DIAGNOSIS OF OROGRAPHICALLY RELATED FORECAST ERRORS

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1. INTRODUCTION

ECMWF operational forecasts and analyses from six winters constitute a large data set to diagnose systematic forecast errors. There are, however, some important limitations to a comparison of successive winters. First of all we have an output from a system in which the forecast model and the data assimilation system have undergone frequent changes. Secondly, we have to take into account that the general circulation pattern can have large interannual differences which may have an effect on the forecast error structure. Despite these two major shortcomings we are able, in such a comparative study, to isolate some errors in the forecasts which have not changed their structure through the six winters of operational forecasts. In this investigation we are especially interested in those errors which are related to errors from orographic forcing.

Though this type of comparative diagnostic may result in some kind of suggestion of possible model errors, we are still far from identifying the physical source of the errors. The highly nonlinear processes of a primitive equation model make a direct cause-effect analysis with standard diagnostic tools very difficult. In a first step to locate the errors sources we use the experimental technique of relaxing the forecast towards the analysis in selected regions where we can identify areas from which large errors emerge.

2. OPERATIONAL D+3 FORECAST ERRORS AT 500 HPA OVER A PERIOD OF 6 WINTERS

In our discussion of the time mean errors we concentrate on the Northern Hemisphere winter. The seasonal mean flow in the middle troposphere has some features which are known to be generated by orographic forcing. General circulation type experiments with mountains and without mountains (Held, 1983) reveal a clear orographically forced component of the stationary eddy geopotential height field (Fig. 1). At high latitudes orographic forcing generates a wavetrain pattern of positive height anomalies over the west coast of Canada and negative anomalies over central parts of North America and along the north-east coast of Asia. The stationary eddy height fields of the 6 winter seasons (Fig. 2a) have a large similarity to the orographic component (Fig. 1) at high latitudes. Thus it seems that orographic forcing determines the positions of the major troughs and ridges in the stationary upper level flow during the Northern hemisphere winter.

2.1 Errors in the mean fields

To investigate the seasonal mean forecast errors we have averaged the forecast minus analysis differences over all forecasts of each winter season verifying on the analysis dates (Fig. 2b). Over North America and further downstream into Europe the mean 500 hPa D+3 height errors have a structure which is very similar to the orographic component of the general circulation experiments (Fig. 1). The error field has an opposite sign compared to the orographic component which suggests an insufficient mountain forcing in the model. The amplitudes of these mean errors were especially large in the first two winter seasons. The investigation of short range forecast errors (D+1, not shown here) by Wallace et al. (1983) led to the conclusion that the mountain heights in the model should be increased. The subsequent introduction of the envelope orography in April 1983 had a beneficial effect on the forecast quality, especially in the medium range. However, the major structure of the seasonal forecast errors was not changed. If we compare errors from 1981/82 with 1985/86 we find an almost identical pattern over North America and the western Atlantic, though a reduction in the magnitude of the errors is evident. The D+3 error pattern examined here is also representative for later forecast steps as shown by Arpe and Klinker (1986).

In the American to European sector of the northern hemisphere, the mean error has an opposite sign to the stationary eddy height field. The substantial

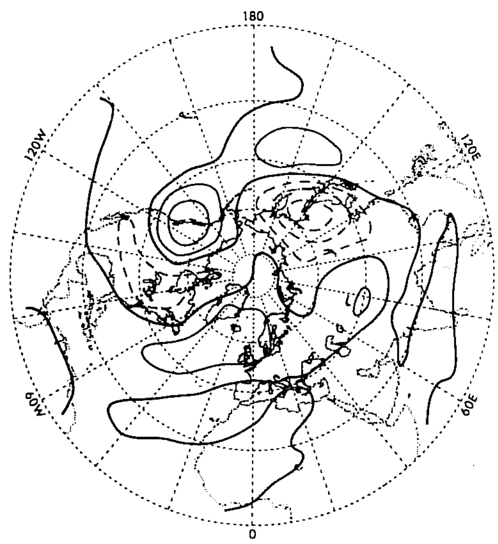


Fig. 1 The 'orographic' component of the stationary eddy height field at 300 hPa as defined by the difference between general circulation experiments with mountains and without mountains (from Held, 1983).

negative height errors in the east Asian coastal region imply, by contrast, an intensification of the climatological trough. Unlike the errors downstream of the Rocky Mountains, the east Asian error structure does not suggest an insufficient forcing of the model mountains over east Asia. Other model problems may be responsible for the erroneous intensification of the east Asian-Pacific trough.

2.2 Errors in the transient fields

To study the transient wave variance of the analyses and forecasts we have used standard spectral techniques to separate frequency bands from the full spectrum (Klinker and Capaldo, 1986). We discuss separately the low frequency (periods longer than 5.8 days) and high frequency (periods between 2.5 and 3.5 days) waves. The spectrum of geopotential height is sufficiently red that the low frequency part is also a good representation of the total variance. For the investigation of baroclinic wave activity the high frequency variance of the meridional wind was calculated.

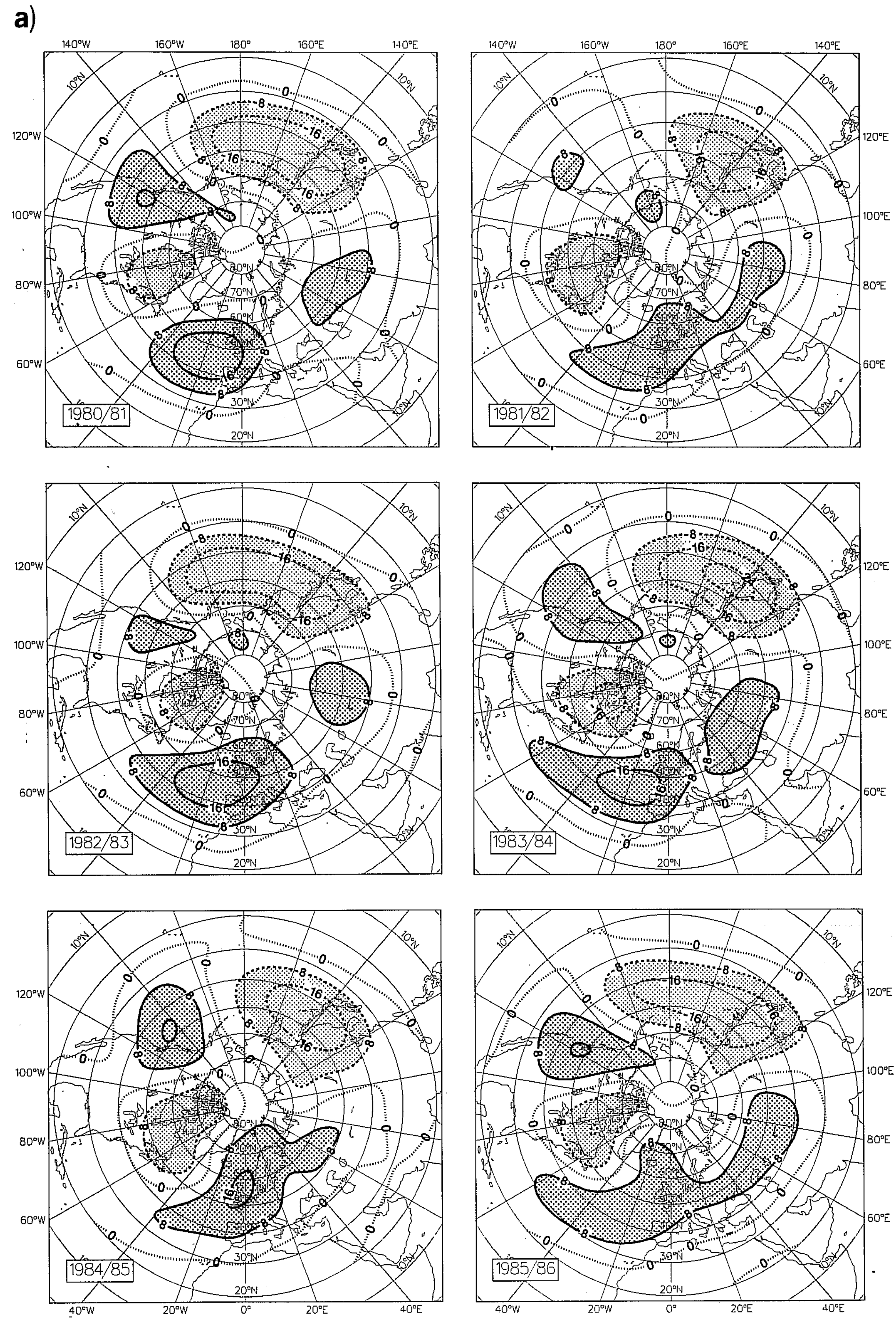
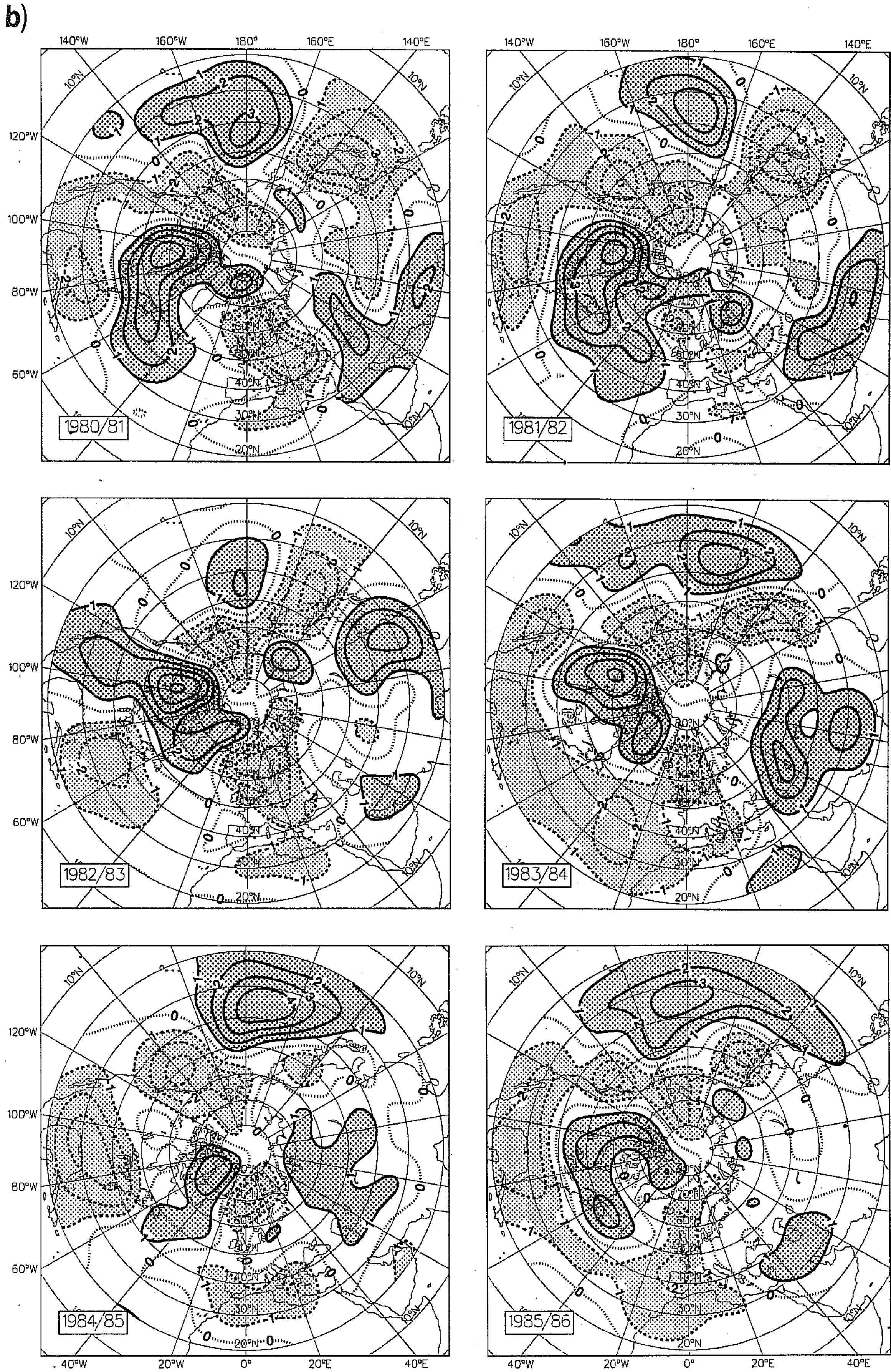


