ENERGETICS AND SKILL OF EXTENDED RANGE PREDICTIONS WITH THE ECMWF T21 MODEL

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ABSTRACT

A series of 28 extended range predictions with the ECMWF T21 model has been investigated in order to find relationships between energetics and forecast skill, which might be useful for an a priori assessment of the latter. The study is limited to northern midlatitudes (27° - 75°N) without regional subdivision; all experiments are for winter cases.

Only a few relationships could be found. The most interesting one exists between the skill of the 30 day mean forecasts and the concurrent baroclinic conversion in the planetary waves (CE1-3) of the model. Correlation coefficients about -0.5 (+0.5) between CE1-3 and RMS-errors (anomaly correlation coefficients) of geopotential height predictions are obtained, which are significant at about the 99%-level. The most outstanding synoptic feature connected with this relationship is a relatively weak trough-ridge system near North America in simulations with small CE1-3 , counteracting an opposite anomaly in the respective verifying analyses.

The existence of the relationship could also be verified in 9 ECMWF-experiments with T42-resolution.

1. INTRODUCTION

The skill of numerical forecasts - especially for the medium and extended range - varies considerably from case to case. It thus seems desirable to supply the user with an a priori assessment of the skill of a single forecast at the time it is issued. This is especially true for the extended range forecasts, where the mean skill is rather low.

In the last few years, therefore, a number of scientists have investigated the reasons of the variation in forecast skill and tried to develop methods for skill prediction. With respect to medium (and short) range predictions, a large number of predictors of forecast skill has been identified, as for instance:

- the skill of previous forecasts from the same model, verifying on the starting date of the forecast in question;
- the spread between individual members of an ensemble of forecasts starting from different analyses or conducted with different models;
- anomalies in the initial or predicted fields, or the predicted development of the (large scale) flow field

(see e.g. Branstator(1986), Dalcher et al.(1988), Kalnay and Dalcher (1987), McCalla and Kalnay(1987), Palmer and Tibaldi(1986,1987), and Wash und Boyle(1986)). The predictors are generally best suited for regional skill prediction, whereas they are of limited or no use for a hemisphere or the globe.

Relatively little has been found up to now for the extended range (predictions beyond day 10). Many investigators have looked for relationships between spread and skill of ensemble forecasts. There is some evidence that useful correlations exist up to the period of days 6-15, but beyond this the results do not give a unique picture (see e.g. the contributions of Baumhefner(1988), Brankovic(1988), Dickinson et al.(1988), and Tracton and Kalnay(1988) in this volume). Roads(1988) concluded from an idealized study that significant spread/skill correlations should be obtainable at least out to day 20, but useful predictions of skill might be limited to only a small number of cases. Dickinson et al.(1988) found correlations between initial field anomalies and forecast skill again up to the period of days 6-15. Murphy and Dickinson(1987) presented results of extended range integrations, which suggest that large predicted anomalies for days 1-15 point to relatively high forecast skill, especially for days 16-30.

The present paper tries to identify relationships between initial or forecast energy budget terms and skill of extended range predictions, whereby an ensemble of 28 experiments with the ECMWF T21 model is used. Section 2 describes the experiments and evaluation procedures. Section 3 presents the results, mainly in form of correlation coefficients between energy budget terms and skill scores and synoptic charts of 500hPa heights. Section 4 demonstrates that the most interesting relationships may also be found in some experiments with higher horizontal resolution. Finally, a summary is contained in section 5.

2. EXPERIMENTS AND EVALUATIONS

The investigation is based on a total number of 28 60-day-predictions with the ECMWF T21-model, in the version used at the University/ Max-Planck-Institut in Hamburg (see Dümenil and Schlese, 1987). Starting dates are the 1.12., 11.12., 21.12., 1.1., 11.1., 21.1. and 1.2. in the winter seasons 81/82 to 84/85. Starting time is generally 12Z, whereas 00Z results are used for verification purposes. For convenience, predictions for (n-1/2) days will be referred to as n day predictions. For the integrations, sea surface temperatures were set to their (time dependent) climatological mean values.

The northern midlatitude belt (27° - 75°N) has been chosen to look for relationships between the skill of the forecasts and the energetics of the initial fields and the forecasts themselves. Energy budget terms are area mean values of AZ, CA, AE, CE, KE, CK, KZ and CZ (see Arpe et al., 1986, for a description of the defining equations and the evaluation procedure). For the forecasts, they are evaluated on a day to day basis and then averaged in time.

The skill of the forecasts is expressed by area mean values of root mean square errors (RMSE) and anomaly correlation coefficients (ACC) for the time-averaged geopotential height predictions. (Ensemble mean values of ACC have generally been built by first z-transforming the ACC, taking the average of the transformed values and then retransforming.)

Both, energy budget terms and skill scores are calculated for different regimes of zonal wavenumbers, especially 0, 1-3, 4-9 and 1-21 (or 1-16 for energy budget terms, which is considered to be practically identical to 1-21). The wavenumber regime will generally be indicated by appending the values for the wavenumbers to the symbol of the term considered (e.g. KE1-3, RMSE4-9, etc.).

All analyses (for the initial fields and the verifications) are from the ECMWF (see 6.). The same is true for the climate, which is based on the analyses for the period Jan.1979 to Dec.1984. However, for the verification in one particular winter season, the analyses of just this season have been excluded.

3. RESULTS

3.1 Correlation coefficients

Correlation coefficients (r) have been determined between the values of the energy budget terms and the RMSE and z-transformed ACC (ZACC) values. All relevant series have been proven not to be distinguishable from normally distributed series at a 95% (or even a 90%) level (Kolmogorov-test; see Taubenheim, 1969). Therefore, the significance of the correlations can be determined with the values given in Table 1.

$\lvert r \rvert$	.250	.317	.374	.479	.588
signif. level	80%	90%	95%	99%	99.9%

Table 1 Corresponding values of correlation coefficients and significance level of the correlations between two series of 28 normally distributed numbers each.

Correlations have generally been determined between the energy budget terms of a certain wavenumber regime (0, 1-3, 4-9 and 1-16) and the skill of the forecasts in the same wavenumber regime (except 1-16) as well as the skill in the wavenumber regime 1-21; the latter representing the skill of the "total" forecasts. (Verifications of the fields including the zonal means, i.e. for zonal wavenumber regime 0-21, yielded unsatisfactory results for the ACC, which in some of the pressure levels did not converge to zero with increasing forecast time.)

Time intervals considered are days 1-10, 11-20 and 1-30, where - on average - the 28 forecasts have at least some skill (i.e. positive ensemble mean ACC).

In order to get a first impression, whether a certain energy budget term (as specified in 2.) might be useful for predicting forecast skill, it has been checked, whether distinctly more than five percent of the correlation coefficients in which the term is involved are significant at the 95% level. (A rigorous proof, whether more correlation coefficients are significant at the 95% level than might be expected by chance, cannot be obtained easily, because the terms entering into the correlations are interrelated themselves, as is e.g. obvious for the forecast skill (RMSE or ACC) of the 10 day mean and 30 day mean predictions.)

Only few significant correlations are found for the zonal mean budget terms (AZ,KZ,CZ) and the barotropic conversion term (CK), which are therefore excluded from further discussions.

For the eddy kinetic and eddy available potential energy (KE,AE), only about 5% of the correlation coefficients are significant at the 95% level, but these are all due to positive correlations with the RMSE in the first 10 day period. An illustration of the results is given in Table 2.

	RMSE1-21 1-10d	ZACC1-21 1-10d
KE1-16, 0d	.312	.091
KE1-16,1-10d	.384	.134
AE1-16, 0d	.521	.051
AE1-16,1-10d	.277	.223

Table 2 Correlation coefficients between initial or predicted values of eddy energies and RMSE or ZACC for wavenumber regimes and period as indicated. The underlying series are from 28 predictions and for the region 27° -75°N and 1000-30hPa. Underlined figures are significant at the 95% level.

