representation of the orography, and second subset used T106 orography, but the diffusion coefficients used for T63. Results are shown in Fig. 5 in terms of anomaly correlations of 500 mb 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. 5, but the reverse is found to be the case for anomaly correlations of 1000 mb height and for standard deviations of the height field errors. The small number of cases must also be borne in mind.

Examples of local beneficial impacts of increased horizontal resolution which are almost certainly related to increased resolution of the model orography will be discussed in the following two sections. To counterbalance these, Figure 6 presents a case (specially selected from the first set of comparisons) where use of higher-resolution orography contributed little to a substantial improvement of T106 over T63 in the second half of the forecast range. Illustrated are mean 500 mb heights for days 5 to 10 for standard T106 and T63 forecasts, for a T106 forecast with T63 orography, and for the verifying analysis. The standard T106 forecasts accurately matches the analysis in its depiction of the blocking pattern centred over Northern Europe, in contrast to the performance of T63, which produces a block, but with a quite erroneous flow pattern. Running the T106 forecast with T63 orography reproduces much of the detail of the standard T106 forecast, although some deterioration in the trough extending southeastwards from southern Greenland can be seen. This predominant insensitivity to orographic resolution occurs in this case despite a marked sensitivity to the use of envelope orography, as indicated in ECMWF/SAC(85)4.

Sensitivity to the magnitude of horizontal diffusion has been examined in cases other than those contributing to the mean results shown in Fig. 5. Although these generally confirm the choice made at the time of operational implementation of T106 resolution, clear exceptions are found. A striking example is presented in Figure 7. In this case doubling the coefficients of horizontal diffusion had a clear benefit for the T106 forecast beyond day 6, as seen from the objective verification in the upper panel of Figure 7. The corresponding T63 forecast also showed a much less rapid fall in skill than did the standard T106 at the end of the forecast range (lower panel). It was observed in this case that there was a much more pronounced than usual "spin-up" of vertical velocity in the tropics. The T106 forecast was thus rerun with the higher level of diffusion for the first day only, reducing it linearly to the standard lower value between day 1 and day 2. Objective verification for the extratropical Northern Hemisphere, shown also in the upper panel of Figure 7, indicates a performance very similar to (and slightly better than) that of the forecast which used higher diffusion throughout the 10-day range. Synoptic assessment confirms both this result, and that a substantial part of the improvement of T63 over T106 beyond day 7 has the same synoptic character as the improvement of T106 forecasts by use of higher horizontal diffusion.

3. FIRST RESULTS FROM T159

The Scientific Advisory Committee was informed at its 1986 Session that the Centre had begun a limited programme of experimentation with the spectral model at a resolution of T159. This resolution was chosen because it was the largest that could be run with acceptable efficiency within the memory constraints of the Centre's computer system, although each forecast took too long a time to be operationally feasible (8-9 hours for the 16-level vertical resolution used for the first experiments). A one standard deviation envelope orography with T159 resolution was used, and initial and other surface fields were interpolated from operational T106 fields. The operational T106 forecasts were available for comparison, and T42 and T63 forecasts were also carried out. Three 10-day predictions were run, and these were subsequently supplemented by three one-day forecasts for cases of rapid oceanic cyclone development. Following presentation of the earliest results with T159 to the SAC last year, a more thorough examination of these forecasts has been undertaken.

An initial date of 20 March 1986 was chosen for the first case because of an Alpine lee cyclogenesis early in the forecast range which was underestimated by the operational forecast. Clear improvements were found with increasing resolution, both in the intensity and position of the cyclone, and in the detail of local flow patterns near orography. These are not illustrated here as a second example of lee cyclogenesis will be discussed in the following section. Instead, we present a variety of other results from this case.

In the middle of the forecast range, synoptic differences became apparent over northern Europe. Figure 8 illustrates how the 5-day prediction of a low which was located in reality over southern Sweden is progressively and significantly improved as resolution was increased. T159 also gives the best indication of a second, weaker low to the west. There is much less synoptic difference between T63, T106 and T159 over southern Europe (not shown) at this time, but quite distinct sensitivity in the prediction of precipitation can be seen in Figure 9. In most respects the expected increase in detail with increasing resolution is such as to bring forecast and observation closer together.

As horizontal resolution increases, models can be expected to represent a larger degree of explicit orographically-induced gravity wave activity. Fig. 10 presents cross-sections of wind and potential temperature at day 6 of the T42, T63, T106 and T159 forecasts, again for the 20 March initial conditions. Each section cuts 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 are rather insensitive to horizontal resolution, with a predominantly westerly incident flow. Small-scale wave motion over and immediately downstream of the Rockies ridge is evident in the T159 forecast, but not at lower resolutions.

The forecasts discussed above were carried out without the parameterization 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 parameterization 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 as in Figure 10, but for the divergence field, are presented in Figure 11 and show 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. These forecasts were all carried out using the formerly-operational 16-level resolution. During testing of the increased stratospheric resolution of the now-operational 19-level version, more extreme cases where strong mountain waves appeared explicitly at T106 and T63 truncations were examined. These showed a more 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 model, an apparently effective remedy, at least for the short term, but one which should not be seen as obviating the need for a much more thorough study of this topic as horizontal and vertical resolution increase further.

The use of increased horizontal resolution, with its attendant reduction in horizontal diffusion coefficients, is generally found to exacerbate the problem of "spin-up" discussed in paper ECMWF/SAC(87)6. This is illustrated in Figure 12 by plots of global-mean precipitation rates as functions of forecast range, for T63, T106 and T159 forecasts from 20 March 1986. There is a significant increase, as resolution increases, in the unrealistically high rates found in the first 2½ days, and a smaller increase beyond this time. Examining the breakdown into convective and large-scale precipitation reveals a predominant increase in the convective component in the early part of the forecast range, the smaller increase later on being associated with more large-scale rather than convective precipitation.

One further pre-existing modelling problem has been found to become more pronounced in the T159 forecasts. The early experimentation with T106 revealed a tendency for "noise" to develop in the planetary boundary layer in cases of strong flow over ocean surfaces. As reported in ECMWF/SAC(85)4, this was remedied by revising the time-stepping algorithm used in the parameterization of vertical diffusion. This has worked satisfactorily at T106 resolution, but occasional instances of a return of "noise" at T159 resolution have been found. Figure 13 illustrates roughness in temperature contours along a warm front, and the presence of small-scale low-level ascent and descent in the flow along the front. Although the corresponding T106 forecast was somewhat poorer in synoptic detail, it did not exhibit these presumably spurious small-scale features.

It is important, however, to stress that the problem illustrated above is very much an occasional one, and notwithstanding the need for improving the computational stability of the boundary-layer parameterization, sharper and more coherent frontal structures are generally found in the T159 forecasts. One of the cases of rapid cyclone growth is shown in Figure 14. Strong development is found at all three horizontal resolutions (the central pressure was 989 mb 24 hours earlier), but the depth of the low is captured most accurately with T159. It is more difficult to verify differences in thermodynamic structure between T159 and T106 because of the bias of the verifying analysis towards the T106 resolution used in the data assimilation, but the waviness of the cold front at T63 resolution disagrees with the analysis, with the higher resolution forecasts and with satellite imagery. Some of this waviness can also be seen in the T106 forecast, and the occlusion is less advanced and well-defined at this resolution than at T159. Similar results have been found in other cases.

4. FURTHER STUDIES OF INCREASED HORIZONTAL RESOLUTION

A further five cases have been chosen for study of increased horizontal resolution. Four were selected on the basis of an interesting weather development in the short range, to enable global forecasts to be compared with forecasts at resolutions higher than T159 carried out with the limited-area model. Three of these have been integrated to 10 days using the global spectral model at T63, T106 and T159 resolution. The fourth was integrated only to day 3, a fifth case being chosen for 10-day forecasting as it was realized that the sample would otherwise not have included a high-summer case. The set of global forecasts has only recently been completed, and the performance of the LAM is being scrutinized using one of the cases. Here we present first impressions of the results on a case-by-case basis.

(i) 3 March 1982

This initial date was chosen from within the ALPEX period because of the occurrence over the following two days of a lee cyclogenesis which subsequently has been much studied. In particular, sensitivity to horizontal resolution and the use of envelope orography has been examined by Dell'Osso (1984) using the ECMWF grid-point LAM. A period of data assimilation using the current T106 L19 operational system was carried out to provide initial conditions. In Figure 15 we present a subjective analysis of mean sea-level pressure for 12Z 5 March 1982, and corresponding 48-hour spectral forecasts using T63, T106 and T159 resolutions. The 48-hour grid-point forecast with the finest (.46875°) resolution utilized by Dell'Osso is also shown.

It is clear from Figure 15 that the change in resolution from T106 to T159 is such as to allow the forecast to capture local detail present in both the analysis and the high-resolution LAM. Particular examples are the pressure patterns near the Pyrenees and the Italian peninsula. In this case there is little change in intensity with increasing resolution in the spectral forecasts, and only a minor refinement of position. A more substantial impact in these respects, and similar improvement in local detail, is found in the 20 March 1986 case discussed earlier. For this ALPEX case the LAM forecast is better with regard to the intensity of the lee cyclone and the apparent barrier presented to the cold front by the Alpine ridge; as this model used a different initial analysis and earlier version of the parameterizations the differences in performance may not be wholly due to differences in horizontal resolution and numerical technique.

(ii) <u>26 February 1984</u>

This case was chosen because of the availability of detailed observations of a polar low, reported by Shapiro et al. (1987). It was recognized that none of the global resolutions to be used would be sufficiently fine to capture the detailed structure of the low, but it was hoped that the large-scale state would be well enough defined in the initial conditions to make the case a suitable one for studying higher resolution and the performance of different convection schemes using the spectral LAM. Again, a spell of data assimilation using the latest operational system was used to produce initial conditions.

Wind and temperature forecasts at the third model level above the surface are shown for 12Z, 27 February, over the Norwegian Sea in Figure 16, together with an analysis of aircraft measurements of temperature taken at a rather similar height and time. The sharpening of thermal structures with increasing resolution is evident, and more rapid spatial changes in wind speed and direction can be discerned for higher resolution. At T159 resolution a warm tongue extends southwestwards from close to the intersection of the Grenwich Meridian and the 70°N latitude, a feature clearly present in reality.

Turning attention from the short to the later medium range, major forecast errors often make it difficult to assess whether forecast changes brought about by increased resolution are truly beneficial, although the case presented earlier in Figure 6 is an example of a pronounced exception to this rule. The forecast from 26 February 1984, chosen for its short-range interest, was in fact one of relatively high accuracy in the second half of the forecast range, and the differences between T106 and T159 can be directly assessed in comparison with reality. Maps of 1000 and 500 mb height averaged from days 5 to day 10 are compared with corresponding analyses in Figure 17. Although many of the forecast errors are common to both resolutions, differences in phase and intensity between the forecasts are mostly in favour of T159. Examples are the westward extension of the Siberian High and the anticyclone over western Europe. At 500 mb, the two main centres of the circumpolar vortex located near 75°W and the Dateline are deeper and more realistic in the T159 forecast. A tendency for large eddy amplitudes in higher resolution forecasts was found earlier in the comparison of T63 and

T106; it acts to increase forecast accuracy as long as the overall skill of the prediction is high, but tends to bias objective verification towards lower resolution once significant forecast errors have arisen.

(iii) 24 September 1985

The global forecasts in this case were carried out to day 3 to study the evolution of hurricane "Gloria" as it moved towards and then along the eastern seaboard of the USA. The analyzed track of the storm, and the tracks predicted by T106 and T159, are shown in Figure 18. The better track of the T159 forecast, 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 T106 and T159 predictions for the 12-hour period leading up to 12Z, 27 September, are presented in Figure 19, which also includes plotted surface weather reports for 12Z on this day. Differences can also be seen in the precipitation patterns over and to the north of the Great Lakes. Comparison with the surface reports shown in Figure 19 and those of earlier hours indicates that here also the T159 pattern is the more correct.

Two-day forecasts have been carried out using the spectral limited-area model for this case. Distributions of low-level wind from two predictions are shown in the upper panels of Figure 20; the lower panels show the corresponding operational analysis and forecast over the same domain and grid as used by the LAM. The LAM runs used analyzed boundary values, and a resolution equivalent to T212 in a global model. One used the operational parameterization schemes, and for the other the Kuo convection scheme was replaced by the adjustment scheme under development at ECMWF.

These latest results from the limited-area model provide indications both of the promise of the model as a tool for assessing model performance at possible future global resolutions, and of a need for further investigation of the formulation of the model. In the upper right of the domain, the two LAM forecasts are clearly chose to the global forecast, except in the immediate vicinity of the boundary where they more closely resemble the analyzed values. The greater intensity of the cyclone as simulated in the LAM runs is not easily seen in the format of the plots shown in Figure 20, but marked differences in the character and level of the "noise" in the wind field to the east occur between the LAM forecasts with different parameterizations. This is perhaps related to the problem previously discussed with respect to the T159 forecast shown in Figure 13.

Cause for concern about the formulation of the LAM arises from comparing fields over the Gulf of Mexico and to the north, where the two LAM forecasts differ considerably from both the analysis and the global forecast. The spectral representation of the wind field guarantees only that the normal (not the tangential) component matches that of the (analyzed) background value at the boundary. In relaxing the vorticity and divergence field towards the background, a flow parallel to the boundary which varies little with latitude and longitude will not be inhibited. Such a flow can be seen in the LAM forecasts where the boundary intersects the Gulf of Mexico. Detailed investigation of this case will be undertaken prior to further application of the LAM to the other cases presented here.

(iv) 13 December 1986

The short-range feature of interest in this case is a depression of exceptional depth east of southern Greenland. The T159 forecast in the 36- to 48-hour range gave a low some 5 mb deeper and better positioned than that from T106. Rather than illustrate this (a somewhat similar case has been presented in Figure 14), we consider a much grosser aspect of model behaviour, and present in Figure 21 meridional cross-sections of the zonal-mean temperature error averaged from day 5 to 10 for T63, T106 and T159 forecasts. All panels show the tendency of the model to warm the tropical middle and upper troposphere, and to cool at higher latitudes. Consistent with the results on "spin-up" summarized in Figure 12, the tropical warming increases with increasing resolution.

(v) 15 August 1986

This summer case was chosen because it had already been studied from the viewpoint of the parameterization of convection. The 5-day forecasts with T106 and T159 resolution presented in the left-hand panels of Figure 22 exhibit only small differences, both failing seriously in their prediction of the development of the low near 20°W and of the eastward movement of the trough downstream of it. This contrasts with a marked sensitivity of this case to the choice of parameterization of convection. In general, higher resolution cannot be expected to compensate for major errors introduced by other parts of the forecasting system.

Examining difference maps for the whole hemisphere for this case revealed the largest differences over northern North America in the second half of the 10-day range. The right-hand panels of Figure 22 illustrate how the T159 forecast for day 7 captured better the depth and circulation around the low over northwestern Canada and Alaska. Differences in the representations of the cut-off lows to the south can also be seen.

(vi) Objective verification

Overall, 7 T159 forecasts have been carried out to day 10. These, and the corresponding T63 and T106 forecasts, have been verified objectively in the usual way, and mean results for anomaly correlations of the 500 and 1000 mb height fields are shown in Figure 23. Many qualifying remarks could be made in presenting these results, particularly regarding the absence of high resolution in data assimilation, and the small number of (predominantly winter) cases which may make results rather unrepresentative, especially beyond day 6 or 7. Nevertheless, in the range from day 5 to day 7, T159 improves over T106 by between 30 and 50% of the improvement of T106 over T63, a result broadly consistent with what might have been expected on the basis of extrapolating the results presented for T106 and lower resolutions in Figure 1.

5. INCREASED VERTICAL RESOLUTION

Research on the vertical discretization has recently been concentrated on the development of finite-element techniques and it is expected that a scheme using linear elements will be implemented operationally within a few months. Major experimentation with increased vertical resolution has been deferred until this implementation has taken place, but some preliminary work has been carried out at T63 horizontal resolution using the current finite-difference scheme and a 31-level resolution in which layer thicknesses are approximately halved in the free troposphere and around the tropopause. This resolution is shown schematically in Figure 24, together with the current 19-level resolution. The experimentation used initial data interpolated from 16- or 19-level analyses, although the principal testing of this resolution will include its use in data assimilation. As an early forecast became computationally unstable when using the usual T63 timestep of 22½ minutes, all runs were completed using an 18-minute timestep. The instability occurred over Greenland, and further investigation is needed to determine the cause. A CFL problem in the vertical and the semi-implicit gravity-wave treatment are possible candidates.

Seven forecasts have been carried out to 10 days. The first, starting from a special T106 L19 FGGE analysis for 16 January 1979, had shown sensitivity to vertical resolution in much earlier tests with the Centre's original 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 other six were simply chosen at two-monthly intervals from 15 June 1986 to 15 April 1987.

Some aspects of objective verification are shown in Figure 25. The upper four panels present means over the seven cases. Anomaly correlations of 1000 and 500 mb height for the extratropical Northern Hemisphere indicate a small net improvement of the 31-level forecasts over those produced using the standard 19-level resolution. The impact of the resolution increase is less for the Southern Hemisphere, but slightly positive. A clearer beneficial impact is seen in the absolute correlation of 850 mb vector wind for the tropical belt. Such mean verifications must, however, be treated with caution, as examples of pronounced sensitivity have been found later in the forecast range. Anomaly correlations of 500 mb height for the extratropical Northern Hemisphere are shown for two particular cases in the lower panels of Figure 25. In one case the increase in vertical resolution was strikingly beneficial; in the other it was predominantly detrimental. Such large individual variations allow only low significance to be attached to the small differences found in the 7-case mean, although the degree of sensitivity may be an indicator of the potential importance of vertical resolution.