Fig. 2 The stationary eddy geopotential height field at 500 hPa for 6 winters (mean over 112 days, spectral resolution T21). (a) analysis, (b) D+3 forecast errors. Units: dam.



b)
140°W
160°W
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160°E
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80°E
60°E
40°W
20°W
0°
20°E
40°E
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1981/82
1982/83
1983/84
1984/85
1985/86

Fig. 2(b)

2.2.1 Low frequency variance of the geopotential height at 500 hPa

In the horizontal distribution of the low frequency variance of the geopotential height in the 6 winters (Fig. 3a), we find, on average, three major centres of low frequency wave activity: in the north western part of the Pacific, in the north Atlantic, and in northern Europe or northern parts of Russia (though sometimes there is only an extension of the Atlantic maxima). These low frequency variance maxima correspond to persistent anomalies of the northern hemisphere winter circulation (Dole and Gordon, 1983). If we compare the location of the Pacific and Atlantic low frequency variance with the stationary eddy geopotential height field we notice that the areas of maximum low frequency variances are located in the region of strong height gradients between the stationary trough to the west (west Pacific or eastern parts of North America) and the stationary ridge to the east (west coast of North America or east Atlantic).

The forecast errors in the low frequency part of the transient wave activity (Fig. 3b) seem to be connected to the forecast errors in the stationary part of the flow. In all winters we see a correspondence between decreasing heights in the mean fields over the north west coast of north America and in the east Atlantic and European area with an increase of low frequency wave activity. An inspection of time-height sections at selected gridpoints of large low frequency variance suggests that on average low frequency waves are enhanced in those regions with troughs being deeper in the forecast than in the analysis. The close connection between mean errors and low frequency errors suggests that the error source might be the same. We may therefore draw the tentative conclusion that errors in the representation of mountain forcing induce negative mean height errors downstream and also increase the the low frequency wave activity over the north west coast of North America and in the eastern Atlantic-European region.

2.2.2 High frequency variance of the meridional wind at 500 hPa

The high frequency variance of the meridional wind is a suitable quantity to investigate the baroclinic wave activity in the analysis and in the forecast. From the calculated spectra we have separated the high frequency part in a period range from 2.5 to 3.5 days. The variance in this band shows the two major storm tracks over the oceans (Fig. 4a). A clear separation between these tracks exists over the Rocky Mountain range. The starting point of the Atlantic storm track in the lee of the Rockies has a lower latitude than the end part of the Pacific track. Buzzi et al. (1986) suggest that this southward displacement of the storm track is the consequence of transient baroclinic waves passing over a mountain range.

There is a large interannual variation of the intensity and longitudinal position of the maximum high frequency eddy activity. In 1981/82 the baroclinic wave activity was remarkably weak in the Pacific but rather strong in the Atlantic. The largest cross-mountain activity over the Rockies can be seen in 1983/84.

The forecast error pattern for the high frequency variance shows a simple picture (Fig. 4b) with the forecast underestimating the eddy variance nearly everywhere. The decrease of eddy variance in the forecasts seems to be almost proportional to the observed magnitude. During the first 3 winters the reduction is of the order of 30%. After the introduction of the envelope orography the damping of the baroclinic waves became noticeably larger. Thedecrease of variance over the North American part of the storm track reached 40% in the winters 1984/85 and 1985/86 and as much as 60% in 1983/84. This result suggest that the enhanced orography has contributed to an increased weakening of the baroclinic waves. As was pointed out earlier, this type of long term diagnostic suffers from the fact that the model formulation has undergone many changes. However, recent diagnostic calculations comparing model experiments (envelope orography against mean orography) show detrimental effects - the enhanced orography decreases the total kinetic energy more than in experiments with mean orography (private communication, C. Brankovic).

A noticeable increase of high frequency variance can be seen in the first three winters in the eastern Mediterranean. Inspection of daily maps of the height field suggests that this increase of variance is a reflection of eastward moving troughs in the forecast which are nearly stationary in the analysis. This model deficiency, which is even more pronounced at medium frequencies, nearly disappeared with the introduction of the envelope orography (Winters 1983/84 to 1985/86). It seems that with higher mountains the model is able to maintain the almost stationary waves more effectively.

a)

