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"Development of the adiabatic formulation of the ECMWF model"

by

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Meteorological Training Course

Lecture Series

Development of the adiabatic formulation of the ECMWF model

Part 7

Envelope orography

by

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European Centre for Medium-Range Weather Forecasts
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7.1 INTRODUCTION

The problems which arise in relation to orography in numerical weather prediction can be regarded as falling within three broad categories. The first involves the representation, either explicitly or by parametrization, of orographic effects in the model. The second concerns the numerical formulation of the model itself (its coordinates, finite-difference schemes, etc) which should be chosen to avoid computational problems associated with steep orography. Thirdly, there is the interpretation of model output to provide local weather forecasts in mountainous regions. The second of these topics has already been considered in preceding lectures. Attention in this lecture will be concentrated on aspects of the first topic.

Much of the influence of orography on the synoptic- and large-scale flow can be achieved in global models by use of what is commonly referred to as "mean" orography. For finite-difference models this orography is computed as means over model grid-squares of a higher-resolution representation of the earth's orography. In spectral models it is typically computed by a spectral fit to some grid-square mean orography, for example the mean orography defined on the computational "Gaussian grid" of the model. For both types of model, this mean orography may be smoothed further to reduce numerical problems associated with steep slopes.

It has, however, become increasingly recognized in recent years that in addition to the use of such a mean orography, it is important to include a number of effects of sub-gridscale orographic variations. The main processes to include are:

(i) Dynamical low-level blocking (or barrier) effects, the main topic of this lecture.

(ii) Influence of unresolved orographically-forced gravity-wave motion on the large-scale flow. Parametrization of this is discussed in the second module of this training course.

(iii) Enhanced low-level dissipation to represent aerodynamic drag associated with orography on horizontal scales up to about 10 km (Mason, 1987).

The following section presents some reasons to suspect that the low level barrier effect of mountains is not adequately represented by an area-mean orography, and discuss some of the solutions proposed to remedy this deficiency. In Section 7.3 a series of results is presented from a set of experiments which compared medium-range forecasts using mean and enhanced, or "envelope", orographies. It was part of the larger project aimed at assessing the impact of changes in horizontal resolution in the ECMWF model and developing the T106 version of the spectral model for operational implementation. Some discussion of the relationship between envelope orography and parametrized gravity-wave drag is given in Section 7.4.

7.2 REPRESENTATION OF BARRIER EFFECTS, AND THE ENVELOPE OROGRAPHY

Simple considerations of the energy needed to lift an air parcel over a mountain ridge suggest that the height of the ridge will be a dominant factor in determining whether approaching low level air will rise over the ridge, or be decelerated and perhaps diverted sideways. For global numerical models, which typically have mesh sizes upward of a hundred kilometres, grid-square averaging results in a model orography in which maximum heights fall well short of the characteristic ridge heights of many important mountain ranges. A European example is shown in the left panel of Fig. 7.1, which plots the "silhouette" (the maximum height along lines of longitude) presented to meridional flow by the Alps and Massif Central, as described by three orographic representations. The fine-resolution outline is derived from mean orographic heights for 10′ x 10′ grid squares contained in a dataset made available by the US Navy, and the smooth curves are computed from "mean" spectral-model orographies for triangular truncations at total wavenumber 63 (T63) and 106 (T106), as utilized for the experiments described later in this lecture. The height of the Alpine chain is evidently underestimated at both model resolutions, and only for the Rhône valley near 5°E does the 10′ mean silhouette fall below the model profiles. For such narrow mountain ranges there is a clear likelihood that area-averaged model orographies will underestimate barrier effects and give excess flow over ridges.

Both practicl experience and idealized modelling confirm the inadequacy of using an area-mean orography at the resolutions currently used in global models. Wallace et al. (1983) reported diagnostic studies of operational ECMWF forecasts which showed a close relationship between the location of the largest mean short-range forecast errors and the positions of some mountain ranges in the Northern Hemisphere, as shown in Fig. 7.2. Moreover, composites based on different 500 hPa flow patterns over the Rockies showed error to be largest where the flow encountered or crossed the mountains (Fig. 7.3). For the Alps, (negative) biases were largest under conditions of strong north-westerly flow. Integrations of a barotropic model provided evidence that inadequate orographic forcing (as represented by the growth of short-range error) could be an important factor in the subsequent growth of larger-scale systematic errors over the Northern Hemisphere that can be seen in Fig. 7.2.

Case studies have shown that simulation of cyclogenesis in the lee of the Alps is generally improved by using some form of enhanced mountains, either by increasing the height of the

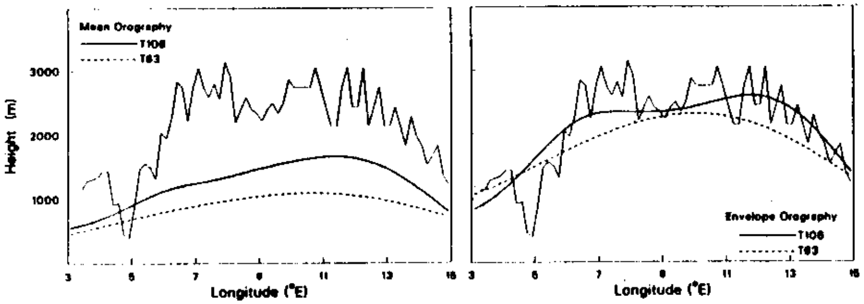

Fig. 7.1 Silhouette presented to meridional flow by the southern European orography between 3° and 15°E. Plotted is the maximum orographic height in metres along lines of longitude from 43° to 48°N for:

Thin solid lines: Mean orography on 10′ x 10′ grid

Thick solid lines: Mean (left) and $\sqrt{2}$ standard-deviation ($\sqrt{2}\sigma$) envelope (right) orographies of T106 spectral model

Dashed lines: Corresponding orographies of T63 spectral model.

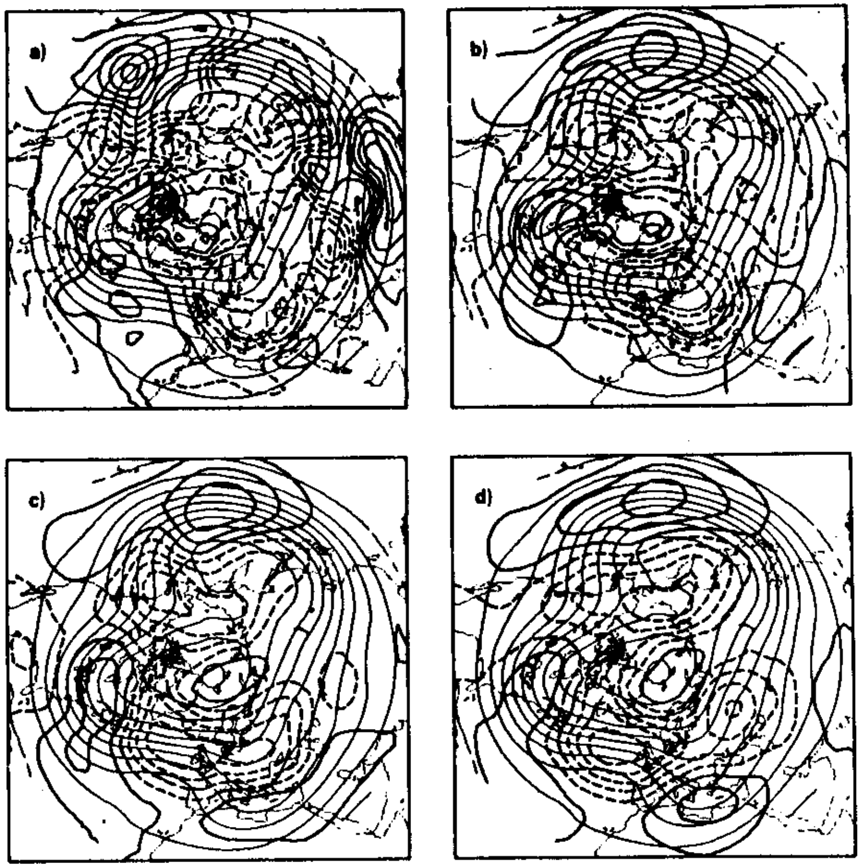

Fig. 7.2 Ensemble mean forecast error fields for ECMWF forecasts of 500hPa height for the 100-day period 1 December 1980 to 10 March 1981 inclusive.
(a) Day 1 forecasts, contour interval 5 m
(b) Day 4 forecasts, contour interval 16 m
(c) Day 7 forecasts, contour interval 30 m
(d) Day 10 forecasts, contour interval 30 m
The background field (light contours) is the mean analyzed 500 hPa height for the same period, contour interval 80 m. Negative contours are dashed. From Wallace et al.(1983).

orography used in the model (e.g. Bleck, 1977; Mesinger and Strickler, 1982, Dell'Osso; 1984; Dell'Osso and Radinovic, 1984) or by blocking the low-level flow more explicitly (Egger, 1972). More generally, experiments by Wallace et al. (1983) and subsequent investigators have shown that overall improvements in medium-range extratropical forecasts result from use of enhanced orography, as discussed further below. Furthermore, Krishnamurti et al. (1984) showed monsoon simulations for the FGGE period to be improved by adopting a similar orography.

