IMPACT OF AN ENVELOPE OROGRAPHY IN THE ECMWF MODEL

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1. INTRODUCTION

The accurate representation of a range of effects of orography is increasingly recognised as an essential component of numerical models of the atmosphere. The problems raised by this are of particular relevance for medium and extended range forecasting and can be grouped in two broad categories.

One is the optimisation of the numerical treatment of the equations in order to minimize errors or inaccuracies associated with steep slopes. Well known examples are aliasing and errors arising from the discrete representation of the pressure gradient terms when using terrain following coordinate surfaces. A considerable amount of literature has been devoted to this topic, and references may be found for example, in the proceedings of the 1979 ECMWF workshop on Mountains and Numerical Weather Prediction. Further discussion of this is outside the scope of this seminar.

The second category of problem is to represent the effects of the mountains on the larger scales of motion. The main processes to parameterize are:

- The dynamical low level blocking (barrier) effect over a wide range of scales; this will be the main subject of this report.

- Generation of smaller-scale vertically-propagating gravity waves and their dissipative effect on the large-scale flow high in the troposphere and stratosphere. This parameterization has been advocated by several authors over a long period of time (e.g. Sawyer, 1959, Bretherton, 1969, Lilly, 1972) and is the subject of another report in these proceedings (G. Shutts).

- Low level drag associated with the very short scales of the orography (up to a few hundred metres) as discussed by Mason in these proceedings.

- Secondary effects which can be due to interactions with precipitation (e.g. Bender et al. 1985), snow cover, surface temperature, cloud cover, etc. These effects are likely to be more important at both extremes of numerical weather forecasting: at short range for the prediction of the actual weather elements and at longer range when differences due to these interactions have time to grow to larger amplitude.

As already mentioned in this report we are mostly concerned with the first point. We shall review the reasons there are to suspect that the low level barrier effect of the mountains is not adequately represented by an area mean orography, and some of the solutions proposed to remedy the problem (Section 2). In Section 3 we shall describe a experimental programme designed to shed some light onto the problem; this was part of a larger project aimed at assessing the impact of horizontal resolution in the ECMWF model. Objective and synoptic results for the Northern Hemisphere will be presented in Section 4 and 5 respectively. Section 6 will be devoted to the sensitivity of the systematic errors to the representation of orography in the Northern Hemisphere. Finally, Section 7 will present a few results for the Southern Hemisphere and the tropics, and will be followed by some general discussion and conclusions.

2. REPRESENTATION OF THE LOW LEVEL BARRIER EFFECTS

Very crudely (and intuitively) the energy needed to lift an air parcel above a mountain is proportional to the height of the mountain and can reach very large values. Thus depending on the strength of the flow, the shape of the mountains, and several other factors, the flow will either be able to go over the mountains, or will be blocked (in particular at the lowest levels), and in all cases will undergo a certain deformation. It is also easy to see that when using an area averaged orography and meshes of the order of several hundred kilometres, the height of many mountain ranges in the model will be too low to simulate accurately this effect, and there is likely to be too much flow over the mountains.

A number of studies are indeed strongly suggestive of such an underestimation of the orographic forcing when using an area-mean orography. For example, cyclogenesis in the lee of the Alps has been found to be improved when using some form of enhanced mountains, either by increasing the height of the orography used by the model (e.g. Dell'Osso and Radinovic, 1984) or by blocking the low level flow more explicitly (e.g. Egger 1972). Both approaches increase the deformation of the flow at the expense of the direct flow over the mountain.

Synoptic-scale blocking over the North Atlantic western European region has also been found to benefit from the use of an enhanced "envelope" orography (Ji and Tibaldi, 1984) and we shall show further examples of this in this paper. Krishnamurti et al. (1984) showed monsoon simulations in the FGGE period to be improved in the FSU general circulation model when using a similar envelope.

Wallace, Tibaldi and Simmons (1983) reported diagnostic studies which demonstrated a close relationship between the structure of the very short range systematic errors of the ECMWF model in winter situations and the position of some mountain ranges in the Northern Hemisphere (the Rockies and Alps in particular). The evidence for the rôle played by the orography in the development of these systematic errors was strengthened further by experiments with a barotropic model.

Pierrehumbert (1984) using the framework of the linear theory first developed by Queney (1947) showed that in order to represent the barrier effect of mesoscale mountains such as the Alps or elements of the Rocky Mountain range, it was more important to preserve the mean maximum height of the cross-flow section than the volume of the mountain (as does the area averaging), in agreement with the intuitive arguments given at the beginning of this section. More recently, nonlinear calculations by Cullen et al. (1985) and Pierrehumbert and Wyman (1985) have led to similar conclusions.

Several approaches have been used in practice to enhance the low level blocking effect of the mountains. Some correspond to a more or less explicit blocking of the low level flow (e.g. Egger 1972, an approach developed subsequently for operational forecasting at DWD). Many others correspond essentially to an increase in the height of the mountains used by the models. For example, following a suggestion by Mesinger (Gerrity, 1985) a 'silhouette' orography is used for global operational prediction at NMC, Washington. This orography approximately simulates the cross-section of the mountains presented to the flow. Such is also the aim of the orography used by the French fine mesh model (Rousseau, personal communication) constructed by an area averaging of the maximum orographic height in 10' x 10' subgrid boxes. Radinovic (1985) has examined a 'valley filling' approach (Mesinger, 1977) attempting to take into account that valleys filled with cold air are very stable and interact very little (under certain conditions) with the rest of the flow, and should therefore be treated as part of the mountain itself (e.g. Bleck, 1977).

At ECMWF Wallace et al. (1983) proposed the use of an orography representing some form of envelope. Following suggestions by J.-F. Geleyn they added to the mean orography twice the square root of its variance over each grid square, as computed from a much finer resolution. When tried in actual forecasts for February 1982 it achieved a significant improvement of objective scores and a reduction of systematic errors, in particular their growth rate. These results were confirmed by further winter experiments with the N48 ECMWF grid point model (Tibaldi, 1985) and with the T63 ECMWF spectral model (Simmons and Jarraud, 1984). However, in contrast to these encouraging results, a number of disturbing features were also observed. The envelope, despite contributing to a significant reduction of the mean errors between Day 7 and 10 of the forecast range, was found to deteriorate slightly the very short range mean errors. There were also concern about the behaviour of the envelope in different weather regimes,and especially in summer situations, as pointed out by Simmons and Jarraud (loc.cit).

In addition some problems occur due to increased local discrepancies between actual and model heights, in particular when using observations (in the data assimilation) or near surface forecast products (low level wind, surface temperatures, etc). Therefore it was decided, as part of the development of the higher resolution ECMWF operational model, to reassess the impact of an envelope at various resolutions.

3. THE EXPERIMENTAL PROGRAMME

In order to get as much confidence as possible in the representativeness of the results, twenty-four cases were selected objectively, namely the 15th of each month from May 1983 to April 1985. For each case 10 day forecasts were made with a mean and an envelope (based on $\sqrt{2}\sigma$, σ being the subgrid standard deviation of the orography from the mean) with the ECMWF spectral model at the four resolutions T21, T42, T63 and T106. In addition a set of T106 forecasts was carried out using a lower envelope based on adding one standard deviation.

Since it would have been impractical to perform data assimilation for all cases, resolutions and orographies, initial conditions were in each case based on the operational T63 analyses which had been produced using one or other of two versions of the $\sqrt{2}$ standard deviation envelope orography. Analyses produced using the earlier version, operational until the end of January 1984 were converted to the later version for the purpose of these experiments. Upper-air fields were formed by spectral fits of fields which had been vertically interpolated from one set of coordinate surface to the other at each point of the model's Gaussian grid. Similar procedures were used to produce the T63 mean orography initial data and all T106 datasets, using mean and envelope orographies created using the higher resolution Gaussian grid. Upper air fields, surface pressures and orographies for the T42 and T21 experiments were obtained directly by truncation of T63 fields. A proper land sea mask was constructed for each resolution from a US Navy 10' x 10' grid. All other surface fields for all resolutions and orographies were derived by simple linear interpolation from the operational T63 initial conditions.

These procedures, together with the use of the operational T63 analyses for verification, inevitably introduce some bias in favour of T63 with envelope orography, but some evidence has been accumulated indicating that these biases are indeed much smaller than the differences observed. In particular some experiments were constructed in which surface fields, such as surface temperature and snow, were initially modified in order to take into account differences in the height of the orography. Subsequent differences in several 10-day forecasts were found to be negligible compared to the ones obtained when comparing mean and envelope orographies. An example will be seen in the lower right part of Fig.5. Also, the impact of computing directly an envelope orography for T42 rather than deriving it from the T63 one was tested in a situation particularly sensitive to the prescription of orography. The resulting differences after 10 days were again very small.

Finally, to reduce the amplitude of orographic ripples over oceans in the operational T106 model, a weak Gaussian filter with a radius of 50 km was applied prior to the spectral fitting of the T106 orographies. When tested in four different situations, it led to very small differences in the height and temperature fields, differences similar to or smaller than the ones obtained by changing the time step, even near the surface. Small precipitation biases associated with the orographic ripples were noticeably reduced.

4. NORTHERN HEMISPHERE RESULTS - OBJECTIVE ASSESSMENT

Most of the objective evaluation presented in this paper is based on anomaly correlations since this measure was found to give results in reasonable agreement with synoptic evaluations and in many, though not all, respects, with indications obtained from other scores such as standard deviations.

Fig. 1 displays the anomaly correlations for the height field at 500 mb (Z500) averaged over the 24 cases for all four resolutions (increasing from top to bottom) and for both mean and envelope orographies. On the right side are displayed the mean differences between the curves on the left. The general impression is that there is a gradual change in the behaviour of the envelope when going from low (T21) to high (T106) resolution, at least in the D+1 to D+5 range: the envelope is clearly damaging the quality of the forecasts at T21, slightly less at T42 and is almost neutral at T63. T106 is the only resolution for which there is a positive signal.

These results are at first sight in contradiction with those of early experiments carried out at ECMWF which reported a larger positive impact from the envelope. However, these experiments did not correspond to as wide a range of independent synoptic situations as in the present sample, and were exclusively winter experiments.

Indications of a different response in summer were subsequently found with the T63 model (Simmons and Jarraud 1984). The 24 cases sampled here were thus divided into two groups of 12, one broadly representing winter (November to April) and one summer (May to October), the division being based on an EOF diagnosis of the annual cycle (Volmer et al. 1983).

Mean differences between 500 mb height anomaly correlations for mean and envelope orographies (similar to those on the right panel of Fig. 1) are presented for each horizontal resolution and season in Fig. 2. In winter (left panel) the beneficial overall impact of the envelope is evident for all resolutions other than T21. Up to day 4 there is a gradual change from T21 to T106 with, as for the whole year, a strong damaging effect of the envelope at T21, and only a very slight worsening at T42. For T63 and T106, however, there is a clear improvement; this being noticeable earlier in the forecast range for T106. Later in the forecast range, quantitative aspects of the improvement due to the envelope at resolutions higher than T21 must be regarded with caution, due to sampling uncertainties. For example, one case at T42 contributes more than 2% to the mean difference for day 10, and the improvement at T63 and T106 from the six cases for winter 83/84 was substantially larger than from the corresponding cases for 84/85. On average though, the T63 improvement is somewhat smaller than the one reported by Wallace et al. (1983). It is also worth mentioning that no obvious worsening at short range is observed at T63, in contrast to the earlier experiments, which used a higher envelope based on two standard deviations.

The results for summer shown also in Fig. 2 are in sharp contrast. The envelope has a detrimental effect in terms of anomaly correlations (although it is almost neutral for standard deviations) across the whole forecast range for T42 and T63. This is noticeable earlier for T42 than for T63. Only for T106 resolution is the performance of the mean and envelope orographies comparable, in an average sense. Fig. 2 also indicates that for T106 there is little to choose, overall, between envelopes based on 1 or √2 standard deviations, the higher orography giving results slightly better than in winter and slightly poorer in summer.

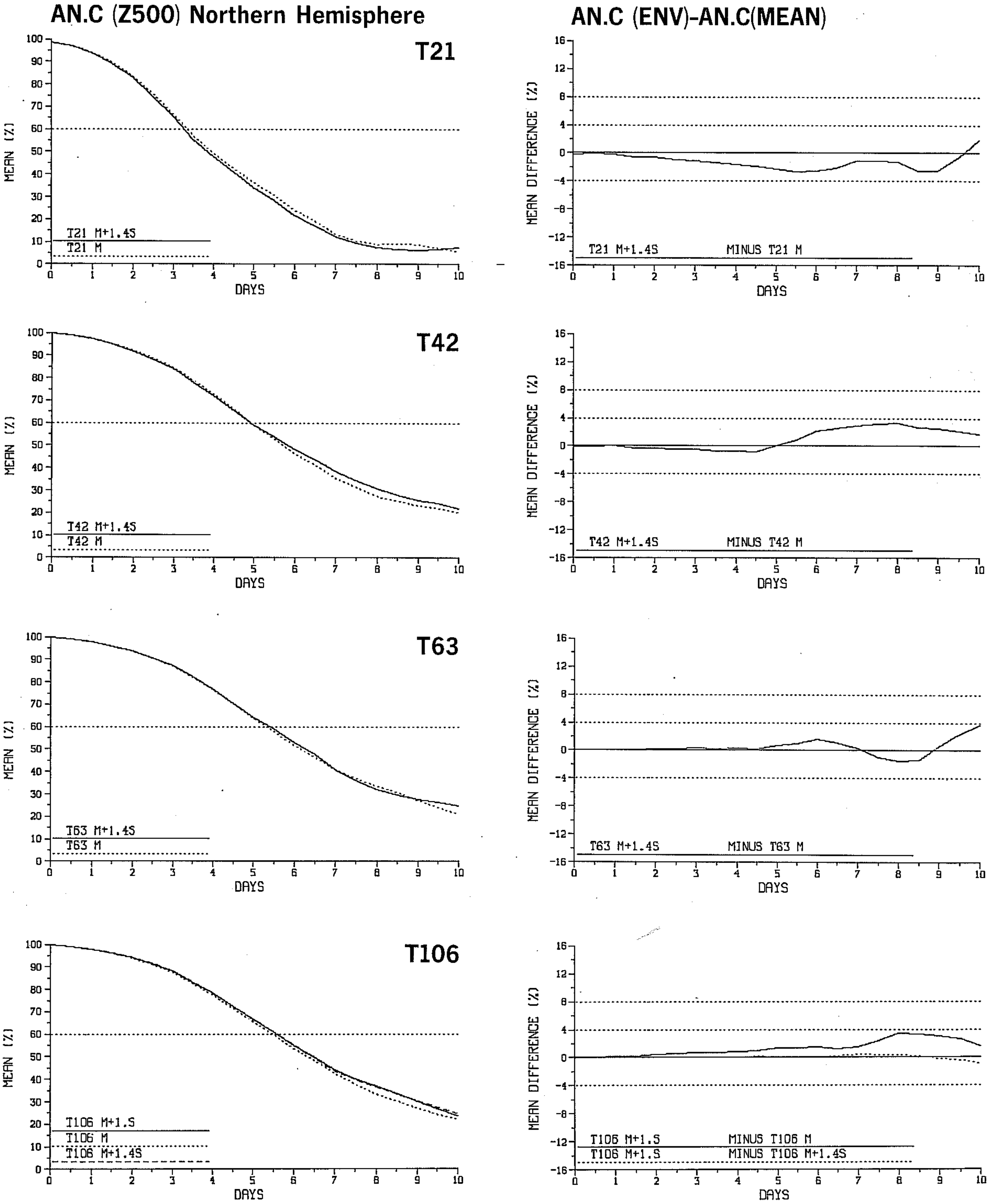


Fig. 1 Mean anomaly correlations of 500 mb height in the Northern Hemisphere for mean (dotted) and ($\sqrt{2}\sigma$) envelope (full) orographies for T21 to T106 resolutions (top to bottom) averaged over 24 cases (left) and corresponding differences (right). In addition, for T106 the dashed line (left) corresponds to a (1σ) envelope orography and the dotted line (right) to the difference between a (1σ) and a ($\sqrt{2}\sigma$) envelope.

