SENSITIVITY OF THE OPERATIONAL ECMWF MODEL TO HORIZONTAL RESOLUTION

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Foreword: This paper is a summary of work done while the author was at ECMWF and will be the subject of a more complete ECMWF technical report produced with A. Simmons who has been actively involved in all aspects of the project.

Abstract: The sensitivity of the operational ECMWF model to horizontal resolution has been investigated in a series of 24 experiments spanning two years. Ten day forecasts have been produced once a month at T21, T42, T63 and T106 resolution. Results demonstrate the inability of the coarse T21 resolution to simulate some basic features of the atmospheric circulation. A clear synoptic improvement, in particular in summer, has been found in the medium range when going from T42 to T63 and further to T106. However no significant modification in the structure or intensity of the so called systematic errors has been observed when increasing the resolution beyond T42. Finally results from some 30 day integrations will be shown.

1. INTRODUCTION

Following the acceptance of a new computer (Cray X-MP/22) in 1983, a major experimental programme was carried out over a period of more than one year. The aim was to make appropriate choices of resolution, orography and other model parameters for a revised operational model which would make optimum use of the features of the new computer. However, it was recognised at the planning stage that this was an ideal opportunity to investigate more generally the sensitivity of forecast quality and model behaviour to horizontal resolution and the representation of orography. Experimental forecasts using mean and envelope orographies were thus carried out at T21 and T42 resolutions, at the (previous) operational T63 resolution, and the proposed T106 resolution. The lower resolution experiments have helped understand the higher resolution results and may provide a basis for future model developments, which in their initial experimental phase will typically involve forecasts at less than the full operational resolution. These experiments may also be of some more widespread relevance for general circulation modelling. The sensitivity of forecasts to the specification of orography at various horizontal resolutions has been investigated in some details by Jarraud et al (1986). This investigation has shown, as expected, a certain convergence as resolution was increased. It has also emphasized the need for a sufficiently fine resolution to treat properly the interactions between the flow and certain mountain ranges, particularly in summer. This paper will thus concentrate on a comparison of forecasts made with the same type of orography (a so-called "envelope") at various horizontal resolutions.

The impact of resolution has been demonstrated by several authors in cases of intense cyclogenesis (e.g. Dell'Osso, 1984, or Jones 1977) or in some remarkable simulations of blocking events (e.g. Miyakoda et al, 1983 for the 1 January 1977 case or Geleyn et al, 1982 for the 16 January 1979 case). Williamson (1978) compared the relative importance of accuracy, resolution and diffusion in a series of 5 day forecasts from 11 January 1973 and found a convergence of solutions with increased resolution as well as a marked sensitivity to horizontal diffusion.

Very few controlled comparisons have been reported using larger samples and models with a comprehensive physical package: Jarraud et al (1981) in a series of seven 10 day forecasts from February 1976 comparing a grid point model and two spectral models using triangular truncations at wavenumber 63 (T63) and 42 (T42) found a mean improvement of 12 to 24 h in predictability of T63 over T42.

The results presented here are from a much larger sample of 24 cases drawn from all seasons over a period of two years. The experimental programme will be described in the following section. It will be followed by an evaluation of the results in the Northern Hemisphere (Section 3). Some results for the Southern Hemisphere and the tropics will be presented in Section 4 and the mean (systematic) errors will be discussed in Section 5.

Finally the sensitivity of a remarkable extended range (30 day) forecast to resolution will be presented in Section 6.

2. DESIGN OF THE EXPERIMENTAL PROGRAM

To try to increase the significance of our results it was decided to select as wide a range of situations as possible. 24 cases were thus chosen, namely the 15th of each month from May 1983 to April 1985.

Forecasts for all 24 cases were carried out with the ECMWF spectral model described in Simmons and Jarraud (1984) using four different triangular truncations for the horizontal resolution: T21, T42, T63, T106.

It would have been quite impractical to perform data assimilation for all cases and resolutions; thus in each case initial conditions were based on the operational T63 analyses. For T106 the upper air fields were obtained by projecting the T63 spectral components on the associated T106 Gaussian grid, then replacing the orography with a new envelope recomputed at T106 resolution followed by a vertical interpolation to the new set of vertical coordinate surfaces. Finally a spectral fit of the fields was performed. Upper air fields, surface pressure and orographies for the T42 and T21 experiments were obtained directly by truncation of T63 fields. 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 verifications, inevitably introduces some bias in favour of T63 but available evidence (from extra experiments not reported here) indicates that this is not enough to invalidate the conclusions presented here. However, the use of T63 surface fields means that these cases cannot be used to gain a comprehensive picture of the influence of higher resolution on forecasts of surface and near surface parameters.

For each particular initial date the same model parameters and parameterisations of subgrid scale processes were used for all resolutions with the exception of the horizontal diffusion (∇^4) coefficients: T63, T42, and T21 forecasts all used the operational T63 values of $2\text{x}10^{15}\text{m}^4\text{s}^{-1}$ for vorticity, temperature and humidity and $2\text{x}10^{16}\text{m}^4\text{s}^{-1}$ for divergence. For T106 the value $1\text{x}10^{15}\text{m}^4\text{s}^{-1}$ was chosen for all variables for the first 19 cases. The coefficients for divergence was subsequently increased to $2.5\text{x}10^{15}\text{m}^4\text{s}^{-1}$ for the final five cases, in order to avoid generation of spurious centres of vertical motions (grid point storms) associated with the convection scheme. The general impact was tested in a few selected cases and was otherwise found to be small enough, not to affect the results shown in the paper.

3. NORTHERN HEMISPHERE RESULTS

3.1 Objective evaluation

Since the quality of forecasts in the Northern Hemisphere exhibits a strong seasonal variation, it was decided to split the two year sample into two groups: one comprising November to April forecasts and defined as winter, and the other one (May to October) defined as summer. Fig. 1 displays anomaly correlation scores for the 500 hPa height field for winter and summer, and a clear progression can be seen in both seasons when going from T21 to T106. As expected there is a much larger improvement of T42 over T21 than of T63 over T42 and further of T106 over T63. This tendency for convergence at higher resolutions does not imply that the forecast differences between T63 and T106 are small throughout the forecast range, but rather that what can be quite large differences later in the range are not systematically in clear favour of the higher resolution. More systematically favourable results at this range may be obtained as other sources of errors, particularly in the data assimilation and parameterisation of subgrid scale processes, are reduced. The improvement of T106 over T63 is larger in summer than in winter and this can be in part explained by the results presented in Jarraud, Simmons and Kanamitsu (1986) which showed a better performance of the envelope orography in summer at T106 resolution. Although these objectively measured mean improvements of T106 over T63 are small compared to total mean errors, they are nevertheless larger than the net improvement found when an envelope rather than mean orography is used at T106 resolution (Jarraud et al, 1986). They are also significantly larger than those observed when comparing a spectral (T63) model and a grid point (N48) model (Girard and Jarraud, 1982). It is also clear from Fig. 1 that summer differences between T63 and T42 culminate around day 5, while those between T63 and T106 reach their maximum only around day 8. This might indicate that at T42 resolution the truncation errors contribute significantly to the total error in the medium range while at T106 it is important to reduce in parallel other sources of error. Similar results (not shown) have been obtained at 1000 hPa. Standard deviations of 500 hPa forecast height field (Fig. 2) from the corresponding analyses present results in a slightly different light: initially there is a large error at T21 (and to a lesser extent at T42) which is considerably reduced on day 1/2. This is associated with the procedure used to obtain initial data: after having reduced the horizontal resolution from T63 to T21 as explained in the previous section, the upper air fields were not reinitialised and so large amplitude gravity waves were generated. Another point worth mentioning is the behaviour of T42 in the later part of the 10 day range - particularly in winter it has the smallest standard deviation beyond day 7, despite having a much larger value than T63 or T106 between days 2 and 5. As we will also see in the synoptic evaluation, this apparently good behaviour is the result of a less structured flow at this range. Conversely, T106, exhibits sharper and stronger features until the end of the 10 day range, and also has slightly worse standard deviation scores by then. At shorter range, results of standard deviation and anomaly correlation scores are in better agreement and as illustrated in Fig. 3 the improvement due to resolution is almost systematic up to days 5 or 6.

3.2 Synoptic assessment

The synoptic assessment has revealed a number of cases in which an increased resolution had a large beneficial impact for a particular feature and also a few situations where it led to a deterioration. Rather than giving detailed synoptic descriptions of selected cases, we shall try to isolate typical situations which are sensitive to the horizontal resolution and to illustrate

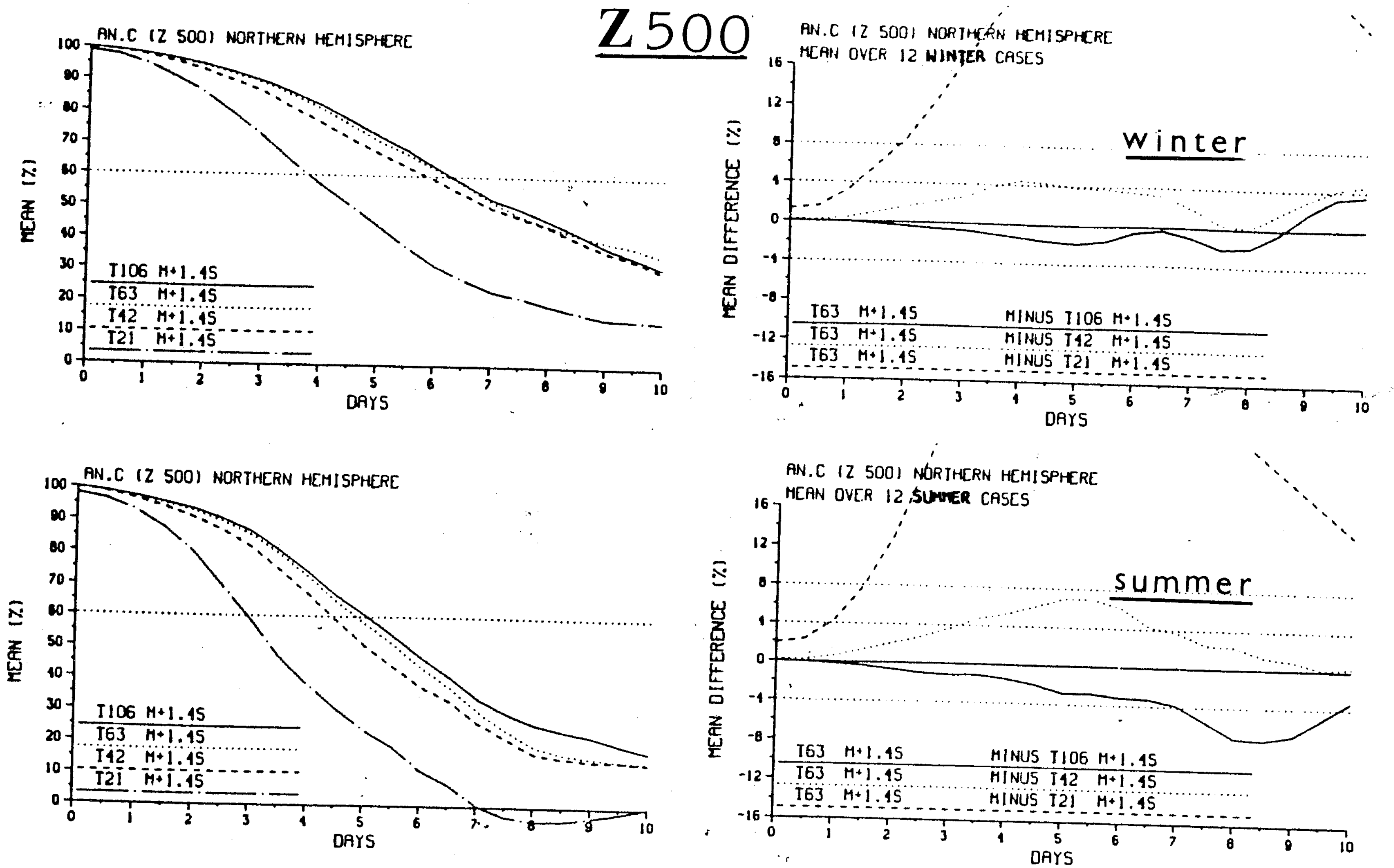


Fig. 1 Mean anomaly correlation of 500 hpa height forecasts in the Northern Hemisphere (20-90°N) (left) and mean differences between T63 and other resolutions (right) for 12 winter cases (upper) and 12 summer cases (lower).

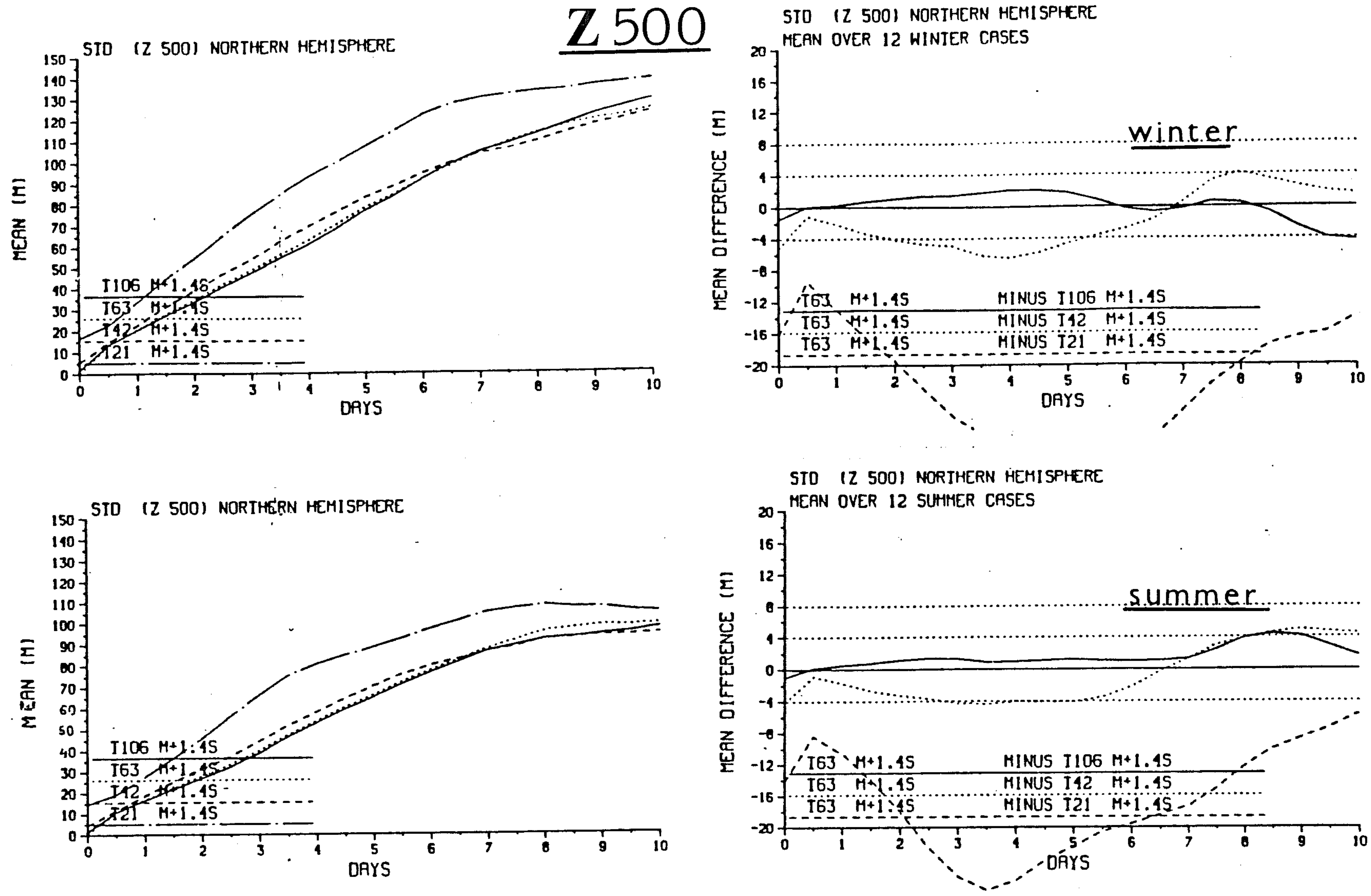
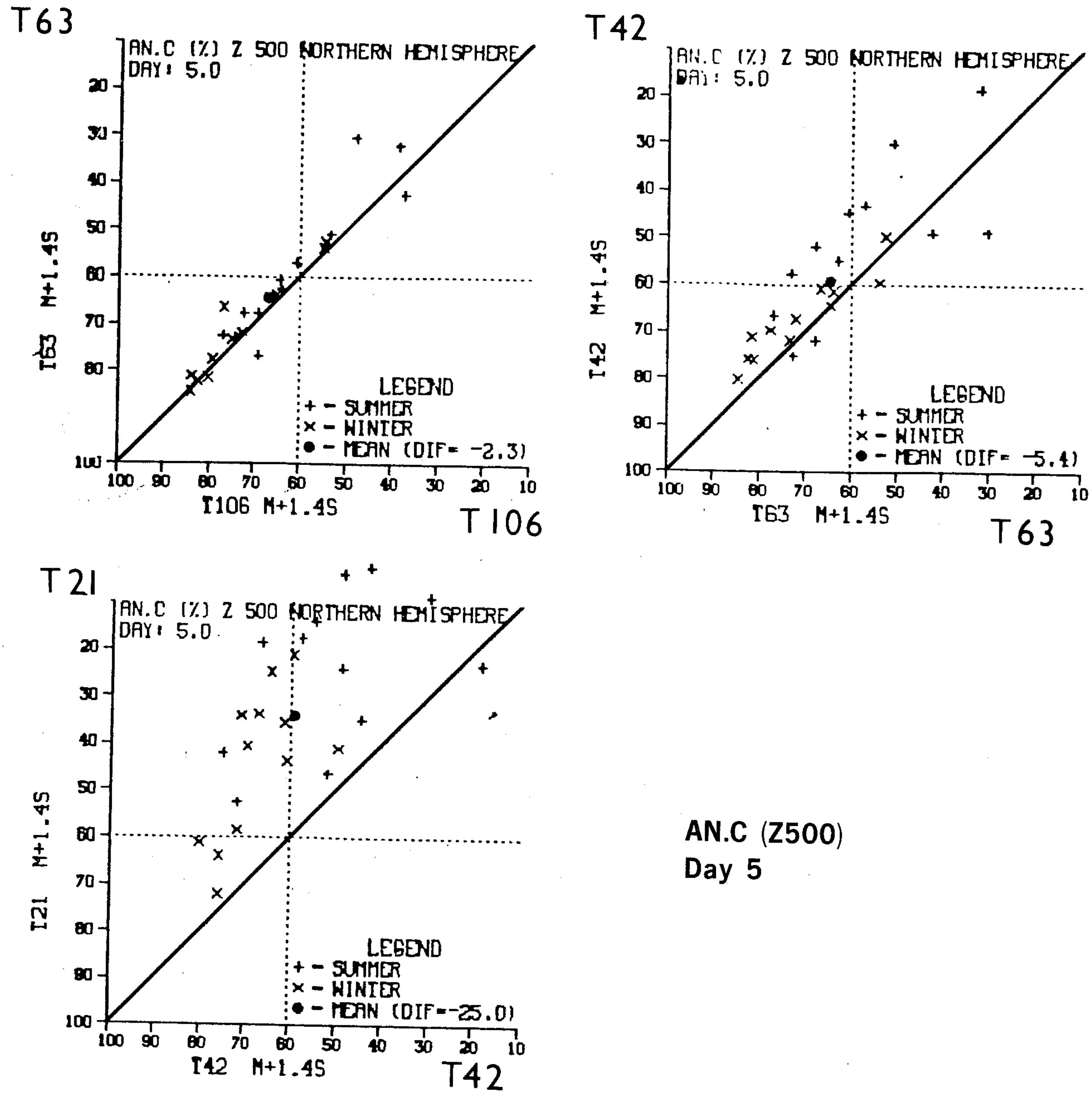


Fig. 2 As Fig. 1 for standard deviations of 500 hpa height forecasts.