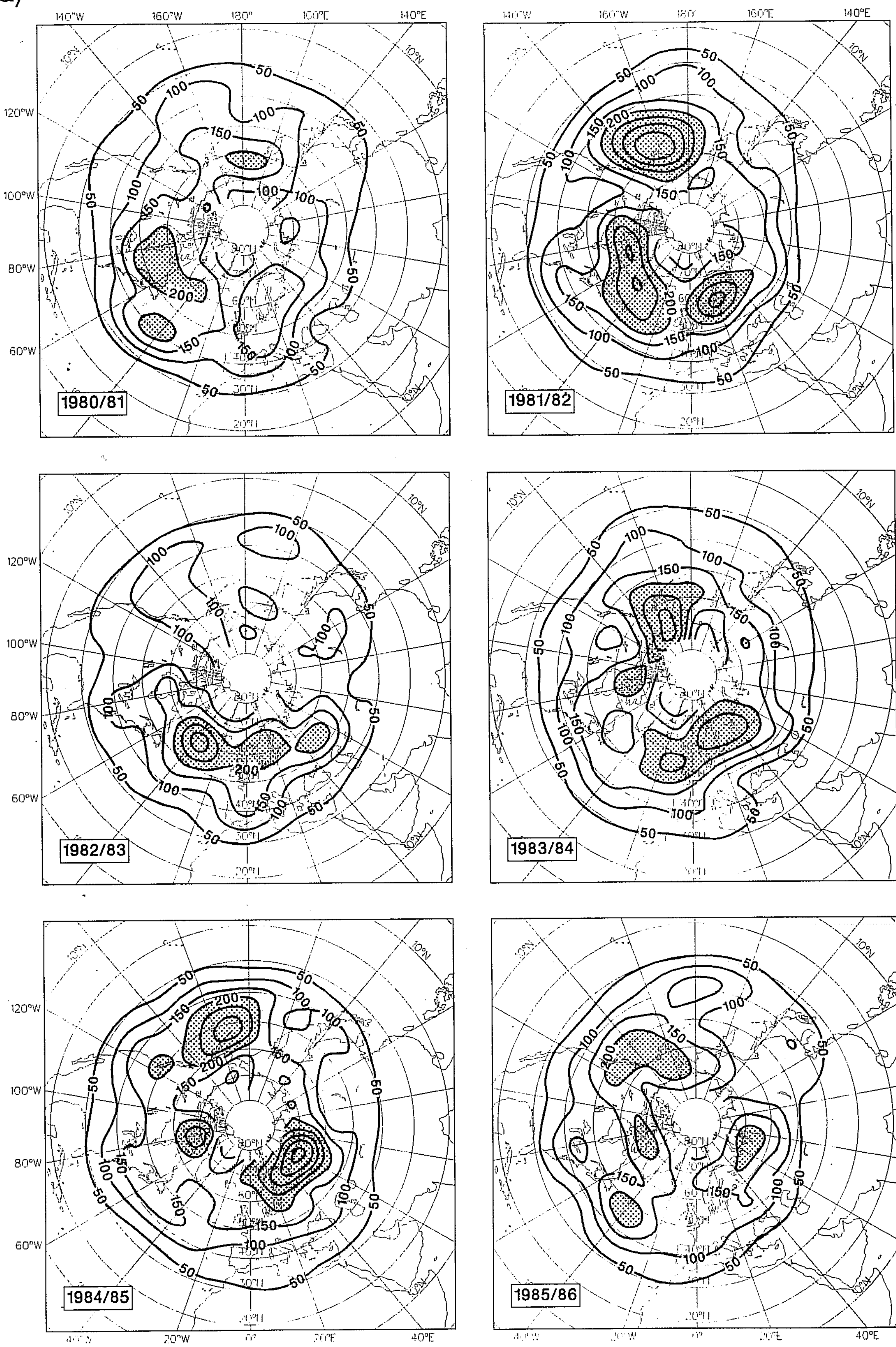
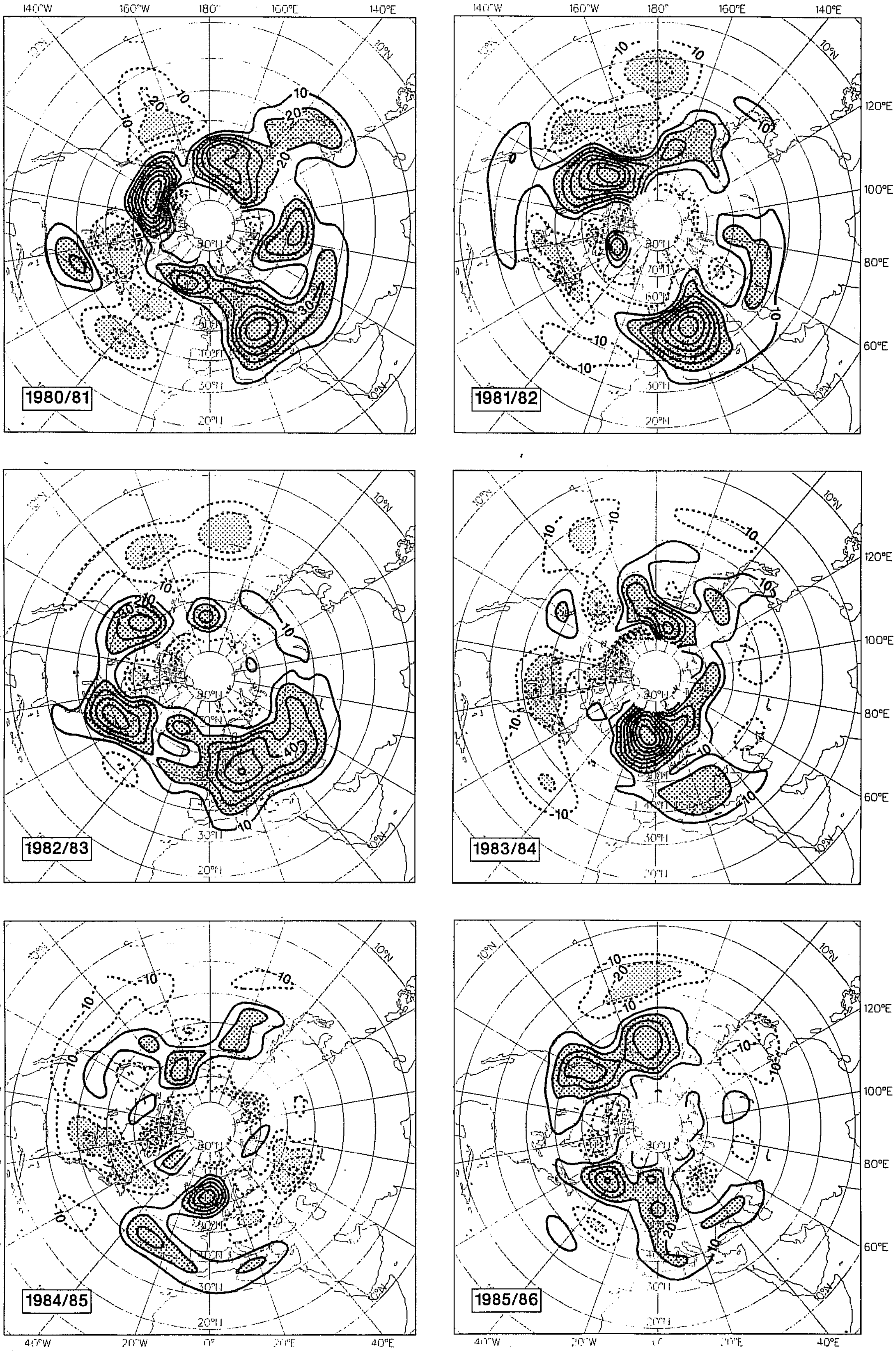


Fig. 3 Low frequency variance of the geopotential height eddies at 500 hPa for 6 winters (time series of 112 days, periods larger than 5.8 days) (a) analysis, (b) D+3 forecast errors.

b)


1980/81
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1985/86
140°W
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120°E
100°E
80°E
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0°
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40°E
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20°N
30°N

Fig. 3(b)

a)