Theoretical and idealized modelling studies demonstrate the dependence of mountain barrier effects on such parameters as the ridge height, mountain shape, static stability, incident flow and Coriolis parameter. Such studies may eventually lead to a soundly-based parametrization of these effects, but in the meanwhile they provide some justification for the use of enhanced explicit orography. In particular, Pierrehumbert (1984) discussed this question in the light of linear solutions for flow over a two-dimensional ridge. He concluded that in order to represent the barrier effect of mesoscale mountains such as the Alps or features embedded in the Rocky Mountain range, it was more important to preserve the maximum height of ridges rather than (as does area-averaging) the volume of the mountain. Support for this conclusion has been provided by subsequent nonlinear calculations (Pierrehumbert and Wyman 1985; Cullen et al., 1987).

Several approaches have been used in practice to enhance the low level barrier effect of mountains. Some correspond to a more or less explicit blocking of the low level flow (e.g. Egger 1972), while many others correspond essentially to an increase in the height of the mountains used by the models. For example, following a suggestion by Mesinger a "silhouette" orography is used for global operational prediction at NMC, Washington (Gerrity, 1985). This orography approximately reproduces the cross-section presented to the flow by the mountains. Radinovic (1985) has examined a "valley filling" approach (Mesinger, 1977) which models a further (and related) sub gridscale orographic effect, namely that valleys filled with cold air are very stable and interact very little (under certain conditions) with the rest of the flow, suggesting that they should be treated as part of the mountain itself (Bleck, 1977).

At ECMWF, attention has been concentrated on use of so-called "envelope" orographies. Following a suggestion of J.-F. Geleyn, and similar to an independent approach by Mesinger and Strickler (1982), the grid-square mean orography is enhanced by adding a multiple of the standard deviation of the sub gridscale orography, as computed from the US Navy dataset referred to earlier. The multiplicative constant is not, however, well defined. For example a factor of 2 yields a model orography which equals the maximum height of the fine resolution orography over each grid square for the idealized case of

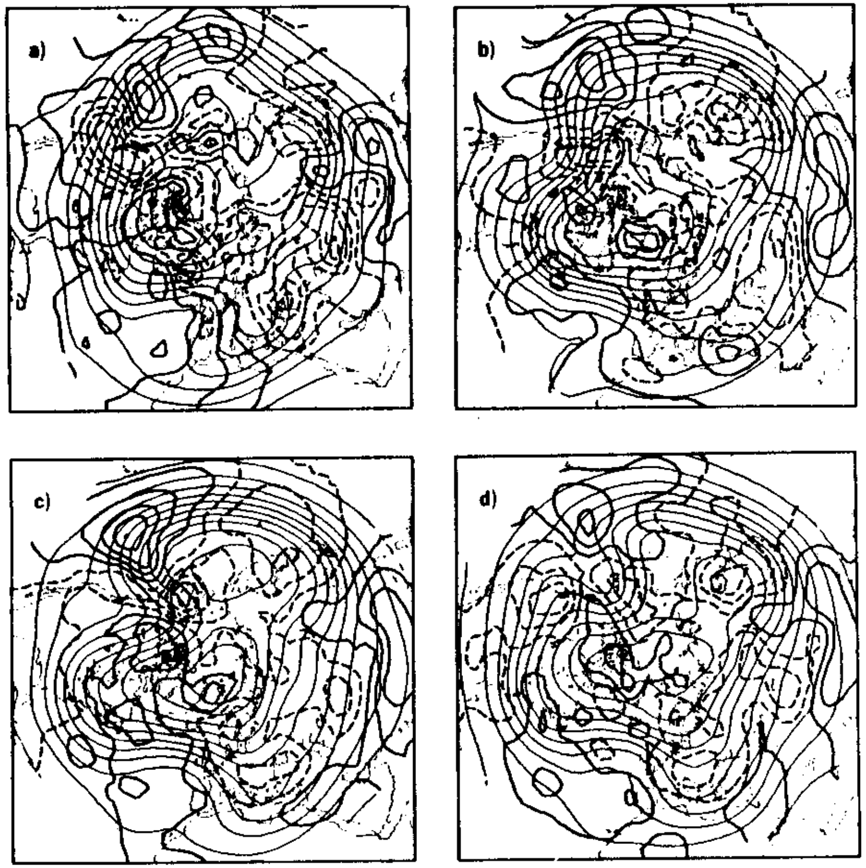

Fig. 7.3 Composite day 1 forecast errors in 500 hPa height (heavier contours) superimposed upon the corresponding composite 500 hPa analyses at verification time, for different flow types over the Rockies. Negative contours are dashed. From Wallace et al.(1983), where a specification of dates may be found.

2-dimensionally sinusoidal sub-gridscale orography (Wallace et al., 1983), whereas a factor of √2 gives the envelope of a sub-gridscale orography which comprises sinusoidal ridges.

The right-hand plot of Fig. 7.1 shows the Alpine silhouette for envelopes based on use of the factor √2, for T63 and T106 spectral resolutions. The height of the Alpine barrier is evidently much better captured by the envelope than by mean orography, for both resolutions. However, area-averaging and spectral-fitting already results in a tendency to enhance the width of narrow mountain ranges, and this becomes more apparent with use of enhanced orography. Fig. 7.4 illustrates this by exhibiting north-south cross-sections through the Alps near 10°E for the 10′ x 10′ mean orography and for mean and √2 envelope orographies at T63 and T106 resolution. There is an evident risk of a detrimental impact of this spreading of the orography, particularly in situations involving flow parallel to a ridge (or the edge of a plateau). Bearing in mind the complexity of the earth's terrain and the variability of atmospheric flow, extensive experimentation is required in practice to determine the choice of mean or enhanced orography, or within the envelope approach the optimal multiplicative factor.

The original experimentation with envelope orography at ECMWF was carried out by Wallace et al. (1983) using a 2 standard-deviation envelope in the 1.875° resolution grid-point model used for operational prediction prior to April, 1983. For a trial series of forecasts from February 1982, objective verification showed that this envelope produced a net improvement in forecast accuracy beyond day 4, including a modest reduction in time-mean error at the end of the forecast range. Forecast improvement was confirmed by further experimentation for January 1981 (Tibaldi, 1986), and for this period the rate of growth of systematic (monthly-mean) error was substantially reduced. Beneficial impact of a range of envelope orographies was also found in winter cases using the ECMWF spectral model at T63 resolution, and an envelope based on √2 standard deviations was introduced operationally at ECMWF in April 1983 along with this model (Simmons and Jarraud, 1984). Beneficial impact of envelope orography on a set of winter forecasts has also been reported by Iwasaki and Sumi (1986).

Despite the encouraging results noted above, a number of detrimental effects of using the envelope were also found. Objective scores indicated a general degradation of short-range forecasts in the studies cited above, and initial experience of the T63 model gave general concern about the behaviour of the envelope in some weather regimes, especially in summer (Simmons and Jarraud, 1984). In addition, some problems occurred due to increased local discrepancies between actual and model heights, in particular when using observations in the data assimilation, and when using near-surface forecast products such as low-level winds and temperature.

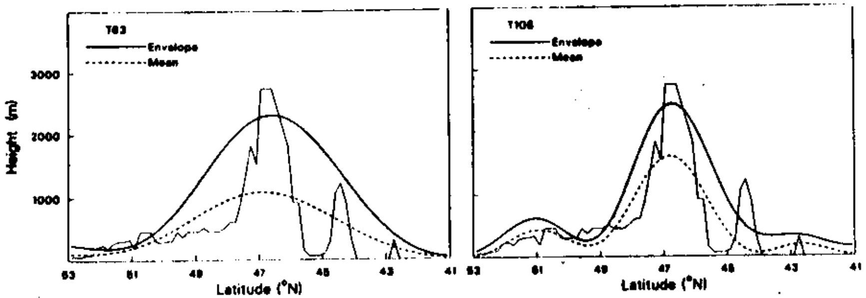

Fig. 7.4 Meridional cross-section of orographic height in metres from 53°N to 41°N at 10° 5′E showing:

Thin solid lines: Mean orography on 10′ x 10′ grid

Thick solid lines: √2σ envelope orographies of T63 (left) and T107 (right) spectral models

Dashed lines: Mean orographies of T63 (left) and T106 (right) models.

7.3 AN EXPERIMENTAL COMPARISON OF MEAN AND ENVELOPE OROGRAPHIES

(a) Introduction

In view of the problems mentioned above, and the obvious sensitivity of the representation of some important mountain ranges to the resolution of the forecast model, as illustrated in Figs. 7.1 and 7.4, it was decided to reassess the use of envelope orography as part of the development of the T106 model. To place results in context, comparisons of forecasts using mean and envelope orographies were made also for lower horizontal resolutions. The 24 cases selected for study were those for which sensitivity to horizontal resolution was discussed in lecture 5 for the √2 standard-deviation envelope orography. For each case 10-day forecasts were made with mean orography and with the √2 standard-deviation envelope using 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 to the mean. Other model details were given in lecture 5.