AN.C (Z500)
Day 5

Fig. 3 Scatter diagrams of D+5 anomaly correlation for 500 hpa height field comparing T106 to T63 (upper left), T63 to T42 (upper right) and T42 to T21 (lower).

them with appropriate examples; most of the comparison will be between T106 and T63 forecasts.

3.2.1 Cut off lows

In an extensive comparison between the ECMWF spectral (T63) and grid point (N48) model, Girard and Jarraud (1982) found a slightly worse treatment of cut off lows by the grid point model, in particular over southern Europe. This was attributed to a coarser effective resolution (~T53). It is also worth mentioning that these situations are often crucial for southern Europe and are generally considered to be difficult for numerical models to handle. The present assessment has confirmed that the formation, movement and filling of cut-off lows is sensitive to the horizontal resolution.

As an example Fig. 4 shows 4½ day forecasts of the 500 hPa height field over Europe at T63 and T106 from 15 May 1984, together with the corresponding verifying analyses. T106 clearly produces a better forecast of the position of the cut-off low over Spain (as well as a slightly better position of the low to the north-west of Ireland), there was also a large difference in the associated precipitation forecasts over Spain and France with the T106 superior to the T63 (not shown). Similar remarkable differences have also been observed on a few occasions in other locations (for example over the Pacific).

On most occasions when a cut-off occurred beyond day 2, T21 was unable to predict its development and even forecasts at T42 were often much less accurate than these at T63.

3.2.2 Fast developing lows

In Jarraud et al (1986) it was shown how a forecast of Mediterranean cyclogenesis was enhanced, even at T106 resolution by the use of an envelope type orography. The same case discussed in the previous section (15 October 1983) is considered here since it is the clearest example of such a cyclogenesis in our 2 year sample. Fig. 5 displays day 4 forecasts of 500 hPa height over the European area at T21, T42, T63 and T106 resolutions, all using an envelope orography. T21 is unable to simulate the cyclogenesis. All higher resolutions develop the low, but the position is much better (that is

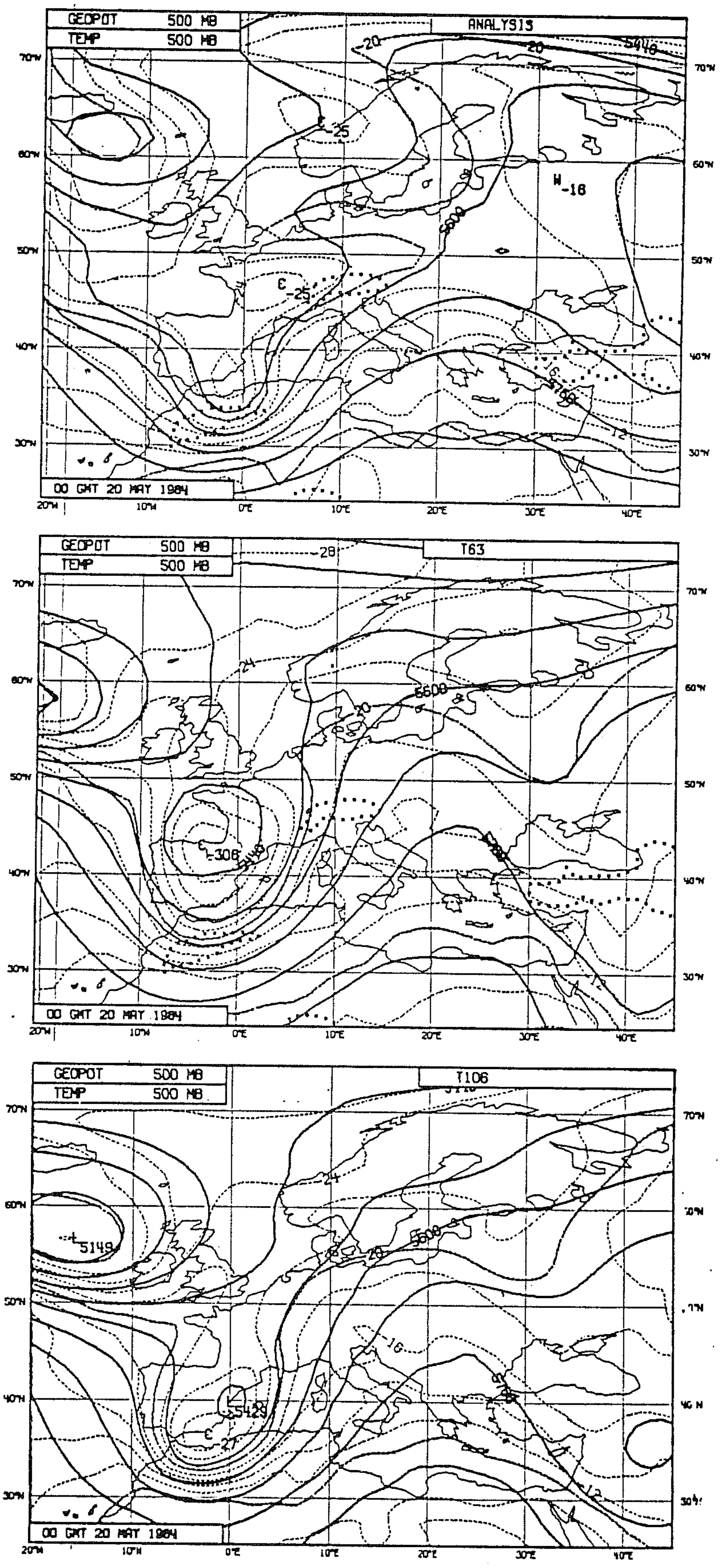


Fig. 4 Analysed 500 hpa height and temperature fields for 20 May 1984 over Northern Atlantic and corresponding T63 and T106 D+4½ forecasts using a ($\sqrt{2}\sigma$) envelope.

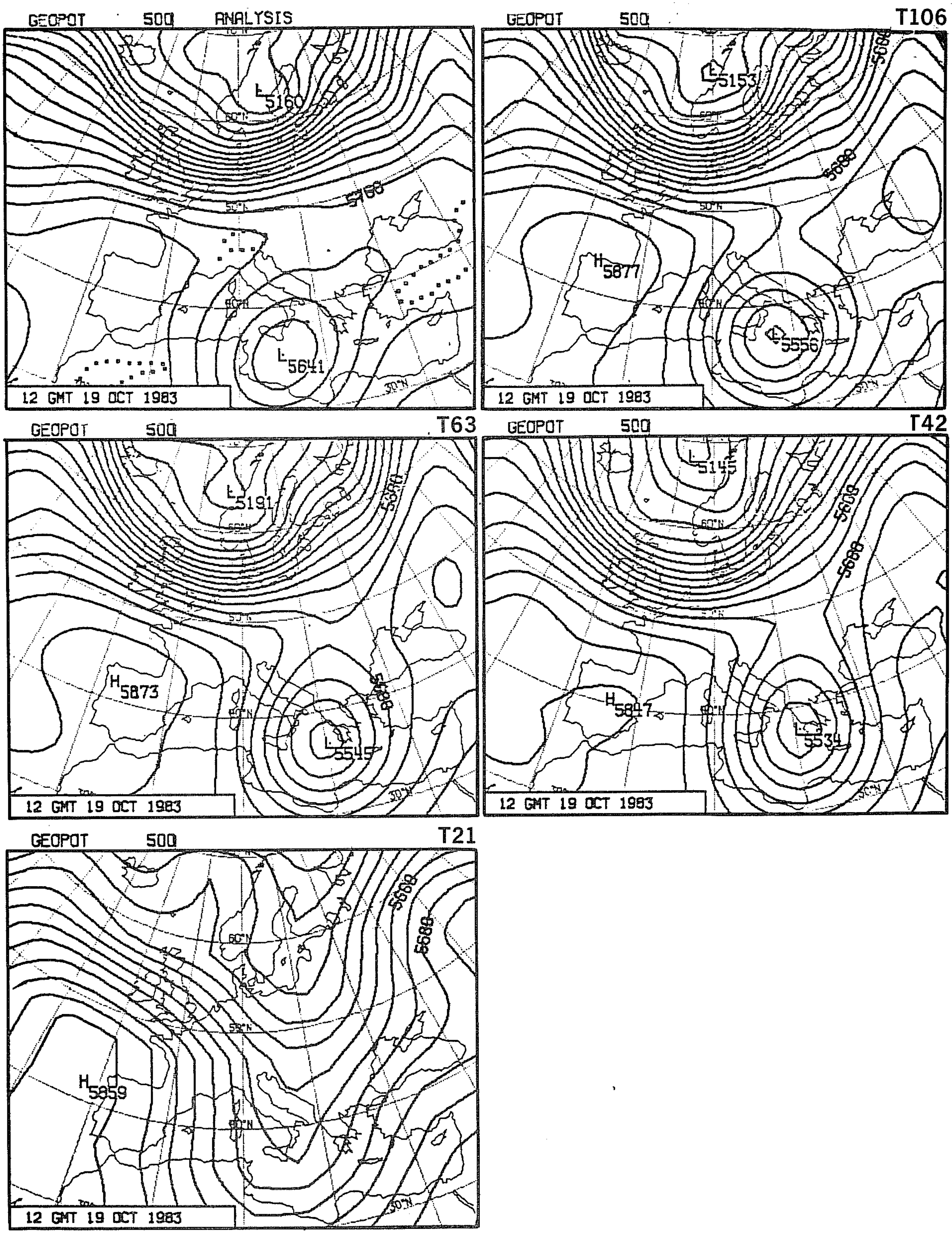


Fig. 5 Analysed 500 hpa height field for 19 October 1983 over Europe (upper left) and corresponding day 4 forecasts by T106 (upper right), T63 (middle left), T42 (middle right) and T21 (lower).

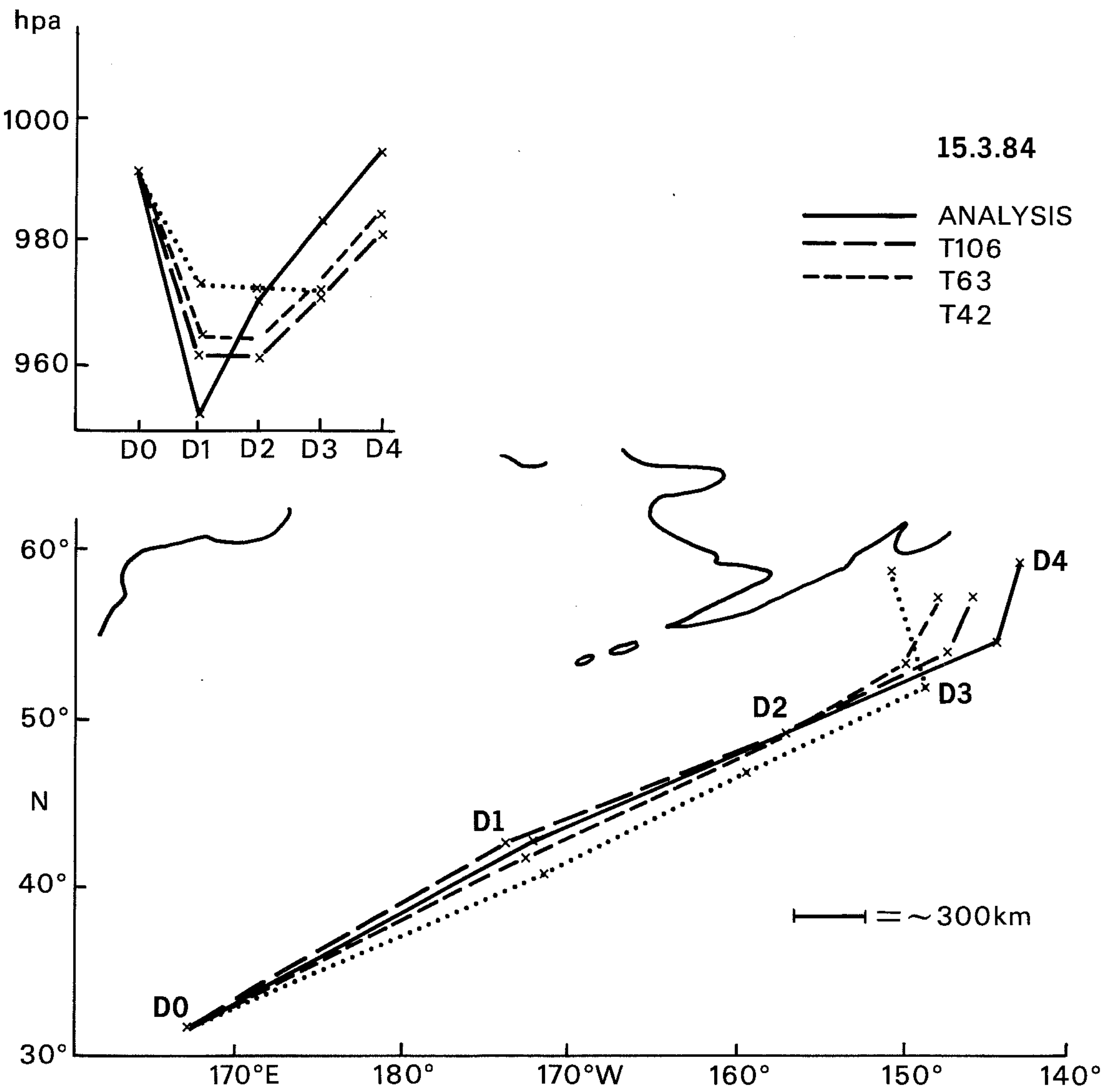


Fig. 6 Upper: Analysed mean seal level pressure at the centre of a Pacific low between 15 and 19 March 1984 and corresponding day 1 to day 4 forecasts by T42, T63 and T106.
Lower: Analysed and forecast tracks for the same low.

further west) simulated at T106 than by either T63 or T42. One can also note a slight tendency at T42 to produce a weaker north-south gradient over northern Europe. This is even worse at T21.

Several other cases of rapidly developing lows were found in the sample. A moderate but significant and almost systematic improvement in the intensity and position of lows was observed in the early forecast stages but with a risk of over developing erroneous systems at a later stage.

Fig. 6 displays the evolution of such a fast developing low in the 15 March 1984 case. As can be seen from the evolution of the depth of the low the quick initial deepening (day 0 to day 1) captured by the analysis is progressively better simulated as resolution is increased, although the models have difficulty in filling it fast enough. Similar results can be seen for the track. As already mentioned, the situation is less clear beyond days 4 or 5 since small scale lows are much less accurately forecast and the prediction of deeper systems at T106 can lead to worse objective scores, as found in a detailed synoptic assessment of the two cases which exhibit the poorest objectively measured Northern Hemisphere performance at T106 relative to T63.