Synoptic impact in the short range has been demonstrated in a second FGGE case, that of the "Presidents' Day Storm". The two upper frames of Figure 26 indicate the development over a 48-hour period of a major storm, analysis of which has indicated the importance of a pronounced tropopause fold which developed upstream prior to the surface cyclogenesis (e.g. Uccellini et al. 1985). A number of forecasts have been carried out based on the T63, 16-level analyses of the "Final III-b" dataset. Two-day T63 forecasts carried out using 16- and 31-level resolutions are shown in the middle panels of Figure 26, and a 16-level T106 forecast is shown lower left. Increasing either the horizontal or the vertical resolution improves the predicted development, with slightly more benefit from the increase in the vertical. Improving the data assimilation also increases accuracy; the lower right panel shows a 19-level T106 forecast from an assimilation using this higher-resolution model and the new data analysis code introduced operationally in September 1986. Similar results have been obtained in forecasts beginning 24-hours earlier, and sensitivity of this case to the parameterization of convection and vertical diffusion has also been found.

Synoptic impact later in the forecast range is demonstrated in Figure 27 in terms of mean 500 mb height maps for days 5 to 10. The two cases chosen are those for which objective verification indicated high sensitivity, as illustrated in the lower panels of Figure 25. The left-hand panels of Figure 27 illustrate the case in which the 19-level forecast gave better results, and a more skilful treatment of the flow in the Atlantic sector can clearly be seen. In the other case a quite erroneous ridge was predicted over the Atlantic by the 19-level version of the model; such a ridge is barely present in the 31-level forecast. Results to date thus point to the Atlantic as being a region particularly sensitive to vertical resolution. Comparing the evolution of the height field in a number of cases points to the Rockies and Greenland as sources of difference, suggesting an interaction between vertical resolution and the representation of orography.

As expected, sharpening of structures in the vertical is found with increasing vertical resolution. Figure 28 presents cross-sections of relative humidity along 45°W from 50°N to the equator for 48-hour forecasts from 15 February 1987 using 19 and 31 levels. Gradients above the planetary boundary layer are much stronger in the 31-level run, and the same is found near 15°N in corresponding sections of potential temperature. Above the boundary layer, there appears with 31 levels to be less oscillation in the vertical on the smallest resolved scale (~ 100 mb in the free troposphere for the 19-level resolution, ~ 50 mb for 31 levels). Relative humidities in the boundary layer are also somewhat lower in the 31-level forecast. Here increasing vertical resolution has had an impact on an aspect of model behaviour profoundly changed by the introduction of a parameterization of shallow convection in May 1985, and re-examination of the model's hydrological cycle and the working of the parameterization of convection at higher vertical resolution appears desirable. Also, if the sharper vertical structures more accurately reflect reality in the short-range forecast, improved initial analyses can be expected from use of the higher vertical resolution in data assimilation.

6. CONCLUDING DISCUSSION

In this paper we have presented results from a number of studies of increased horizontal and vertical resolution. The aim has been both to give examples of some of the improvement in synoptic-scale and local forecasts brought about by increased resolution, and to illustrate some of the modelling problems which are emphasized when finer resolution is used. We conclude by discussing the extent to which this work answers the questions posed by the Scientific Advisory Committee at its 1986 Session.

(i) What improvements are found as resolution is increased? To what extent are these due to

- improved representation of orography?
- improved advection?
- improved performance of parameterizations?
- improved data assimilation?
- increased separation of important synoptic scales from scales where horizontal dissipation acts?

Objective verification of the extensive sets of spectral-model forecasts carried out at horizontal resolutions up to T106 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 can result in some very clear improvements in local forecasts of weather elements such as precipitation, and low-level wind and temperature.

Although a much smaller sample of forecasts is available at resolutions beyond those currently used for operational forecasting, much of the above paragraph appears from the results presented in this paper to apply to the comparison of T159 and T106 as well as that of T106 and T63. Objective verification for the extratropical Northern Hemisphere indicates a maximum mean improvement of T159 over T106 which is about half that of T106 over T63. Some pronounced sensitivity to increasing the vertical resolution from 19 to 31 levels has also been documented. Taken in conjunction with the beneficial impact on data assimilation found previously when increasing vertical resolution in the model stratosphere, this provides evidence to justify first concentrating further study of increased resolution on such an enhancement of vertical resolution, which could be implemented operationally on the CRAY X-MP/48, although extra computer resources would be needed to maintain the current level of research experimentation.

Limited evidence has been presented indicating that both the improved representation of orography and the reduced horizontal diffusion possible with higher horizontal resolution contribute in part to the improvements found as resolution increases. Individual counter examples showing a small role of higher resolution orography and a strongly detrimental impact of lower diffusion (suggestive of a link with the "spin-up" problem) have also been given. The better thermal structures indicated over the ocean presumably indicate an improved advection as resolution increases.

It is difficult to assess the extent to which improvements due to increased horizontal resolution arise as a result of improved performance of the parameterizations. Tiedtke and Slingo (1985) presented evidence based on 8 cases that the new parameterizations introduced in May 1985 had a larger beneficial impact at T106 resolution that at T63. However, in the larger sample of cases for which performance is summarized in Figure 1 we see that the improvement of T106 over T63 is very similar in the first (24-case) set of experiments, which used predominantly the pre-1985 parameterizations, and in the second set, for which the new schemes were used. This may be more than simply due to sampling, as the forecasts reported by Tiedtke and Slingo were all performed from analyses produced using the old parameterization schemes and T63 resolution in the assimilation. It is likely that this gave a different "spin-up" to that which now occurs operationally.

On the positive side it is clear that one product of the parameterization, the rainfall forecast in middle latitudes, improves with increasing resolution. However, we have also illustrated an occasional problem at high resolution with the computational stability of the parameterization of vertical diffusion, and a more general problem of an increasing "spin-up" as resolution increases (and horizontal diffusion decreases). As these modelling problems come to be solved, a further benefit of use of higher resolution should result.

The final question of sensitivity referred to last year by the Scientific Advisory Committee concerned the use of higher resolution in the data assimilation. Technical difficulties prevented an extensive investigation of this question when changing from T63 to T106; evidence presented to the Scientific Advisory Committee at the time (ECMWF/SAC(85)4) indicated some improved fits to data with the higher-resolution model, but was inconclusive with regard to the impact on forecast quality. With regard to the vertical, clear evidence of improved data assimilation resulting from use of the higher stratospheric resolution of the current 19-level model has been discussed by Wergen and Simmons (1986), and in the present paper we have shown for the "Presidents' Day Storm" a beneficial impact of using T106 19-level resolution and the new analysis code, rather than the T63 16-level resolution and earlier code used for the "Final III-b" FGGE analyses. Further attention to this question will be an important component of the forthcoming study of higher vertical resolution.

(ii) What initial data are required and attainable to support a forecasting model with increased resolution?

This question has not been directly addressed in any of the experiments reported here, but as improvements have been found by running higher resolution models from operational analyses, it can be said that the initial observational data currently available will support a higher resolution model. However, results of running T63 and T106 forecasts from the Centre's analyses, and T63 forecasts from analyses produced by the UK Meteorological Office, point out a more discernible improvement of T106 over T63 in those cases where the Centre's analysis gave the better T63 forecast. Thus improved observational coverage, and improved data assimilation techniques, can be expected to lead to a fuller exploitation of the potential of increased resolution.

(iii) What are the problems associated with partly resolving mesoscale features?

The most apparent problem encountered to date concerns orographically-generated gravity waves. These pose problems associated with both the horizontal and the vertical. The increasing appearance of such waves as horizontal resolution increases brings to the fore the question of how to achieve a correct separation between explictly-represented and parameterized components of the wave drag. Inadequate vertical resolution and upper boundary conditions introduce inaccuracy into the explictly-represented component.

(iv) What is the best way of extracting information from the forecasting system? Is an ensemble of forecasts carried out at less than the maximum resolution possible for an individual forecast, the best approach?

The mean differences in skill of T63 and T106 forecasts presented here remain small compared with the large variations in mean skill that are found to occur between one month and another, or indeed compared with shorter-term variations in forecast skill. For the future, one may foresee the use of higher resolution, vertical as well as horizontal, as providing worthwhile increases in synoptic-scale accuracy and local detail in the first part of the medium range. There may, however, be a point in the forecast range beyond which increased computational power is better used to run some form of ensemble of 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 parameterizations, numerical methods and data assimilation techniques, and the extent to which useful information can be extracted from an ensemble. The optimal strategy for one user will in all likelihood be different from that for another, depending on the location, forecast range, and product of prime interest, and a mixed approach involving one high resolution forecast and an ensemble of lower resolution forecasts is a possible compromise. Increased computational power might also be employed to introduce a relatively more expensive data assimilation technique, such as the four-dimensional variational approach now under development.

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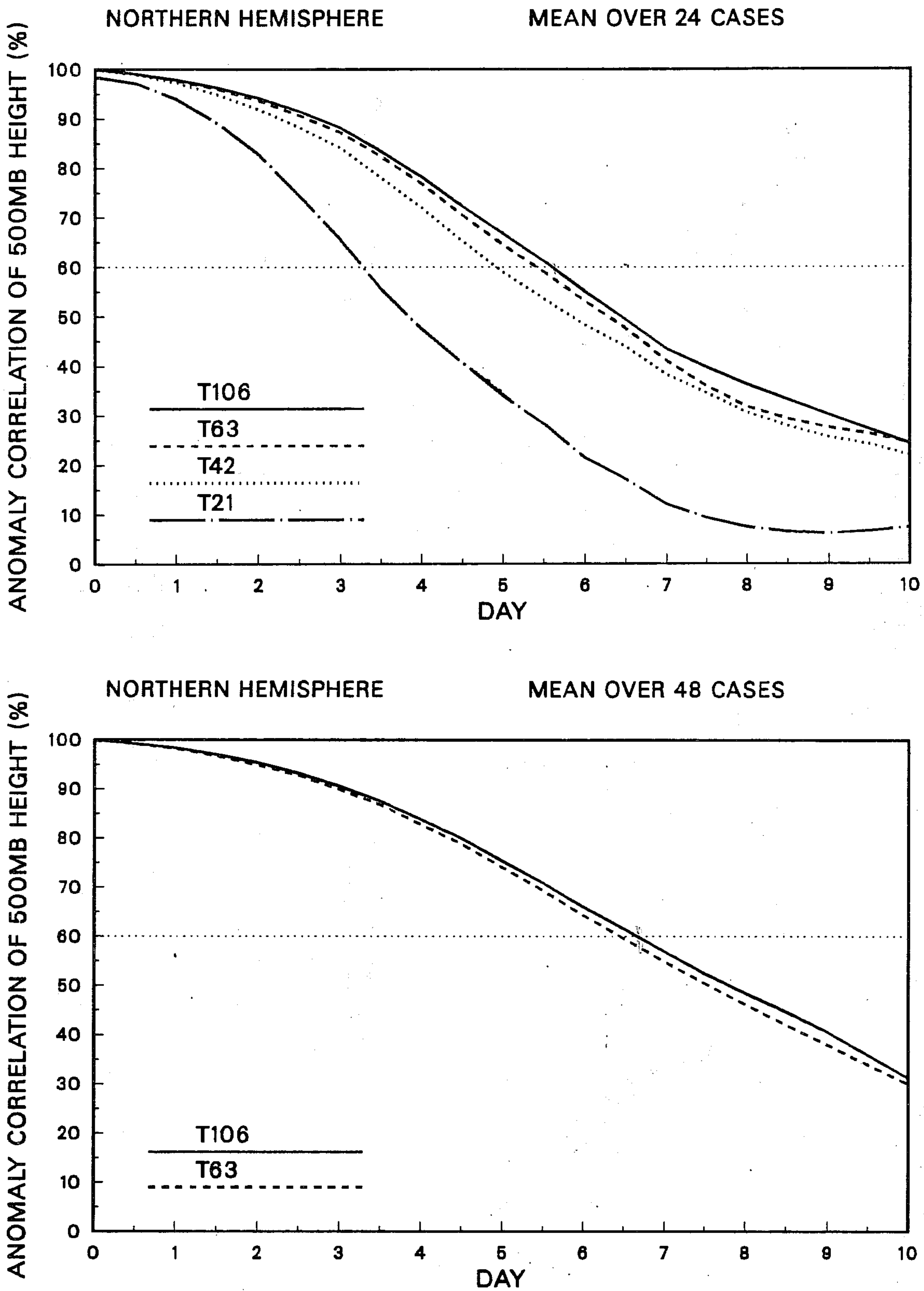


Fig. 1 Anomaly correlations of 500 mb height for the extratropical Northern Hemisphere averaged over sets of 24 (upper) and 48 (lower) cases, for spectral truncations T21, T42, T63 and T106 as indicated in each panel.

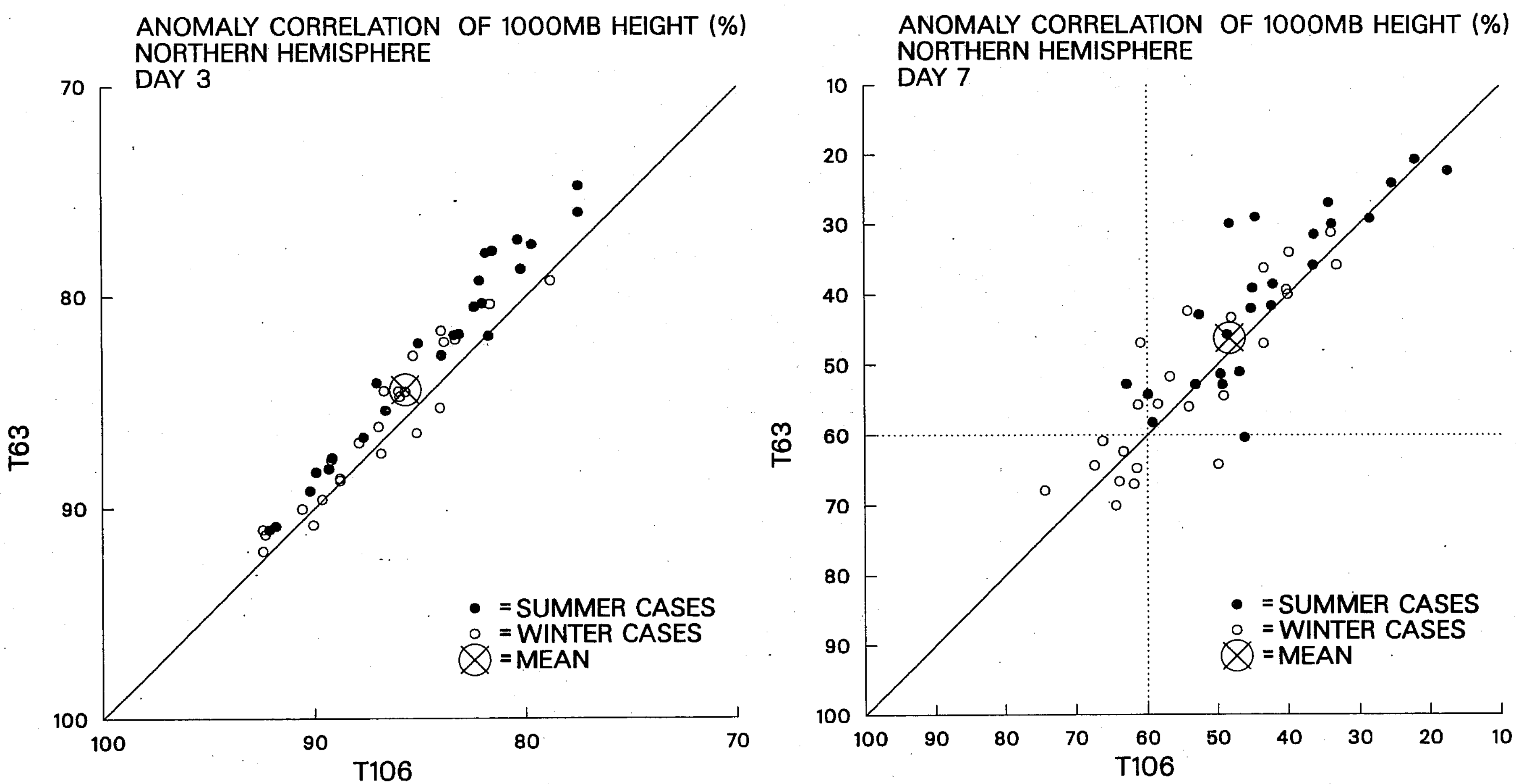


Fig. 2 Scatter diagrams of anomaly correlations of 500 mb height for the extratropical Northern Hemisphere, comparing T63 and T106 forecasts at day 3 (left) and day 7 (right). Points lying above the diagonal indicate better performance of T106. Solid circles denote summer cases, open circles denote winter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

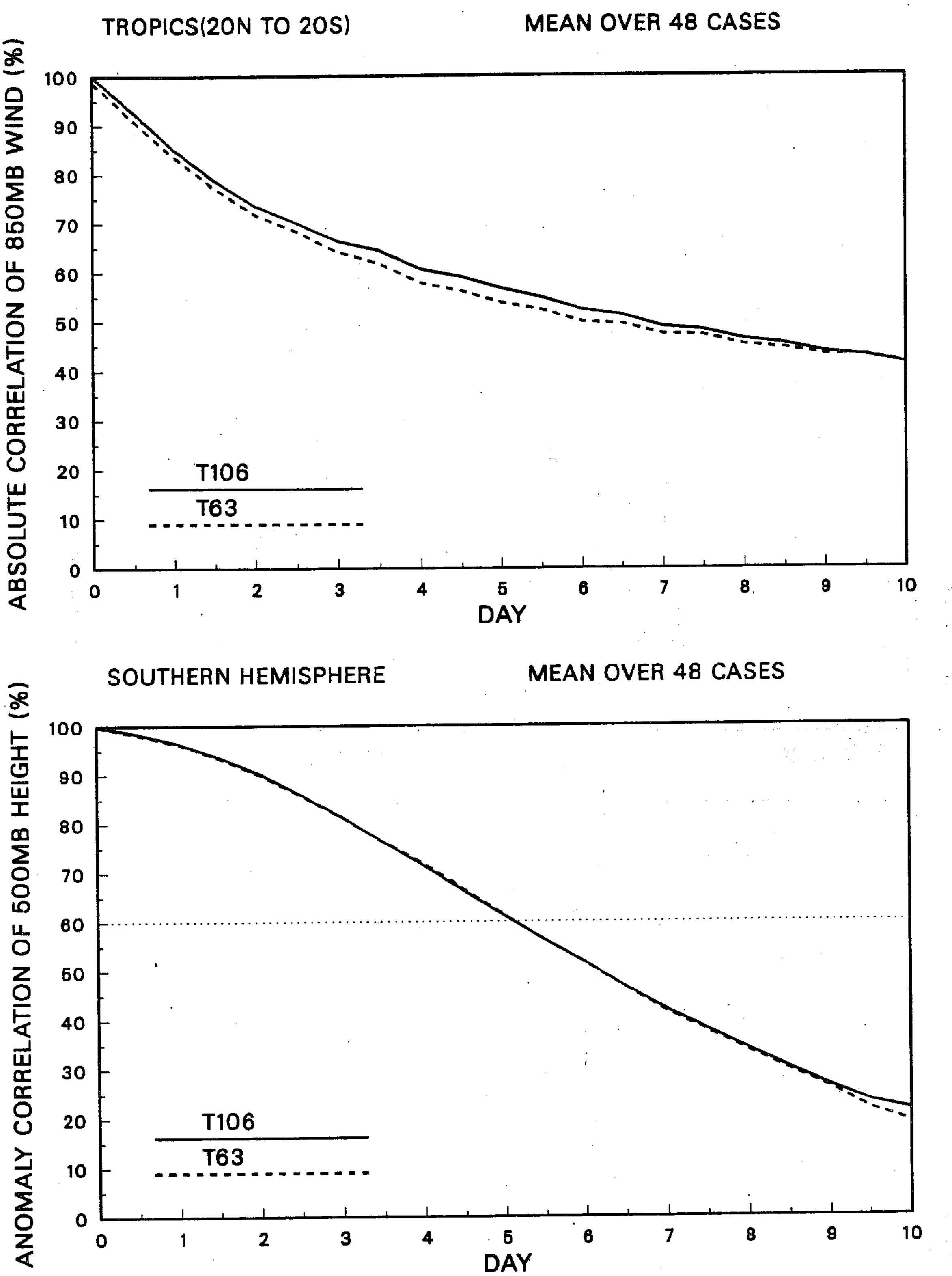


Fig. 3 Absolute correlations of 850 mb vector wind for the Tropics (upper) and anomaly correlations of 500 mb height for the extratropical Southern Hemisphere (lower), averaged over 48 cases for T106 (solid) and T63 (dashed) forecasts.