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 produced using a √2 standard-deviation envelope orography. For T63 initial data with mean orography and all T106 datasets, upper-air fields were formed by spectral fits of fields which had been vertically interpolated from one set of coordinate surfaces to the other at each point of the model's Gaussian grid. For T106, mean and envelope orographies were specially created using the higher resolution Gaussian grid. Upper air fields, surface pressures and orographies for the T42 and T21 experiments were obtained simply by truncation of T63 fields. A proper land sea mask was constructed for each resolution from the 10′ x 10′ US Navy data. 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 to the verification in favour of T63 with envelope orography, but a number of tests have been carried out which indicate that these biases are indeed much smaller than the differences observed.

(b) Objective assessment

In view of previous indications of a different response to enhanced orography in summer than in winter, the 24 cases sampled were divided into two groups of 12, one broadly representing winter (November to April) and one summer (May to October). Average differences between 500 hPa height anomaly correlations for mean and envelope orographies are presented for each horizontal resolution and season in Fig. 7.5. In winter (left plots) 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 a strong damaging effect of the envelope at T21, and a very slight worsening at T42. For T63 and T106 there is a clear improvement, this being noticeable earlier in the forecast range for T106. Later in the range, quantitative aspects of the improvement due to the envelope, which is seen 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 1983/84 was substantially larger than from the corresponding cases for 1984/85.

The results for summer shown also in Fig. 7.5 are in sharp contrast to those for winter. The envelope has a detrimental effect in terms of anomaly correlations 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, according to anomaly correlations. It should, however, be noted that at T63 resolution, standard deviations of forecast error do not show a summer bias against the envelope, and for T106 they are lower with envelope than with mean orography. It can also be seen from Fig. 7.5 that for T106 there is little to choose, overall, between envelopes based on 1 or $\sqrt{2}$ standard deviations, the higher orography giving slightly better results in winter and slightly poorer results in summer. It was the lower of these two envelope orographies that was chosen for operational use with T106 resolution.

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.7.6. 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 envelope orography has a smaller detrimental impact in summer for T21 than for T42 and T63 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. 7.6) there is more variability, and seasonal differences are more clear. The latter is particularly so for T63, with the improvement due to the envelope in winter, and deterioration in summer, occurring in almost all situations.

Examining other levels and variables generally confirms these results. In particular the response observed for the 1000 hPa height fields is similar to that shown for the 500 hPa heights, both in summer and winter. Verifications of both the 500 hPa temperature and the

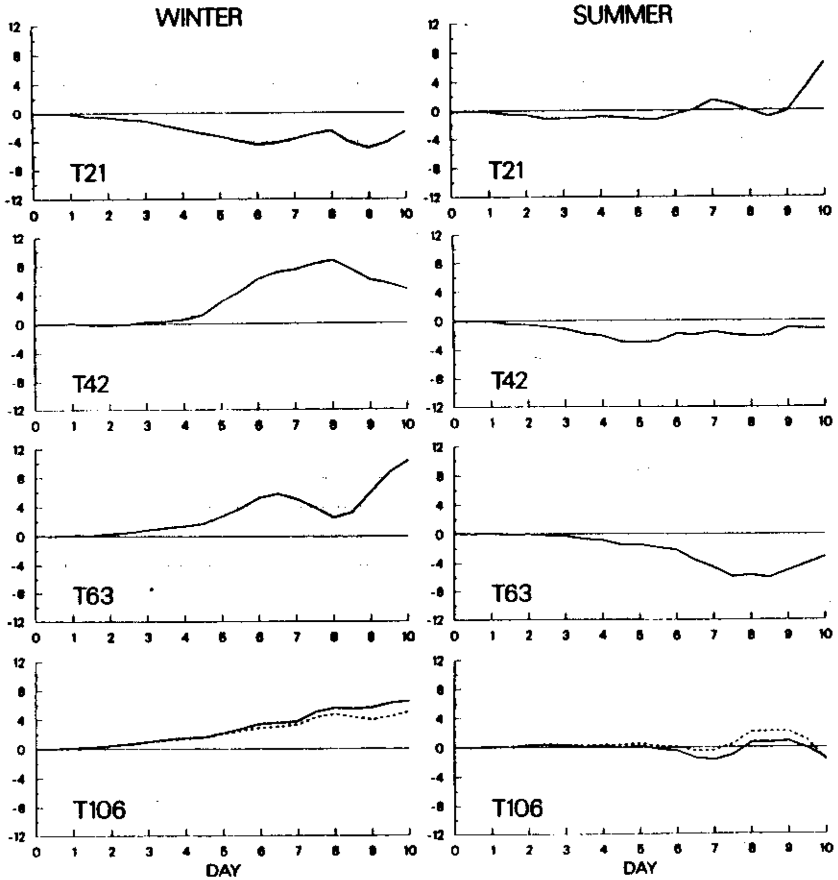

Fig. 7.5 Mean differences in anomaly correlations of 500 hPa height in the extratropical Northern Hemisphere between forecasts using ($\sqrt{2}\sigma$) envelope and mean orographies for T21 to T106 resolutions (top to bottom) averaged over 12 winter (left) and 12 summer (right) cases. In addition, for T106 the dashed line corresponds to the difference between results for the (1σ) envelope and mean orographies.

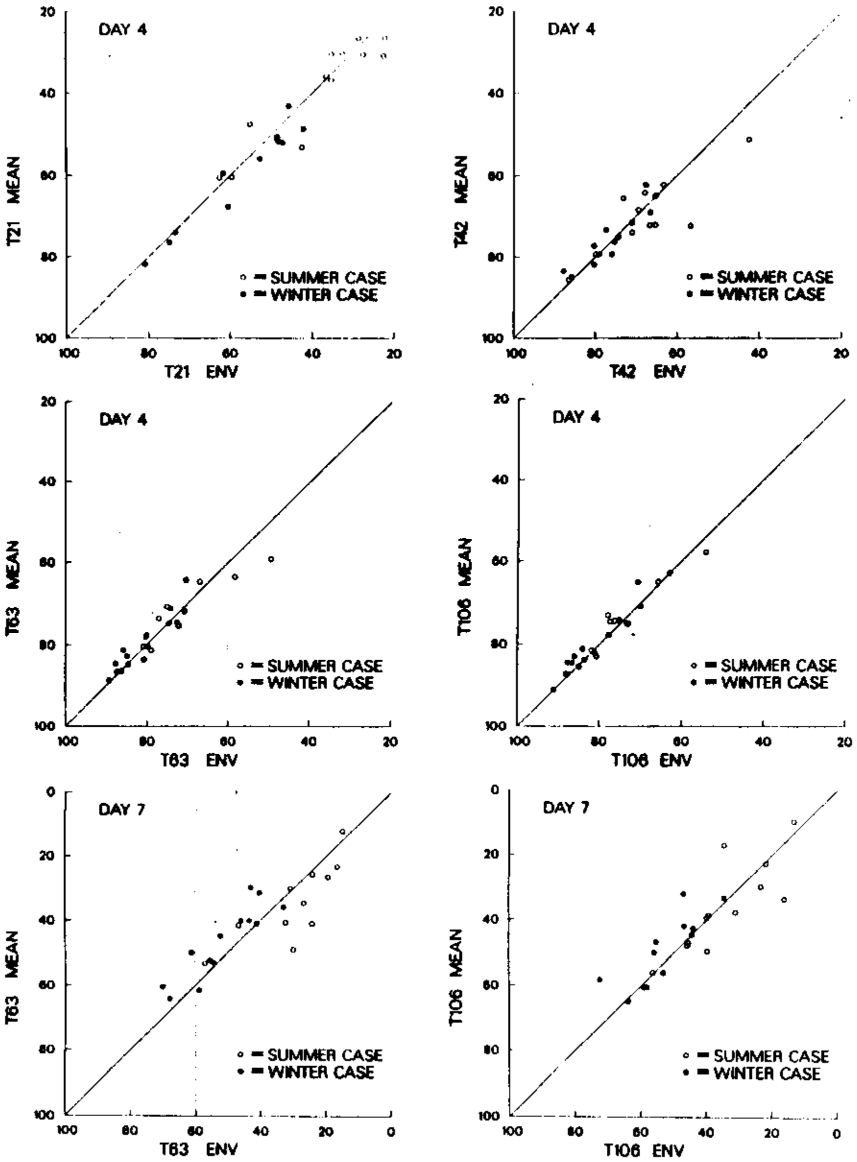

Fig. 7.6 Upper and middle: Scatter diagrams of anomaly correlations of the 500 hPa height field in the extratropical Northern Hemisphere comparing mean and $(\sqrt{2}\sigma)$ envelope forecasts at T21, T42, T63 and T106 resolutions for D+4. Summer cases are represented by + signs, winter cases by x signs, and the mean by a thick dot.