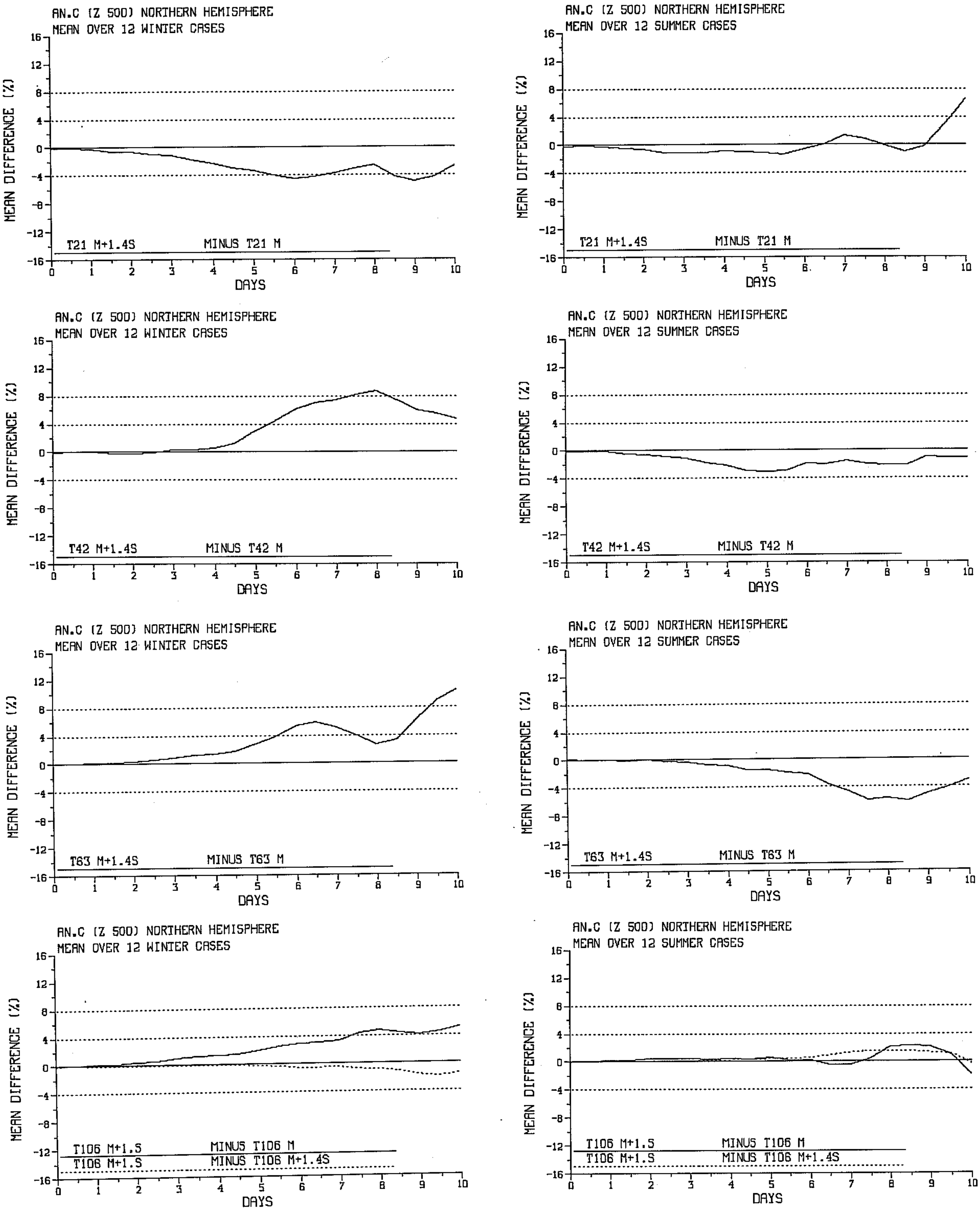


Fig. 2 As right part of Fig. 1 for 12 winter (left) and 12 summer (right) cases.

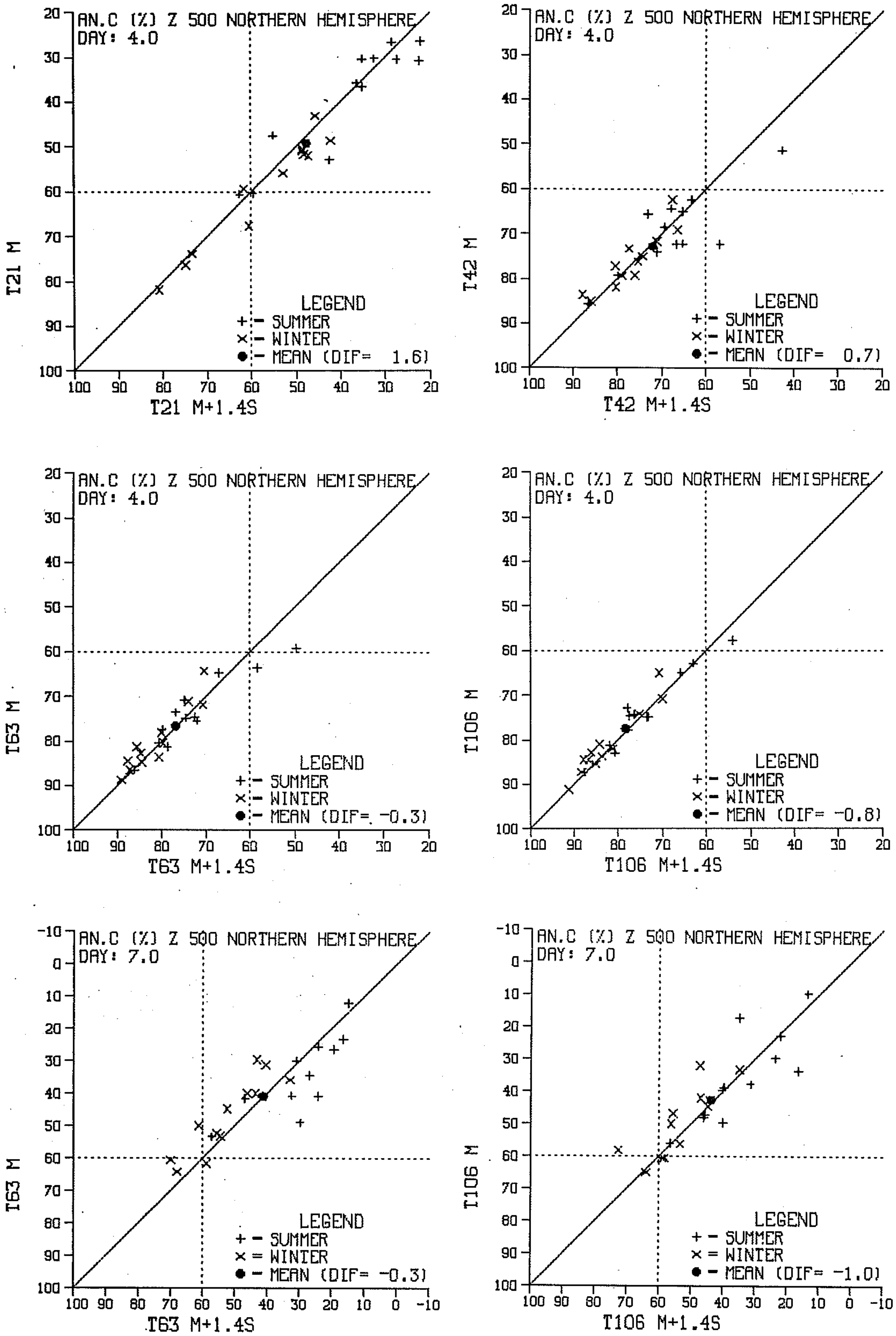


Fig. 3 Upper and middle: scatter diagrams of anomaly correlations of 500 mb height field in the Northern Hemisphere comparing mean and ($\sqrt{2}\sigma$) envelopes at T21, T42, T63 and T106 resolution for D+4 forecasts. Summer cases are represented by + signs, winter cases by x signs, and the mean by a thick dot.

Lower: As above but for D+7 forecasts at T63 and T106 resolutions.

Scatter diagrams showing individual forecast comparisons between mean and ($\sqrt{2}$) envelope orographies for all resolutions for day 4 and for T63 and T106 for day 7 are presented in Fig.3. For T21 there is a considerable dispersion along the diagonal, indicating a highly variable forecast quality with particularly poor results in summer cases (denoted by + signs). This may explain why the T21 seasonal behaviour differs from that for the other resolutions, since in summer the other gross errors produced by the very coarse T21 truncation tend to mask rapidly the impact of the envelope.

Accuracy is considerably higher for the other resolutions at day 4 and it can be seen that there is less scatter across the diagonal for T63 than for T42 and less still for T106 indicating (as might be expected) a decrease in sensitivity to the envelope as resolution increases. There is nevertheless a larger mean improvement due to the envelope at T106 because the smaller differences are more systematically in favour of the envelope. Later in the forecast range (lower part of Fig.3) there is more variability and seasonal differences are more clear, particularly at T63 for which the improvement due to the envelope in winter, and deterioration in summer, occur in almost all cases. Examining other levels and variables generally confirms these results, but suggests for the 500 mb temperature and the 850 mb wind fields a slightly more positive impact of the envelope at T63 resolution, and a more systematic benefit at T106. The response observed for the 1000 mb heights is similar to that already shown for the 500 mb height fields, both in summer and winter.

5. NORTHERN HEMISPHERE RESULTS - SYNOPTIC ASSESSMENT

A detailed synoptic assessment of forecasts has been carried out for the extratropical band of the Northern Hemisphere, concentrating on the evolution of forecast differences from what are typically, in the early part of the range, small deviations localized in particular mountainous regions. Earlier reports have emphasized the importance of the Rocky Mountain chain, and here we shall not attempt to give another detailed illustration of similar cases. We shall rather concentrate on synoptic examples illustrating some particular aspects of the objective scores and demonstrating how several mountain ranges other than the Rockies prove to be important in turn or simultaneously. We shall also attempt to relate the way the flow is modified by the change from mean to envelope orography to the arguments examined in Section 2 and show how forecast differences tend to originate where a strong flow is incident upon a mountain range. These differences subsequently propagate, mostly downstream.

5.1 A Winter case

As a first example of a winter case where the use of an envelope improved significantly forecasts in the medium range, Fig.4 displays two day 7 forecasts of 500 mb height, and differences between the forecasts, for the 15 January 1984 case using T106 mean and ($\sqrt{2}$) envelope orographies. Differences are particularly large over the Bering Strait and North Asia in connection with a different position of a strong anticyclone. In the analysis and envelope orography forecast the anticyclone is positioned at 150°E and a ridge extends south westwards towards Siberia. With the mean orography the anticyclone is displaced by more than 20° eastwards and a low pressure belt has broken the associated ridge. By looking backwards in time and running an experiment with mountains modified in the eastern part of Asia, it was possible to show that the differences were of a very complex nature, with

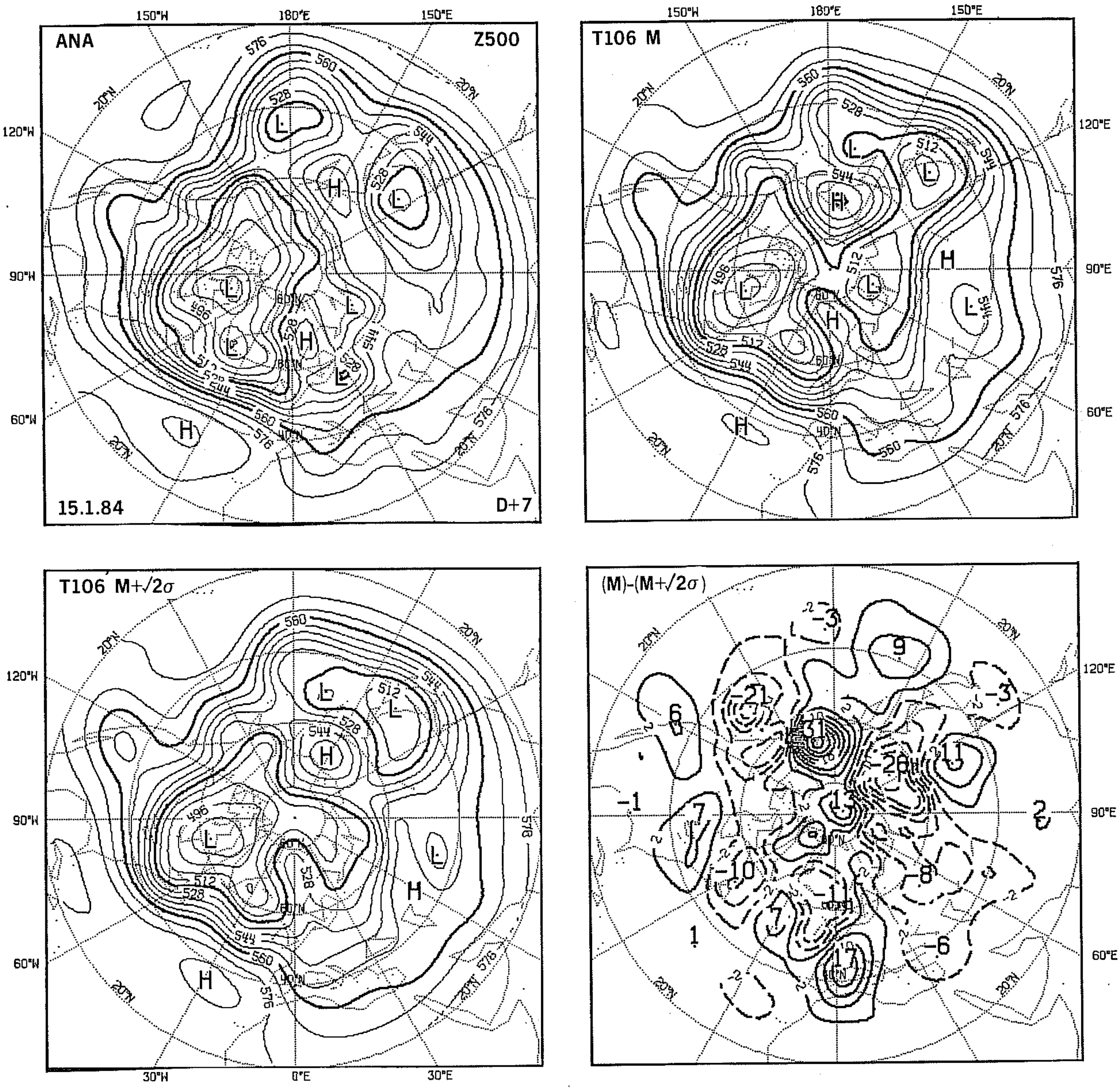
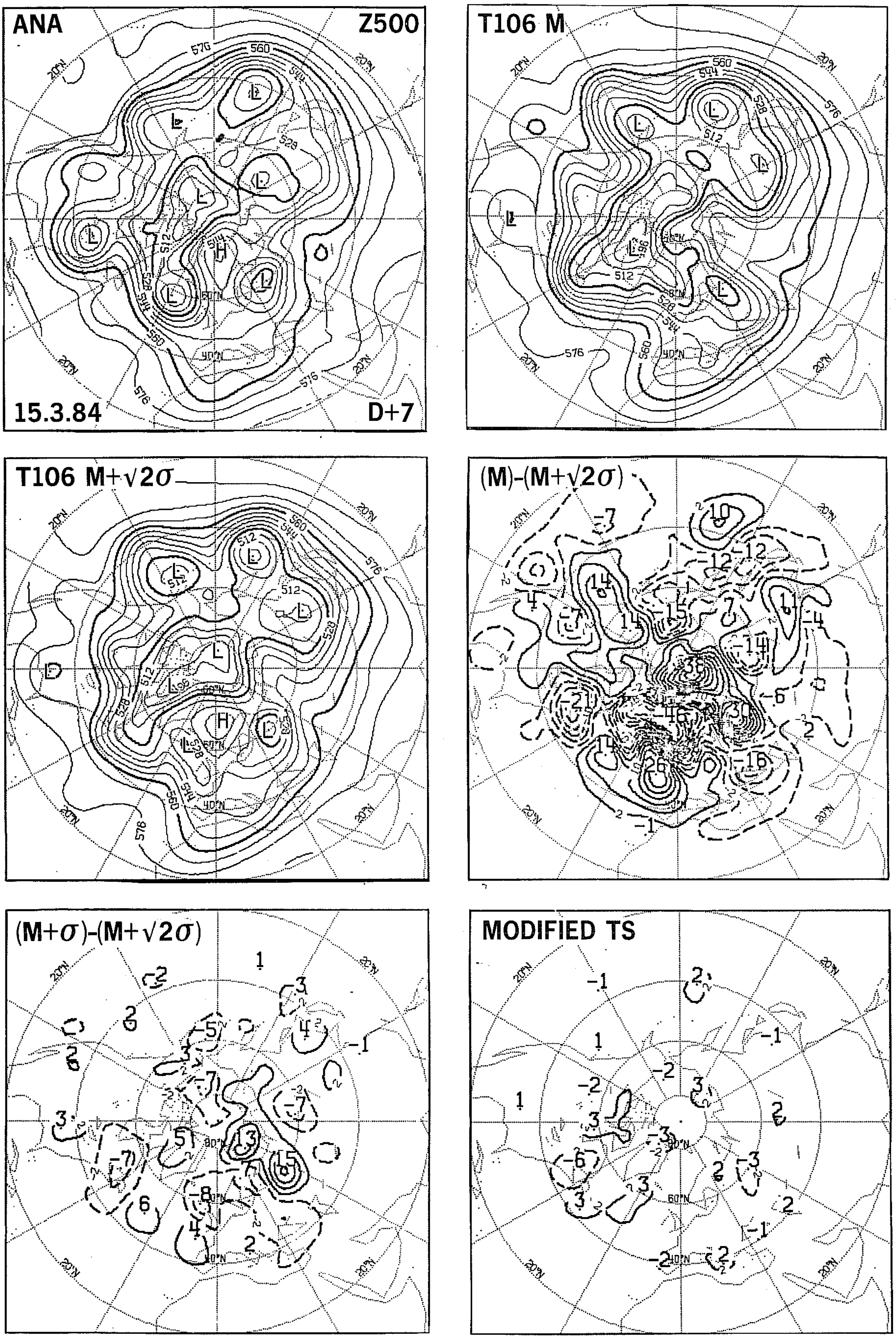


Fig. 4 Analysed 500 mb height field for 22 January 1984 and corresponding D+7 T106 forecasts using a mean and a ($\sqrt{2}\sigma$) envelope orography, together with the associated difference map. Units: dam.


ANA Z500 15.3.84 D+7

T106 M

T106 M+√2σ

(M)-(M+√2σ)

(M+σ)-(M+√2σ)

MODIFIED TS

Fig. 5 Analysed 500 mb height field for 22 March 1984 and corresponding D+7 T106 forecasts using a mean and a (√2σ) envelope orography together with the associated difference maps. In addition are shown differences between (1σ) and (√2σ) envelope forecasts (lower left) and between two runs with the (√2σ) envelope but using different surface temperatures (lower right)(see text).

several mountain ranges contributing to the final improvement. The principal benefit was from use of the envelope for the Asian mountains, but the envelope over the Rockies also helped to a certain extent. Also evident in Fig.4 are differences over western Europe and the North Atlantic, again in favour of the envelope. These could be traced back to northeastern North America and the south of Greenland.