3.2.3 Complex low systems

Generally, it has been found that in cases where secondary waves are developing, or where complex low systems with more than one centre are present, T106 resolution is better able to emphasize the active centre, whereas T63 to a certain extent and T42 to a much larger extent tend either to merge the various systems, or to develop the wrong one. Fig. 7 displays an extreme example for the 15 January 1984 case. Comparing the day 6 forecasts at T42, T63 and T106, it can be seen that the complex structure over the Atlantic is completely missed at T42. The situation is slightly better at T63, but only at T106 is there success in simulating the Atlantic outbreak over southern France and the cut off low near the British Isles associated with a northerly flow over the Greenwich Meridian. It also produces a more useful forecast of the north Pacific depression. Despite all this, the T106 objective scores (in terms of both anomaly correlations and standard deviations) were not higher than those for T63 or T42 at this stage, confirming that they should be used with some care: they were adversely

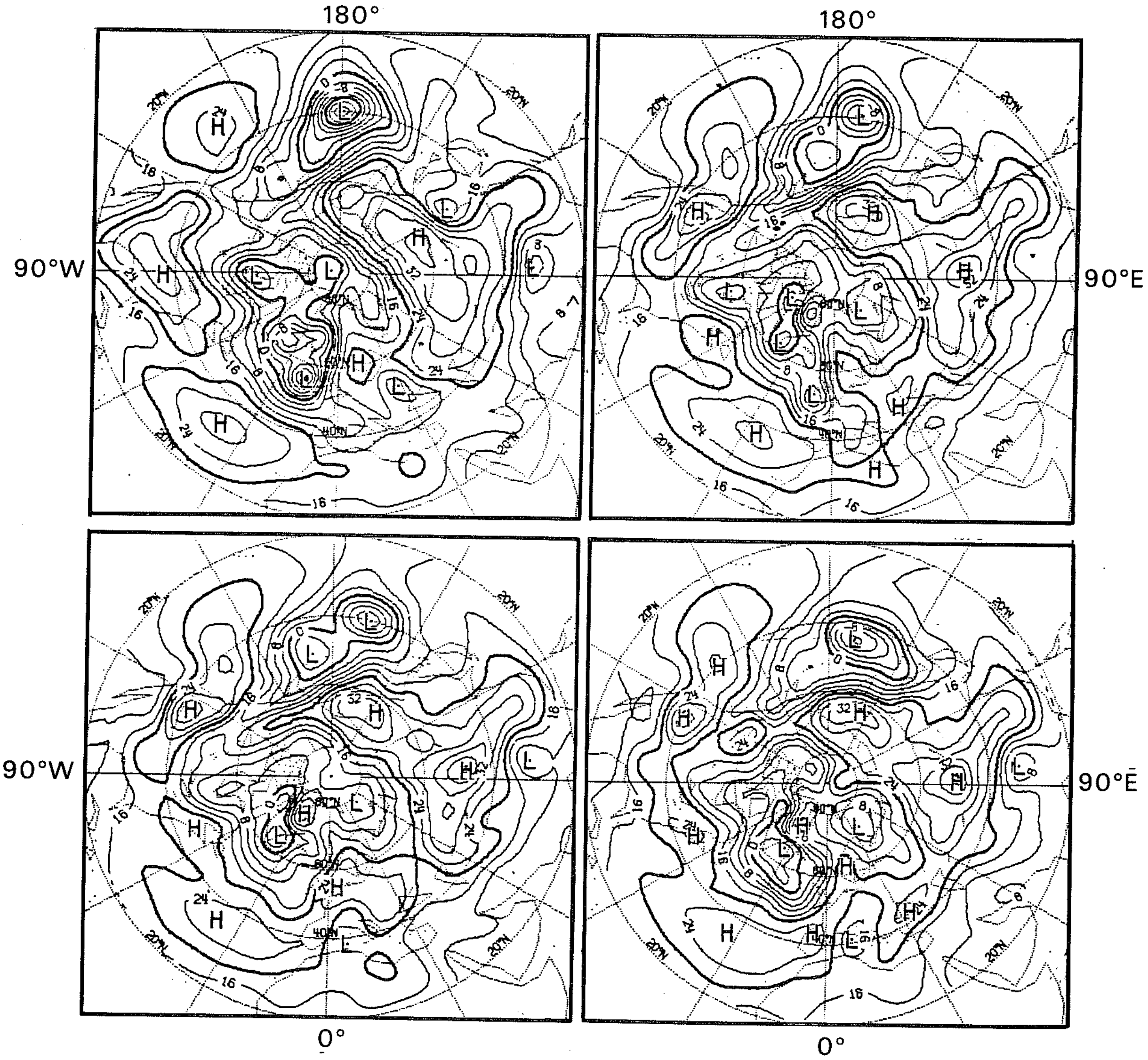


Fig. 7 Analysed 1000 hpa height field for 21 January 1984 (upper left) and corresponding day 6 forecasts by T106 (upper right), T63 (lower left) and T42 (lower right).

affected by the position of the cut off near Ireland which, despite being more informative, was forecast slightly too much to the west, and also by the trough towards eastern Siberia and the low 'under' the Tibetan Plateau being too weak.

3.2.4 Differences over Eastern Asia

Objective verifications were performed over a number of selected areas in the Northern Hemisphere, and an almost systematic improvement of T106 over T63 was found in an area covering much of China and Japan. An illustration of this is given in Fig. 8 which shows a day 7 forecast of 500 hPa height at T106 and T63 for the 15 April 1984 case. As on several other occasions the T63 forecast predicts a trough over Japan extending further south than for T106. An extra experiment was run at T63 using a mean orography which significantly improved the trough over Japan and brought the T63 forecast into slightly closer agreement with that at T106. Amongst the other differences worth noting is the spurious cut-off near the date line.

3.2.5 European blocking

It has already been shown (Tibaldi and Ji, 1983) that horizontal resolution can be crucial in the simulation of a European block; this was confirmed by the 15 March 1984 case (Fig. 9). The block is quite accurately forecast at T106 in the day 5 to day 10 range, and much less so at T63. For T42 and T21 it is even worse with no indication remaining of the cut-off over Finland. In Jarraud et al (1986) the role of the East Canadian mountains for a proper simulation of the block was demonstrated, and in order to check how much of the improvement of T106 over T63 was due to the better definition of mountains, it was decided to run a T106 forecast using the T63 mountains. The result is shown in Fig. 9 and it is very close to the T106 forecast using T106 mountains (the main difference is in the intensity of the Atlantic cut-off). Thus, in this case, the better simulation at T106 is mostly due to the extra degrees of freedom available during the course of the integration (the initial data have only a T63 resolution) and not to the indirect effect of resolution through a more accurate representation of orography.

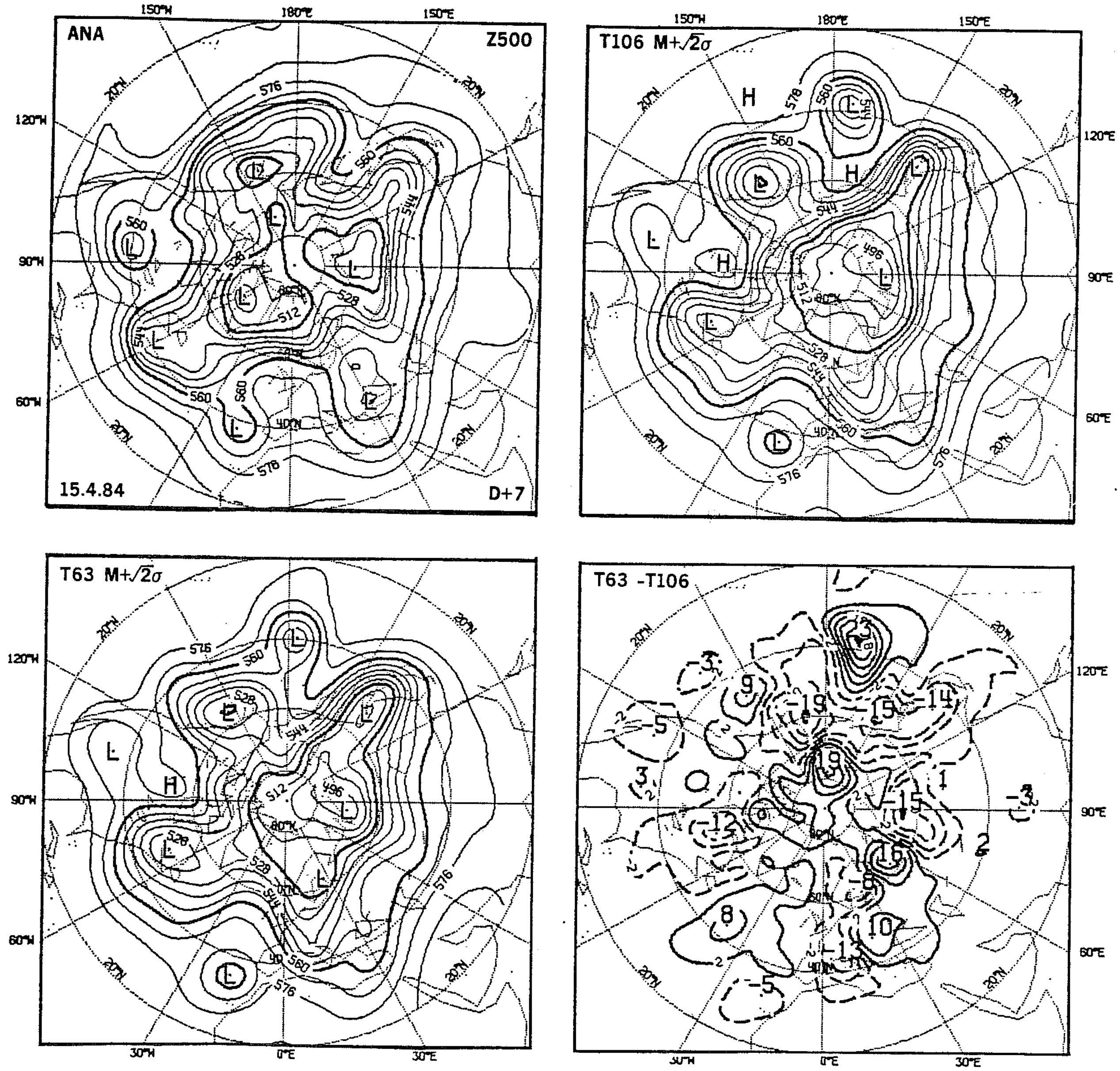


Fig. 8 Analysed 500 hpa height field for 22 April 1984 and corresponding D+7 T106 and T63 forecasts together with the associated difference map.

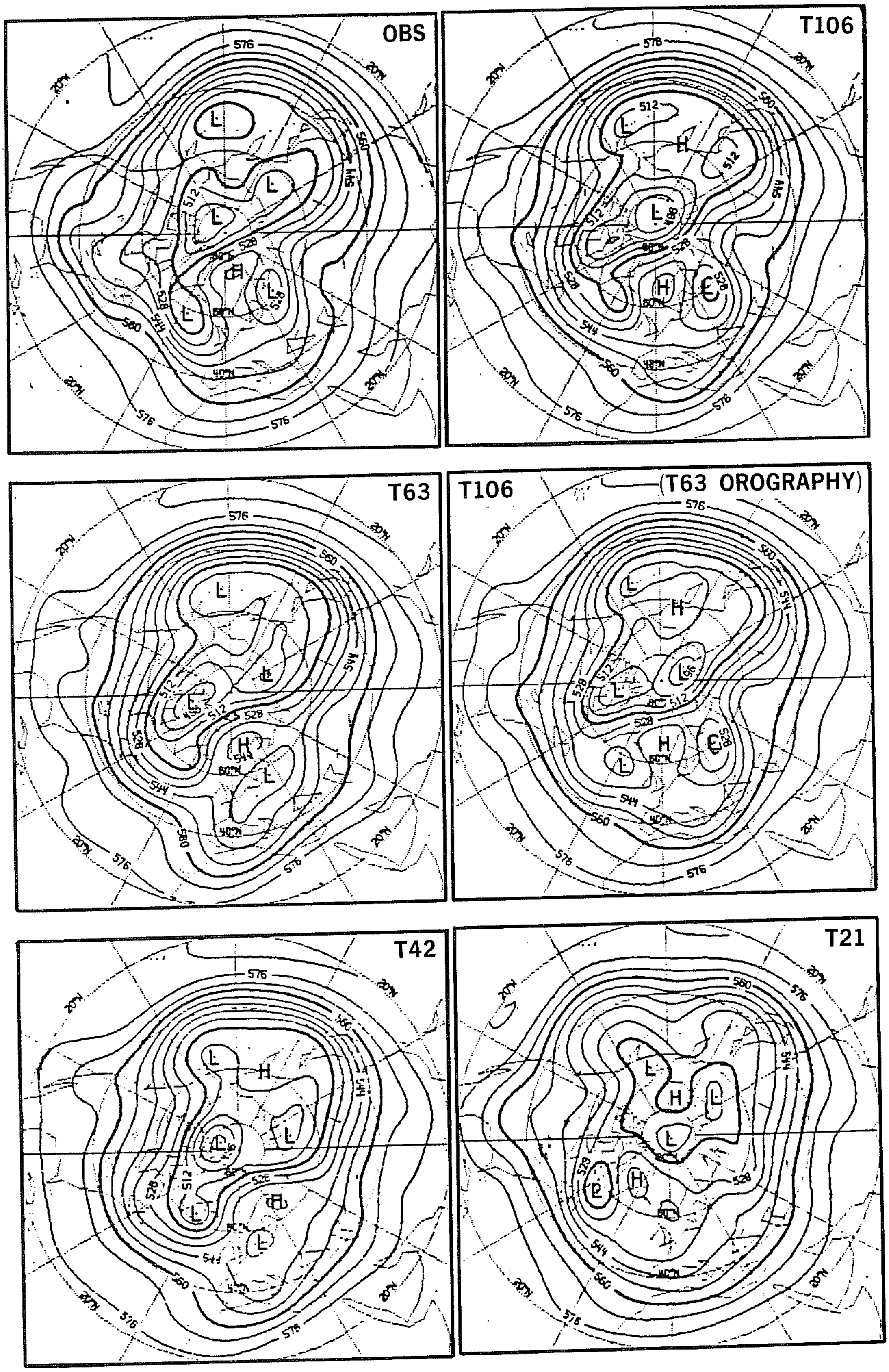


Fig. 9 Mean analysed 500 hpa height averaged between 20 and 25 March 1984 (upper left) and corresponding mean day 5 to day 10 forecasts by T106 (upper right), T63 (middle left), T42 (lower left) and T21 (lower right). In addition a T106 forecast using T63 mountains is shown in the middle right panel.