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

850 hPa wind fields indicate a slightly more positive impact of the envelope at T63 resolution, and a more systematic benefit at T106.

(c) Synoptic assessment

A detailed synoptic assessment of forecasts has been carried out for the extratropical band of the Northern Hemisphere, with emphasis placed on examining the evolution of forecast differences from initially small values localized in particular mountainous regions. In the examples presented here we illustrate some particular aspects of the objective scores and present a sample of cases directly related to the European sector. A much wider sample is discussed in a report by Jarraud et al.(1986), on which this lecture is largely based.

- A European block

The crucial rôle of envelope orography in the successful prediction of a European block is shown in Fig. 7.7. This figure displays mean 500 hPa height fields from day 5 to day 10 of T106 forecasts from 15 March 84, together with the verifying analysis, which is shown in the upper left panel. The forecasts used mean (upper right), $\sqrt{2}$ standard-deviation envelope (lower left) and 1 standard-deviation envelope (lower right) orographies. Differences between the mean-orography forecast and the two envelope forecasts are particularly large over northwestern Europe and the North Atlantic, the structure of the block being well captured with the envelope but not with the mean orography. Differences between the two forecasts using envelope orography are evidently very much smaller, particularly in the vicinity of the blocking high. This result is strongly confirmed by objective scores, the anomaly correlation of 500 hPa height at day 7 over the "European" region 20°W-45°E, 30°N-75°N, being 3.3% for mean orography, 85.6% for the 1 standard-deviation envelope and 84.4% for the $\sqrt{2}$ standard-deviation envelope. It is clear that in this case the impact of the enhanced orography is far from linearly dependent on the amplitude of the envelope increment. Sensitivity to horizontal resolution for this case was discussed in lecture 5.

Examining difference maps earlier in the forecast range revealed a relatively complex evolution, but it has been possible to demonstrate the particular importance of the North Canadian mountains and Greenland in the establishment of the block. A number of experiments were carried out in which the ($\sqrt{2}$ standard-deviation) envelope orography was reduced to the mean in a particular region, and four examples of mean day 5-10 forecasts are presented in Fig. 7.8. Comparing first the upper-left map with Fig. 7.7, it can be seen that using mean orography over northern Asia (60°E-190°E; 40°N-80°N) had impact only over the North Pacific. Doing the same over the Rocky Mountains (170°W-100°W; 20°N-80°N) led to some modification to the structure of the ridge over the Rockies themselves, and to a slight erroneous deepening of the cut-off south of Iceland, but gave relatively little overall

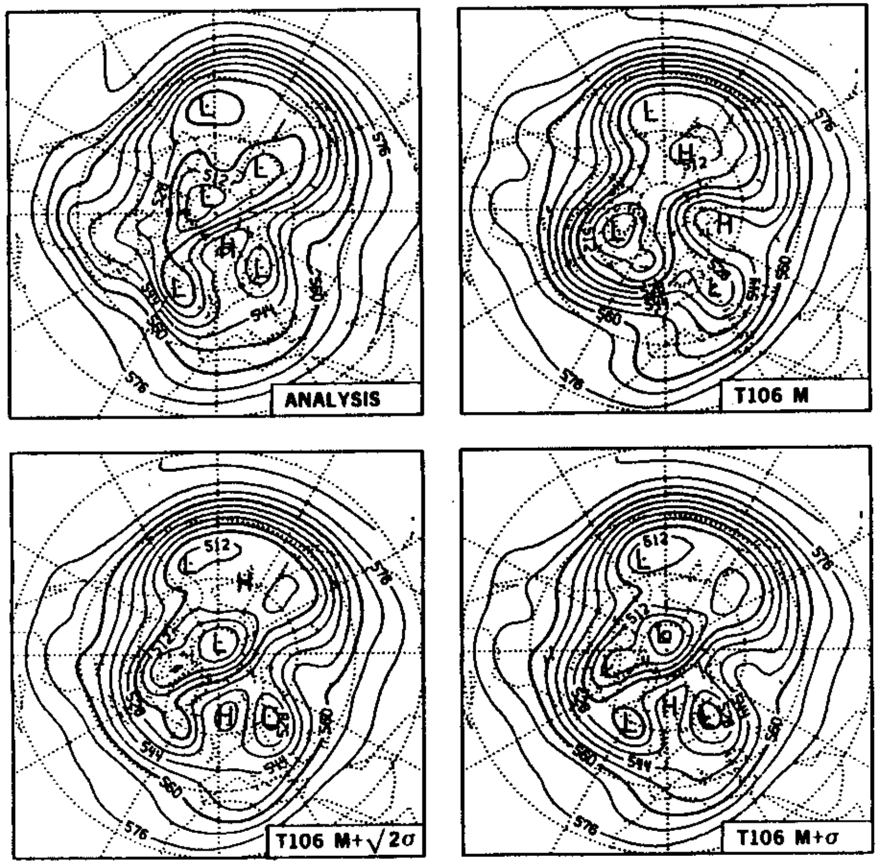

Fig. 7.7 Mean analyzed 500 hPa height field (contour interval 8 dam) for the period 20-25 March 1984 (upper left) and corresponding fields from T106 forecasts from 15 March using the following orographies:

Upper right: Mean

Lower left: $\sqrt{2}$ standard-deviation envelope

Lower right: One standard-deviation envelope

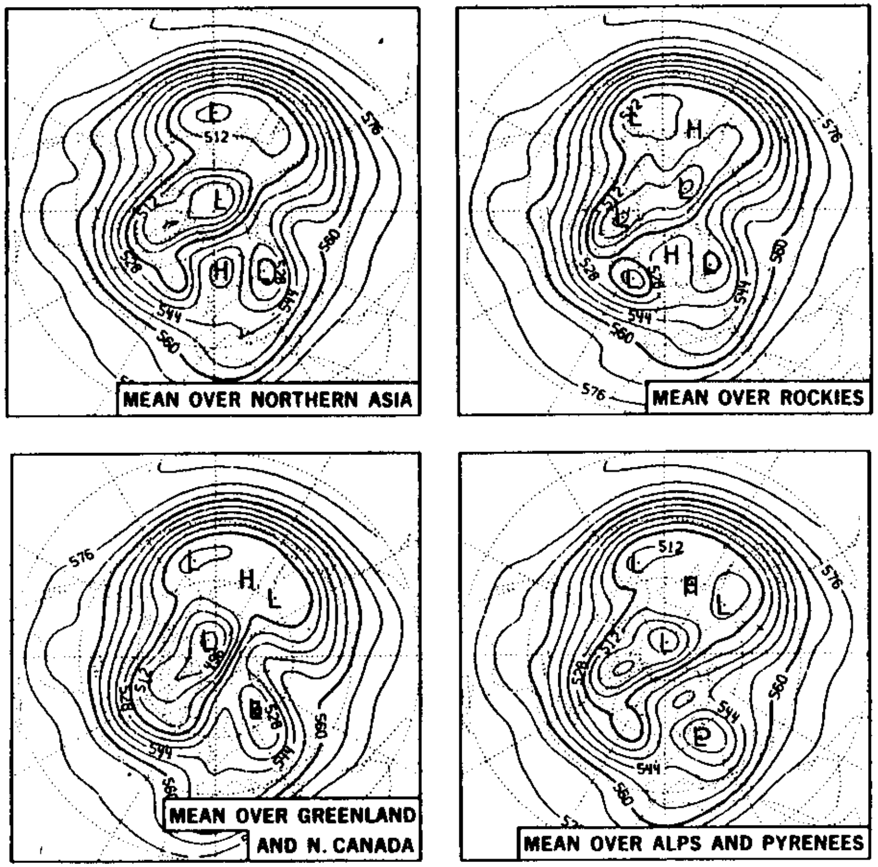

Fig. 7.8 Mean 500 hPa height forecasts as in Fig. 5, but using the following $\sqrt{2}\sigma$ orographies:

Upper left : Envelope, but mean over Northern Asia

Upper right : Envelope, but mean over Rockies

Lower left : Envelope, but mean over Greenland and Northern Canada

Lower right : Envelope, but mean over Alps and Pyrenees impact, as may be seen from the upper-right map of Fig. 7.8. Conversely, the lower-left map shows how a much more dramatic impact was obtained by using a mean orography over Greenland and northeast Canada (10°W-100°W; 45°N-90°N). In this case the forecast with the composite orography is very much closer to that with the mean orography everywhere than it is to that with the complete envelope, for all features in the Atlantic and Eurasian sectors. The lower-right panel shows a smaller, but still significant influence of the Alps and Pyrenees (10°W-25°E; 25°N-55°N). Using a mean orography over this area degrades the 5-day average forecast such that the low over eastern Europe is located slightly more to the south and east, with a weakening of high pressure over the Greenwich meridian and a north-westward tilt of the Siberian ridge. Despite this apparent success for the envelope, it should be noted that the envelope forecast failed to simulate the disappearance of the block over the final two days of the forecast. The decay was in fact better represented when using mean orography over southern Europe, a result which may be related to the more westerly position of the European low.