5.2 A European block

As a second example, the crucial rôle of an envelope in the formation of a European block is shown in Fig.5. This figure displays day 7 T106 forecasts from 15 March 84, together with the corresponding difference map and verifying analysis. Differences are particularly large over North western Europe and the North Atlantic and the structure of the block is well captured with the envelope but not with the mean orography. Although the structure of the differences earlier in the forecast range is fairly complex, it was possible to demonstrate the importance of the North Canadian mountains and Greenland in the establishment of the block. The role of the Rocky mountains was much smaller. Fig.5 (lower left) also displays the differences between forecasts using 1 and $\sqrt{2}$ standard deviations. They are much smaller than differences between mean and ($\sqrt{2}$) envelope, a result confirmed by objective scores.

Two additional experiments were performed on this case in order to test the impact of the procedures used to create the initial conditions. One was to run with a mean orography but with the surface temperatures corrected according to the height difference between mean and envelope orographies (cf Section 3). Another one was carried out to test the procedure used to perform the vertical interpolation and consisted in interpolating from the envelope to the mean and back to the envelope, and then to run a 10 day forecast. In both cases the impact was found to be negligible (e.g. Fig.5 lower right, for the impact of the change in the surface fields).

5.3 Mediterranean cyclogenesis

For the European region the importance of enhancing the orographic forcing of the Alps to improve the simulation of Mediterranean cyclogenesis has been stressed by many authors (e.g. Mesinger and Strickler 1982) and similar results have been obtained here on the very few cases of our sample when such cyclognesis occurred (e.g. Simmons, 1985, and Jarraud, 1985). But the Alps can also be responsible for significant medium range differences over more remote places.

A striking illustration was obtained for the 15 February 1985 case. In order to check the impact of the Alps on some differences seen over Europe a T63 10 day forecast was rerun using an envelope everywhere except over the western European region, where a mean orography was used. As expected, differences at short range were mainly confined to the European area, with some downstream propagation over North Siberia from day 4 to 7, as seen in Fig.6 (which also shows the difference in orography) for the 1000 mb height field. By day 10, associated with the northward displacement of the jet and the establishment of an anticyclone over Europe, the differences there had decayed. In contrast, they reached a very large amplitude over the north Pacific in connection with an intense low system (cf. Fig.7). At this stage, none of the forecasts is good, but (assuming a potential exists for accurate prediction at the 10-day range) this result demonstrates the possible importance of the European mountains (and perhaps also other ranges of similar scale) for future improved medium range forecasts over the hemispheric domain.

5.4 Sensitivity in eastern Asia

Despite the significant overall benefit from using an envelope in winter for the Northern Hemisphere, strong evidence has been found of a detrimental

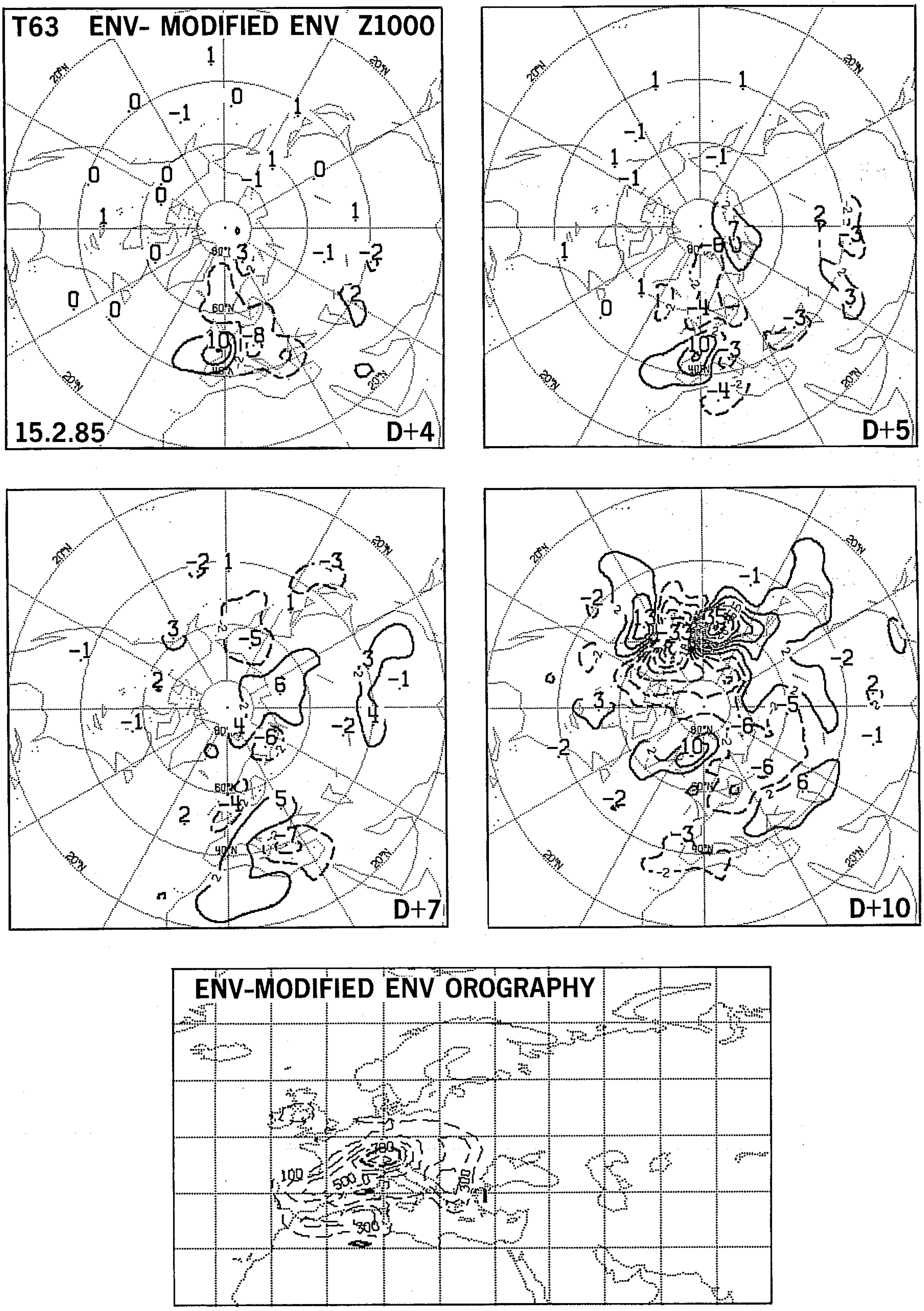


Fig. 6 Difference maps of 1000 mb height field between D+4, D+5, D+7 and D+10 T63 forecasts from 15 February 1985, using either a ($\sqrt{2}\sigma$) envelope or the same envelope reduced to the mean over western Europe. The difference (in m) between the two orographies is shown in the lower panel.

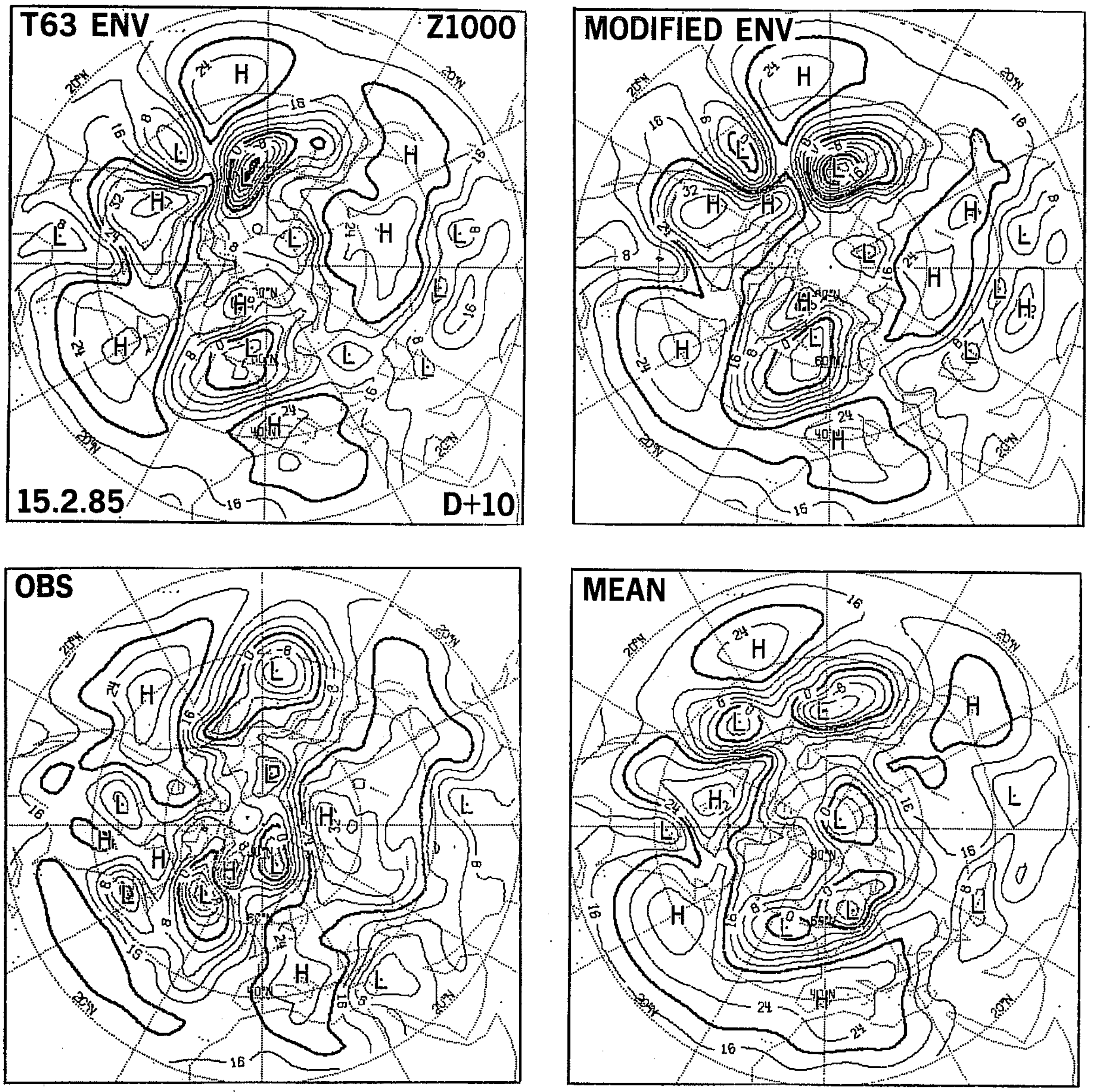


Fig. 7 1000 mb height fields for the D+10 T63 forecasts from 15 February 1985, and the corresponding observed field.

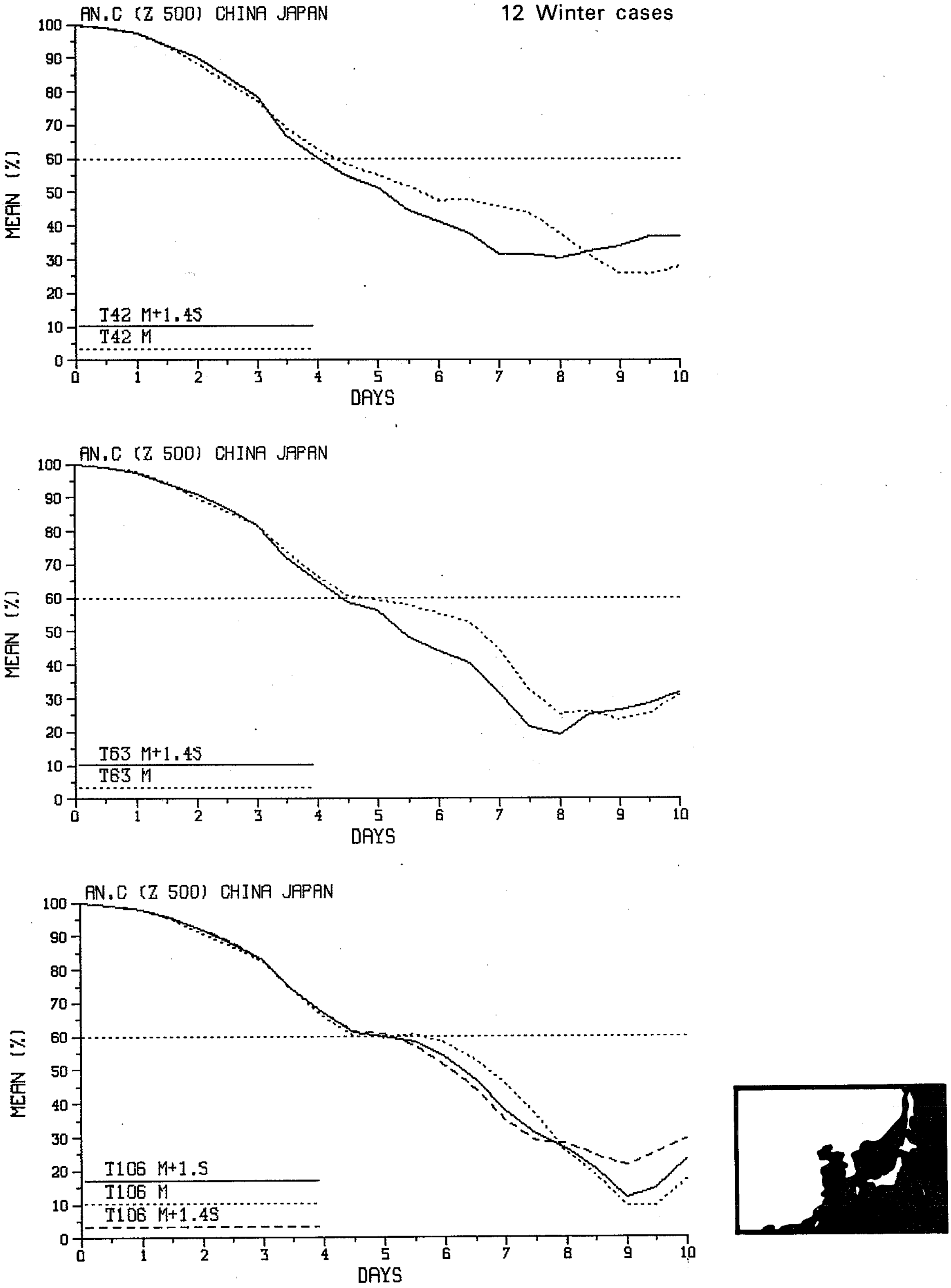


Fig. 8 Mean anomaly correlations of 500 mb height fields averaged over 12 winter cases for the region 100°E to 150°E and 20°N to 55°N at T42, T63 and T106 resolution (from top to bottom) using mean or envelope orographies.

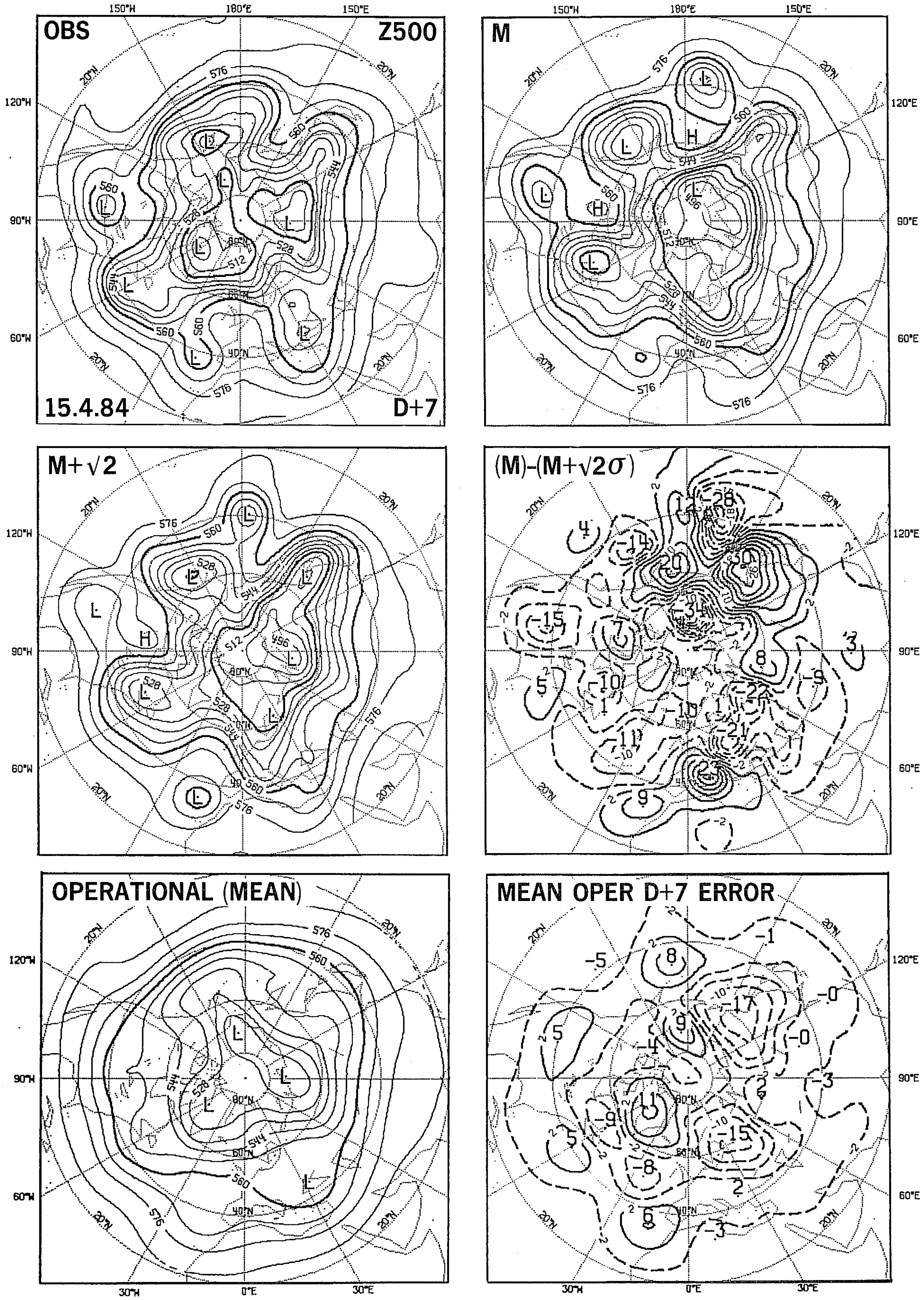


Fig. 9 Analysed 500 mb height field for 22 April 1984 and corresponding D+7 T63 forecasts using a mean and a ($\sqrt{2}\sigma$) envelope orography together with the associated difference map. In addition the lower panel shows the mean analysed maps for April 1984 (left) and the corresponding mean D+7 error of the ECMWF operational model (right).

effect in eastern Asia: anomaly correlations computed for a region including much of China and Japan revealed poorer results with the envelope in winter, the effect decreasing with increasing resolution (Fig.8).