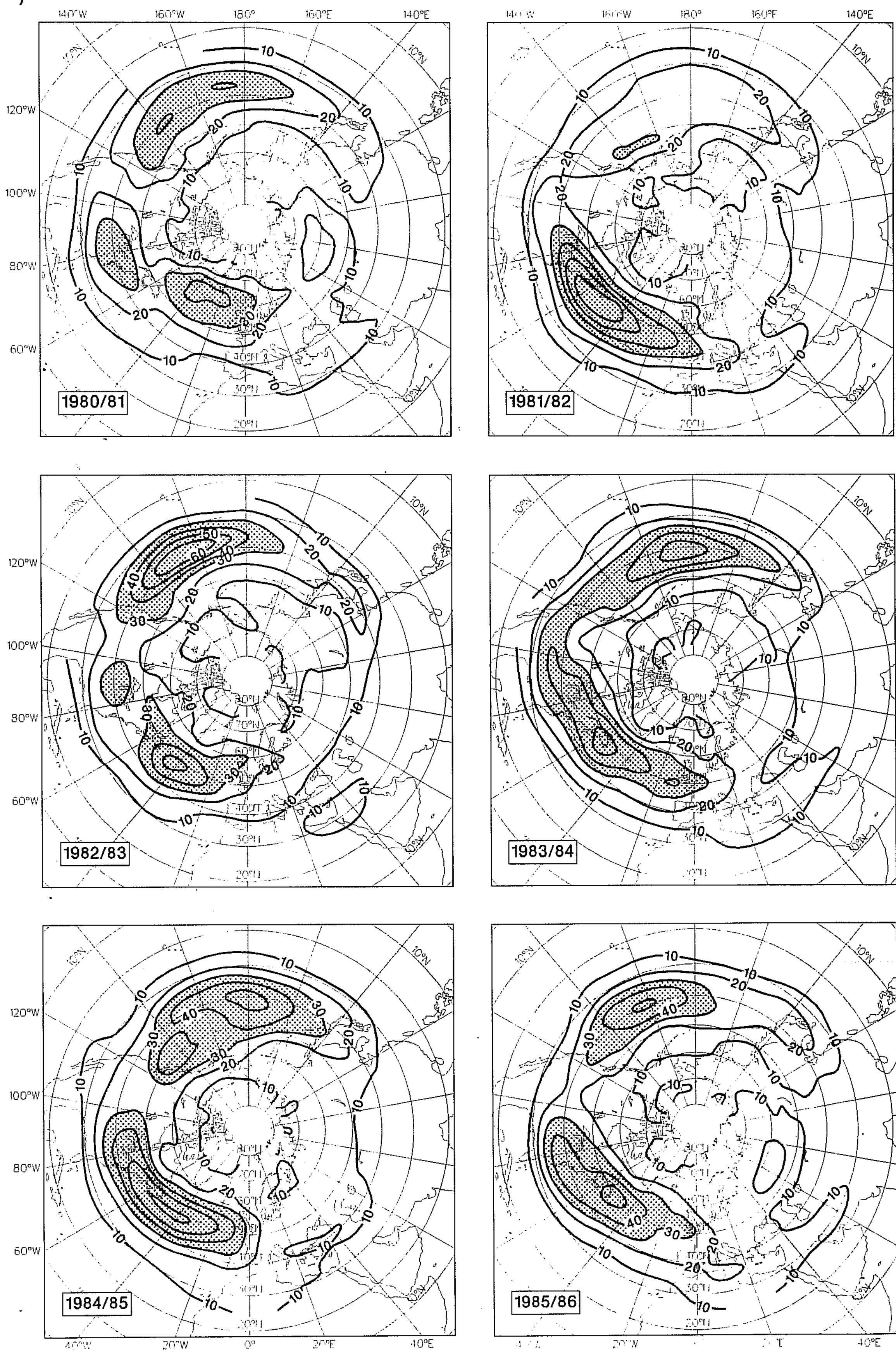
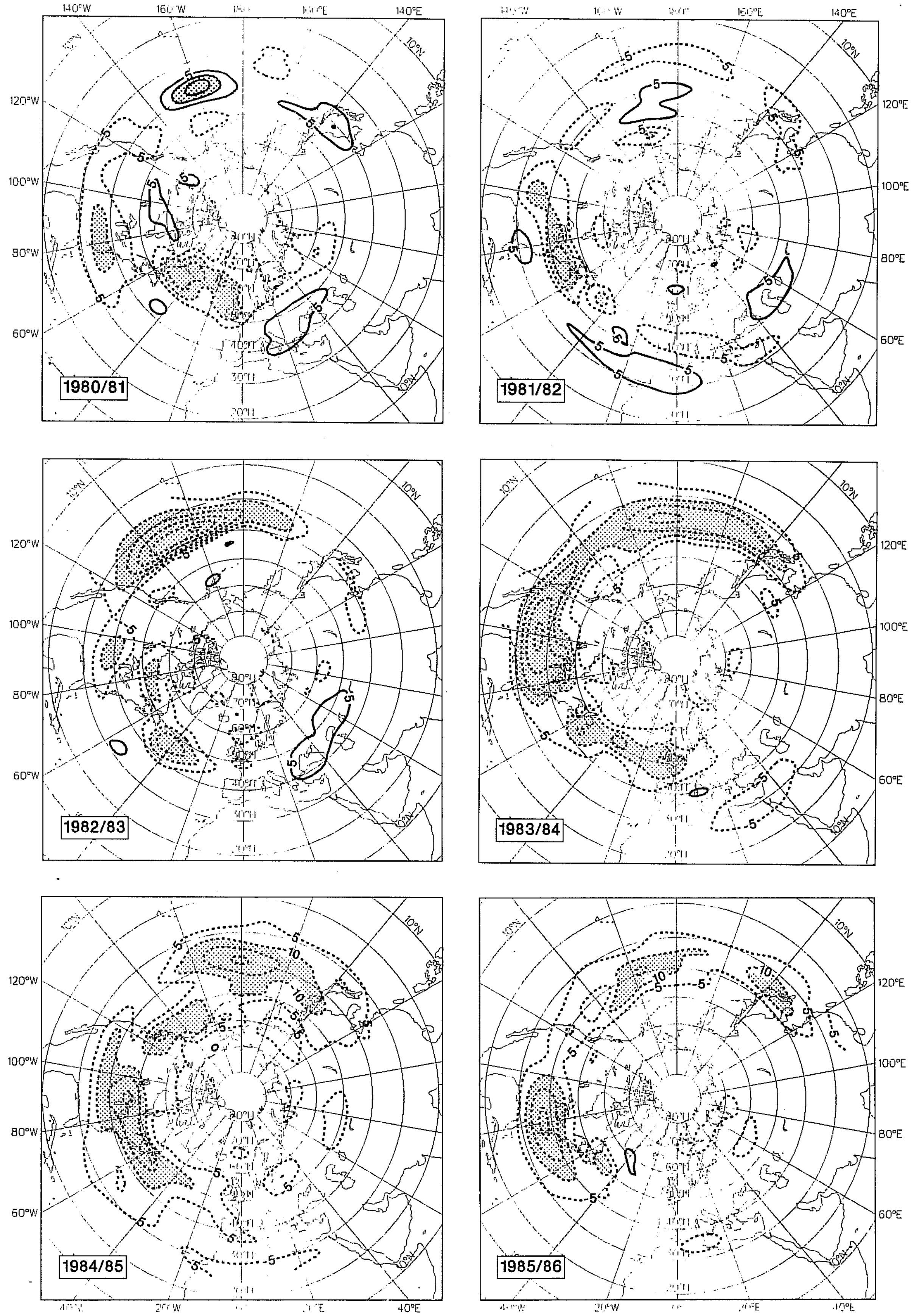


Fig. 4 High frequency variance of the meridional wind eddies at 500 hPa for 6 winters (time series of 112 days, periods between 2.3 and 3.5 days) (a) analysis, (b) D+3 forecast errors.

b)


140°W
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1981/82
1982/83
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1984/85
1985/86

Fig. 4(b)

3. DIAGNOSIS OF FORECAST ERRORS BY RELAXATION EXPERIMENTS

The short presentation of some aspects of the seasonal forecast errors and errors of transient wave activity in the forecast shows that it is difficult to separate errors which are induced by the model mountains from errors which are generated by other processes. There is, however, an experimental method which provides a regional partition of forecast errors. During the forecast the prognostic fields can be relaxed towards the analysis in selected regions by adding an additional term to the tendency equations in those regions.

This correction term is proportional to the current forecast error, with the constant of proportionality (or the relaxation coefficient) determining the time scale of the relaxation. To enable a continuous relaxation during the forecast we have interpolated the analysed fields of mass and wind from the 6 hourly values (archived in model level format) to half hourly values matching the timestep of the model. The economic T42 (triangular truncation) version of the ECMWF spectral model has been used. Increases of resolution beyond T42 have little effect on the character of time mean errors (Cubasch and Wiin-Nielsen, 1986).

For the experimental investigation of the systematic errors we have selected 4 initial days from the winter season 1983/84. These days are spread over the season to avoid any overlapping of the forecast periods.

The types of experiments carried out and their identifiers are listed in Table 1.

3.1 Relaxation over the continents

Before we investigated errors originating from the mountains we carried out a set of sensitivity experiments in which we were able to partition the forecast errors into errors originating from continental and oceanic areas by relaxing the forecasts over the continents only (this experiment will be denoted by RL - relaxation over land). In Fig. 5 we compare 10 day mean forecast errors from control runs (CON-RG,Fig.5a) with forecast errors where relaxation was carried out over land only (RL-RG, Fig. 5b). In the latter errors, which we may call the sea errors because all error growth over land is suppressed by the relaxation, we notice a distinct difference between the Pacific and the Atlantic. Over the central parts of the North Pacific positive errors in the height field have grown to almost the same level in

Control experiment	CON
Global relaxation	RG
Land relaxation	RL
Land relaxation excluding the Himalayans	NOH
Relaxation upstream the west coast of North America excluding the Rocky Mountains	NOR
Relaxation upstream the west coast of North America including the Rocky Mountains	RR