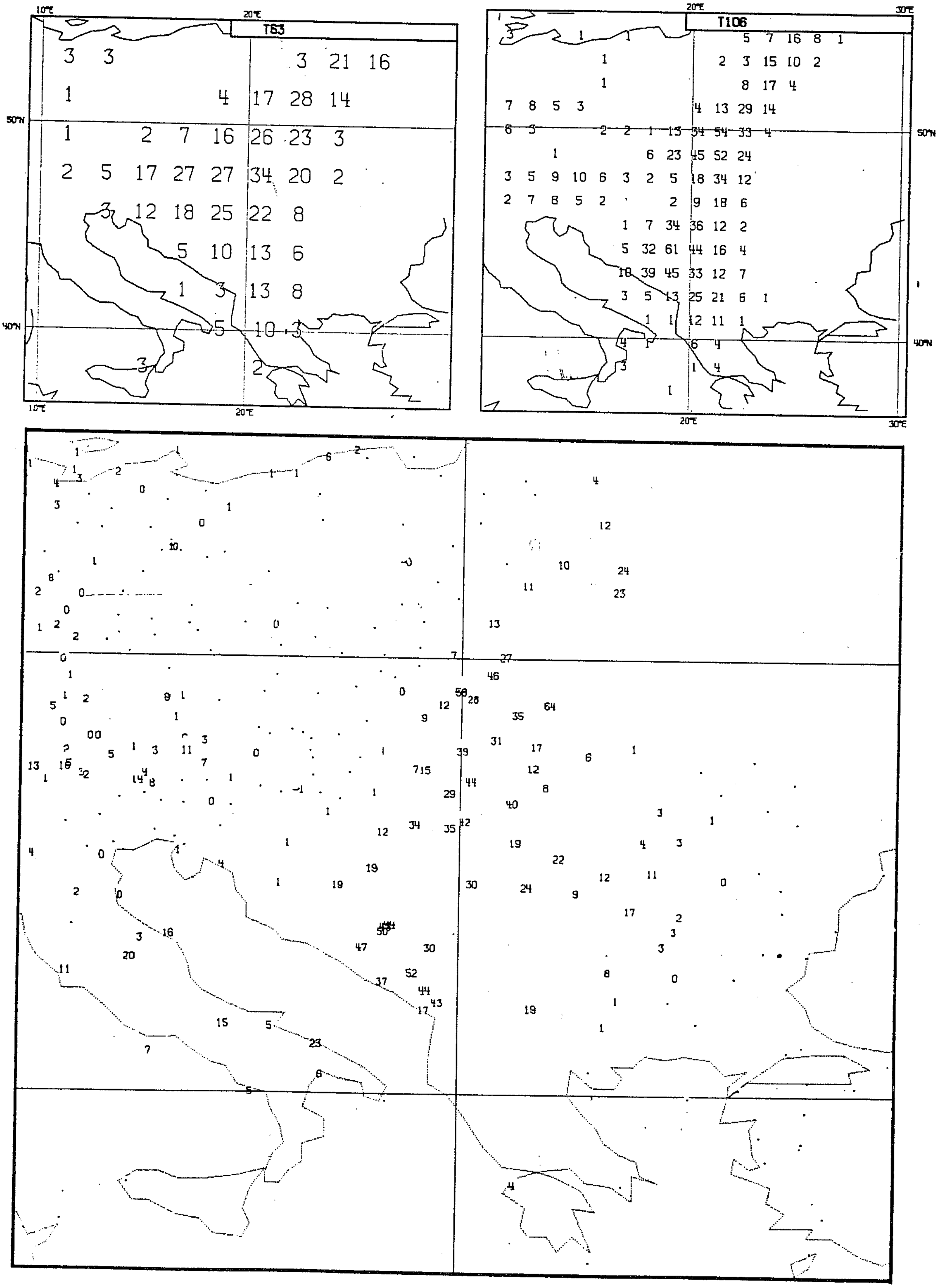


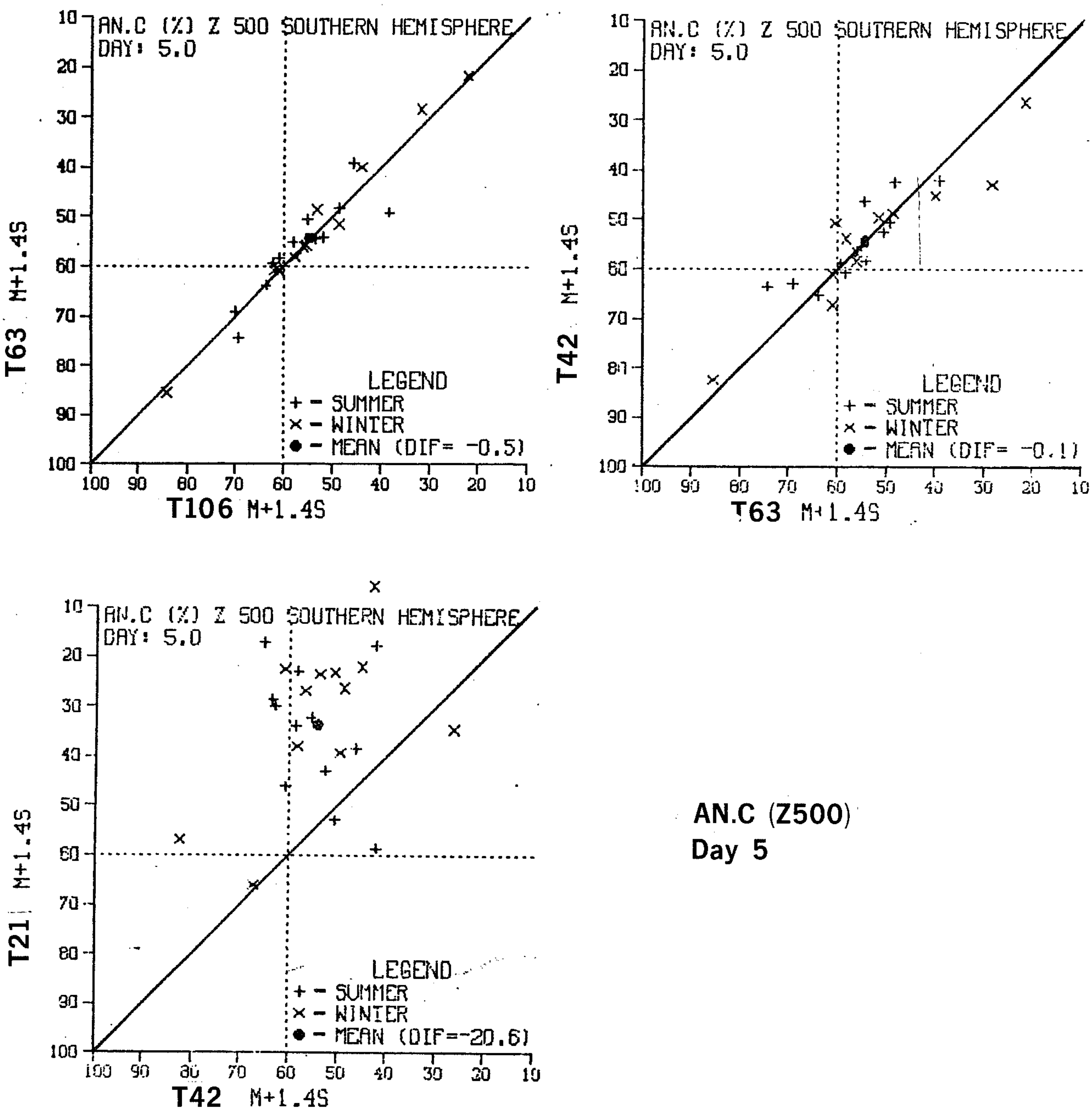
Fig. 10 Precipitation totals (mm) between days 2 and 3 of T63 (upper left) and T106 (upper right) forecasts from 15 September 1983, and corresponding observed values (lower map). Forecast values are plotted at each grid point where the precipitation exceeded 1 mm. Observations of no precipitation are represented by a dot, and a zero denotes that a trace was observed.

3.2.6 Forecasts of near surface fields

Small improvements in synoptic scale forecasts coupled with a finer description of the orography often combined to yield pronounced improvements in precipitation patterns or in near surface wind. An illustration of this is given in Fig. 10. Accumulated precipitations between days 2 and 3 for T63 and T106 forecasts from 15 September 1983 are displayed together with corresponding observed values, observations of no rain being denoted by a dot. T63 produces only one zone of heavy rain centred over Hungary and extending well over Austria, Yugoslavia and Poland. T106 on the other hand forms two main centres of heavy rain, and a less widespread distribution in good agreement with the observations. This is closely related to the better separation of the Carpathian Mountains and Dinaric Alps at T106 (at T63 resolution they form a single broad mountainous area.) Both forecasts failed to predict the showery rainfall observed over Italy. The superior ability of the T106 model in forecasting separate centres of rain was observed on many occasions. However, the amount of precipitation was sometimes over estimated, possibly in connection with the weaker horizontal diffusion used at T106, in particular for divergence. It should also be emphasized that verification of rain forecasts was done mostly over Europe where there is a reasonably dense and reliable network of observations. Thus little is known about the impact of horizontal resolution for large scale or convective rain over oceanic regions. However, on several occasions, clouds associated with frontal structure could be compared with satellite pictures which showed a distinct sharpening of fronts at T106 (often an improvement) and better simulation of occlusions. Finally it should be stressed that precipitation forecasts (even at T106) proved rarely useful over Europe beyond day 5 since even a small error in the large scale forecasts can induce very different interactions with the mountains.

4. RESULTS IN THE SOUTHERN HEMISPHERE AND THE TROPICS

In the Southern Hemisphere, the mean impact of resolution on the objective verification of forecasts is small for all resolutions above T42 as can be seen in the scatter diagrams presented in Fig. 11. The spread across the diagonals is somewhat smaller than shown in Fig. 3 for the Northern Hemisphere, suggesting a smaller sensitivity to resolution, but the main difference is that improvements due to resolution are largely systematic up to day 5 in the Northern Hemisphere, whereas resolution differences above T42 do not lead to systematic improvements in the Southern Hemisphere. This result



AN.C (Z500)
Day 5

Fig. 11 As Fig. 3 for Southern Hemisphere.

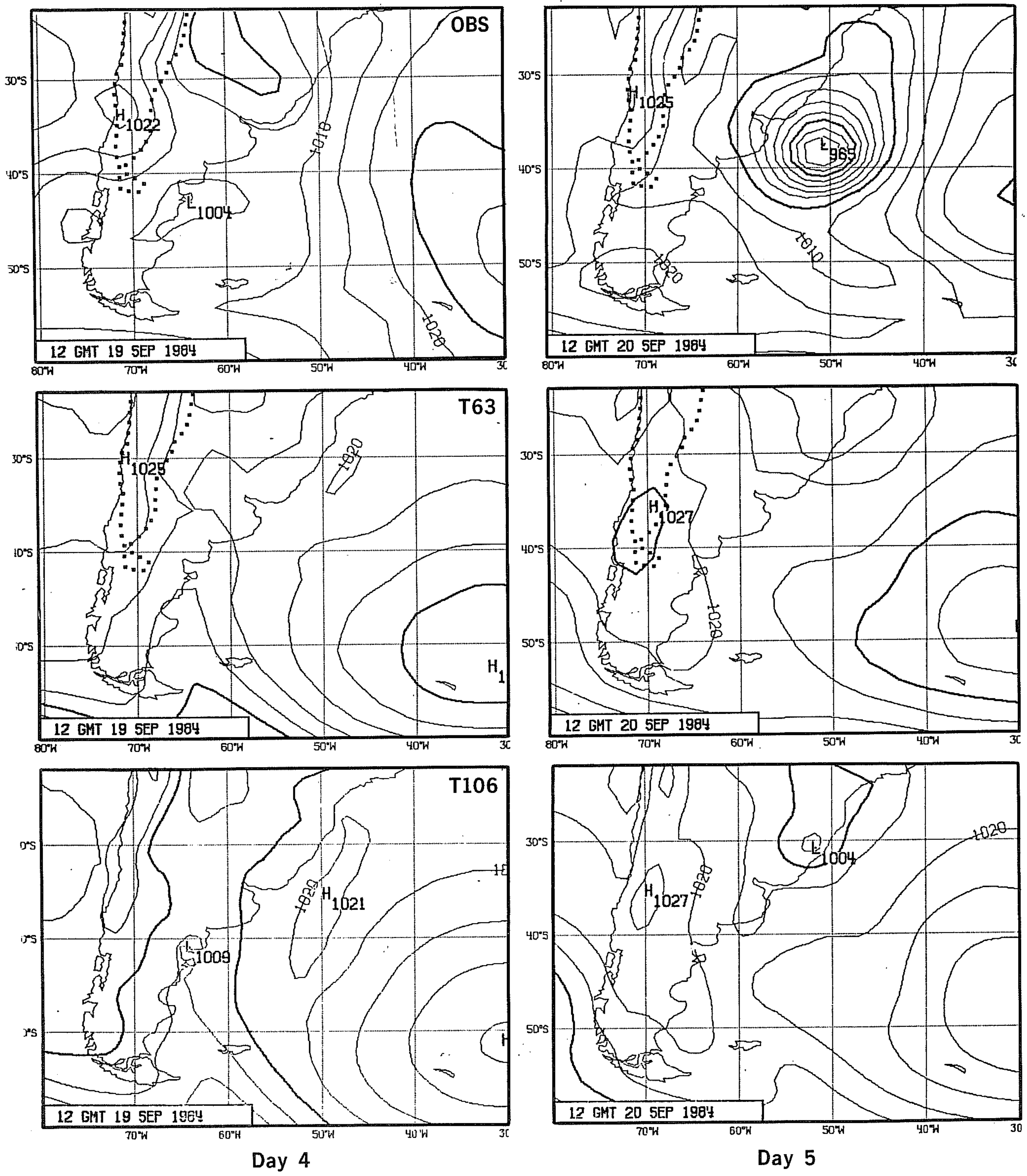


Fig. 12 Analysed mean sea level pressure for 19 September (upper left) and 20 September 1984 (upper right) and corresponding day 4 to 5 forecasts from 15 September 1984 by T63 (middle) and T106 (lower).

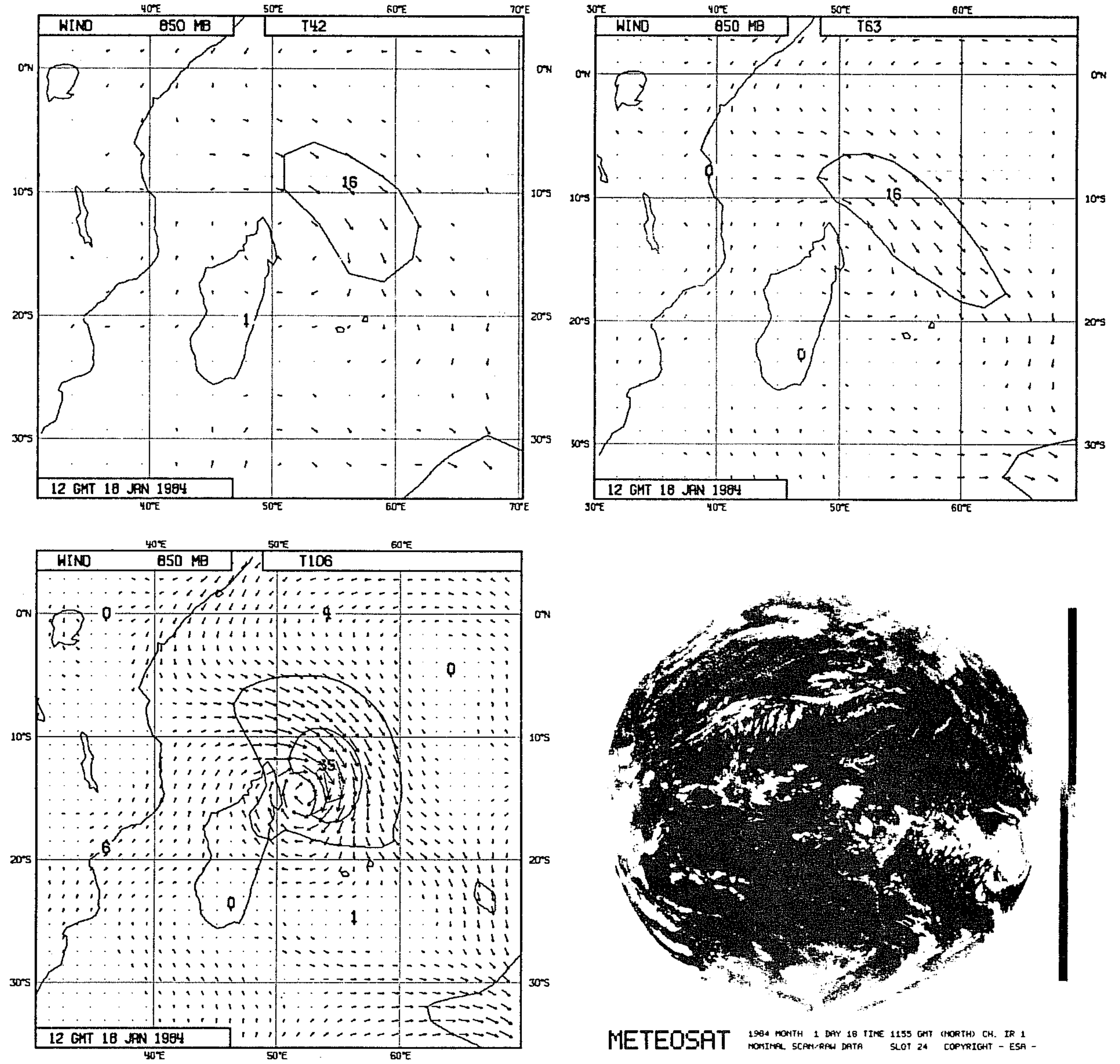


Fig. 13 Day 3 850 hpa wind forecasts from 15 January 1984 by T42, T63 and T106 together with the corresponding infrared meteosat picture for the 18 January 1984.

is consistent with the fact that other errors, in particular in the knowledge of the initial state, are larger in the Southern Hemisphere, and their subsequent growth tends to mask any impact from resolution beyond T21. The poorer results of the low resolution are due to a large extent to a severe underestimation of the strength of westerly mid latitude flow which is in agreement with results of some climate simulations (e.g. Manabe et al, 1979). Despite the scores from different resolutions being more similar than in the Northern Hemisphere, significant differences could be found on a number of occasions, in particular in the simulation of deepening lows, most of them in favour of T106. An example is shown in Fig. 12. A spectacular deepening of a low near Argentina occurred between 19 and 20 September 1984. The indication provided at T106 is already more accurate by day 4 and the deepening more pronounced by day 5 (although it is not intense enough and the flow is still located near the coast).

In tropical and subtropical regions some sensitivity has been found in the prediction of cyclones or intense depressions, both in the intensity and the location of the tracks. If present in the initial conditions, these systems tend to be slightly deeper in T106 forecasts and tend to follow somewhat more accurate tracks. An example is presented in Fig. 13 of a tropical cyclone (Domoina) which developed in the Indian Ocean, crossed Madagascar and followed the eastern coast of Africa southwards, causing severe damage ; the infrared Meteosat picture for 18 January 1984 shows the cloud mass associated with it near Madagascar. Corresponding day 3 forecasts of the 850 hPa at T42, T63 and T106 are displayed over a reduced area. The intensity of the wind forecast at T106 is significantly stronger and could have provided a useful warning. Of course the prediction of such events is also very sensitive to the parameterisation of convective subgrid scale processes, but this kind of result is probably encouraging enough to justify a more comprehensive evaluation of the behaviour of the ECMWF operational model in such situations.

Another significant difference between the T106 and T63 resolutions has been found in the prediction of the mid tropospheric temperature field over South Asia, but no synoptic interpretation has been sought to date.

5. MEAN (SYSTEMATIC) ERRORS

Maps of the mean error of the 500 hPa height averaged for days 8-10 of the forecast range and for the 12 "winter" cases are shown in Fig. 14. The errors at T21 resolution bear some similarity in pattern to those at higher resolution, but the predominant difference is between T21 and T42 rather than between T42 and higher resolutions. The hemispheric root mean square (RMS) of this mean error is also rather higher at T21 than at other resolutions, in contrast to results from climate simulations of the Northern Hemisphere height field which show a deterioration with increasing resolution (Manabe et al, 1979; Cubasch, 1981). Differences between T42 and higher resolutions vary from location to location, but the sample size may not be sufficient to assign significance to most of these. In particular the splitting of the 12 winter cases into two sub-ensembles of 6 cases, corresponding to the first and second year winters, would have shown an important interannual variability. However, there is no suggestion of an overall deterioration of mean forecast errors with an increase in resolution from T63 to T106. Earlier in the forecast range, mean errors generally decrease with increasing resolution. A close inspection of Fig. 14 reveals that tropical height biases are very similar at T21, T42 and T63, but are significantly smaller at T106. Overall T106 yields a fall of .7K in the erroneous global mean cooling compared to T63 or T42. Experiments suggest that this difference at T106 can be largely accounted for by the reduction in horizontal diffusion, particularly on the divergence field.

Fig. 15 presents for the same 12 winter cases the evolution of the variance (RMS deviation from the mean over the 12 cases) for all resolutions. The evolution for the persistence forecast (labelled analysis in Fig. 15) is not linear and this confirms that our sample may not be large enough. Nevertheless the decrease in variance in the second half of the forecast range is quite large at T21 and is significantly reduced with increased resolution. This higher level of variance might of course have contributed to the degradation of the objective scores for T106 beyond day 5 when synoptic features are not so accurately forecast.

