# PLANETARY-SCALE DIABATIC FORCING ERRORS IN THE ECMWF MODEL

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## Abstract

The systematic errors of the ECMWF model are investigated with special emphasis on the fields of diabatic forcing.

Over the main tropical convective areas the outgoing longwave radiation is predicted to be too large for all forecast ranges, mainly due to an insensitivity of the radiation scheme to clouds.

Short range forecasts (day 0-1) of precipitation seem to be near to reality. The forecast precipitation amounts drop rapidly after 3 days in the tropics of the summer hemisphere. In the short as well as in the medium range forecasts an overprediction on the windward side and an underprediction in the lee of the main mountain ranges is indicated for the European area, which is of opposite sign of the error pattern of the former operational gridpoint model. Precipitation in the Mediterranean area is predicted too low mostly due to single events of heavy observed precipitation which are not forecast.

The impact of sea surface temperature anomalies on the performance of the model have been investigated by comparing the December to February season for 1985/86 with 1986/87, i.e. a non-ENSO with an ENSO event. Short range forecasts of tropical precipitation and vertical velocity differ realistically between both years but these differences disappear totally in the medium range forecasts.

Investigations of the variability of the systematic error of wind and temperature during recent years give an insight into the importance of different processes on the systematic error. Largest improvements were gained from the introduction of a shallow convection parametrization in connection with other model changes. Improvements were seen in the stratosphere from a revision of the radiation scheme and from the introduction of a gravity wave drag parametrization. Since the introduction of an envelope orography the variances of wind and temperature by transient waves have been underpredicted.

## 1. INTRODUCTION

The verification of diabatic forcing in forecast models suffers from the major problem that the truth is hardly known. Hollingsworth et al. (1980) restricted therefore their investigation of impacts from different parametrization schemes to the response of the mid latitude circulation. More recent studies, e.g. Tiedtke et al. (1988) give insight into the performance of parametrization schemes by comparing diabatic forcings based on two different schemes.

In this study a number of different problems related to diabatic forcing are investigated. We start in Section 2 with an investigation of global energy and humidity budgets using a broad data base. The only quantity which is directly related to diabatic forcings and which is globally available for verification is the outgoing longwave radiation (OLR) as measured by satellite. This quantity is verified in Section 3. In the tropics OLR measurements have also been used to estimate precipitation amounts (Arkin, 1984). In Section 4 such estimates are compared with forecast results and climatological estimates (Jaeger, 1976). The change in precipitation distribution during the course of the forecasts gives some insight into model deficiencies. SYNOP data over Europe are quite dense and give the opportunity to verify the precipitation forecasts for some gridpoints, as is discussed in Section 5. In Section 6 the ability of the ECMWF model to respond to changes of sea-surface temperatures (SST) is investigated by comparing forecast data during years with and without ENSO (El Niño-Southern Oscillation). In Section 7 a six year history of systematic errors of wind and temperature will be discussed in connection with changes in the analysis/forecasting scheme. This will provide estimates of the sensitivity of the model performance to different parametrized processes.

A general description of the ECMWF analysis/forecasting scheme is given by Hollingsworth et al. (1986) who also point out differences to other schemes. A more detailed discussion of the model is given by Simmons et al. (1988) concerning the dynamics and by Tiedtke et al. (1979) concerning the parametrization schemes. The analysis scheme is described by Shaw et al. (1987). More specialized aspects of the schemes are referred to in the text especially in Table 1 which lists the main model changes in recent years.

Table 1: Important changes in the analysis-forecast scheme

| | | |
|---|---|---|
| (a) | September 1982 | Diabatic Initialization (Wergen 1987). |
| (b) | April 1983 | T63 model (Girard and Jarraud, 1982) with an envelope orography (Tibaldi, 1986, Jarraud et al., 1988). |
| (c) | March 1984 | The model horizontal diffusion was increased (reduced again in May 1985). |
| (d) | May 1984 | Diurnal cycle was introduced into the model. |
| (e) | May 1984 | The analysis was subjected to extensive revisions (Shaw et al., 1987). |
| (f) | July 1984 | Correction to the moisture dependence of specific heat was introduced. |
| (g) | December 1984 | A modified radiation scheme and stratospheric drag were introduced (Ritter, 1985; Slingo and Ritter, 1985). |
| (h) | February 1985 | The analysis scheme was modified which affected the large scale wind field. |
| (i) | May 1985 | The new T106 model became operational together with the introduction of a shallow convection scheme, modified Kuo-scheme and new representation of cloudiness (Tiedtke et al., 1988; Simmons et al., 1988). |
| (j) | March 1986 | Tides are handled by initialization. |
| (k) | March 1986 | Use of satellite precipitable water content data and modified (reduced) use of SYNOP data in humidity analysis (Illari, 1988). |
| (l) | May 1986 | Model levels were increased to 19 (Simmons et al., 1988). |
| (m) | July 1986 | Gravity wave drag parametrization was introduced (Miller and Palmer, 1987). |
| (n) | September 1986 | The analysis scheme was modified (Lönnberg et al., 1986). |
| (o) | April 1987 | The parametrization of surface processes was revised (Blondin and Böttger, 1987). |
| (p) | July 1987 | The analysis uses only 7 instead of 11 layers of SATEM data (Kelly and Pailleux, 1988). |
| (q) | December 1987 | A tighter quality control of cloud drift winds in the analysis was introduced. |
| (r) | January 1988 | Vertical diffusion scheme above PBL was removed. |

## 2. GLOBAL ENERGY AND HUMIDITY BUDGET

The global energy and humidity budgets ought to be balanced when averaged over a long period. A first test for the model performance is therefore how far these balances are fulfilled at different forecast ranges. Fig. 1 shows for two seasons the heating of the model atmosphere by sensible heat fluxes from the surface, by large scale precipitation and by convective precipitation. For constant atmospheric temperatures the sum of these (total input) has to be balanced by cooling due to radiative processes. In the short range forecasts there is an obvious imbalance leading to a temperature increase. The imbalance in the short range forecast (spin-up) is of special concern to ECMWF. It reflects inconsistencies between analysis and model which are partly removed by an initialization scheme (Wergen, 1987) but needs further attention.

In the medium range forecasts the balance is better fulfilled but at a lower level than estimated by Hoyt (1976). Hoyt's estimates not only suggest that there is too little cooling by radiation but also too little heating by at least one of the three input processes. The heating by the two types of precipitation can also be found in the budget for humidity (Fig. 2). Also in this budget one finds a spin-up and an imbalance in the short range forecasts. In the medium range forecasts the balance is nearly achieved and lies in the range of estimates by Hoyt. The insufficient heating in the medium range forecasts in Fig. 1 can therefore only be attributed to the sensible heat fluxes but the estimates by Hoyt may not be accurate enough to justify such a deduction.

During the spin-up the imbalance in the humidity budget leads to a reduction of the atmospheric humidity content, especially in the tropics. The imbalance in the sensible heat budget implies a warming of the atmosphere especially in the middle and upper tropical troposphere which will be discussed further in Section 7.4.

## 3. VERIFICATION OF OLR

The only variable directly linked to diabatic forcing which is globally available for verification is the outgoing longwave radiation (OLR) measured from satellite. In Fig. 3 seasonal means of the day 1 and day 10 forecasts are compared with the observations provided by NOAA/CAC. On the whole one

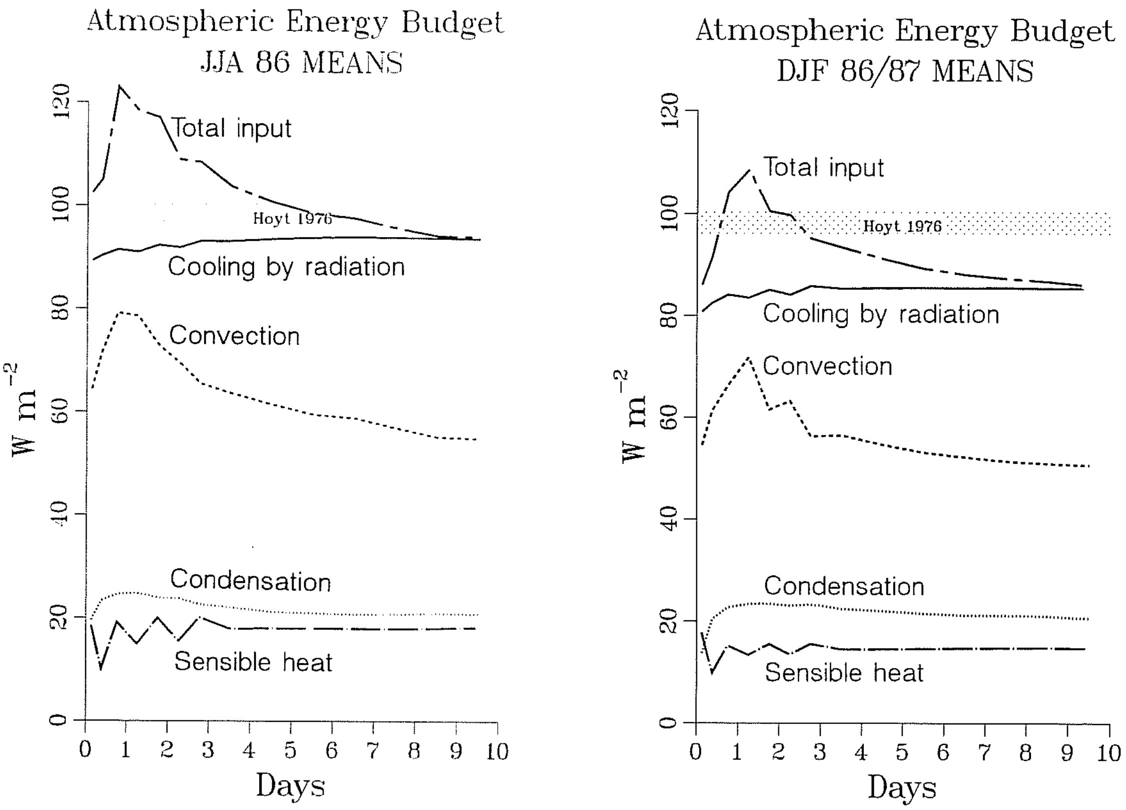


Fig. 1 Global mean heating of the atmosphere by sensible heat flux, large scale precipitation and convective precipitation, the sum of these three processes (total input), and the cooling by radiation during the course of the forecasts in DJF 86/87 and JJA 86. The stippled area indicate climatological estimates of the radiative cooling by Hoyt (1976).

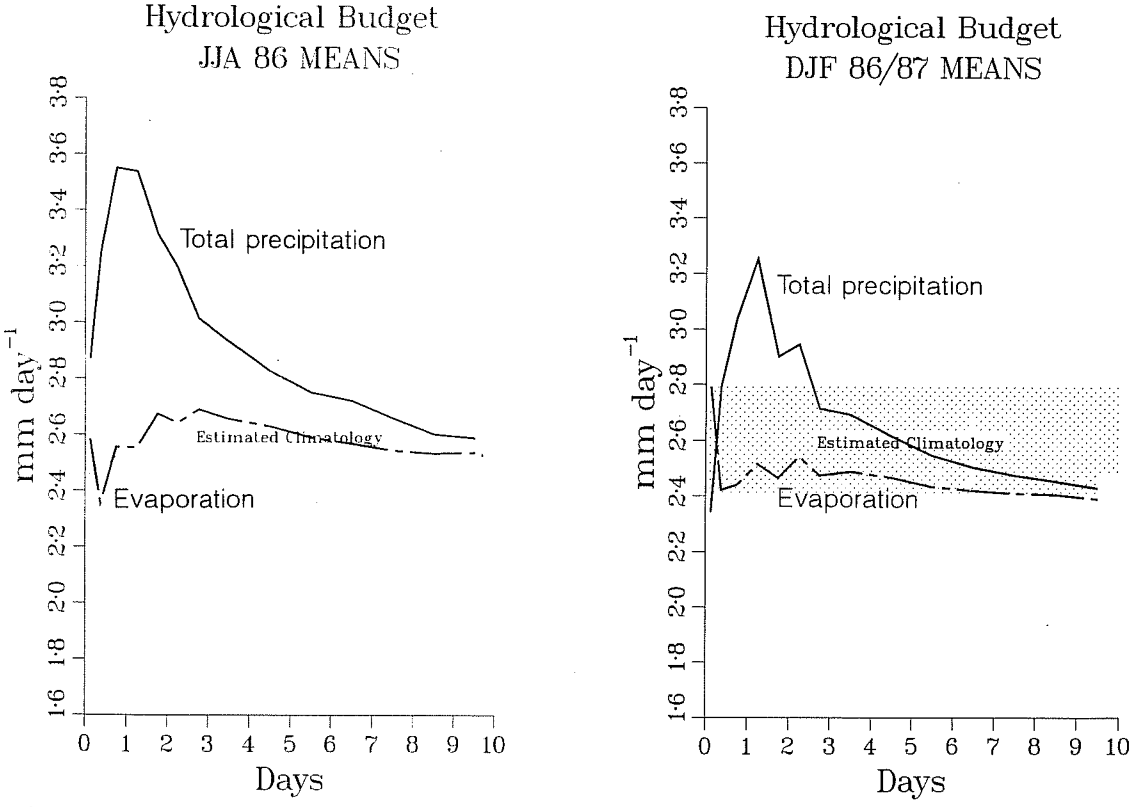


Fig. 2 Global mean precipitation and evaporation during the course of the forecasts in DJF 86/87 and JJA 86. Estimated climatological values by Hoyt (1976) are indicated by the stippled areas.

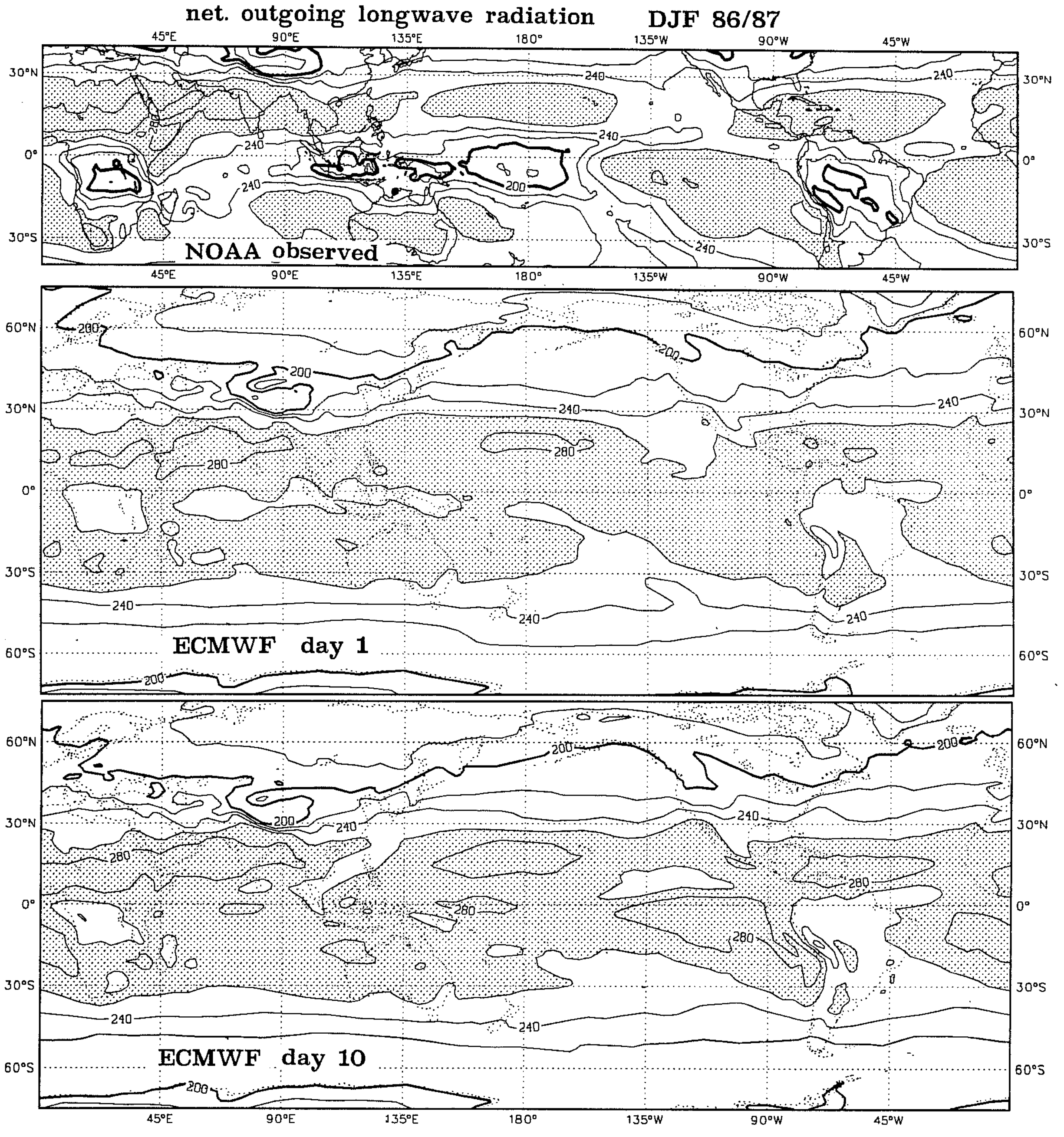


Fig. 3 Net outgoing longwave radiation during DJF 86/87 as observed by NOAA (1987, by courtesy of P. Arkin) from satellite and in the day 1 and day 10 ECMWF forecasts. Contour interval: 20 W/m$^2$; areas with more than 260 W/m$^2$ are shaded.

finds similarities in the patterns but there is also a bias towards higher values in the forecasts. Of special concern are the differences over the main areas with tropical convection, i.e. central Africa, Indonesia and west Pacific, and central south America. Observed values in these areas range from 180 to 200 $Wm^{-2}$ while forecasted values range from 240 to 260 $Wm^{-2}$. Short range and medium range forecasts are very similar in this respect.