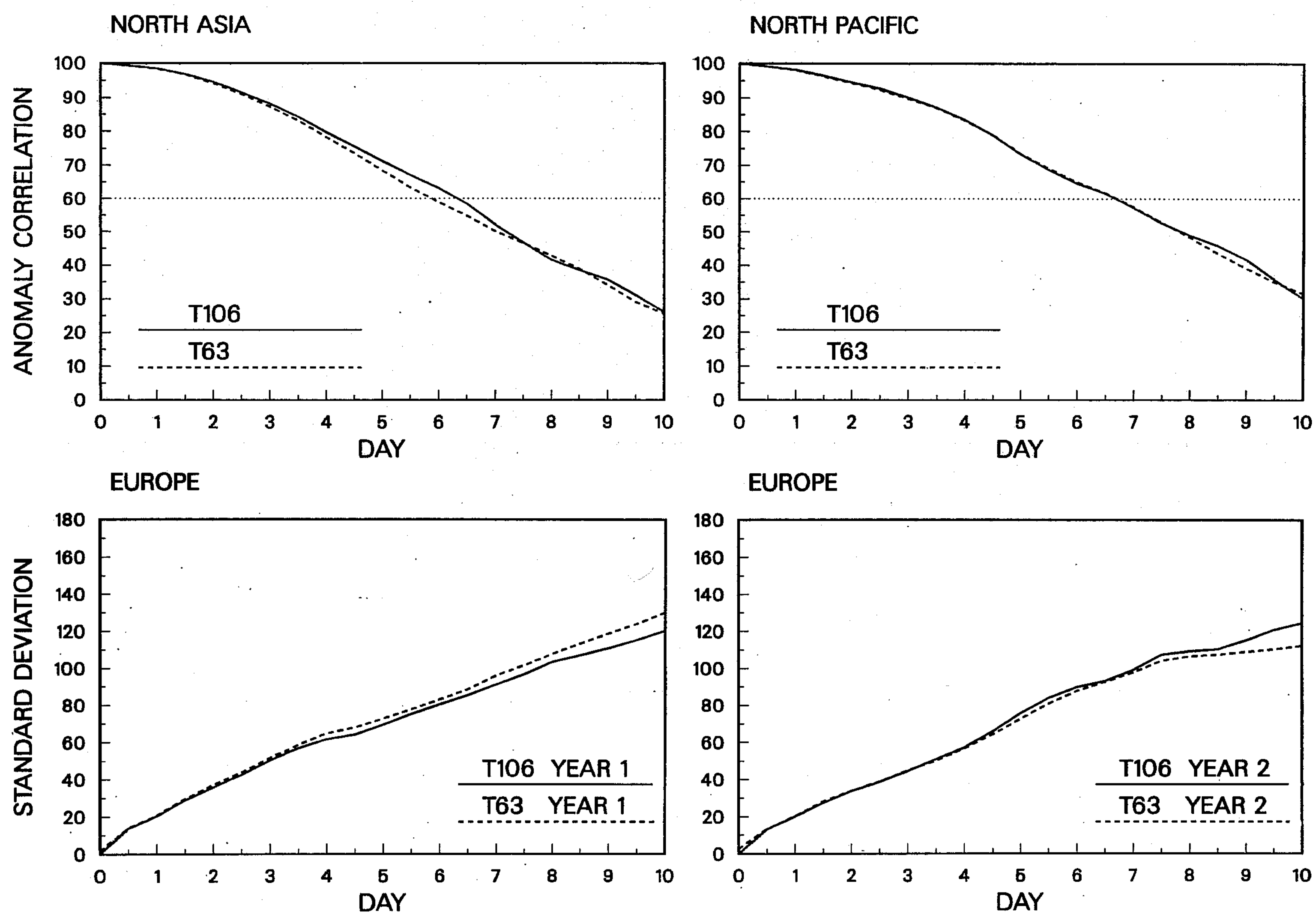
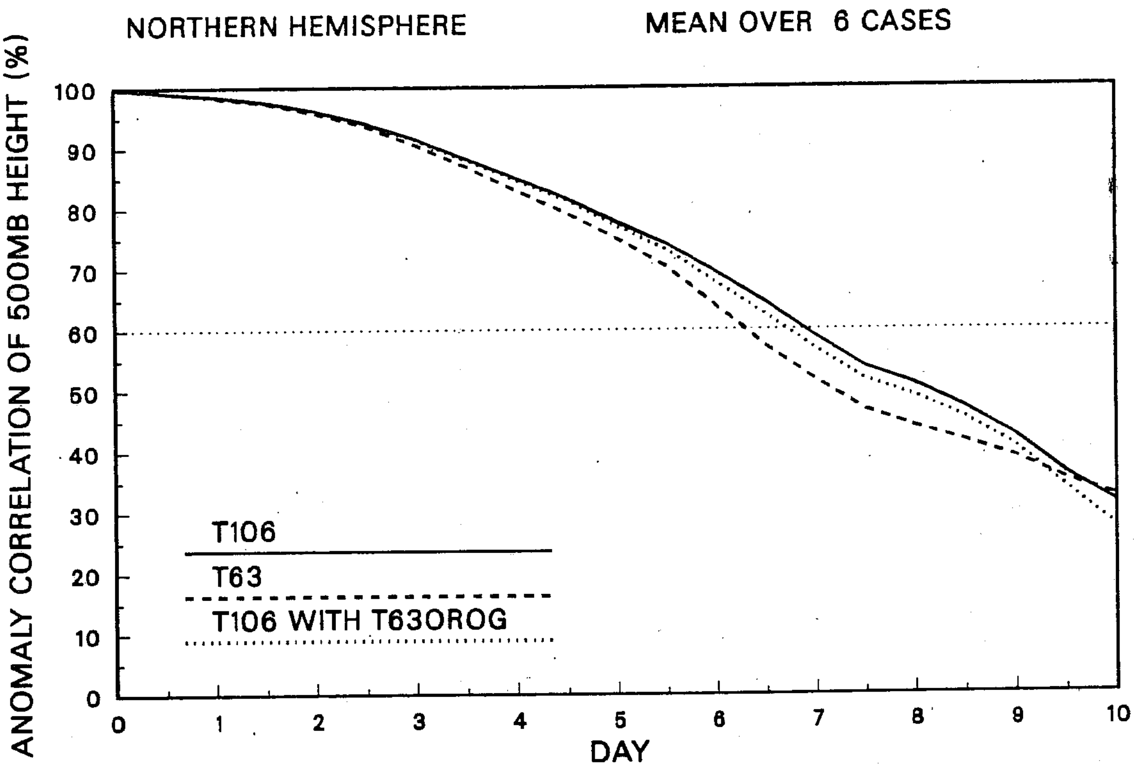


Fig. 4 Mean comparisons of T106 (solid) and T63 (dashed) forecasts of 500 mb height for the 48-case sample, based on:
Upper left - Anomaly correlations over North Asia (45°E-150°E; 45°N-80°N)
Upper right - Anomaly correlations over the North Pacific (145°E-130°W; 25°N-60°N)
Lower left - Standard deviations for the first 24 cases over Europe (20°W-45°E; 30°N-75°N)
Lower right - Standard deviations for the second 24 cases over Europe



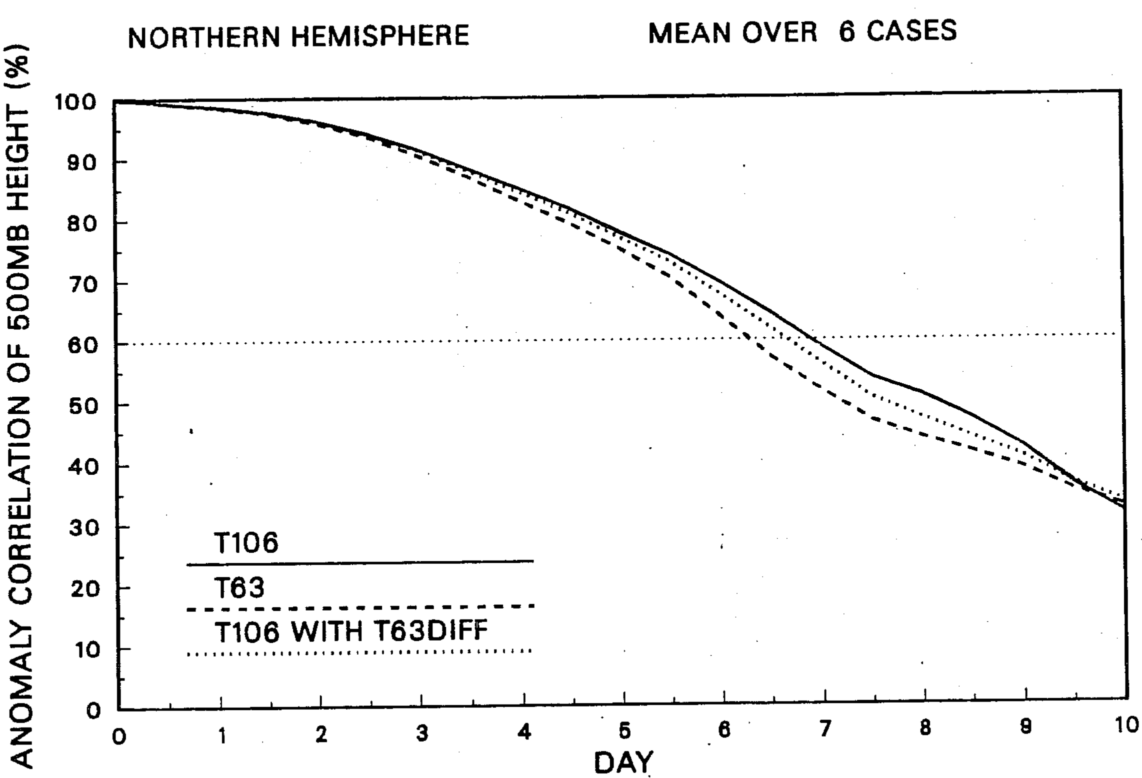


Fig. 5 Mean anomaly correlations of 500 mb height for the extratropical Northern Hemisphere, for 6 cases carried out at T106 (solid) and T63 (dashed) resolution, and for T106 forecasts carried out with T63 orography (dotted, upper panel), and with T63 diffusion coefficients (dotted, lower panel).

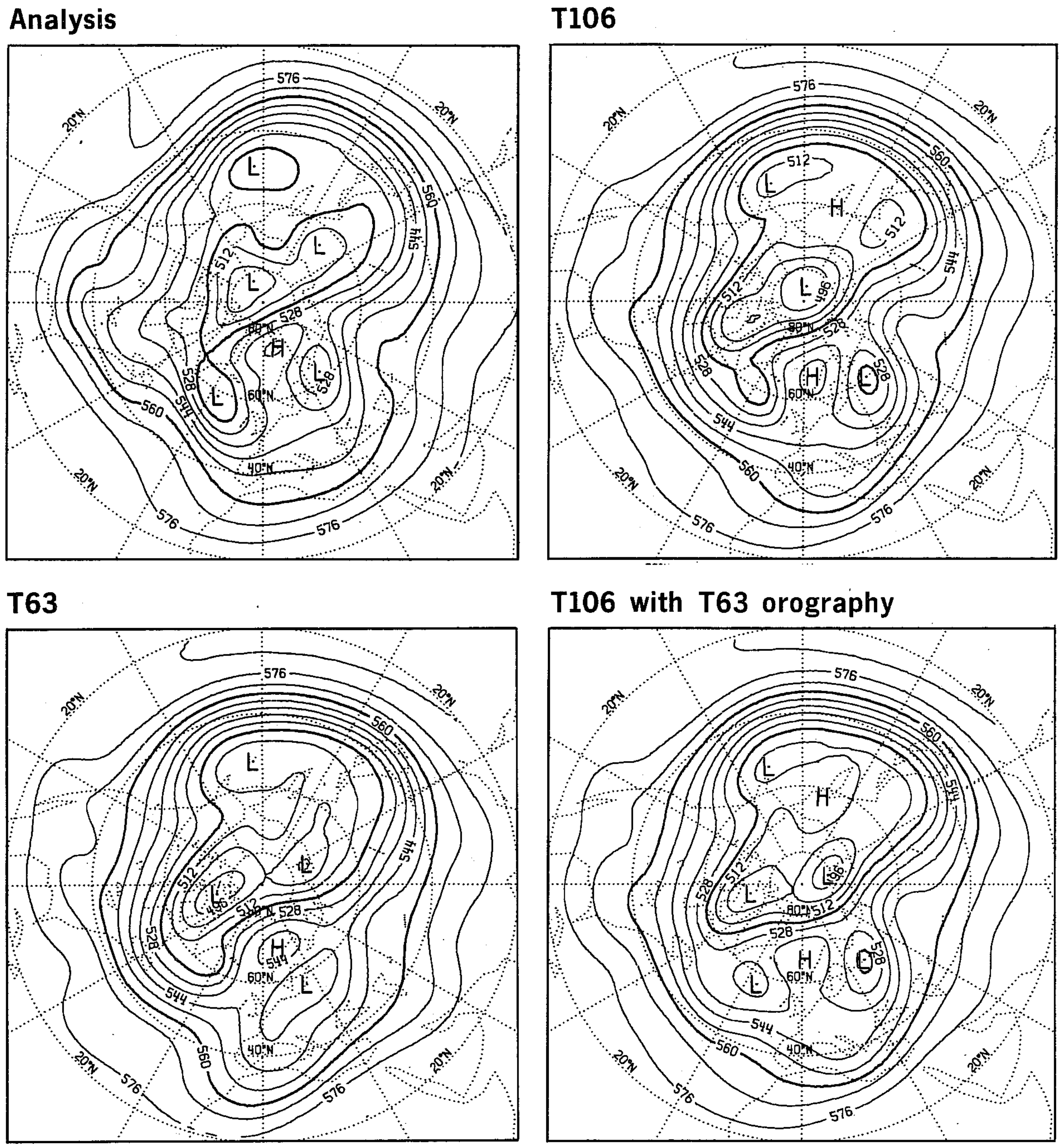


Fig. 6 Mean analyzed 500 mb height field (contour interval 8 dam) for the period 20-25 March 1984 (upper left), and corresponding forecasts from 15 March using:
Upper right - T106 resolution (and orography)
Lower left - T63 resolution (and orography)
Lower right - T106 resolution but T63 orography.

