IMPACTS OF CHANGES IN THE ECMWF ANALYSIS-FORECASTING SCHEME ON THE SYSTEMATIC ERROR OF THE MODEL

K. Arpe
European Centre for Medium-Range Weather Forecasts
Reading, U.K.

Abstract

In recent years the systematic error of the ECMWF model has been reduced considerably. Modifications of the parametrization of convection and radiation gave the largest impacts. Further improvements were found from the restriction of a general vertical diffusion to the boundary layer, the introduction of a gravity wave drag parametrization and an increase of vertical resolution in the stratosphere. The improvements were clearest for the December to February season.

The Hadley circulation in the analysis was strongly affected by model changes. The analysed zonal mean 500 mb vertical velocity near the equator has been increased from less than 5 mPa/s before September 1982 (diabatic initialization) to more than 50 mPa/s after May 1989 (massflux, radiation, gravity wave drag). This latest model change resulted in a doubling of the mean vertical velocity in the analysis. The larger values in the analysis seem to be supported by observational data. The model changes had, however, only very small impacts on the mean vertical velocity in the day 10 forecasts. Up to May 1989 they led more to a decrease than increase of the Hadley circulation. There is now a much larger diurnal cycle in the vertical velocity of the model compared to the analysis over South America and Africa.

The model is now maintaining the level of eddy kinetic energy of the analysis while there was a decrease in the years before 1988. Improvements resulted from the restriction of vertical diffusion to the boundary layer and from the May 1989 model change, especially the modification of the radiation scheme. Connected with these improvements (increases) of eddy kinetic energy in the forecasts is an increase of conversions from eddy available potential energy to eddy kinetic energy which is now larger in the forecasts than in the analysis.

In respect to diabatic forcing the investigation concentrated on the May 1989 model change. It has led to many improvements; especially the outgoing longwave radiation looks now realistic. In the medium range forecasts the evaporation over oceans agree with climatological estimates; however, in the short range a spin-up of evaporation and precipitation still gives rise to some concern. The evaporation in the short range forecasts over tropical oceans is too low probably due to the way satellite data are used in the analysis scheme.

1. INTRODUCTION

Model errors which arise in nearly every forecast or series of forecasts are referred to as the systematic errors of the model. (See for example Hollingsworth et al., 1980). Much attention has been given to these errors and many changes have been introduced in to the analysis/forecasting scheme in order to reduce them. Arpe and Klinker (1986) and Heckley (1985) have given a first documentation of the different aspects of the systematic error of the ECMWF model and have discussed the connections between errors. In the following the impacts of the different model/analysis changes on the model performance are discussed. Table A gives an overview of those changes which produced larger impacts.

The investigation focuses on monthly and seasonal means of day 10 forecasts. It tries to assign variations of forecast errors to changes in the analysis/forecasting scheme and to demonstrate the importance of different components of the model for its performance. Problems in so doing arise from natural seasonal and interannual variabilities in the analyses and forecasts. This is especially important for the extratropics for which only quantities from the same season should be compared. This may also apply for global averages, because the impact of a model change which affects, for example, only the Northern Hemisphere winter circulation, will not be seen before December of the year following the introduction of the model change. Further problems in assigning error variations to analysis/model changes arise from the fact that sometimes several changes have taken place within short intervals. During the course of the following discussions of different aspects of the systematic errors, an attempt has been to take account of all these possible pitfalls, or to mention possible alternative interpretations.

The systematic error is also often called the climate drift of the model and the time until this drift has reached its asymptotic value varies considerably for different quantities. In the short range forecasts the trend may even be of different sign than in the more extended range forecasts. We are concentrating here on the mean day 10 forecast errors because it is the longest range operationally available and therefore nearest to its climatological value. Different model changes are found to be of different importance for different forecast ranges, e.g. one can expect changes in the analysis/initialization scheme to be more important for the short range forecasts than for medium range forecasts while there may be model changes which influence the climatological behaviour of the model although the impact on the day 10 forecast is still small.

In the following sections different meteorological variables will be investigated for impacts from the different changes in the analysis/forecasting scheme. Of special interest will be the impacts from the recent change from a Kuo to a massflux convection parametrization

Table A: Important changes in the analysis-forecast scheme

September 1982	Diabatic Initialization (Wergen 1987).
April 1983	T63 model (Girard and Jarraud, 1982) with an envelope orography (Tibaldi, 1986, Jarraud et al., 1988) and 16 hybrid levels in the vertical (Simmons and Burridge, 1981).
November 1983	Analysis of soil moisture and snow cover.
March 1984	The model horizontal diffusion was increased (reduced again in May 1985).
May 1984	Diurnal cycle was introduced into the model.
May 1984	The analysis was subjected to extensive revisions (Shaw et al. 1987).
July 1984	Correction to the moisture dependence on specific heat was introduced.
November 1984	Analysis increments evaluated directly on model levels (Unden, 1984).
December 1984	A modified radiation scheme and stratospheric drag were introduced (Ritter, 1985; Slingo and Ritter, 1985).
February 1985	The analysis scheme was modified which affected the large scale wind field.
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. 1989; Slingo, 1987).
March 1986	Tides are handled by initialization (Wergen, 1989).
March 1986	Use of satellite precipitable water content data and modified (reduced) use of SYNOP data in humidity analysis (Illari, 1986, 1989).
May 1986	Model levels were increased to 19 (Simmons et al. 1989).
July 1986	Gravity wave drag parametrization was introduced (Miller and Palmer, 1987).
September 1986	The analysis scheme was modified (Lönnberg et al., 1986).
November 1986 - March 1987	Problems with temperature observations from satellite.
April 1987	The parametrization of surface processes was revised (Blondin and Böttger, 1987).
July 1987	The analysis uses only 7 instead of 11 layers of SATEM data (Kelly and Pailleux, 1988).
December 1987	A tighter quality control of cloud drift winds in the analysis was introduced.
January 1988	Vertical diffusion scheme above PBL was removed (Miller, 1988).
January 1988	Analysis of divergent wind improved (Unden, 1989).
July 1988	Analysis of small scales improved.
September 1988	New method of satellite retrievals by NOAA/NESDIS.
November 1988	Change to initialization.
January 1989	Reduced impact of satellite humidity on analysis.
May 1989	New radiation scheme (Morcrette, 1989, 1990), replacement of Kuo by mass-flux convection (Tiedtke, 1989), revised gravity wave drag.

which was introduced together with a modification of the radiation and the gravity wave drag scheme in May 1989 of which the two former changes are thought to be the more important ones.

2. ZONAL MEAN OF ZONAL WIND

One of the most persistent components of the systematic error of almost all global NWP models can be found in the zonal mean of the zonal wind. Fig. 1 shows examples for December to February (DJF) 1986/87 and DJF 1988/89. The mean analysed fields and the day 10 forecast errors are shown. The error fields in the tropics are dominated by an easterly bias, especially in the upper troposphere. Between 30°N and 55°N the westerlies are forecast to be too strong. During DJF 1986/87 the error pattern relative to the analysed subtropical jet stream implies that the jet stream in the forecast is shifted poleward and upward. Such a poleward shift has been found for all years but since DJF 87/88 it is accompanied by a strengthening of the jet. When looking into other seasons, one finds already in earlier years indications of this strengthening. Arpe and Klinker (1986) pointed out that the strengthening of westerlies at about 40°N consisted of an equatorward shift of the polar jet in some regions and a poleward shift of the subtropical jet in other regions. In the Southern Hemisphere one finds similar characteristics in the error fields, especially if one compares the winter seasons in both hemispheres (not shown).

Arpe and Klinker (1986) pointed out that an increase in westerlies between 30°N and 55°N is accompanied by an increase in eddy momentum flux. The resulting divergence of eddy momentum flux is large enough to balance the budget of zonal momentum. Cause and effect are however unclear and Arpe (1987) could not find any correlation between the strength of the error in the wind field and the error of the eddy momentum flux.

The error pattern in the vertical at 10°-15°N in connection with the pattern of the mean field suggests that the model reduces the vertical wind shear by dissipative mechanisms which was one of the main reasons for the restriction of vertical diffusion to the boundary layer in January 1988.

The error of the zonal mean of zonal wind grows steadily during the 10 day forecasts, and experiments with extended range forecasts (Palmer et al., 1989) have shown a further growth of error to about day 25. It should also be noted that this error pattern is typical of global forecast models and a growth up to day 25 has been found also in the NMC model (Tracton et al., 1989).

In order to examine the impact of model changes on the systematic error of zonal mean winds, the seasonal mean day 10 forecast errors have been averaged in the vertical in two slabs, 500-200 mb and 100-50 mb. They are presented in time-latitude cross-sections in Fig. 2.

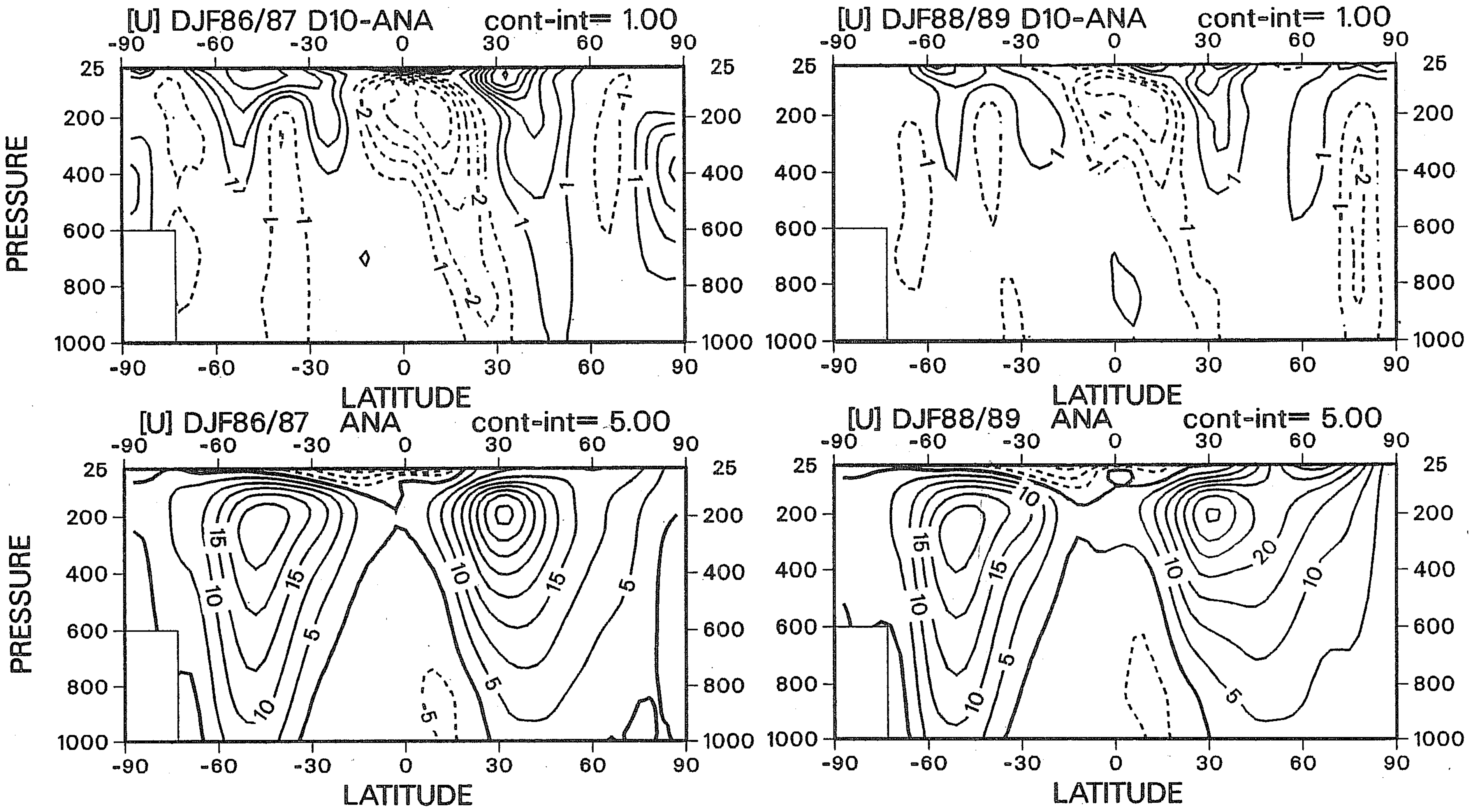

Fig 1: Zonal mean of zonal wind in the analysis during DJF 86/87 and DJF 88/89 (lower panels) and the day 10 forecast errors (upper panels). The zero contour in the error panels is suppressed.

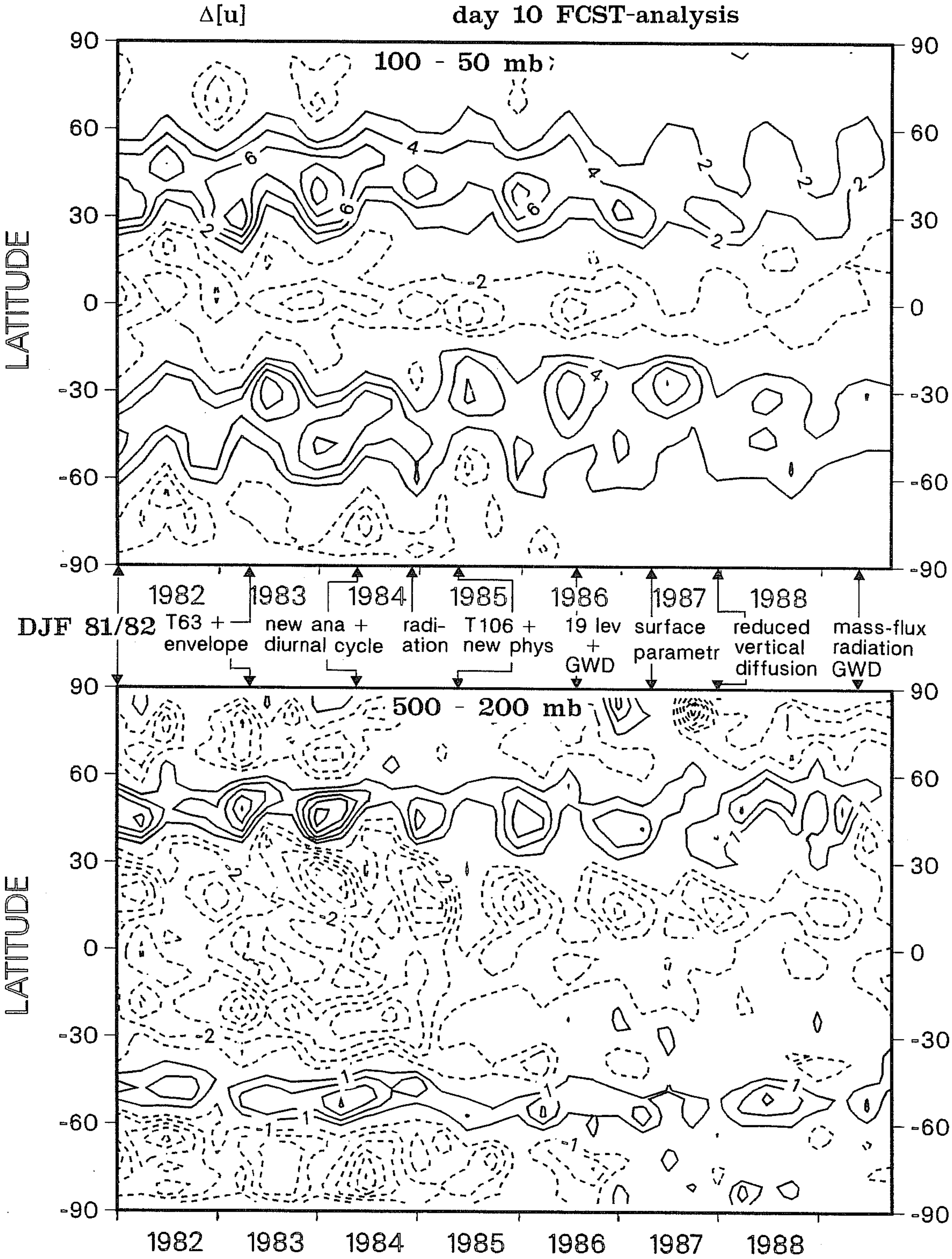

Fig. 2: Zonal and vertical means of zonal wind errors of the day 10 forecasts. Values represent seasonal means. Zero lines are suppressed. Upper panel: 100-50 mb mean; contour interval: 2 m/s. Lower panel: 500-200 mb mean; contour interval: 1 m/s. Ticks on the abscisse indicate the DJF season.