Table 1: Type of experiments

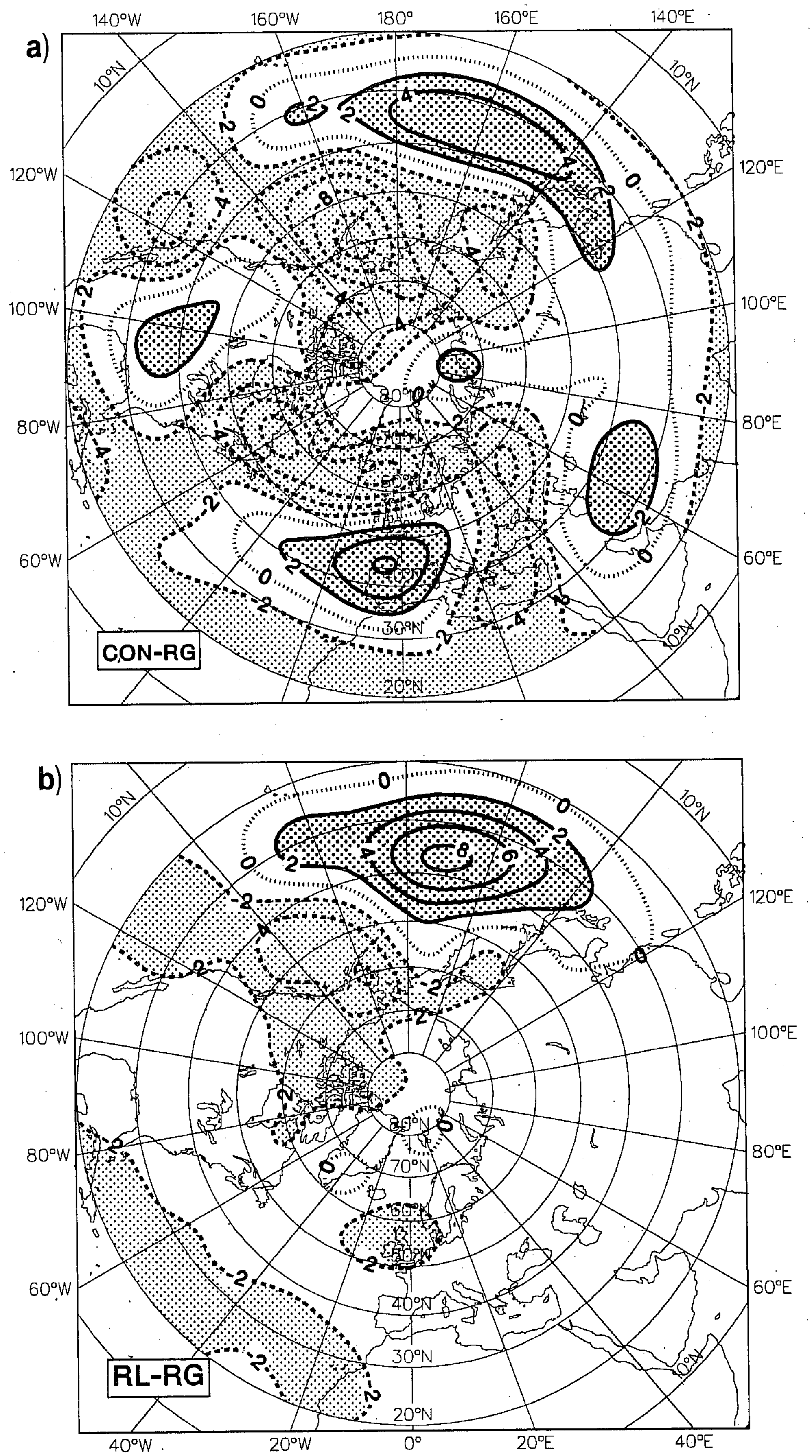


Fig. 5 Mean ten day height errors at 500 hPa. (a) Errors of control forecasts. (b) "Sea errors", defined as differences between forecasts relaxed over land and globally relaxed forecasts (RL-RG). Mean over 10 days and 4 sets of experiments, spectral truncation T21, units: dam.

both forecasts. Despite the relaxation over land the negative height errors near the coast of Alaska are only slightly smaller than in the control forecast. By contrast the relaxation over the American continent has led to a substantial reduction of the Atlantic errors. These results suggest that errors over the Pacific are dominated by errors originating from oceanic regions whereas the Atlantic errors are mainly of continental origin.

3.2 Relaxation or no relaxation over the Rockies

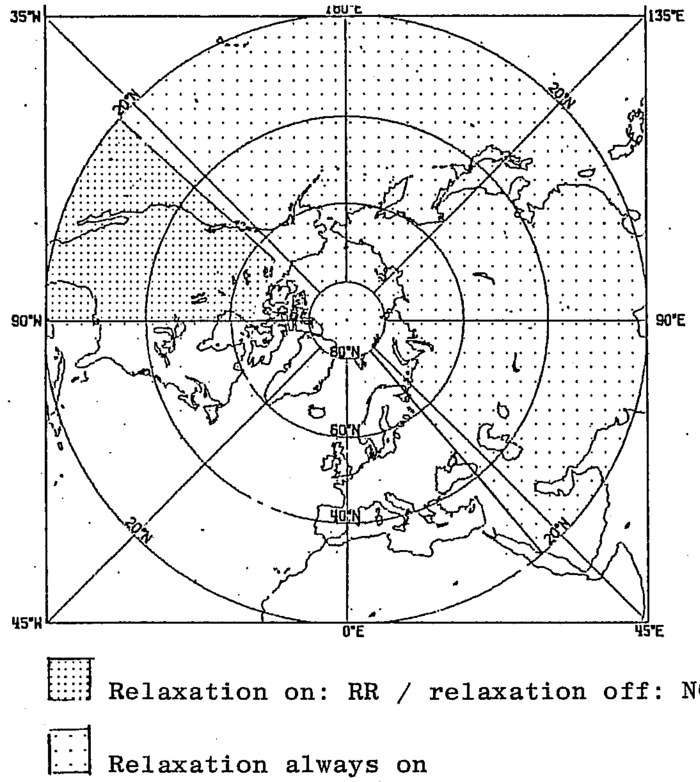
As we have found a large sensitivity of the Atlantic error pattern to error forcing over North America we want to isolate the main error source region even further. The Rocky Mountains, which constitute a major barrier for the zonal flow, are the most likely candidate for error production.

With the relaxation technique we can examine the mountain forcing problem under conditions in which the flow meeting the mountain barrier is almost error free (to within the accuracy of the analysis). We make two types of experiments NOR and RR. In both experiments we relax the forecast a long way upstream of the Rockies (Fig. 6). In experiment NOR there is no relaxation between the Rockies and the Ural Mountains. By placing the boundary of the relaxation in this experiment on the windward side of the mountains we allow the errors originating from the Rockies to develop and propagate downstream. In a second experiment (RR) the Rockies are included in the relaxation area and thereby we exclude errors from mountain forcing. The differences between these two experiments (NOR-RR) then reveal the role of mountain forcing errors downstream the Rockies.

3.2.1 Propagation of errors

As a first step in our error analysis we ask if there are preferred error tracks and if there are regions which can be identified as a starting point of error propagation.

For the examination of error propagation we use the vorticity as a parameter. From consecutive maps of vorticity differences between relaxation experiments excluding and including the Rocky Mountains in the relaxation area we can follow the propagation of differences downstream in the flow. These vorticity differences have a wavelike structure of wavenumber 8 to 10 and a phase speed between 12 and 15 m/sec. Locally we can expect that the propagating errors



Relaxation on: RR / relaxation off: NOR

Relaxation always on

Fig. 6 Relaxation mask for the Rocky Mountain experiments.

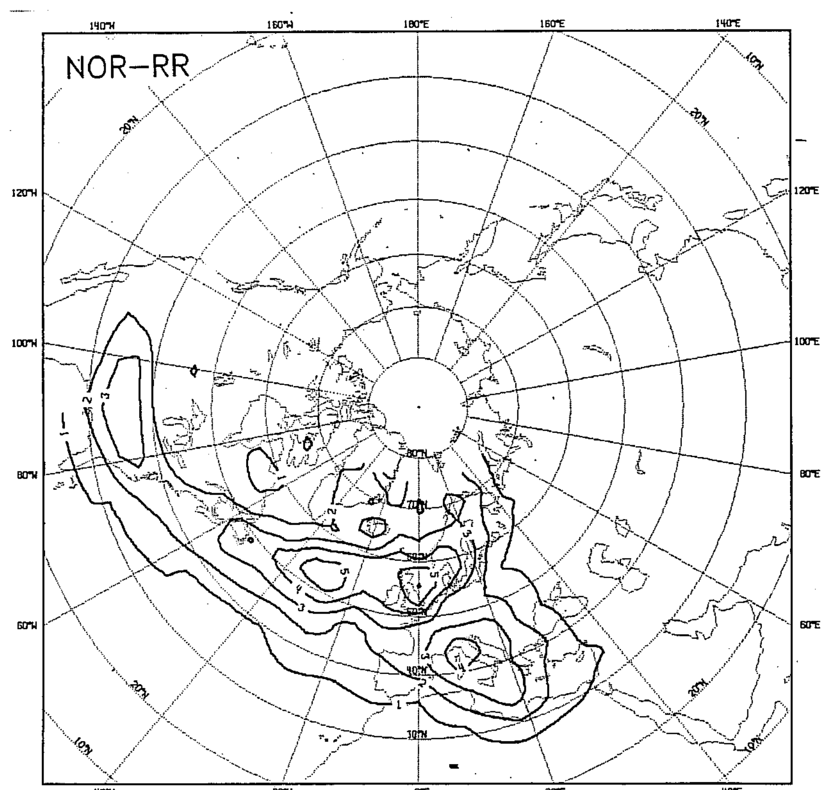


Fig. 7 Track mountain forcing errors at 500 hPa, averaged over 4 sets of experiments. The figure shows the high frequency variance (periods smaller than 3.3 days) for the vorticity differences between experiments excluding and including the Rocky Mountains in the relaxation (NORR-RR). Units: 10^{-10} s^{-2}.

produce vorticity oscillations in the forecast differences with periods close to 3 days. A high pass frequency filter (periods smaller than 3.3 days) will therefore be applied to vorticity error variance to identify error tracks.