The large positive correlation coefficients in the first column obviously reflect the well-known fact that in case of large disturbance amplitudes forecasts are likely to produce large RMSE. The small (but not significantly) positive values in the second column indicate that at the same time ACC values tend to be somewhat higher than normal. This may be due to the fact that the ACC, similarly to the RMSE, appears to be sensitive to the magnitudes of the disturbance amplitudes, as has been discussed by Arpe et al.(1985).

Since both the eddy energies as well as the forecast skill indicators are dominated by the planetary waves, similar correlation coefficients as in Table 2 are obtained, if one considers these waves separately.

The most interesting results have been obtained for the baroclinic conversion term (CE). A total fraction of 15% of the correlation coefficients, in which this term is involved, is significant at the 95% level. For the conversion term between zonal and eddy available potential energy (CA),the correlation coefficients with the forecast skill indicators are generally similar to those obtained for CE. This is not surprising, since they tend to be correlated with each other at least for the time scales considered here (10 to 30 days). This has been shown e.g. by Schilling(1987) for single zonal wavenumbers (1 to 8) in the atmosphere north of 45°N, and has also been verified for our own 30 day mean forecast results for the wavenumber regimes 1-3 and 4-9 (not shown). The absolute values of the correlation coefficients with the forecast skill indicators are generally lower for CA than for CE and all miss the 95% significance level (though some of them only slightly). Therefore, the following discussion will concentrate on CE.

Results obtained for the 30 day mean forecasts are presented in Table 3. Six of the eight correlation coefficients shown in the Table are significant (or almost significant) at the 95% level. The sign of the correlations with ZACC is in any case opposite to that with RMSE. Thus, forecasts with high initial values of CE1-3 tend to be poor according to both measures of skill. Analogously, forecasts with high values of CE1-3 during the forecasts time tend to be good according to both measures. The reverse is true with respect to CE4-9 instead of CE1-3.

For the 10 day mean forecasts most of the corresponding correlations are insignificant, some showing opposite sign than those for the 30 day mean forecasts. An exception is a rather pronounced relation between the forecasts skill in the second period (days 11-20) and the initial values of the baroclinic conversion in the synoptic scale waves (CE4-9), where correlation coefficients of -.477 and .556 (with RMSE and ZACC, respectively) are obtained.

	RMSE1-21 1-30d	ZACC1-21 1-30d
CE1-3, 0d	.304	-.175
CE1-3,1-30d	-.474	.468
CE4-9, 0d	-.366	.360
CE4-9,1-30d	.404	-.366

Table 3 Correlation coefficients between initial or predicted values of baroclinic conversion terms and RMSE or ZACC for wavenumber regimes and period as indicated. The underlying series are from 28 predictions and for the region 27° - 75°N and 1000-30hPa. Underlined figures are significant at the 95% level.

In the following, the relation between the 30 day mean forecast skill and the concurrent baroclinic conversion in the planetary waves, will be examined in some more detail. It has been selected, since it yields the highest correlation coefficients in Table 3. Moreover, the other relations are probably not independent of it. Thus, for instance, the 30 day mean values of CE1-3 and CE4-9 in our 28 forecasts are correlated with a coefficient of -.39 (i.e. at the 95% level).

As can be seen from Table 4, the relation between the 30 day mean CE1-3 and forecast skill is more pronounced if one considers only the troposphere instead of the total atmosphere, and if the forecast skill is determined from the planetary waves only instead from all waves. (The ACC values have only been determined for the total atmosphere and for single levels, not for the troposphere separately).

	RMSE		ZACC		
	1-21	1-3	1-21	1-3	
CE1-3	-.474	-.516	.468	.550	1000-30hPa
	-.583	-.661	-	-	1000-300hPa

Table 4 Correlation coefficients between CE1-3 and RMSE or ZACC in wavenumber regimes 1-21 and 1-3 for 30 day mean forecasts. The underlying series are from 28 experiments and for the region 27° - 75°N and total atmosphere (upper line) or tropsphere (lower line). All figures are significant at the 95% level.

If forecast skill is defined for individual pressure levels, the highest correlation coefficients with the (vertically integrated) CE1-3 are obtained in the middle and upper troposphere, whereas near the surface no significant correlations can be found. This is illustrated in Fig.1 for tropospheric mean values of CE1-3 and the forecast skill in the planetary waves.

Finally, Fig.2 gives an impression about the degree of regularity of the connection between the 30 day and area mean values of CE1-3 and forecast skill indicators.

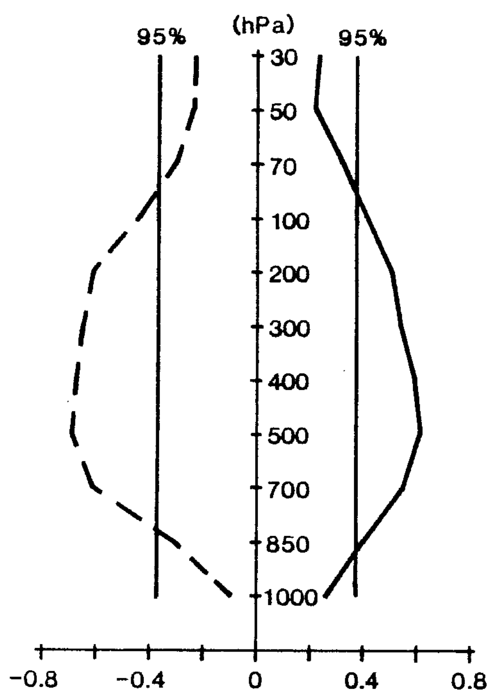


Fig. 1 Correlation coefficients between tropospheric mean values (1000-300hPa) of CE1-3 and RMSE1-3 (---) or ZACC1-3 (——) in individual pressure levels for 30 day mean predictions. The underlying series are from 28 experiments and for the region 27° - 75°N. The 95% significance level is indicated by vertical lines.