A dominant feature between 30°N and 60°N is the annual cycle of the errors with maximum values during winter. This pattern has changed for the 500-200 mb slab since DJF 87/88 to lowest values in winter and highest in summer. The summer 1988 error in the 500-200 mb layer (more than 2 m/s) is the largest ever found for this season in this latitude belt, only 1984 comes close. JJA89 has an error pattern in this latitude best similar to the one before 1985 in this season with slight increases of westerlies between 50°N and 60°N and reduced westerlies between 30°N and 50°N though the tropical errors are now much lower. Some of the recent changes in the systematic error could be due to an anomalous circulation of the real atmosphere: i.e. the analysed subtropical jet for DJF 87/88 and JJA 88 was slightly shifted poleward, which helped to reduce the DJF 87/88 day 10 forecast error and the analysed subtropical jet for DJF 88/89 was weaker than normal while the polar jet was stronger. Both anomalies are not only features of the ECMWF analyses but have also been found in the NMC analyses (White, pers. comm.). Below we will see that the model changes have contributed to the reduced systematic errors as well.

Arpe (1988a) found a correlation between the forecast error from 30°N to 60°N and the tropical stratospheric QBO; low errors are found when the QBO is in a phase with westerlies at 50 mb at the equator. This relation remains valid but the available time series is still too short to be statistically significant and the true nature of such an oscillation may be concealed by the many model changes. The convective activity in the tropics has been found to correlate with the stratospheric QBO, i.e. tropical storms are stronger when the QBO is in the westerly phase (W. Gray, pers. comm.). This may be the link between the stratospheric QBO and the amplitude of the systematic error in extra tropics. In the Southern Hemisphere a biennial cycle in the amplitude of errors dominates over the annual cycle.

Impacts from model changes can be found in April 1983 (T63/envelope orography) which resulted in an increase in systematic errors especially in the stratosphere. This finding contradicts the expectations from extensive model comparisons before this model change became operational. Dominant reductions of systematic errors are connected with the revision of the radiation scheme in December 1984 and the T106/convection model change in May 1985. The former had the larger impact on the stratosphere and the latter on the upper troposphere especially in the tropics. The increase of model resolution from T63 to T106 is unlikely to be responsible for the reduction of the systematic error (Tibaldi et al., 1989). The introduction of a shallow convection parametrization in May 1985 has had probably the largest impact (Tiedtke et al., 1988).

A further reduction of errors between DJF 85/86 and DJF 86/87 is seen most clearly in the stratosphere. Forecast experiments (Miller and Palmer, 1987) suggest that this part of improvement is due to the introduction of a gravity wave drag parametrization (GWD). The increase of vertical resolution of the model, mainly in the stratosphere, led to a general improvement of the forecast through improved analyses but also improved the mean forecasts, especially of the jet splitting over Europe (Simmons et al., 1988).

The reduction of errors during DJF 87/88 especially in the stratosphere has already been discussed above. The possible impacts from an anomalous circulation have been mentioned but the reduction is probably mainly due to the restriction of vertical diffusion to the boundary layer.

The most recent major change of the model was introduced on 2 May 1989, when the Kuo convection scheme was replaced by a massflux scheme and when the radiation as well as the gravity wave drag parametrization were revised. The problem of seeing the impact of this change in Fig. 2 has already been mentioned above and therefore the impact of this change is illustrated in Fig. 3 in which the zonal mean wind components are compared between both schemes during a parallel run from 19 April to 1 May 1989. For this period the model changes lead to analyses differences with up to 1.2 m/s weaker easterlies in the tropical middle troposphere and up to 1.0 m/s weaker westerlies equatorwards of the subtropical jets. In the day 10 forecasts one finds improvements due to the new scheme in the troposphere north of 40°N and in the stratosphere. There is a deterioration in the day 10 forecasts for the middle and upper tropical troposphere with a signature similar to the differences in the analysis differences. The similarity of the mean zonal wind error patterns in the day 10 forecasts (also seen in shorter range forecasts) of the new scheme and the pattern of differences between the analysis in the upper tropical troposphere suggests that the old analysis is the more realistic one in this respect. It is however interesting to note that the error is less prominent for monthly means for May and June 1989, but the evolution of an easterly error between 30°N and 50°N in Fig. 2 during JJA89 may be connected with the easterly error between 15°N and 30°N during April. This question will be further addressed in the following sections.

3. GEOGRAPHICAL DISTRIBUTION OF HEIGHT AND WIND ERRORS IN EXTRATROPICS

Another widely used parameter to display the systematic error of a model is the 500 mb height field which is shown in Fig. 4 for the DJF season since 1985/86, i.e. the winters since the T106/convection model change. Arpe and Klinker (1986) found in their investigation of the systematic error in the extratropics that the errors of geopotential height or wind field implied a reduction of amplitudes of standing waves in the forecast. This can be seen from positive day 10 errors where there is a trough in the analysis and negative errors where there is a ridge. For Europe the error implies a weakening of the diffluent flow. This is still a problem of the present model although it has become less

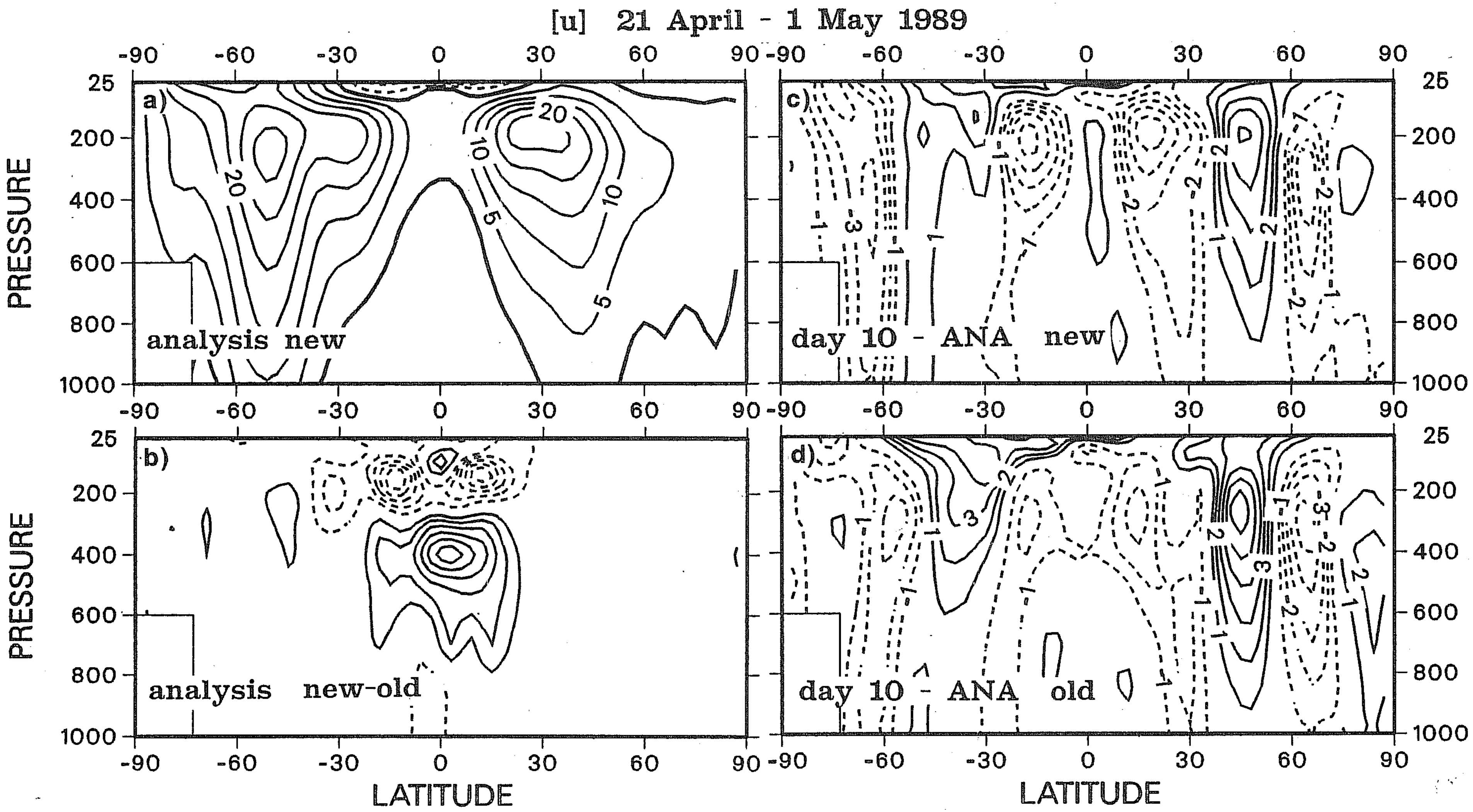

Fig. 3: Zonal mean of the zonal wind during the parallel run between 19 April and 1 May 1989 (mean of 13 cases)

a) Mean initial analysis, new scheme. Contour interval 5 m/s.
b) Difference between mean initial analyses of both schemes. Contour interval 0.2 m/s.
c) Day 10 forecast error with new scheme. Contour interval 0.5 m/s.
d) Day 10 forecast error with old scheme but new analysis for verification. Contour interval 0.5 m/s

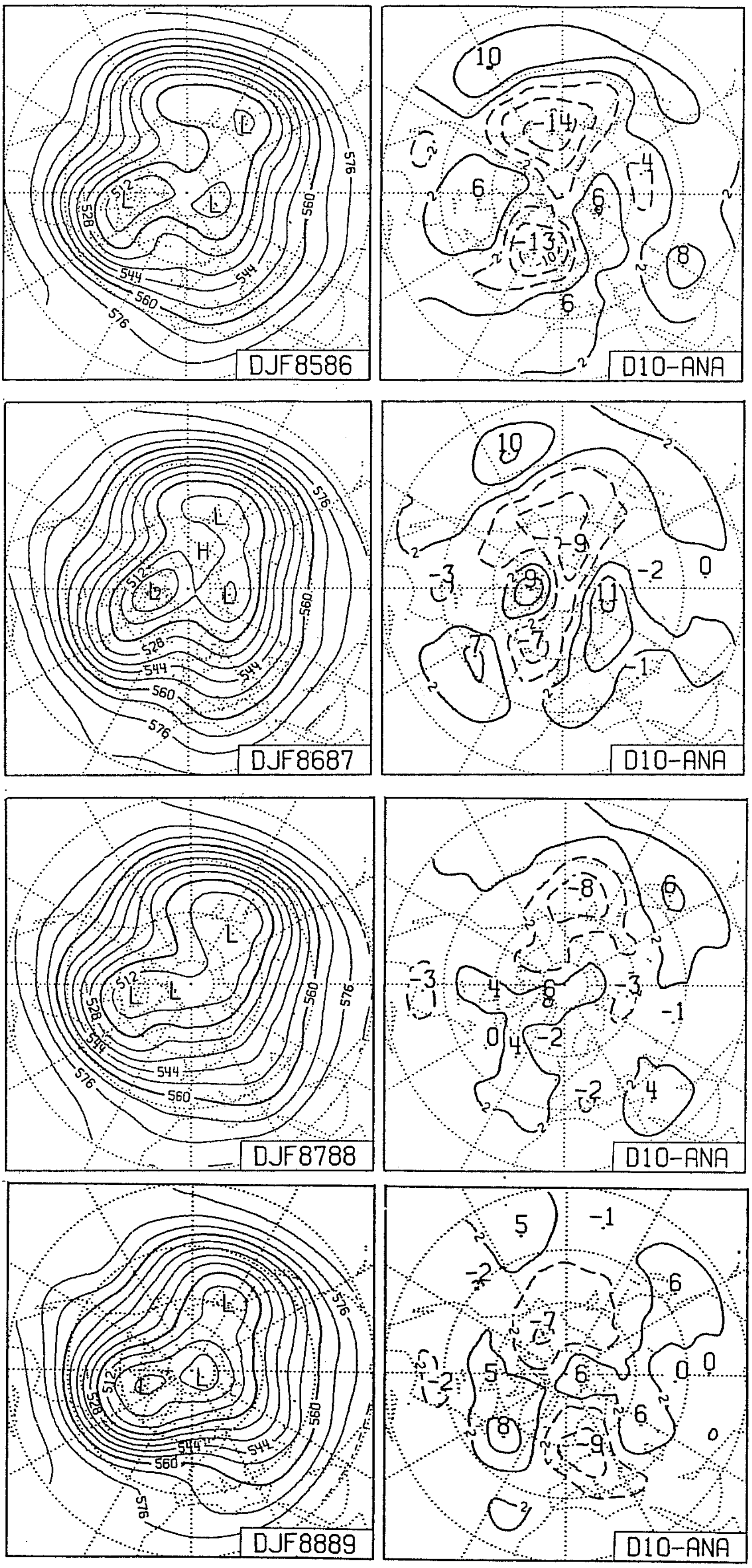

Fig. 4: 500 mb height fields and their day 10 forecast errors for the season DJF from 1985/86 to 1988/89. Contour interval is 8 dam for the mean heights and 4 dam offset by 2 dam for the errors.

severe. Arpe and Klinker showed errors for DJF 83/84 which are comparable in strength and pattern to those of DJF 85/86 which means that the T106/convection model change was only of minor importance for this component of the systematic errors. This is also revealed by a sequence of error maps shown by Arpe (1988a).