The lower part of Fig. 15 shows the mean RMS differences between various resolutions together with the RMS error of T106 forecasts. Despite a certain convergence with increasing resolution the differences between T63 and T106

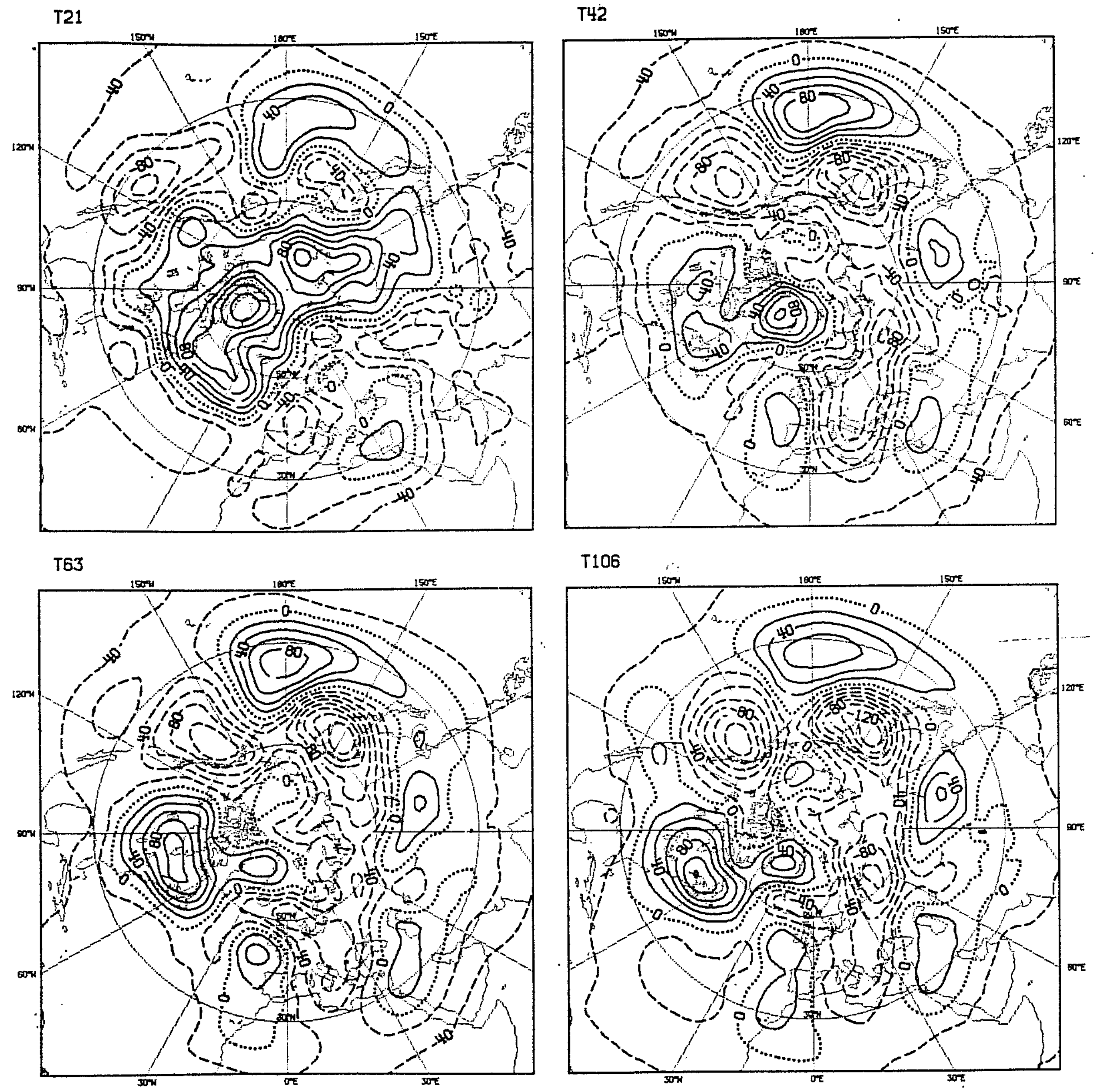
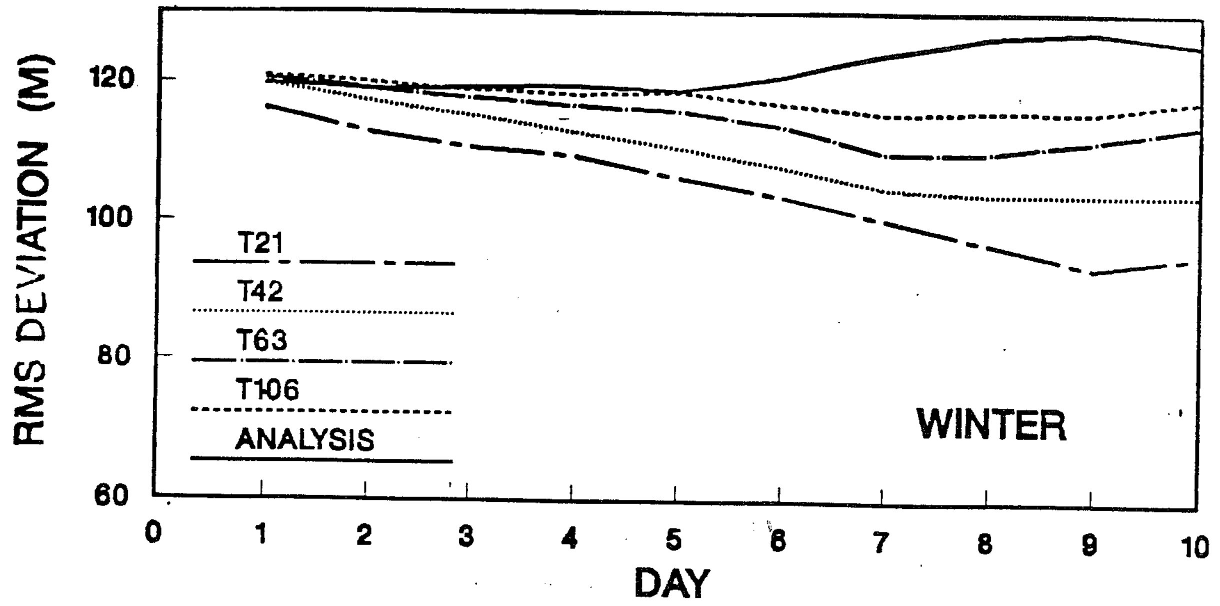


Fig. 14 Errors in the 500 hpa height fields averaged over days 8, 9 and 10 and the 12 "winter" cases, for T21, T42, T63 and T106 forecasts. Positive contours are solid, and negative contours dashed. The contour interval is 20 m.



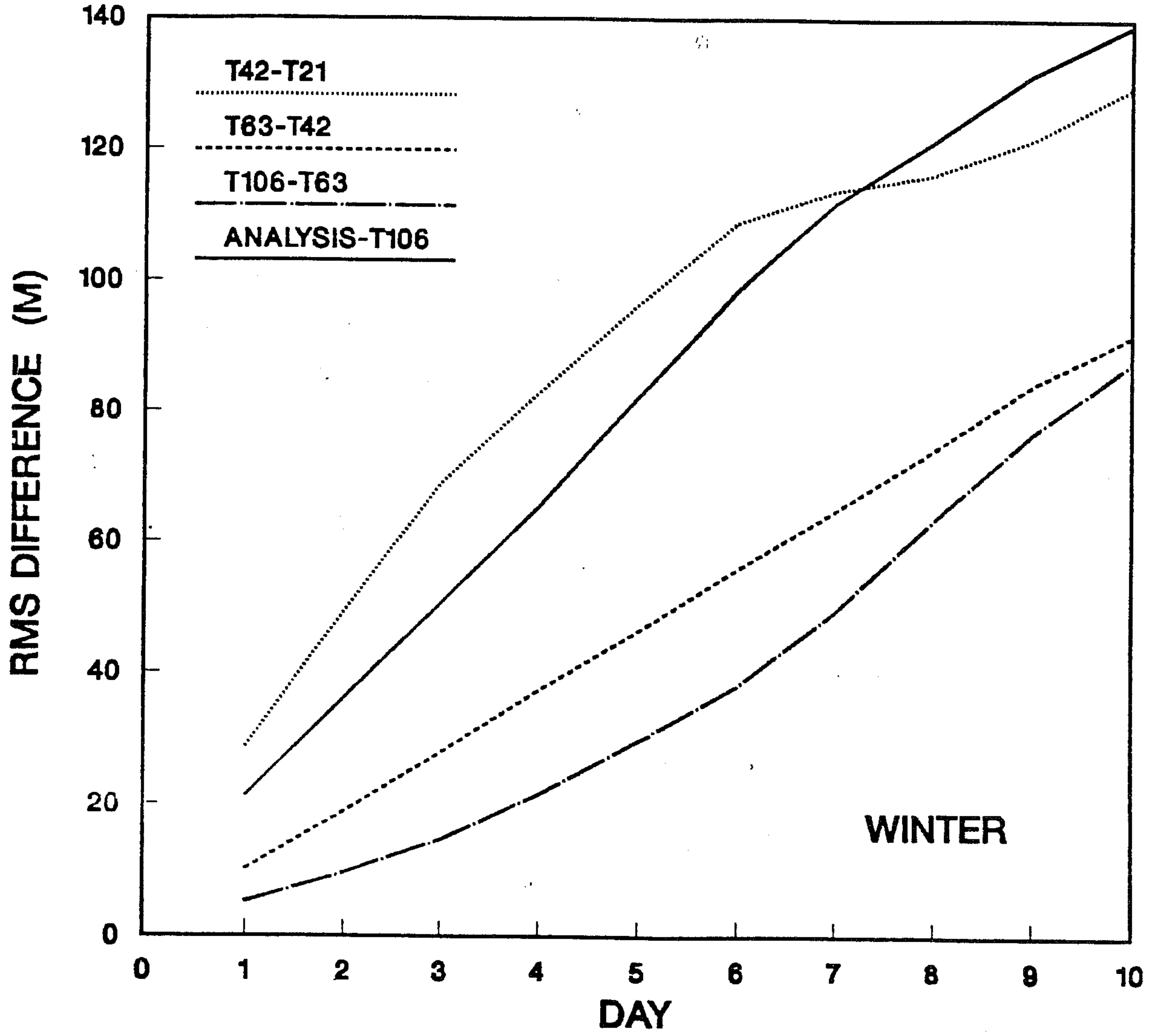


Fig. 15 Upper: RMS deviation from the mean 500 hpa height field averaged over 12 winter cases as a function of forecast day. The curved labelled "analysis" corresponds to persistence forecast.
Lower: Mean RMS differences between 500 hpa height forecast averaged over 12 winter cases together with the RMS for T106 forecasts.

are not negligible compared with the total errors on day 10, suggesting that some more benefit could be obtained if other error sources can be reduced. Note also the very large amplitude of the differences between T42 and T21 even at short range, casting some more doubts on the generality of conclusions which might be drawn from very coarse resolution experiments.

Very similar conclusions have been obtained for the 12 summer cases both for the evolution of the variance (not shown) and the mean day 8-10 errors (Fig. 16). T42, T63 and T106 errors resemble each other both in amplitude and pattern; also to a certain extent they resemble the winter error patterns, but the main centres are positioned slightly more to the north reflecting the northward shift of atmospheric activity during summer. The T21 errors are also similar in pattern, but their amplitude (in particular at high latitudes) is much larger.

The same comments could apply to the mean errors in the Southern Hemisphere in both seasons. Fig. 17 illustrates this point for the austral summer. Note that the mean errors at all resolutions except T21 are slightly weaker than the corresponding ones in the Northern Hemisphere for the boreal summer. This is not true for the winter season (not shown). The very large errors at T21 correspond to a general weakening of the north-south gradient and of the associated westerly winds as found by Manabe et al (1979).

In all seasons (and hemispheres) similar errors were found at 1000 hPa, confirming their barotropic character which has already been discussed by several authors (e.g. Wallace et al., 1983).

Finally looking at a zonal Fourier decomposition of the mean kinetic energy in the Northern Hemisphere troposphere between day 8 and 10 of the forecast range reveals that unlike other models, the ECMWF forecasts do not seem to become too zonal in the medium range (Fig. 18). However, the ratio of zonal to eddy kinetic energy tends to increase due to a decrease of eddy kinetic energy. This tendency is clear in the planetary waves (wave numbers 1 to 3) and also in the shorter waves (beyond wave number 10). For the planetary waves an improvement with resolution is clear. For the shorter waves (beyond wave number 20) the higher level of kinetic energy maintained at T106 is connected with the higher level of variance observed for the higher resolution.

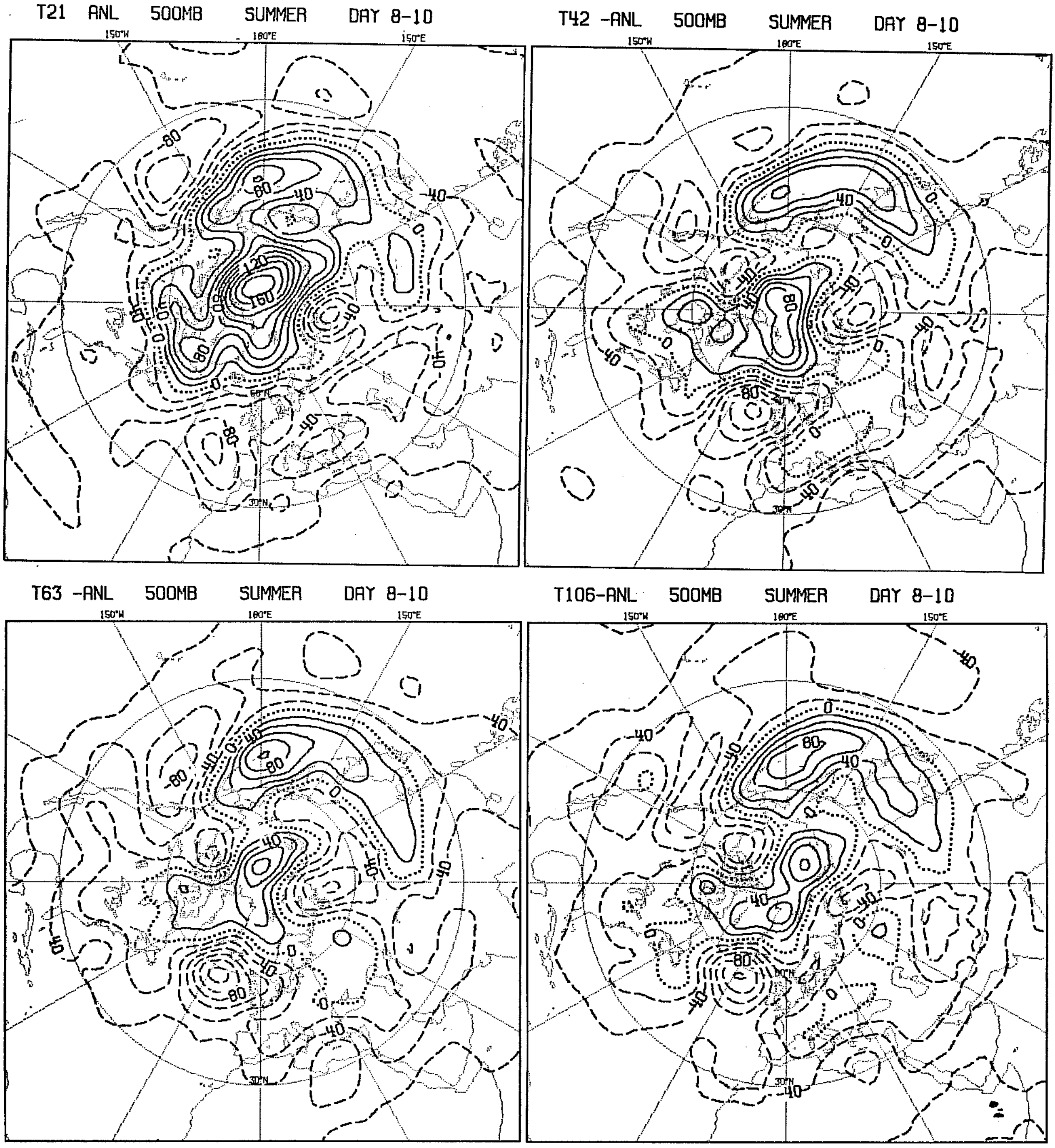


Fig. 16 As Fig. 14 for Northern Hemisphere summer.