The horizontal distribution of this variance at 500 hPa (Fig. 7) clearly depicts the major error track originating from the low latitude region of the Rocky Mountains. The error track follows closely the usual storm track across southern parts of the North America and the Atlantic, and splits into a northern and southern branch over Europe.

3.2.2 Errors of the baroclinic waves

The existence of a well defined error track makes it very interesting to investigate the transient wave errors. To concentrate our discussion on the baroclinic waves we have selected the meridional wind as a parameter and calculated the variance in a frequency band which contains periods of up to 3.3 days only. The variance distribution at 500 hPa in the analysis (Fig. 8a) shows the Atlantic storm track extending from the lee of the Rocky Mountains into western Europe. Though this storm track represents only 40 days (four ten day experiments) of the winter season we find a close agreement to the seasonal mean storm track (winter 1983/84 in Fig. 4a).

In the control forecasts the baroclinic waves suffer a weakening which amounts to a reduction of variance in the order of 40% (Fig. 8b) in the North American and west Atlantic part of the storm track. Though the spectral technique using only 20 write up times in the time series suffers from poor spectral resolution we found a good agreement to the seasonal day-3 forecast errors (Fig. 4b) for the 1983/84 season. The differences in high frequency variance between the two experiments excluding and including the Rocky mountains in the relaxation domain (NOR-RR, Fig. 8c) show a strong weakening of the baroclinic waves in the lee of the Rockies and further downstream over the Atlantic. This result suggests that errors from the main mountainous region of North America cause a damping of the baroclinic waves in the Atlantic storm track.

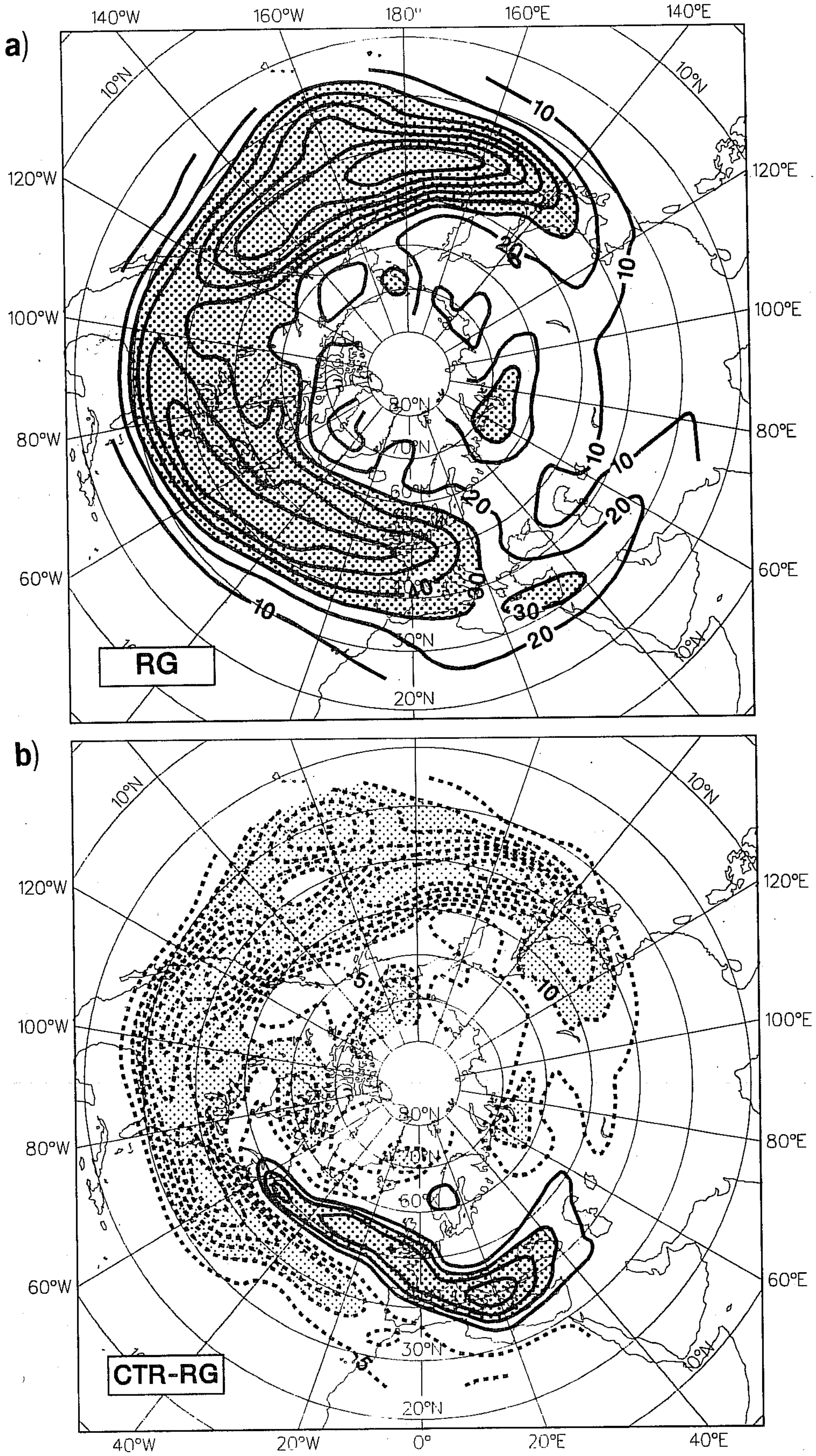
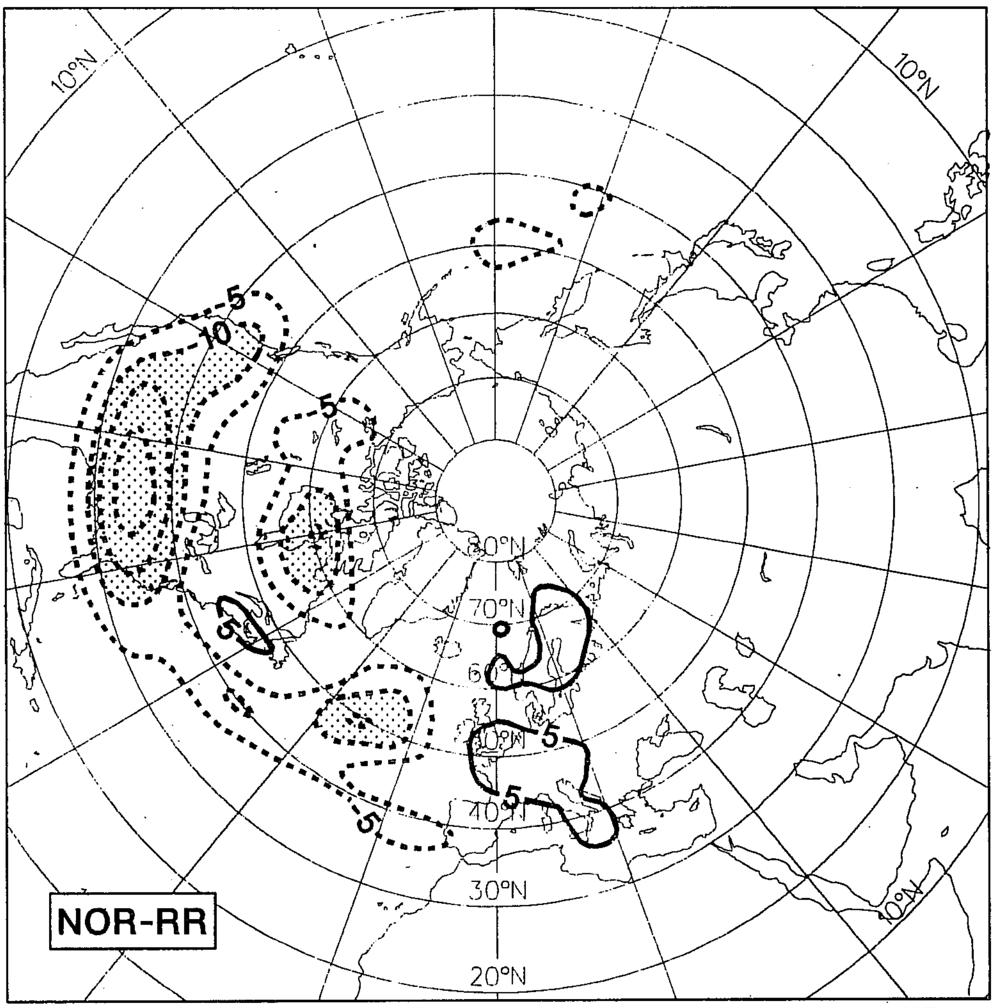