These results are in agreement with limited area model studies carried out at ECMWF (Dell'Osso and Chen, 1984). In addition Sumi and Kanamitsu (1984) noted a tendency of the T42 JMA model, despite using a mean orography, to overestimate airflow round rather than over the Tibetan plateau, in contrast with the situation for the Rockies. This Asian region has also to be found (e.g. Chung et al. 1976) to be one of the most active in the Northern Hemisphere for winter cyclogenesis.

An interesting example of an unusually large negative impact is shown in Fig.9. It displays a D+7 500 mb height forecast by T63 for the 15 April 84 case. The envelope forecast exhibits an erroneously deep and eastwards displaced trough near 135°E in a manner representative of a systematic deficiency of the operational forecasts for this month (Fig.9 lower part). Better results were obtained with the mean orography and differences were found to originate essentially from the north and east Asian mountains.

5.5 Summer results

In summer the deterioration observed at T63 resolution due to the use of an envelope appears over several areas. On a number of occasions, it is quite large over the North Atlantic and Europe, on other occasions over the North Pacific, but rarely over North America. This appears to be a consequence of a lesser role of the Rocky mountains in summer, when the main flow is located in a more northerly position.

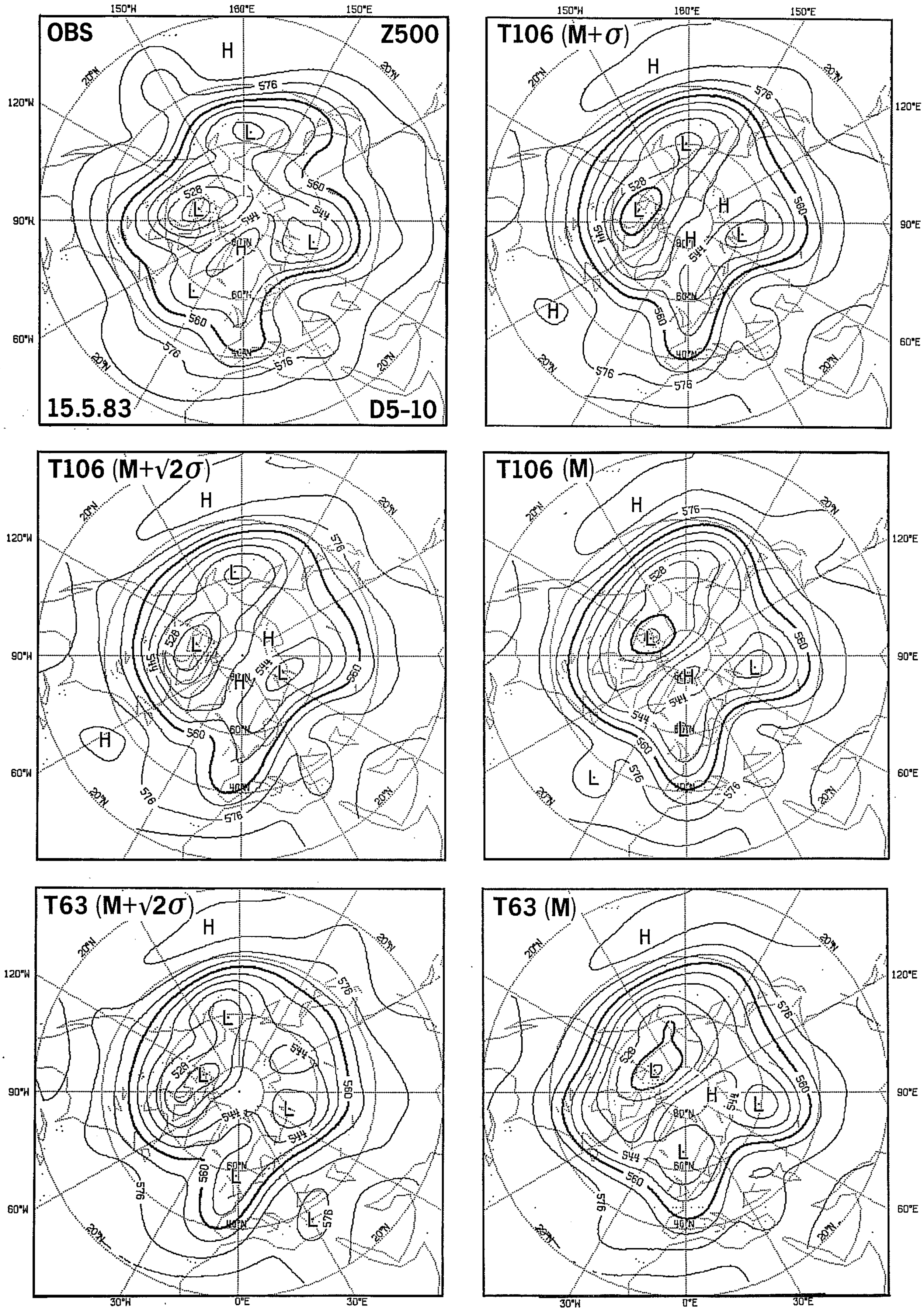
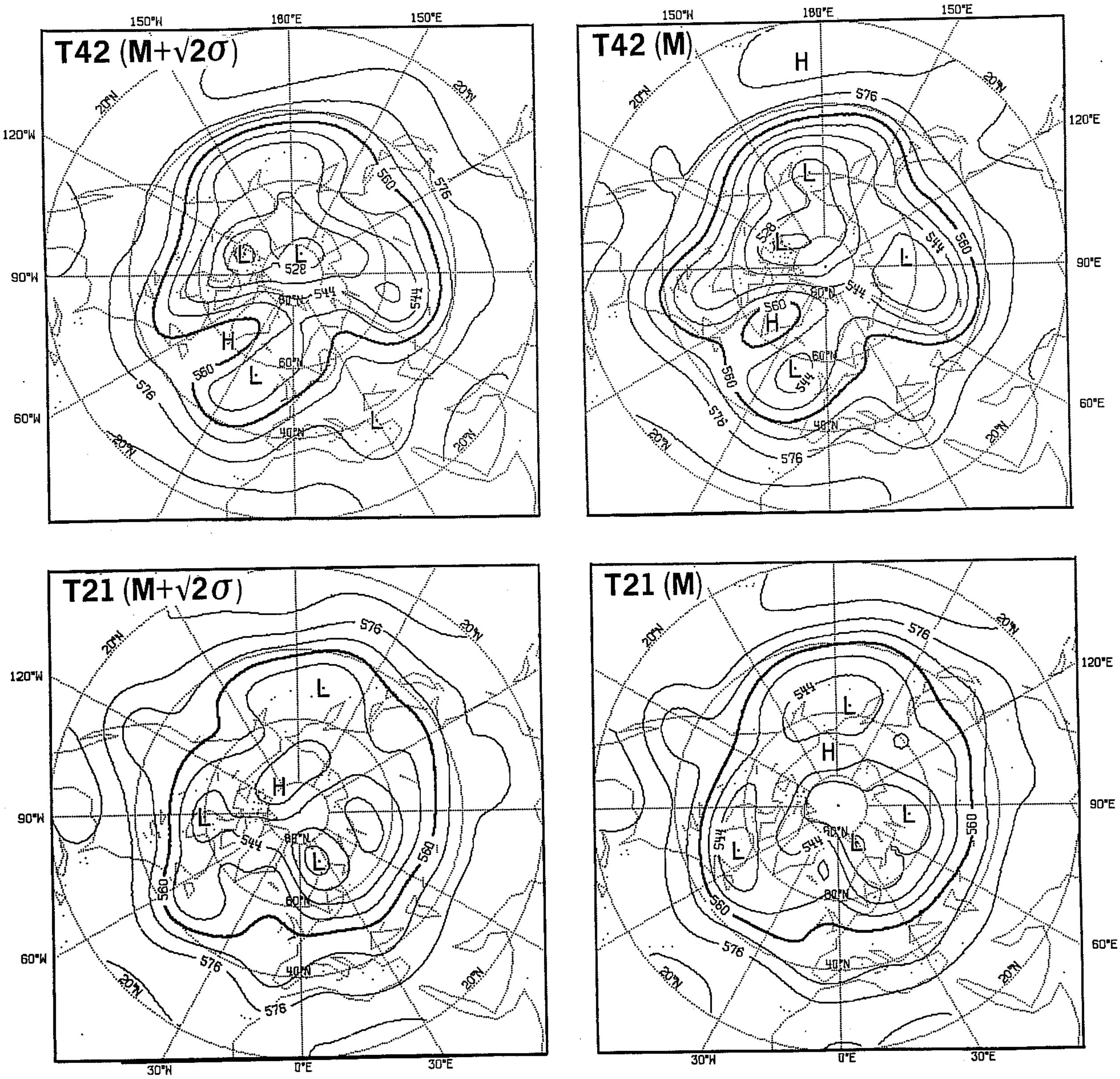


Fig. 10 Analysed 500 mb height field averaged between 20 and 25 May 1983 and corresponding D+5 to D+10 mean forecasts by T106 to T21 using ($\sqrt{2}\sigma$) (left) and mean (right) orographies. In addition (upper right) is a D+5 to D+10 mean forecast by T106 using a ($\sqrt{\sigma}$) envelope.


T42 (M+√2σ)

T42 (M)

T21 (M+√2σ)

T21 (M)

Fig. 10 (cont).

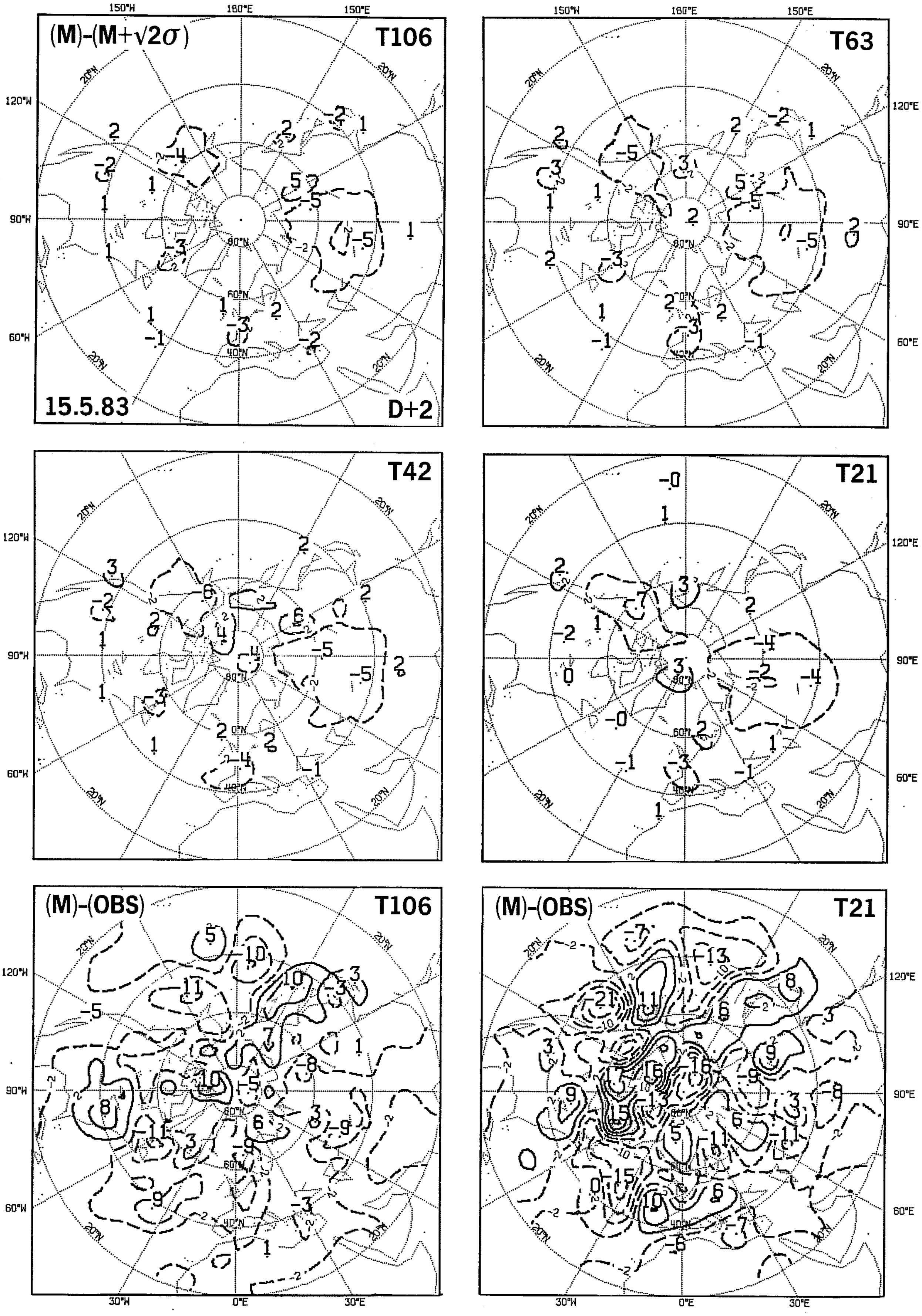


Fig. 11 Difference maps of 500 mb height field corresponding to D+2 forecasts by T106 to T21 (upper and middle) using mean and (√2σ) envelope orographies. The lower panel shows the corresponding actual errors for T106 (left) and T21 (right) D+2 forecasts using a (√2σ) envelope.

As a first example of such a deterioration, Fig. 10 shows maps of day 5 to day 10 average fields for the 15 May 1983 case. At T63 the envelope is clearly damaging the stationary part of the flow. The trough over western Europe lags behind, another one over western Siberia is too weak, and the ridge further east non existent. The ridge over eastern Europe is much too weak. All these features are better treated when using a mean orography. At T106 resolution the damaging effect of an envelope based on $\sqrt{2}$ standard deviation is similar in structure, but significantly reduced in amplitude. If the envelope is based on 1 standard deviation there is no obvious worsening (Fig. 10 upper right). At T42 the maps are not as good as the T63/T106 ones, both for mean and envelope orographies. They are even worse at T21 with the flow having much less structure, and much weaker gradients, making it more difficult for large differences to show.

Examination of the individual maps at T106 and T63 revealed that some of the differences over Asia grew almost in place. In particular, in this case, as in several other cases, the Siberian trough was found to extend less to the south when the envelope was used. Some other differences originated from the Northern extreme of North America (from Alaska to Greenland) and contaminated the European area in four to five days.

Another interesting point is illustrated in Fig. 11. In this case, as in most other cases the signature of the differences between forecasts using mean and envelope orographies is very similar at all resolutions up to day 2 or 3. Later they of course tend to diverge in connection with the different synoptic evolution induced by different truncation errors. Note (lower part of Fig. 11) that these similar signatures are superimposed as actual errors which are very different for T21 and T106, consistent with the deterioration in objective scores seen at T21 and the improvement at T106.

5.6 Role of Greenland and nearby islands in summer

One of the critical areas for the interactions between the flow and the orography in summer is Greenland and the mountainous islands to the west. In five of the twelve cases, and in others outside this sample, large differences over the North Atlantic, Europe and North Asia appeared to originate from this region, leading in most cases to a degradation of forecasts when using an envelope. A clear example is shown in Fig. 12, which presents day 4 forecasts from 15 May 1984 by T63 and T106. At T63 there is a large (although small scale) difference over the North Atlantic associated with a cut-off low south of Iceland, which later results in a very different forecast over Europe, albeit by then at a time range when neither mean nor envelope forecast is very good. Examination of the evolution in time of differences maps shows how this difference developed from the area west of Greenland, where the flow was active in this situation. Other differences can be seen in the position of the cut-off over Spain and the intensity of the ridge over the Rocky Mountains, both differences having grown in situ. Over North Asia a low is further south when using the mean orography (as in several other occasions, as already mentioned). Fig. 12 also shows how differences between mean and envelope forecasts are generally smaller for T106, particularly over the North Atlantic. This is likely to be due to a better definition of the fairly high but isolated mountains west of Greenland; at T63 these appear as a broad mountainous extension of Greenland, particularly so in the case of the envelope orography.