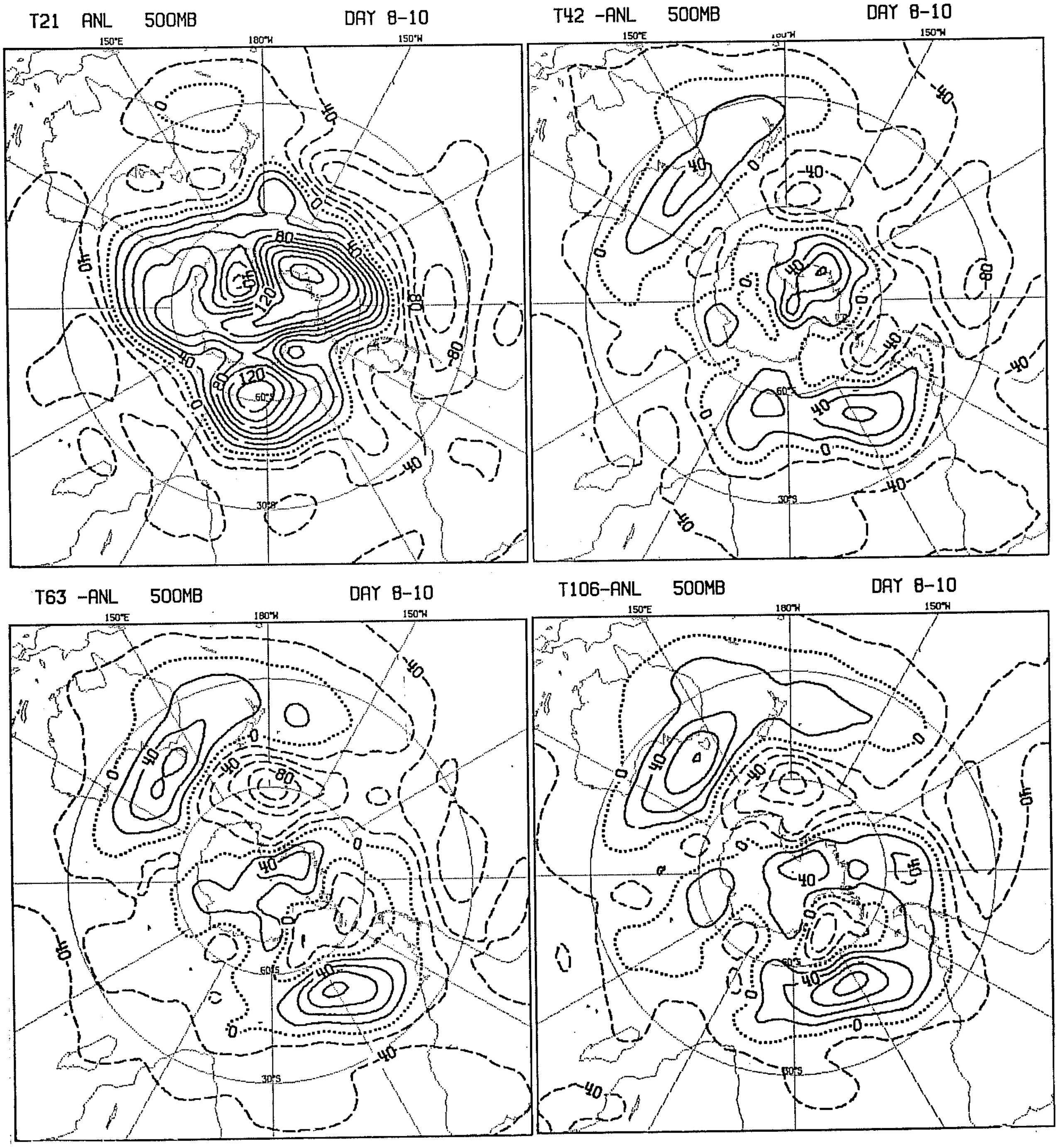
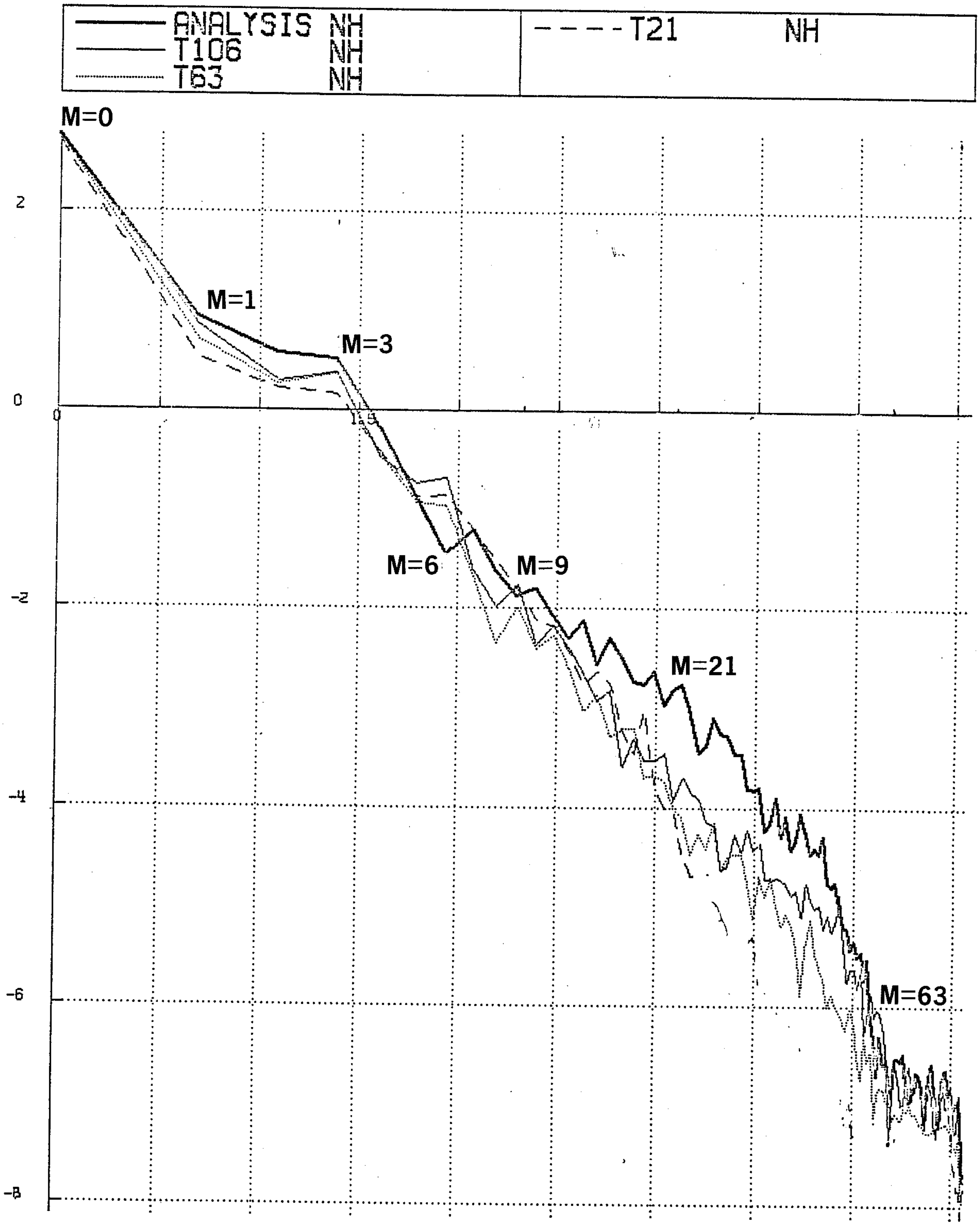


Fig. 17 As Fig. 14 for Southern Hemisphere summer.



KE 200 D8-10 WINTER

Fig. 18 Zonal Fourier decomposition of kinetic energy at 200 hpa in the Northern Hemisphere (20-80°N) averaged between day 8 and 10 of the forecast range for T106, T63 and T21 together with the analysed spectrum.

6. SENSITIVITY OF EXTENDED RANGE FORECASTS TO RESOLUTION

In this section, we shall present results from a 30 day winter experiment performed to assess the behaviour of the new T106 model in extended range forecasts. The initial date, 17 January 1984, was selected because it had been used for a number of other 30 day experiments at ECMWF, thus allowing extra comparisons to be made. The results proved to be spectacular, as can be seen in Fig. 19: this displays the analysed 500 hPa and 1000 hPa height field for 12 February 1984 and the corresponding 26-day forecasts at T106 and T63. For T106 forecastsit is generally useful. The long wave pattern is reasonably well captured - particularly the trough-ridge-trough pattern over the Atlantic and Europe, and also the different flow over North America. At 1000 hPa there is a good similarity between the analysis and the forecast for the double low structure over the north eastern Atlantic, the anticyclonic band extending towards Asia and even for the smaller scale low over the eastern Mediterranean which is associated with the upper air trough. The T63 forecast is significantly worse in several aspects: the anticyclonic block over western Europe has disappeared and the cyclonic circulation is much too strong over the Atlantic. However, the long wave pattern still has some correlation with the observed one. This is not the case for the T21 forecast which, in addition, shows a pronounced weakening of gradients. Fig. 20a shows the observed evolution over the Atlantic and Europe between 25 January and 16 February. The maps are averaged over 3 day periods in order to filter out some of the unpredictable short scales features. The corresponding T106 forecasts are displayed in Fig. 20b (right) and Fig. 20b shows the results at T63 and T21. The flow undergoes significant changes during the period: after being very zonal over the Atlantic a strong ridge develops in the second part of the forecast which later tilts southwest to northeast. These changes are reasonably well simulated at T106, although the building of the ridge is slightly late. This is confirmed by the Hovmöller diagrams shown in Fig. 21 for the latitude band 45°N to 65°N and wavenumbers 1 to 9. The T106 evolution beyond day 20 is quite successful with a time lag of 1 to 2 days. T63, although successful until day 10 or 12, completely fails to simulate the building of the west European ridge in the second half of the forecast and this again can be seen in the Hovmöller diagrams of Fig. 21. At T21 the forecasts are already bad by day 10 and the Hovmöller diagram shows a worrying westward, rather than eastward, orientation in the later part of the forecast.

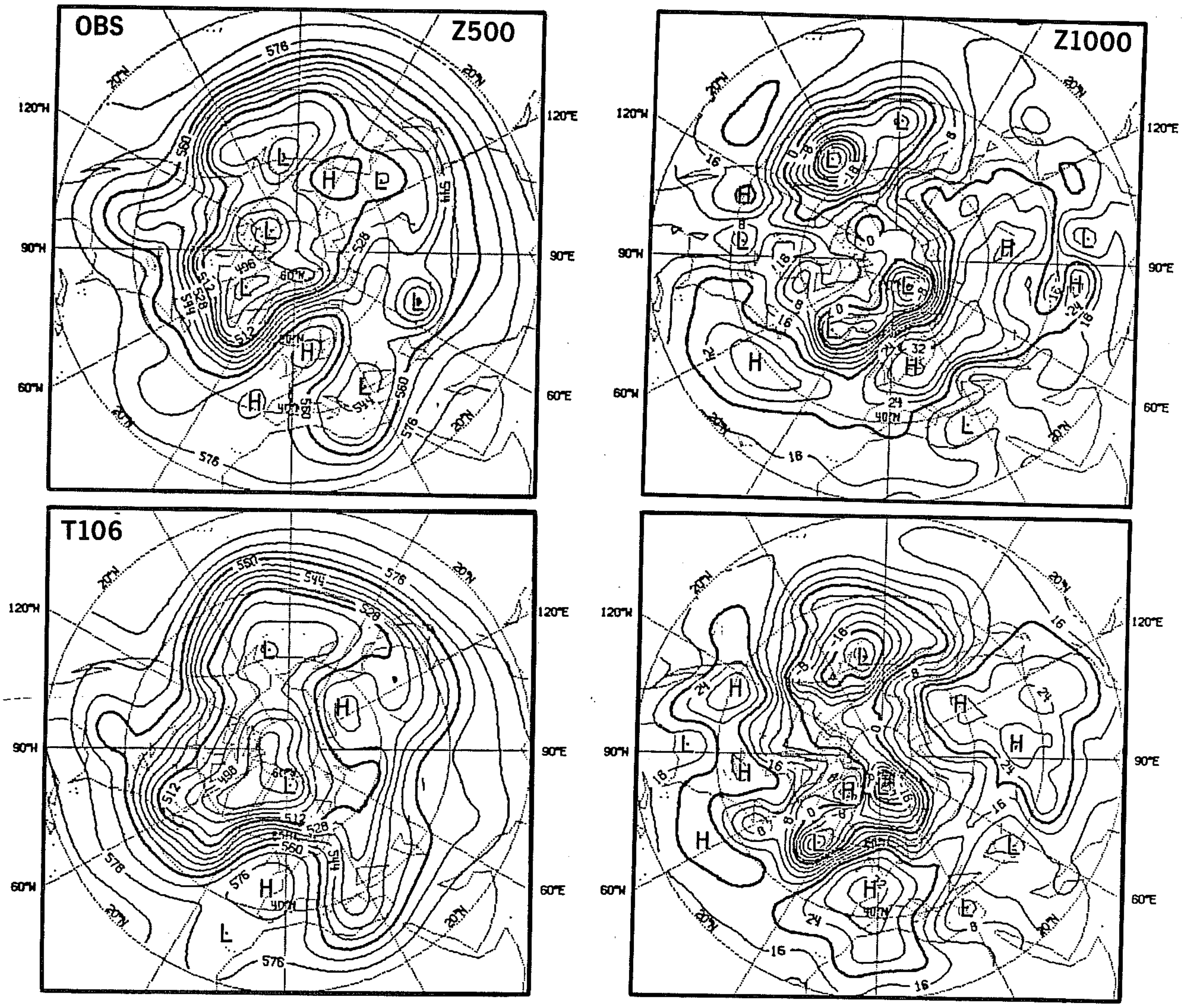


Fig. 19a Observed (upper) and day 26 forecast by T106 (lower) 500 hpa (left) and 1000 hpa (right) height field for 12 February 1984.

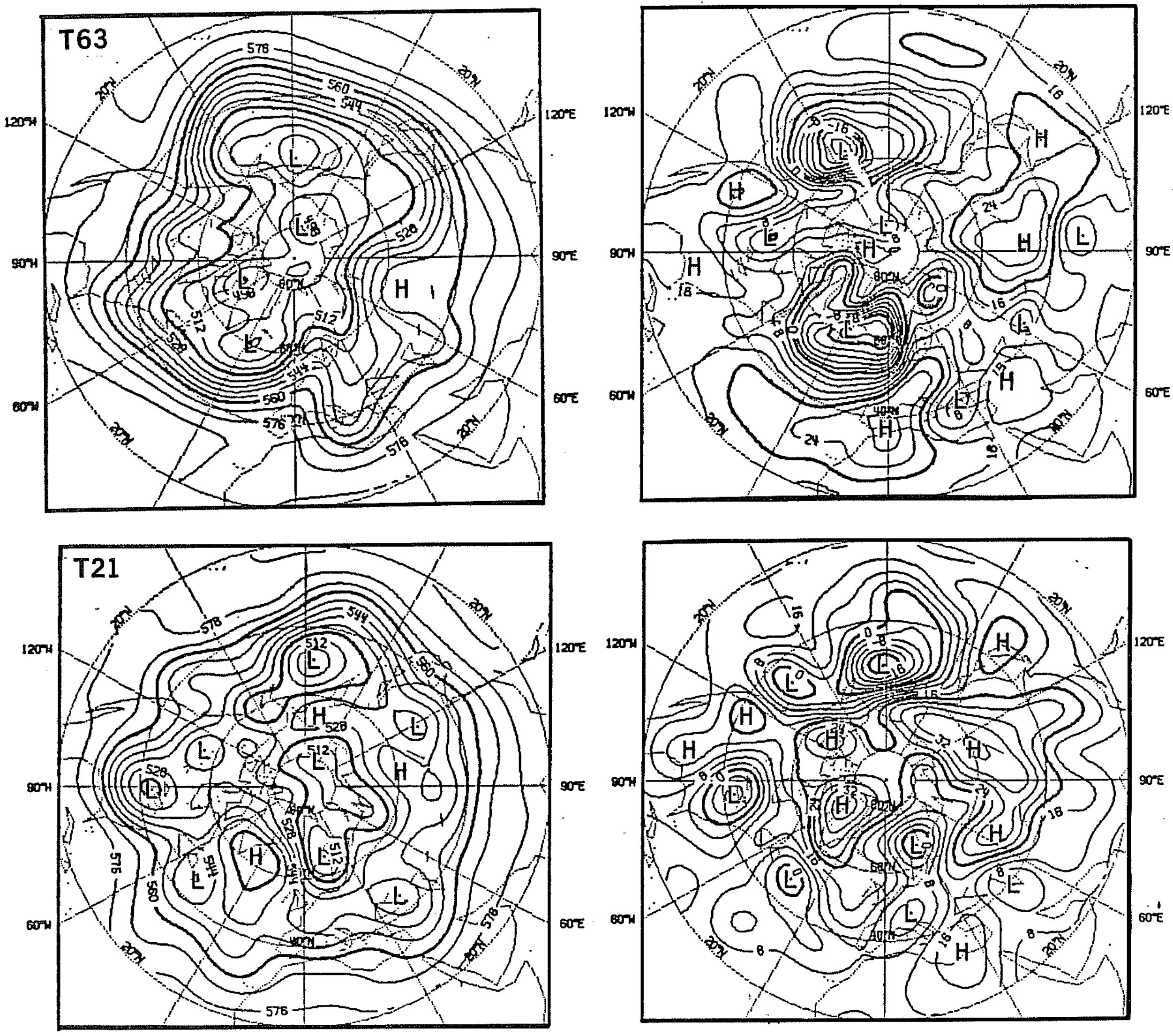


Fig. 19b As Fig. 19a for day 26 forecasts by T63 (upper) and T21 (lower).

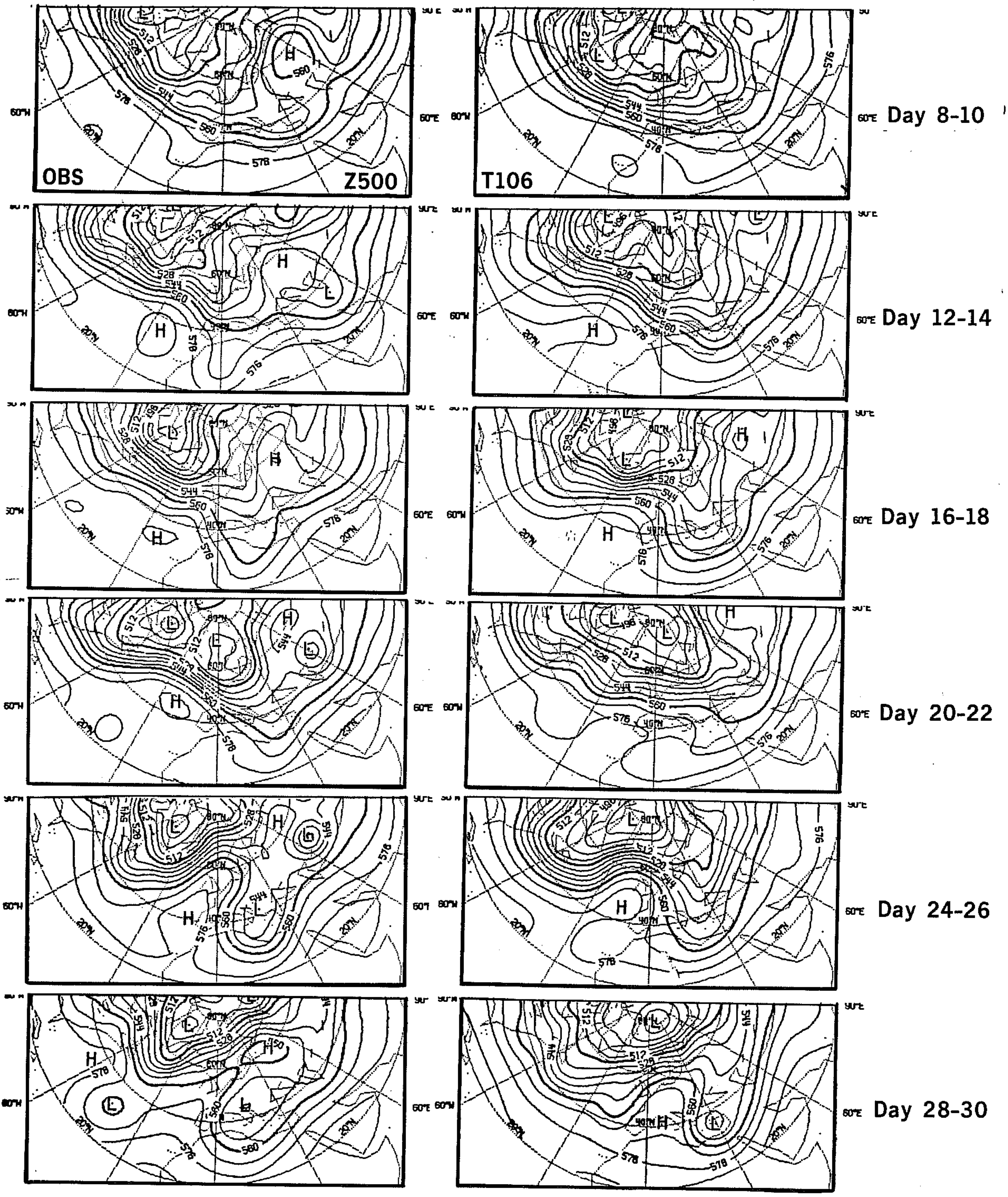


Fig. 20a (Left) analysed 500 hpa 3 day averaged height maps 25-27 January, 29-31 January, 2-4 February, 6-8 February, 10-12 February and 14-16 February (top to bottom) and corresponding day 8 to 10 up to day 28 to 30 T106 forecasts (right).