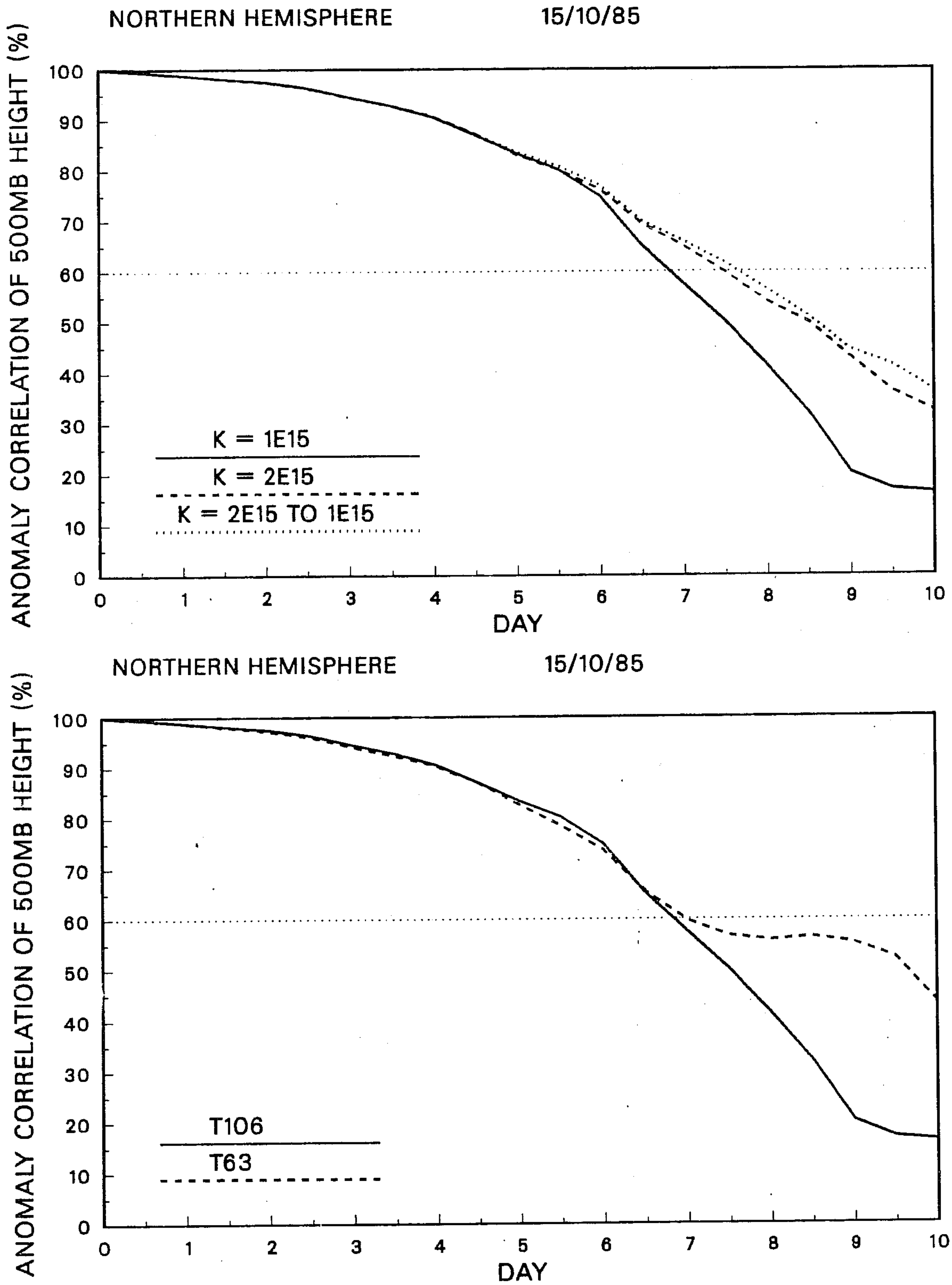


Fig. 7 Anomaly correlations of 500 mb height for the extratropical Northern Hemisphere, for forecasts from 15 October 1985. The upper panel shows T106 results obtained with standard horizontal diffusion coefficients (solid line), with coefficients twice the standard value (dashed), and with coefficients which reduce from the larger to the smaller values between days 1 and 2 (dotted). T106 and T63 forecasts are compared in the lower panel.

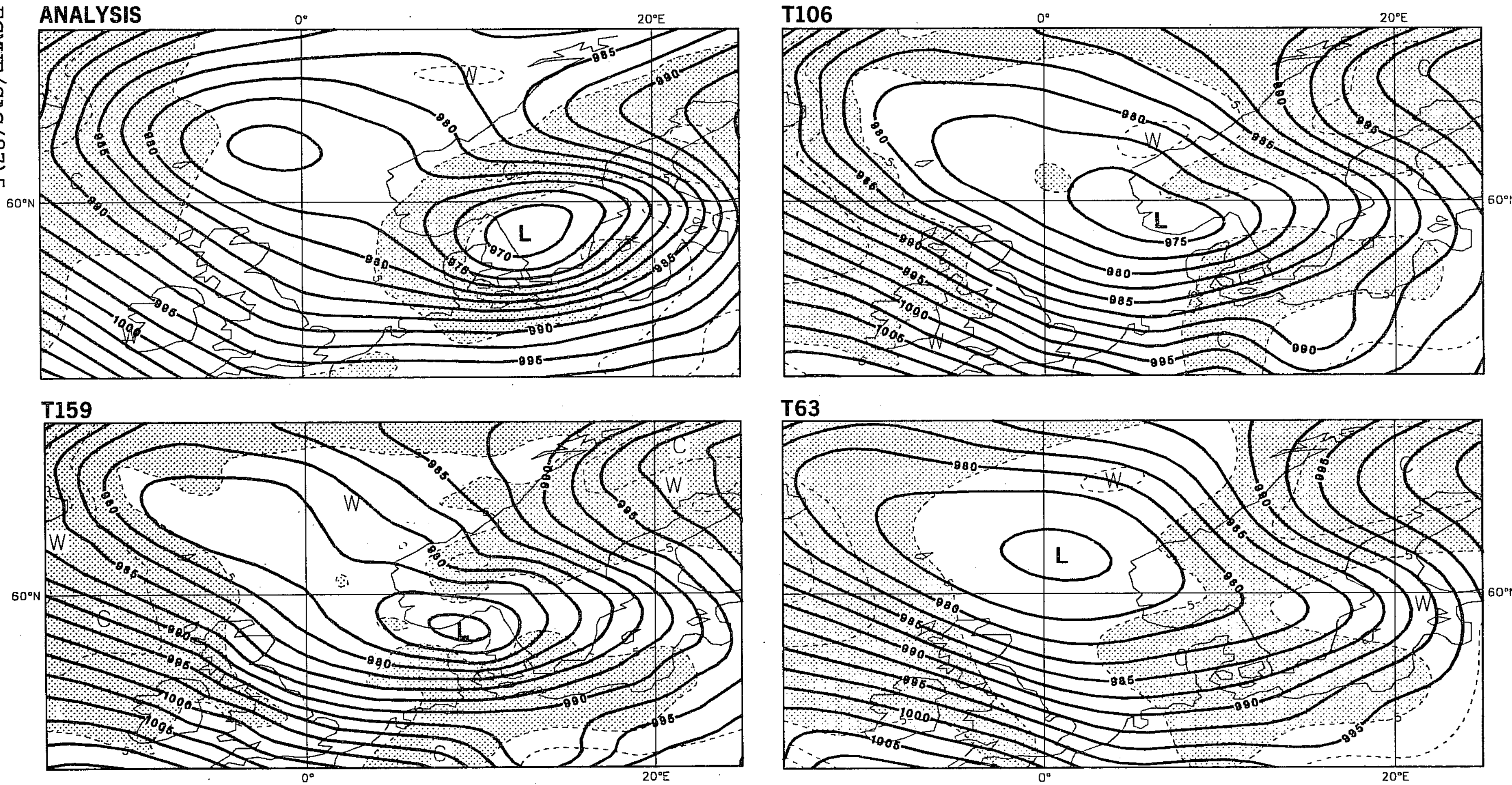


Fig. 8 The operational (T106) analysis for 12Z, 25 March 1986 (upper left), and 5-day forecasts valid at this time performed using horizontal resolutions T106 (upper right), T159 (lower left) and T63 (lower right). Solid lines show mean sea-level pressure with a contour interval of 2.5 mb, and 850 mb temperature is denoted by dashed contours, with 2 K interval, and by shading values below -5°C.

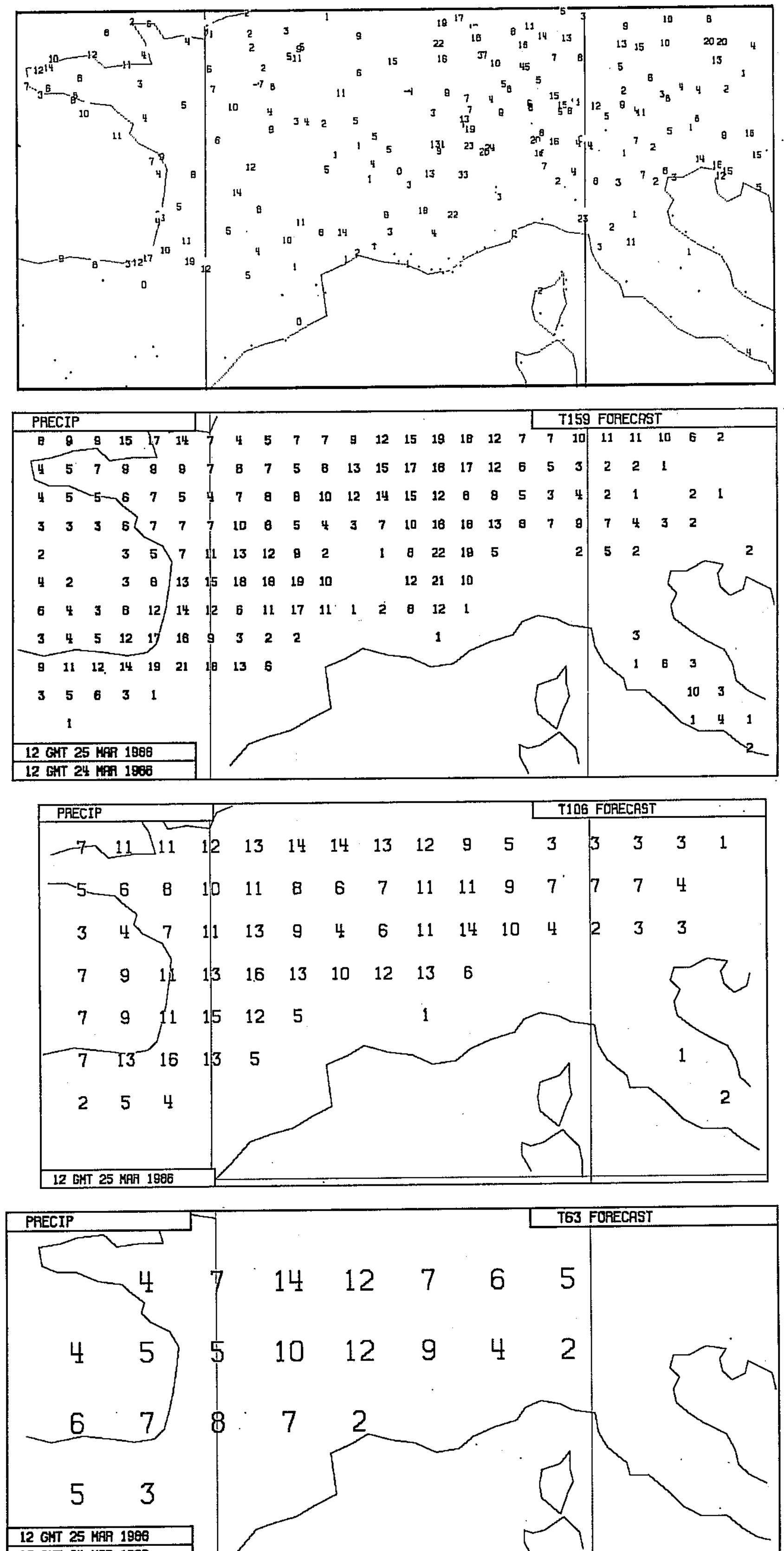


Fig. 9 24-hour net precipitation (mm) for the period 12Z, 24 March to 12Z, 25 March 1986. Observed values are shown in the upper plot, and predicted values are for T159 (upper middle), T106 (lower middle) and T63 forecasts from 20 March 1986.

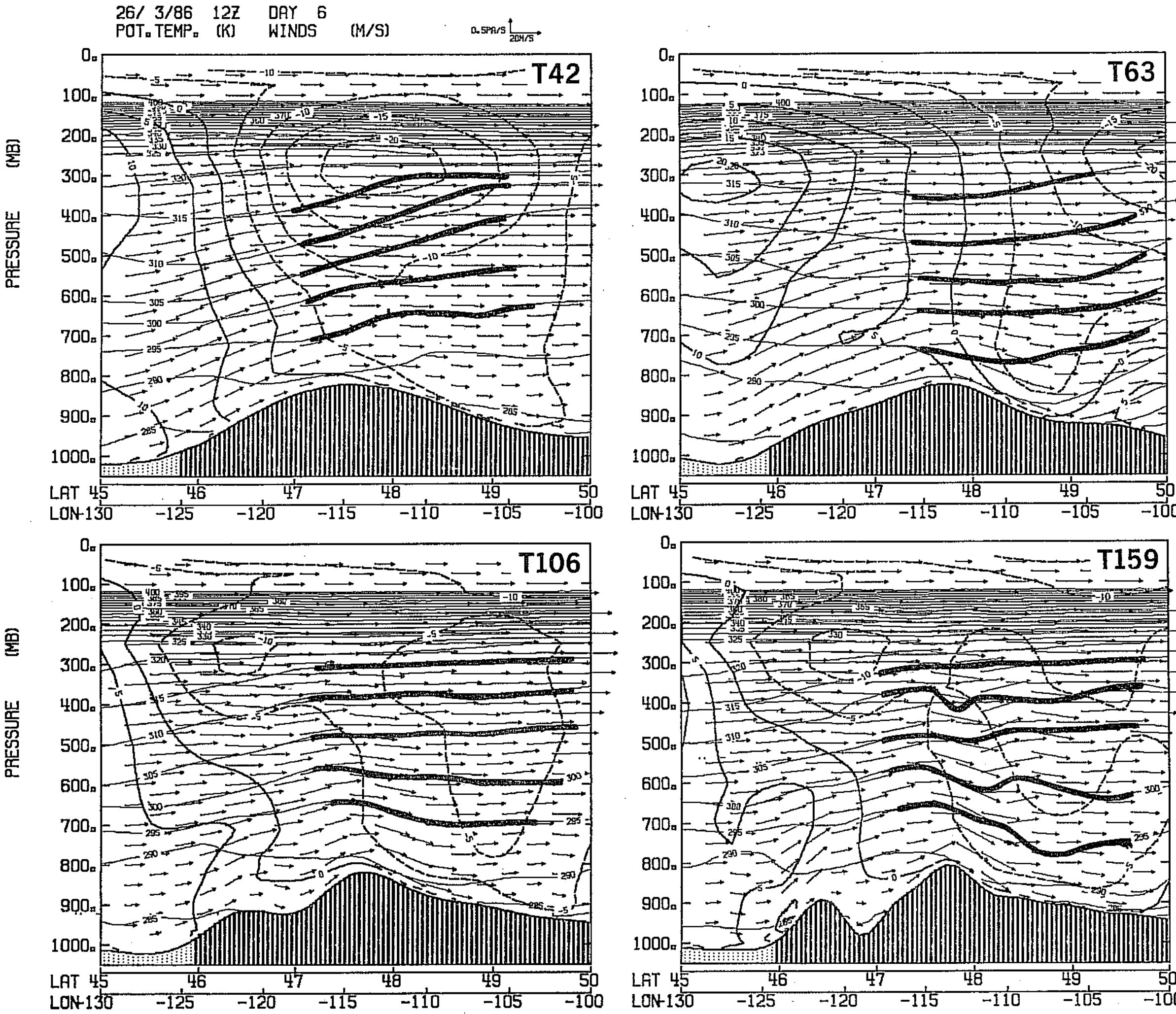


Fig. 10 Cross-sections of potential temperature and winds from 45°N, 130°W to 50°N, 100°W for day 6 forecasts from 20 March 1986, using resolutions T42 (upper left), T63 (upper right), T106 (lower left) and T159 (lower right).

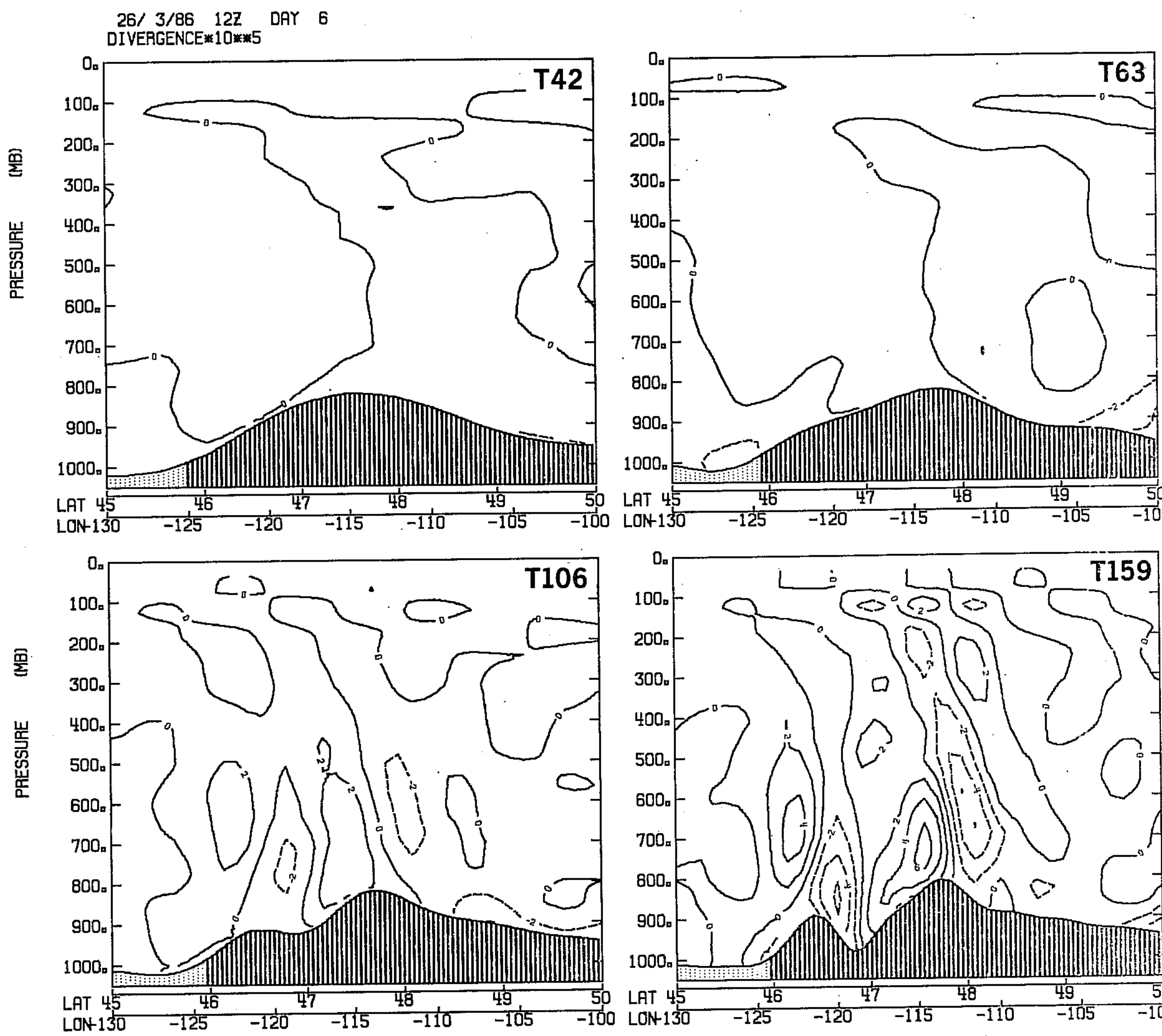


Fig. 11 Cross-sections of divergence from 45°N, 130°W to 50°N, 100°W for day 6 forecasts from 20 March 1986, using resolutions T42 (upper left), T63 (upper right), T106 (lower left) and T159 (lower right).