The increase of zonal mean zonal winds between 30°N and 60°N shown above arises mainly from the oceanic areas which can best be seen for DJF 85/86 and DJF 86/87 in Fig. 4. This erroneous increase of westerlies over the oceans can be interpreted as an insufficient deceleration at the jet exits. It is accompanied by an eastward extension of the storm tracks. Some of the reduction of errors between the winters 85/86 and 86/87 is due to the introduction of a gravity wave drag parametrization and the increase of vertical resolution. A further reduction of error after DJF 86/87 is possibly due to the restriction of vertical diffusion to the boundary layer. We cannot be certain of this because of a natural variability in the error field. During DJF 87/88 the analysed 500 mb height field was very favourable for the model because of a zonal circulation over the Atlantic and there the model's tendency for a zonalization of the flow could not lead to large errors. The typical error pattern over the Atlantic/European area reappeared in DJF 88/89. Arpe (1988a) found that in mid-latitudes the model has a preferred circulation which is similar to the atmospheric circulation during an ENSO event.

Many forecast models show similar systematic errors some of which are illustrated in Fig. 5. Mean 500 mb height errors of the day 5½ forecasts made by ECMWF are compared with day 5 forecast errors made by NMC and JMA all verifying at 00 UTC for a period from 21 December 1988 to 28 February 1989 (selecting only those days for which data were available from all three centres). Similarities in the patterns are obvious. ECMWF shows lowest errors despite the 10% longer forecast range. There is, however, a slight bias in favour of the ECMWF model for the Pacific area because of the use of ECMWF analyses for verification.

Arpe and Klinker (1986) found a steady growth of the error from day ½ onwards. Also during DJF 88/89 there is some signature of the day 10 error patterns already in the day 1 forecasts (not shown) but its growth is slow during the first 5 days. The relatively large errors in the day 5½ forecasts shown in Fig. 5 compared to the day 10 forecast in Fig. 4 is due to the different sample used in both averages. In forecast experiments beyond day 10 a further growth of error has been found up to day 20 (Brankovic, pers. comm.) at least for the model which was operational during 1985/86.

The split of the jet in the mean analysis over Europe is closely connected with the occurrence of blocking in this area. The failure of the model to predict such a split of the jet must therefore be seen in connection with the failure of the model to predict blocking mean day 5 500 mb height error 21 Dec.88 - 28 Febr.89

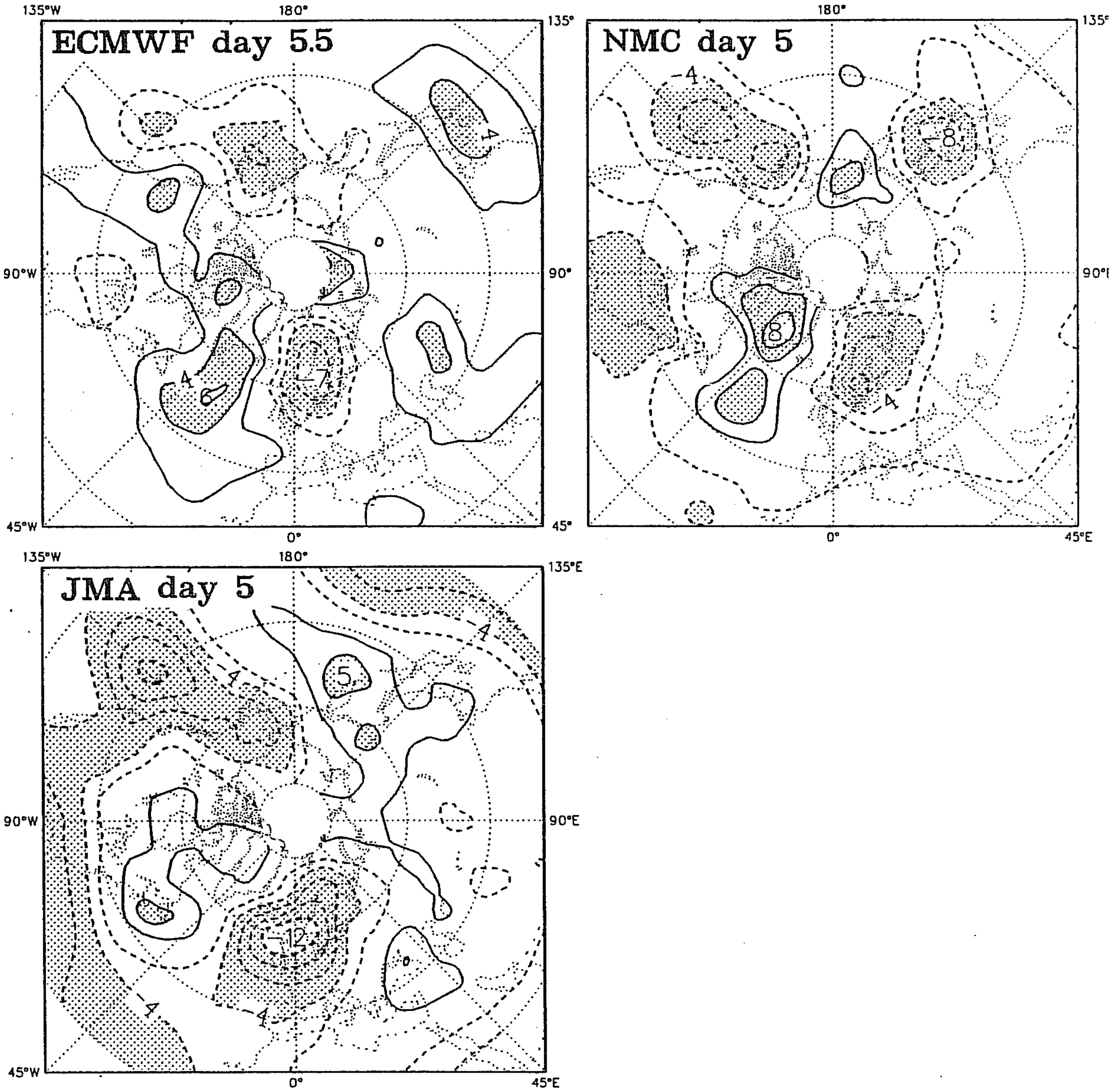

Fig 5: 500 mb height fields error of the day 5½ forecasts by ECMWF and the day 5 forecasts by NMC and JMA during the period 21 December 1988 to 28 February 1989 for those days when all 3 forecasts were available. Contour interval is 2 dam; the zero line is suppressed.

events beyond day 4. Tibaldi and Molteni (1989) have shown that the model not only fails to predict the correct timing of blockings but also the right frequency of occurrence. Other preferred areas for blocking occur over the northern Pacific and south of New Zealand. In both these areas the 500 mb height errors are mostly negative as is the case over the Atlantic/European area.

On investigating the height field errors at different levels, one finds that they have an equivalent-barotropic nature in the troposphere. The area with negative values over Europe hardly changes its position between 1000 and 10 mb. There is however also a baroclinic component with zonal wave number one which leads to a rise of forecast heights on the Pacific side in the stratosphere. In Fig. 6 this behaviour is demonstrated in a longitude-height cross-section for the latitude belt between 55°N and 65°N during DJF 88/89.

In the Southern Hemisphere the May 89 model change did not lead to reductions of mean 500mb errors at least when comparing JJA 89 with those of the two years before (not shown).

4. TROPICAL WIND ERRORS

The dynamics of the tropical troposphere is characterized best by the 850 and 200 mb wind field. In Fig. 7 the analyses and day 10 forecasts are shown for JJA 88. The dominant features of the 850 mb wind field are the trade winds and the Indian summer monsoon. The latter is too weak in the forecast. There is also a shift of the main axes of the flow: the analysed monsoon passes the Indian subcontinent at its southernmost tip while its position is further north in the day 10 forecasts. In this respect there is an improvement in JJA 89 (not shown).

With regard to the trade winds Arpe and Esbensen (1989) have found that trade winds at the surface in the ECMWF day 1 forecasts are probably too weak. For the day 10 forecasts at 850 mb (Fig. 7) such a statement can only be made for the trade winds over the equator. The easterlies in the forecasts are too weak over the eastern tropical Pacific, an error which has been found for many years in winter as well as in summer. During JJA 89 the winds in the day 10 forecasts at the equator around 150°W are increased to more than 10m/s, however the analysed values are considerably reduced in this year, probably due to an error in the transmission of wind observations by buoys. At 200 mb (Fig. 7) the easterlies are forecast to be too strong in this area, i.e. the error has a baroclinic character. We have noted above an increase of zonal mean easterlies in the forecasts of the tropics at 200 mb and from Fig. 7 it is clear that the eastern Pacific is the main contributor but with additional contributions from the western Pacific and the western Indian Ocean. Also during DJF the

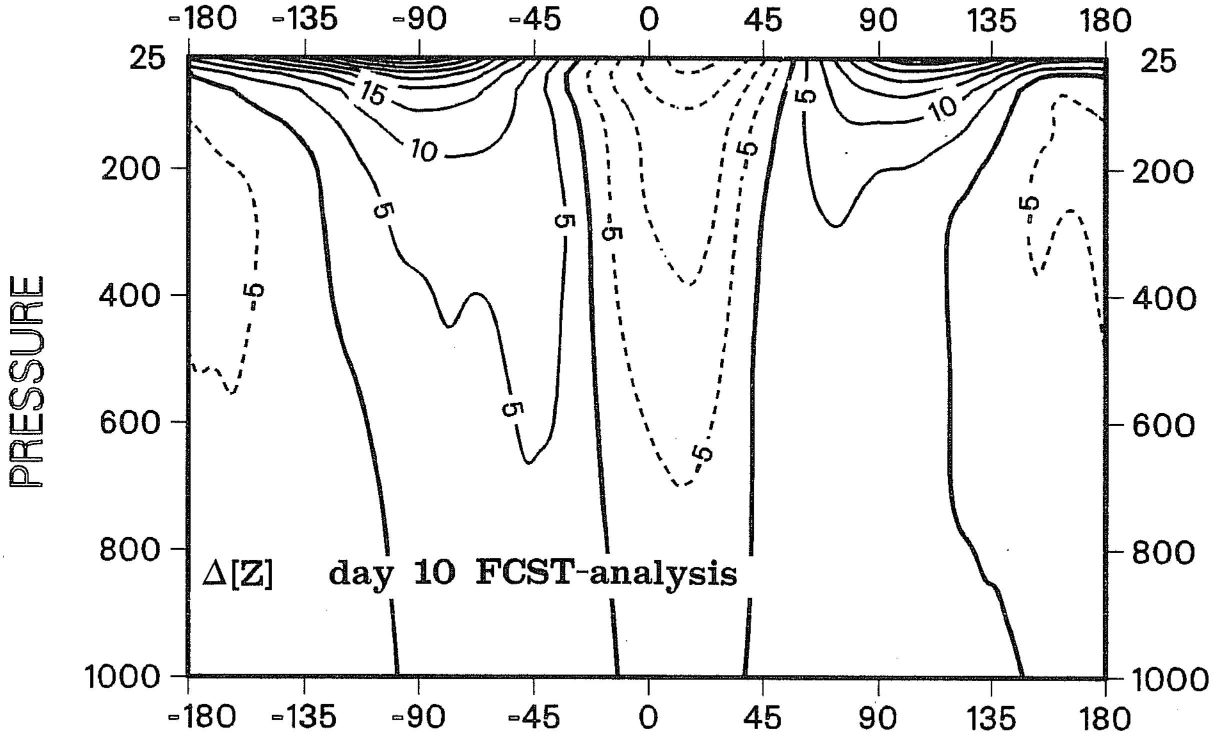

Fig. 6: Longitude-height cross-section of the day 10 height errors for a latitude belt between 55°N and 65°N during DJF88/89. Contour interval is 5 dam.

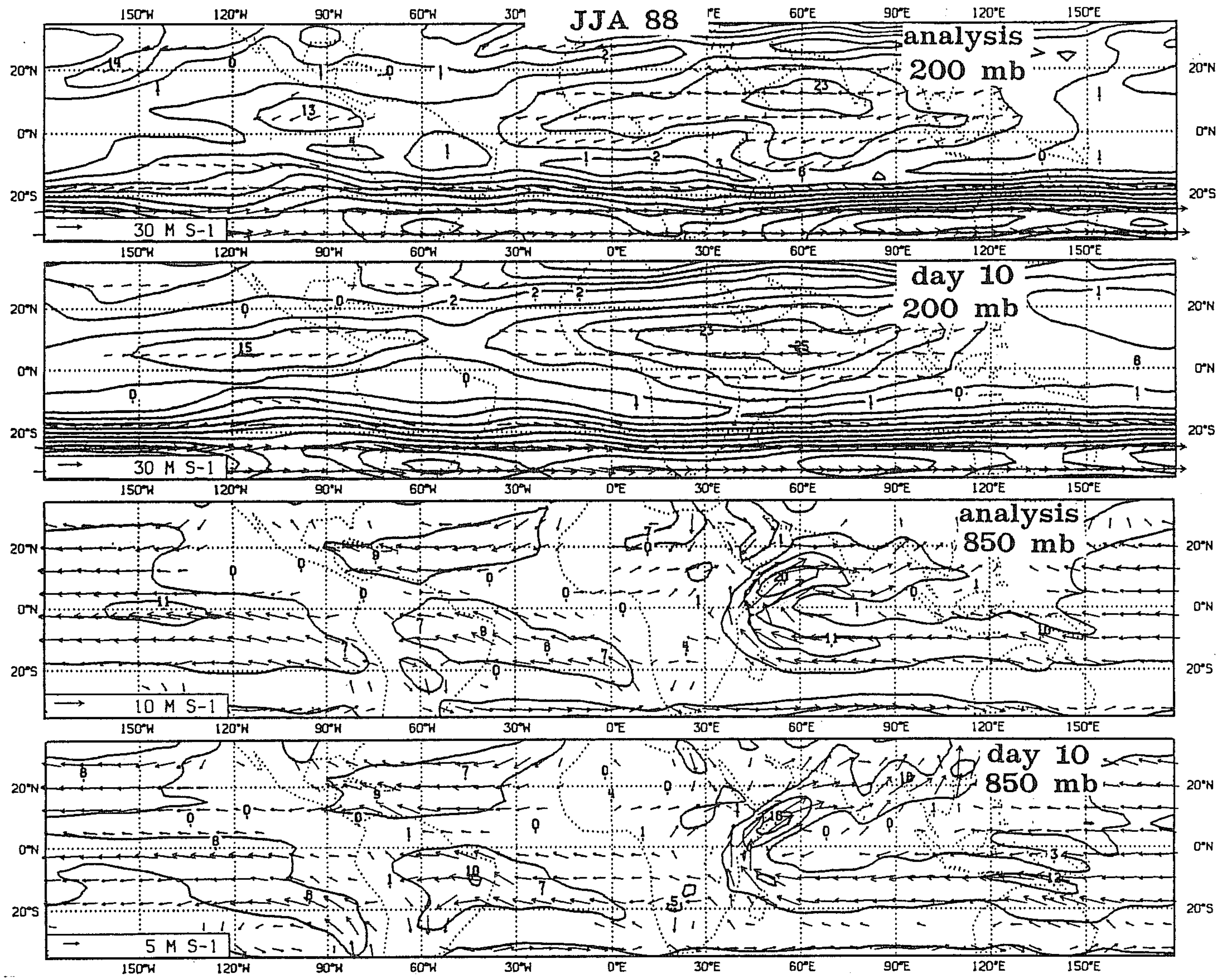

Fig 7: Mean 850 and 200 mb windfield during JJA 88 in the analysis and the day 10 forecast. Contour interval of isotachs: 5 m/s.

eastern Pacific is the dominant contributor to an easterly error in the 200 mb wind field (not shown), although the fields for this period look very different. During DJF marked westerlies over the eastern Pacific in the analysis are weakened in the forecasts.