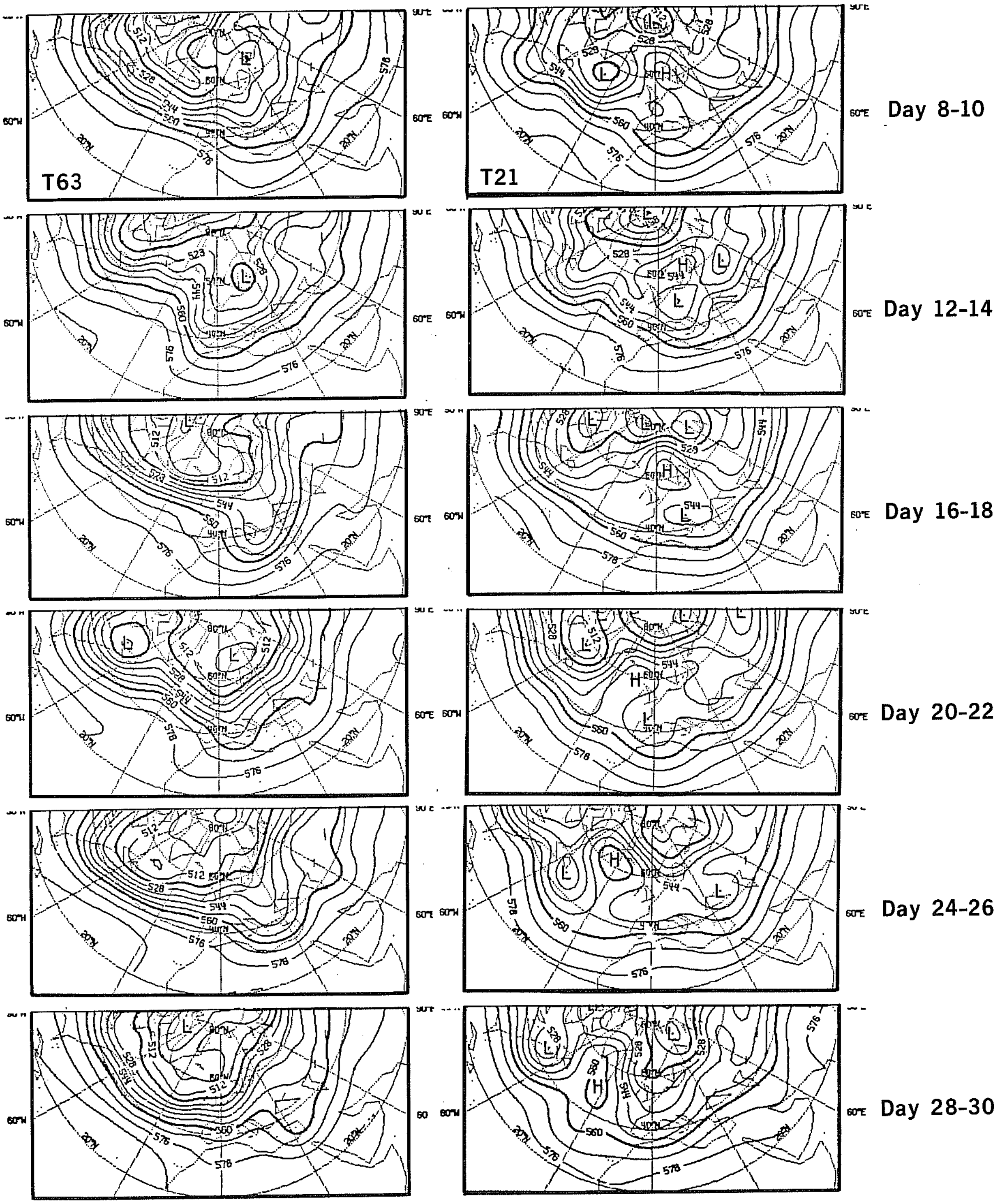


Fig. 20b As right panel of Fig. 20a for T63 (left) and T21 forecasts (right).

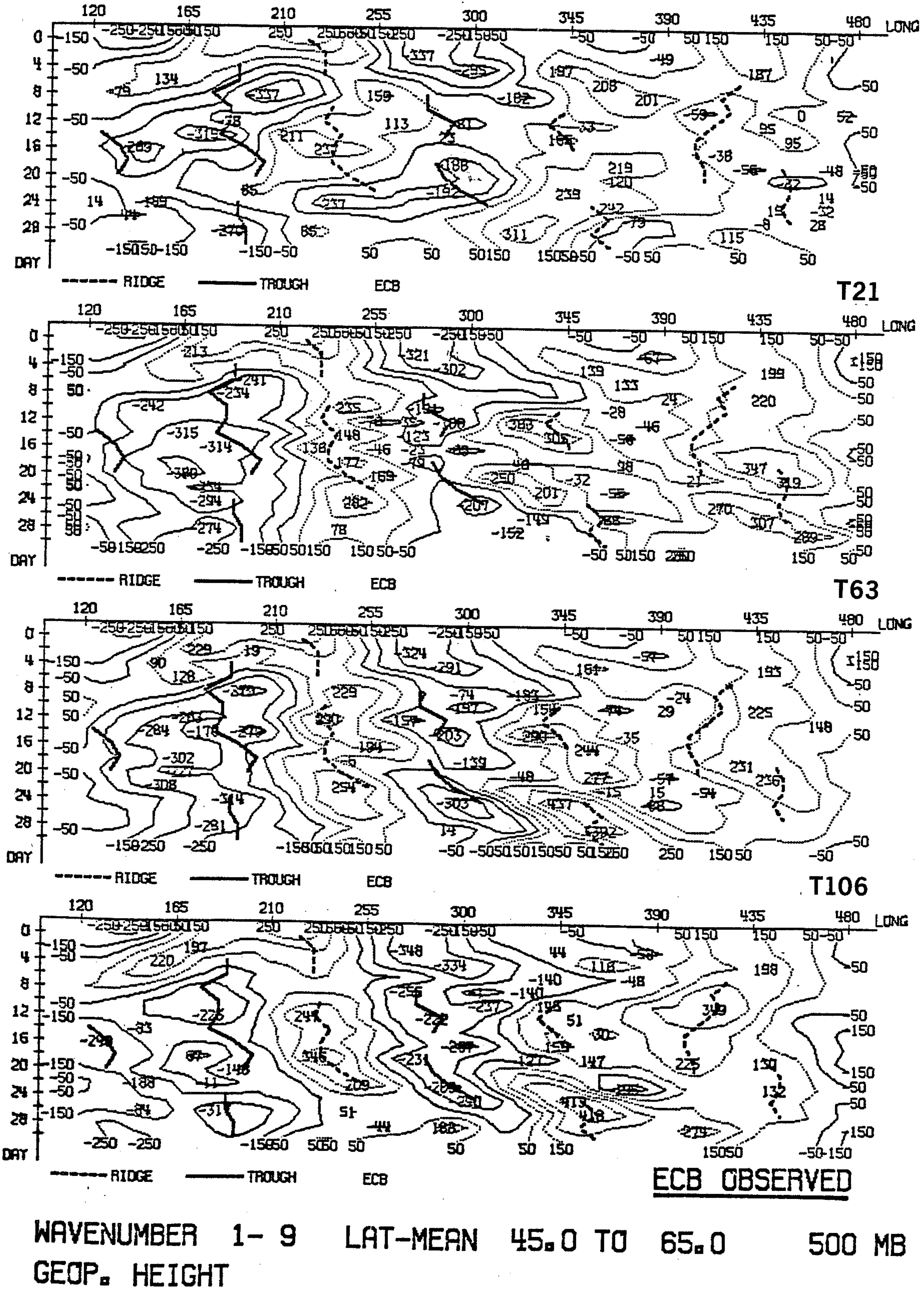


Fig. 21 Hovmöller diagrams for latitude band 45 to 65°N for 500 hpa height forecasts by T21, T63 and T106 (only zonal Fourier components 1 to 9 are kept) and corresponding analysed field.

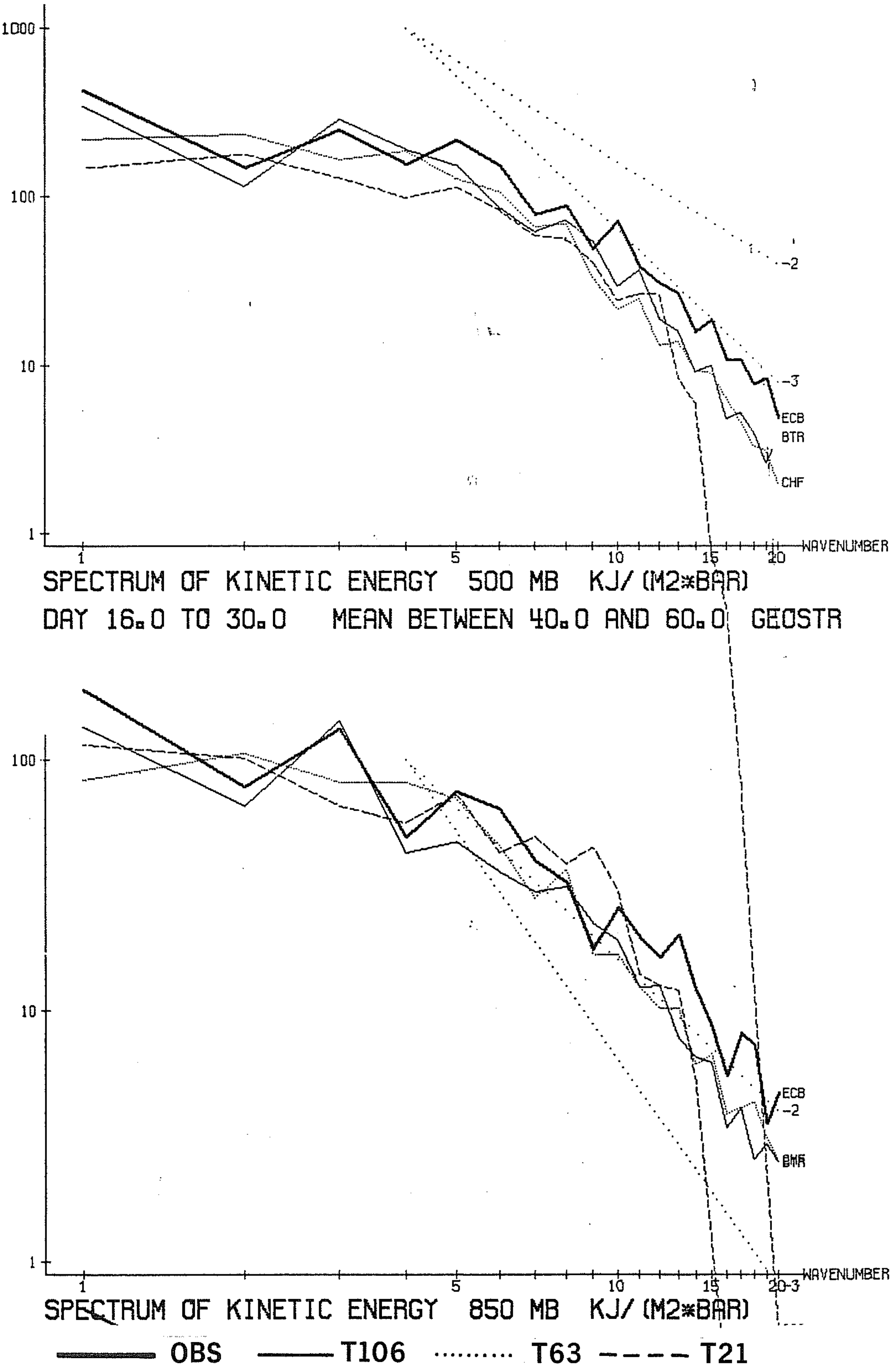


Fig. 22 Spectra of kinetic energy at 500 hpa (upper) and 850 hpa (lower) averaged from days 16 to 30 and between 40°N and 60°N for the analysed field (thick continuous line) and for forecasts by T106 (thin continuous line), T63 (dotted line) and T21 (dashed line).

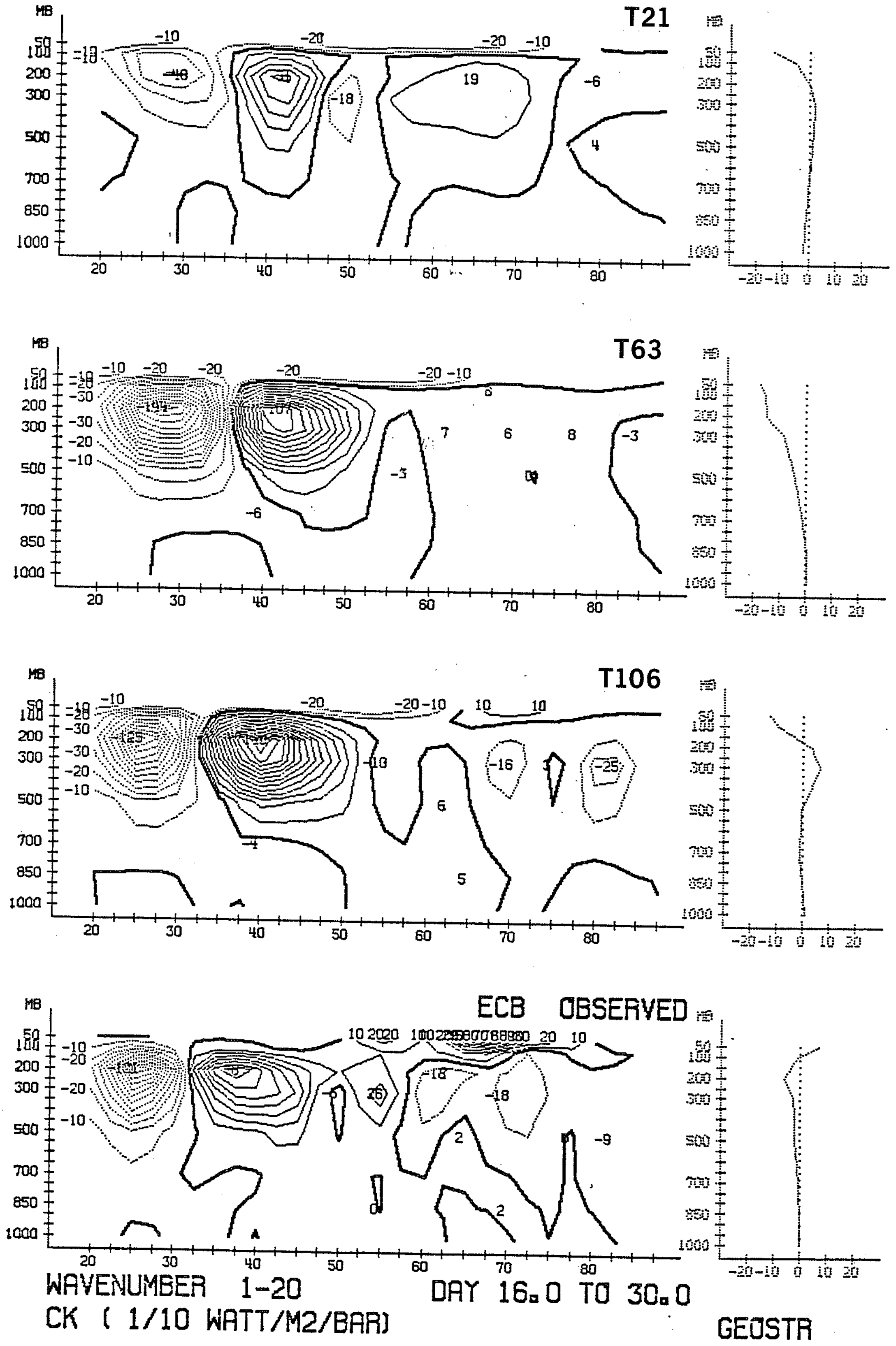


Fig. 23 Pressure latitude cross section of CK (conversion of eddy to zonal kinetic energy) averaged between day 16 and 30 of T21, T63 and T106 forecasts (zonal Fourier wavenumbers 1 to 20) and corresponding analysed cross section.