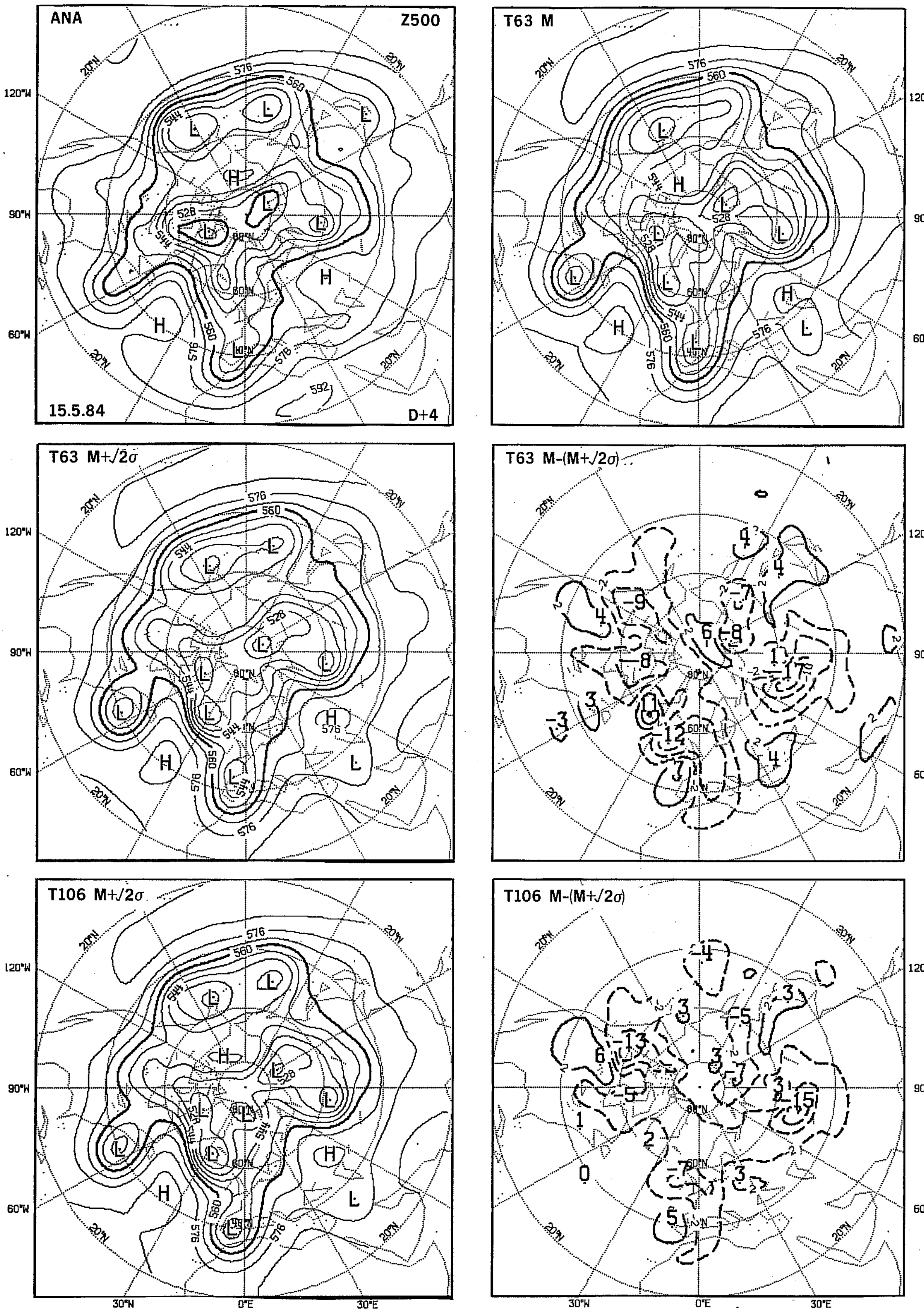


Fig. 12 Upper and middle: Analysed 500 mb height field for 19 May 1984 and corresponding D+4 T63 forecasts using a mean and a (√2σ) envelope orography together with the associated difference map. Lower: D+4 T106 forecast using a (√2σ) envelope and corresponding difference map.

5.7 Case with large differences over Eastern Siberia

An example of large differences over Eastern Siberia and the North Pacific is shown in Fig. 13. This presents 6 day forecasts from 15 June 1984. The envelope orography forecast exhibits major phase errors with respect to the deep cut-off low off the Asian coast and the trough near 150°W, these errors being substantially less for the mean orography. Here (as in several other cases) differences could be tracked back to the Asian mountains to the north and the east of the Tibetan plateau.

To demonstrate further this point an experiment was run where the envelope was used everywhere except in eastern Asia where the mean was used (differences are shown in the lower part of Fig. 13). The results turned out to be very close to those of the forecast with the mean orography used everywhere. As often in summer, mean and envelope produced more similar forecasts at T106 (not shown).

6. IMPACT ON MEAN (OR SYSTEMATIC) ERRORS

In order to illustrate the relative importance of total errors and of mean errors, Fig. 14 shows the ensemble-mean root mean square (rms) error for the 500 mb height field for the 12 winter forecasts performed with T106, and the rms error of the corresponding ensemble-mean forecast. Similar results are displayed in Fig. 15 for summer.

Using a mean orography, the systematic errors (averaged between day 5 and 10) account for about 14.5% of the total error in winter and slightly more (18.5%) in summer. When using an envelope these figures reduce to about 12.5% in winter and 15% in summer. The winter figures are significantly lower than the ones (of the order of 25%) obtained by Hollingsworth et al. (1980) using a

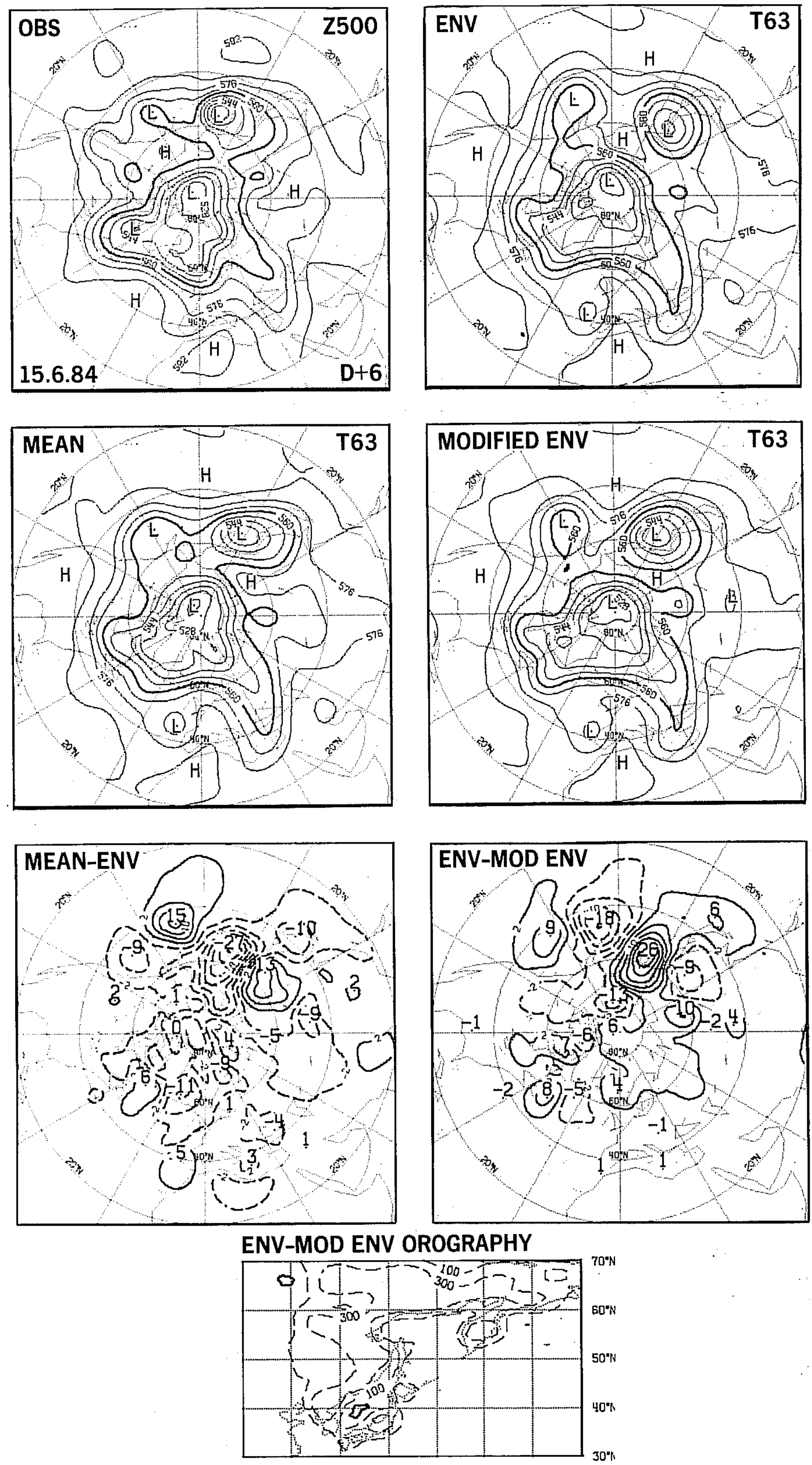


Fig. 13 Analysed 500 mb height field for 21 June 1984 and corresponding T63 D+6 forecasts using a ($\sqrt{2}\sigma$) envelope (upper right) a mean (upper middle left) and a modified envelope orography (upper middle right) where the mean has been used over eastern Asia. The corresponding orography difference is displayed in the lower panel.
The figure also displays the corresponding D+6 difference maps (lower middle) between mean and ($\sqrt{2}\sigma$) envelope (left) and between ($\sqrt{2}\sigma$) envelope and modified envelope (right) orographies.

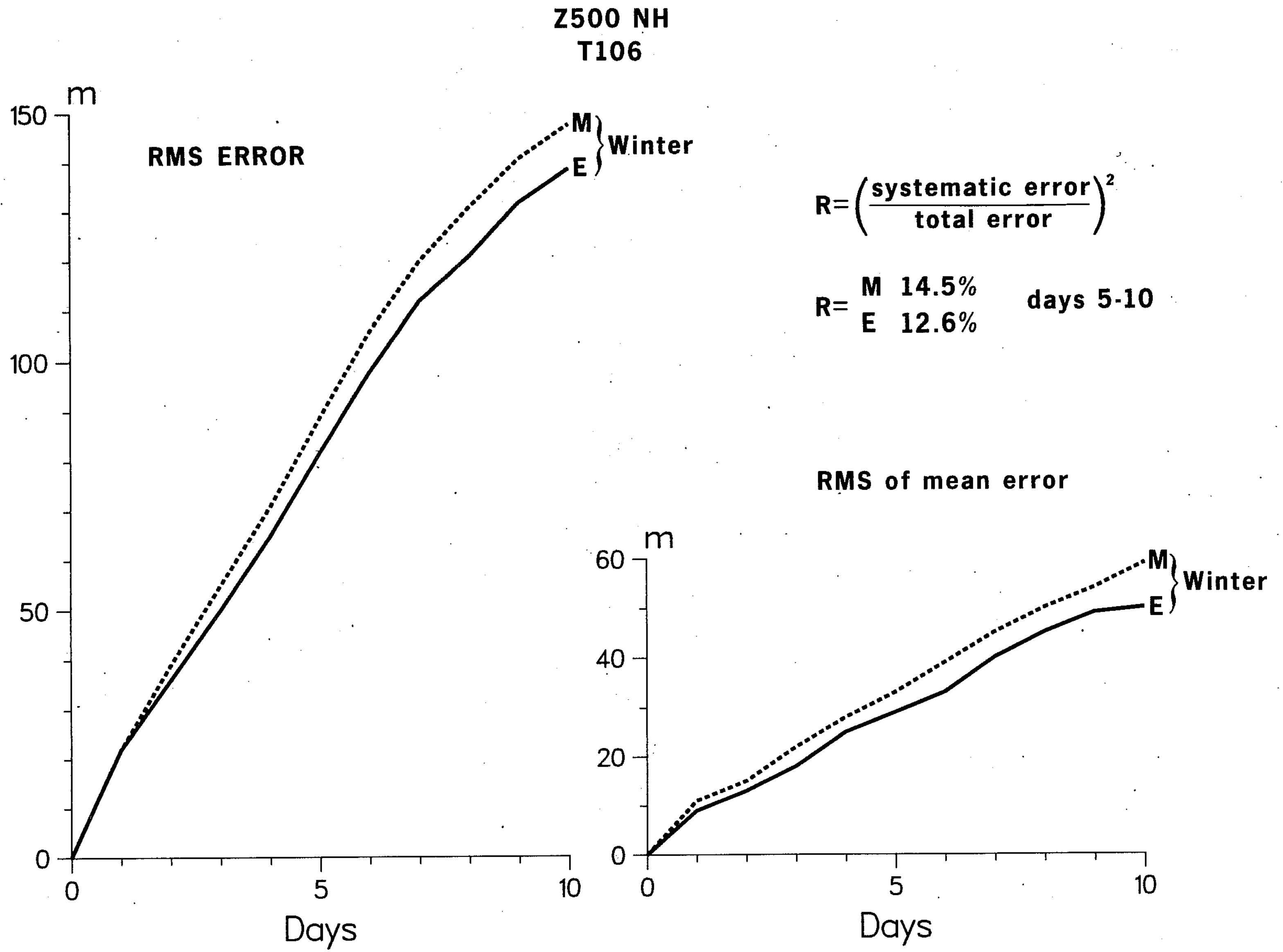


Fig. 14 (Left) mean rms error of 500 mb height forecasts in the extratropical Northern Hemisphere by T106 using an envelope (full line) or a mean (dashed) orography for 12 winter cases.
(Right) similar figure for the rms error of the ensemble mean forecasts.

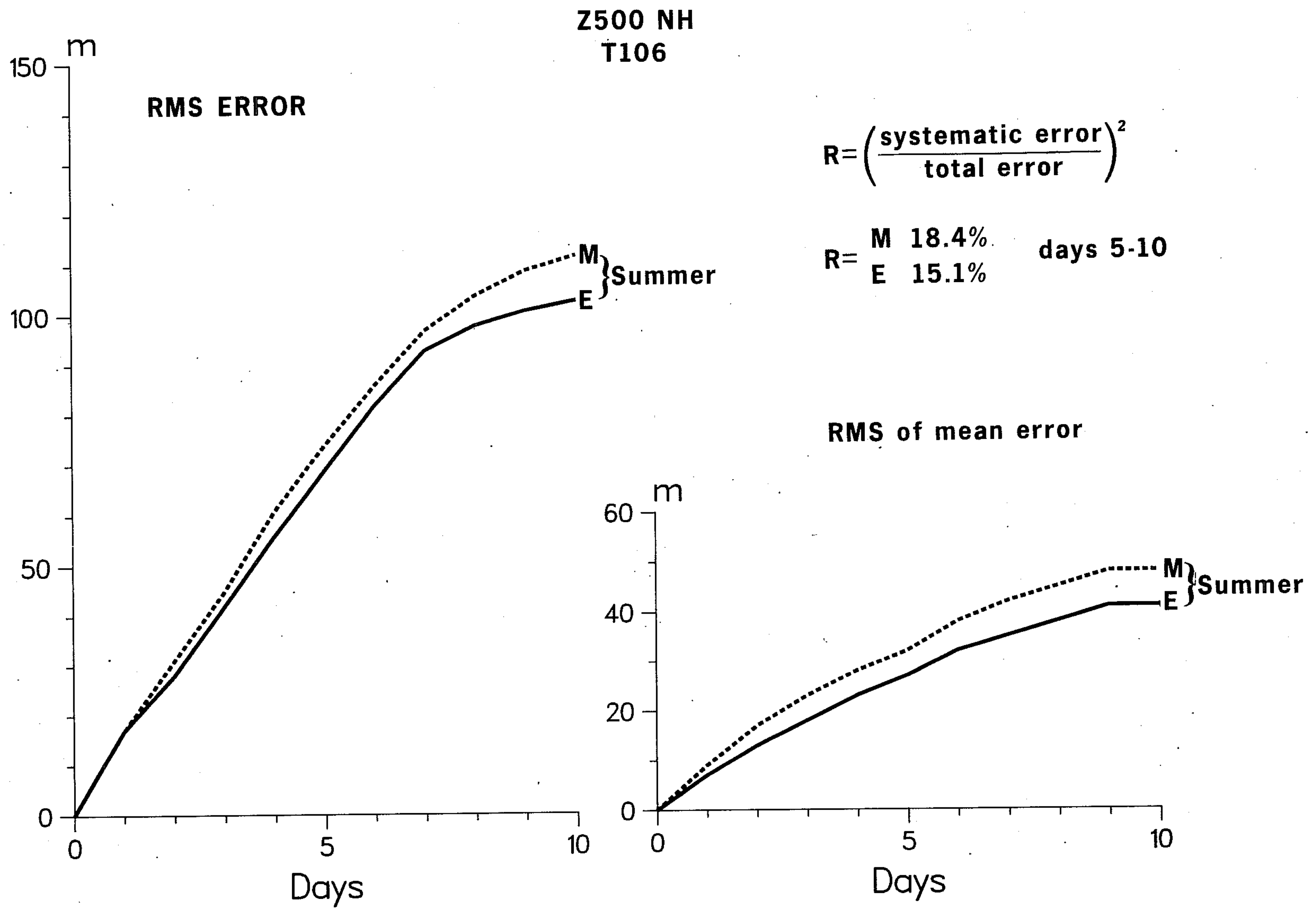


Fig. 15 As Fig. 14 for summer.

smaller sample of less independent initial conditions and a more primitive version of the ECMWF forecasting system (including the use of a highly smoothed version of a mean orography).

From Figs. 14 and 15 it is clear that the envelope orography at T106 has a positive impact in both winter and summer, and not only on the systematic part of the error, at least in terms of rms. It should be recalled that in Section 4, there was no mean improvement shown in summer when forecasts were judged in terms of anomaly correlations. Similar results have already been mentioned for T63 namely a summertime deterioration due to the envelope when judged in terms of anomaly correlations and a neutral effect in terms of standard deviation.