The minima in observed OLR values are due to high level cloudiness in these areas. In Fig. 4 the mean cloud coverage of high clouds is mostly more than 60% in the day 1 forecasts. This is quite high if one takes into account that there are also cumulus clouds. There is further a sharp drop in model cloudiness from day 1 to day 10 which is not accompanied by an increase of model OLR. From this we can deduce that it is not the amount of cloudiness which leads to too large OLR values in the model. Studies by Morcrette (pers. comm.) suggest that the specified optical depths of model clouds is too low and that cloud effects are underestimated in the present radiation scheme.

The effect of this error on the performance of the model is difficult to estimate because the error influences also the solar radiation absorption and both effects may cancel each other. However one can expect an impact on the vertical profile of heating and so on the temperature profile.

## 4. VERIFICATION OF PRECIPITATION ON PLANETARY SCALES

The data available for verifying the precipitation on planetary scales are indirect estimates from OLR measurements (tropical areas) and direct estimates from climatological estimates. In Fig. 5 zonal means of precipitation at different forecast lengths are compared with climatological estimates by Jaeger (1976) and with estimates from OLR measurements (Arkin, 1984). Three seasonal means are investigated.

The forecasts show the spin-up which was already discussed above for global means; it is clearest in the tropics. Maximum precipitation occurs in the day $\frac{1}{2}$ - $1\frac{1}{2}$ forecast means. After 2 days the precipitation decreases rapidly. During DJF (December, January and February) the decrease is especially strong between 2°S and 12°S where day 9-10 values are only half of the day $\frac{1}{2}$ - $1\frac{1}{2}$ values. During JJA (June, July and August) the main drop is shifted to 10°N-20°N.

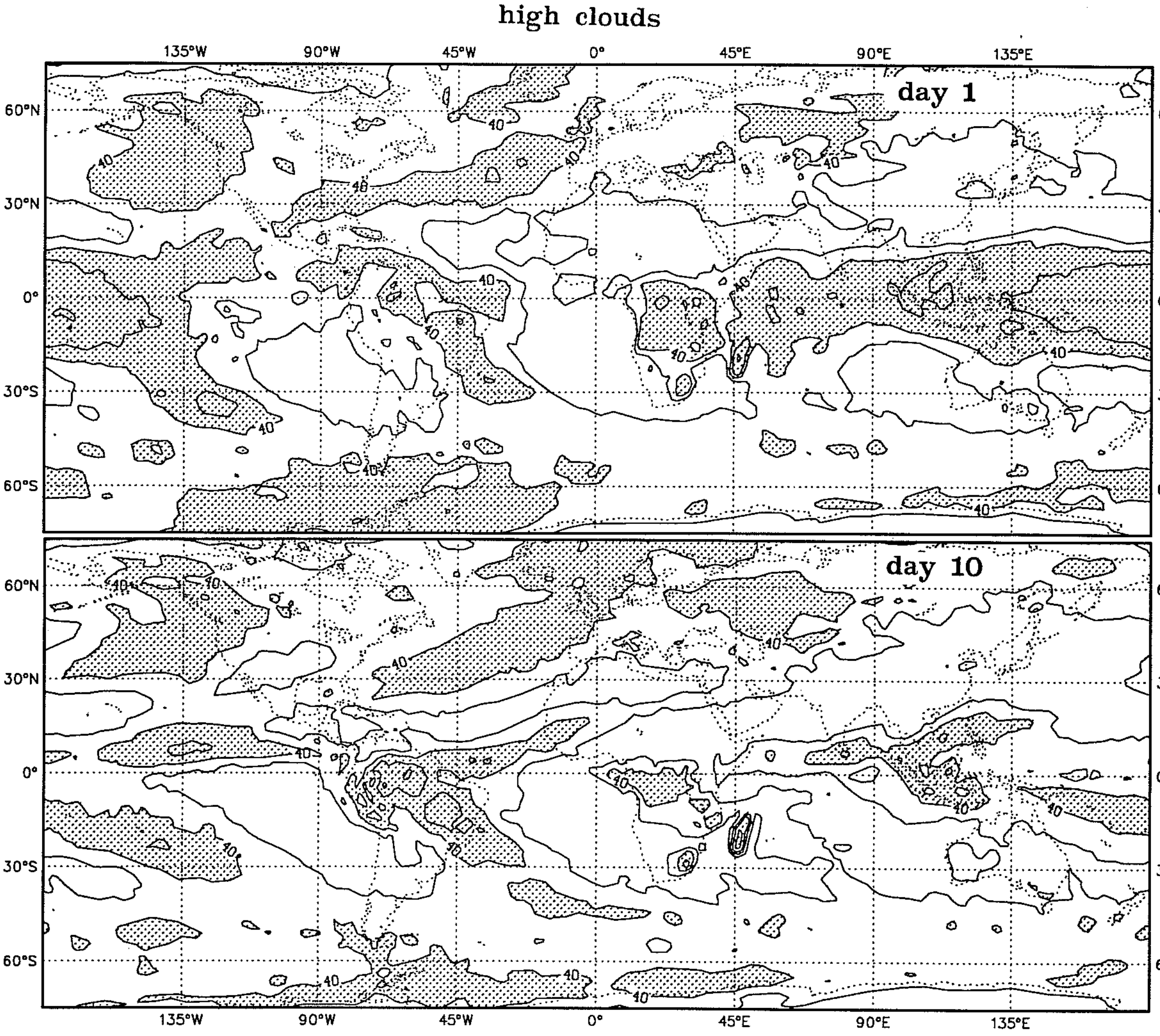


Fig. 4 Percentage of cloudiness by high clouds during DJF 86/87 in the day 1 and day 10 ECMWF forecasts. Contour interval: 20%; areas with more than 40% are shaded.

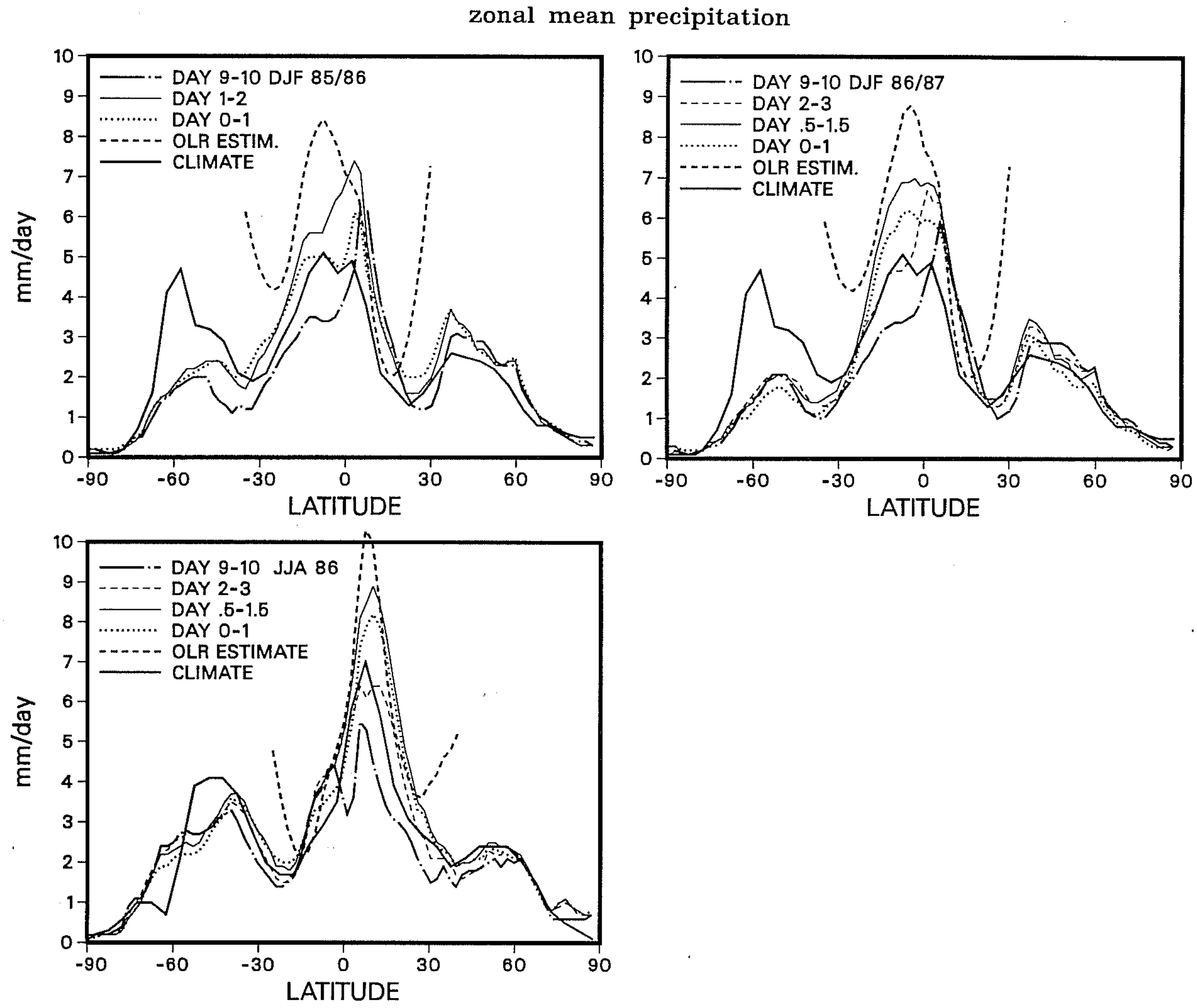


Fig. 5 Zonal mean precipitation during DJF 85/86, JJA 86 and DJF 86/87 for different ranges in the ECMWF forecasts and estimates from OLR measurements. Climatological estimates by Jaeger (1976) are given for comparison.

The distribution of the shortest range forecast (day 0-1) precipitation agrees best with the climatological one though with higher values in the tropics and much lower values in southern mid latitudes. The agreement is best during JJA 86 and during the NON-ENSO winter DJF 85/86.

Estimates from OLR measurements in the tropics give even higher values than the forecasts at their peak of the spin-up, especially at those latitudes where the precipitation collapse is strongest in the medium range forecasts. It is interesting to note that the subtropical minima in the OLR estimates are much closer to the equator than the ones in the forecasts. The estimates from OLR measurements become increasingly unreliable away from the tropics and this may affect the positions of the minima. Jaeger's estimates show the minima between both other extremes.

The decrease of precipitation in the tropics in the summer hemisphere clearly is model error which has also implications for mid latitudes. It is however difficult to judge how serious other differences between the estimates are. It may even be that the very short range forecasts are the best estimates of the truth. An exception is perhaps the tropics of the southern hemisphere during DJF where most likely also short range forecasts underestimate the precipitation amounts.

In Fig. 6 the geographical distribution of precipitation is shown for different ranges of forecast for DJF 86/87. In the short range forecasts the impact from the ENSO event is obvious with maximum values near the date line, which will be further discussed in Section 6 and where also comparisons with OLR estimates are shown.

The decrease of precipitation in the southern hemisphere tropics which was found in the zonal means is mainly located in the convective areas of the eastern hemisphere but also in the SPCZ (South Pacific Convergence Zone). In the western hemisphere one finds an increase of tropical precipitation though mainly in the northern hemisphere where the ITCZ (Inner Tropical Convergence Zone) becomes increasingly stronger and sharper. This increase of precipitation continues through the 10 forecast days over the eastern Pacific, whereas over the Atlantic a maximum is reached earlier.

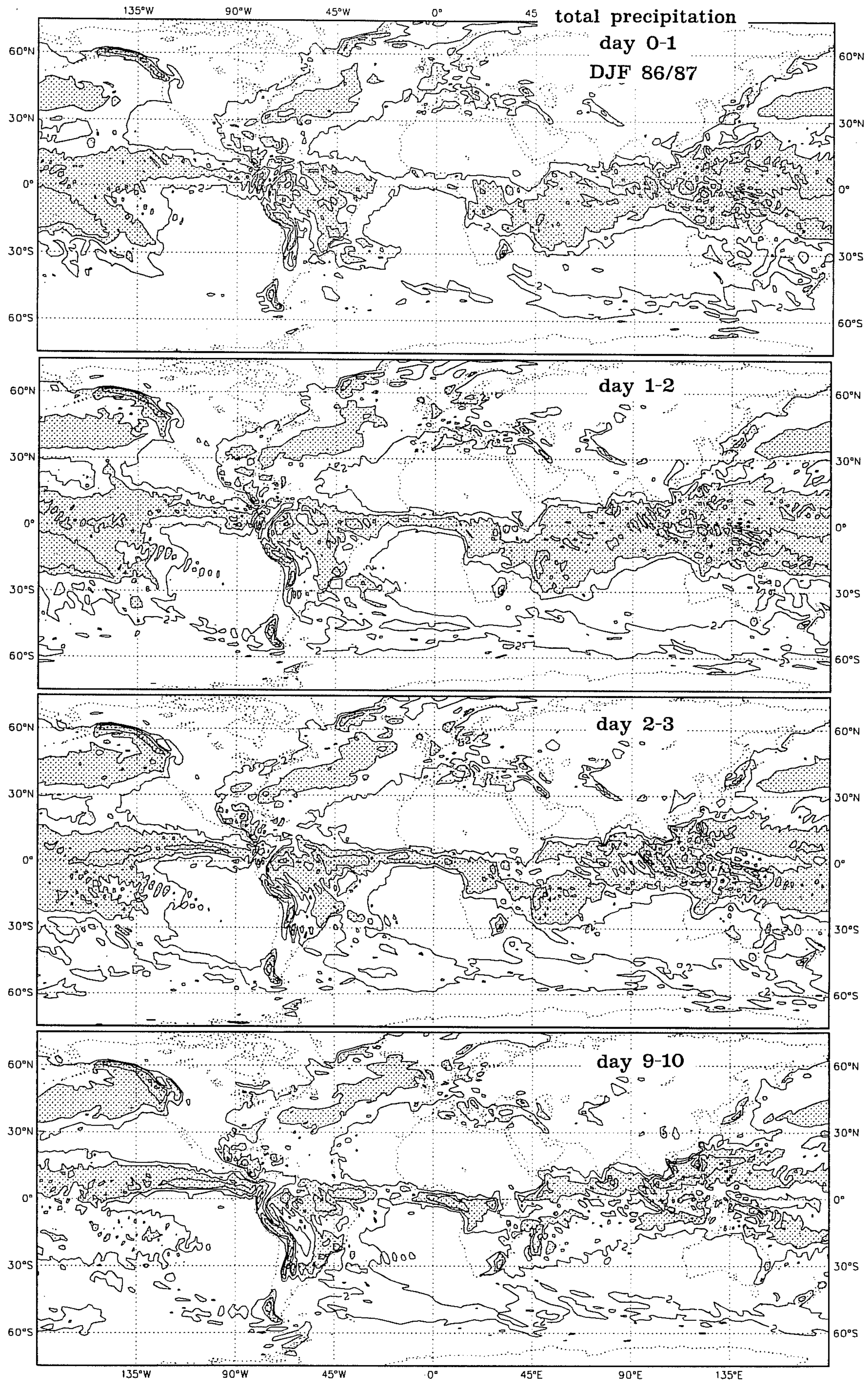


Fig. 6 Total precipitation during the course of the forecasts in DJF 86/87. Contours at 2, 5, 10 and 20 mm/day; areas with more than 5 mm/day are shaded.