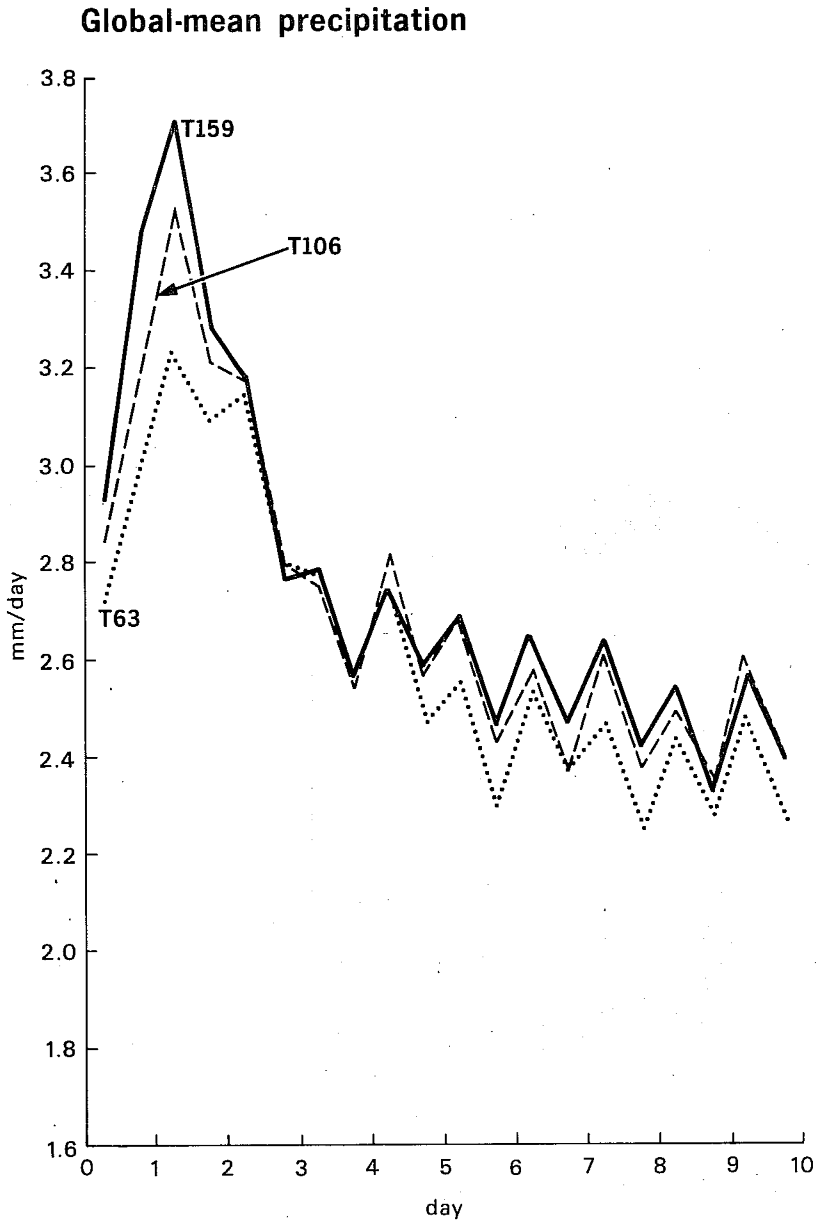


Fig. 12 Global-mean precipitation rates for T159 (solid), T106 (dashed) and T63 (dotted) forecasts from 20 March 1986.

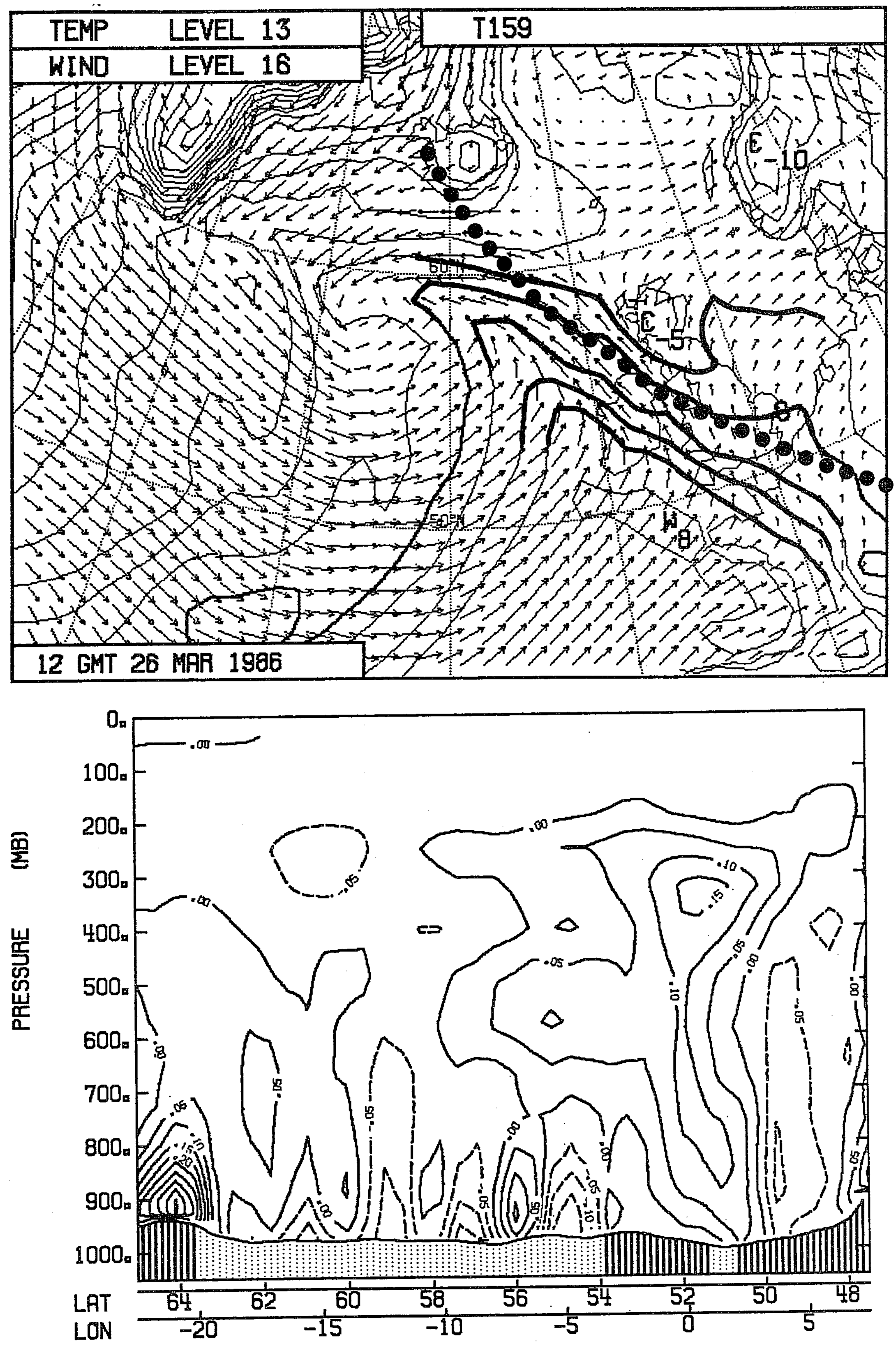


Fig. 13 Upper panel: Wind at the lowest model level (level 16) and temperature (contour interval 2 K) at level 13 for the 6-day T159 forecast from 20 March 1986.
Lower panel: The corresponding cross-section of vertical velocity (Pa s^{-1}) taken along the dotted line shown in the upper panel.

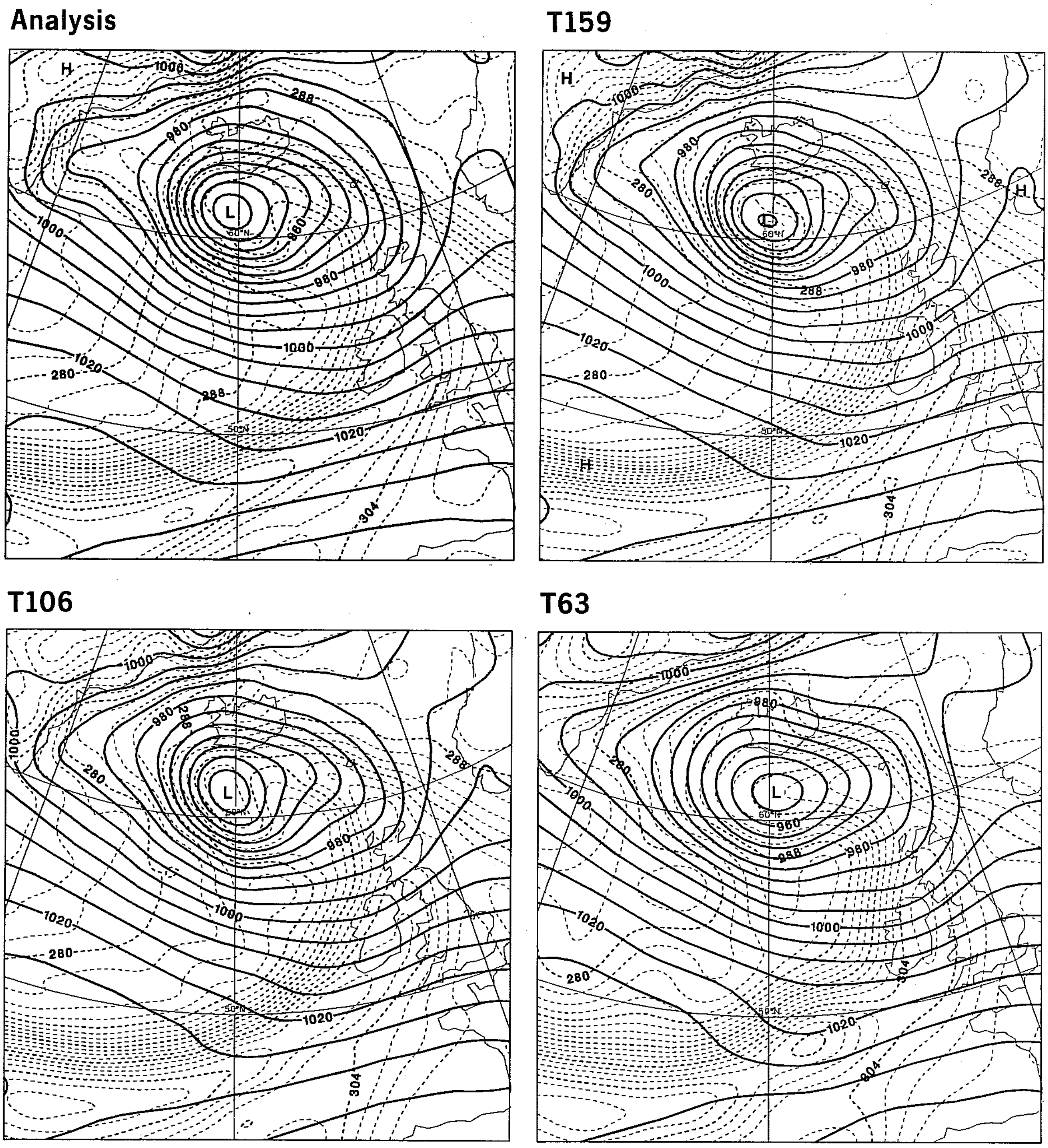
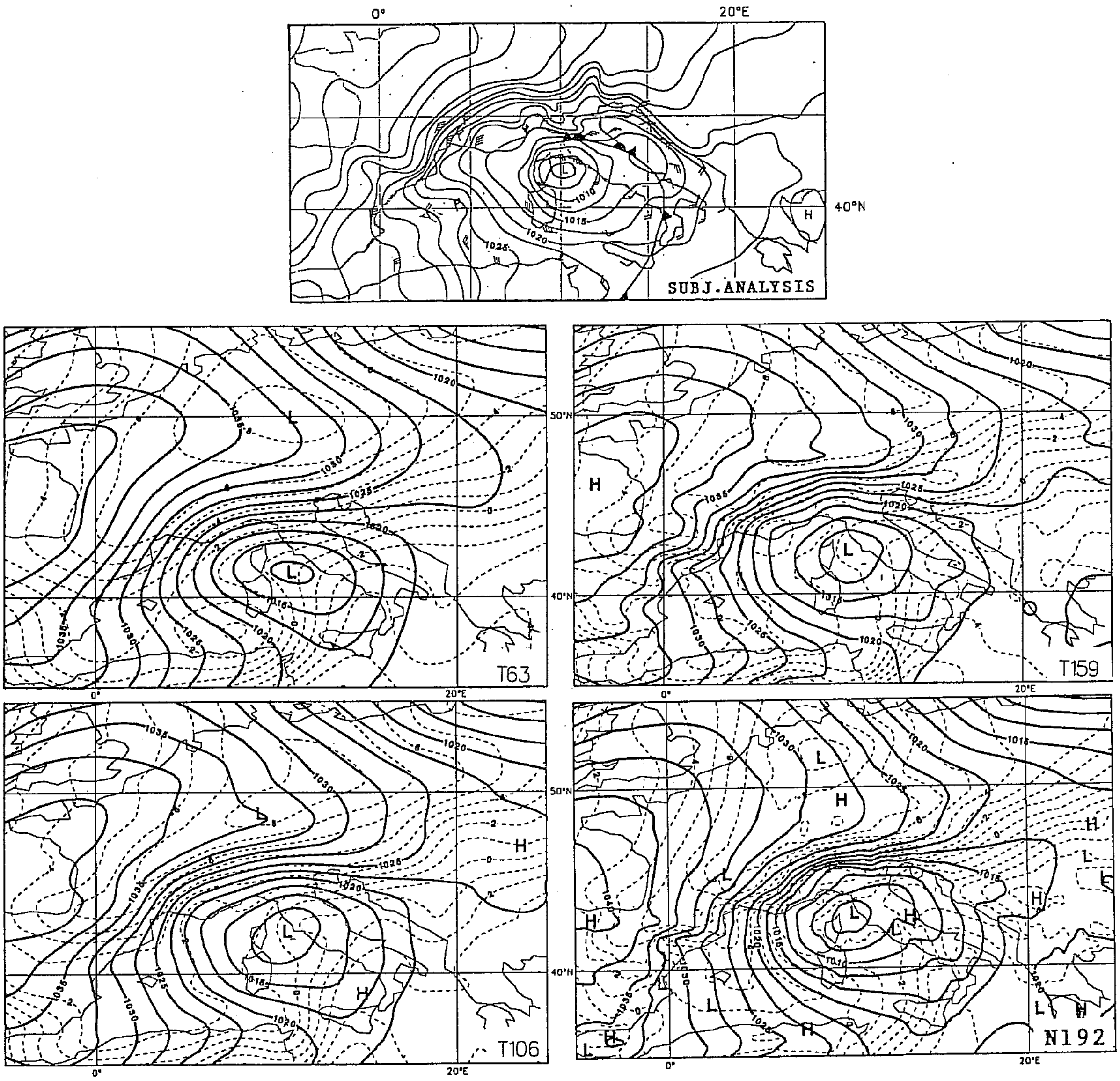


Fig. 14 The operational analysis of mean sea-level pressure and 850 mb equivalent potential temperature for 13 January 1986 (upper left), and one-day T159 (upper right), T106 (lower left) and T63 (lower right) forecasts verifying on this date. Contour intervals are 5 mb and 2 K respectively.



Pmsl and 850hPa temperature Verifying date: 82030512 Range: 48h

Fig. 15 A subjective analysis of mean sea-level pressure (contour interval 2.5 mb) for 5 March 1982 (upper), and 48-hour forecasts of mean sea-level pressure and 850 mb temperature (contour interval 1 K) using:

Middle left : Spectral model at T63 resolution
Lower left : Spectral model at T106 resolution
Middle right : Spectral model at T159 resolution
Lower right : Grid-point limited-area model at N192 resolution.