- 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. Bleck, 1977; Mesinger 1977; Mesinger and Strickler 1982; Dell'Osso 1984). Similar results have been found here on the very few cases of our sample when such cyclogenesis occurred.

As an example, Fig. 7.9 shows day-3 forecasts of 500 hPa height and 850 hPa wind for 18 October, 1983, using mean and $\sqrt{2}$ envelope orographies at T106 resolution, together with the verifying analysis. The situation is a classical one for lee cyclogenesis. On 16 October, a very intense cyclonic circulation prevailed over western Europe, associated with a deep low centred north of Scotland. One day later, the 500 hPa trough had deepened and reached Scandinavia, extending southward with an indication of a cut-off over the Alps, and with a surface low appearing over the northern Adriatic. By the 18th, as shown in the upper panels of Fig. 7.9, an intense closed cyclonic circulation had been established over southern Italy, with strong northeasterly flow immediately to the south of the Alps.

The corresponding day-3 forecast with envelope orography (Fig. 7.9, middle panels) is in many respects satisfactory, although the cut-off low is positioned too far to the east. When using mean orography (lower panels) there is a weaker cyclonic circulation at 850 hPa, and the low is positioned even further eastward. Examining the 850 hPa flow in the vicinity of the Alps suggests that both forecasts underestimate the barrier effect of the mountain range, but the forecast using the envelope is clearly closer to reality than that using mean orography in this respect.

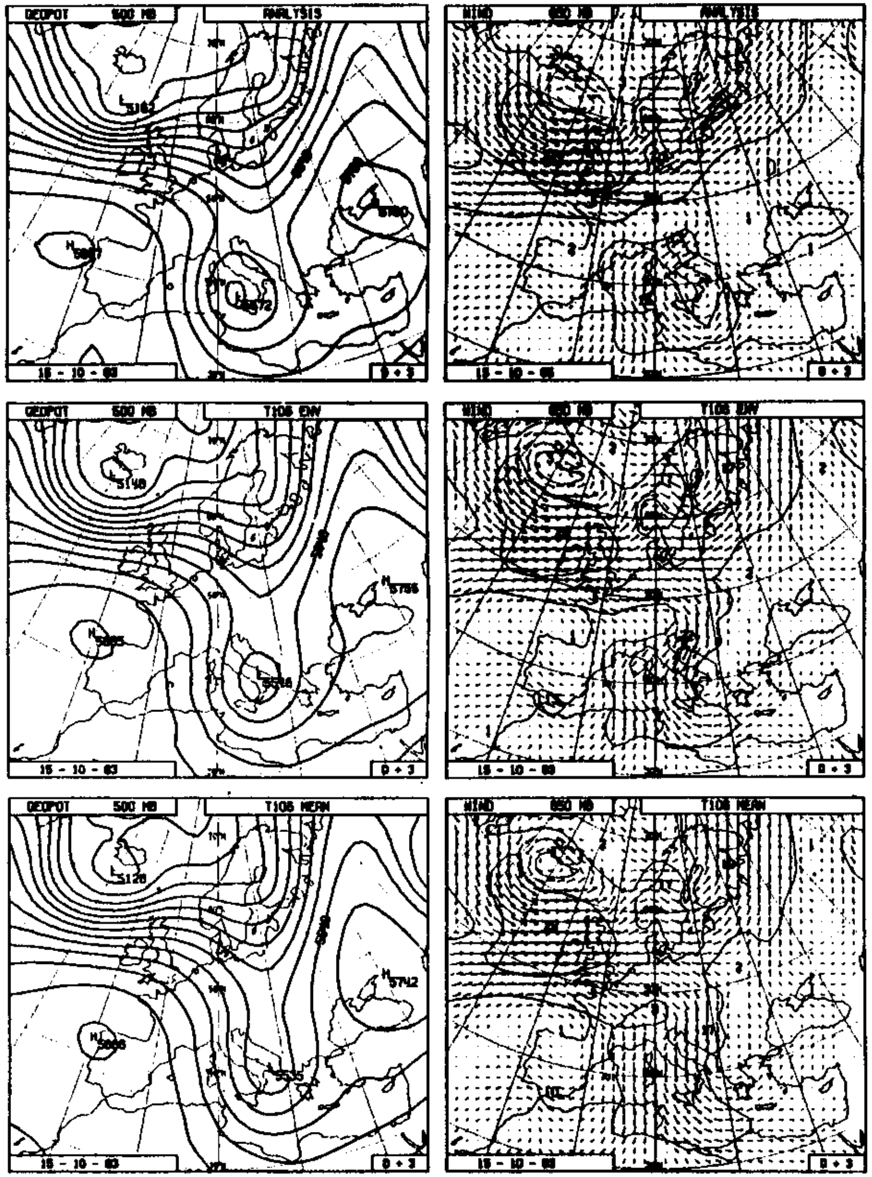

Fig. 7.9 Analyzed maps showing 500 hPa height (upper left, contour interval 6 dam) and 850 hPa wind (upper right, contour interval 10 ms^{-1}) for 18 October 1983. T106 forecasts from 15 October are also shown, for ($\sqrt{2}\sigma$) envelope orography (middle) and mean orography (lower).

- Propagation and amplification of differences

The representation of a mountain range such as the Alps has already been shown to be important locally in the examples of cyclogenesis and blocking, but such ranges can also be responsible for significant differences later in the medium range over quite distant places. A striking example, from the 15 February 1985 case, serves to illustrate how differences commonly propagate downstream and then amplify where the environment is favourable.

In order to check the impact of the Alps on some features observed over Europe, a T63 10-day forecast was rerun from 15 February 1985 using the envelope orography everywhere except over western Europe, where mean orography was used instead. Fig. 7.10 shows how, as expected, large differences in the early medium range were mainly confined to the region over which the orography was changed. These differences were associated with the position of a cut-off low (better predicted with envelope orography), and decayed together with the cut-off itself.

However, as seen also in Fig. 7.10, between days 4 and 7 another small area of differences, which had originally propagated northwards, reached the northern branch of the jet, and propagated downstream (with relatively little amplification) following the coast of Siberia. Differences then amplified rapidly when they reached the North Pacific. Maps of the full 1000 hPa height fields for day 10 (not shown) reveal major differences in an intense low located near the Dateline. By day 10 neither of the forecasts is particularly good, but this example demonstrates a sensitivity to remote influences from quite small regions which has to be borne in mind in research aimed at providing reliable forecasts for the later medium range.

From the synoptic assessment of all 24 cases Jarraud et al.(1986) were unable to identify any cases of large amplification of differences associated with upstream propagation. Significant downstream amplification of differences occurred almost systematically in connection with systems which themselves were developing quickly.

- An example of deterioration at lower resolution due to the envelope in summer

In summer the deterioration found 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 and northeastern Asia, 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.

One of the critical areas for interaction between the flow and the orography in summer is Greenland and the mountainous islands to the west. In five of the twelve summer cases,

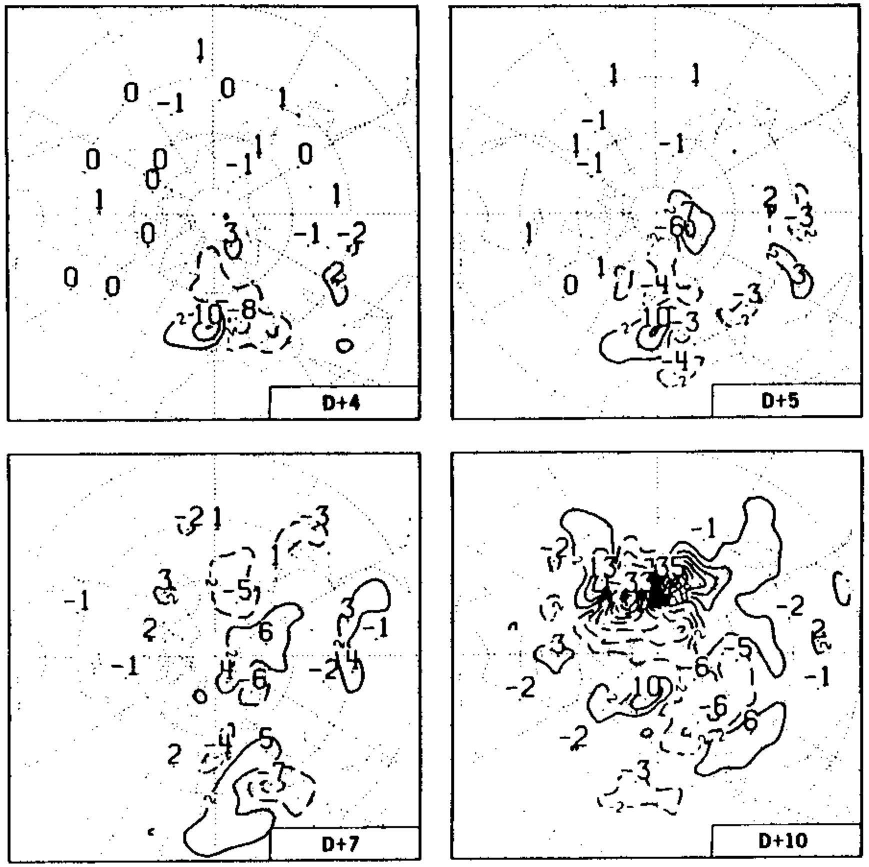

Fig. 7.10 Forecast-difference maps (in units of dam) of 1000 hPa height for D+4, D+5, D+7 and D+10 T63 forecasts from 15 February 1985. One forecast used the (√2σ) envelope everywhere, and the other used the same envelope, but reduced to the mean over western Europe.