In mid latitudes there is not as much change during the course of the forecast and the distribution and its amounts appear realistic. The major change is an eastward extension of the precipitation in the northern hemisphere storm track areas which has to be seen in connection with a similar shift of cyclone tracks and N-E extensions of the jet streams (Arpe and Klinker, 1986). This error is not primarily a deficiency of the parametrization scheme but reflects more the errors in the dynamics. The short range forecasts of precipitation are further investigated in more detail for Europe in the next section because sufficient precipitation data for verification are available there in the ECMWF archives.

## 5. VERIFICATION OF PRECIPITATION OVER EUROPE

Although there are quite a few observational stations for precipitation available for Europe, their density (at least those available in the ECMWF archive) may still be insufficient to calculate representative area means, especially for mountainous areas or areas with mostly convective precipitation. This problem should be kept in mind in the following discussion and is the reason for giving the numbers of observations used for area means in the following presentations.

To generate a geographical distribution of observed precipitation for Europe, all observed values for boxes of the size 2.25° x 2.23° , which corresponds to 4 grid points of the present T106 model, have been averaged. Fig. 7 upper left panel shows the observations for January 1987. Boxes without any observations are left blank except for a few boxes which have been interpolated subjectively to enable the contouring program to function. In the lower right panel the mean number of stations used for each box average are displayed. There are quite large areas with less than 4 observations per day for a box and for these areas one has to be especially careful when interpreting the data, e.g. the large precipitation values over the Baltic Sea are probably unrepresentative or faulty.

On the whole the distribution of observed precipitation is smooth and agrees fairly well with the corresponding values of the short range forecasts (upper right panel). Large amounts of precipitation can be found along the Norway coast, over Spain, the northern Mediterranean, the Alps, Yugoslavia and Turkey and low values are noteworthy for Sweden and the English Channel. The high

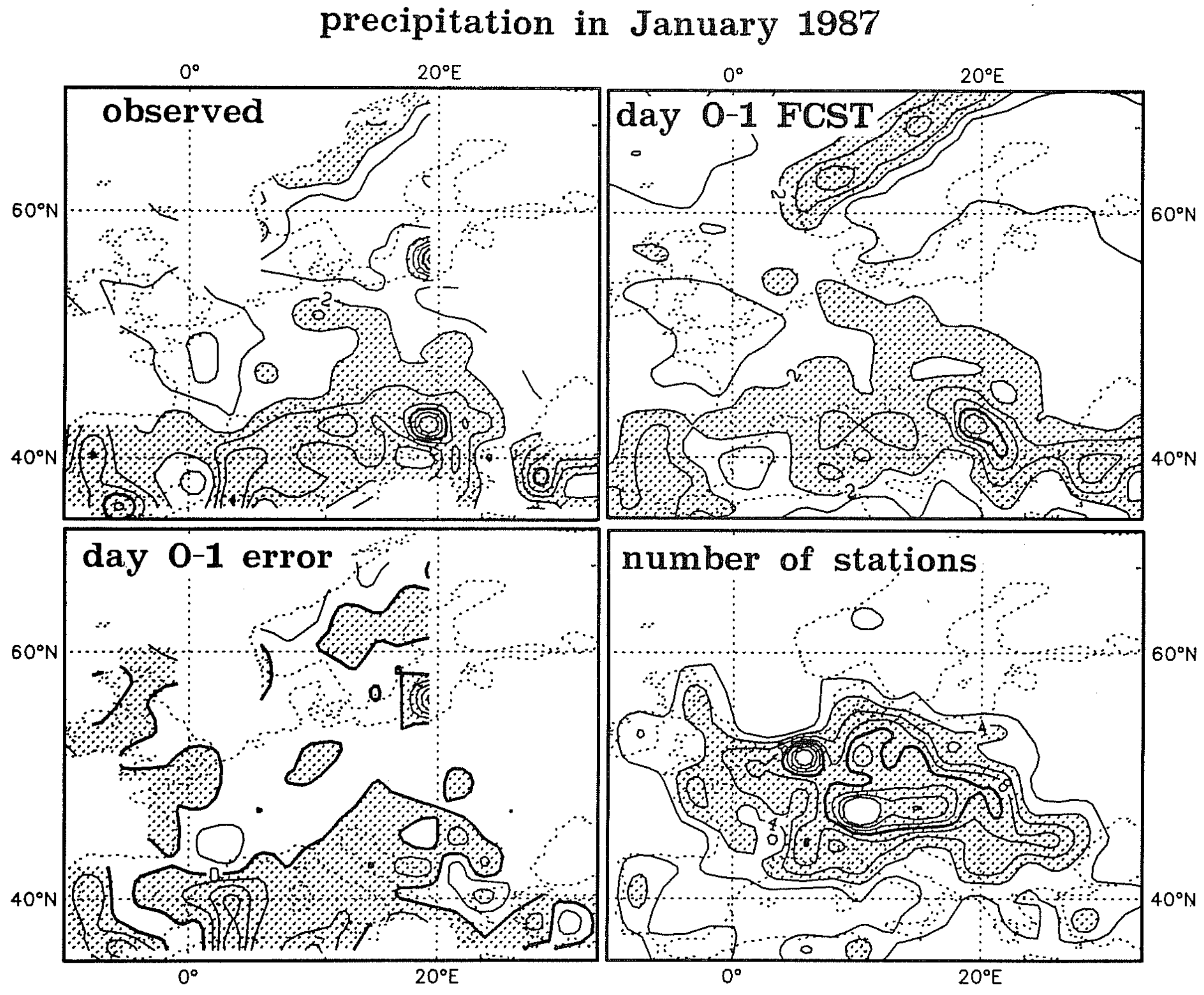


Fig. 7 Upper panels: observed and predicted (day 0-1) precipitation in boxes of 4 model grid points (2.25° x 2.2426°) during January 1987. Contour interval: 1mm/day; areas with more than 2 mm/day are shaded. Boxes without observations are left blank.

Lower left panel: Difference between prediction and observation. Contour interval: 1mm/day; negative areas are shaded.

Lower right panel: Average number of stations per box. Contour interval: 2 observations per box; areas with more than 4 observations per box are shaded; no contours beyond 16 observations per box.

correspondence is reflected by the error field in the lower left panel where errors of more than 1 mm/day are hardly found when sufficient observational data are available.

The model systematically overpredicts the precipitation on the Norwegian side of the Scandinavian mountain range and northwest of the Alps/Massif Central while it underpredicts it in lee of these mountains. Investigations of more extended forecast periods have revealed similarities with this error pattern. The systematic error of precipitation in the ECMWF model operational before 1984 has been investigated by Johannessen (1982) and by Molteni and Tibaldi (1985). For the orographically influenced errors they found opposite signs compared to the ones of the present model.

In Fig. 8 the corresponding maps for August 1987 are displayed. Again a good correspondence between observations and short range forecasts can be found but with somewhat less skill than in January. The Mediterranean is much drier in this month compared to January which is reflected by the observations as well as the forecasts.

A relative maximum of forecast precipitation over Spain is also verified by observations but with lower amounts. The low data density in this area is, however, a major problem for evaluating the model performance. This applies also for the Scandinavian mountain range where one can find larger errors.

The region including the Massif Central and the Alps is well covered with observation. Here one finds the error characteristics similar to those during January 1987, i.e. underprediction of precipitation on the wind ward side of the mountains and overprediction in the lee. A similar distribution can also be found during July 1987 (not shown) and in more extended forecast periods.

For a better understanding of the errors in the monthly means, timeseries of precipitation at selected model grid points are shown in Fig. 9. For each month four model grid points with a good coverage of observation stations have been selected. All observations for which the grid point is representative have been averaged and are compared with corresponding values of the day 0-1 and day 1-2 forecasts.

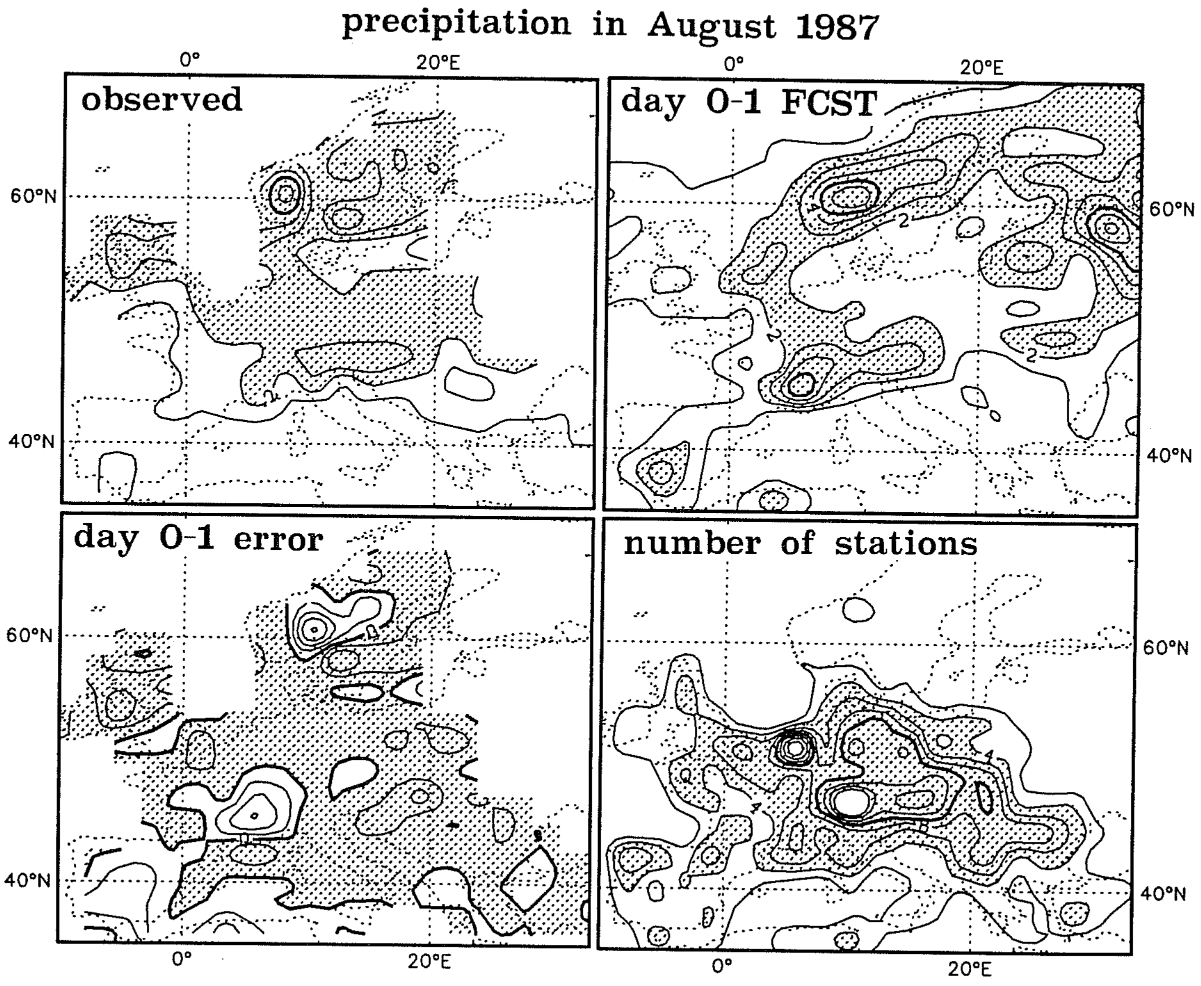


Fig. 8 Same as Fig. 7 for August 1987.

daily mean precipitation

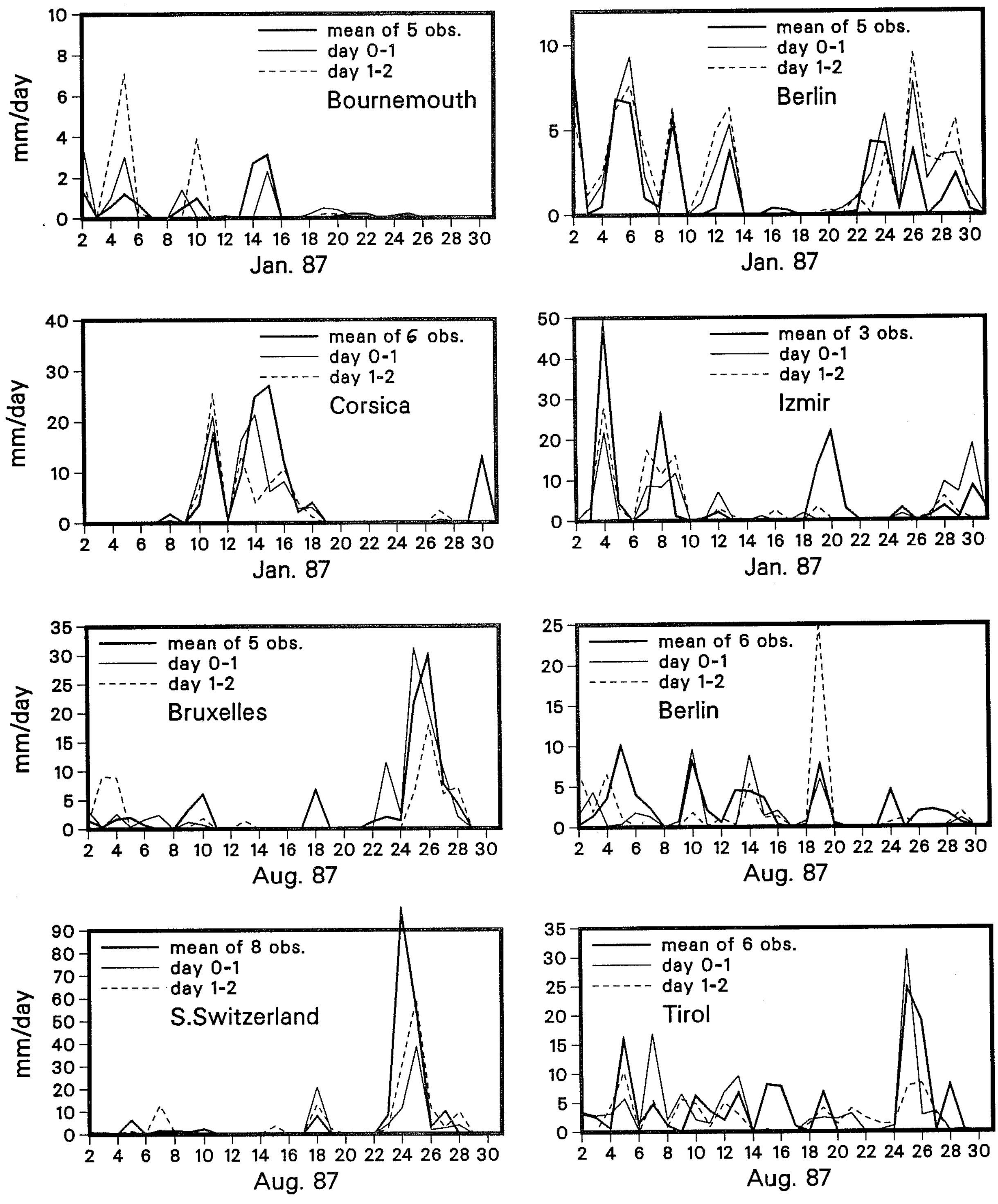


Fig. 9 Daily mean precipitation at selected model grid points (1.125° x 1.1213°) during January and August 1987. Values at a day X is the accumulated precipitation between 12 GMT at day X-1 and 12 GMT at day X. Observations are averages of all available SYNOP stations for which the grid point is representative. The number of stations involved for each gridpoint is given. Below for each grid point the used stations are listed:

Berlin: 09379, 09385, (09490), 10381, 10382, 10384.
Bournemouth: 03740, 03746, 03853, 03862.
Bruxelles: 06350, 06447, 06450, 06451, 06458.
Corsica: 07754, 07756, 07761, 07768, 07790.
Izmir: 16667, 17180, 17218.
S.Switzerland: 06672, 06753, 06759, 06760, 06762, 06770, 06782, 06783
Tirol: 11146, 11207, 11210, 11212, 13008, 16040.