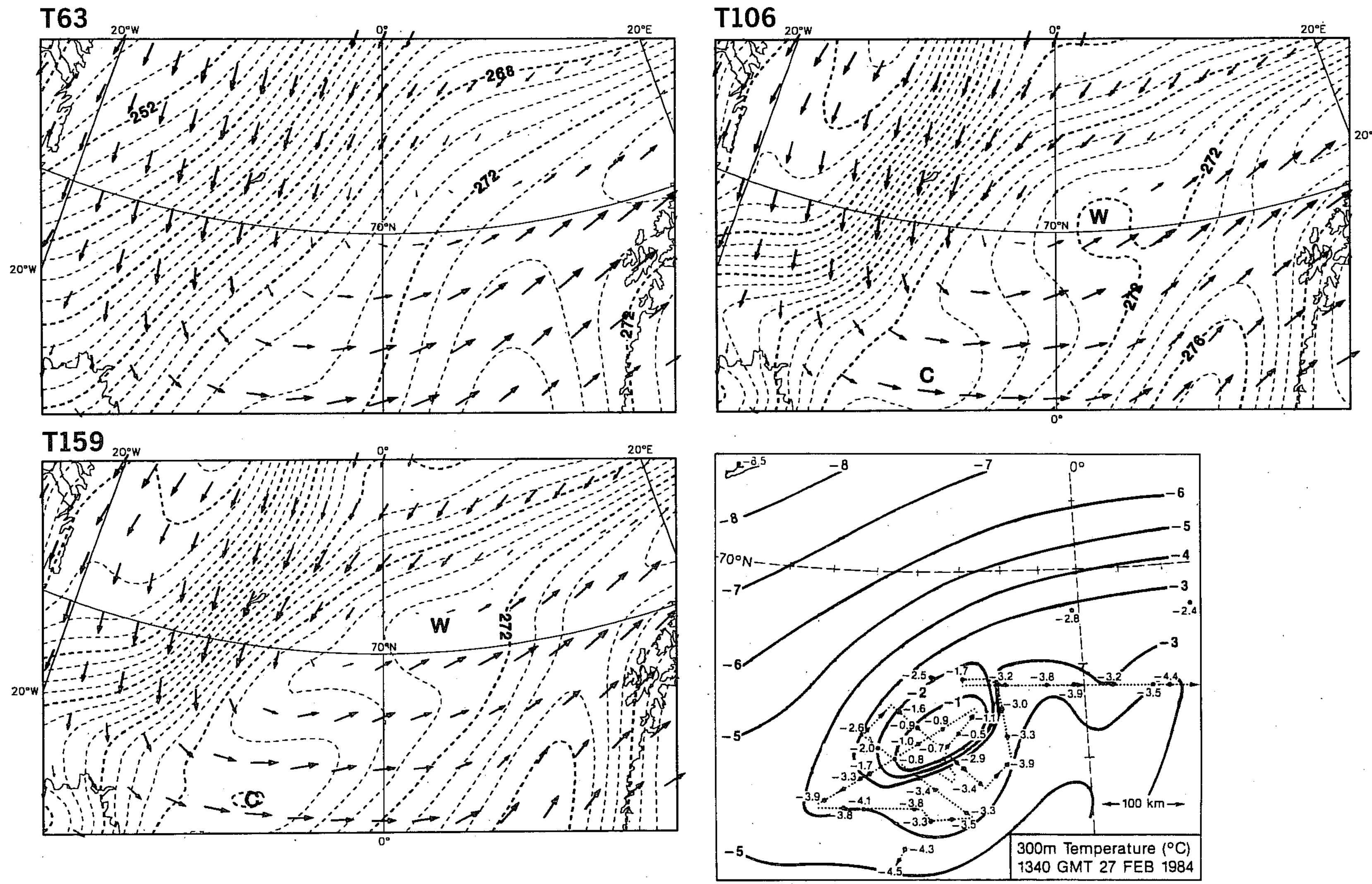


Fig. 16 Wind arrows and temperature contours (interval 1 K) for model level 17 (approximately 370 m) for 1-day T63 (upper left), T106 (upper right) and T159 (lower left) forecasts from 12Z, 26 February 1984. An analysis by Shapiro et al. (1987) of aircraft measurements taken at 300 m shortly after this time is shown (for a smaller domain) in the lower right panel.

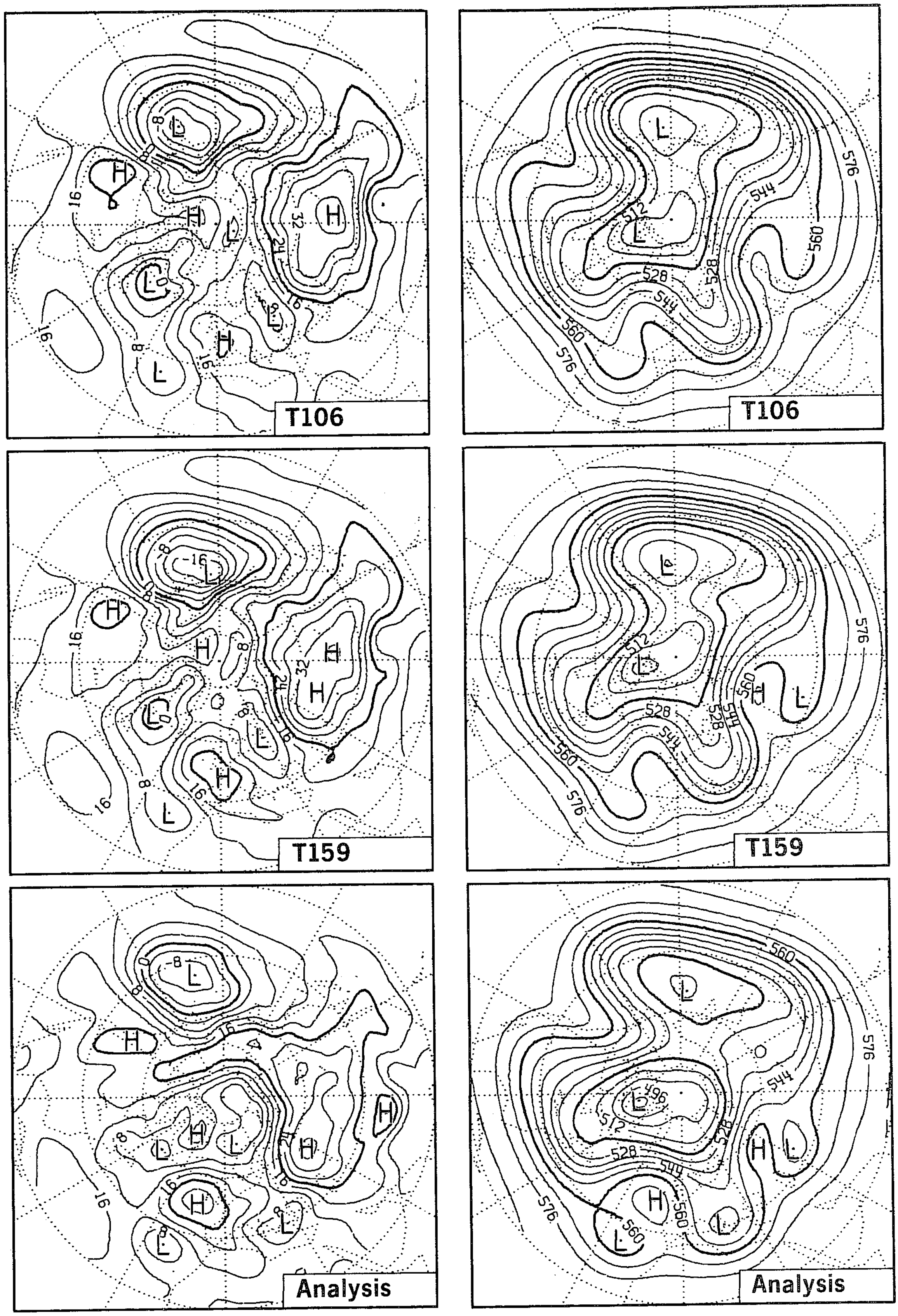


Fig. 17 Mean analyses of 1000 mb (left) and 500 mb (right) height for the period 2-7 March 1984 (lower), and corresponding maps for T106 (upper), and T159 (middle) forecasts from 26 February 1984. Units are dam.

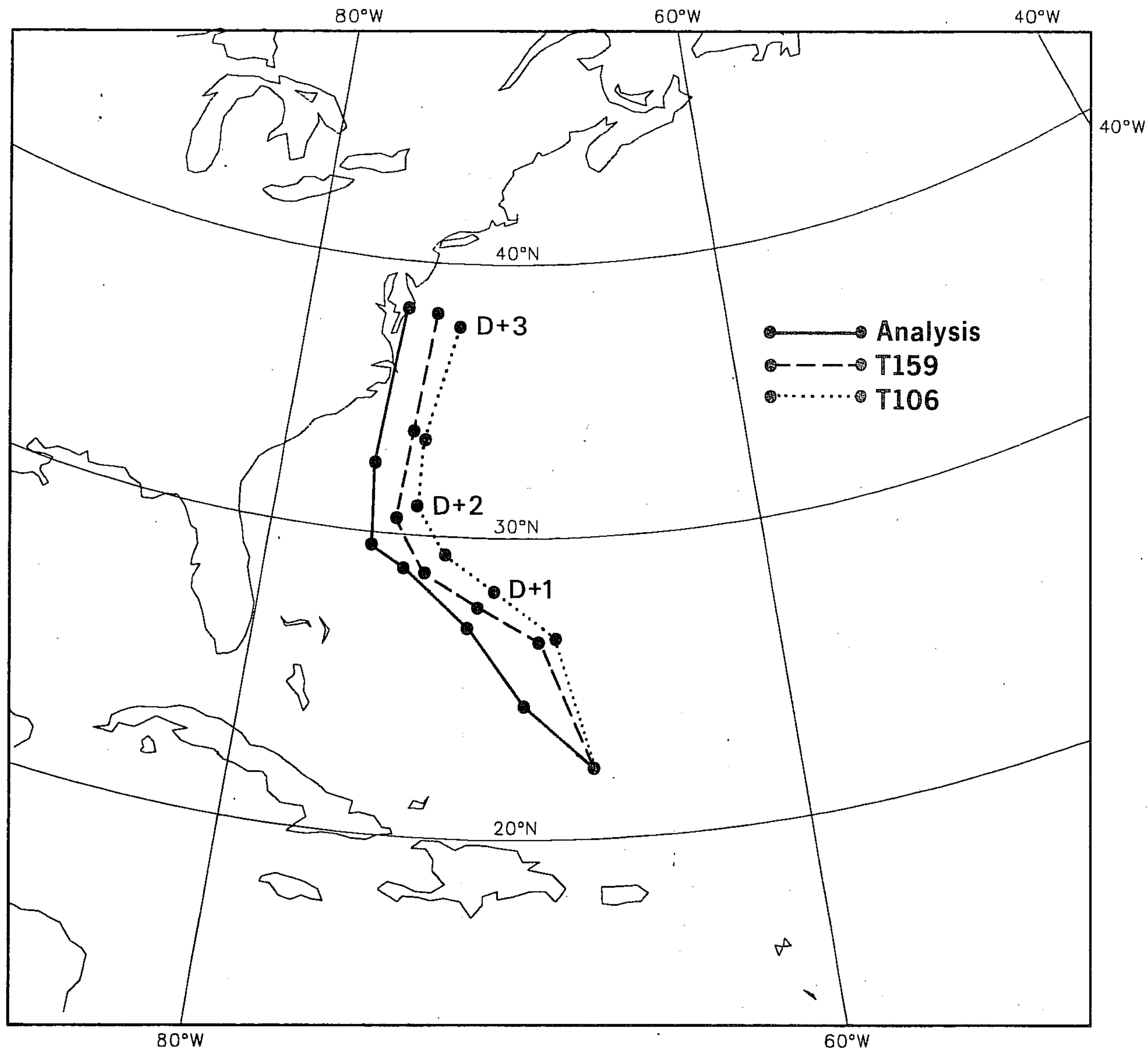


Fig. 18 Tracks of hurricane "Gloria" as analyzed operationally (solid line) for the period 24-27 September 1985, and as forecast from 24 September using T106 (dotted) and T159 (dashed) resolutions.

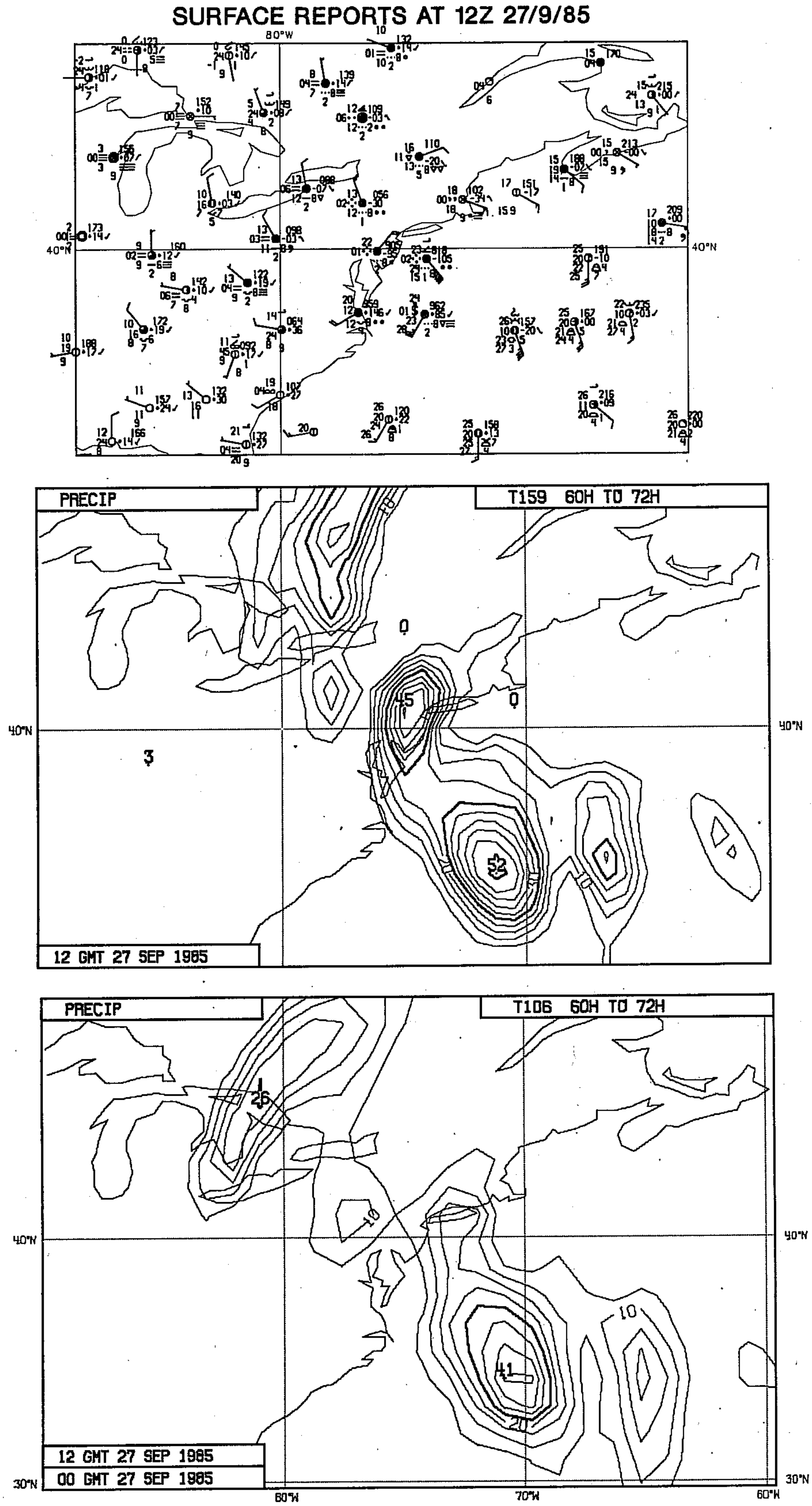


Fig. 19 Surface weather reports at 12Z, 27 September 1985, and precipitation (mm) for the period 00 to 12Z produced by T159 (middle) and T106 (lower) forecasts from 12Z, 24 September.