Error patterns similar to those in DJF were found during the parallel run at the end of April 1989. In Fig. 8 the wind fields at 200 mb are compared. Over the eastern tropical Pacific both the new day 10 forecast and the analysis show westerly flow, which is not simulated by the old model. The new model is also superior over the Gulf of Guinea.

Above, an increase of errors of zonal means of zonal wind in the new model has been found at 200mb around 20°N and 20°S (see Fig. 3). The main contribution for this comes in the Northern Hemisphere from the areas over west Africa, the eastern Pacific and north India/south China. In the Southern Hemisphere the zonal mean error results from nearly all latitudes. During May and June 1989 when the new model was operational these problems were visible in zonal means but hardly in maps. It is not clear if the errors which emerged during the parallel run reflect the special synoptic situation (nearer to a winter circulation) during these 13 days, which may have been favourable for the old model, or if the adjustment of the analyses to the new model was not completed during the 13 days.

The variability of the systematic error in the tropical wind in the years before 1989 has been illustrated by Arpe (1987) with error maps of the 200 mb streamfunction which clearly revealed the improvements with the T106/convection model change. Since then the error maps for DJF are dominated by a dipole pattern over the eastern Pacific. During May this typical error pattern can still be seen while it changes for the summer season. A time series of 200 mb streamfunction error maps for May 1986 to 1989 is shown in Fig. 9. Improvements in the model performance were most likely achieved by the revision of vertical diffusion in January 1988 and by the May 1989 model change. Sardeshmukh and Hoskins (1988) relate the error pattern over the eastern Pacific to a weakening of the divergent flow over the Indonesian area during the forecast and we will see below that the latest improvement in the streamfunction is also accompanied by a reduction of divergent flow errors.

Fig. 9 reveals also that the increase of easterlies in the zonal means of the forecasts, shown above, cannot be related to an increase of errors in the streamfunctions. It must therefore result from a shift in the positions of error centres to a similar latitude so that small errors at different longitudes are now of the same sign at about 20°S and 20°N while they were of different signs before.

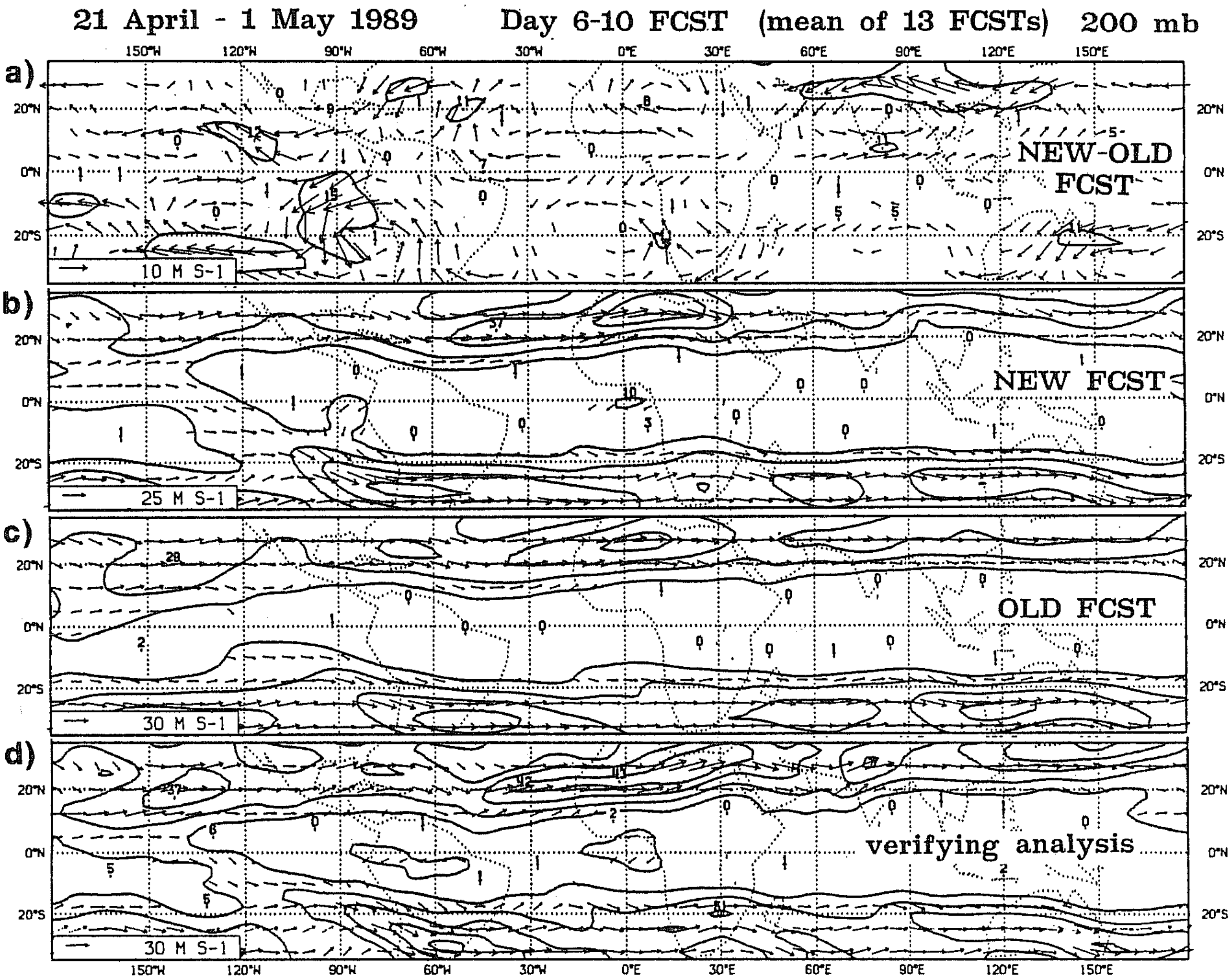

Fig 8: Mean 200 mb wind field for the parallel run between 19 April and 1 May 1989 (mean of 13 cases). Contour interval:10 m/s.

a) Analysis using the new model verifying for the mean day 6-10 forecasts.
b) Mean day 6-10 forecast with old forecast model.
c) Mean day 6-10 with new forecast model.
d) Difference between both forecasts.

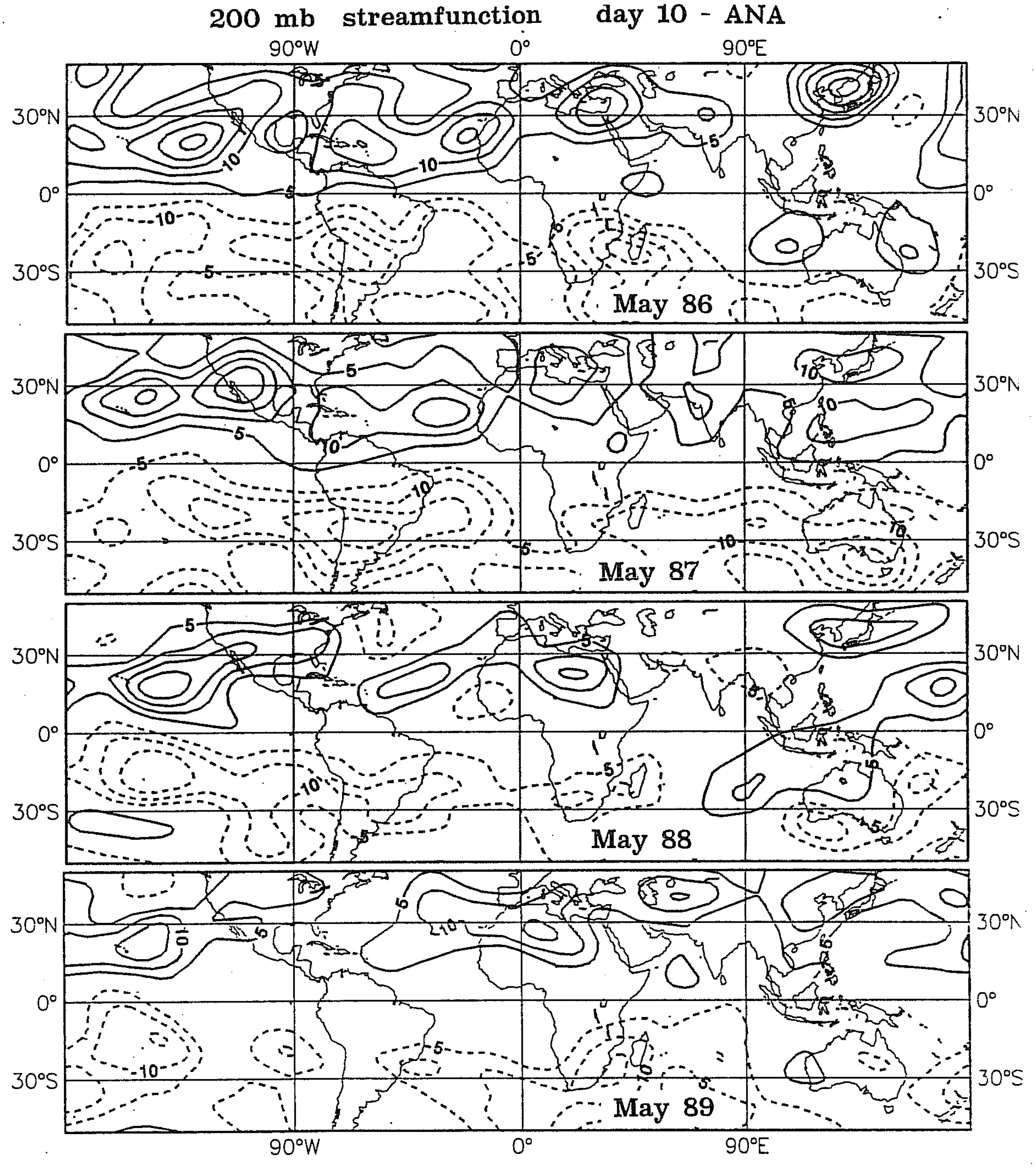

Fig. 9: Day 10 forecast errors of the 200 mb streamfunction (May 1986 - May 1989). Contour interval: 5x10^{+6} m/s^2; zero line is suppresssed. One contour interval in 10° of latitude corresponds to 5 m/s.

Interannual variability of the errors may have helped to show a positive impact from the May 1989 model change as there is no such positive impact to be seen when comparing JJA or SON means from the last 2 years.

5. DIVERGENT WIND

The driving force for the atmospheric circulation is the convective activity in the tropics. Its integrated strength can be measured by the large scale divergence or vertical wind component. Fig. 10 gives the meridional wind component at 850 mb as well as averages between 250 and 100 mb for the tropics (15°N-15°S). Clear annual cycles are shown by the analyses as well as by the forecasts. The largest impacts on the analysis can be found from the diabatic initialization in September 1982, from the T106/convection model change in May 1985 and from the May 1989 model revision. During 1986/87 the analysed amplitudes are the largest for the period before May 1989 which could reflect an impact of the ENSO event.

The impact in the forecasts is much smaller and the better verification between September 1982 and May 1985 is only due to the analyses which were more favourable for the model but, most likely, less correct in this period. The May 1989 model change led to a clear strengthening of the Hadley circulation also in the day 5 and day 10 forecasts. During 1987 and 1988 both the analysis and the forecast show some reduced amplitudes. The timing of the decrease points to a change in the parametrization of surface exchanges in April 1987. This model change reduced the evaporation over land considerably and unexpectedly also over oceans in the short range forecasts (Arpe and Esbensen, 1989). Reduced evaporation can weaken the tropical convection which means a weakening of the Hadley circulation.