In most cases the occurrence of precipitation was well simulated by the model but quite often with errors in the amounts. At Berlin there are several days in January with overprediction of precipitation. This is connected with snow showers in cold air outbreaks. It could be a systematic error because it was found also for other grid points but one has also to keep in mind that snow fall measurements in windy conditions are unreliable and lead often to underestimations of the true values (Sevruk, 1983). The underprediction of precipitation at Berlin on 23 January occurred when a small scale cyclone moved over the area. The overprediction of precipitation between the 4th and 5th January at Bournemouth occurred when a cold front passed the area.

The performance in August is generally worse than in January which is probably connected with a higher proportion of convective precipitation during summer. This is also reflected by a higher variability from one station to another within one grid point (not shown). Large errors over southern Switzerland on the 23 to 24 August occurred when a cold front reached the Alps leading to a cyclone development. These large errors are not reflected in the monthly mean error maps (Fig. 8) because of the larger boxes used there which allows for a compensation of errors of neighbouring model grid points.

The grid point Tirol, a point at the border between Italy, Austria and Yugoslavia, has been chosen because of larger errors in the monthly mean map in this area. The performance at this grid point suggests that the monthly mean error results either from the sum of many small errors or from an unrepresentative distribution of observational stations in the coarser grid which was used for Fig. 8 because the neighbouring grid points were less well covered by observations.

In the Mediterranean area there have been many occasions of observed heavy precipitation which was not simulated by the model. Some of this is indicated by the timeseries of Izmir but mostly the data density in this area is very low and therefore it is not clear how representative these errors are.

This section has shown that it is difficult to verify precipitation using SYNOP observations. Grid points with a good data coverage verified favourably in the short range forecasts. The skill drops rapidly after 3 days of forecasts. There seems to be a systematic error in connection with orography and with the occurrence of convective precipitation in cold air outbreaks in winter.

## 6. IMPACT OF SST ANOMALIES ON THE GENERAL CIRCULATION

Above, some problems in the model performance with respect to diabatic processes have been shown as far as this was possible by direct verification. Below, a more indirect approach will be taken by showing effects of different diabatic forcings on the forecasts. In this section seasonal means of DJF 85/86 and DJF 86/87 are compared. We will assume that the essential difference between both years results from the ENSO event during 1986/87. The SST's between both years at the equator at about 140°W differ by more than 2.5 K.

Fig. 10 shows the precipitation in both years over the Pacific in the short and medium range forecast and estimates from OLR measurements. The estimates of precipitation from OLR measurements should only be used for the tropics, during DJF between 20°N and 40°S (Arkin, pers. comm.), because the accuracy drops rapidly beyond these limits. The short range forecast and the estimates from OLR show good similarities in their patterns and both reflect the change from a non ENSO to an ENSO event. Differences in the amounts have already been mentioned in Section 4. The comparison of these maps with those for the day 9-10 forecasts reveals enormous changes. In the medium range forecasts the precipitation is much more concentrated at the ITCZ and the ITCZ has moved northward in the Indonesian region. The total disappearence of differences between both years is interesting from the point of SST anomalies: the direct boundary forcing from the ocean is obviously of minor importance for the simulation of precipitation in the tropics.

A reduced sensitivity to SST anomalies has been found also in other models, i.e. SST anomaly experiments have often been carried out with double the true amplitudes to gain a clear impact. The present version of the ECMWF model is remarkable in so far as it seems to be totally insensitive. This insensitivity has already been experienced by Cubasch (1986) who carried out SST anomaly experiments with a recent version of the ECMWF model while Arpe and Wallace (1983) found quite reasonable impacts from SST anomalies when using the grid point version of ECMWF models which was operational until April 1983.

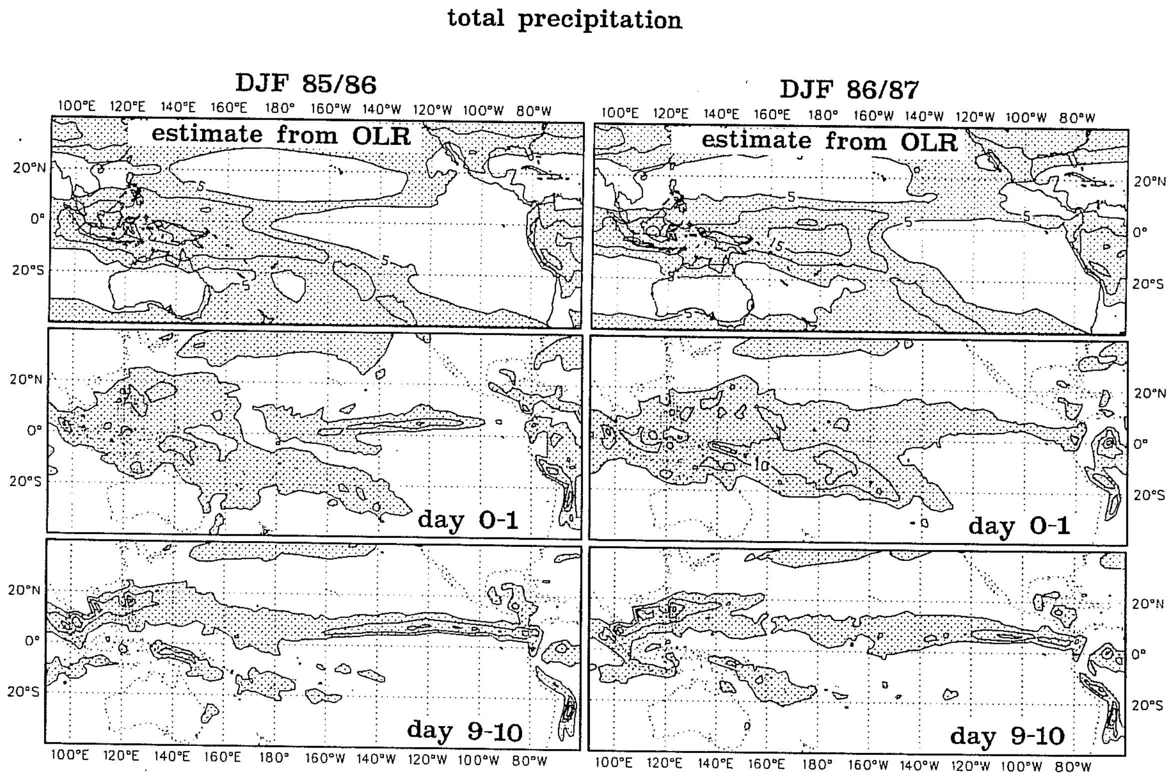


Fig. 10 Total precipitation over the Pacific Ocean in the short (day 0-1) and medium (day 9-10) range forecasts in DJF 85/86 and DJF 86/87 as well as estimates from OLR measurements. Contour interval: 5 mm/day; areas with more than 5mm/day are shaded.

Increased precipitation during ENSO events have to go hand in hand with increased evaporation and this has in fact been found in the short range forecasts though less over the area with increased SST but more over the adjacent subtropics (not shown). Hardly any of the enhanced evaporation survives in the medium range forecasts.

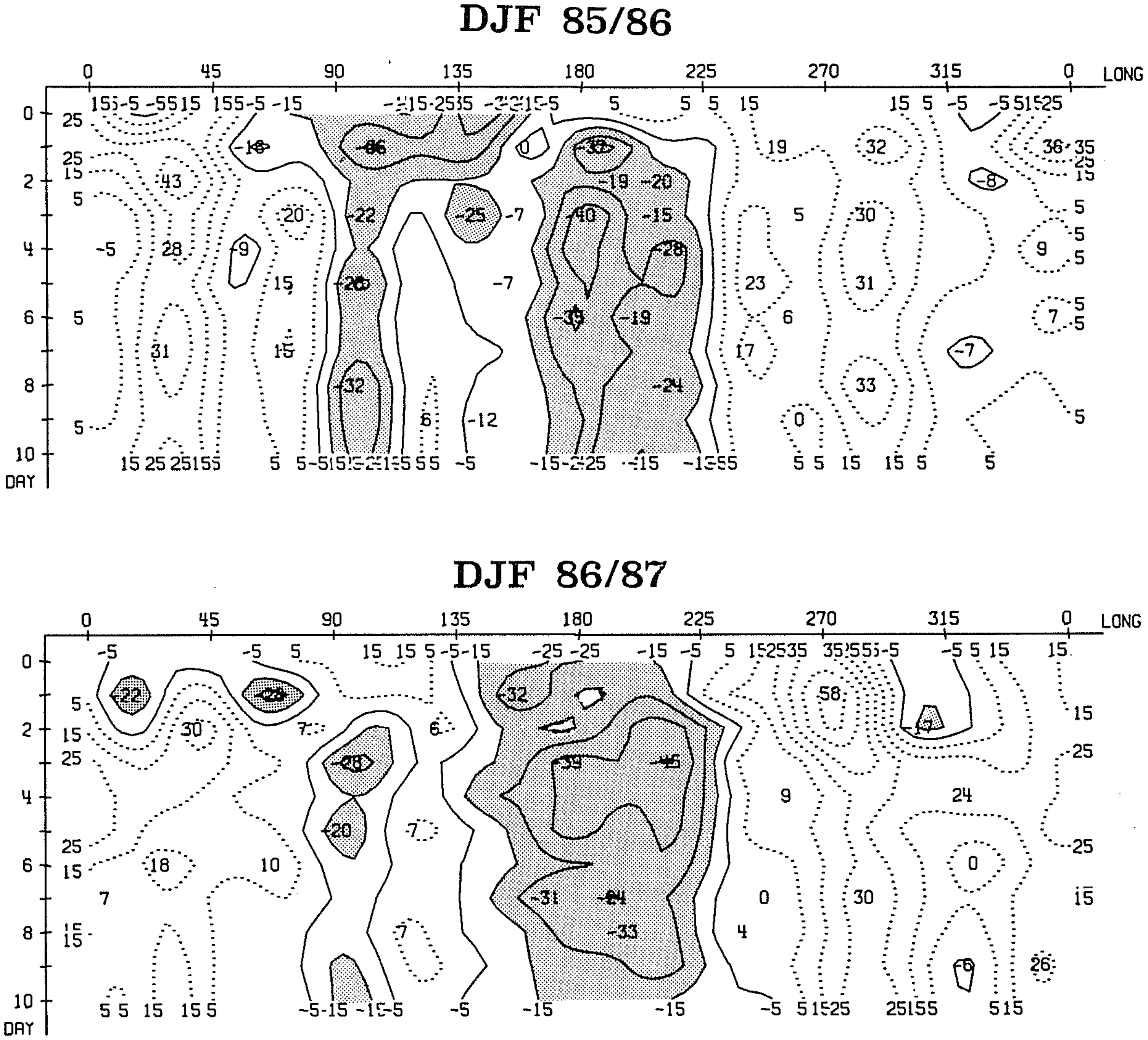
Closely connected with the distribution of precipitation is the vertical velocity which is demonstrated in Fig. 11 by trough-ridge diagrams of the 500 mb vertical velocity for the tropical belt between 10°N and 10°S for seasonal mean 10 day forecasts.

The analyses (day 0) show a strong ascent around Indonesia (135°E) during DJF 85/86 and around the date line during DJF 86/87 in agreement with the precipitation distribution shown above. At about day 2 there is a rapid change in the pattern and after 3 or 4 days the distributions in both years are very much alike. The horizontal distribution of vertical velocity in the tropics at day 10 in both years is quite similar to the analysed one during DJF 86/87, i.e. the model drifts to a distribution which is typical of an ENSO event.

A word of caution should be added here because when investigating mean maps of the vertical velocity one would hardly come to the same statement perhaps because contribution from zonal means and from shorter waves are disregarded in the trough-ridge diagrams of Fig. 11 and because of averaging over a wider belt in which rising and sinking motions may compensate each other. Nevertheless, the better correspondence between distributions of tropical vertical velocity in day 10 forecast with analysed ones during ENSO events is consistent with reduced systematic errors of the model in extratropics during ENSO events as discussed by Arpe (1988a).

## 7. IMPACT FROM MODEL CHANGE ON SYSTEMATIC ERRORS

The existence of systematic errors is a major problem of forecast models. The systematic errors of the ECMWF model have been reduced or at least their growth has been retarded in recent years. In the following we will show the effects of many changes in the analysis/model system. The intensity of impacts on the systematic error by changes of the formulation of different


DJF 85/86

DJF 86/87

Fig. 11 Trough-ridge diagrams of the vertical velocity at 500 mb between 10°S and 10°N during DJF 85/86 (upper panel) and DJF 86/87 (lower panel). The mean evolution during a 10 day forecast is shown. Only contributions from waves with zonal wavenumbers up to 9 are included. Contour interval: 10 mPa/s offset by 5 mPa/s.

processes may give indications of the importance of the process for the performance of the model.

## 7.1 Zonal mean of zonal wind

One of the clearest components of the systematic error can be seen in the zonal mean of zonal wind. Cross-sections of the analysis of the zonal mean wind during DJF 86/87 and of the day 10 errors in Fig. 12 demonstrate the nature of this error. In the tropics one finds easterly components in the error field and between 30°N and 55°N westerly components. In the stratosphere westerly components dominate the error field. At the position of the northern hemisphere subtropical jet the error distribution means a northward and upward shift of the jet. Such a poleward and upward shift can also be seen for the southern hemisphere jet stream although it is much weaker. Arpe and Klinker (1986) give a more detailed description of this error.

In Fig. 13 the variability of this error in time is shown by displaying seasonal means of the vertical mean between 500 and 200 mb (lower panel) and between 100 and 50 mb (upper panel) of the day 10 errors of the zonal mean wind. A dominant feature is the annual cycle with largest errors in the winter hemisphere, especially in the northern hemisphere. There is also a biennial cycle, discussed by Arpe (1988a). In the context of the present study the changes in the error patterns due to analysis/model changes are quite interesting. Table 1 gives a list of analysis/model changes which are regarded to be of most importance.