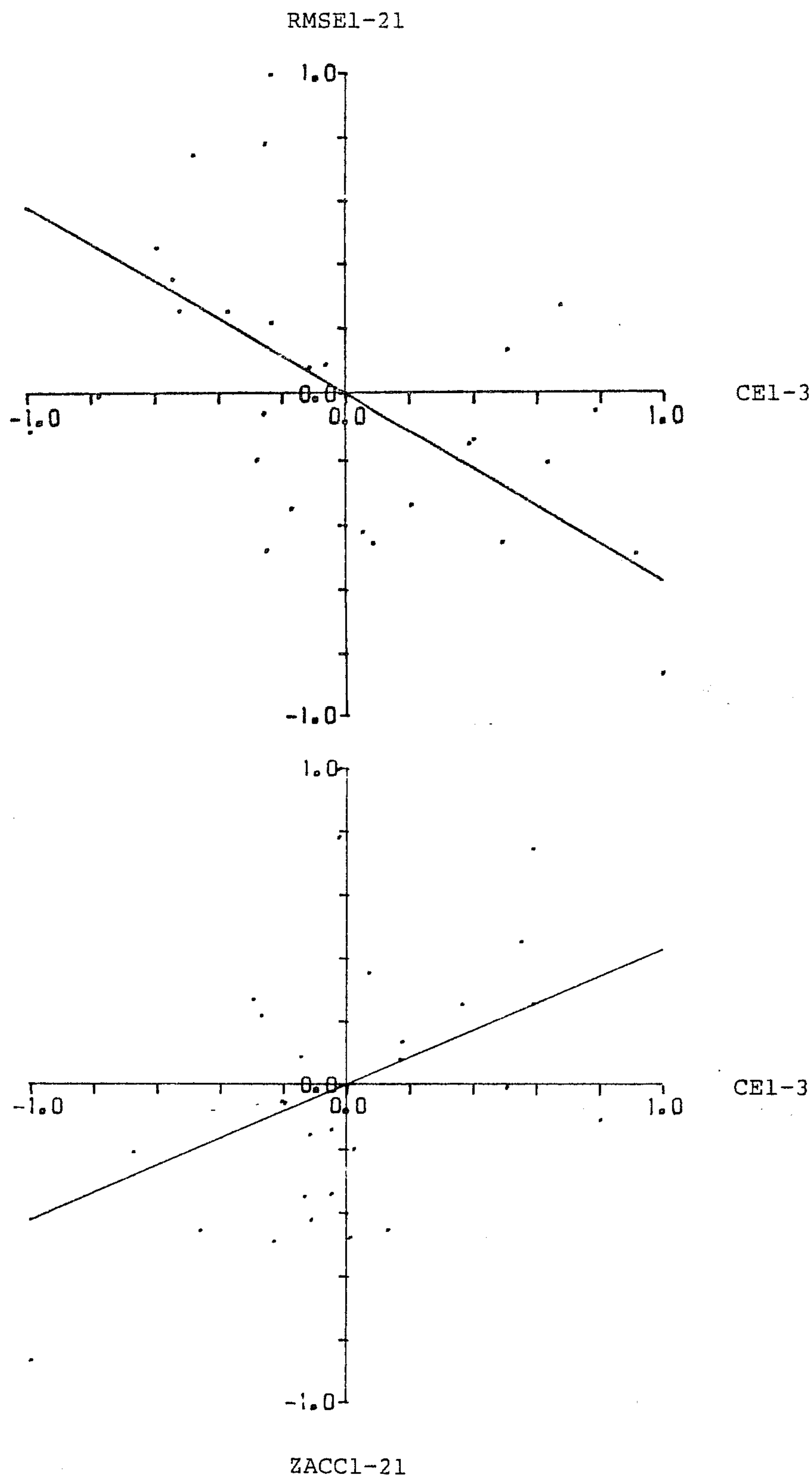


Fig.2 Scatter diagrams for deviations of CE1-3 from its ensemble mean value versus skill scores (RMSE1-21, top, and ZACC1-21, bottom) for 30 day mean values in the region 27° -75°N and 1000-30hPa. All quantities have been normalized by their maximum absolute values. Also shown are the regression lines between the normalized quantities.

3.2 Energy cycles for good and poor 30 day mean forecasts

Whereas in 3.1 correlations between individual energy budget terms and forecast skill have been discussed, we will present here the total energy cycles for good and poor 30 day mean forecasts. For this purpose, the 28 experiments have been numbered according to ascending values of RMSE (N_{RMSE}) and descending values of ACC (N_{ACC}) for the 30 day mean fields (1-30d) in the region 27° -75°N and 1000 -30hPa. The sum of ranks $N_{RMSE}+N_{ACC}$ of each experiment was used to define subensembles of the five best and the five worst forecasts, respectively. Energy cycles are shown in Fig.3 for the initial fields of the forecasts (upper part) and the 30 day mean forecasts themselves (lower part).

As can be seen from the Figure, differences in CE1-3 and CE4-9 between good and poor forecasts always have exactly the sign, which would be expected from the correlations given in Table 3. In most cases, the magnitudes of the differences are weakly significant. The (insignificant) differences in CA1-3 and CA4-9 always have the same sign as those in CE for the corresponding wavenumber regime. Differences in AE and KE in these wavenumber regimes are insignificant except for KE4-9 in the initial fields. In most cases, they, too, have the same sign as those in CE, but this is not true for AE1-3.

Of special interest in this connection is the 30 day mean energy balance in the planetary waves. We do find the differences in CE1-3 between good and poor forecasts, which are to be expected from the strong correlation between this term and the forecast skill. We also find similar (though insignificant) differences in CA1-3. But there are only very small differences in KE1-3 and no differences at all in AE1-3. Thus, the planetary wave energetics in the good 30 day mean forecasts are only characterized by large values of the baroclinic conversions and not simultaneously by large values of the eddy energies.

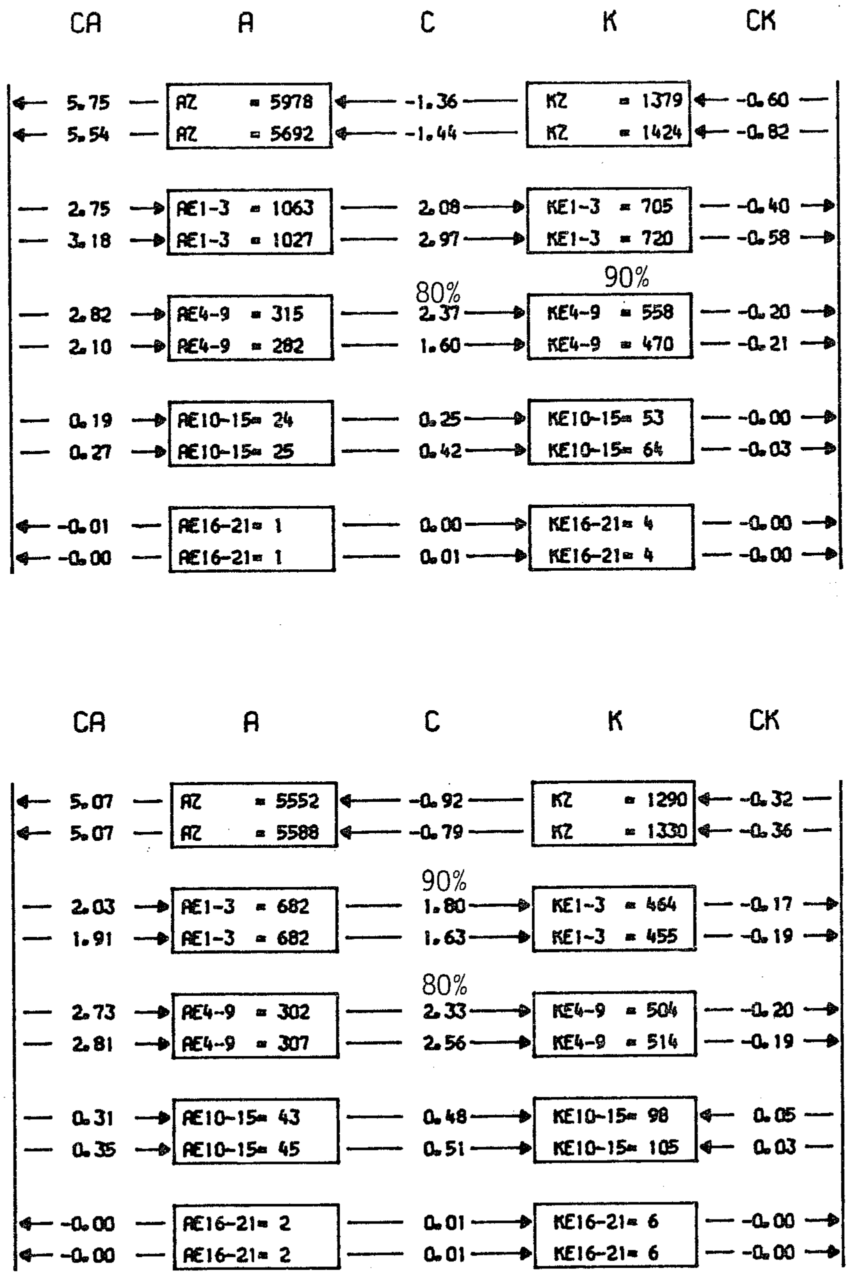


Fig.3 Energy cycles averaged over the five best and worst 30 day mean forecasts (upper and lower numbers, respectively) in the initial field (upper diagram) and in the forecasts themselves (lower diagram). All numbers are based on area mean values for 27°-75°N and 1000-30hPa. For zonal mean quantities and the zonal wavenumber regimes 1-3 and 4-9, the significance level of the differences between the numbers for good and poor forecasts is indicated by percentage values, whereever it is at least 80% (t-test, see Taubenheim, 1969). Energy values are in kJm^{-2}, conversion terms in Wm^{-2}.