The May 1989 model change, i.e. replacement of a Kuo by a massflux convection scheme and revision of the radiation and gravity wave drag parametrization, led to a dramatic change in the analysed Hadley circulation as is indicated by Fig. 10. This is illustrated better by zonal mean cross-sections of the vertical velocity during the parallel run in April 1989 which are shown in Fig. 11. The maximum rising motion in the new analysis at the equator nearly doubled compared to the old analysis and also in the day 10 forecasts there is a rise by 50%. This has increased the discrepancy between analyses and forecasts. A major problem with the tropical vertical velocity had been that the updraughts in the forecasts did not penetrate high enough. This has now been clearly improved. Also, time series of vertical velocities at 500 mb (not shown) have been investigated. They indicate a doubling of the Hadley circulation in the new analysis while this model change hardly affected the day 10 forecasts. The latter is inconsistent with the results shown in Fig. 11. 500 mb vertical velocities in the day 10 forecasts show a weakening of the Hadley circulation with the radiation modification in December 1984. Below it will be shown that at this time the lower troposphere was considerably stabilized. The vertical velocity field reveals also an increase

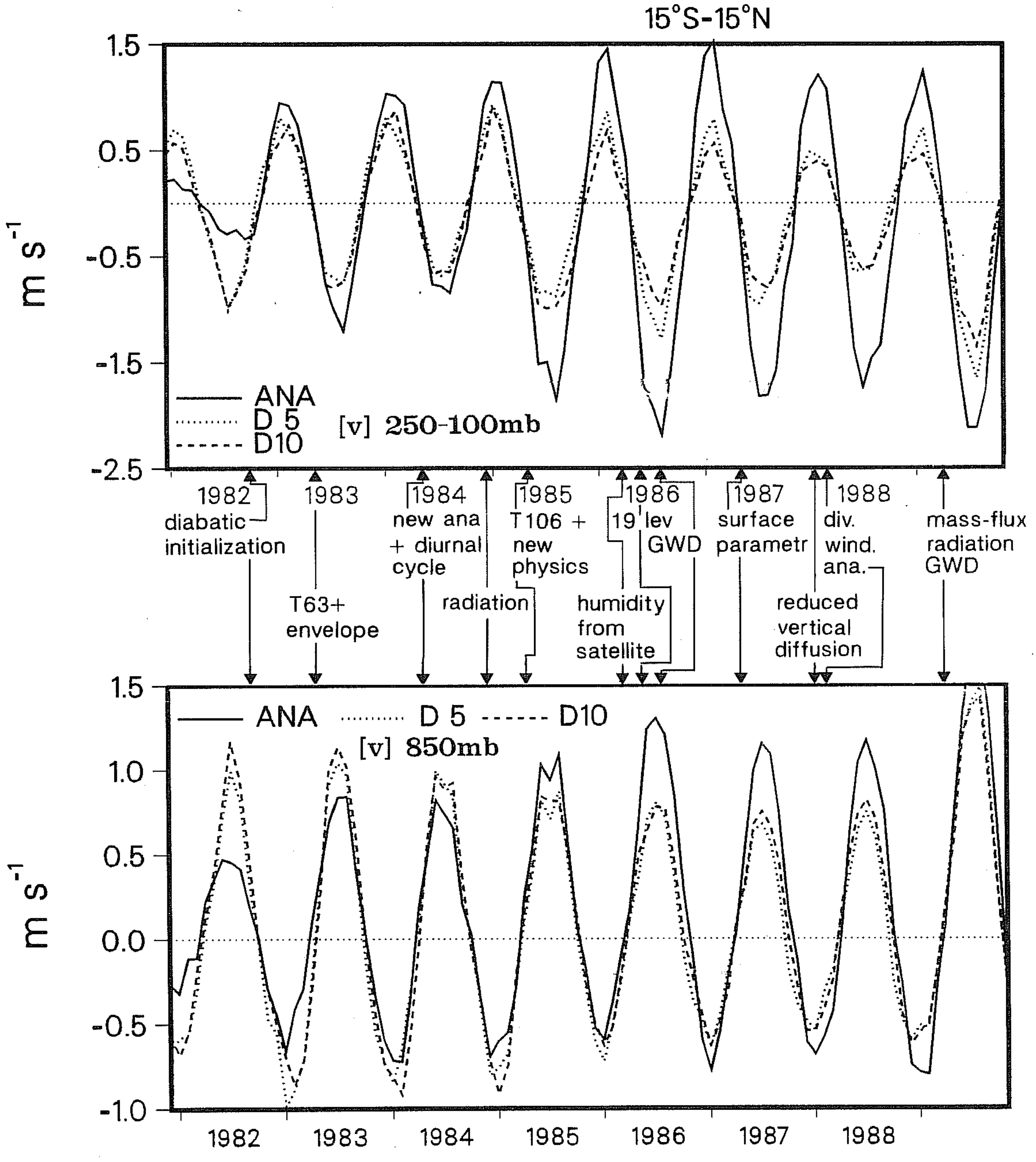

Fig. 10: Variability of the mean meridional wind (monthly averages) between 15°S and 15°N since December 1981. Forecasts and analyses are compared for the upper troposphere (250-100 mb) and for the lower troposphere (850 mb). Ticks on the abscisse indicate Januaries.

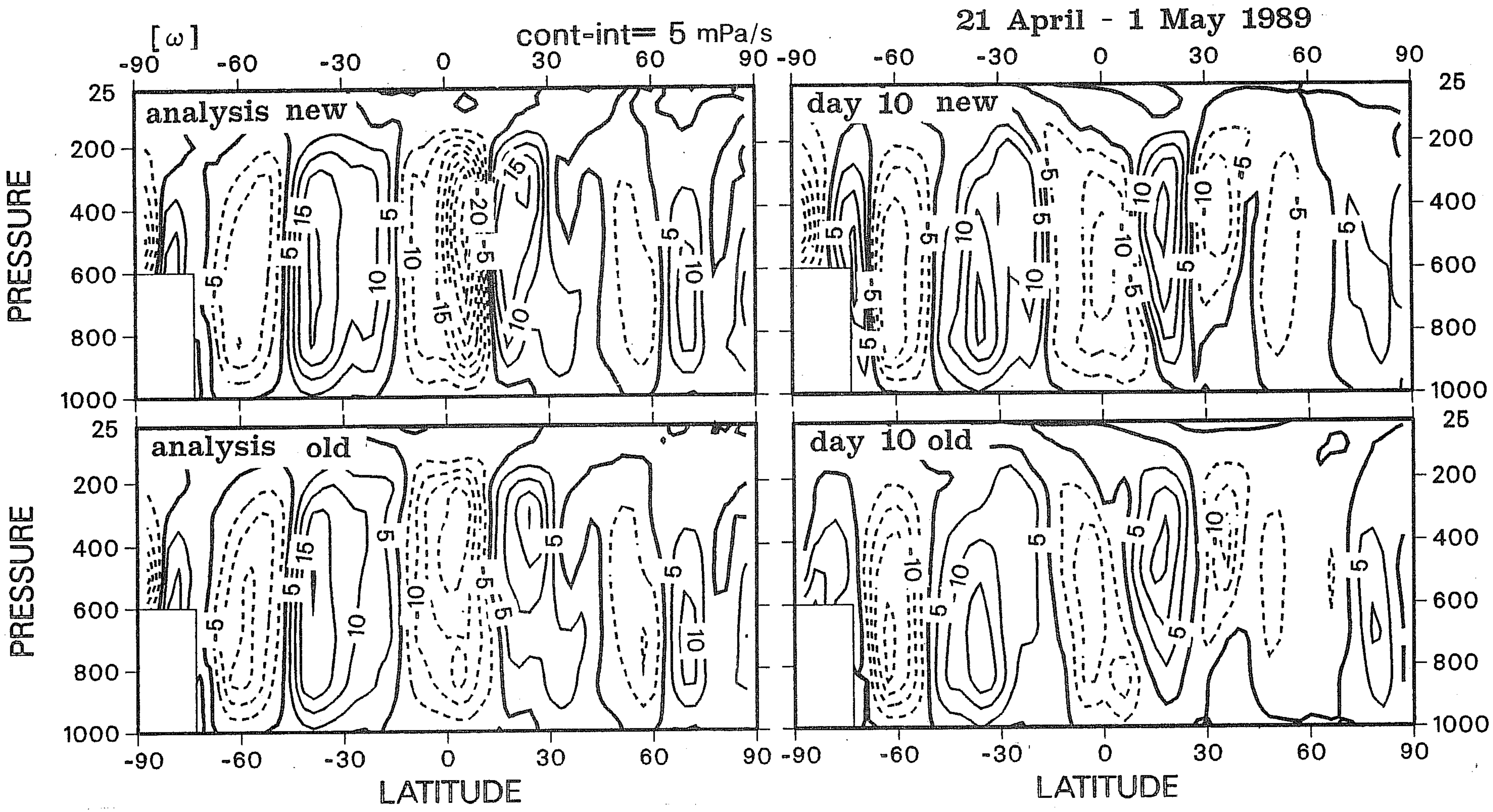

Fig. 11: Zonal mean vertical velocity $(\frac{dp}{dt})$ for the parallel run between 19 April and 1 May 1989 (mean of 13 cases). Contour interval: 5 mPa/s. Left panels: analyses; right panels: day 10 forecasts; upper panels: new scheme; lower panels: old scheme.

of the Hadley circulation in the analysis during Spring 1986, probably due to the use of satellite humidity observations. A better treatment of tides in the initialization may have helped as well.

The larger impact of the model changes on the analysis than on the forecasts is connected with the existence of a spin-up in the early forecast range, which will be discussed below. The amount of convection during the first 6 hours of forecast is essential for the tropical vertical velocity in the first guess which feeds information into the analysis. It will be shown that the spin-up of the model was changed essentially in May 1989 with much stronger convection during the first 6 hours in the new model.

In order to display the geographical distribution of the divergent wind we will follow common practice and show in Fig. 12 a sequence of maps of the 200 mb velocity potential for the month of June. The velocity potential maps of the day 10 forecasts have hardly changed during the first 3 years but a clear increase in strength especially for Central America can be found for June 1989. The analyses show much more variability in strength as well as patterns, again Central America has been affected most by the recent model changes. The enhancement over Central America as well as over Africa means an enhancement of the ITCZ.

Arpe (1987) and others have shown a collapse of the forecast divergence over Indonesia which is also indicated in Fig. 12 for the years up to 1988. The May 1989 model change seems to have reduced this problem. Also for the June to August season such an improvement has been found but for the September to November season the impact of this model change in respect to the divergence over Indonesia is small. Heckley (1985) reported about a lowering of the maximum of the vertical velocity in the forecasts over the Indonesian area which seems to be no longer a problem (not shown but indicated in Fig. 11 for zonal means).

The impact of the May 1989 model change on the analyses of the divergent flow as shown in Fig. 12 does not seem to be exceptional but when investigating the 500 mb vertical velocity enormous increases from 1988 to 1989 can be found (not shown). Over northern South America, Central America and Central Africa the analysed vertical velocities are now 10 times as large as in the year before. This can be found for June means as well as for JJA or SON means. Comparisons with observations suggest that these much larger values are reasonable. Also investigations by Mo (pers. comm.) suggested that the former ECMWF analysed vertical velocities in the tropics were too weak.

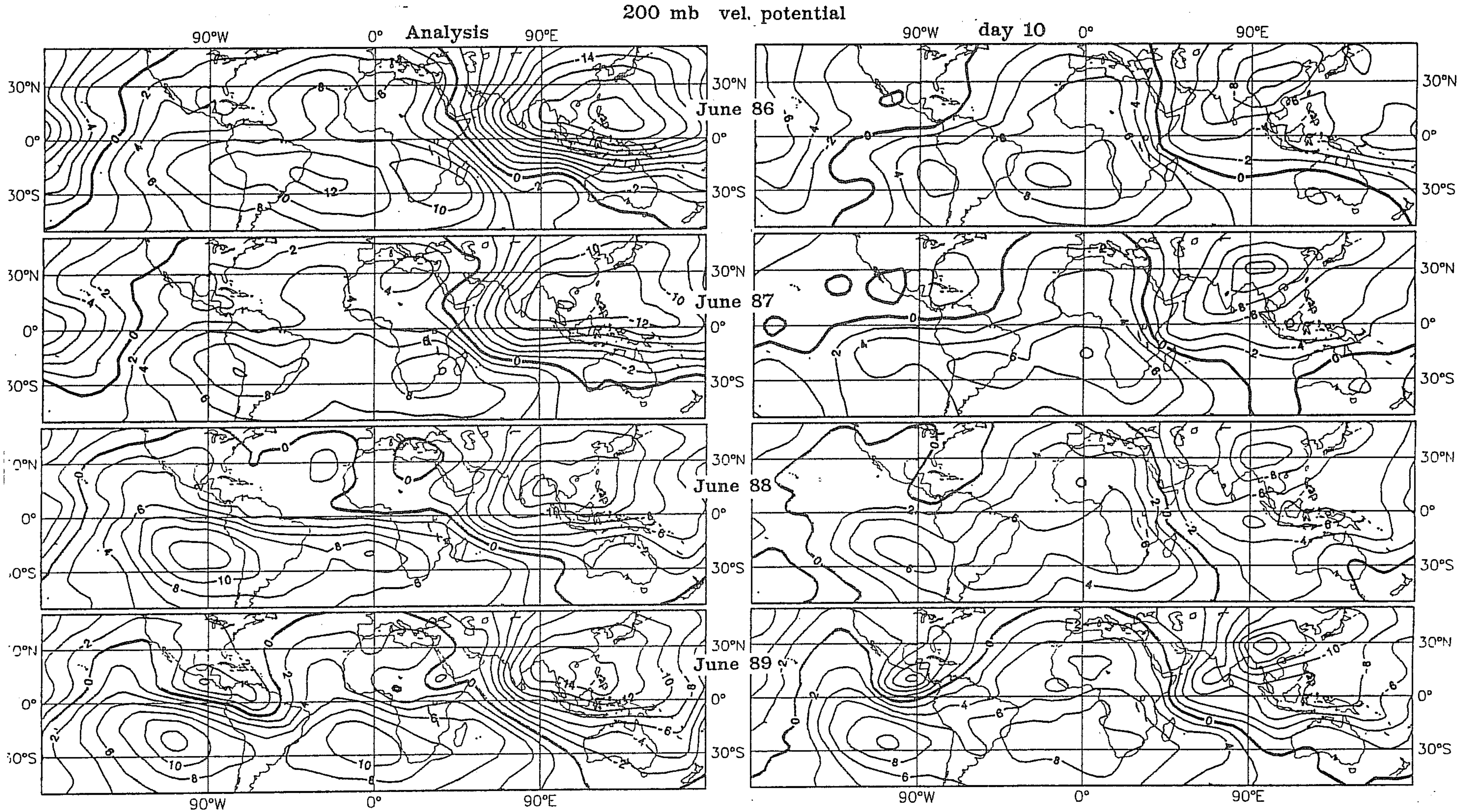

Fig. 12: Velocity potential during June at 200 mb in the analyses as well as the day 10 forecasts during 1986, 1987, 1988 and 1989. Contour interval: $1 \times 10^{+6}$ m/s^2. Left panels: analyses; right panels: day 10 forecasts.