A first change in the error characteristics can be found with the introduction of the T63 model together with an envelope orography in April 1983. Before this date the operational model was a N48 grid point model using a mean orography. Before the introduction of the new model extensive comparisons had been carried out (Girard and Jarraud, 1982, and Tibaldi, 1986) from which more a decrease of the systematic errors was anticipated. However Fig. 13 shows clearly an increase, especially in the stratosphere.

A clear reduction of errors occurred with the revision of the radiation scheme in December 1984, mainly in the stratosphere. Further improvements can be found with the introduction of the T106 model together with major changes of

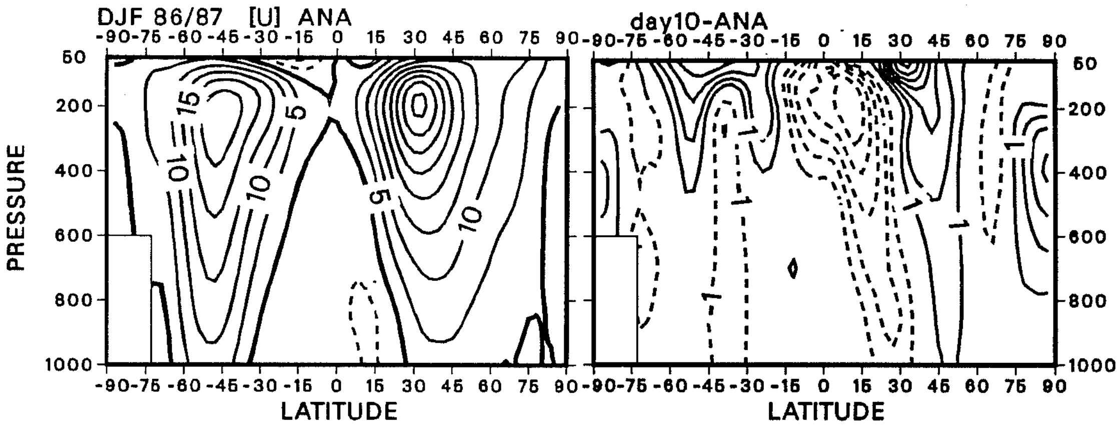


Fig. 12 Analysed zonal mean zonal wind and its day 10 forecast error during DJF 86/87. Contour interval: 5 m/s for the analysis and 1 m/s for the errors. The zero line is suppressed for the errors.

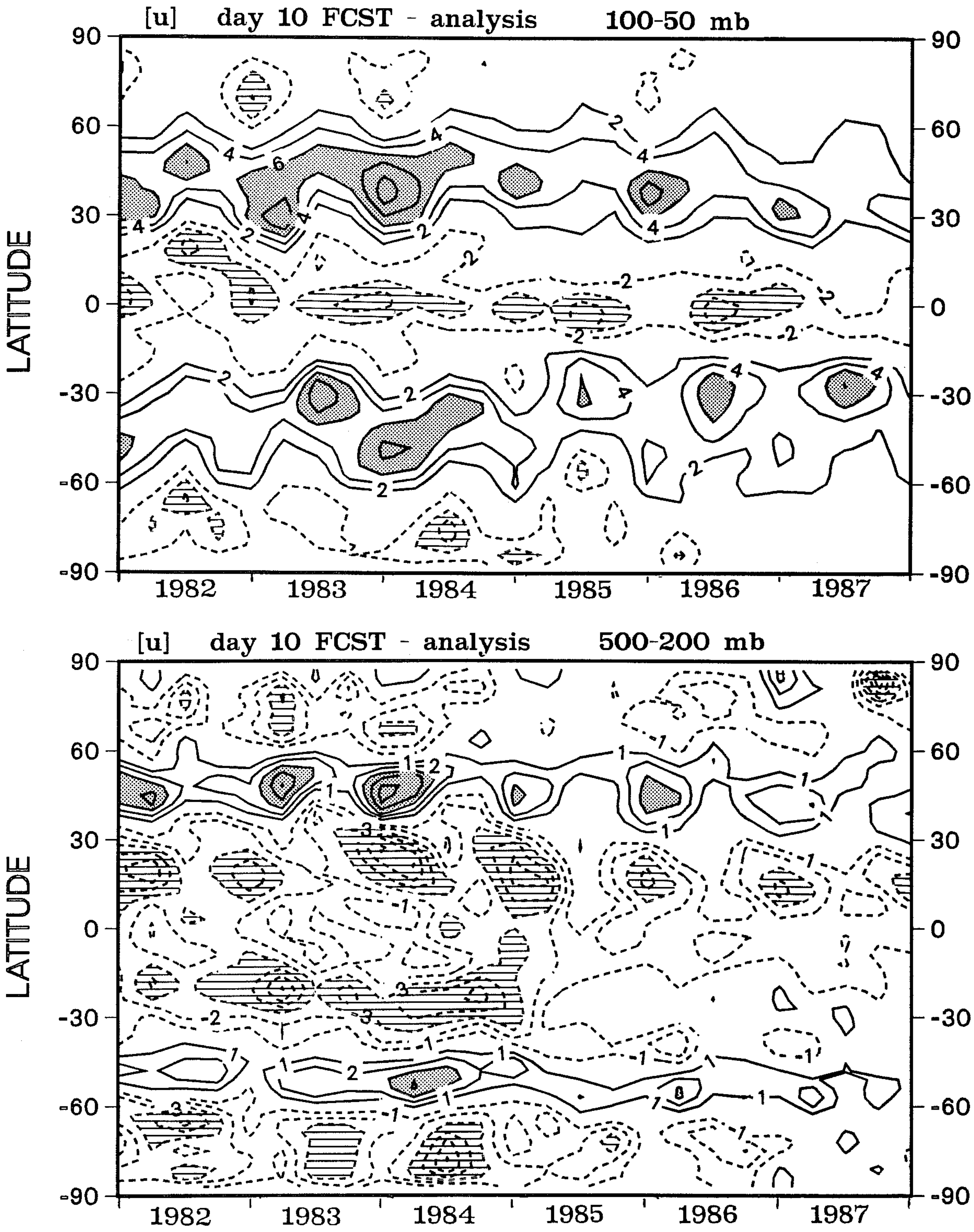


Fig. 13 Zonal and vertical means of zonal wind errors of the day 10 forecasts. Values represent seasonal means. Zero lines are suppressed. Upper panel: 100-50 mb mean; contour interval: 2 m/s; areas with errors larger than 6 m/s and less than -4 m/s are shaded. Lower panel: 500-200 mb mean; contour interval: 1 m/s; areas with absolute errors larger than 3 m/s are shaded. Ticks on the abscisse indicate the season DJF.

the convection scheme in May 1985, especially the introduction of a shallow convection. Experiments have shown that the increase of resolution from T63 to T106 tends to increase the systematic error in the upper troposphere (Tibaldi et al., 1987) and therefore one can assume that the improvements shown here are due to the revision of the parametrization scheme (Tiedtke et al., 1988).

Some further improvements can be seen with the introduction of a gravity wave drag parametrization in July 1986 together with an increase of vertical resolution from 16 to 19 levels in May 1986, especially in the stratosphere. Simmons et al. (1988) have found a general improvement of the model performance from the increased vertical resolution mainly from improved analysis which were gained from a higher resolution model in the analysis cycle. Miller and Palmer (1987) have demonstrated the positive impact on the systematic error from the parametrization of gravity wave drag.

Further reductions of errors are found for DJF 87/88. Several changes in the analysis/forecasting system have taken place which might have affected the systematic error but the main cause for the low errors is probably an anomalous circulation of the real atmosphere. During this season the subtropical jet in the northern hemisphere in the analysis is positioned further poleward which is more favourable for the model climate. This was not only found in the ECMWF but also in the NMC analysis.

A connection between errors of the zonal mean wind and of the eddy momentum flux have been pointed out by Arpe and Klinker (1986). Increases of eddy momentum fluxes in the forecasts at 30° to 40° in the winter hemisphere are consistent with poleward shifts of the subtropical jets. The long time series of data, now available, allows an investigation on the correlation between these errors. In Fig. 14 the vertical means (1000-50 mb) of these errors are shown in latitude-time cross-sections. Errors of eddy momentum fluxes are shown for the day 5 forecasts because they have nearly reached saturation within this forecast range while for the zonal mean wind again the day 10 forecast errors are shown. However the choice of forecast range is of no relevance for the following arguments.

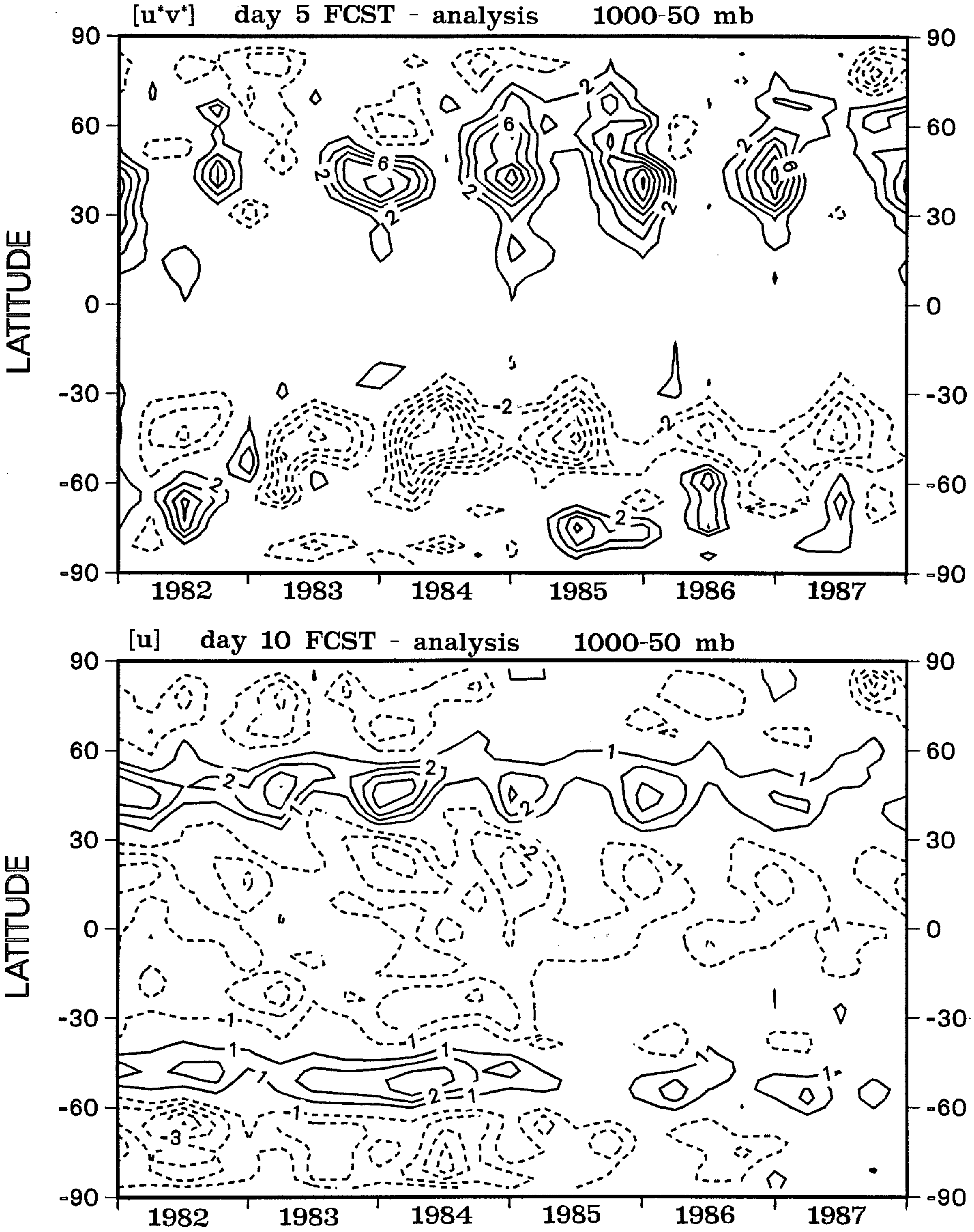


Fig. 14 Zonal and vertical (1000-50 mb) means of zonal wind errors of the day 10 forecasts (lower panel) and of eddy momentum flux error of the day 5 forecasts (upper panel). Zero lines are suppressed. Contour interval: 1 m/s wind errors and 2 $m^2/s^2$ for eddy momentum flux errors.

In the northern hemisphere the main reduction of errors of zonal mean winds occurs during the end of 1984 (revision of the radiation parametrization affecting mainly the stratosphere) while there is more an increase of errors of the eddy momentum fluxes. In the southern hemisphere the decrease of errors of the zonal mean wind are probably more due to the model changes during May 1985 (shallow convection, etc.) but what ever the correct date, it does not agree with the date of reduction of errors of eddy momentum fluxes which happened after JJA 85. One can conclude that there is no obvious correlation between these errors although from the momentum budget such a correlation could have been expected.

## 7.2 Geographical distribution of rotational wind errors

During their investigation of the ECMWF model errors in the extra tropics Arpe and Klinker (1986) found that the errors of geopotential height or wind fields implied that the amplitudes of standing waves were reduced. This was especially obvious for the diffluent flow over Europe which is severely weakened in the forecasts. This is still a problem of the present model though less severe at least if one is investigating seasonal mean fields. Here we want to concentrate more on the tropics and therefore maps of streamfunction errors during the last four winters are shown in Fig. 15 and 16.

The dominant feature of the error at 200 mb (Fig. 15) is a general meridional gradient in the tropics which agrees with enhanced easterlies in the zonal mean wind field of the day 10 forecasts in the upper tropical troposphere shown in Fig. 12 and 13. Also the reduction of this error in 85/86 is obvious. One can also recognize the zonalization in mid-latitudes which has been mentioned above. Interesting for the discussion of divergent wind errors below is a dipole pattern in the streamfunction error field over the eastern tropical Pacific. At 200 mb this error has been strengthened in the last two years. It has to be seen in connection with a weakening of the forecast divergent wind over the Indonesian area (Sardeshmukh and Hoskins, 1988) but their explanation of this error is not the only possible one. Also during JJA (not shown) the dominant feature of the 200 mb streamfunction error is a general meridional gradient at the equator, however with less longitudinal structure. The main difference to