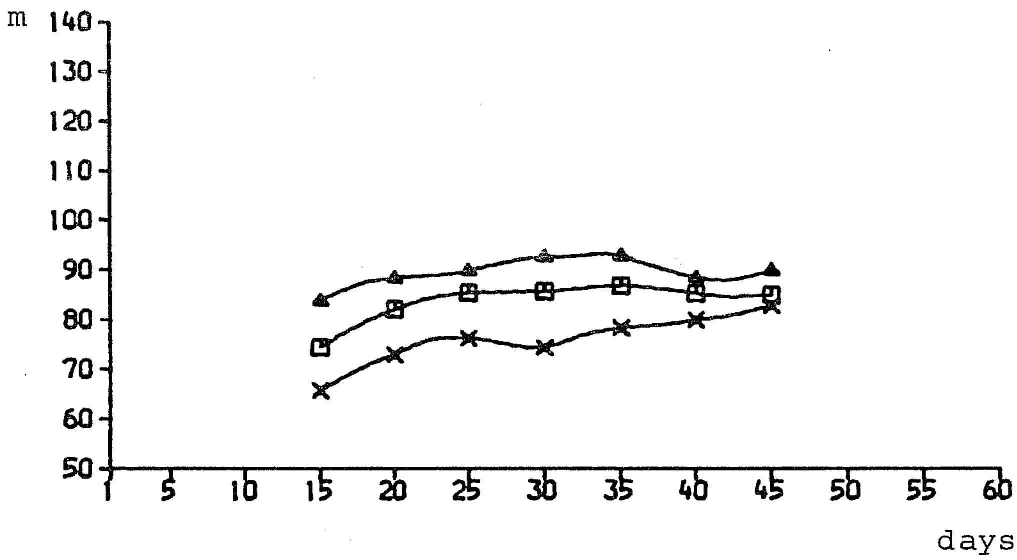
3.3 Differences between forecasts with high and low 30 day mean values of CE1-3

This chapter will be mainly concerned with the question, whether there are typical synoptic differences between forecasts with high or low 30 day mean values of CE1-3. For this purpose, subensembles of five experiments, each, with the highest and lowest mean values of CE1-3 in the period of days 1-30 and the region 27° -75°N and 1000-30hPa were created and compared to each other as well as to the total ensemble of 28 forecasts.

First of all, Fig.4 demonstrates the average skill of the forecast ensembles. As can be seen from the upper part of the Figure, 30 day mean RMSE values for the experiments with high CE1-3 are lower than those for the experiments with low CE1-3 throughout the forecast time. Up to the period of days 11-40 (i.e. the mean time of day 25), these differences are significant at the 95% level (t-test). Corresponding differences in the ACC values (lower part of the Figure) only occur in the beginning of the forecasts. They just miss the 95% significance level for the first 30 day period.

Fig.5 compares 30 day mean 500hPa height forecasts and corresponding analyses for the total ensemble of 28 forecasts and the subensembles of 5 forecasts, each, with high and low CE1-3, respectively. The mean observed field in Fig.5a may for practical purposes considered to be the winter climate field of the 500hPa height (though actually analyses for the period 2 Dec. to 3 Mar. enter and are attributed variable weights).

Error structures for the two subensembles are similar over most of the eastern part of the hemisphere (0°-140°E), with somewhat higher amplitudes for the forecasts with high CE1-3. Over the rest of the hemisphere, errors are generally much more pronounced for the sub-ensemble with low CE1-3. The most striking feature is a relatively weak simulation of the trough-ridge system near North America in these cases, counteracting an opposite anomaly in the verifying analyses (see below). Note, that in the western part of the hemisphere and over the western North Pacific the error structure for the total forecast ensemble is similar to that for the subensemble with low



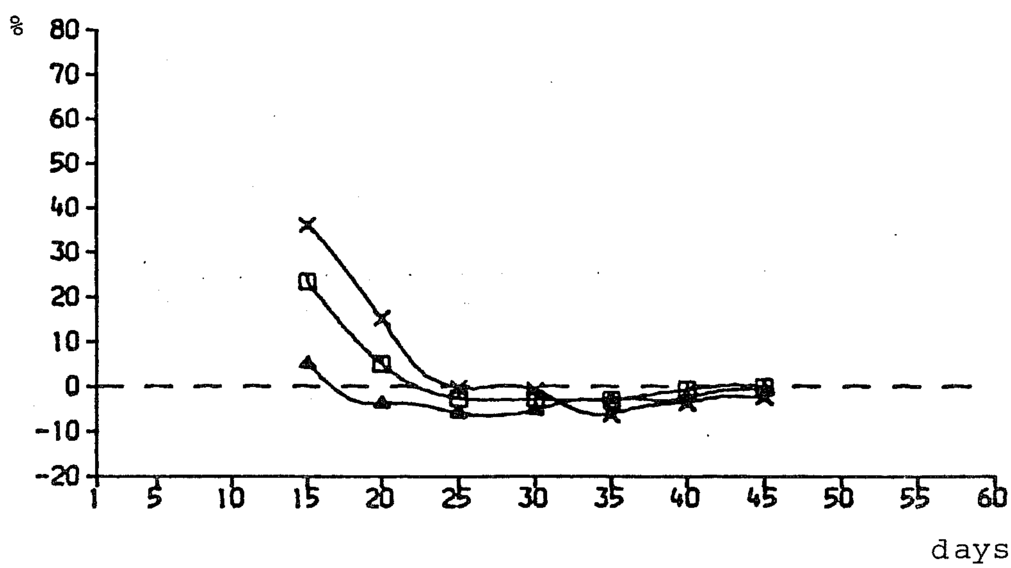


Fig.4 Ensemble averages of 30 day mean RMSE (top) and ACC (bottom) for overlapping 30 day intervals. The ensembles are composed of all experiments(□), five experiments with the highest (×) and five experiments with the lowest (Δ) mean values of CE1-3 in the first 30 day period (dd 1-30).