Fig. 8 High frequency variance and variance errors for the meridional wind (periods smaller than 3.3 days) at 500 hPa, averaged over 4 sets of experiments. (a) variance of the globally relaxed forecasts (RG), (b) control forecast errors (CON-RG), (c) difference between the experiments excluding and including the Rocky Mountains in the relaxation (NOR -RR). Units: $m^2\ s^{-2}$.

c)



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80°N
70°N
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40°N
30°N
20°N
10°N
NOR-RR
40°W
20°W
0°
20°E
40°E

Fig. 8(c)

3.2.3 Horizontal structure of the time mean error

The effect of mountain forcing errors on the time mean flow pattern can be estimated from error maps at 500 hPa showing the difference between the experiments excluding and including the Rockies in the relaxation (Fig. 9). For the 10 day mean we notice a large similarity to the control forecast error structure (see Fig. 5a). The positive height errors over central and northern parts of North America and negative height errors over the Norwegian Sea are also very similar to the seasonal D+3 forecast pattern for the winter 1983/84 (Fig. 2b)

3.3 Relaxation or no relaxation over the Himalayas

To investigate the impact of errors in the Himalayan area on the flow further downstream we modified our land-only relaxation experiments (RL). In this experiment (NOH) we excluded additionally a region downstream from the windward side of the Asian mountains (see Fig.10). In the experiments where forecasts were relaxed towards analyses over land (RL) we found only a small impact on the evolution of errors over the Pacific. Therefore we can only expect small effects of mountain errors over east Asia on the flow further downstream.

3.3.1 Propagation of errors

The downstream propagation of errors from the Himalayan region can again be identified from local spectral analysis of vorticity errors for the full forecast period in the same way as for the Rocky Mountain experiments. The distribution of the high frequency variance of vorticity errors shows the major error track (Fig. 11). The key region for downstream propagating errors turns out to be in north-west China on the lee side of the Altai-Sajany mountains. This is known to be an area where the largest frequencies of cyclogenesis occurs (Chung et al., 1976). The error track then follows the usual storm track north of the subtropical jet axis across the Pacific and ends where the relaxation dampens all errors over the American continent.

3.3.2 Errors of the baroclinic waves

The main activity of the baroclinic waves in the Pacific is closely connected to the subtropical jet stream. These baroclinic waves follow a track about 5 degrees north of the jet axis (see Fig. 8a).

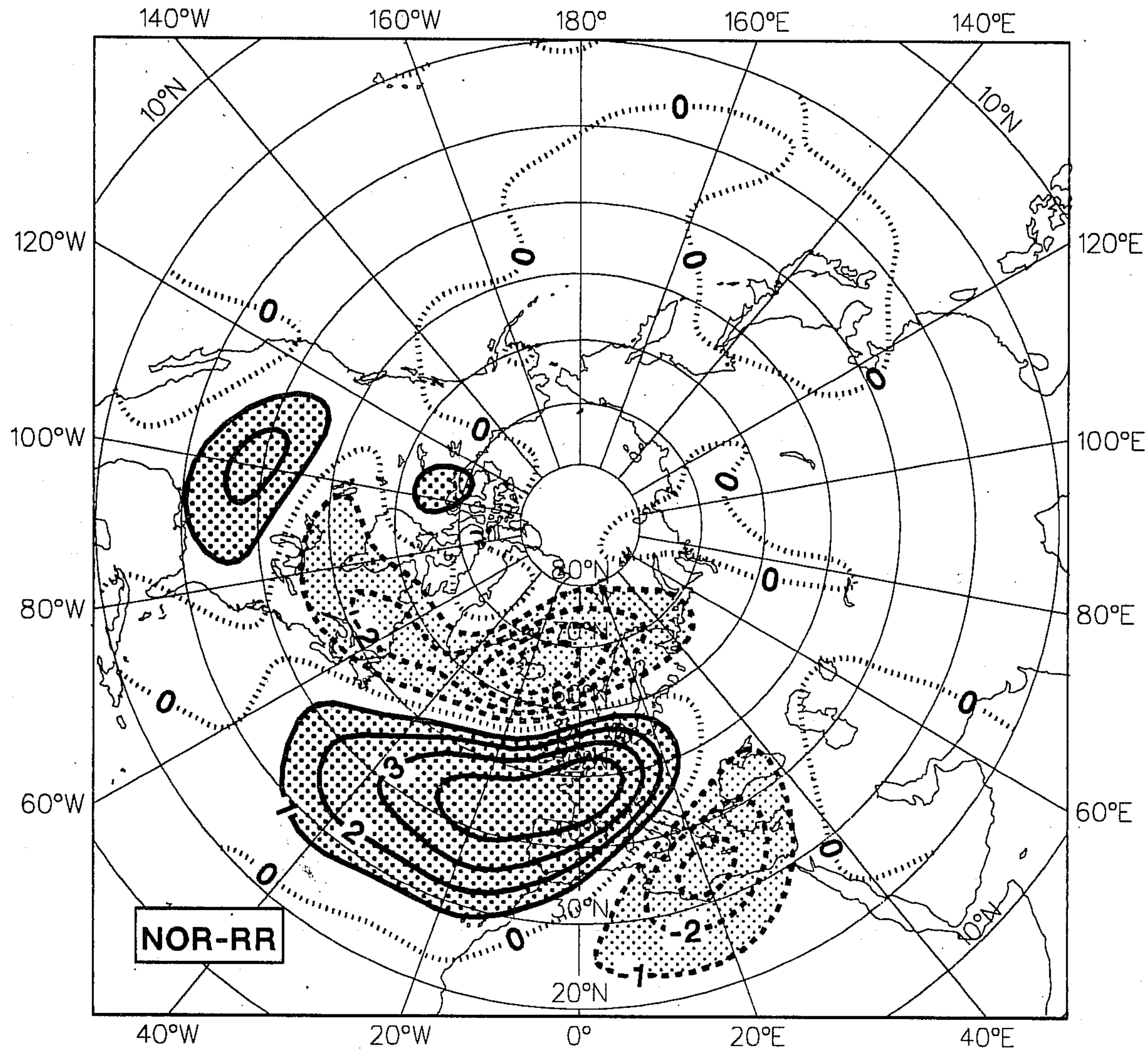
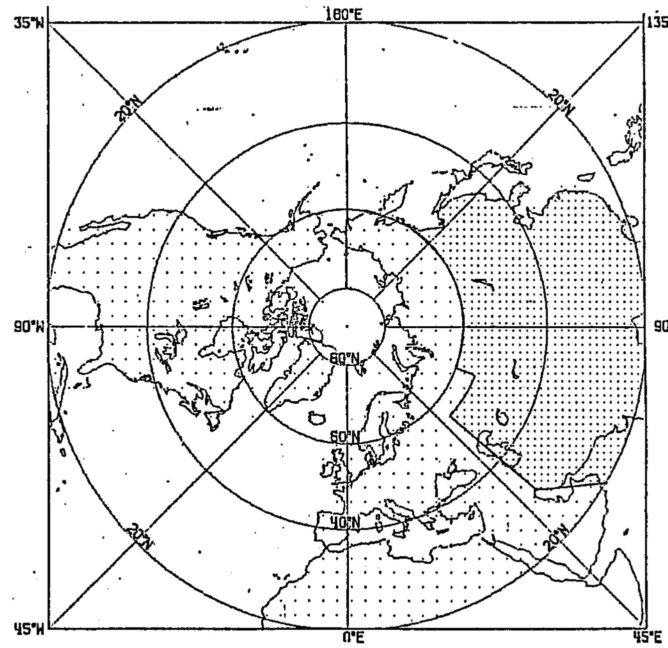


Fig. 9 Mean height errors at 500 hPa, averaged over 10 days and 4 sets of experiments, spectral truncation T21, units: dam. Errors are defined as differences between experiments excluding and including the Rocky Mountains (NOR -RR). Units: dam.



Relaxation on: RL / relaxation off: NOH

Relaxation always on

Fig. 10 Relaxation mask for the Himalaya experiments.