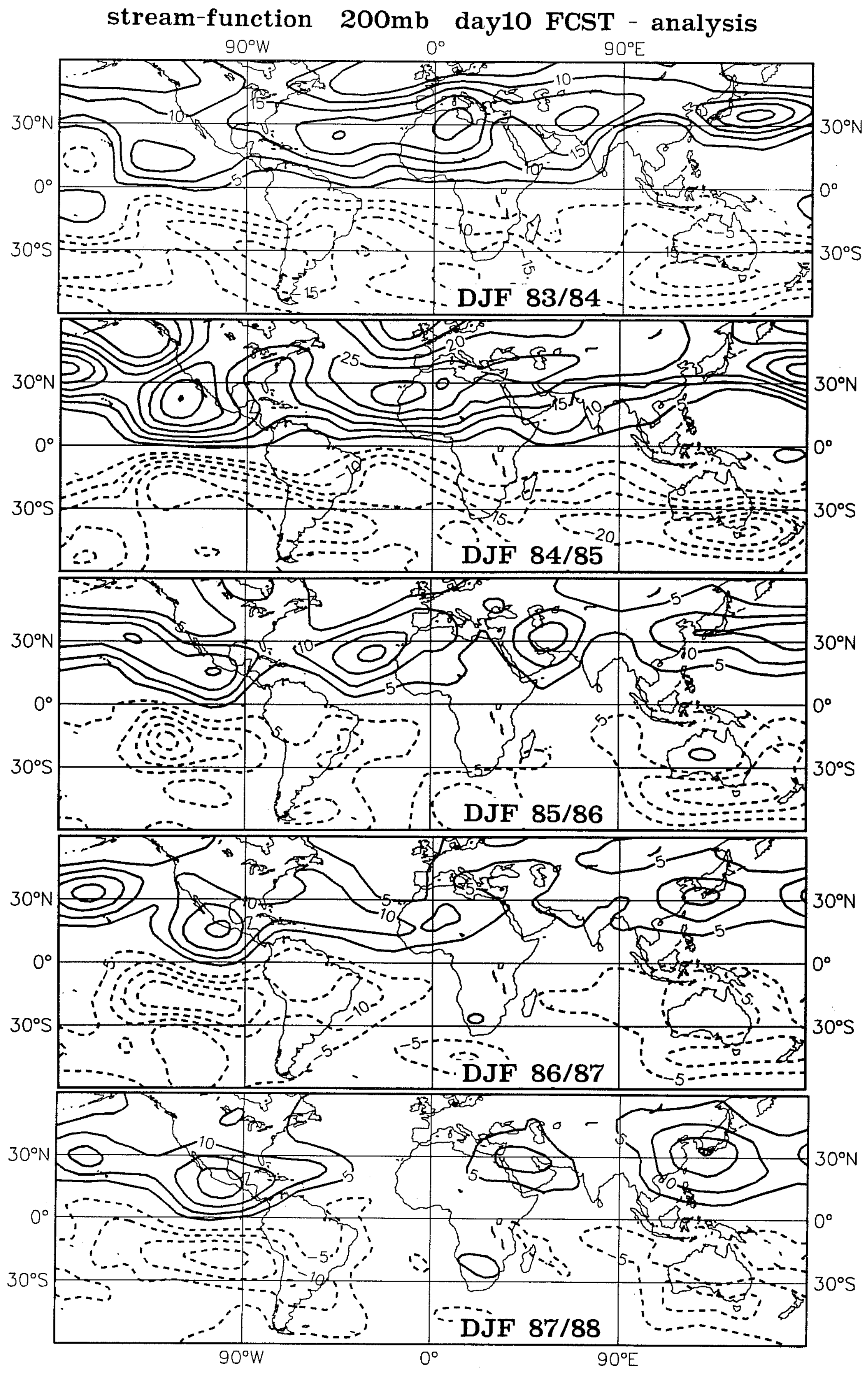
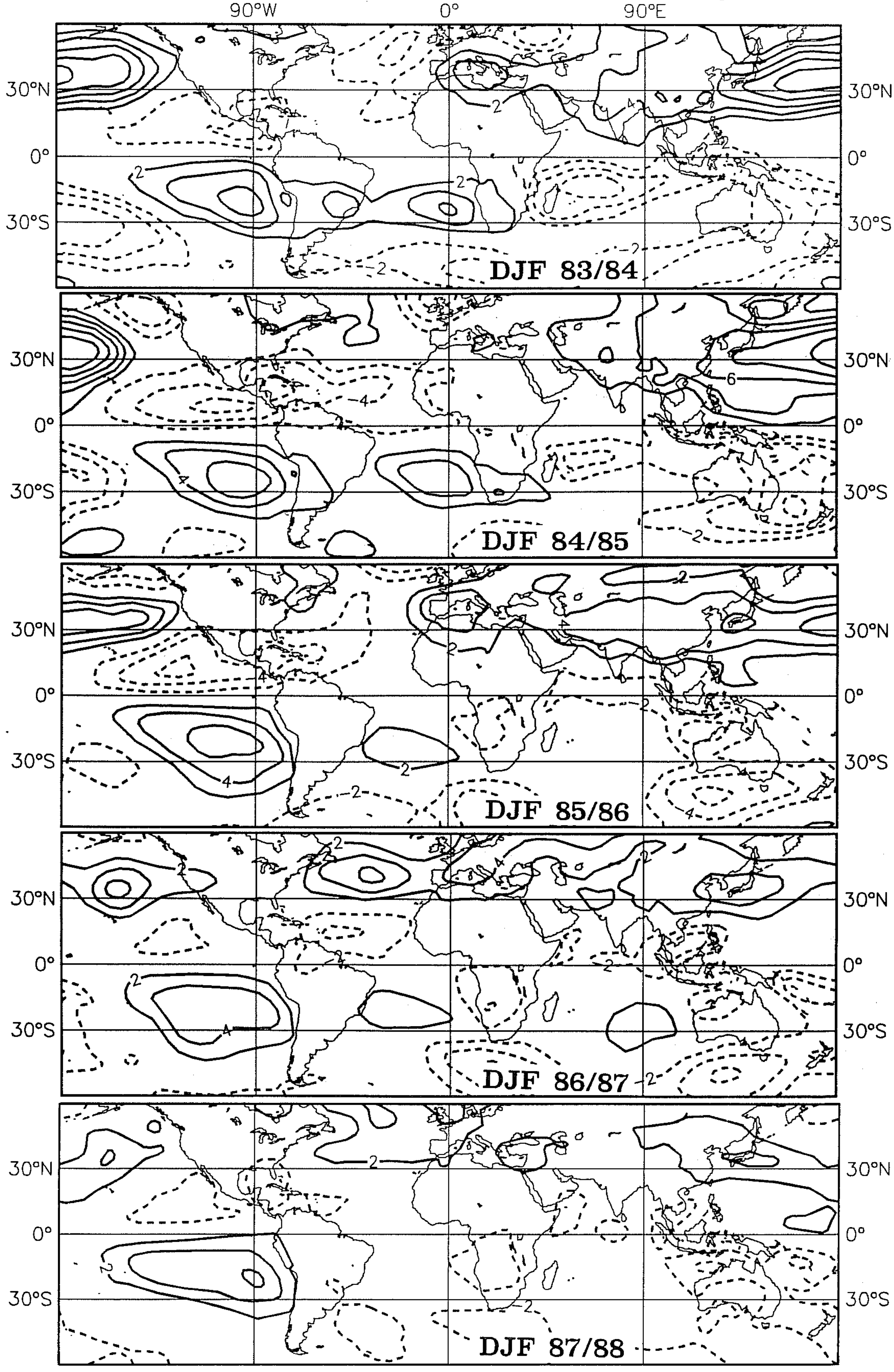


Fig. 15 Day 10 forecast errors of the 200 mb stream-function during DJF of 5 years. Contour interval: $5\times10^6$ $m^2/s$; zero line is suppressed. One contour interval in 10° of latitude corresponds to 5 m/s.



stream-function 850mb day10 FCST - analysis

Fig. 16 Same as Fig. 15 but for 850 mb and a contour interval of $2\times10^6$ $m^2/s$.

DJF can be found between 60°E and the date line probably connected with the Monsoon circulation during JJA.

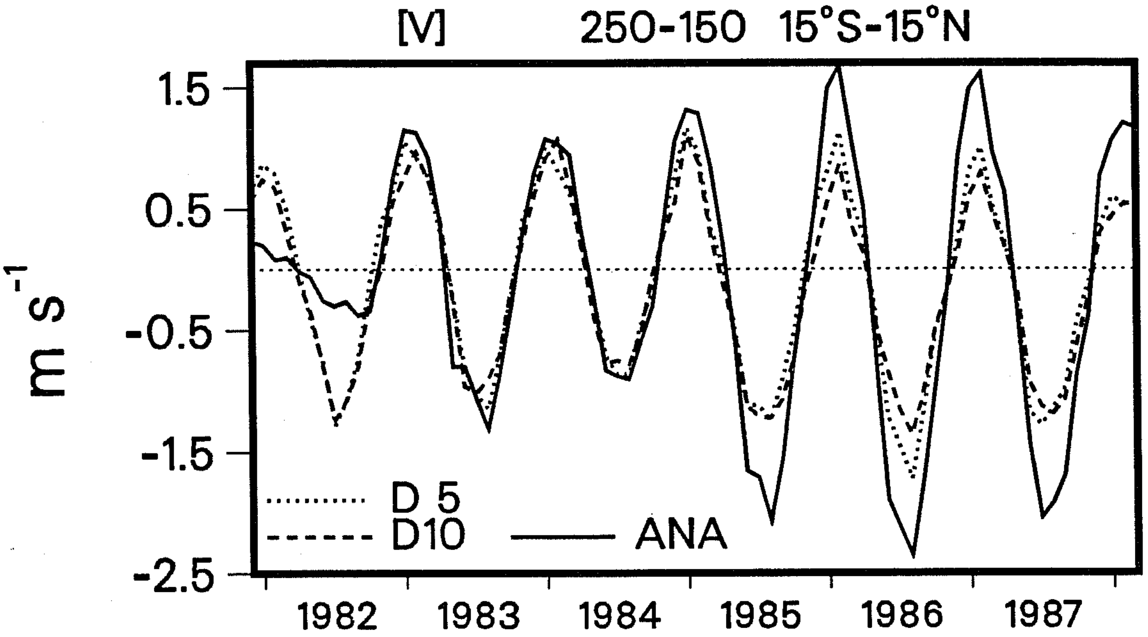
At the 850 mb level (Fig. 16) the dipole in the error fields of streamfunctions over the eastern tropical Pacific is clearly present in all four years. The opposite sign compared to 200 mb reveals the baroclinic nature of this error. At 850 mb this error means a weakening of the trade winds and the associated subtropical anticyclones. A similar error can also be found over the Atlantic Ocean. During JJA a weakening of the trade winds can be found as well but errors in the area of the Monsoon circulation are the dominant feature of this season. For the 850 mb level improvements in recent years can be found for the JJA season but less for DJF.

### 7.3 Divergent wind component

In Fig. 17 the zonal means of the meridional wind component in the tropics at two levels is shown in time sequences since December 1981 comparing analyses, day 5 and day 10 forecasts with each other. This is a variable which can be expected to be most sensitive to the choice of parametrization scheme. However, the largest changes of this quantity is not found in the model simulations but in the analyses. The amplitudes in the analysis are considerably enhanced in September 1982 (diabatic initialization) and further enhanced in May 1985 (T106, shallow convection, etc.). On the other hand, the forecasts show a trend of slight reductions in the amplitudes. This reduction is only small and on the whole gradual except for the 850 mb level in May 1985 which brought a larger reduction for the winter northerlies.

Almost opposite impacts from the May 1985 model changes on the analysis and the forecast are unexpected and are probably connected with a stronger spin-up in the present model which leads to an overshooting in the 1 to 2 day forecasts in the present but not earlier model. The spin-up in the model can influence the analysis through the first guess in the analysis cycle.

Considerable modifications of the analysis scheme have taken place during the 6 years but none of them lead to as large changes as those from the diabatic initialization and the May 1985 model change.



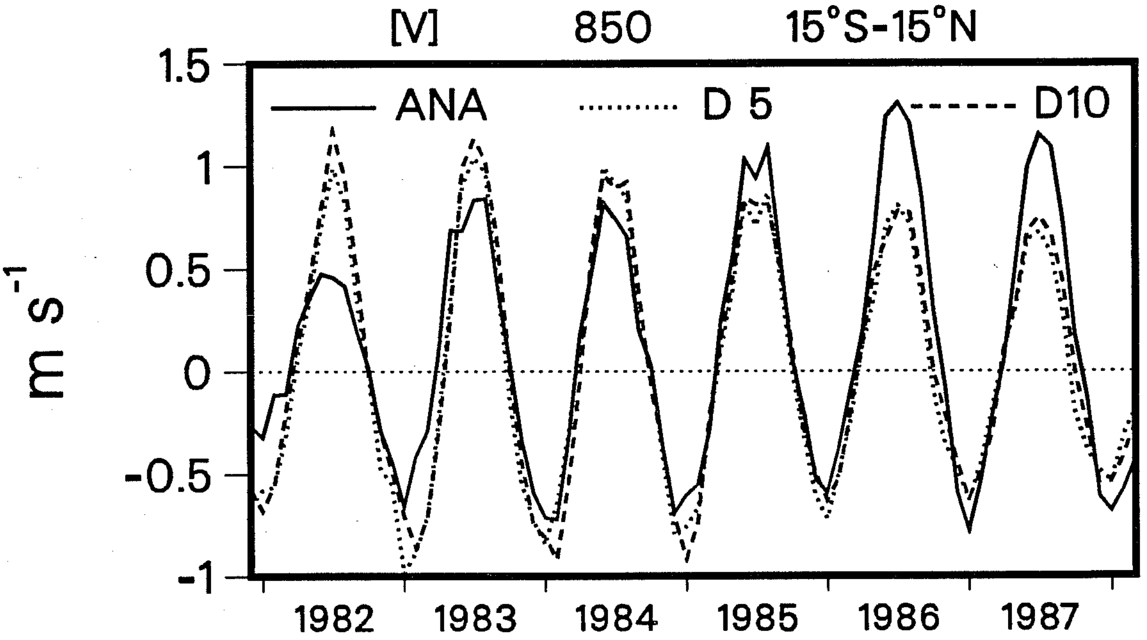


Fig. 17 Variability of the mean meridional wind (monthly averages) between 15°S and 15°N since December 1981. Forecasts and analyses are compared for the upper troposphere (250-150 mb) and for the lower troposphere (850 mb). Ticks on the abscisse give the positions of Januaries.

The large variations in the analysis of the mean meridional circulation stress the uncertainty of our knowledge of the truth. The fact that the model verified best between September 1982 and May 1985 does not mean that the model in that period was superior to the present one. Comparisons with observed data suggest that the present larger analysed values are more correct than those from before May 1985 and that they still may be underestimated. With this in mind the reduction of meridional flow in the forecasts with the May 1985 model change means a deterioration of the model performance.

The uncertainty of our knowledge of the truth on the divergent component of the flow should be kept in mind also for the following discussion on the geographical distribution of the divergent wind.

Following common practice the divergent flow is represented in Fig. 18 and 19 by the velocity potential because it emphasizes more the large scale features. The divergence is presented by the Laplacian of the field which can partly be seen by the curvature of the contours and only for the longest waves the distribution of velocity potential and divergence become identical. The divergent wind is represented by the gradients with the wind blowing from low to high values.

On the whole one finds marked weakening of the forecast divergent flow compared to the analyses. In many respects the error field is a mirror image of the analyses with opposite sign and smaller values. Three areas are especially severely affected: The central tropical Pacific, central Africa and the Caribbean Sea. The bad performance over the central Pacific seems to contradict our finding in Fig. 11 in which trough-ridge diagrams of the 500 mb vertical velocity suggest a good performance in this area for this year but one has to keep in mind that the vertical velocity corresponds to the integral of the divergence of the wind. The decrease of divergence at 200 mb over the western Pacific is in accordance with an error in the rotational wind over the eastern Pacific (see Fig. 15) as pointed out by Sardeshmukh and Hoskins (1988). Over the Caribbean Sea in the upper troposphere a convergence in the analyses is replaced by a divergence in the day 10 forecasts.