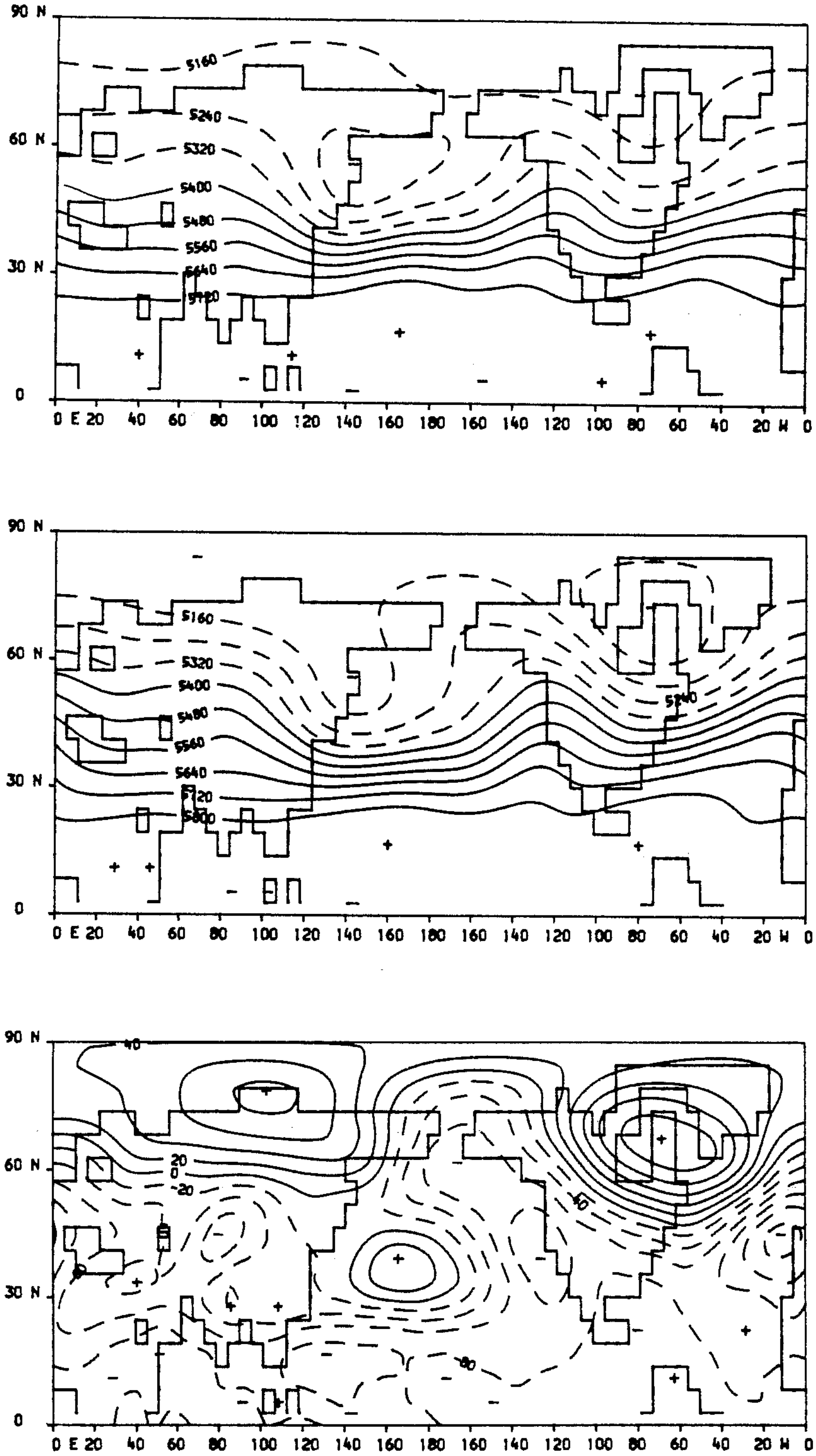


Fig.5 Ensemble averages of 30 day mean forecasts (top), corresponding analyses (middle) and differences (forecasts minus analyses; bottom) for the northern hemisphere 500hPa height fields. Contours are labeled in m.
a) Total ensemble of 28 forecasts