In Fig. 13 the drift of climatology during the course of a 10 day forecast is illustrated by vertical profiles of the vertical velocity for an area with maximum rising motion (5°S-10°N, 75°W-40°W). Analyses and forecasts for 00UTC and 12UTC are grouped separately in two panels because one can expect much larger precipitation and larger vertical velocities in late afternoon or evening (00UTC) than in the morning (12UTC). This diurnal cycle is clearly indicated by the analyses as well as the forecasts. However, the model overdoes this in the medium range forecasts. Meisner and Arkin (1987), have shown for most of Brazil a clear evening peak of precipitation, but for the area chosen here there is much less of a clear diurnal cycle. This is indicated in Fig. 13 by relatively large analysed vertical velocities, also at 12UTC. The nearly complete suppression of convection by the model in the morning is a clear deficiency which occurs in the forecasts not only over northern South America, but also over Central Africa and Indonesia.

By comparing the different stages in the analysis cycle one finds quite large impacts from the initialization while the first guess and the uninitialized analysis are very similar. In Fig. 13 it appears as if the initialization increment is opposite to the model changes in the short range forecasts but taking also 06 and 18UTC analyses and the other areas into account it is suggested that the initialization is forcing the analysis towards the values for the next analysis time. This could be explained by the fact that the initialization procedure evaluates the diabatic forcing using a 2 hour forecast, while the first guess and the real atmosphere are forced diabatically only from processes up to the analysis time, which means a marked difference in the phase of the diurnal cycle.

One can conclude that the divergent wind component in the tropics is still insufficiently known and unsatisfactorily simulated by the model although considerable improvements have been made in the last 10 years.

6. TEMPERATURE

In Fig. 14 the zonal mean temperature error of the day 10 forecasts during JJA 89 and DJF 88/89 are shown. During DJF 88/89, which is similar to JJA 88, the middle and upper tropical troposphere is warmed by up to 2K during the 10 days and the lower troposphere is generally cooled. For JJA 89 these errors are considerably reduced however there is an increase of cooling in the lower polar stratosphere. Such a cooling of the lower stratosphere of the summer hemisphere seems to be a common error of many models. To what extent this increase in JJA 89 is due to the model change is not clear, but forecast experiments with the new radiation scheme only have shown some increase of this error. The temperature fields are related to the height and wind fields by the hydrostatic and geostrophic relation and so are their error fields. The increases of westerlies with height between 30°N and 45°N, shown in the error fields of Fig. 1, correspond to meridional

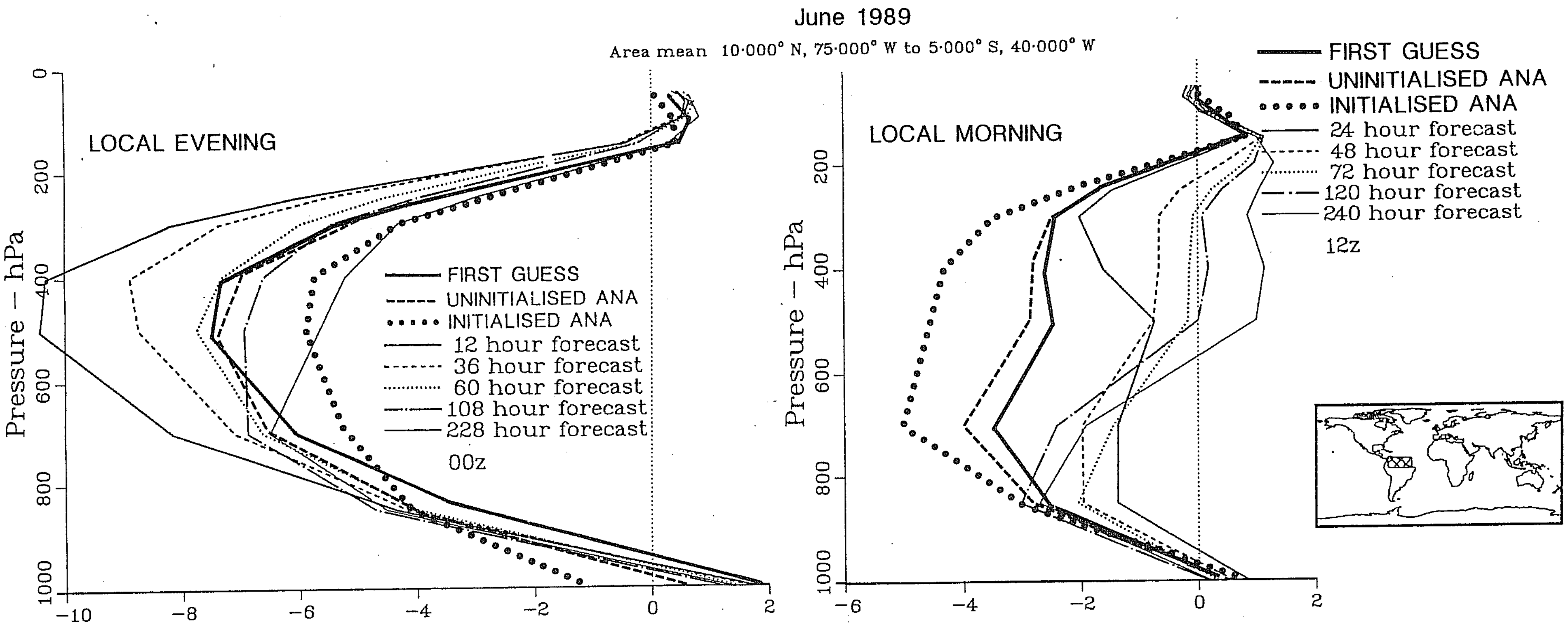

Fig. 13: Vertical profiles of vertical velocity over northern South America (5°S-10°N, 75°W-40°W). Initialized and uninitialized analyses as well as first guesses and forecasts of different ranges are compared for 00 UTC (left panel) and 12 UTC (right panel).

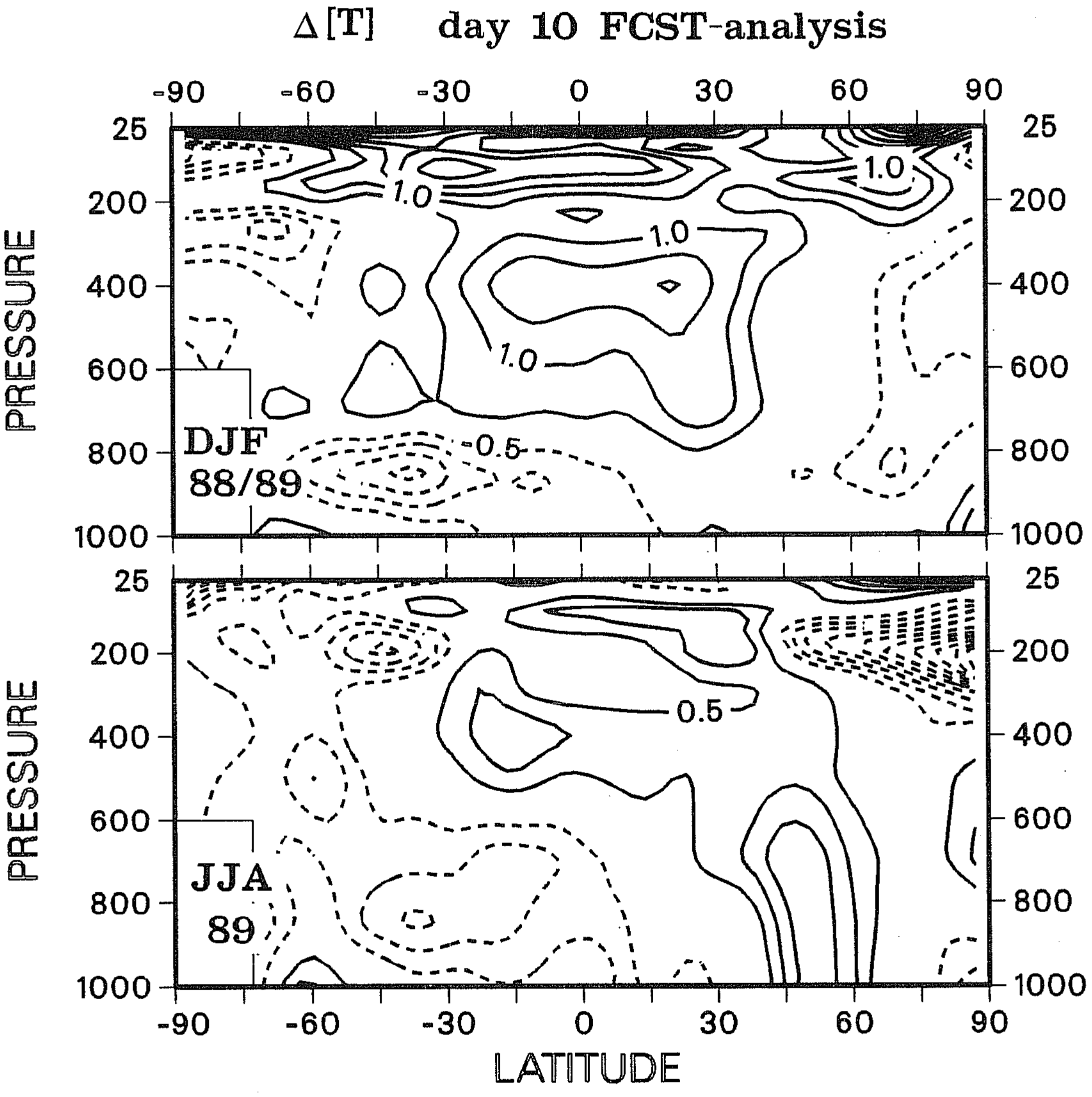

Fig. 14: Day 10 forecast error of zonal mean temperatures during DJF 88/89 (upper panel) and JJA 88 (lower panel). Contour interval: 0.5 K. The zero line is suppressed.

gradients of temperature errors in Fig. 14. The systematic errors of the temperature are clearest in the tropics, where they develop very quickly in 1-2 days and continue to grow up to day 10.

Fig. 15 shows the variability of the systematic error of the temperature in the tropics at day 5 and day 10 during the last 8 years. As with the divergent wind the absolute values instead of errors are shown because a model change can easily influence the analysis as well. At 850 mb the most dominant impact can be seen with the T106/convection model change in May 1985. This model change reduced the cooling in the forecasts from about 3K to about 1K. A further clear impact comes from the introduction of the T63/envelope orography model in April 1983. At this time the error was increased by about 0.5K and may partly be due to changes in the orography. The introduction of an envelope orography with the T63 model caused an average rise of the orography bringing the mean 850 mb level nearer to the earth surface. This increased the diurnal cycle of the 850 mb temperatures and may have led to a general increase in temperature. A rise of the orography means that there are more points for which the 850 mb temperature has to be extrapolated below the ground. For these points an increase of temperature is likely. The increase of horizontal resolution from T63 to T106 in May 1985 reduced the effect of the envelope orography and reduced this warming effect.

There is a large interannual variability in the analysed 850 mb temperature. It is partly natural variability (ENSO events) and partly due to changes in the analysis/forecasting scheme. From the ENSO event in 1982/83 one would have expected an increase in temperature at 850 mb during 1982, but the main increase occurs between January and March 1983. This is too late to be explained by the ENSO event and too early to be due to the T63/envelope model change. It may be that the impact from the ENSO event was concealed because of the eruption of El Chichon in March/April 1982 which led to a cold bias of up to 2K in satellite sea surface temperature measurements and may have reduced the analysed sea surface temperatures. The eruption has probably led to a reduction of atmospheric temperatures in the lower troposphere and an increase in the upper troposphere and in the stratosphere. During July 1982 the model switched from using climatological SSTs to analysed SSTs which also may have had an impact on the 850 mb temperature analysis.

At 500 mb the main variations of the systematic error are due to the model changes in December 1984, May 1985 and May 1989, i.e. mainly changes in the parametrization of radiation and convection. The steep increase of analysed temperatures in October to December 1982 and the decrease from May 1988 to January 1989 are possibly connected with the developments of ENSO or anti-ENSO events respectively. Comparing the analysed data

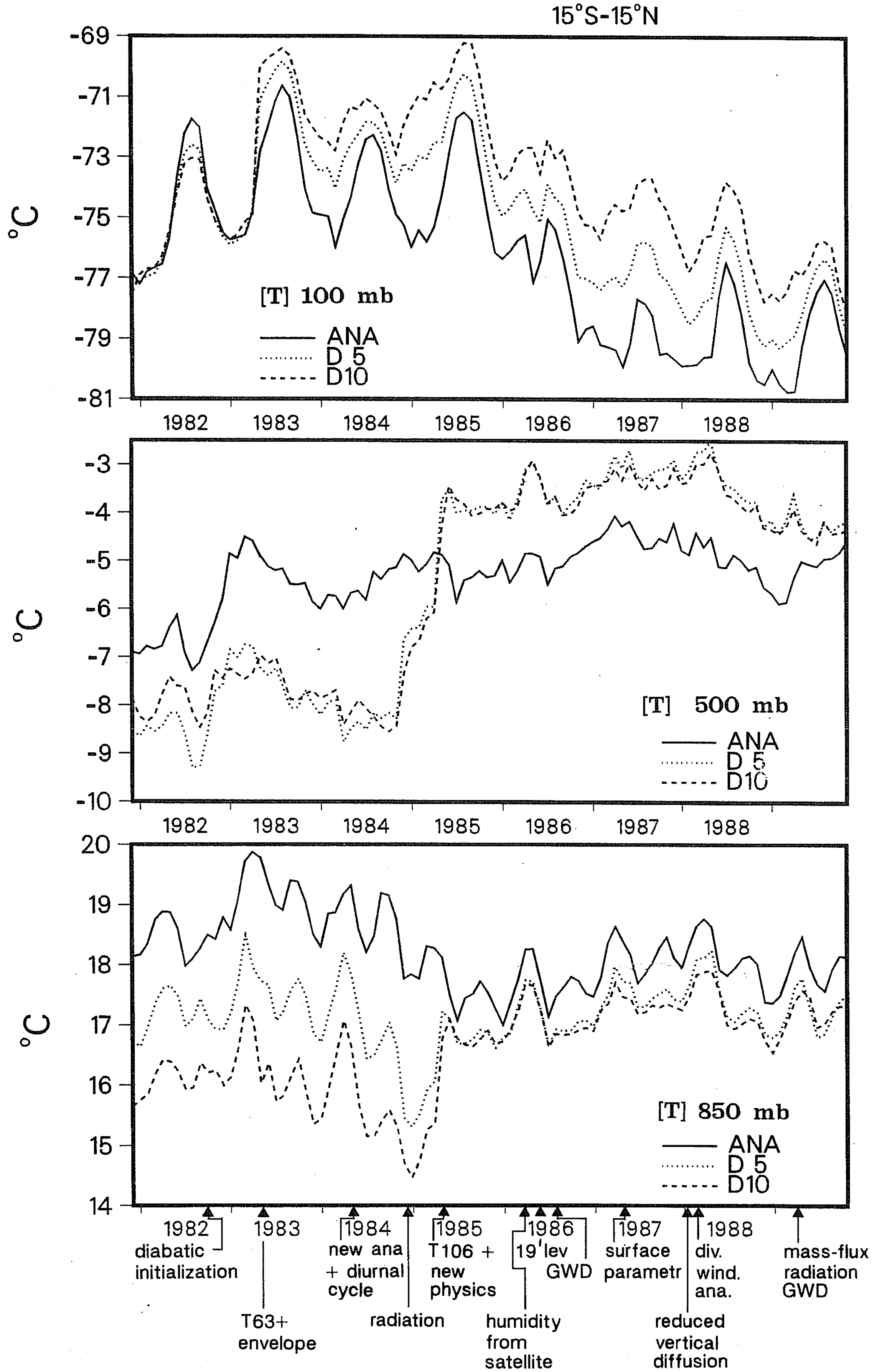

Fig. 15: Zonal mean temperature in the tropics (15°S-15°N) in the analysis, the day 5 and day 10 forecast at 850, 500 and 100 mb. Values represent monthly means. Ticks on the abscisse indicate Januaries.

used here with those by Oort (1990) gives confidence that most of the trends shown here reflect true temperature trends of the atmosphere but some impacts from the analysis/forecasting scheme on the analysis data can be recognized as well, e.g. the T106/convection modification in May 85 increased the analysed temperature average of the Northern Hemisphere troposphere (850-300mb) by 0.2K and the introduction of the T63 envelope model (April 1983) led to a spurious increase of the Northern Hemisphere stratospheric temperature (200-50mb) by about 0.7K which was later removed with the introduction of the 19 level model.