By investigating the variability of the velocity potential in the analyses, the forecasts and the forecast errors (not shown), one finds again largest

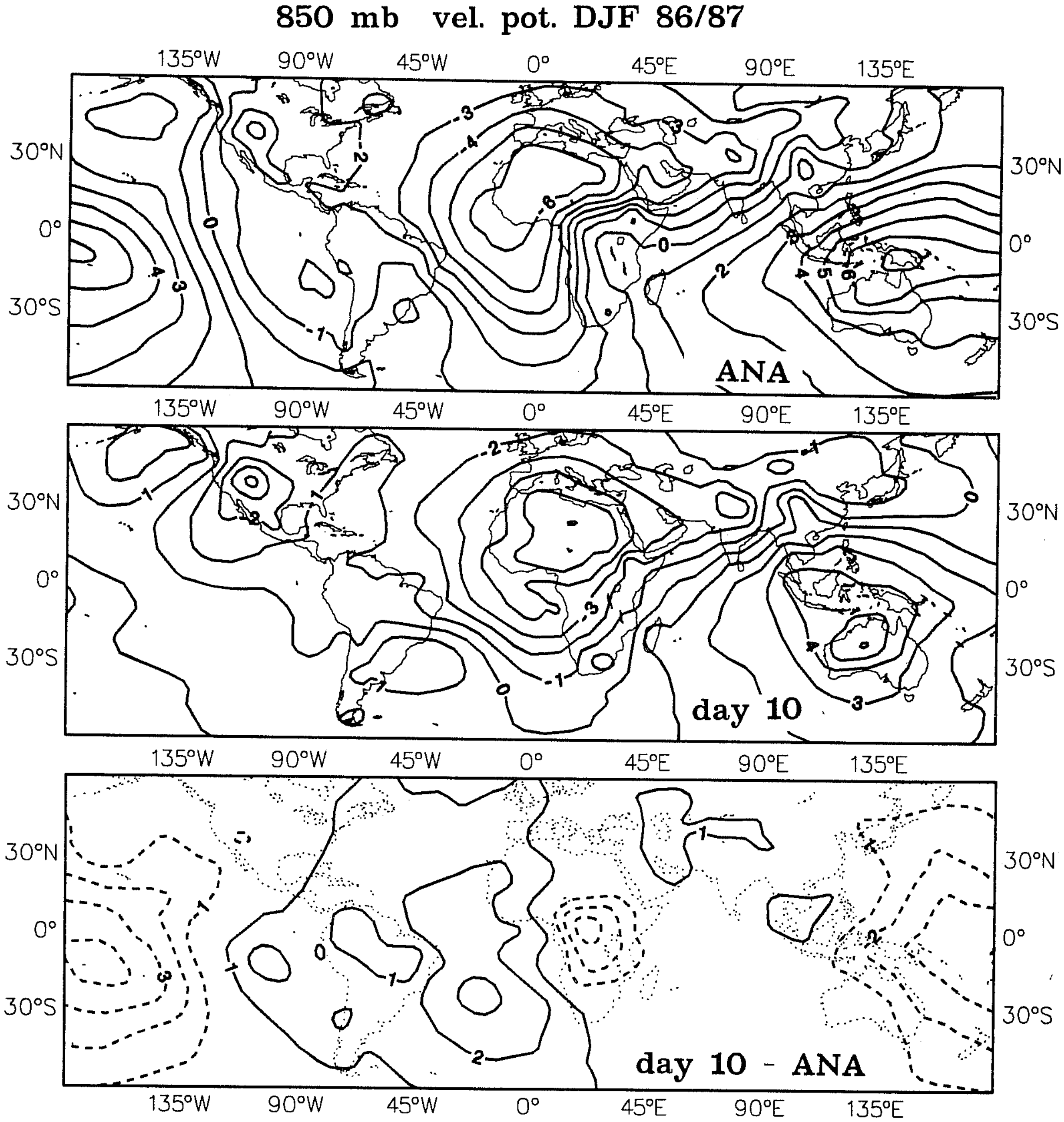


Fig. 18 Velocity potential during DJF 86/87 at 850 mb in the analyses (upper panel) and the day 10 forecasts (middle panel) and the difference between both (lower panel). Contour interval: 1x10$^6$ m$^2$/s, in the error field the zero line is suppressed.

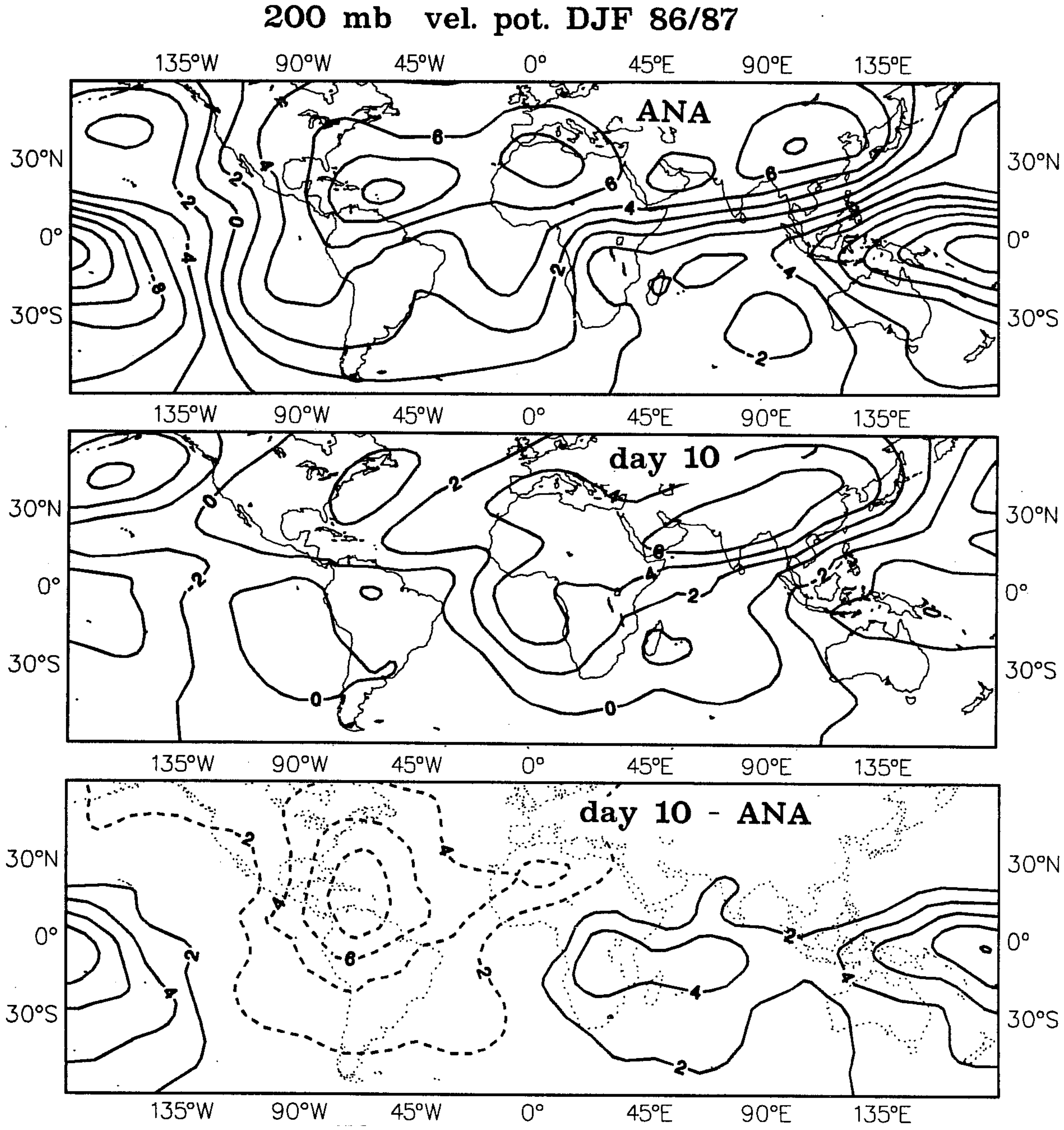


Fig. 19 Same as Fig. 18 for 200 mb and a contour interval of $2 \times 10^6$ $m^2/s$.

impacts from the model changes in May 1985 (T106, shallow convection, etc). Contrary to the zonal means it is not so much the analysis but the forecast data which was affected. Before those changes the velocity potential did not weaken as it does in the present model. Because of errors in the positions of maxima and minima and larger amplitudes in the forecasts of the earlier version of the model one might expect larger errors in the earlier model which is hardly found. On the other hand one would not say either that the earlier model was superior to the present one. The statement which can be made is that the error characteristics have changed considerably with the May 1985 model changes and that the present model suffers from a severe damping of the divergent flow.

The smaller damping of divergence wind over Indonesia before May 1985 is according to Sardeshmukh and Hoskins (1988) consistent with a weaker dipole in the error field of 200 mb streamfunctions in Fig. 15.

### 7.4 Zonal mean temperature error

In Section 2 it has been shown that there is an imbalance in the short range forecasts between cooling and heating of the model atmosphere which has to lead to an overall warming. Fig. 20 reveals that this warming is confined to the middle and upper tropical troposphere, especially strong at the tropical tropopause. This is the area where in Section 3 errors of OLR have been found but it is not clear if the OLR errors are connected with the errors in the temperature field.

In the extra tropical stratosphere and the lower toposphere cooling prevails. The vertical distribution in the tropics of cooling in lowest layers and heating above means a stabilization of the lower tropical atmosphere and is clearly connected with a decrease of convection and weakening of divergent winds in the tropics which have been shown above. Also the loss of sensitivity of the atmosphere to SST anomalies, discussed in Section 6, may be due to this increased stability.

How these tropical temperature errors have changed during the last 6 years is displayed in Fig. 21.

Temperature values near the tropical tropopause may suffer from the interpolation method used at ECMWF (see Arpe, 1988b). An effect of this problem can be seen in Fig. 21 for the 100 mb level. In May 1986 the number of levels of the model was increased from 16 to 19 mainly increasing the resolution in the stratosphere. This decreases the 100 mb temperatures to probably more realistic values in the analyses as well as in the forecasts. A further cooling of analyses and forecasts in January 1988 is due to the removal of a vertical diffusion above the PBL.

There are only few reliable temperature measurements in the tropical free atmosphere and therefore the analysed values can be expected to be sensitive to analysis/model changes, e.g. there is an increase of 1.5 K at 500 mb from the diabatic initialization in September 1982 and a decrease by 1 K at 850 mb from the revision of the radiation scheme in December 1984 and a further reduction in May 1985 (T106, shallow convection, etc).

The latter decrease and an increase at 850 mb with the introduction of the T63 model in April 1983 may be due to changes in the orography which occurred at the same times. The introduction of an envelope orography with the T63 model gave an average rise of the orography bringing the mean 850 mb nearer to the earth surface which increases the diurnal cycle of the 850 mb temperatures but also could lead to a general increase of temperature. A part of this could be due to a higher proportion of extrapolations below ground. The increase of horizontal resolution from T63 to T106 in May 1985 reduced the effect of the envelope orography and by this reduced its warming effect.

Further changes of the analysis/forecast scheme modified the analysed temperatures but are difficult to identify because these changes were smaller than the natural variability of the analysed temperature.

The most dramatic changes in the forecasts occurred in May 1985 (T106, shallow convection, etc) at 850 and 500 mb and in December 1984 (radiation) at 500 and 50 mb.

As the temperatures at different levels behave differently one has to expect strong variations of the static stability during this period of 6 years. Fig. 22 demonstrates this by temperature differences between two levels in the

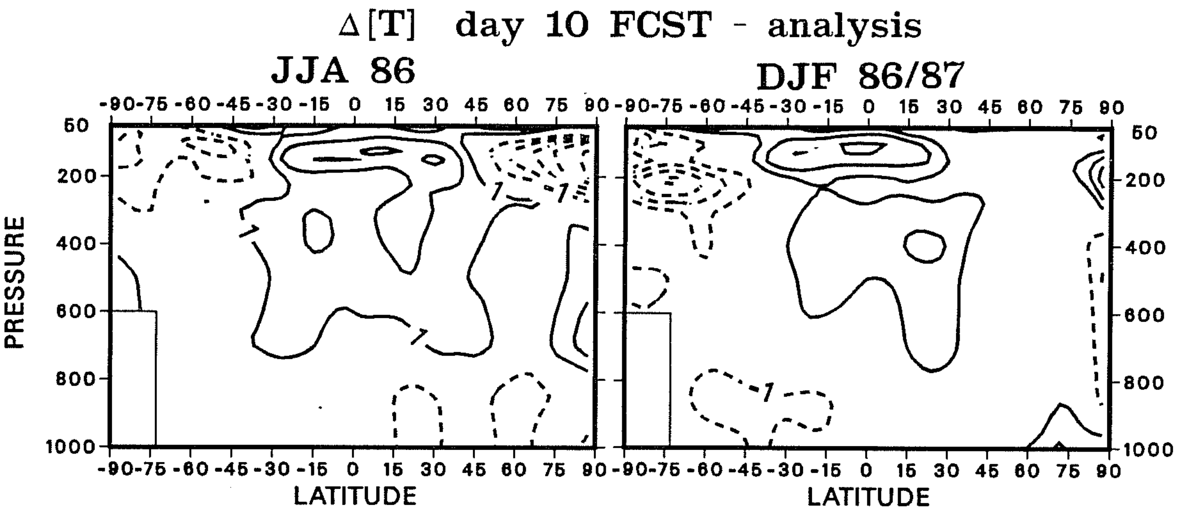


Fig. 20 Day 10 forecast error of zonal mean temperatures during DJF 86/87 and JJA 86. Contour interval: 1 K; the zero line is suppressed.

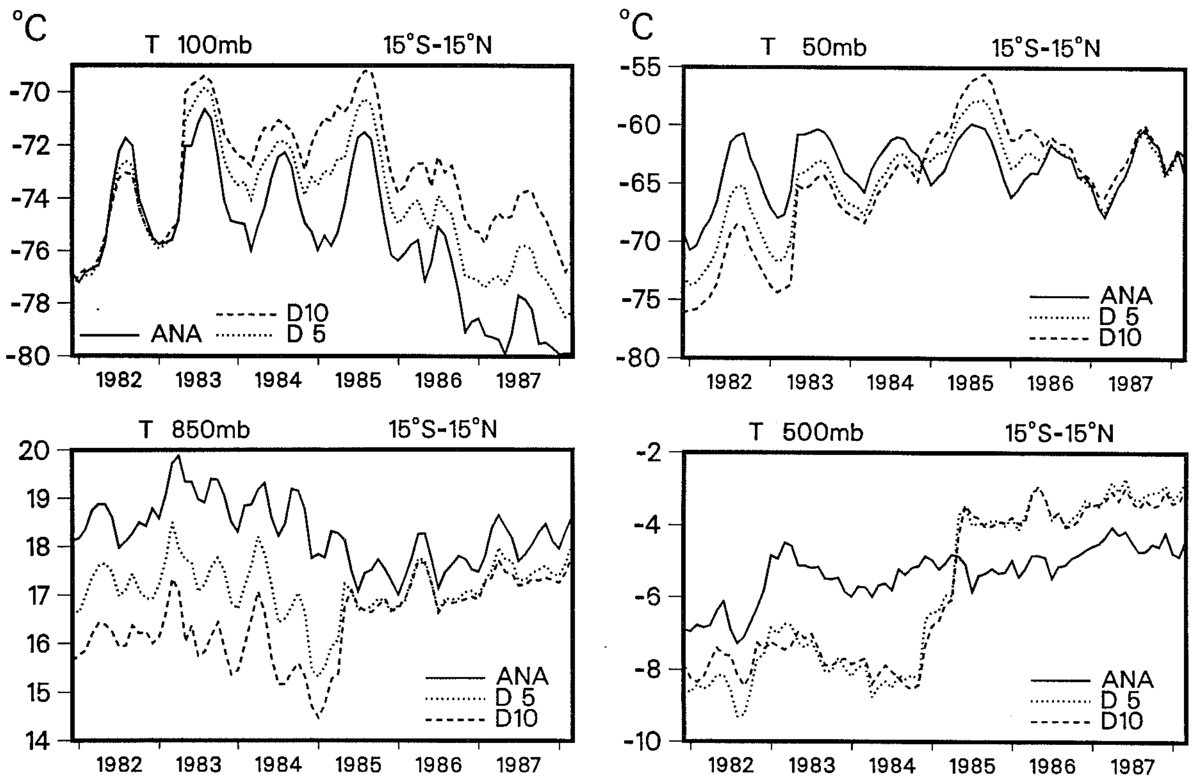


Fig. 21 Zonal mean temperature in the tropics (15°S-15°N) in the analysis, the day 5 and day 10 forecasts at 850, 500, 100 and 50 mb. Values represent monthly means. Ticks on the abscisse indicate Januaries.