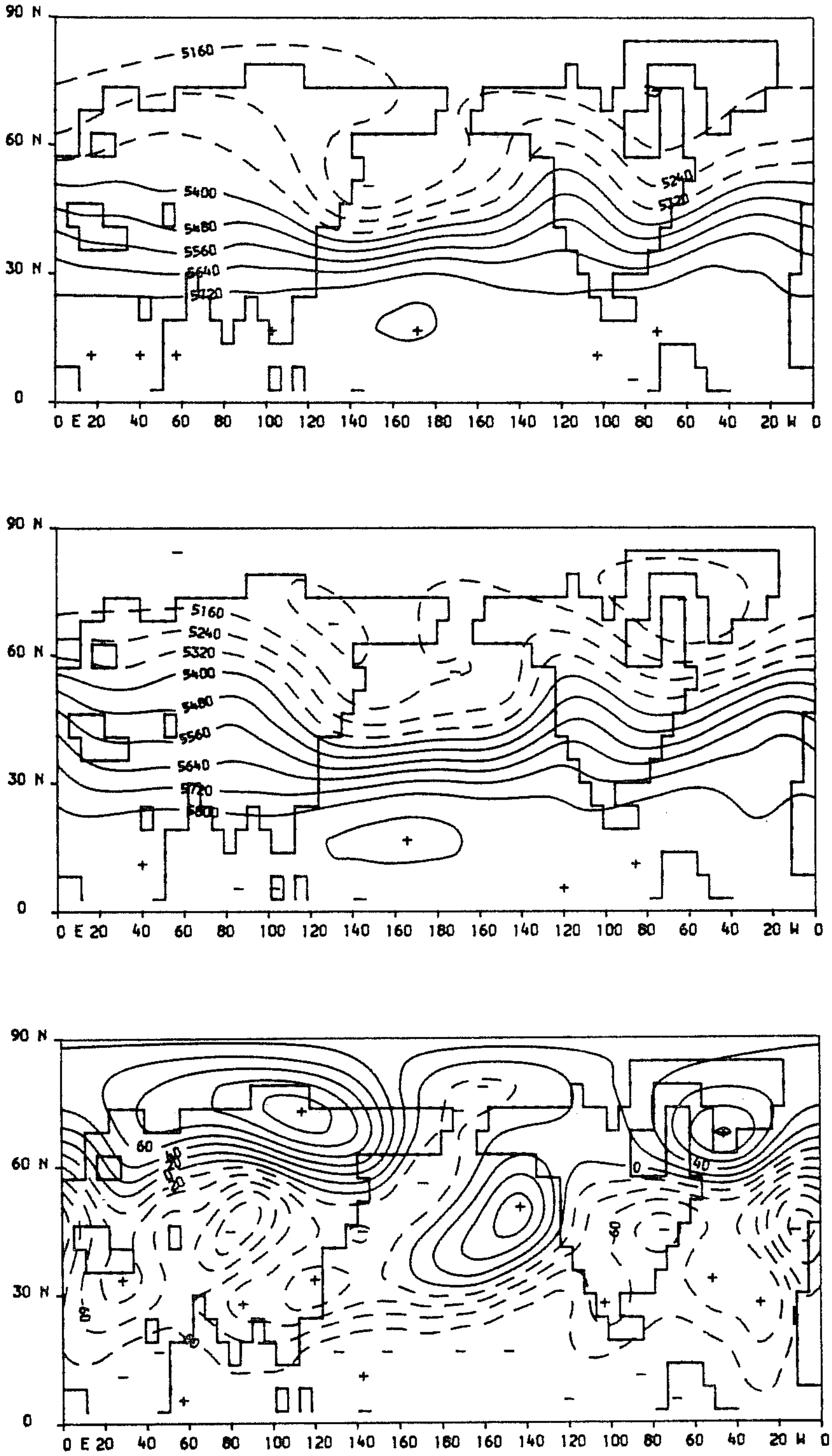


Fig.5 (continued)
b) Ensemble of 5 forecasts with maximum values of CE1-3

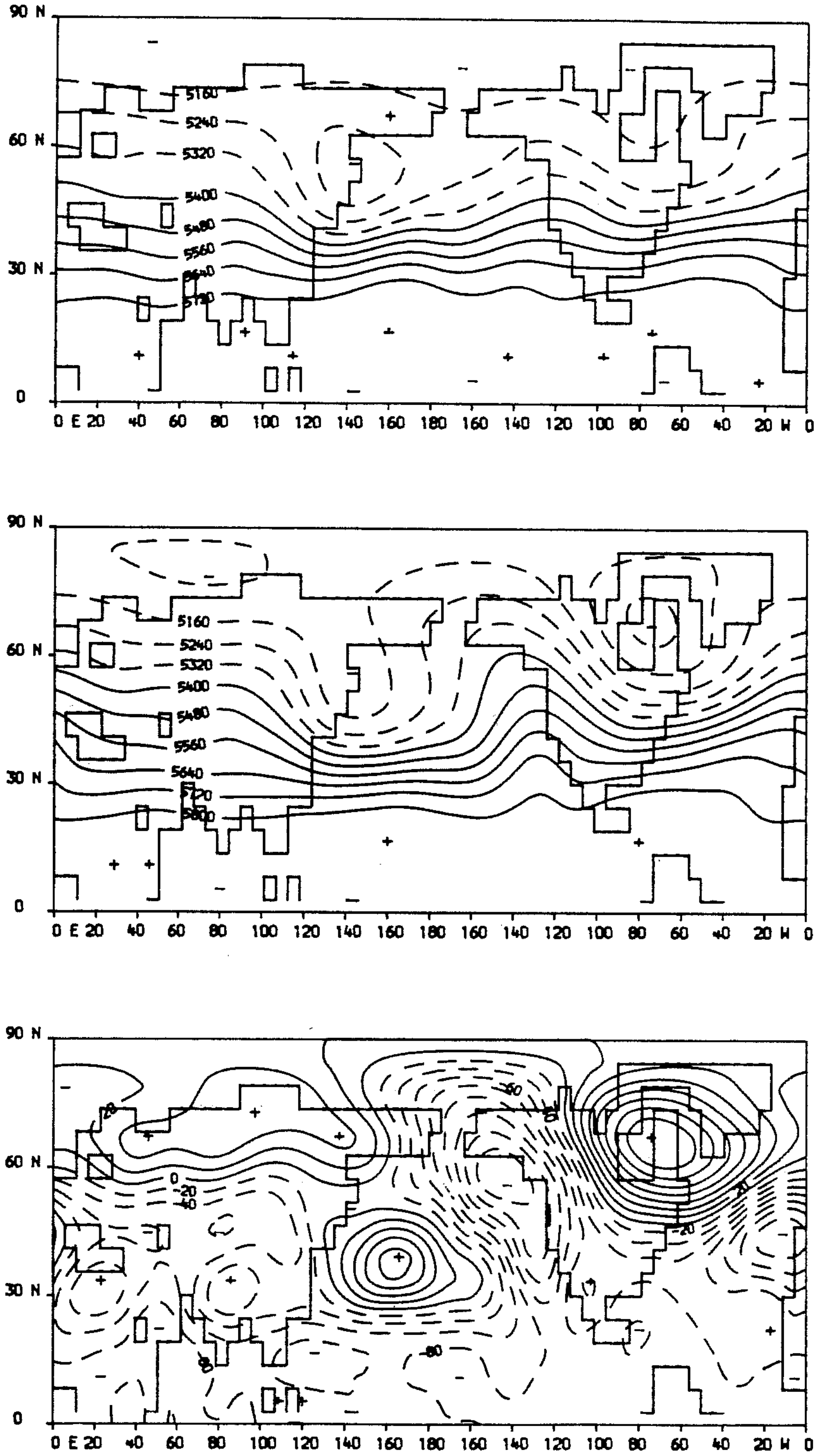


Fig.5 (continued)
c) Ensemble of 5 forecasts with minimum values of CE1-3

CE1-3 values, whereas it is partly different for the subensemble with high CE1-3.

Differences between the mean verifying analyses of the subensembles and climate (as derived from the ECMWF analyses for the period Jan.1979 to Dec.1984) are shown in Fig.6. As can be seen from the figure, the observed anomaly field for the subensemble with maximum values of CE1-3 resembles the well-known PNA pattern (Wallace and Gutzler, 1981), especially over the North Pacific and the southeastern part of North America. This corresponds to the results of Palmer and Tibaldi(1987), who found that for the PNA mode being in this phase, medium range forecasts from the ECMWF model as well as extended range forecasts from some other models tended to be good. In our case, however, the field is distorted over the northwestern part of North America, where it is more or less in phase with the model's systematic error structure (compare lower part of Fig.5a) and thus helps to reduce model errors in these cases.

On the other hand, the observed anomaly field for the subensemble with minimum values of CE1-3 is opposite to the model's systematic error over large parts of the North Pacific and North America. It thus tends to increase model errors in these cases.

The mean initial fields for the subensembles with high and low 30 day mean CE1-3 (Fig.7) are, of course, somewhat rough since only five cases are contained. However, they show at least two distinct anomalies. One is a positive anomaly over northern Asia for the subensemble with high CE1-3, where the corresponding forecasts produce a large positive error. The other is an abnormal ridge near western North America for the subensemble with low CE1-3. Compared to its counterpart in the climatological mean field (see second picture in Fig.5a) it is displaced to the west in its southern part and unusually strong in the north.

As can be seen in some detail in Fig.8, this ridge is flattened out in the first 10 day forecast period and afterwards is redeveloped rather weakly farther to the east, whereas in reality it maintained its abnormal position and strength at least to some degree.

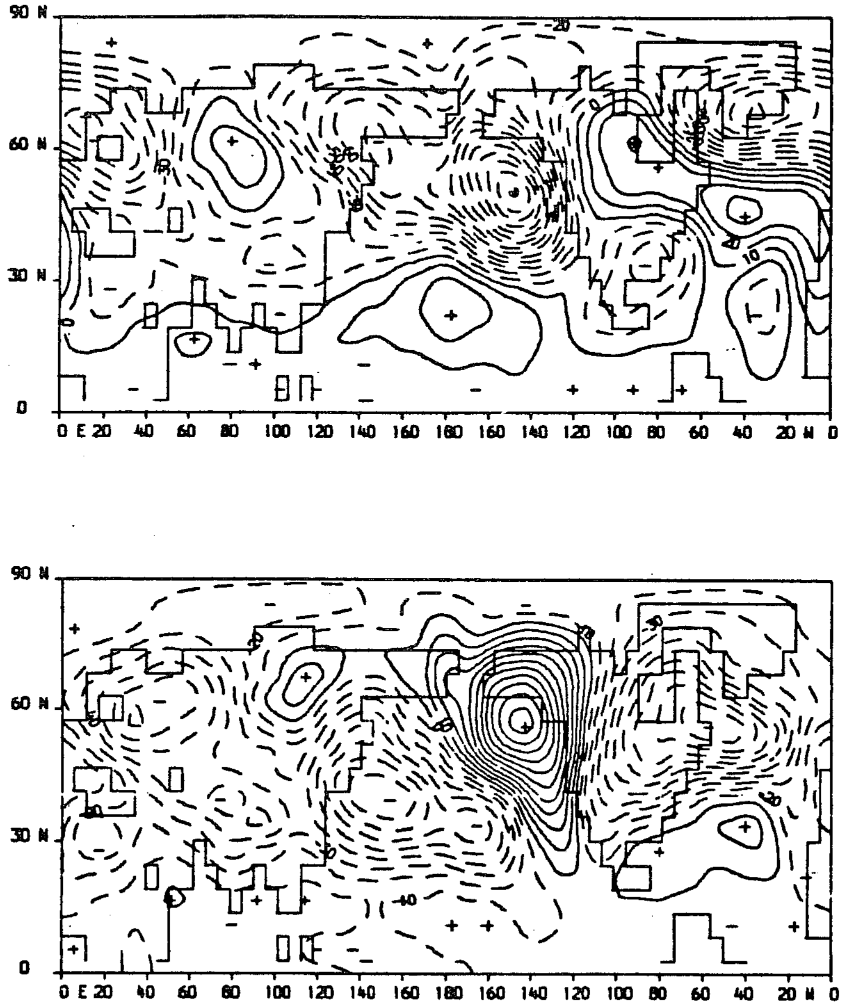


Fig.6 Ensemble averages of 30 day mean 500hPa height anomalies in the verifying analyses for five cases with high (top) and low (bottom) 30 day mean predicted values of CE1-3. Contours are labeled in m.