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 the envelope. An example is shown in Fig. 7.11, which presents results at day 6 for T63 forecasts from 15 May 1984. It can be seen that there are significant differences between the mean and envelope orography forecasts over the northern Atlantic and Europe, associated with a ridge to the southeast of Greenland, a cut-off low over western Europe, and a weaker trough near the Caspian Sea. Mean orography evidently gives a better prediction of each feature.

Examination of the evolution in time of differences from the start of the forecast suggested a crucial rôle of the mountainous area west of Greenland, and this has been confirmed by an experiment in which the envelope was reduced to the mean over this area. The results at day 6 are also shown in Fig. 7.11, and the forecast is evidently much closer to that obtained with the global mean orography than with the envelope, as emphasized by the difference maps. The flow over southern Europe is much better, the small revision to the orography (shown also in Fig. 7.11) being sufficient to remove the erroneous trough over Italy present in the envelope forecast. The Atlantic ridge is closer to reality, and the Caspian trough is better positioned. The change in orography also reduces some of the difference seen over western Siberia in the upper right of the map frame. A distinctly smaller sensitivity to the envelope was found at T106 resolution in this case, due presumably to a better definition of the fairly high but isolated mountains west of Greenland. At T63 these are represented as a broad mountainous extension of Greenland, particularly in the case of envelope orography, which appears to present too much of a barrier to the incident flow.

- A beneficial summer impact of the envelope over the Alps

Although the impact of the envelope orography in summer was generally detrimental at T63 resolution, this was far from systematic for all areas and cases. We present in Fig. 7.12 day-3 T63 forecasts of 500 hPa height and 850 hPa wind fields over Europe. When using mean orography a cut-off low is positioned too far to the south over the Gulf of Genoa, and at 850 hPa there is strong flow across the Alps, whereas the observed flow was deflected westward on the northeastern side, with southeasterly flow over northern Italy. With the envelope, these features are significantly better predicted. At T106 resolution, the longitude of the 500 hPa cut-off was improved when using mean orography, but in other respects the benefits of the envelope were almost equally clear. These benefits appear consistent with a better representation of the low-level barrier effect discussed earlier.

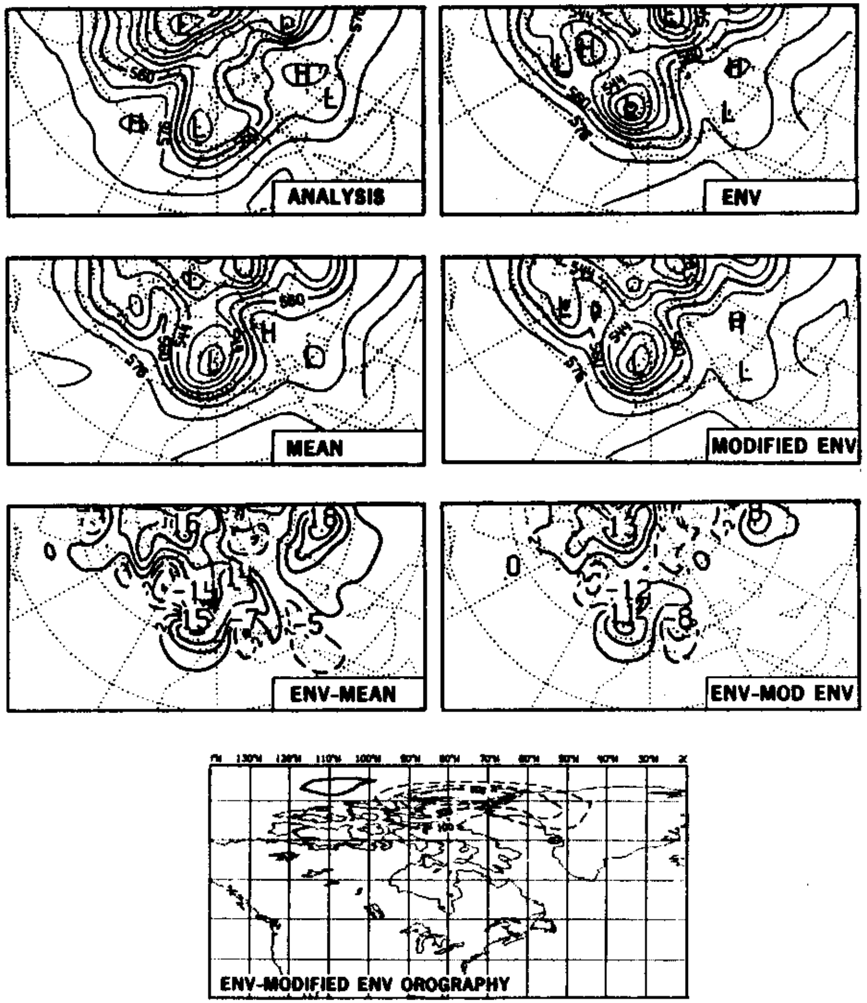

Fig. 7.11 The analyzed 500 hPa height field for 21 May 1984 (upper, left) and corresponding D+6 T63 forecasts using $\sqrt{2}\sigma$ envelope orography (upper, right), mean orography (upper middle, left), and a modified envelope orography which is reduced to the mean west of Greenland (upper middle, right). The reduction in orography (in m) is shown in the lowest panel. Differences between envelope and mean forecasts, and between envelope and modified envelope forecasts are also shown (lower middle, left and right respectively).

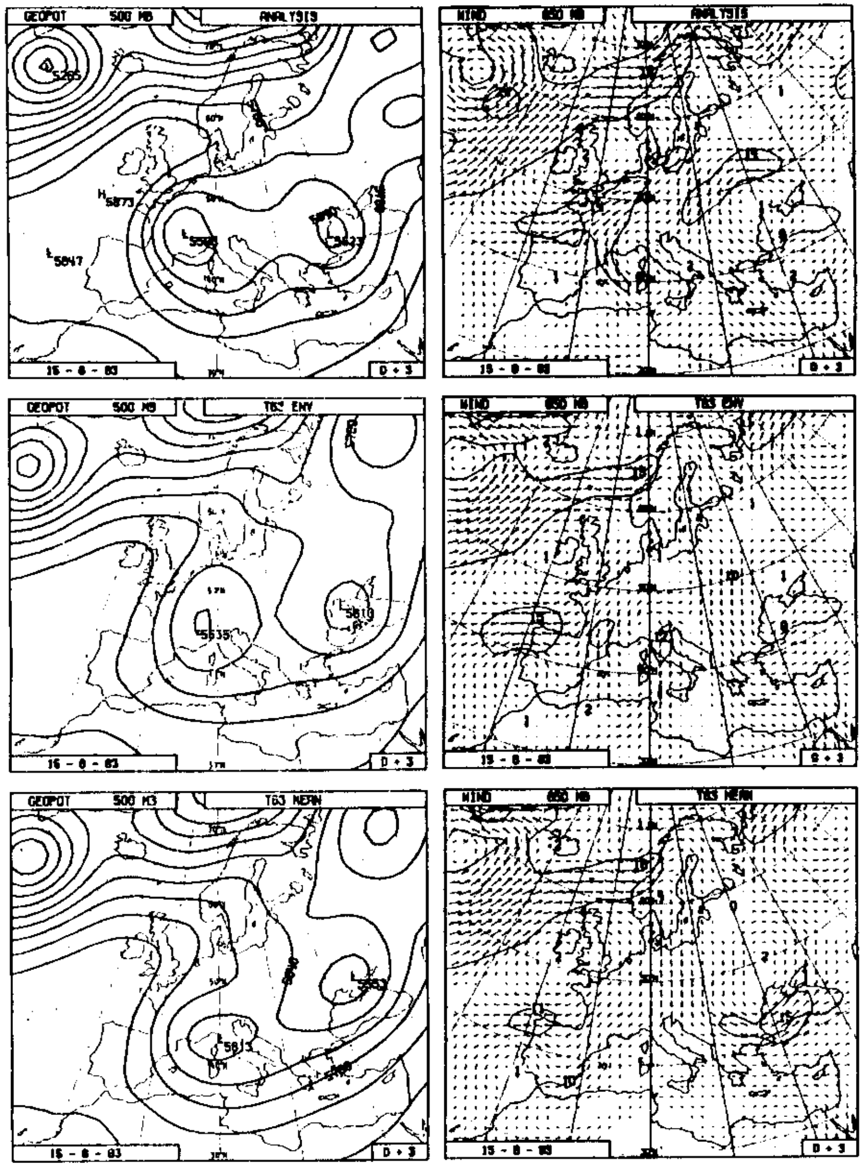

Fig. 7.12 Analyzed maps showing 500 hPa height (upper left, contour interval 6 dam) and 850 hPa wind (upper right, contour interval 10 ms^{-1}) for 18 June 1983. T63 forecasts from 15 June are also shown, for $\sqrt{2}\sigma$ envelope orography (middle) and mean orography (lower).