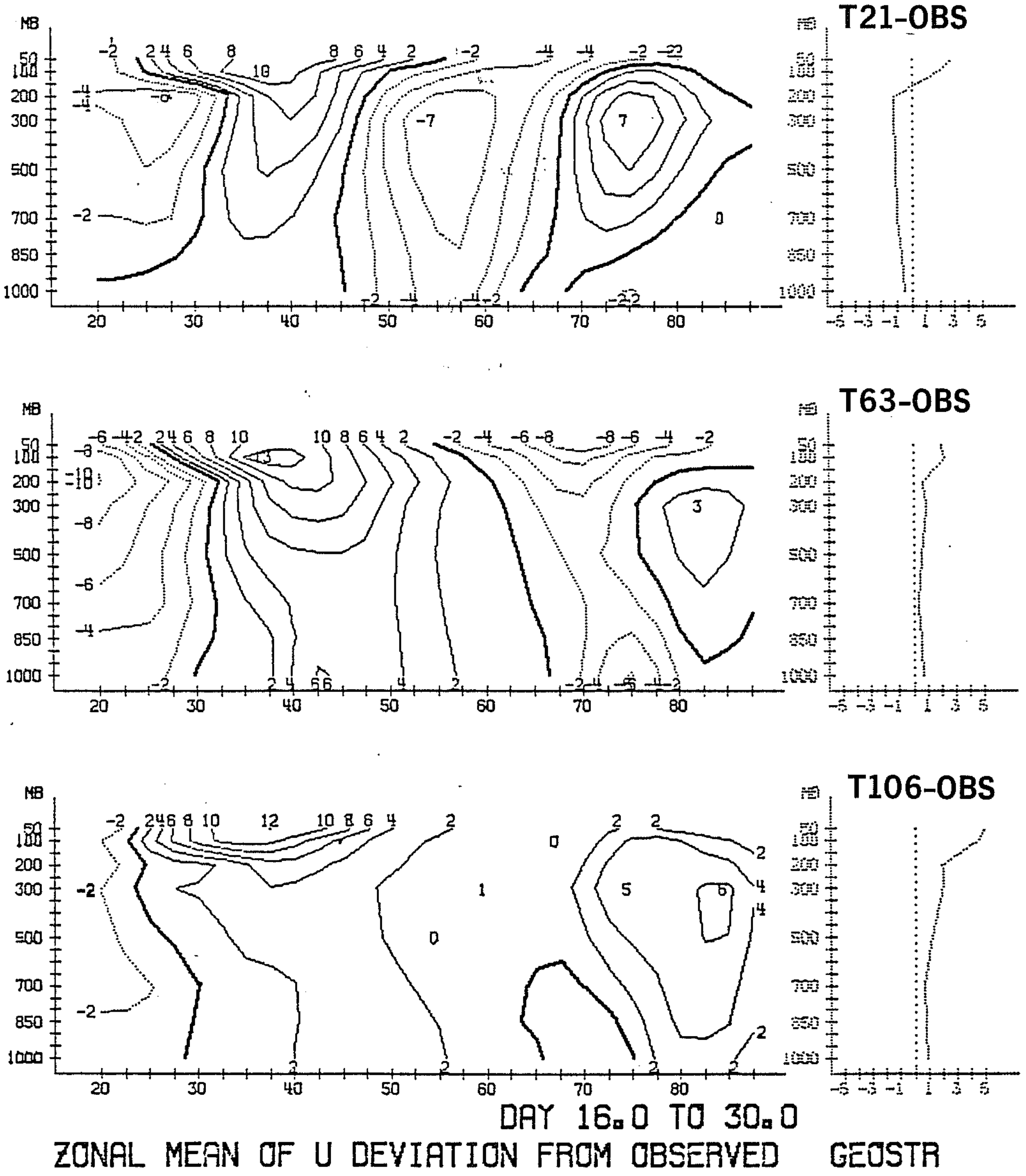


Fig. 24 Pressure latitude cross sections of the zonal mean of the mean error of zonal wind (averaged between day 16 to 30).

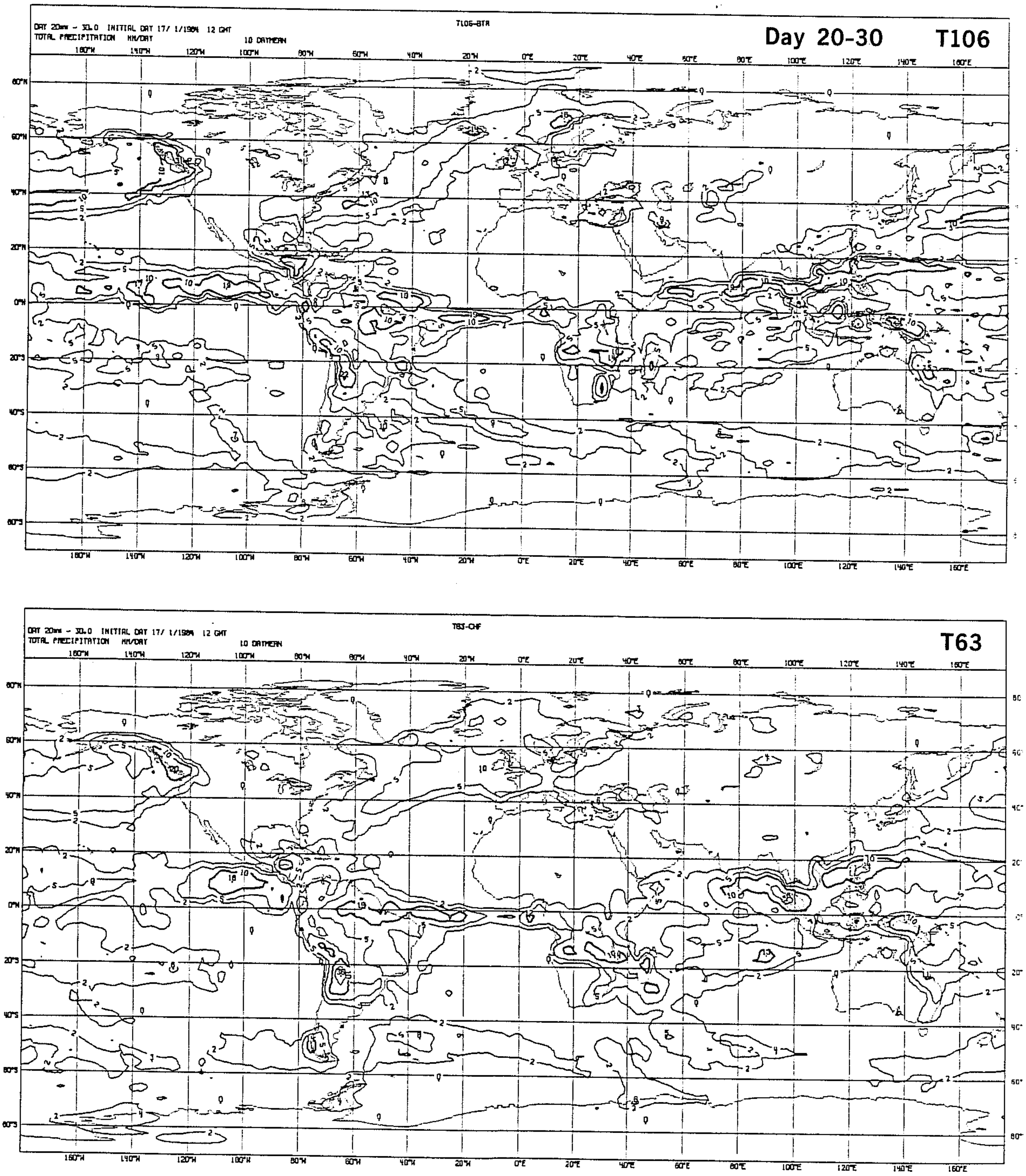
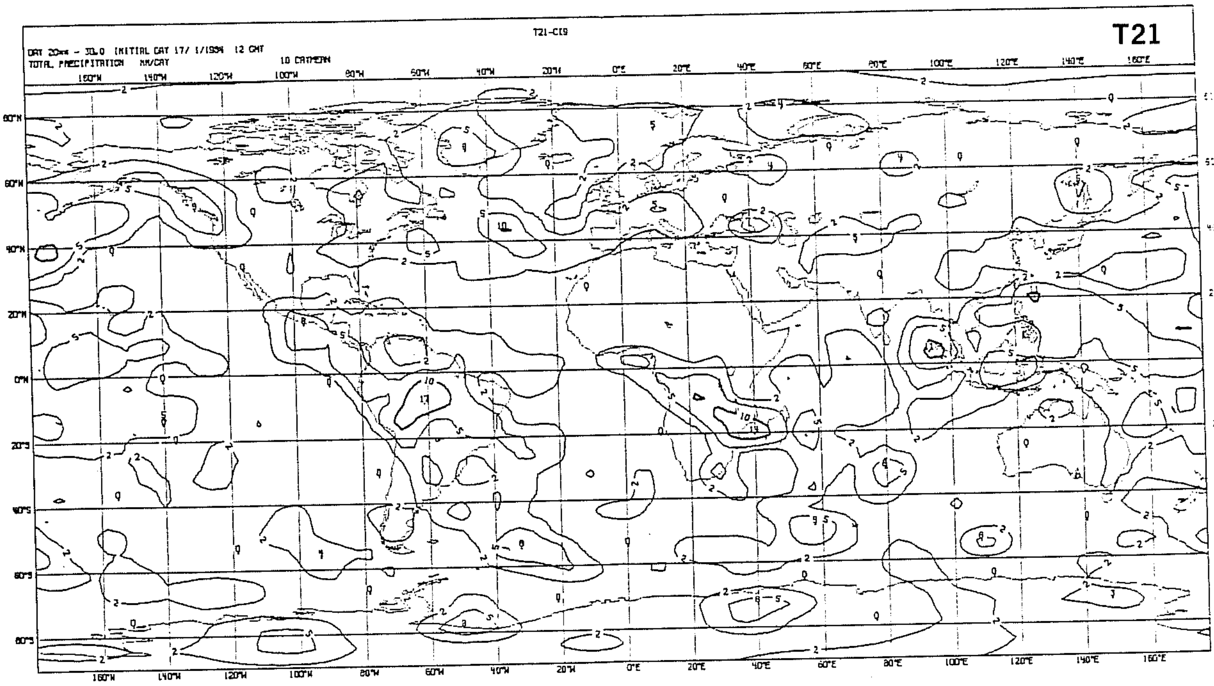


Fig. 25a Precipitation rates (mm/day) averaged over the last 10 days of 30 day T106 (upper) and T63 (lower) integrations from 17 January 1984.



FEBRUARY CLIMATE (after Jaeger)

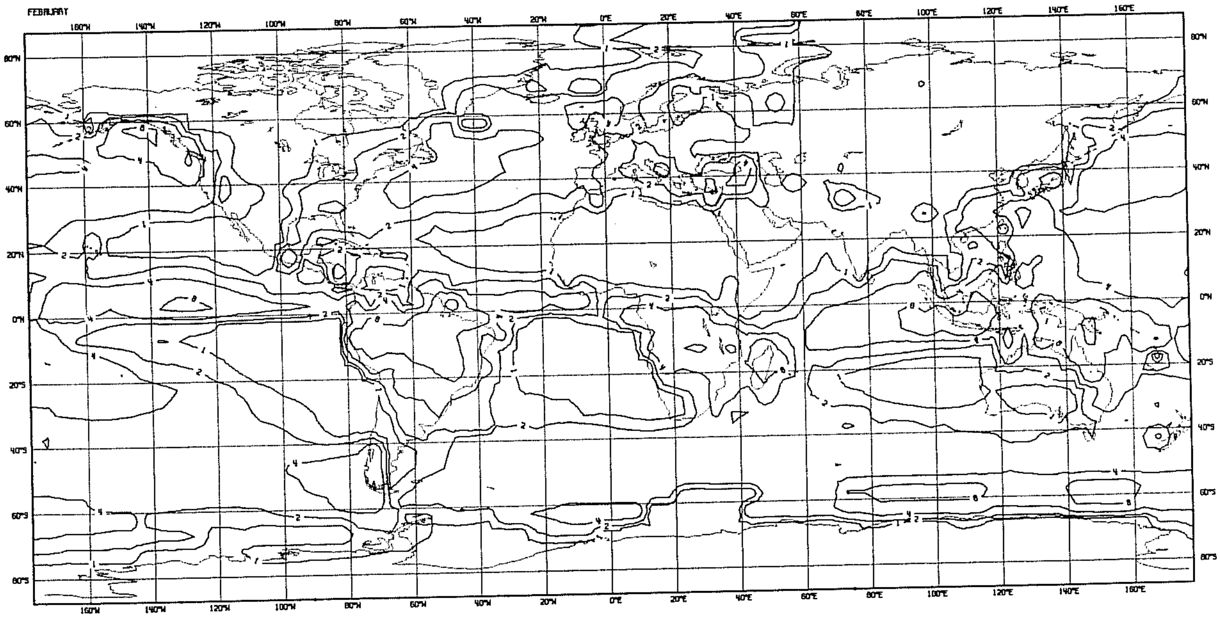


Fig. 25b As Figure 25A for T21 integration (upper) and February climate (after Jaeger) (lower).

The distribution of mean kinetic energy at 500 and 850 hPa averaged between days 16 and 30 (Fig. 22) reflects the very good synoptic behaviour at T106, in particular in the long waves, and the poorer behaviour at T21. This is confirmed by the pressure latitude cross-sections of the CK term (conversion from zonal to eddy kinetic energy) in the Northern Hemisphere between days 16 and 30 (Fig. 23): the two major conversion bands are much too weak at T21. The resulting zonal mean pressures for the zonal wind are shown in Fig. 24: at low and middle latitude the impact of resolution is spectacular throughout the troposphere. The over strong westerlies seen at mid-latitudes at T63 are significantly reduced at T106. At T21 the westerlies tend to be underestimated due to a general weakening of the north-south gradient (as mentioned in the previous section for the Southern Hemisphere).

In the tropics and the Southern Hemisphere, the forecasts were by no mean as good as in the Northern Hemisphere. However, the impact of resolution can be seen clearly in the global precipitation maps accumulated between days 20 and 30 of the forecast: differences in the extra tropics can, to a large extent, be attributed to the different synoptic resolution. In the tropical band however, the ITCZ is more pronounced in the T106 simulation than in the T63 one, particularly over the Pacific and the Indian Ocean. The T21 simulation is once more much poorer with no real indication of an ITCZ and the cyclone track over the Atlantic is much too far to the south. In the Southern Hemisphere, several isolated precipitation maxima over the oceans do not seem to correspond to plausible cyclone tracks.

Of course the very good results obtained with the finest resolution should not be generalised too quickly in terms of potential predictability of the model. However, they suggest that in some cases errors in the smaller scales do not really affect the evolution of the large scales in the troposphere, and that even beyond day 20 some small scale features might be accurately forecast when they result from interactions between the large scale flow and smaller scale slowly evolving conditions (SST, mountains, land sea mask, ...). The results shown in this section also suggest that, in order to obtain the best possible results, it may be necessary in some cases at least to use the most sophisticated and unfortunately, the most expensive model. Furthermore the climate drift does not seem to get any worse when resolution is increased beyond T63, but of course this has to be confirmed by more experimentation.

Finally these results emphasise the limits of the coarse resolution (T21) model in simulating some basic mechanisms of the atmospheric circulation. Unfortunately it also tends to rule it out as a tool which could be used to obtain 'cheaper conclusions' on the behaviour of models at higher resolution, since some fundamental features are misrepresented (e.g. cyclone tracks, ITCZ, conversion of kinetic energy, ...).

7. SUMMARY

The sensitivity of medium range forecasts made by the ECMWF spectral model has been investigated in a series of 24 10-day experiments performed over a period of two years. Objective verifications showed a distinct improvement of the highest resolution (T106) over the previous operational (T63) model, in particular in summer. From a synoptic point of view, the increase in resolution has been found to improve almost systematically the forecasting of fast developing lows, (both of their tracks and their initial deepening phase). Increased resolution is also beneficial in the simulation of cut-offs, or of complex low systems, where it helps identify the correct main centre and reduces a tendency, seen at lower resolution, to merge the various centres into a single larger scale low. A European block was successfully simulated 5 to 10 days in advance only at T106. Also in the forecasts of near surface parameters (precipitations or near surface winds) the improvement due to increased resolution was mainly systematic, in particular at shorter range, due to both the better description of mountains and to slightly more accurate forecasts of upper air fields.

No obvious deterioration has been observed in the mean errors at T106 compared to those at either T63 or T42, which suggests that the latter (T42) may be used in development phases in order to get some preliminary insight. No such conclusion can be drawn for the T21 model which has a significantly different behaviour and displays, in many respects, worse error patterns.

The sensitivity to resolution has been found to be generally smaller in the Southern Hemisphere and the tropics, except perhaps for the simulation of fast developing lows or tropical cyclones. However, in those areas an inadequate knowledge of the initial state often masks any improvement which might be obtained from a finer horizontal resolution.

Finally results from a 30 day winter experiment performed at T106, T63 and T21 resolution have been presented. No unexpected problems occurred at the highest resolution. On the contrary, the T106 forecast yielded some useful information even beyond day 25 while the T63 forecast was unable to simulate the evolution of the large flow beyond day 20. T21 results further stressed the limits of what can be achieved at lower resolution.

In conclusion, we think that the positive impact of increasing resolution from T63 to T106 has been demonstrated for the ECMWF forecasting system. A number of conclusions might be relevant for other forecasting systems and they also suggest that even more benefit could be obtained from a further increase in resolution, not only for parameters such as precipitations or surface winds, but also for larger scale features. It would be even more beneficial if other sources of error, in particular in the knowledge of the initial state and in the parameterisation of subgrid scale processes, could be reduced.

Acknowledgements

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