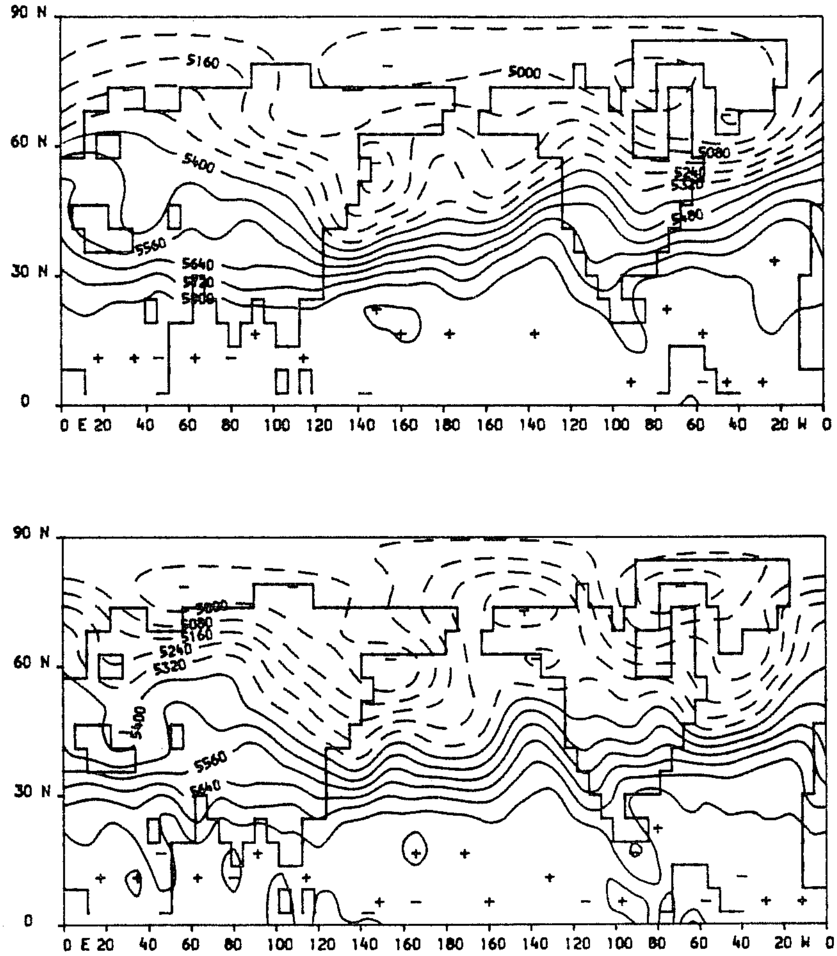


Fig.7 Ensemble averages of initial 500hPa height fields for the forecasts with maximum (top) and minimum (bottom) 30 day mean values of CE1-3, respectively. Contours are labeled in m.

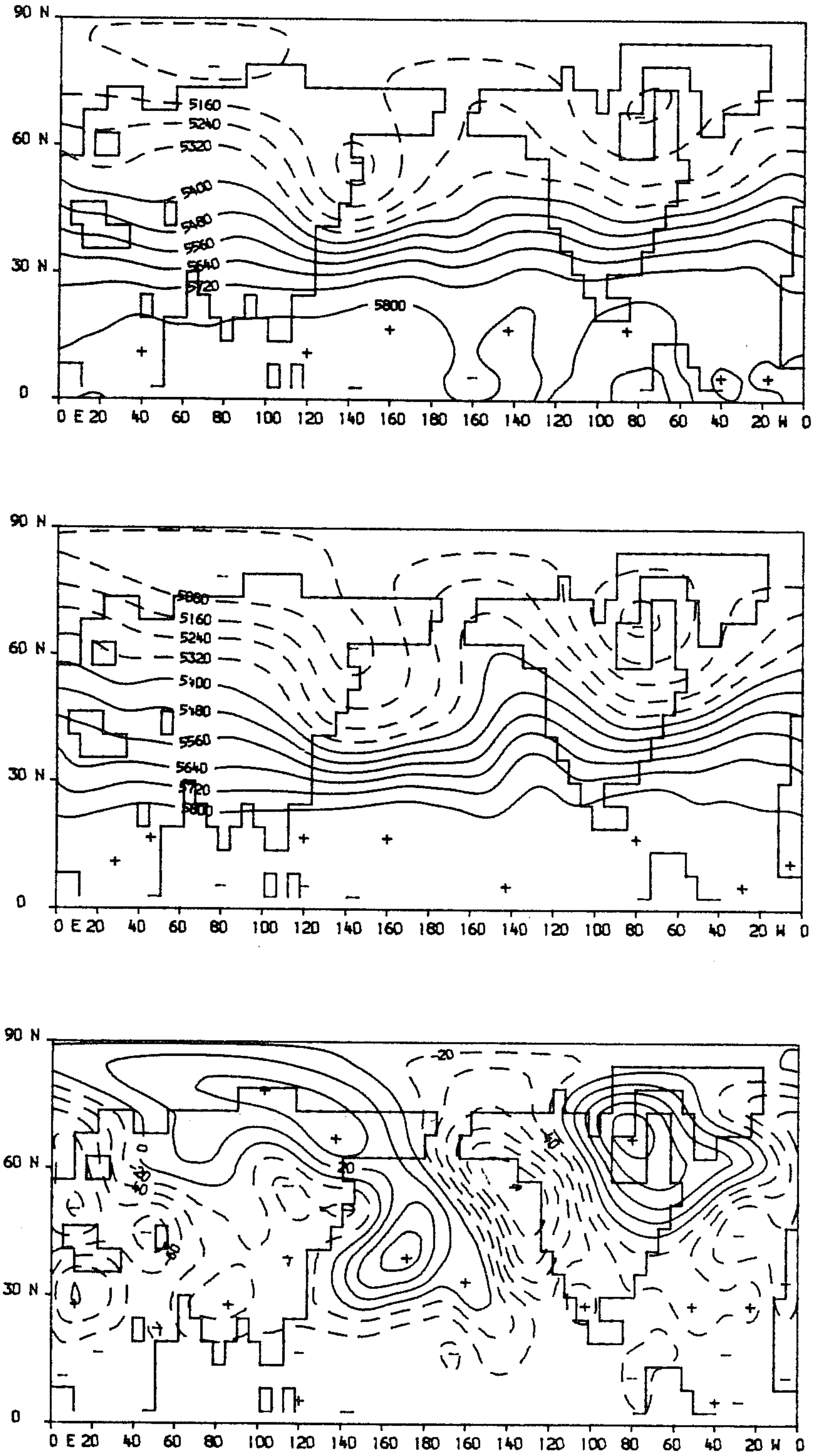


Fig.8 Ensemble averages of 10 day mean forecasts of 500hPa height for the subensemble with minimum 30 day mean values of CE1-3 (top), corresponding analyses (middle) and differences (forecasts minus analyses; bottom). Contours are labeled in m. a) dd 1-10