At 100 mb an increase of errors occurred with the T63/envelope orography model change. The increase of model levels from 16 to 19 resulted in a cooling of the analysis as well as the forecasts which can be explained by the interpolation from model to standard pressure levels (Arpe, 1988b). A model level now nearer to the 100 mb level allows a more realistic tropical tropopause. Later the same year the systematic error was further increased, probably due to a further reduction of analysed temperatures with the revision of the analysis scheme in September 1986 which were not mirrored by the model. The revision of vertical diffusion in January 1988 most likely led to a reduction of model errors and to a cooling of the tropical tropopause in the forecasts. The May 1989 model changes clearly led to a reduction of errors and have raised the analysed temperatures (during the parallel run by 0.4 K).

Above, it was shown that the lower troposphere is generally cooled by the model while the middle and upper troposphere is heated. This means a stabilization of the lower troposphere especially in the tropics. Arpe (1988a) has speculated that this error may be connected with the model's insensitivity to sea-surface temperature anomalies. In Fig. 16 we demonstrate how this deficiency in the static stability has evolved during the last years. Time series of zonal mean temperature differences between 850 and 500 mb for two latitude belts are shown. Larger values mean less stable conditions. In the tropics (9°S-9°N) the stability of the analysed as well as the forecast lower atmosphere changed dramatically with the revision of the radiation parametrization in December 1984. At this time also the Hadley circulation (500 mb vertical velocity at the equator) in the forecasts was weakened, although not in the analysis. A further stabilization of the model atmosphere is due to the T106/convection model change in May 1985. Possibly due to the reduction of vertical diffusion in January 1988 or more likely to an analysis modification around the same time the stability of the analysed atmosphere decreased, which was not mirrored in the forecasts. The May 1989 model change reduced the gap between analysis and forecast but the model atmosphere is still too stable compared to the present analysis although it has now values similar to those in the analyses during 1985/86. During the course of the forecast the stability increases very quickly, in about 2 days, and has to be seen in connection with the spin-up of convective activity.

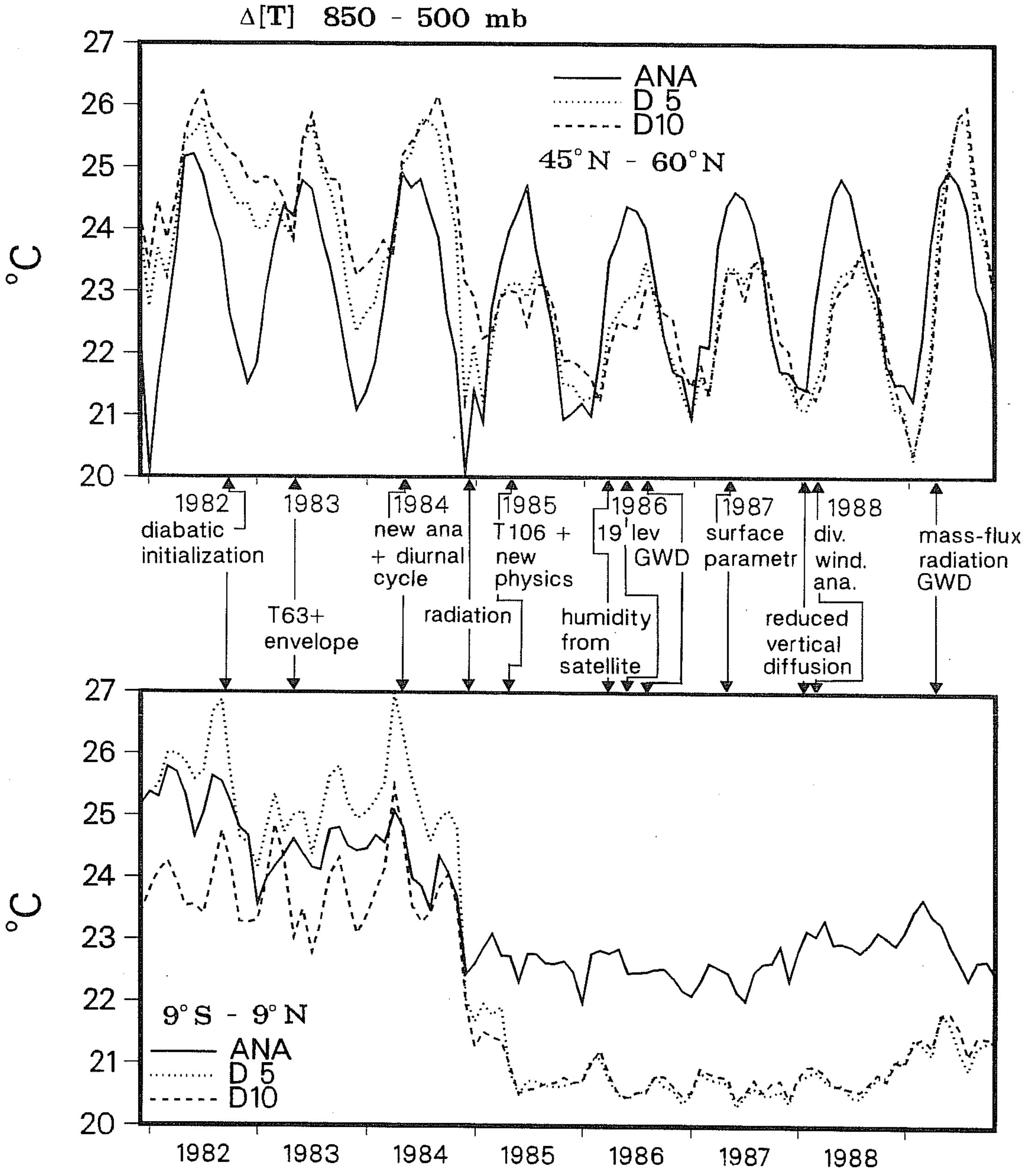

Fig. 16: Static stability of the lower troposphere represented by zonal mean temperature differences between 850 and 500 mb in the analysis, the day 5 and day 10 forecasts. Values represent monthly means. Ticks on the abscisse indicate Januaries. Upper panel: 45°N-60°N; lower panel: 9°S-9°N. Larger values mean less stable conditions.

For the extratropics the same model changes are important in this regard as well, except that the stabilization since early 1985 is restricted to the summer months when the convection is most active. The May 1989 model change has led to a destabilization in the extratropics, during summer. There is already a change in the day 5 and 10 values during DJF 88/89 compared to the winters before, but there is no model change in 1988 which could explain it.

A study of the deviations of the temperatures from their zonal means reveals large impacts from the May 1989 model change on the planetary waves in the lower troposphere. Before this model change the amplitudes of these waves were underpredicted and after that they were overpredicted. A large portion of the latter overprediction is due to contributions from standing waves and the errors of these standing waves are exhibited in Fig. 17. Mean day 10 700mb temperature errors of JJA 88 are compared with those of JJA 89. During JJA 89 a strong wavenumber 2 pattern is evident with much larger errors than in the year before. Errors are especially large over high ground. More solar radiation is now reaching the ground and leads there to higher temperatures and larger sensible heat fluxes.

7. HUMIDITY

Because of large observational errors and because of much smaller spatial scales in the distribution of humidity, it is very difficult to analyse this quantity. For these reasons one can expect large impacts from changes in the analysis/forecasting scheme as is illustrated in Fig. 18 for the 850 and 700 mb levels.

The largest impacts both on the analyses and the forecasts in the tropics (Fig. 18, lower panel) resulted from the T106/convection model change in May 1985. At this time the humidity at 700 mb and above was reduced. Despite this large change in the analysed values the forecast values always stay 1-2 g/kg lower than the analysed values. The decrease of humidity during the course of the forecast occurs mainly in the first few days when there is a large discrepancy between precipitation and evaporation as is shown below. This general deficiency has been considerably reduced with the May 1989 model change at least for 700 mb and higher levels. These model changes led also to clear impacts on the analysis values. Tiedtke et al. (1987) have shown that the humidity analysis is dominated by the first guess and Heckley (1985) discussed how the spin-up of precipitation and evaporation during the forecast in the assimilation cycle can lead to an excessively moist analysis and a consequent decrease of humidity in the medium range forecasts.

More recently it has been found that the drying during the forecast is concentrated over the tropical mainly southern oceans where there are only a few conventional observational data. In the Pacific area radiosonde data are available only at 00UTC and at these points one finds

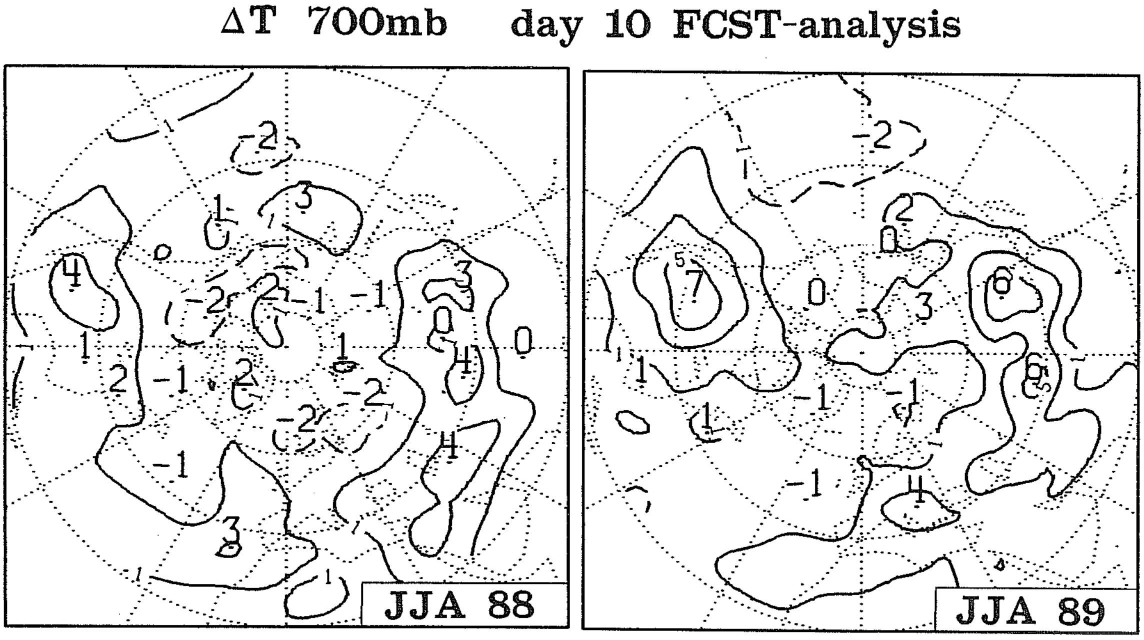
ΔT 700mb day 10 FCST-analysis

Fig. 17: Day 10 temperature errors at 700mb during JJA1988 and 1989. Contour interval: 2K offset by 1K.