In order to illustrate how the mean differences develop during the course of the forecast, Fig. 16 shows (envelope-mean) maps for the 500 mb height field averaged over the winter cases for forecast days 1, 2, 3 and 4 and T63 resolution. As early as day 1 there is a significant planetary scale component arising as the average of local differences directly related to the Rocky Mountains, Greenland and mountains of Southern Europe and Asia. Up to about day 5 these differences grow largely in place with some spreading taking place. Note that on average the mean 500 mb height tends to be higher with the envelope.

The resulting mean errors for day 1 and 2 are shown in Fig. 17 for the mean and envelope orographies at T63; it appears that in contrast to the results of Wallace et al. (1983) there is a significant reduction of the short range systematic errors, a reduction much larger than that likley to be due to

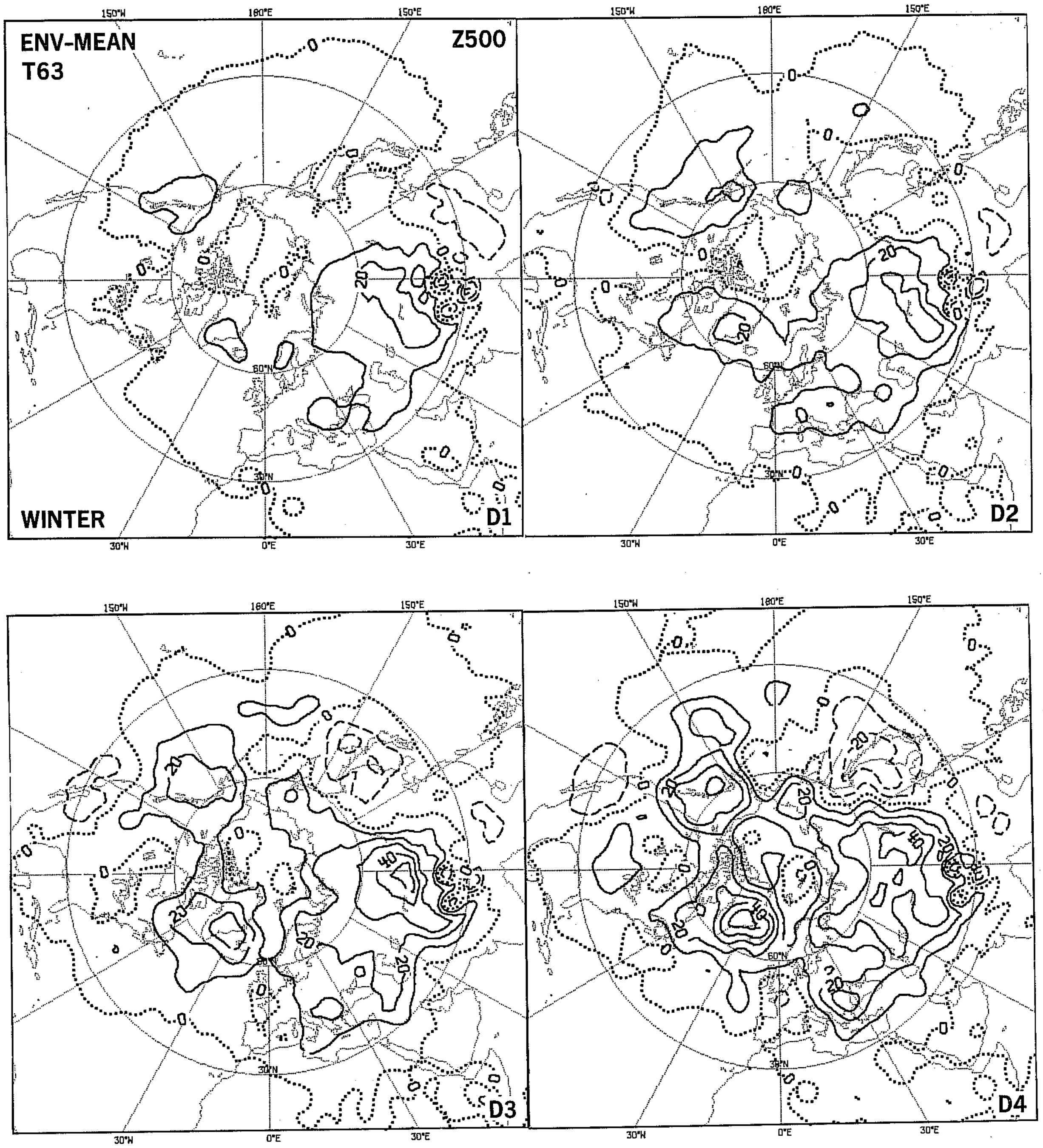


Fig. 16 Mean over 12 winter cases of differences between D+1, D+2, D+3 and D+4 500 mb height forecasts by T63 using a mean and a ($\sqrt{2}\sigma$) envelope orography.

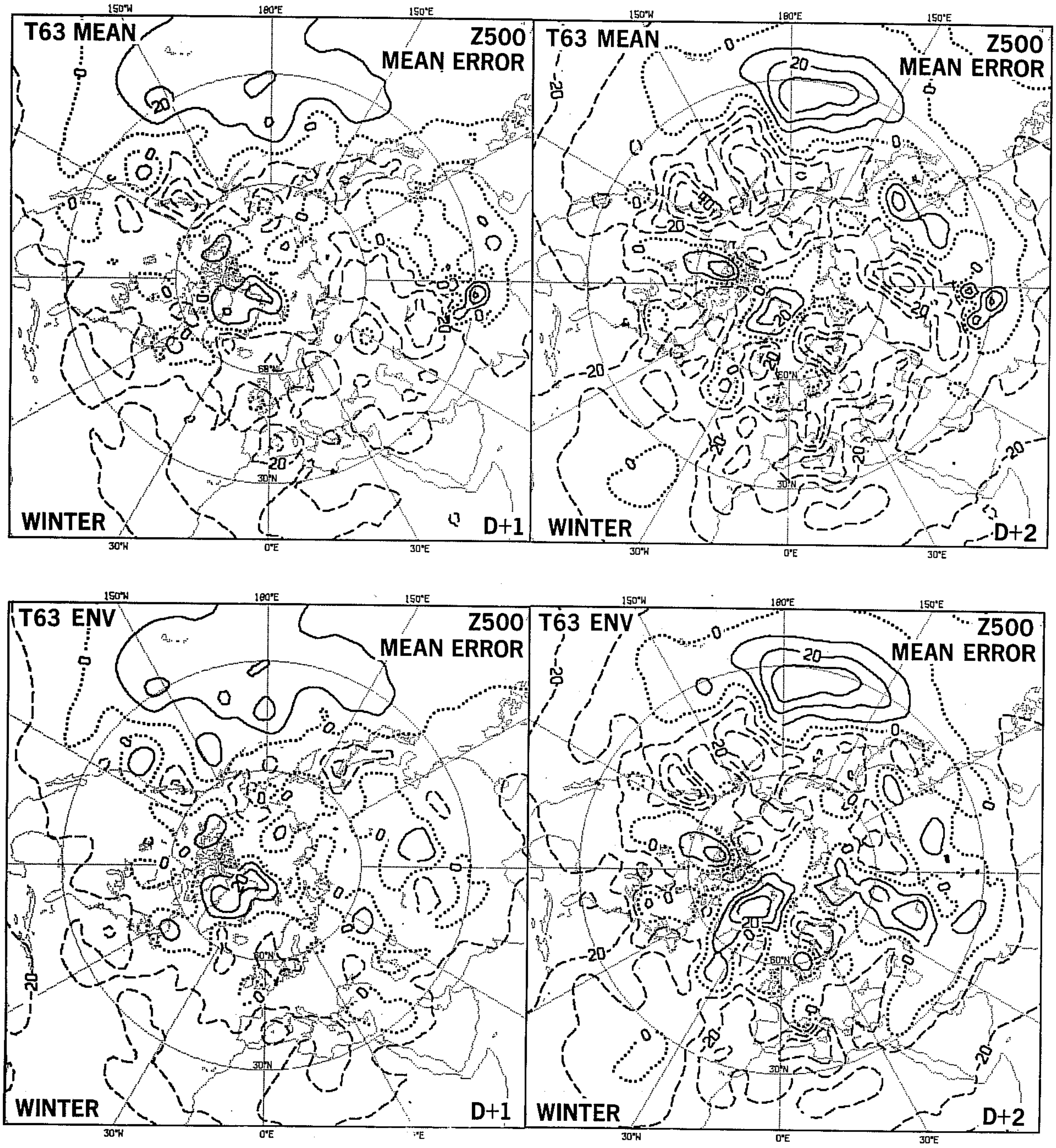


Fig. 17 Mean over 12 winter cases of the D+1 and D+2 500 mb height forecast errors by T63 using a mean (upper) or a ($\sqrt{2}\sigma$) envelope (lower) orography.

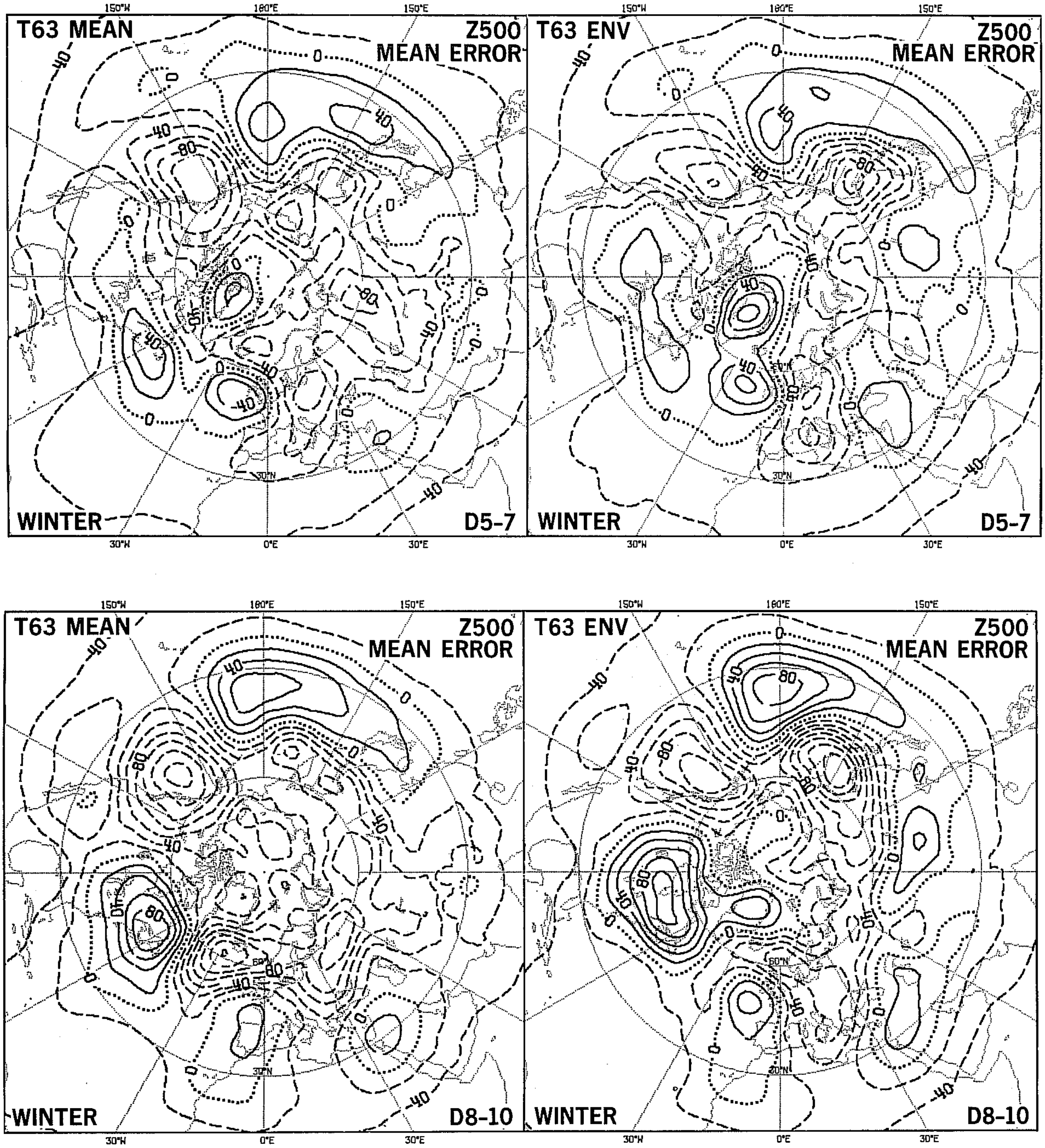


Fig. 18 As Fig. 17 for D5-7 (upper) and D8-10 (lower) mean forecast errors by T63 using a mean (left) or a ($\sqrt{2}\sigma$) envelope (right) orography.

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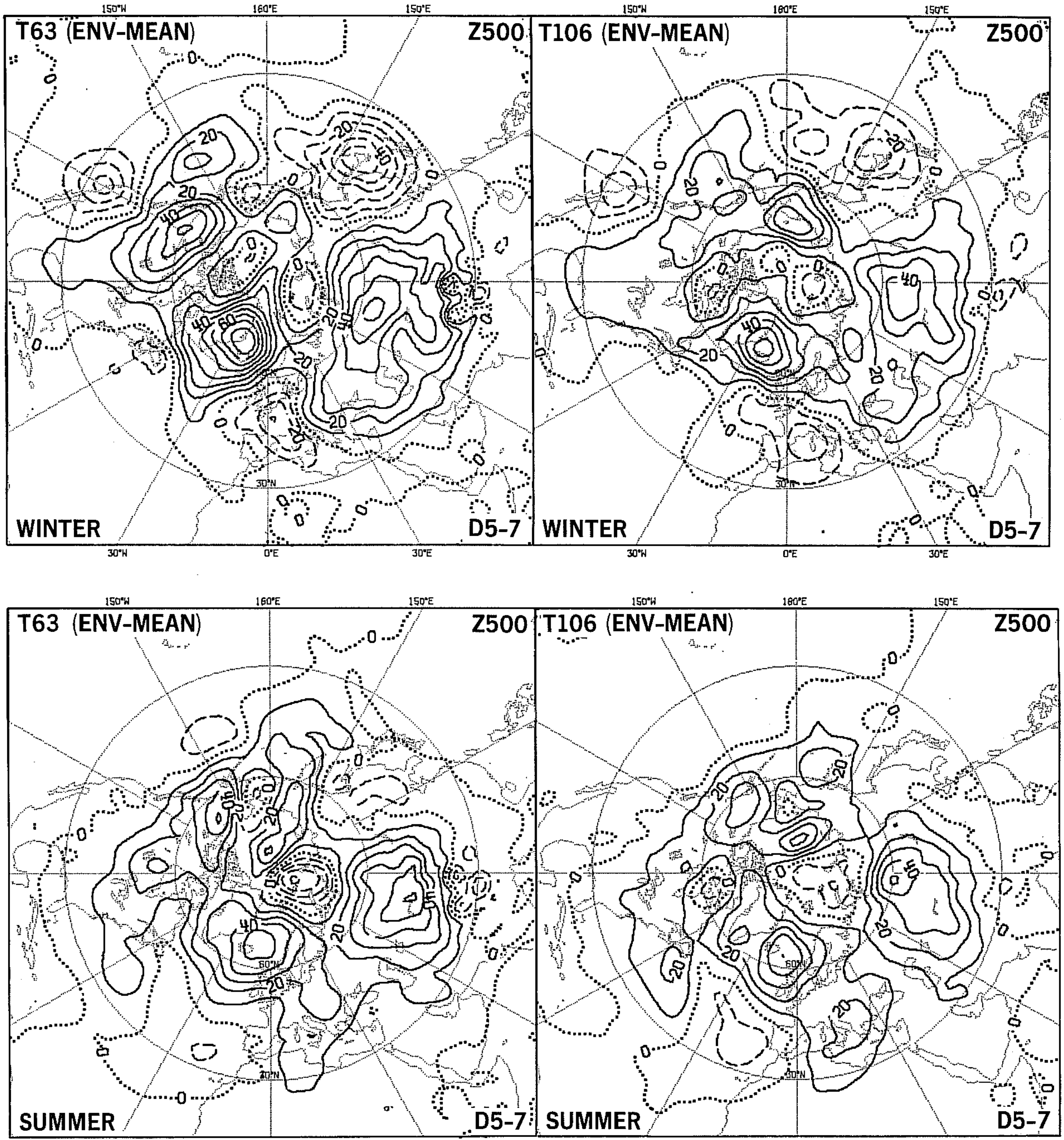

Fig. 19 As Fig. 16 for difference corresponding to D5-7 T63 (left) and T106 (right) forecasts in winter (upper) and summer (lower).

analysis biases, almost everywhere except possibly near Greenland. As found by Wallace et al., the large error in the low mid-latitude Pacific is not affected by the change in the orography.

In the later part of the forecast range (day 8 to 10) the centres of difference between mean and envelope forecasts tend to drift eastward, following a similar drift of the systematic errors themselves (cf Fig. 18), suggesting that some planetary scale adjustment might be taking place. As in previous studies, the envelope by then has contributed to reduce significantly the mean errors near the Rocky mountains and over the North Atlantic and Europe. There is however a slight increase over North America and a more considerable one over eastern Asia, in agreement with the synoptic results.

As mentioned in the synoptic evaluation, the differences between forecasts using envelope and mean orographies are smaller at T106 than at T63. This is clearly seen in the mean differences in winter (Fig. 19 upper) but also in summer (Fig. 19 lower). Another striking feature of Fig. 19 is the similarity between the summer and winter mean response to the change in orography. The amplitude is slightly weaker in summer, and the difference centres located at low mid-latitudes, over California and the north west Pacific, for example, tend to be reduced or even to disappear, reflecting the northward displacement of the dynamically active part of the flow in summer.