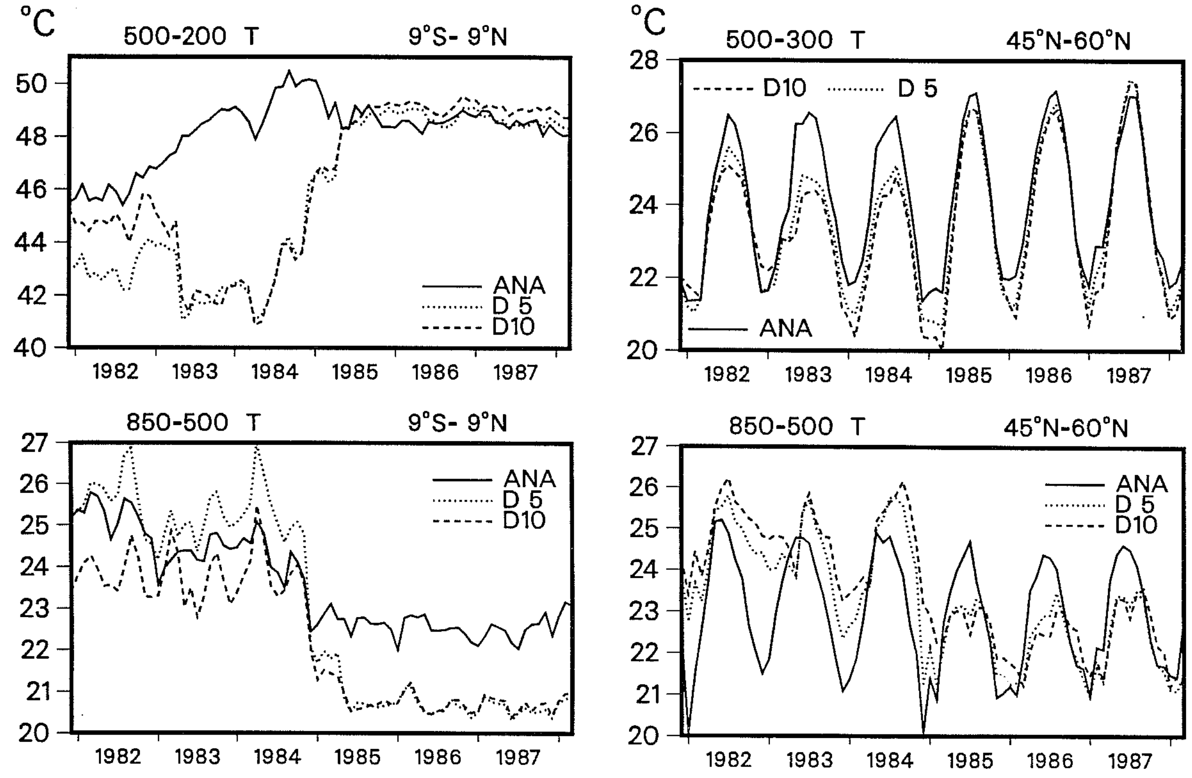


Fig. 22 Static stability represented by zonal mean temperature differences between two levels in the analysis, the day 5 and day 10 forecasts. Values represent monthly means. Ticks on the abscisse indicate Januaries. Left panels: 9°S-9°N; right panels: 45°N-60°N.

lower and upper troposphere. Above it has already been shown that the lower tropical troposphere is stabilized during the course of the forecast. This stabilization occurs very quickly, within 2 or 3 days of forecast, and is fully established in the day 5 forecasts as shown by Fig. 22. This problem arose with the changes in December 1984 (radiation) and May 1985 (T106, shallow convection). Fig. 22 reveals also the sensitivity of the analysed values to these model changes.

In the upper tropical troposphere one finds more a gradual destablization of the analyses over several years while there are several steps in the forecasts: a stabilization in April 1983 (T63, envelope) and destabilizations around July 1984, December 1984 (radiation) and May 1985 (T106, shallow convection, etc). Again the error establishes already in the short range forecasts.

Fig. 22 shows also similar graphs for northern mid latitudes which again show major impacts from the May 1985 model changes, again a general stabilization of the lower troposphere.

### 7.5 Variances and covariances (space domain)

A convenient measure for variances and covariances in the atmosphere are the energetics as formulated by Lorenz (1955). For details of the calculation used in this study see Arpe et al. (1986). Fig. 23 shows global averages of energy amounts during JJA 86 and DJF 86/87 during the course of the forecasts. The dominant feature is the drop of eddy energies (KE and AE) and increase of zonal energies (KZ and AZ). Above it has been discussed that there is a reduction of amplitudes in the standing waves but most of the reduction of eddy energies in Fig. 23 results from the transient waves, because the standing waves contribute rather little to the total eddy energies.

Fig. 24 shows how the eddy kinetic energies in the analysis and the forecast have changed in recent years. Contributions by planetary waves (zonal wavenumbers 1-3) and synpotic waves (zonal wavenumber 4-9) are displayed separately because of different trends in both wave groups. From April 1983 onwards the eddy activity in the forecast is reduced, most likely due to the introduction of the envelope orography.

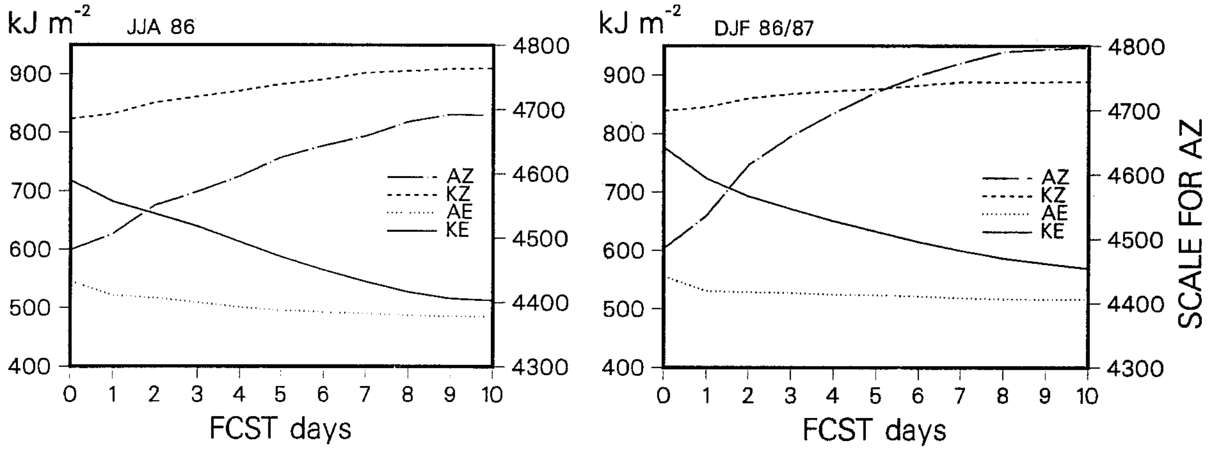


Fig. 23 Global averages of energy amounts during the course of the forecasts in JJA 86 and DJF 86/87.

KE = eddy kinetic energy AE = eddy available potential energy

KZ = zonal kinetic energy AZ = zonal available potential energy.

Scale on the left refers to KE, AE and KZ while the scale on the right refers to AZ.

The period December 1984 to April 1985 is characterized by especially low values in the forecasts. The modification of the radiation scheme seems to have lead to a decrease which is then compensated by the May 1985 model changes (shallow convection, etc.). Controlled experiments on the impact of the modification of the radiation scheme have not been investigated concerning the eddy kinetic energy but Tiedtke and Slingo (1985) have found increases of KE from the May 1985 model changes in respect of the parametrization scheme.

During DJF 86/87 and 87/88 the error of the planetary wave kinetic energy is especially small. This reduction of error results from a reduction of analyzed winter maxima (September 1986 modification) as well as from an increase of forecast winter maxima, probably due to the gravity wave drag parametrization.

The better performance of the model with respect to eddy kinetic energy of the synoptic scale waves (zonal wavenumbers 4-9) with the grid point model, i.e. before April 1983, is compensated by worse performance with respect to the conversion from eddy available potential energy to eddy kinetic energy, shown in Fig. 25. The January 1988 model change (reduced vertical diffusion) shows a trend of the error characteristics of the energetics of synoptic waves towards those of the old gridpoint model, i.e. too much conversion but less reductions of eddy kinetic energy amounts. The real problem with the model has not been changed through the years which is a too efficient energy conversion especially by baroclinic waves. Arpe and Klinker (1986) have shown that the baroclinic waves are more strongly tilted (vertically and horizontally) in the model than in the analysis so that the model gives either stronger conversions or lower energy amounts. They also raised the question if the analysis is correct in this respect and we still do not know the answer. Arpe et al. (1986) have shown that the conversions in the analyses have been increasing in recent years and that they are approaching values of short range forecasts which is another indication of uncertainties in our knowledge of the true values. With this uncertainty in mind it is probably better to aim for the right amount of eddy kinetic energy instead of energy conversion.

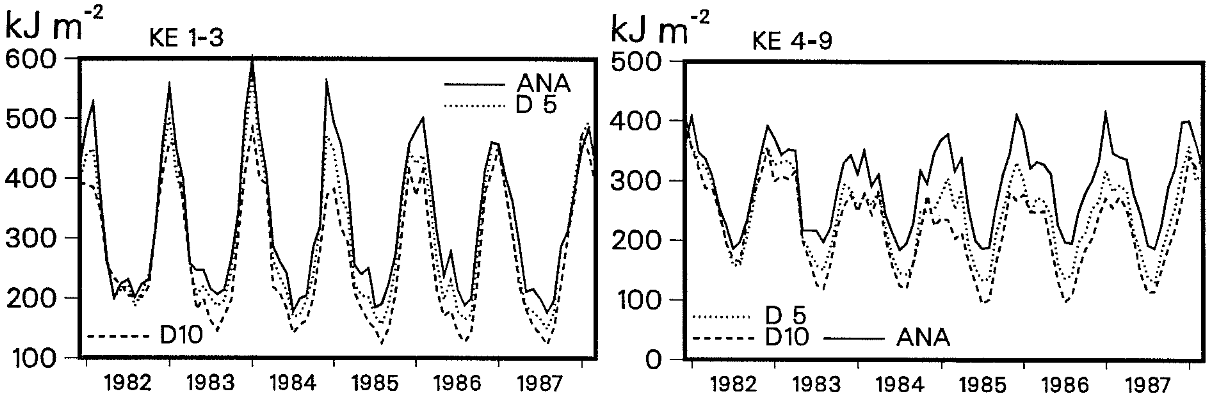


Fig. 24 Northern hemisphere mean eddy kinetic energy by planetary (zonal wavenumbers 1-3) and by synoptic (zonal wavenumbers 4-9) scale waves in the analyses, the day 5 and day 10 forecasts. Values represent monthly means. Ticks on the abscisse indicate Januaries.

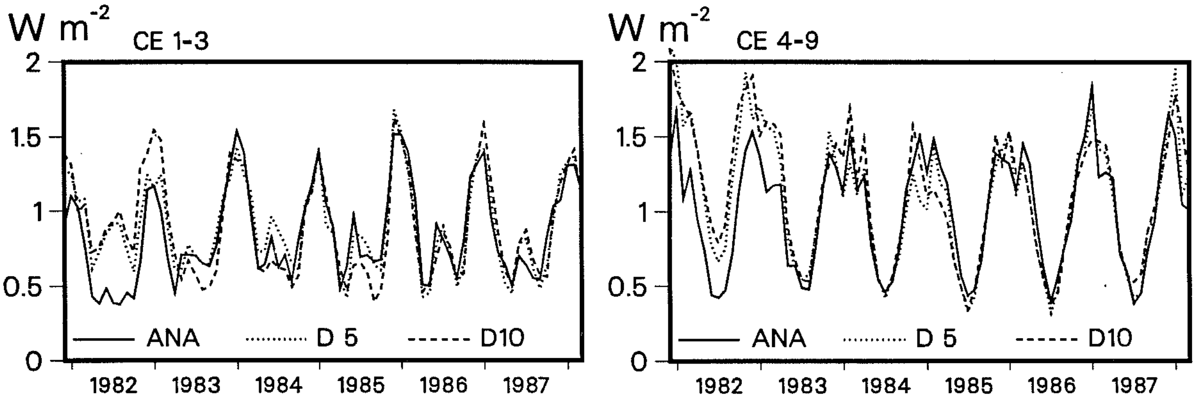


Fig. 25 Same as Fig. 24 but for the conversion from eddy available potential energy to eddy kinetic energy.

## 8. CONCLUSION

The systematic errors of the ECMWF model have been investigated with special emphasis on diabatic forcings.

Budgets of energy and humidity are unbalanced in the short range forecasts mainly due to an overshooting of convective precipitation. This leads to a general heating and drying of the model atmosphere. By day 10 a balance is nearly reached but with too low radiative cooling and perhaps too low sensible heat fluxes compared to recent estimates (Hoyt, 1976).

The outgoing longwave radiation (OLR) over the main tropical convective areas is predicted clearly too large in all forecast ranges. This is mainly due to an insensitivity of the radiation scheme to clouds. The impact of this error on the model performance is unclear because this problem will affect also solar radiation which may cancel the error of longwave radiation and also because it is the divergence of the radiative fluxes which is important and not the radiative fluxes themselves.

Comparisons of precipitation in the model with climatological values or with estimates from OLR measured from satellites suggest that short range forecasts (day 0-1) are nearest to reality with precipitation amounts in the tropics which are higher than climatological estimates by Jaeger (1976) but lower than estimates from OLR. In the medium range forecasts there is clearly too little precipitation in the tropics of the summer hemisphere.

Verification of precipitation for Europe using SYNOP observations reveals good correspondence between short range forecasts (day 0-1 or day 1-2) and observations. In monthly means gridpoint values deviate from observations hardly by more than 1 mm/day as along as there are several observational stations available to calculate a mean for a gridpoint. However, an overprediction on the windward side and an underprediction in lee of main mountain ranges (Massif Central/Alps and Scandinavia) seems to be a systematic error. In this respect the error characteristics has changed completely to an earlier version of the ECMWF model. The precipitation in the Mediterranean Sea area is mostly predicted too low. This results mainly from single events with heavy observed precipitation which were not forecast but the verification for these areas are characterized by an insufficient density of observational data. In middle Europe with a better data density there is a good correspondence between short range forecasts of precipitation and observations of daily averages. There may be a tendency to overpredict convective precipitation in cold air outbreaks. For forecast ranges beyond day 3 this correspondence ceases quickly which is probably less a direct problem of the parametrization scheme but more due to error in the predicted flow.

Impacts from sea surface temperature anomalies on the performance of the model have been investigated by comparing the season December to February for 1985/86 with 1986/87, i.e. a non-ENSO with an ENSO event. In the short range forecasts the tropical precipitation and vertical velocity differ realistically between both years but these differences disappear totally in the medium range forecasts. The model atmosphere tends more to a circulation which is typical for an ENSO event. It has been speculated that this insensitivity to sea surface temperature anomalies is due to a stabilization of the lower tropical troposphere.

Investigations of the variability of the systematic errors of wind and temperature during the last years gave an insight into the importance of different processes on the systematic error. Largest improvements were gained from the introduction of a shallow convection parametrization together with other model changes in May 1985. This model change was most important for the tropics but affected also the mid latitudes especially in the southern hemisphere. The stratosphere gained most improvement from the revision of the radiation scheme in December 1984 and from an introduction of a gravity wave drag parametrization in July 1986. Variances of wind and temperature by transient waves are underpredicted since the introduction of the envelope orography in April 1983. This error has been enhanced since then probably due to the revision of the radiation scheme in December 1984.

Improvements of the parametrization of convection and radiation have been found to have the largest impacts on the model performance and further work on these will most likely be beneficial also in the future. Especially the cloud-radiation interaction appears to be wrong and is presently being studied. A further point of concern is the insensitivity of the model to sea surface temperature anomalies.

In many respects it has been shown that the lack or inaccuracy or unrepresentativeness of observational data is a major problem for evaluating the performance of the model and special effort should be put on improving this situation.

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