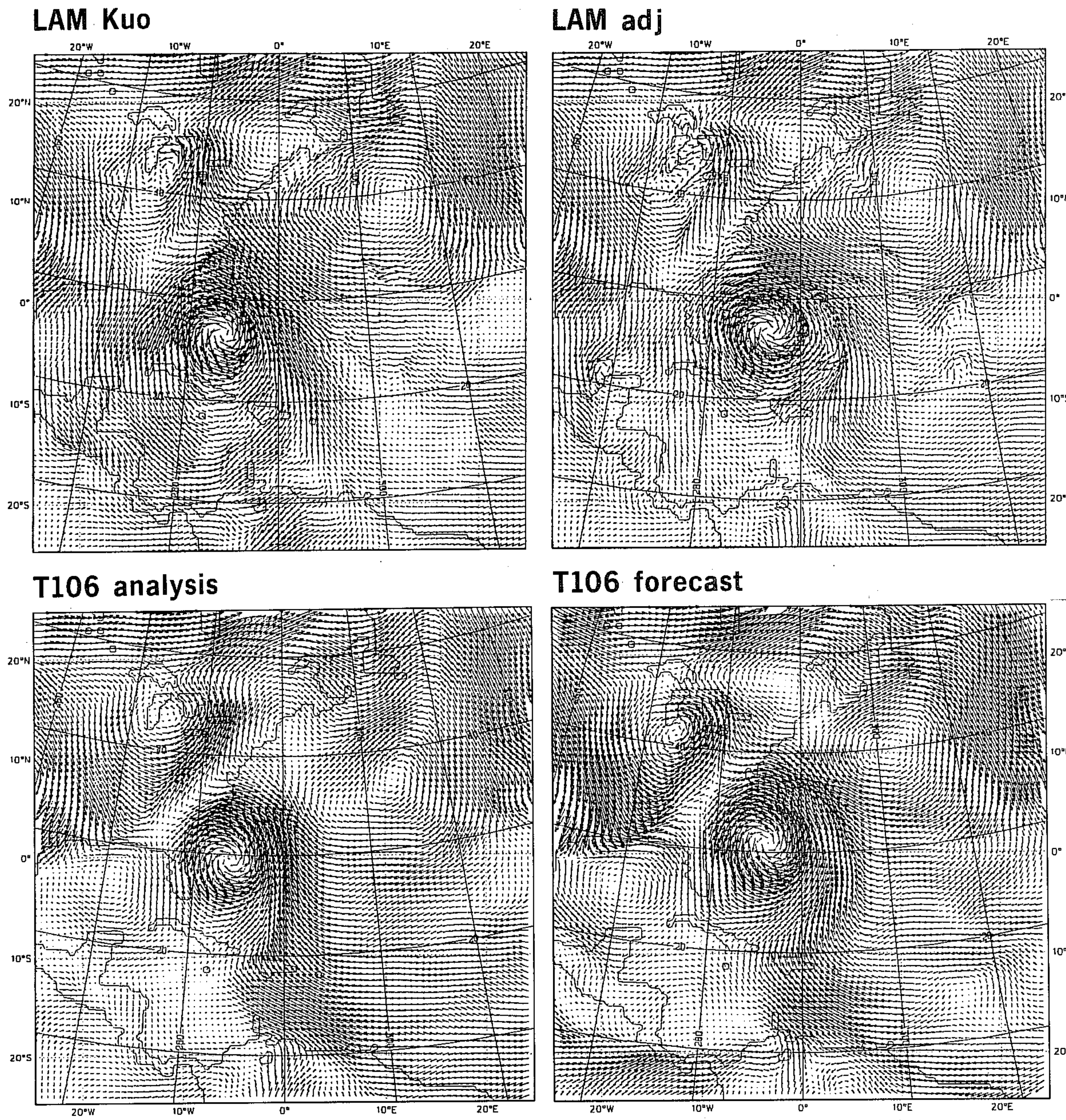


Fig. 20 Winds at model level 13 (out of 16) for 12Z, 26 September 1985, from:
Upper: 48-hour limited-area model forecasts using analyzed boundary values and a resolution equivalent to T212 with the operational Kuo convection scheme (left) and the adjustment scheme (right).
Lower: The operational T106 analysis (left) and 48-hour T106 forecast (right).

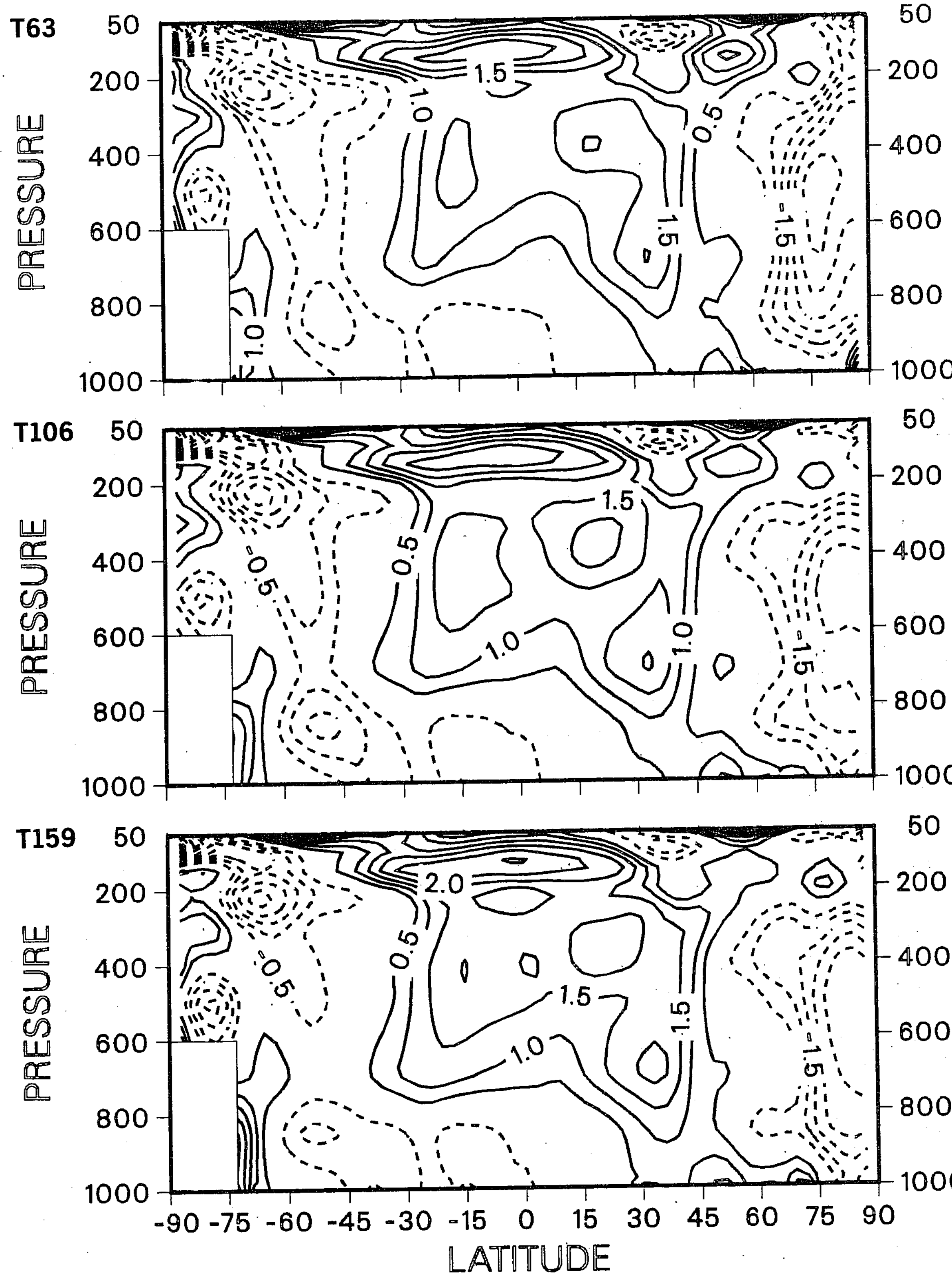


Fig. 21 Cross-sections of the zonal-mean temperature error (contour interval 0.5 K) averaged from days 5 to 10 of T63 (upper), T106 (middle) and T159 (lower) forecasts from 13 December 1986.

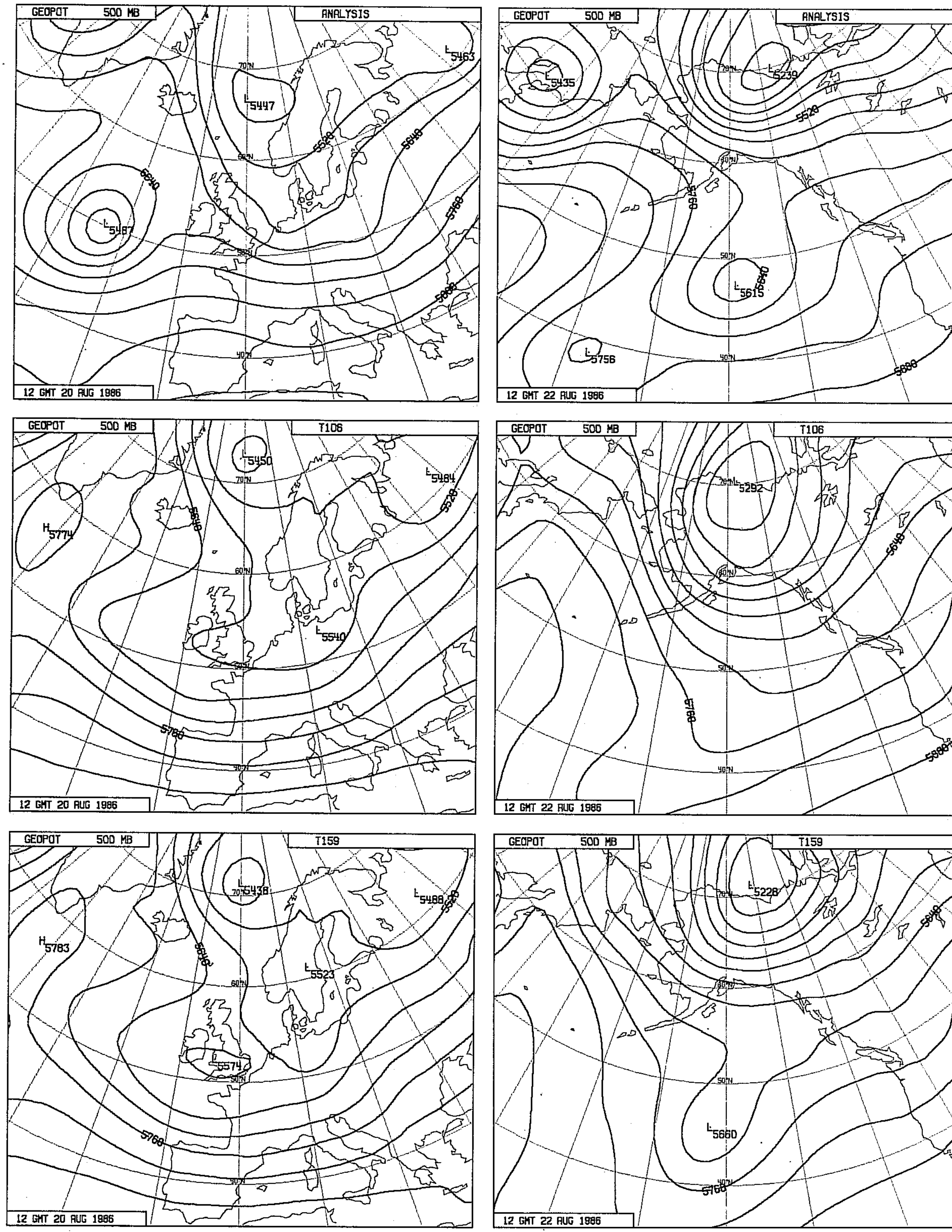


Fig. 22 Analyses of 500 mb height (contour interval 60 dam) for 20 August (upper left) and 22 August (upper right) 1986, and corresponding 5- and 7-day forecasts with T106 (middle) and T159 (lower) resolutions.

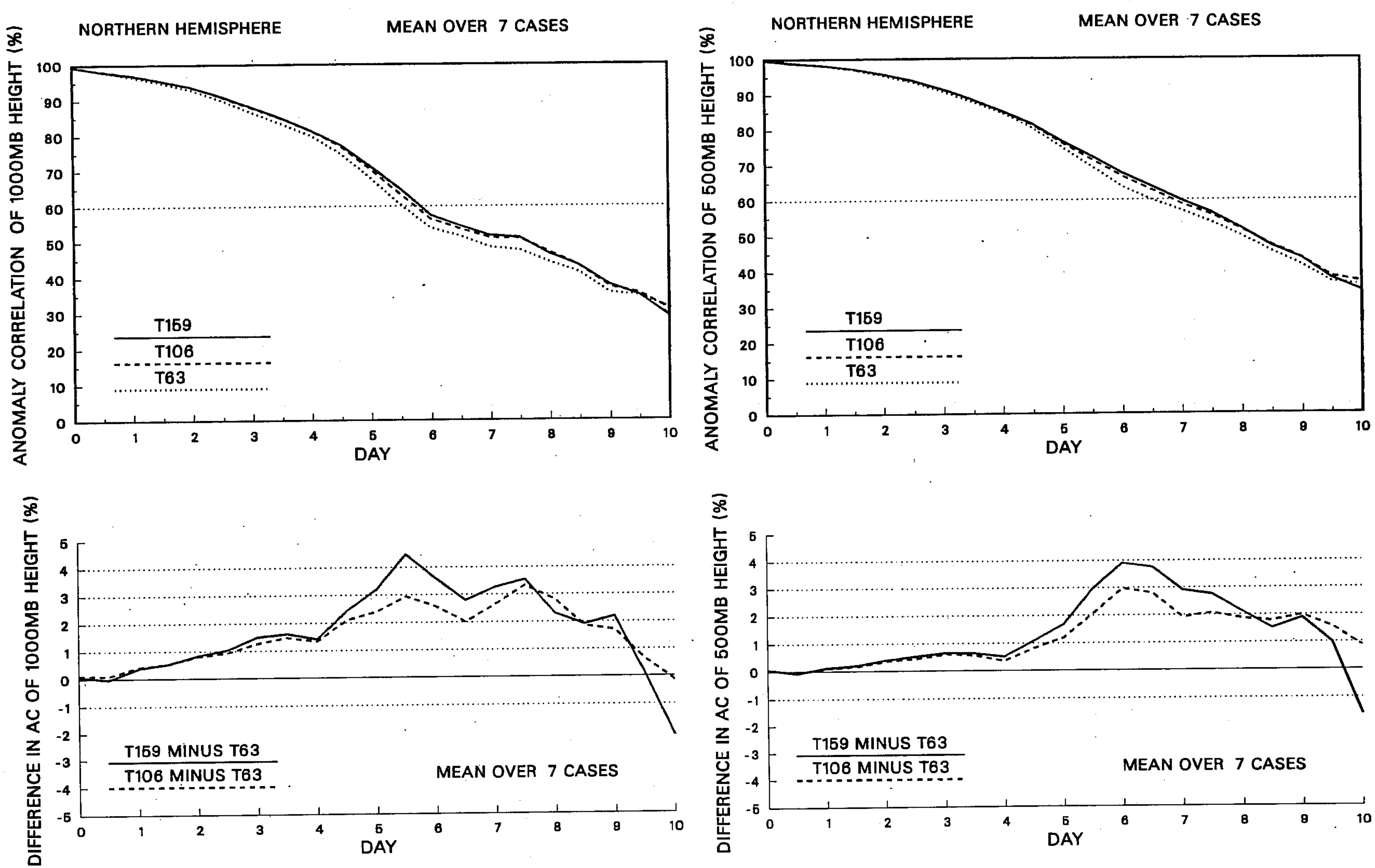
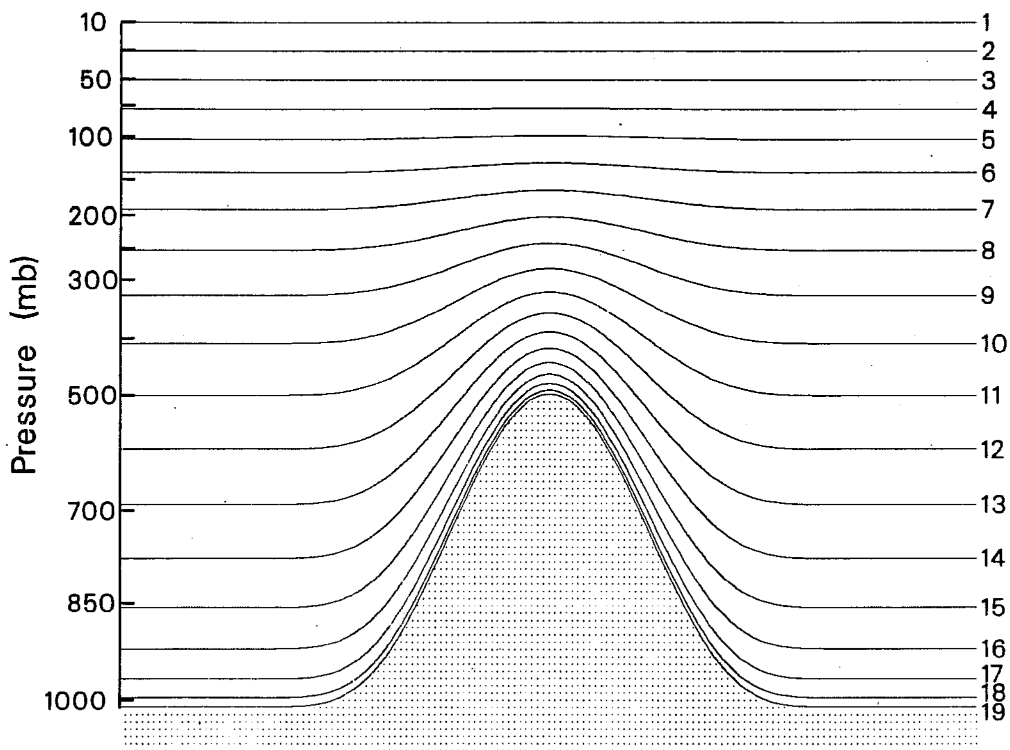
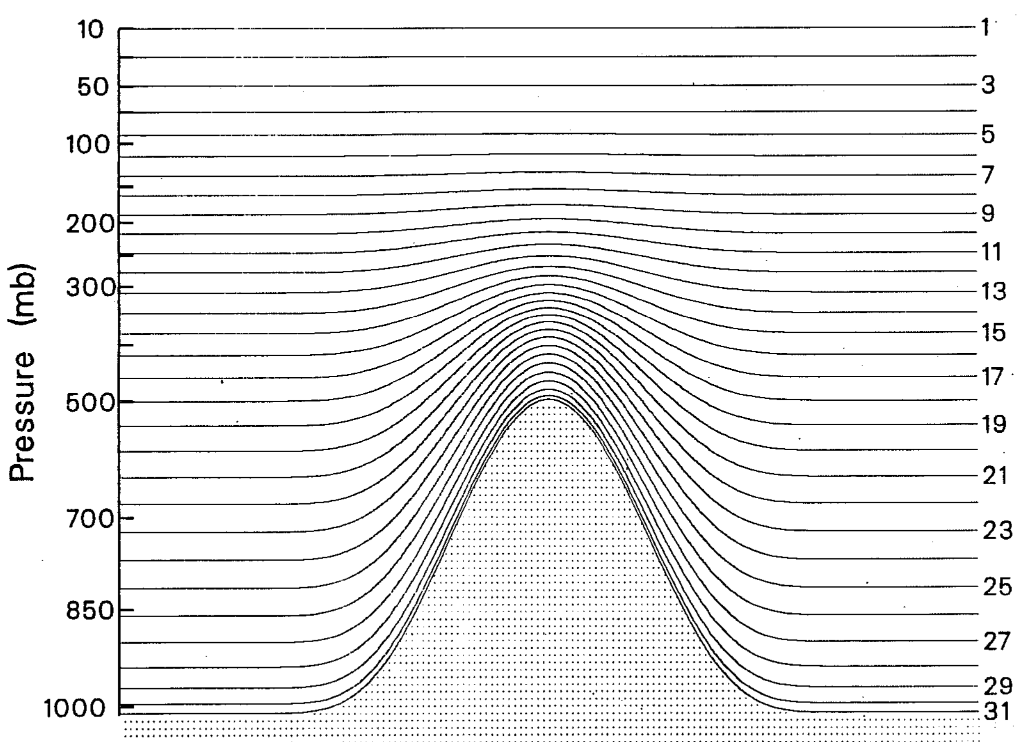


Fig. 23 Mean anomaly correlations of 1000 mb (left) and 500 mb (right) height for forecasts with T159, T106 and T63 resolutions. The upper panels display full values, and differences are shown in the lower plots.