The envelope has also been found, as in previous studies, to reduce the generation of too much zonal kinetic (KZ) energy in the troposphere at the expense of eddy kinetic energy (KE). Fig.20 shows how the level of KE at

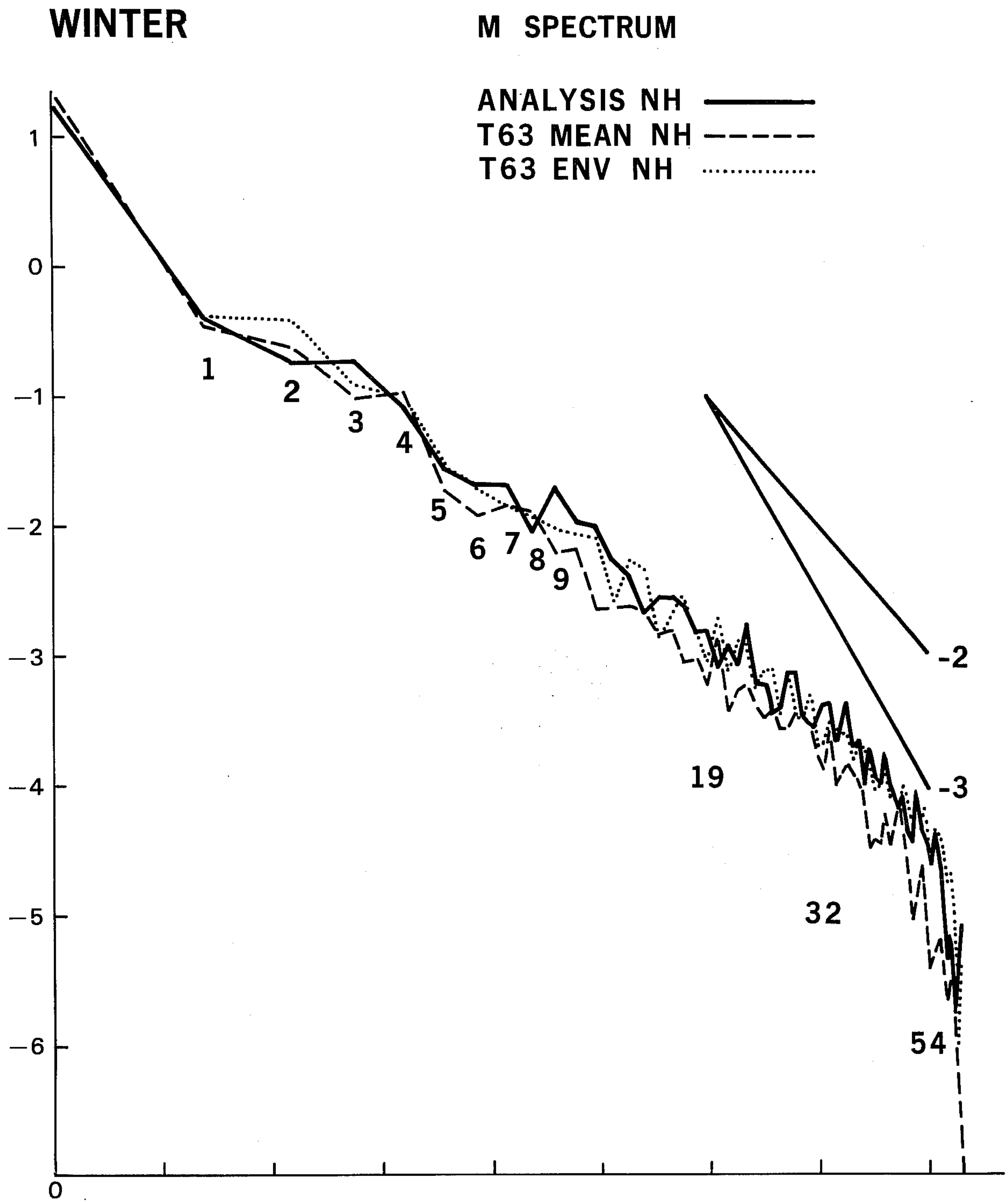

Fig. 20 Zonal spectral decomposition of the 850 mb kinetic energy observed (thick full line) and corresponding mean forecast by T63 using a mean (full line) and a ($\sqrt{2}\sigma$) envelope (dotted line) averaged over 12 winter cases.

850 mb is increased for almost all zonal wave numbers in the later part of the forecast (days 8 to 10) and how except for wave number 2 it agrees better with the analysed values. This impact comes mostly from the better treatment of the zonal component of the wind (not shown). Similar results have been obtained at other levels and resolutions and in summer. It should be noted that the increase of KE in wavenumber 2 is in disagreement with the results of experiments reported by Tibaldi (1985), who suggested from a set of cases from January 1981 that a Rossby wave resonance mechanism could be responsible for the action of the envelope on the planetary scales.

7. THE SOUTHERN HEMISPHERE AND THE TROPICS

Although most attention has been paid to results for the Northern Hemisphere, a few results for the Southern Hemisphere and the Tropics deserve mention.

In the Southern Hemisphere, the sensitivity to orography is not surprisingly less at all model resolutions and seasons than found for the Northern Hemisphere (compare Figs. 21 and 13). A possible exception is for the T21 resolution which appears anomalous in a number of respects and which seems, due to its coarseness, to misrepresent significantly the effect of the Antarctic massif. In most individual cases examined at higher resolution, the differences originated near the southern Andes and Drake passage, although they did not grow to the amplitude found for the Northern Hemisphere. This is clearly seen in mean difference maps at T63 (Fig.22) which exhibit a relatively simple pattern of upstream and downstream propagation in apparent accord with linear Rossby wave theory.

Very similar results are obtained at T106 (and T42) resolutions, but not T21, where mean differences tend to develop also near Antarctica. Also of interest

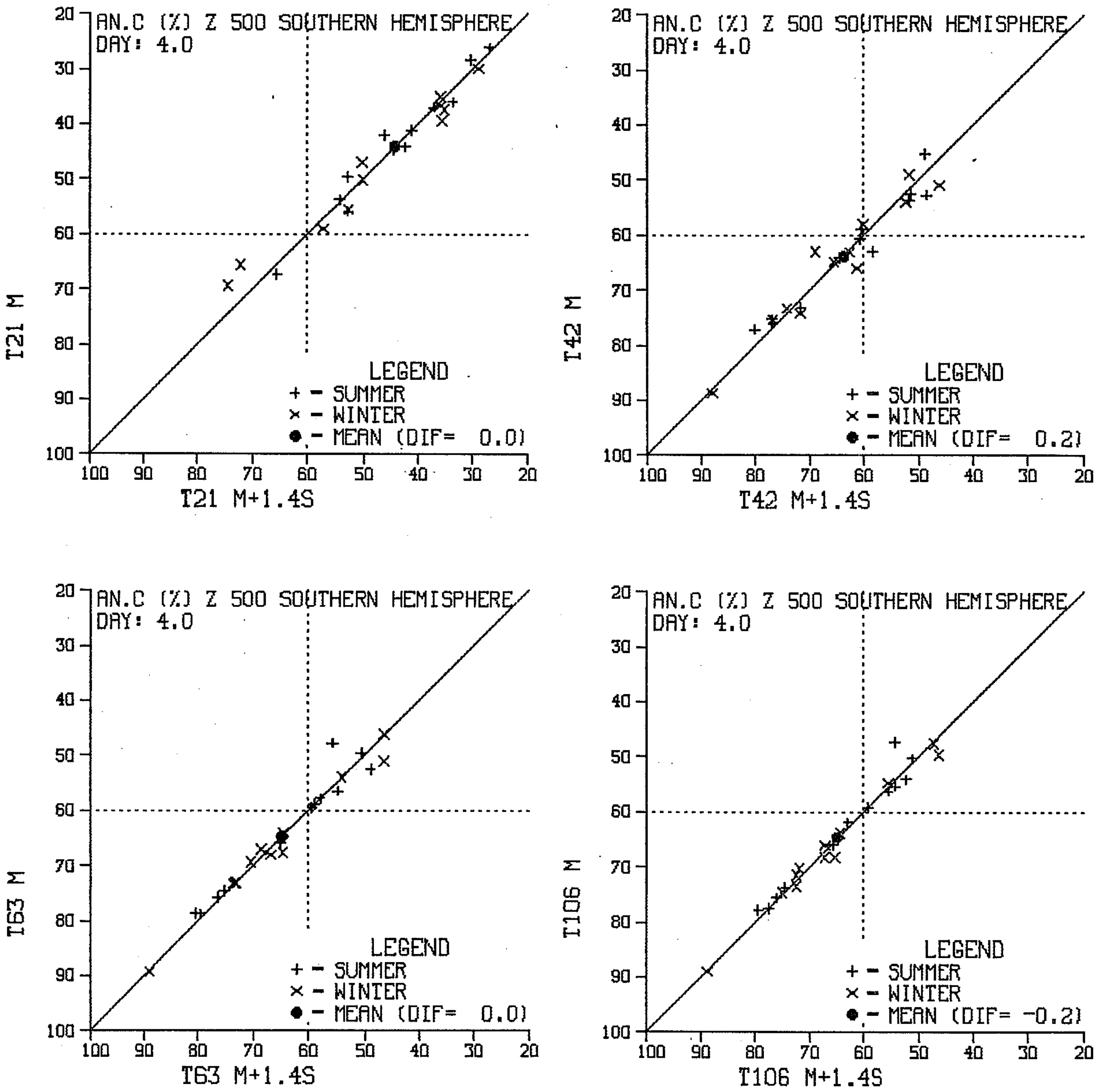

Fig. 21 As upper and middle part of Fig.3 but for the Southern Hemisphere.

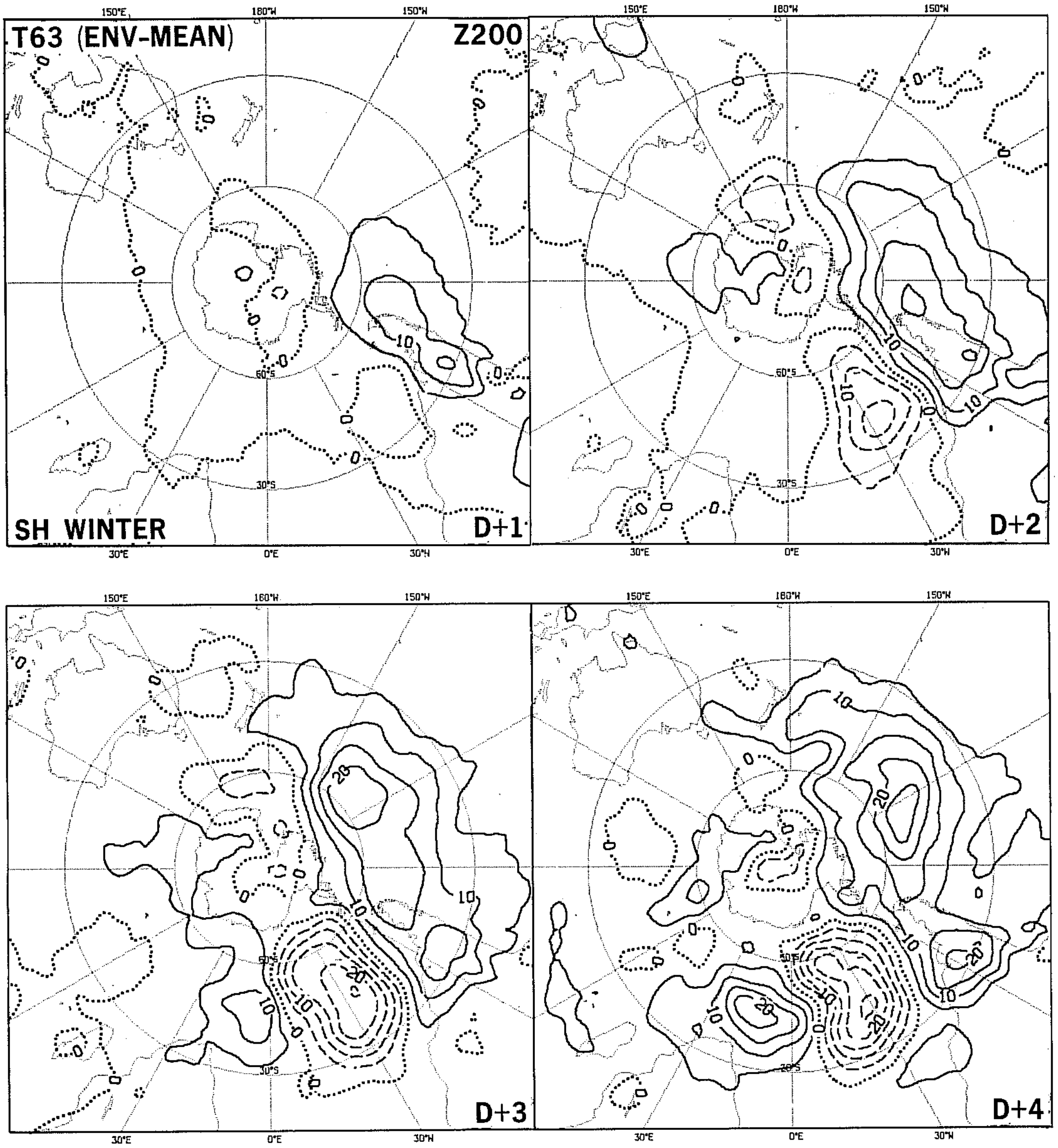

Fig. 22 As Fig. 16 but for 200 mb height field in the Southern Hemisphere (Southern Hemisphere winter cases).

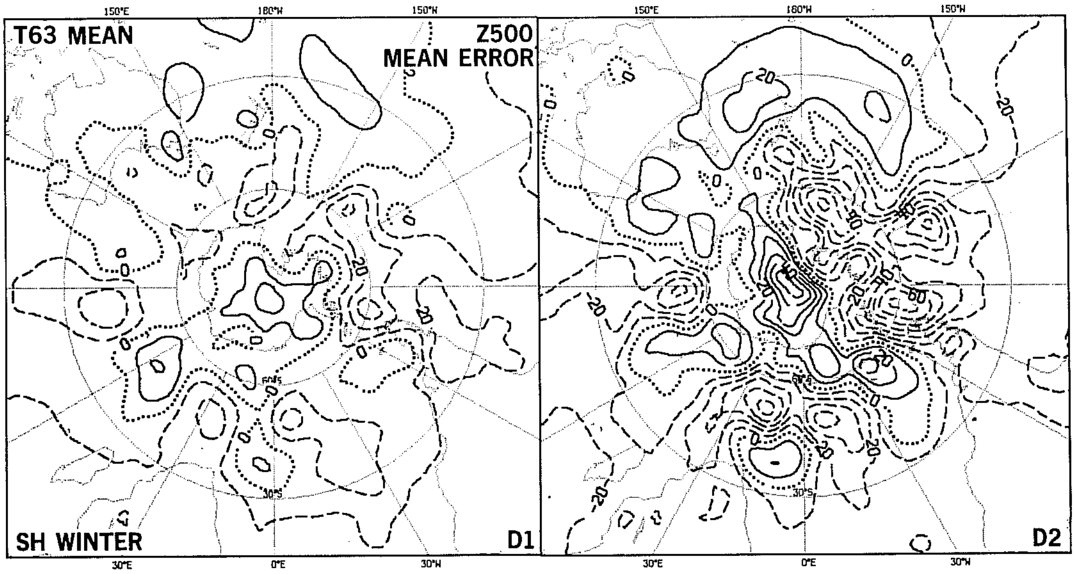

Fig. 23 Mean errors in the Southern Hemisphere for D+1 and D+2 forecasts by T63 using a mean orography (southern hemisphere summer cases).

is the fact that in contrast to the Northern Hemisphere, the short range (day 1) mean error with the mean orography (Fig.23) shows a structured pattern which except for the Andes cannot be associated with mountain ranges, and probably reflects some systematic problems with observations (Hollingsworth et al. 1985).

In the tropics, a large sensitivity to the envelope has been found in the lower troposphere for some objective scores (anomaly correlation of 1000 mb height, absolute correlation of 850 mb wind) but not for standard deviation or root mean square scores, as is shown in Fig.24 for T106. The difference increases mostly in the first two days and is then more or less uniform.

Similar results are found at other resolutions (cf Fig.25). Up to day 5 differences are almost systematic and slightly more pronounced at T63. Further synoptic investigation is underway and the first results available have revealed that some aspects of the flow are indeed better predicted with an envelope.

Zonal mean distributions of precipitation show no clearly significant increase, due to the envelope, as in the example shown in Fig.26. Since August 1983, the spectral model has included a modified 'horizontal' diffusion of temperature to avoid spurious warming of mountain tops and triggering of convective precipitation. This combined with the lower ($\sqrt{2}$) envelope and perhaps the use of the spectral technique probably accounts for the absence of an increase in tropical precipitation of the type reported by Tibaldi (1985). Examination of actual maps of precipitation accumulated over 10 days does however reveal a modest increase in the precipitation associated with mountains both in the tropics and at mid latitudes. This is compensated by a slight reduction in the surrounding neighbourhoods.