- Further results

Amongst other results, a beneficial tendency of the use of envelope orography was for lows to be located further to the north over Siberia, an example of which will be presented in the following section. However, some problems were seen at all seasons with the envelope representation of the Asian relief, in agreement with some earlier studies (Sumi and Kanamitsu, 1984; Dell'Osso and Chen, 1986). Ensemble- and time- averaged errors were generally reduced by use of the envelope, though not dramatically, and not at all locations.

Although most attention has been paid to investigating results for the Northern Hemisphere, some consideration has also been given to the sensitivity of forecasts for the Southern Hemisphere and the tropics. Not surprisingly, in the Southern Hemisphere, the sensitivity to the representation of orography is less at all model resolutions and seasons than found for the Northern Hemisphere. An exception is for the T21 resolution which appears anomalous in a number of spects 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. They were slightly larger in the Austral winter than in summer.

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

To relate these objective differences to a synoptic interpretation, one example over the southern Asia region is presented. Here the signal from objective verification was particularly clear, and the region was found by Krishnamurti et al.(1984) to be very sensitive to the use of an envelope orography. Fig. 7.13 presents day-2 forecasts of 850 hPa wind at T63 resolution for the 15 June 1984 case. Several features are slightly better simulated using the envelope, specifically the cyclonic curvature of the flow in the South China Sea, and over Burma, and a more accentuated trough south of Sri Lanka. The latter is consistent with a more substantial influence of the mountains in the southwest of India (the Western Ghats), as emphasized by Krishnamurti et al.(loc. cit.). However some features are worse with the envelope. The wind off the Somalian coast is too strong, and the same is true over southern China. This contributes to the different signal seen in the root mean square error.

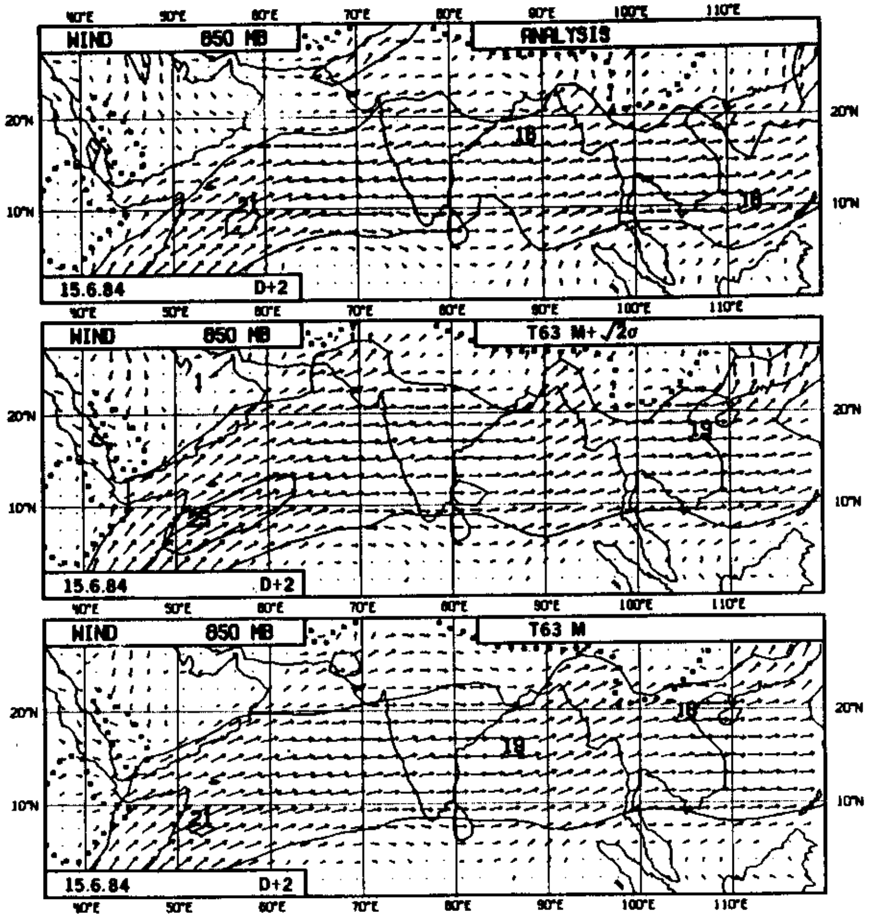

Fig. 7.13 Analyzed 850 hPa wind field for 17 June 1984 (upper) and D+2 T63 forecasts verifying on this date using envelope (middle) and mean (lower) orography.

7.4 ENVELOPE OROGRAPHY AND GRAVITY-WAVE DRAG

The results presented in the preceding section were obtained prior to the introduction of a parametrization of gravity-wave drag (Miller and Palmer, 1987). Some similarity between the impact of envelope orography and the impact of gravity-wave drag has already been illustrated for the model climatology in the preceding lecture. Objective verification of medium-range forecasts carried out using mean and (one standard-deviation) envelope orographies, and with and without gravity-wave drag, has shown that the best results were attained (at least at T106 resolution) by using a combination of envelope orography and the wave-drag parametrization developed by Miller and Palmer. This combination was chosen for operational forecasting. However, the verification also showed that the gravity-wave drag scheme had a larger beneficial impact when used with mean orography than when used with the envelope. It is of interest to examine this impact from a synoptic viewpoint.

The case chosen for illustration is one from the sequence of experiments discussed in the preceding section. The initial date is 15 October 1983, and the subsequent evolution of the model atmosphere reveals sensitivity to orography both in the position of a low over Siberia and in the development of a depression in the lee of the Alps (see Fig. 7.9). T106 resolution was used for the forecasts.

Maps of 500 hPa height for the two-day forecasts are presented in Fig. 7.14 for a region east of the Caspian Sea. The comparison of the mean- and envelope- orography forecasts carried out without gravity wave drag reveals the more northerly (and more correct) position of the low in the forecast with envelope orography discussed by Jarraud et al.(1986). Including the wave-drag parametrization with mean orography can be seen to result in a northward shift of the low, although it remains to the south of the position with envelope orography. Adding gravity-wave drag to the forecast with envelope orography gives a much smaller improvement.

Day-3 forecasts of the Mediterranean cyclogenesis are presented in Fig. 7.15. Here there is little sensitivity to the inclusion of gravity-wave drag, although it gives rise to a slight fall in surface pressure over southern Italy for both mean and envelope orography, thereby slightly increasing forecast accuracy in both cases. Sensitivity to the change from mean to envelope orography is more pronounced.

A larger impact of gravity-wave drag is seen in maps of 850 hPa wind for day 5 shown in Fig. 7.16. The change from mean to envelope orography results in a more westerly and more accurate position for the cyclonic centre over the Mediterranean. Including the parametrization of gravity-wave drag gives rise to a simliar shift in position. This occurs