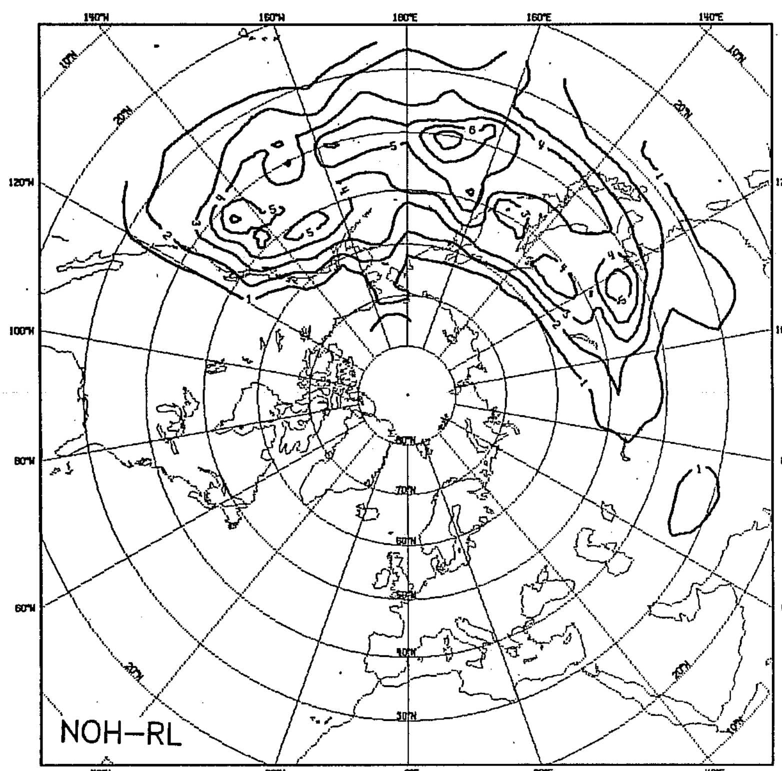


Fig. 11 Track of mountain forcing errors at 500 hPa, averaged over 4 sets of experiments. The figure shows the high frequency variance (periods smaller than 3.3 days) for the vorticity differences between experiments excluding and including the Himalaya in the relaxation (NOH-RL) Units: $10^{-10}\ s^{-2}$

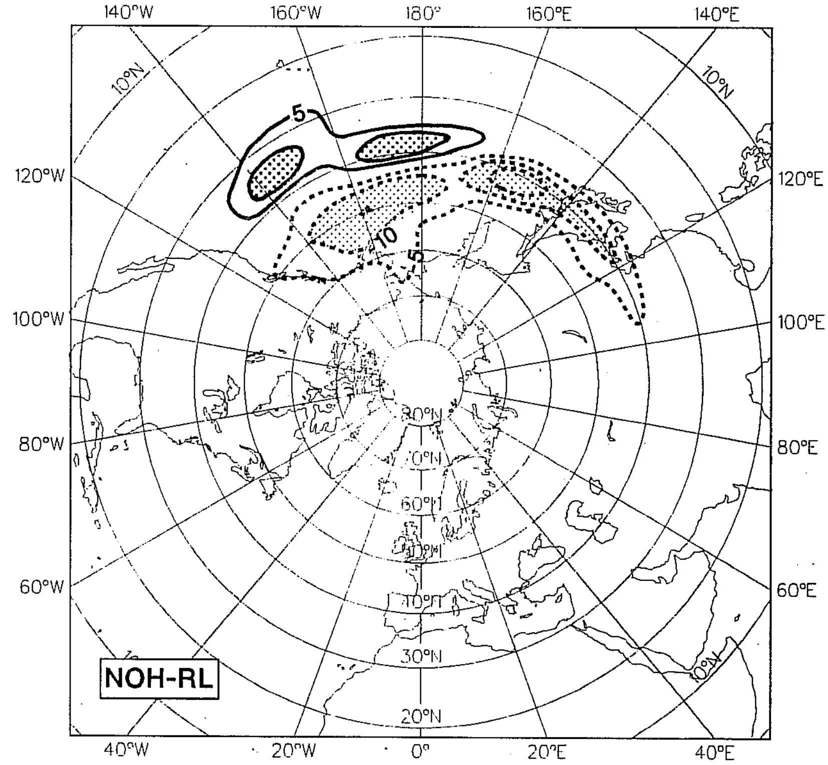


Fig. 12 High frequency errors for the meridional wind (periods smaller than 3.3 days) at 500 hPa, averaged over 4 sets of experiments. Difference between experiments including and excluding the Himalaya in the relaxation (NOH-RL). Units: $m^2\ s^{-2}$.

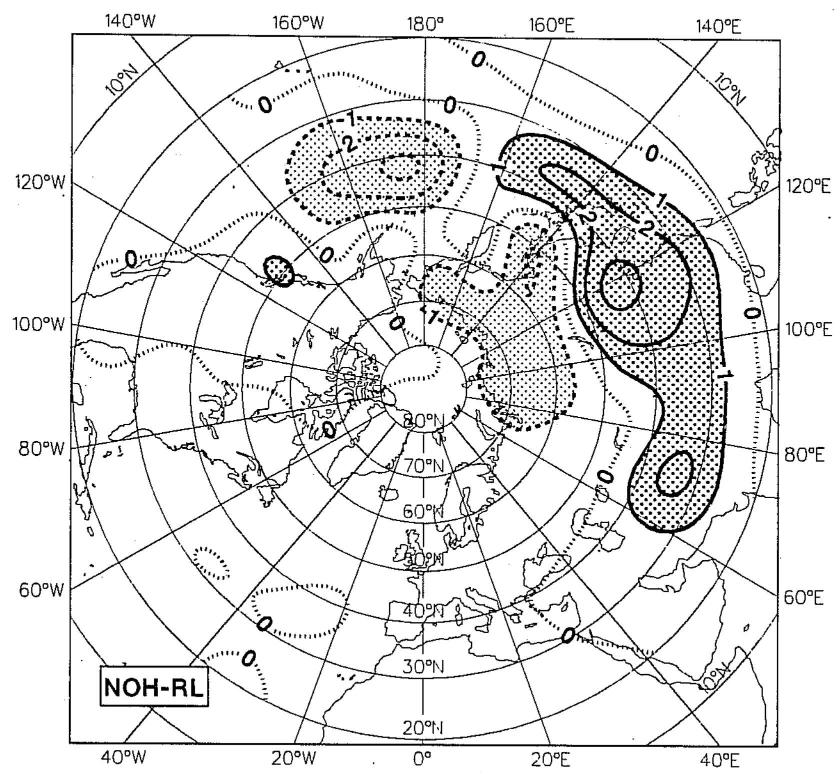


Fig. 13 Mean height errors at 500 hPa, averaged over 10 days and 4 sets of experiments, spectral truncation T21, units: dam. Errors are defined as differences between experiments excluding and including the Himalaya in the relaxation (NOH-RL). Units: dam.

In the control forecasts the baroclinic waves are weakened over almost the entire Pacific with the strongest damping taking place in the centre of the wave activity (Fig. 8b). The errors, as they appear in the difference between the experiments excluding and including the Himalayas in the relaxation (NOH-RL), show a dipole structure with increasing values south of the storm track centre and decreasing to the north (Fig. 12). This structure differs from the control forecast errors, and its magnitude is only a third of the control forecast errors. This suggests that errors generated in the Himalayan region have a smaller influence on the transient waves further downstream than errors over the Rocky mountains have for the baroclinic waves in the Atlantic storm track.

3.3.3 Horizontal structure of the mean errors

The fact that errors from the Asian continent do not change the typical time mean error pattern over the Pacific was demonstrated with the relaxation over land (see Fig. 5b). The dipole structure of too low heights close to the coast of Alaska and too large heights just south to 40°N in the control forecast is little affected by relaxing the forecast over land. The differences between the forecasts including and excluding the Himalayas in the relaxation region are shown in Fig. 13. Here we see an anticyclonic error pattern in the lee of the Himalayas and a cyclonic pattern further downstream, rather like the Rocky Mountain experiments. Unlike over the Atlantic where height errors due to mountain forcing problems are similar to the control forecast errors, the height errors in the Pacific due to errors in the Himalaya region have a orientation opposite to the control forecast errors. The magnitude of Pacific "mountain errors" is also much smaller than the Atlantic "mountain errors".

4. CONCLUSIONS

The nonlinear complexity of a primitive equation model makes it difficult to isolate errors of certain processes from the diagnosed errors of operational forecasts. From the investigation of six winters of operational forecasts we can make only some speculative conclusions about the extent to which orographically related forecast errors are part of the total errors. Very useful additional information can be gained by performing some relaxation experiments in which certain areas in the forecast are relaxed towards the analysis. From these experiments we could separate the errors originating from mountainous region from other errors. We can combine the long-term comparative diagnostics and the experimental diagnostics to give the following conclusions concerning orographically related forecast errors.

i) Time mean and transient errors in the lee of the Rocky Mountains are to a large extent produced by errors generated in the mountainous region itself.

ii) Errors from the Rocky Mountains form a rather narrow wave train along the Atlantic storm track and lead to substantial weakening of the baroclinic waves.

iii) The mountain forcing induced mean error pattern explains a part of the typical time mean operational forecast errors of positive height errors over central parts of North America and negative height errors in the North Atlantic-western European region.

iv) Errors in the Pacific are affected by mountain forcing problems in the model to a much lesser extent than errors in the Atlantic.

v) The negative mean height errors along the north east coast of Asia cannot be explained by errors originating from the Asian mountain region.

vi) The effect of mountain forcing problems on the transient waves in the Pacific is comparatively small. The higher frequency errors have a rather broad error track, though it is noticeable that these errors do not originate from the main Himalayan mountain massif, but rather from the Altai-Sajany mountains which have a more perpendicular orientation to the flow.

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