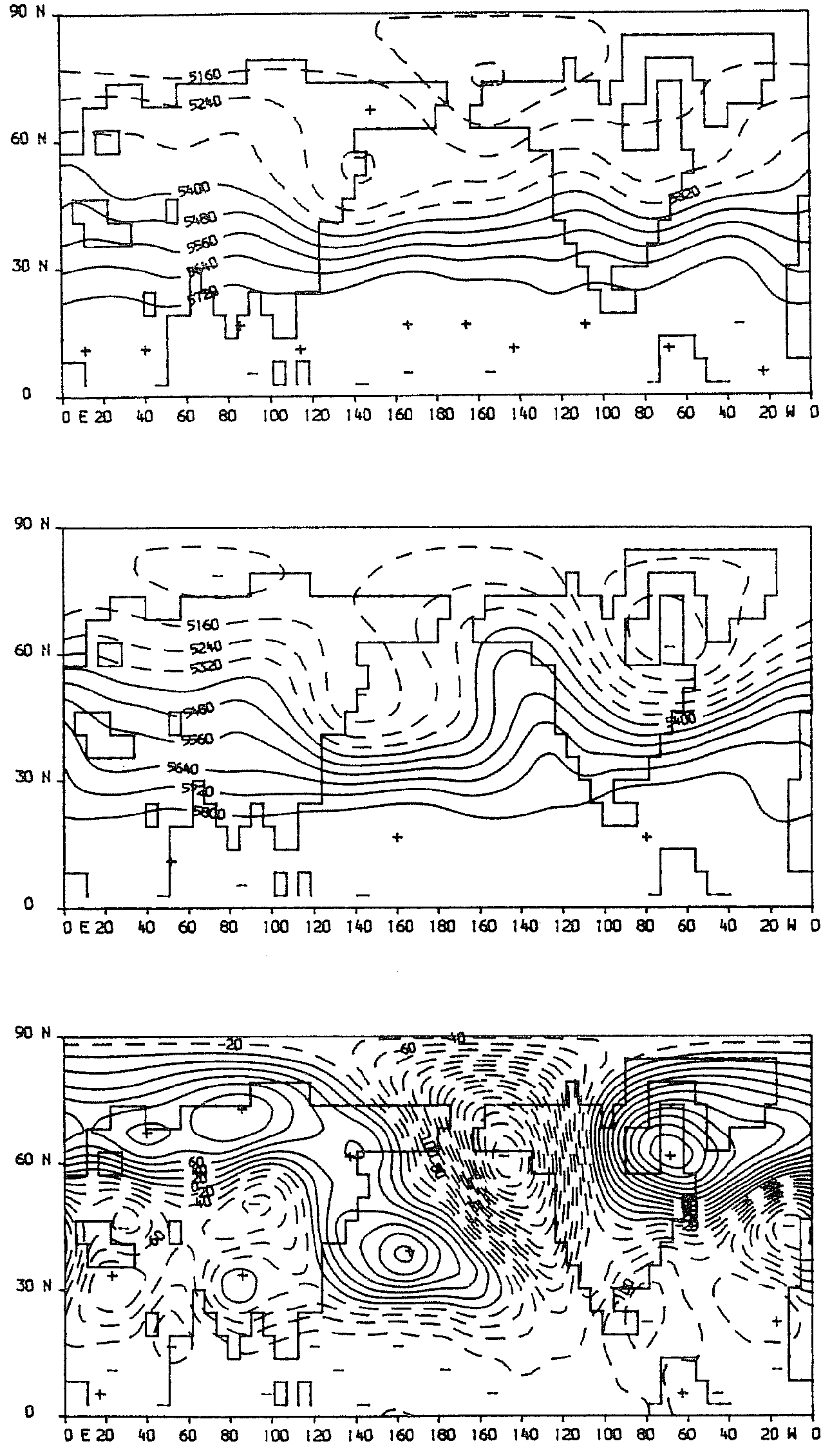


Fig.8 (Continued)
b) dd 11-20

In summary, some distinct anomalies appear in the mean synoptic fields of the subensembles with high and low 30 day mean CE1-3, respectively. The existence of the above mentioned anomalies in the initial and forecast fields is supported by most of the individual forecasts of each subensemble, i.e. they appear in at least three of the five cases, which constitute the respective subensemble. (The anomalies of the verifying analyses have not been looked at for individual cases.)

From the synoptic results, two conclusions might be drawn with respect to the forecast of forecast skill:

- Since there are especially large anomalies found around North America, a similar examination on a regional basis might lead to even more pronounced relations between energetics and forecast skill.
- Generally the existence of the synoptic anomalies connected with high and low values of CE1-3, respectively, points to the possibility that at least part of the predictive value of the correlation between CE1-3 and forecast skill might also be captured by determining correlations between (initial and predicted) field anomalies and skill.

4. COMPARISON WITH SOME T42 FORECASTS

Medium and long range forecasts with the ECMWF T21 model are known to be distinctly different from (and inferior to) forecasts with higher horizontal resolutions (T42, T63 and T106; see e.g. Molteni et al., 1987, and Jarraud, 1987). Moreover, Brankovic(1987, pers. comm.) demonstrated that the energetics are quite different as well, if one compares forecasts with T21 to those with the other resolutions (though this is not especially pronounced for the baroclinic conversion term CE, which we have been mostly dealing with).

Therefore, some T42 forecasts were studied to examine, whether similar correlations between CE and forecast skill might be found at this resolution as well. The experiments used were nine 60 day day forecasts with starting dates 1.1 , 21.1 , 1.2 and 11.2 in the years 1984 and 1985, and 11.1 in 1985 (see Molteni et al., 1987). These forecasts were evaluated with procedures available at the ECMWF.

Results obtained for the 30 day mean baroclinic conversion terms, vertically integrated over the total atmosphere, and the forecast skill indicators in 500hPa are presented in Table 5. As can be seen, correlation coefficients obtained for the T42 model are similar to those for the T21 model. Of course, a total number of nine forecasts with the T42 is too small to prove the significance of the correlations (though, actually, the figures obtained for the RMSE are in themselves significant at the 95% level). But the results clearly indicate that the correlations between baroclinic conversion terms and forecast skill demonstrated in this paper are not confined to the T21 model.

	T21 model		T42 model	
	RMSE1-21	ZACC1-21	RMSE1-42	ZACC1-42
CE1-3	-.461	.405	-.689	.482
CE4-9	.382	-.384	.682	-.391

Table 5 Correlation coefficients between 30 day mean (dd 1-30) predicted values of CE1-3 and CE4-9, vertically integrated for 1000-30hPa, and total wavenumber RMSE or ZACC in 500hPa. The underlying series are from 28(9) predictions with the T21(T42) model and for the region 27^{c} - 75^{c}N.

5. SUMMARY

A series of 28 extended range predictions with the ECMWF T21 model has been investigated in order to find relationships between energetics and forecast skill.

Significant correlations were found between initial or forecast values of eddy energy conversion terms and skill scores for the geopotential height forecasts. Probably the most interesting one is a positive (negative) correlation between the 30 day mean predicted values of the conversion term in the planetary waves (CE1-3) and the ZACC (RMSE) of the 30 day mean forecasts. It seems to be especially useful for predicting forecast skill in the middle troposphere, whereas obviously not much information can be extracted for the near surface fields.

Inspection of synoptic charts of 500hPa heights for cases with high and low 30 day mean forecast values of CE1-3, respectively, reveals anomalies in the initial fields, the predicted fields and the verifying analyses. From these charts, one might draw two conclusions:

- Since there are especially large anomalies found around North America, a similar investigation as done here, but on a more regional basis might lead to even more pronounced relations between energetics and forecast skill.
- The existence of anomalies in the initial and the forecast fields points to the possibility that at least part of the predictive value of the correlation between CE1-3 and forecast skill might also be captured by determining correlations between field anomalies and skill.

The most interesting correlations could also be found in 9 ECMWF-experiments with T42-resolution.

6. REMARK

After completion of the study, it has been noted that the last 8 of the 28 initial analyses suffer from a problem. A change of the orography in the operational ECMWF model at coastal lines introduced on 1.2.1984 (see Jarraud et al., 1986, for a partial description) has obviously not been taken into account during the interpolation procedure necessary for our experiments. Since this introduces distortions only in the mass field and no further initialization is being done, most of the error should be interpreted by the model as gravitational modes. We therefore assume that the results presented here are not seriously affected. This is supported by the fact that only one out of the corresponding 8 forecasts is among the five poorest (see 3.2), whereas one of them is the best of all 28 forecasts.

7. ACKNOWLEDGEMENT

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