Full levels 19-level model



Full levels 31-level model

Fig. 24 Distributions of the "full" levels where winds, temperature and humidity are represented for the 19-level operational resolution and the experimental 31-level resolution.

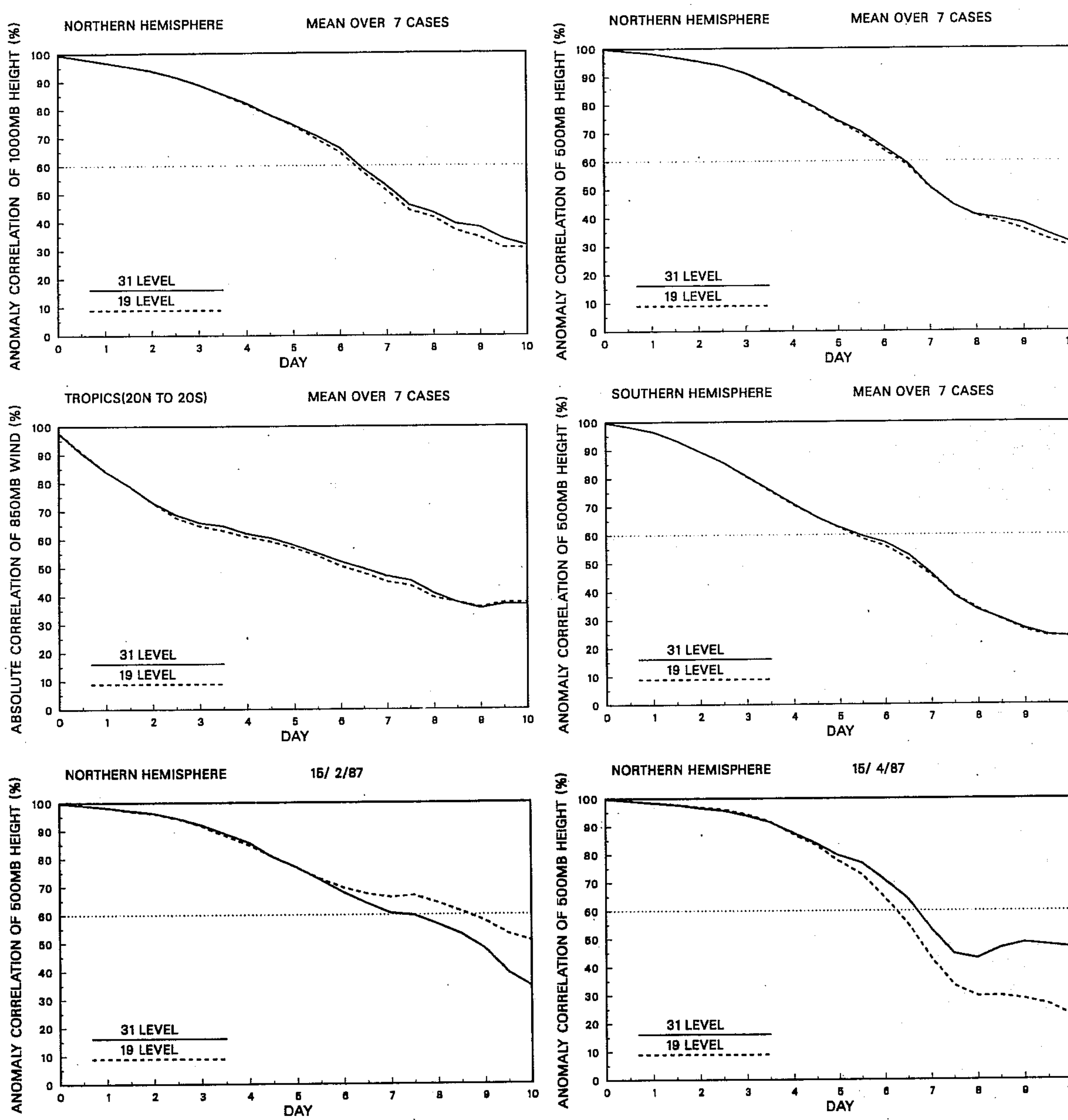


Fig. 25 Aspects of the objective verification of 19-level and 31-level T63 forecasts. The upper and middle panels present 7-case averages of:

Upper left : Anomaly correlations of 1000 mb height for the extratropical Northern Hemisphere.

Upper right : Anomaly correlations of 500 mb height for the extratropical Northern Hemisphere

Middle left : Absolute correlations of 850 mb vector wind for the Tropics

Middle right : Anomaly correlations of 500 mb height for the extratropical Southern Hemisphere

The lower two panels present anomaly correlations of 500 mb height for the extratropical Northern Hemisphere for two individual cases exhibiting high sensitivity.

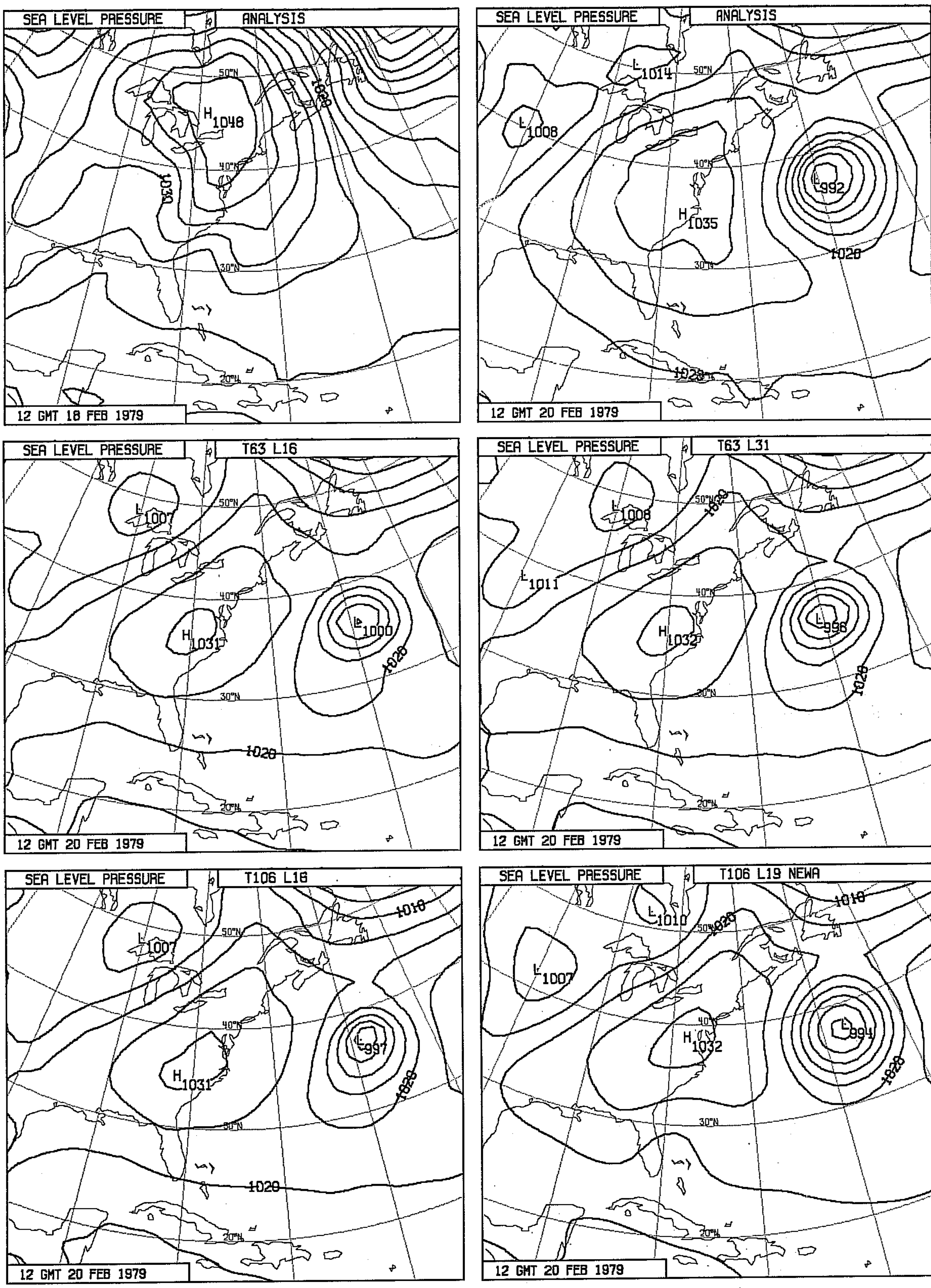


Fig. 26 Analyses of mean sea-level pressure (mb) for 18 and 20 February 1979 (upper left and right) and 48-hour forecasts from 18 February using:

Middle left : T63 and 16 levels from (T63) Final IIIb analysis

Middle right : T63 and 31 levels from Final IIIb analysis

Lower left : T106 and 16 levels from Final IIIb analysis

Lower right : T106 and 19 levels from analysis produced with current T106 L19 system.

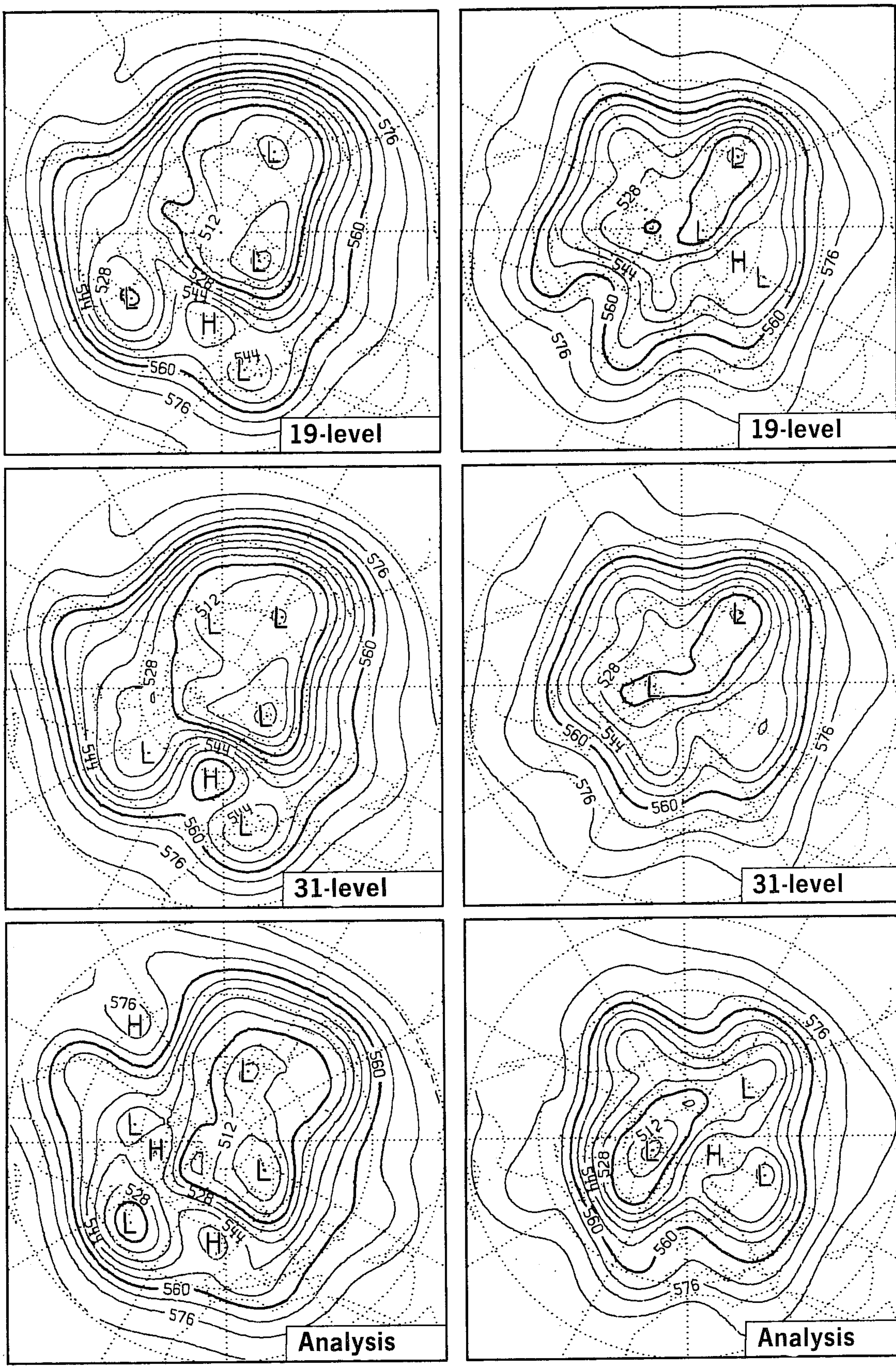


Fig. 27 Mean analyses of 500 mb height (dam) for the periods 20-25 February (lower left) and 20-25 April (lower right) 1987, and corresponding 19-level (upper) and 31-level (middle) forecasts from 15 February (left) and 15 April (right).

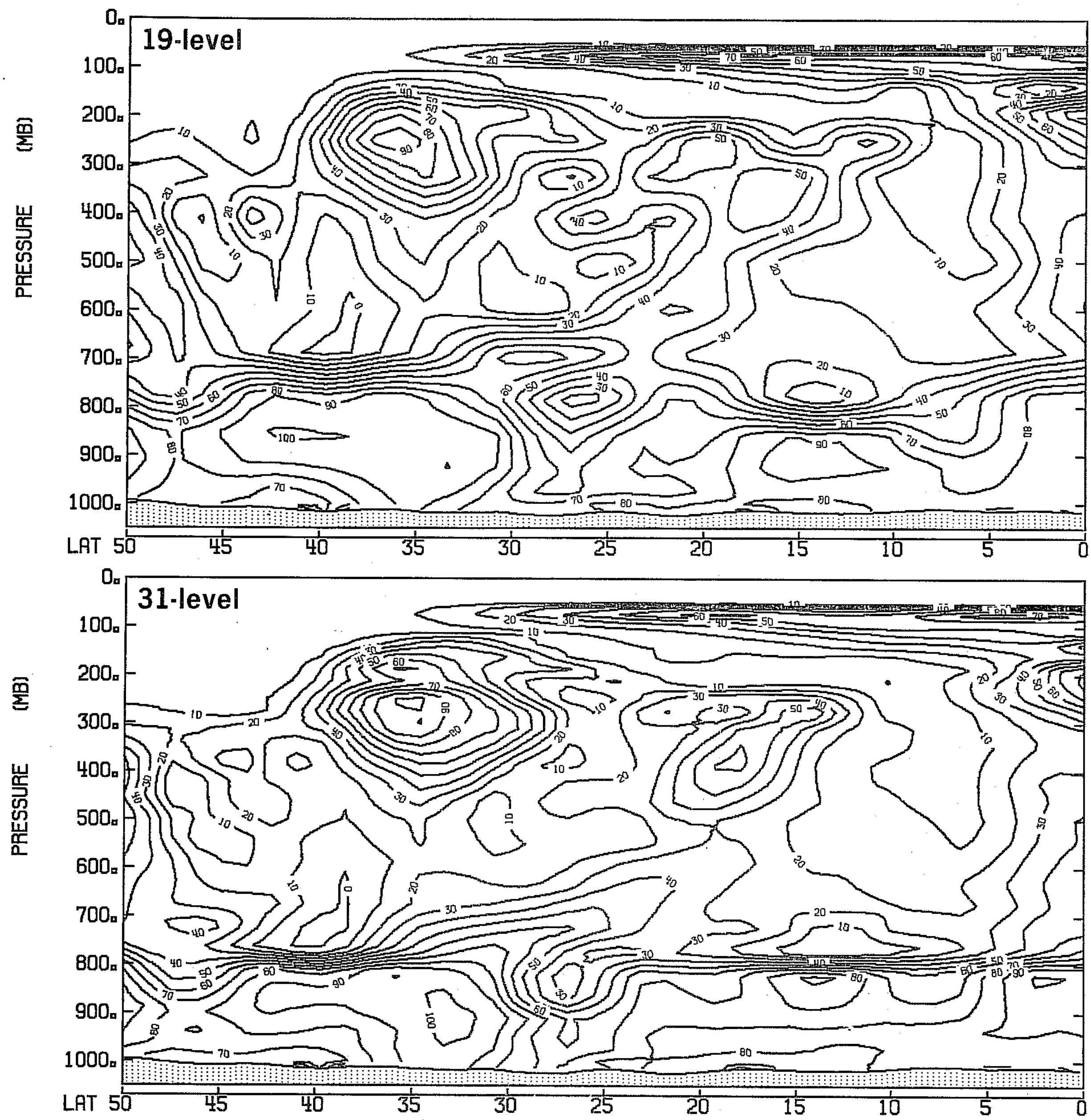


Fig. 28 Cross-sections of relative humidity (%) from 50°N to the equator along 45°W for day-2 forecasts from 15 February 1987 using 19-level (upper) and 31-level (lower) vertical resolutions.