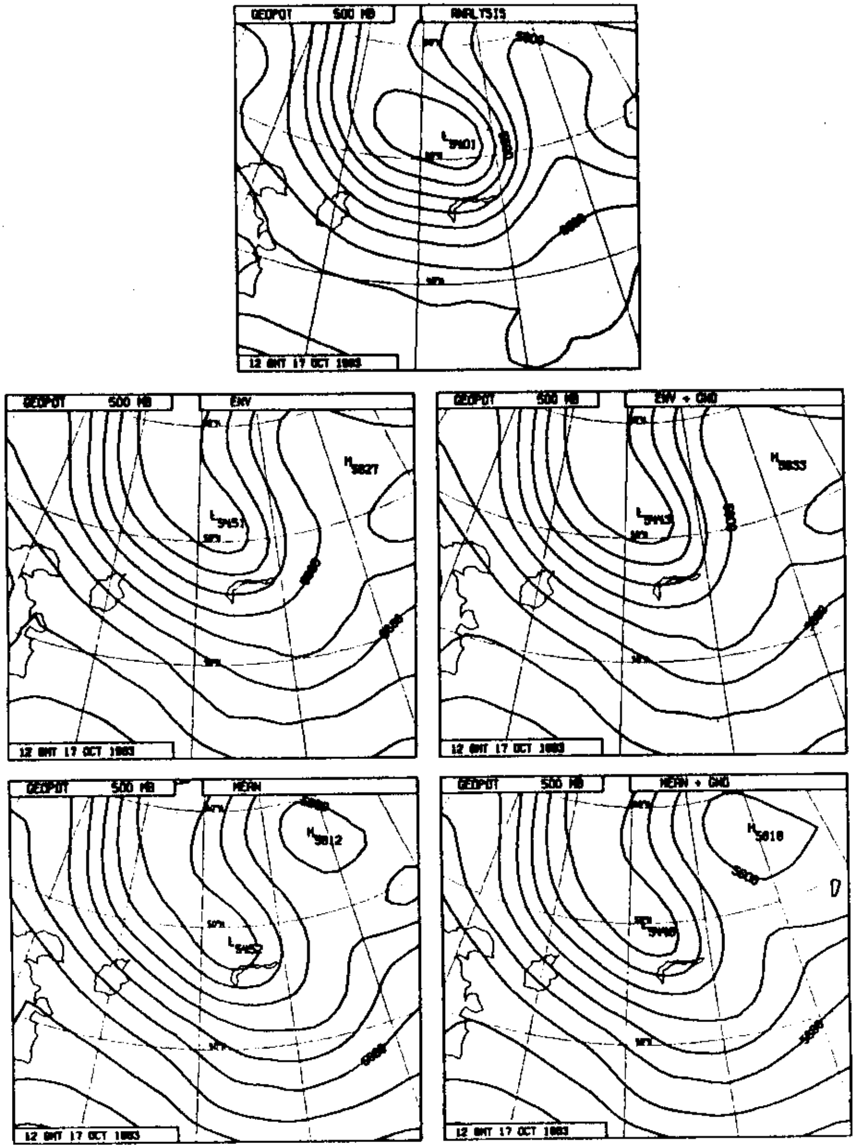

Fig. 7.14 The verifying analysis (upper) of 500 hPa height (contour interval 40 dam) east of the Caspian Sea for 17 October 1983, and 2-day forecasts with:

Middle left - envelope orography without gravity-wave drag
Middle right - envelope orography with gravity-wave drag
Lower left - mean orography without gravity-wave drag
Lower right - mean orography with gravity-wave drag

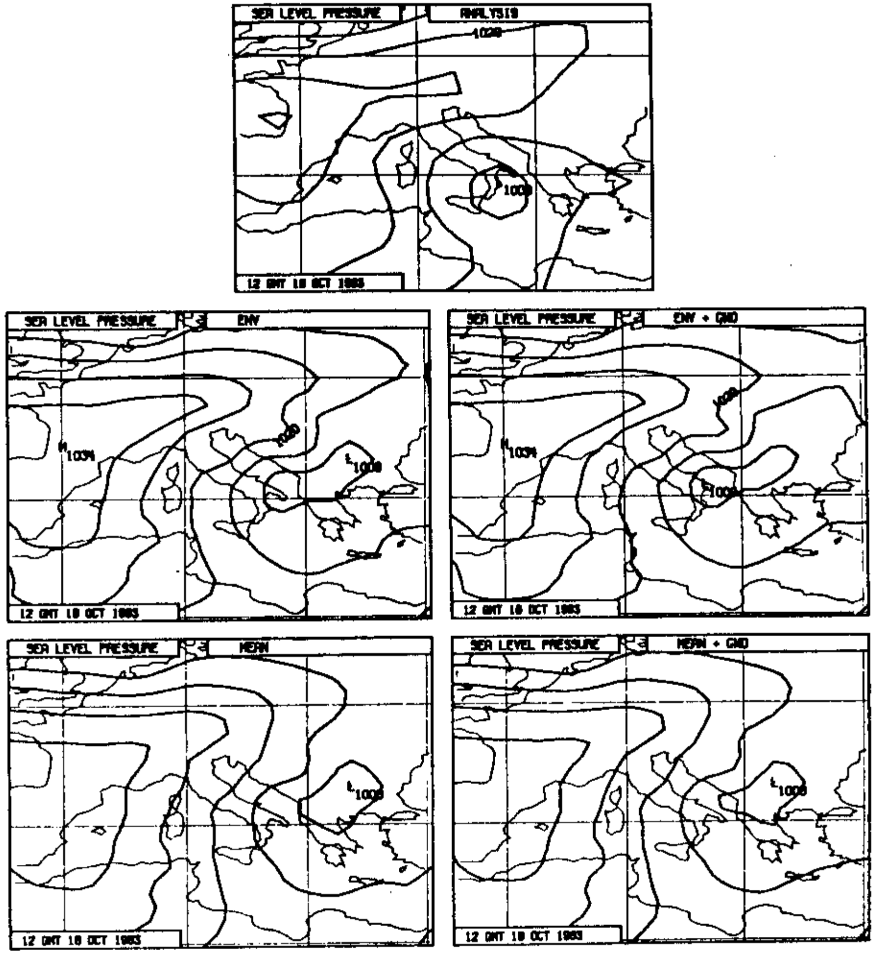

Fig. 7.15 The verifying analysis (upper) of mean sea-level pressure (contour interval 5hPa) for 18 October 1983, and 3-day forecasts with:

Middle left - envelope orography without gravity-wave drag
Middle right - envelope orography with gravity-wave drag
Lower left - mean orography without gravity-wave drag
Lower right - mean orography with gravity-wave drag

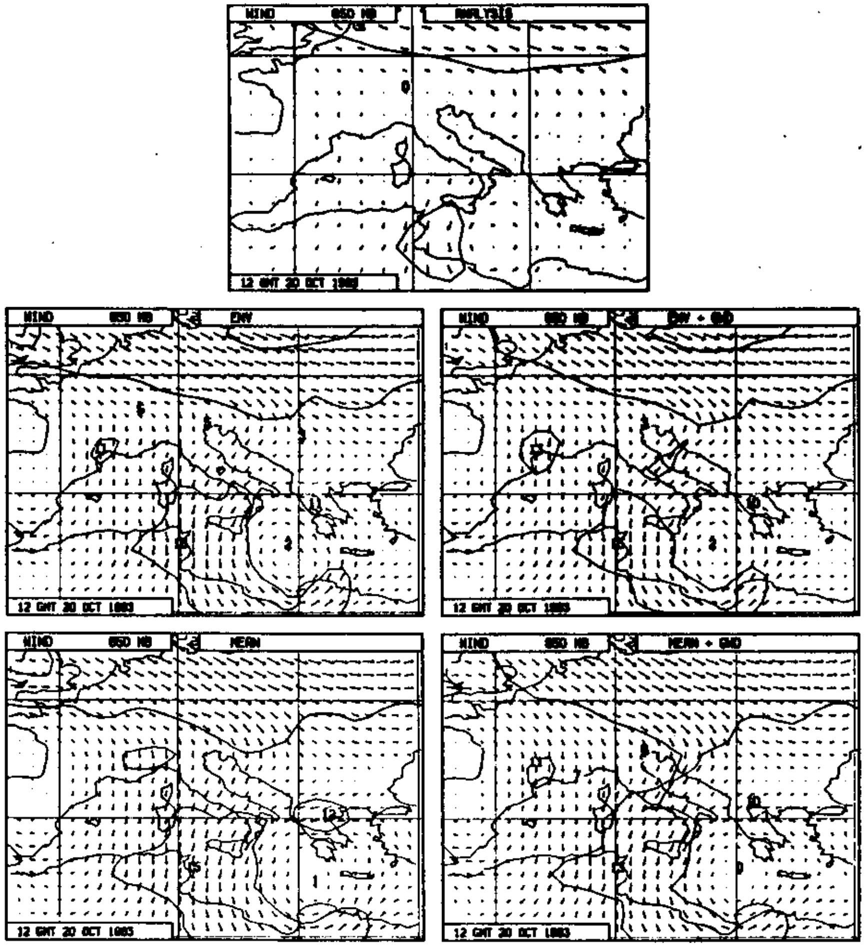

Fig. 7.16 The verifying analysis (upper) of 850 hPa wind (ms^{-1}) for 20 October 1983, and 5-day forecasts with:

Middle left - envelope orography without gravity-wave drag
Middle right - envelope orography with gravity-wave drag
Lower left - mean orography without gravity-wave drag
Lower right - mean orography with gravity-wave drag

for both orographies, with accuracy highest for the combination of envelope orography and gravity-wave drag. With mean orography the drag parametrization also results in a clear shift in the flow maximum over southern France from the southwestern Alps to the vicinity of the Golfe du Lion, and this gives a flow distribution rather close to that found with envelope orography and no gravity-wave drag. A forecast with mean orography in which the parametrization was changed so as to give a larger low-level component to the drag shows an even more apparent "barrier" effect of the Alps.

Synoptic assessment of other cases has led to generally similar results. This suggests that mean orography plus a parametrization that gives a larger low-level drag than does the current scheme could well give a better overall performance than the combination of envelope orography and gravity-wave drag. The ability to vary the amount of drag according to the direction of the low-level flow, the static stability, and the nature of the sub gridscale orographic variability may be crucial in this respect. At the time of writing a revision of the operational gravity-wave parametrization scheme which gives more low-level drag is close to implementation, and the comparison of mean and envelope orographies will shortly be re-examined.

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