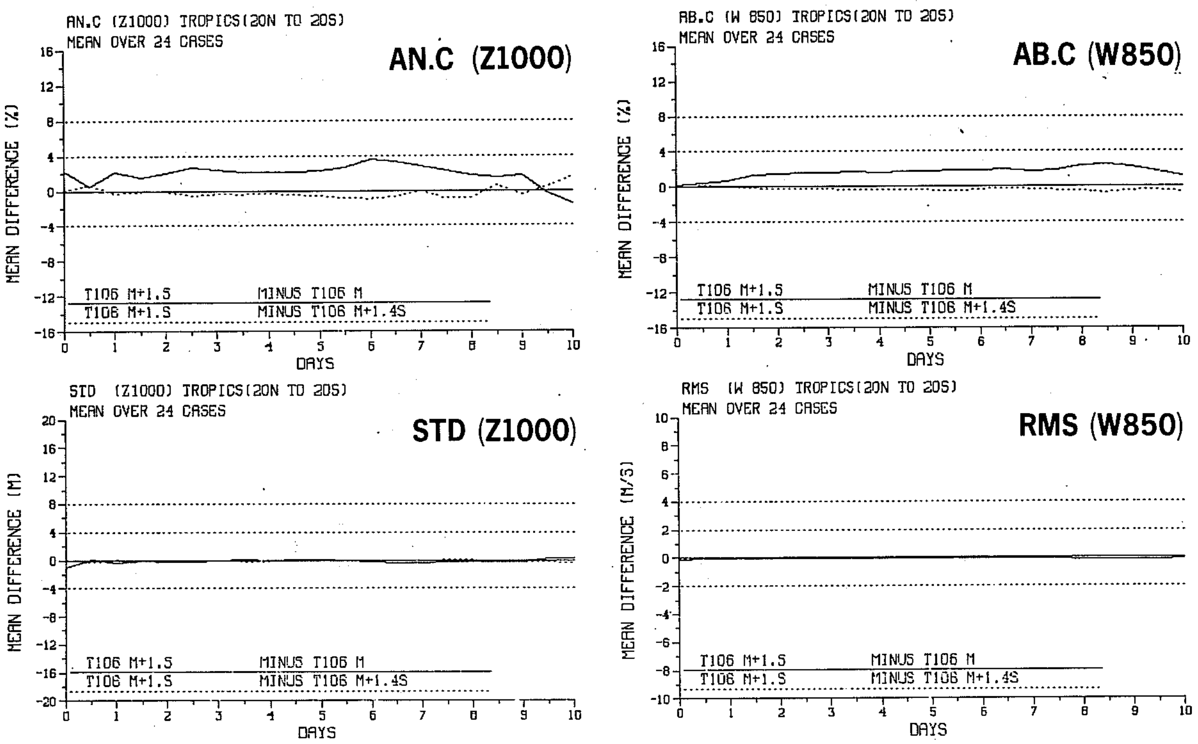

Fig. 24 Mean difference of anomaly correlations and standard deviations of 1000 mb height field (left) and of absolute correlations and root mean square errors of 850 mb wind field (right) between T106 forecasts using a (1σ) envelope and a mean orography (full line) and a (1σ) envelope and a (√2σ) envelope (dotted line). The results are averaged over 24 cases in the band 20°N to 20°S.

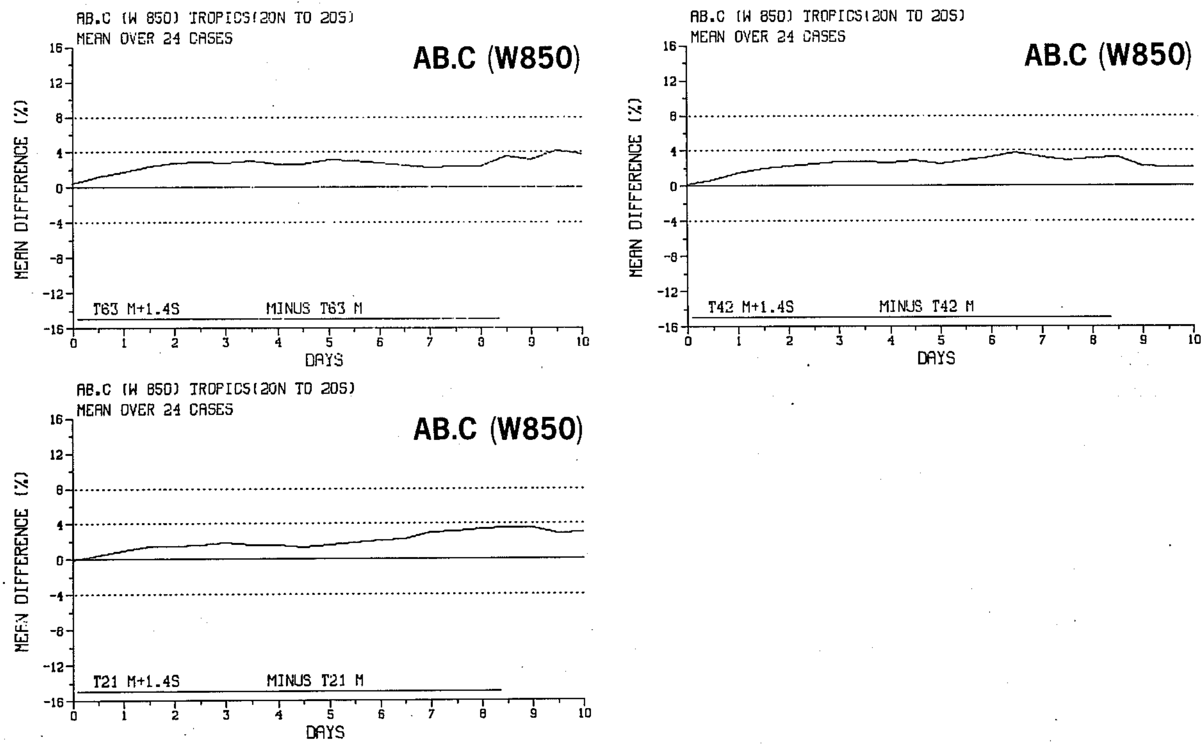

Fig. 25 Mean differences of absolute correlations of 850 mb wind field between (√2σ) envelope and mean orographies for T63, T42 and T21 resolution, averaged over 24 cases in the band 20°N to 20°S.

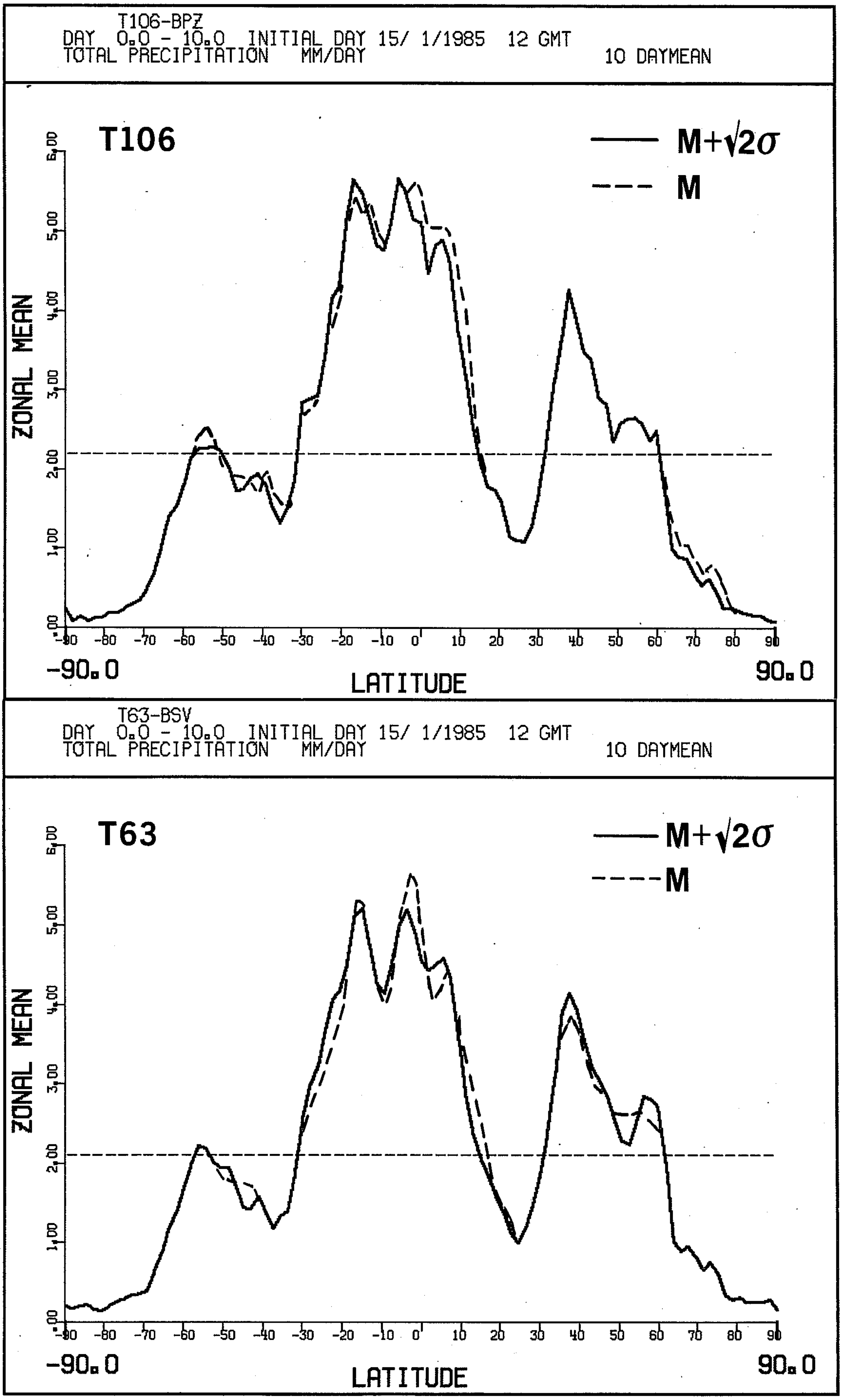

Fig. 26 10-day accumulated total precipitation, zonally averaged from T63 (lower) and T106 (upper) forecasts using a (√2σ) envelope (full line) and a mean (dashed line) orography (15 January 1985 cases).

8. SUMMARY AND DISCUSSION

As part of a more general programme, a series of experiments was performed in order to assess the impact of an envelope orography at various horizontal resolutions. The initial motivation for having an envelope was based on diagnostic studies of the initial growth of the mean errors of the model (Wallace et al, 1983) but it was also more intuitively justified by the need to represent more accurately the low level barrier effect of some mountain ranges. This point has been recently supported by simplified models (e.g. Pierrehumbert, 1984; Pierrehumbert and Wyman, 1985; Cullen et al. 1985). The results we have obtained are consistent with this theory. In winter the envelope has been found to be mostly beneficial to the quality of the forecasts at all resolution, when the flow impinges directly on mountain ranges like the Rockies.

In summer the situation is rather different, with the envelope having a detrimental effect at T42 and T63 resolutions, but not at T106. Synoptic analysis, and some recent experimentation using composite orographies, suggest that this may be explained by the more northerly position of the jet in summer This jet interacts with mountains which no longer appear primarily as a barrier, but rather (as in the case of the islands west of Greenland), more as isolated peaks. At T63 and T42 resolution the envelope tends to create an artificial barrier. T106 shows less of a problem since it allows a better separation of localized features. Some problems are also seen in all seasons, in connection with the envelope representation of the Asian mountains, corresponding not only to the Tibetan plateau, but also to the other mountain ranges to the north and north-east.

In all cases the impact of the envelope has been found to cause local modifications, which tend to propagate and to amplify (principally on synoptic scales) following the upper level flows. A large part of the hemisphere can be influenced in 7 to 10 days. The largest differences are found to take their origin and develop in regions of intense activity (strong gradients, deep lows, etc.). This local amplification and spreading is in part immediately perceived diagnostically as a modification to the low-wavenumber components of the flow, and it is evident that care has to be exercised in the interpretation of such results of spectral analysis.

Furthermore, the short range differences tend to be similar at all resolutions (including T21) indicating that the effect of the envelope at higher resolution (T63 and T106) does not come only from the shortest scales. This result is also consistent with the hypothesis that the important feature is the enhancement of the local height of the barrier presented to the flow. However, our results (particularly in summer up to at least T63 resolution) also show the limitation of such an approach, since it is not desirable to create a barrier effect for all types of mountains (for example isolated mountains) and since this effect should ideally depend on the direction of the flow.

It seems therefore desirable that more sophisticated approaches be investigated to simulate this dynamical response, in particular for models with rather low resolution. Such a strategy is not an alternative, but rather a complement to the parameterizations of gravity wave drag and of subgrid stress effects due to mountains, which clearly correspond to different physical processes. However, since all three processes act to reduce the overall westerly flow in middle latitudes, care must be taken during model development to achieve the correct balance between these mechanisms. There is an evident danger in tuning one representation to compensation for the deficiencies (or absence) of another.

Acknowledgement

We are indebted to J.M. Hoyer for the help he gave us in the experimental phase, and to H. Pümpel and H. Böttger for many helpful remarks and discussions in the synoptic assessment of the results.

References

Bender, M., E. Tuleya and Y. Kurihara, 1985: A numerical study of the effect of a mountain range on a landfalling tropical cyclone. Mon.Wea.Rev., 113, 567-582.

Bleck, R., 1977: Numerical simulation of lee cyclogenesis in the Gulf of Genoa. Mon.Wea.Rev., 105, 428-445.

Bretherton, F.P., 1969: Momentum transport by gravity waves. Quart.J.R.Meteor.Soc., 95, 213-243.

Chung, Y.S., K. Hage and E. Reinhelt, 1976: On lee cyclogenesis and airflow in the Canadian Rocky Mountains and the East Asian Mountains. Mon.Wea.Rev., 104, 879-891.

Cullen, M., S. Chynoweth, C. Parret and R. Purser, 1985: On some aspects of flow over synoptic scale topography. Met.011 Technical Note No.216, Submitted for publication.

Dell'Osso, L. and S.-J Chen, 1984: Genesis of a vortex and shear line over Qinghai-Tibet plateau - numerical experiments (Paper presented at the International Symposium on the Tibet Plateau and Mountain Meteorology. March 1984, Beijing, China).

Dell'Osso, L. and D. Radinovic, 1984: A case study of cyclone development in the lee of the Alps on 18 March 1982 Beitr.Phys.Atmos., 57, 369-379.

Egger, J., 1972: Incorporation of steep mountains into numerical forecasting model. Tellus, 24, 324-335.

Gerrity, J.P., 1985 NMC/GFDL Medium-Range Prediction Model in Research Activities in Atmospheric and Oceanic Modelling, Report No.8, WMO, Geneva, p.5.4.

Hollingsworth, A., K. Arpe, M. Tiedtke, M. Capaldo and H. Savijärvi, 1980: The performance of a medium range forecast model in winter - impact of physical parameterizations. Mon.Wea.Rev., 108, 1736-1773.

Hollingsworth, A., D.B. Shaw, P. Lönnberg, L. Illari, K. Arpe and A.J. Simmons, 1985: Monitoring of observation and analysis quality by a data assimilation system. Mon.Wea.Rev., in press.

Jarraud, M., 1985: On the impact of orography and resolution in the ECMWF spectral model. Proceedings of an international symposium on Current Problems in Long and Medium Range Numerical Weather Forecasting. April 1985. Budapest, Hungary.

Ji, L.R. and S. Tibaldi, 1983: Numerical simulations of a case of blocking. The effects of orography and land sea contrast. Mon.Wea.Rev., 111, 2068-2086.

Krishnamurti, T.N., K. Ingles, S. Cocke, T. Kitade and R. Pasch, 1984: Details of low latitude medium range numerical weather prediction using a global spectral model. Part II Effects of orography and physical initialisation. J.Meteor.Soc. Japan, 62, 613-648.

Lilly, D.K., 1972: Wave momentum flux. A GARP problem. Bull.Am.Meteor.Soc., 20, 17-23.

Mesinger, F., 1977: Foreward-Backward Scheme and its use in a limited area model. Beitr. zur Phys. det Atmos., 50, 200-210.

Mesinger, F. and R.F. Strickler, 1982: Effect of mountains on Genoa cyclogenesis. J.Meteor.Soc. Japan, 60, 326-338.

Pierrehumbert, R.T., 1984: Linear results on the barrier effects of mesoscale mountains. J.Atmos.Sci., 41, 1356-1367.

Pierrehumbert, R.T., and B. Wyman, 1985: Upstream effects of mesoscale mountains. J.Atmos.Sci., 42, 977-1003.

Queney, P., 1947: Theory of perturbations in stratified currents with application to airflow over mountain barriers. Department of Meteorology, University of Chicago, Misc.Rep.No.23, 67pp.

Radinovic, D., 1985: A valley filled orographic representation in numerical weather forecast models. ECMWF Tech.Memo.No.99, 58pp.

Sawyer, J., 1959: The introduction of the effects of topography into methods of numerical forecasting. Quart.J.R.Meteor.Soc., 85, 31-43.

Simmons, A.J., 1985: The treatment of orography in numerical weather prediction models. GARP Special Report No.43, WMO, Geneva, II-57 to II-77.

Simmons, A.J. and M. Jarraud, 1984: The design and performance of the new ECMWF operational model. Proceedings of ECMWF Seminar on Numerical Methods for Weather Prediction, 5-9 September 1983, 113-164.

Sumi, A. and M.Kanamitsu, 1984: A study of systematic errors in a numerical weather prediction model. Part I: General aspects of the systematic errors and their relation with the transient eddies. J.Meteor.Soc. Japan, 62, 234-251.

Tibaldi, S., 1985: Envelope orography and the maintenance of quasi stationary waves in the ECMWF model. To appear in Advances in Geophysics.

Volmer, J.P., M.Déqué, and M.Jarraud, 1983: Large scale fluctuations in a long range integration of the ECMWF spectral model. Tellus, 35A, 173-188.

Wallace, J.M., S.Tibaldi and A.J.Simmons, 1983: Reduction of the systematic forecast errors in the ECMWF model through the introduction of an envelope orography. Quart.J.R.Meteor.Soc., 109, 683-717.