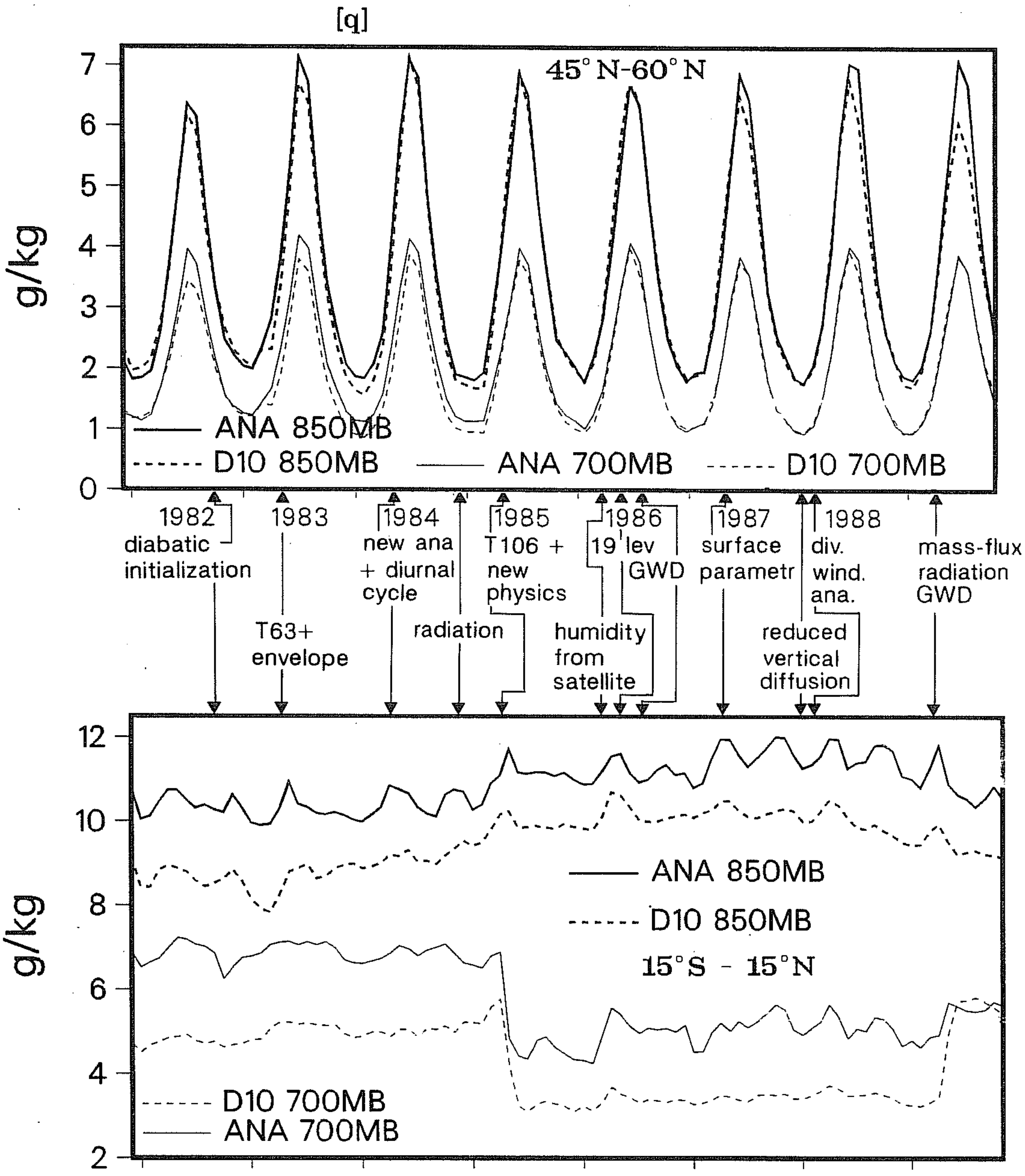

Fig. 18: Zonal mean mixing ratio in the tropics (15°S-15°N) in the analyses (solid lines) and the day 10 forecasts (dashed lines) at 850 mb (thick lines) and at 700 mb (thin lines).

a diurnal cycle of up to 2g/kg in the analysis with lower values when radiosonde observations are available. These facts suggest that the analysis may be too humid due to incorrect usage of satellite observations.

Further impacts can be seen with the T63/envelope orography model which brought an increase of humidity in the analysis and more so in the forecast which means a reduction of errors. Increases of analysed humidities resulted from the use of satellite measurements together with a reduced use of SYNOP data in March 1986 (700 mb) and from the modification of surface parametrizations in April 1987 (850 mb), both resulting in larger systematic errors. The latter increase of humidity is inconsistent with our expectation of the impact of a reduced evaporation at this model change. Illari (1987) has shown that the analyses after the March 1986 change (i.e. use of satellite humidity measurements and reduced use of SYNOP data) agree better with observations from radiosondes than the earlier analyses.

The humidity in mid-latitudes (Fig. 18, upper panel) is much less reduced during the forecast and the analysed as well as the forecast values are much less sensitive to analysis/forecast scheme changes as already pointed out by Arpe and Klinker (1986). However, in recent years one finds increasing drying at 850mb during summer. In geographical distributions (not shown) the drying before the May 1989 model change was confined to areas which were already dry in the analyses while areas which were wet in the analysis (i.e. with values larger than 60%) became even more humid in the forecasts. This increased the gradients but hardly affected zonal mean values. After May 1989 the drying is more evenly distributed over all areas.

8. ENERGETICS

A convenient measure for variances and covariances in the atmosphere are the energetic quantities as formulated by Lorenz (1955). For details of the calculation used in this study see Arpe et al. (1986). Fig. 19 shows global averages of energy amounts for June 1988 and June 1989 during the course of the forecast. The dominant feature in the forecasts before May 1989 is a drop in eddy kinetic energy (KE) and an increase in zonal energies (KZ and AZ). Above, it has been discussed that there is a reduction in amplitudes of the standing waves, but most of the reduction of the eddy kinetic energy in Fig. 19 occurs in the transient waves, because the standing waves contribute little to the total eddy energies. The May 1989 model change reduced this problem considerably and one now finds the error tendency typical of the pre-May 1989 model only in the very short range forecasts. The drop of eddy kinetic energy in the early forecasts is confined to synoptic scale waves in the old as well as in the new model. Looking into the geographical distribution (not shown) one finds that this increase of eddy energy in the new model is confined to the Northern

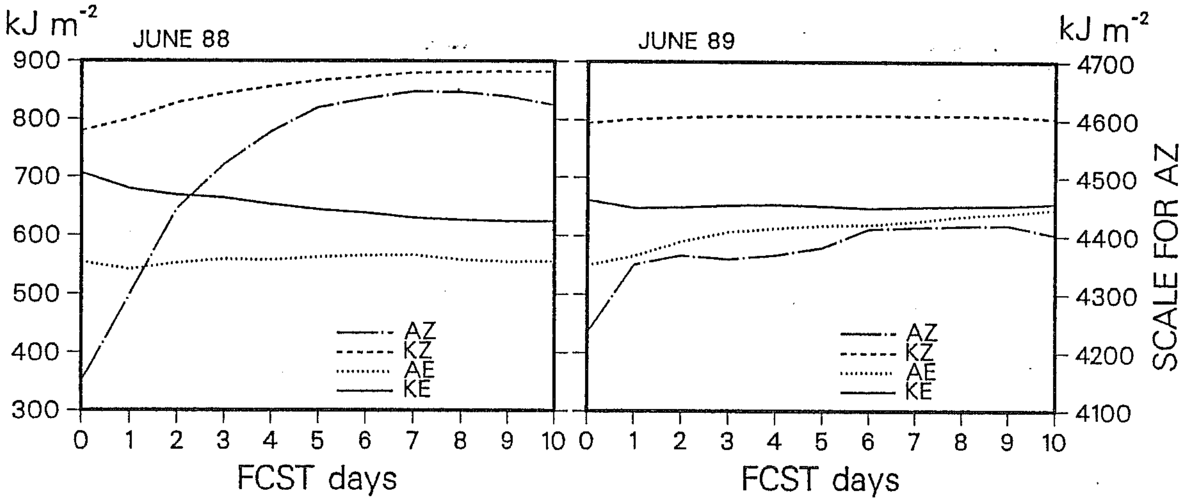

Fig. 19: Global averages of energy amounts during the course of forecasts in June 1988 and June 1989.

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.

Hemisphere, at least for JJA while the Southern Hemisphere, especially the subtropics, were already improved by the restriction of vertical diffusion to the boundary layer in January 1988.

Fig. 20 (upper panel) shows how the eddy kinetic energies in the analysis and the forecast have changed in recent years. Only contributions from synoptic waves (zonal wavenumbers 4-9) are displayed. In general, the eddy activity is lower in the forecasts than in the analysis and from April 1983 onwards the reduction is especially large, this being most likely due to the introduction of the envelope orography. A further reduction in the eddy kinetic energy can be seen following the revision of the radiation scheme in December 1984. This error is reduced in January 1988 as a result of the reduction of vertical diffusion and is further reduced by the May 1989 model change (mostly due to the revision of the radiation scheme).

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, and after the May 1989 model change is compensated by a worse performance with respect to the conversion from eddy available potential energy to eddy kinetic energy, shown in Fig. 20 (lower panel). i.e. too much conversion when there is less reduction in eddy kinetic energy. The real problem with the model has not been changed over the years: there is still 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 conversion or lower energy amounts. It is, even now, not clear whether the analysis is correct in this respect. 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. It is also known that satellite temperature soundings tend to underestimate vertical as well as horizontal gradients. With this uncertainty in mind it is probably better to aim for the right amount of eddy kinetic energy instead of energy conversion.

A more detailed investigation reveals for the shorter synoptic waves a poleward shift of the maxima which has to be seen in connection with the poleward shift of the jet stream. Although it has been found above that such a poleward shift of the zonal mean jet stream is no longer obvious it is still clearly indicated in the eddy kinetic energy of the shorter waves. For the planetary waves one finds a strong increase of the conversion from eddy available potential energy to eddy kinetic energy in the forecasts since the May 1989 model change (not shown) which has to be seen in connection with the warming over the continents and cooling over oceans in the lower troposphere discussed above.

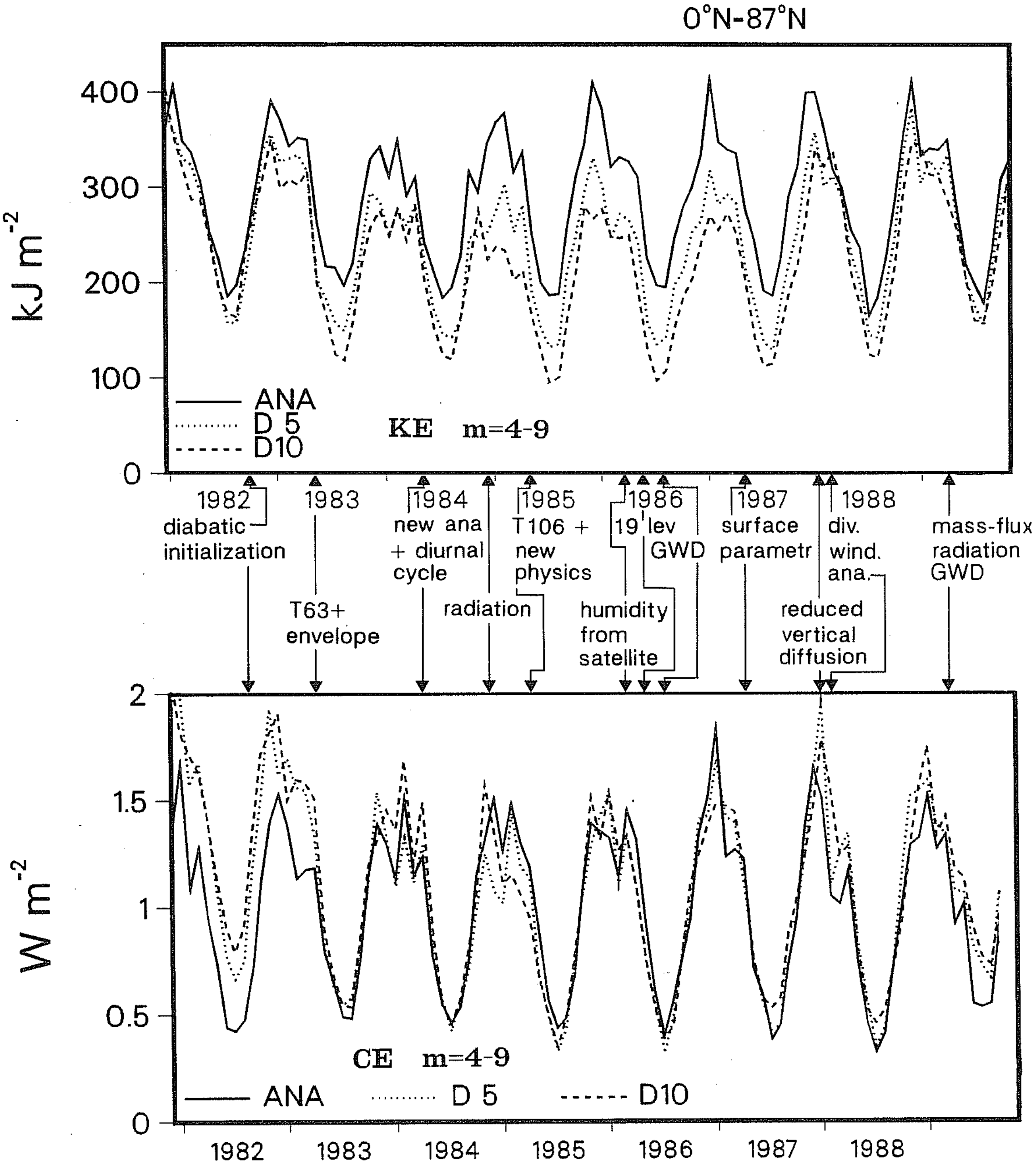

Fig. 20: Northern hemisphere mean eddy kinetic energy by synoptic (zonal wavenumbers 4-9) scale waves in the analyses, the day 5 and day 10 forecasts (upper panel) and the conversion from eddy available potential energy to eddy kinetic energy (lower panel). Values represent monthly means. Ticks on the abscisse indicate Januaries.

9. DIABATIC PROCESSES

The latent and sensible heat budgets for the atmosphere ought to be balanced when averaged over a long period. An important test of model performance is how far these balances are fulfilled at different forecast ranges. In Fig. 21 both budgets are shown for June 1988, which is representative for the model before the May 1989 change, and for June 1989, representative for the time after that. After day 3 only 24 hour averages are plotted instead of 12 hour averages and the first two points are averages for the 0 to 6 hour and 6 to 12 hour forecasts respectively, which explains the "disappearance" of the diurnal cycle in the medium range.

The heating of the model atmosphere by sensible heat flux from the surface, by large scale precipitation and by convective precipitation (the sum of these is the total input) has to be balanced by cooling due to radiative processes. In the hydrological budget the total precipitation has to be balanced by evaporation. During June 1988 there is an obvious imbalance in the short range forecasts leading to a temperature increase and drying of the atmosphere, as shown in the previous sections. The overshooting of precipitation is dominated by tropical areas. The imbalance in the short range forecasts (spin-up) reflects inconsistencies between analysis and model which are partly removed by an initialization scheme (Wergen, 1987, 1989). They are partly caused by deficiencies in the parametrization scheme. The May 1989 model change has reduced this problem considerably and there is now a near balance for the heat budget throughout the forecast which agrees with our finding in section 6 that there is hardly any warming of the model atmosphere. In the hydrological budget one still finds too low evaporation in the short range forecasts to achieve a balance. In section 7, it has been suggested that the analysis scheme produces too high moisture values in areas where there are only satellite observations available. Therefore, the low evaporation data in the early forecasts may reflect the models reaction to wrong analysis data.

Fig. 21 contains also estimates of climatological values for the radiative cooling and the evaporation by Hoyt (1976) which for June agree better with values by the old model. In the new model the evaporation and precipitation in the day 10 forecasts are increased by 10-15% compared to the old ones. Also the sensible heat flux at the surface is increased. The total input in the energy budget is now balanced by a 20% higher cooling from radiative processes. How far these increases of heating or cooling in the new model mean improvements or deteriorations is difficult to judge because of our insufficient knowledge of the truth. Three examples demonstrate this problem: i) Hoyt's estimates do not allow for an annual cycle while the ECMWF model is more realistic in this respect. In the model there is less cooling by radiation during DJF than during JJA which means that the new model agrees better with Hoyt's estimates than the old model for this season. ii) Comparisons of

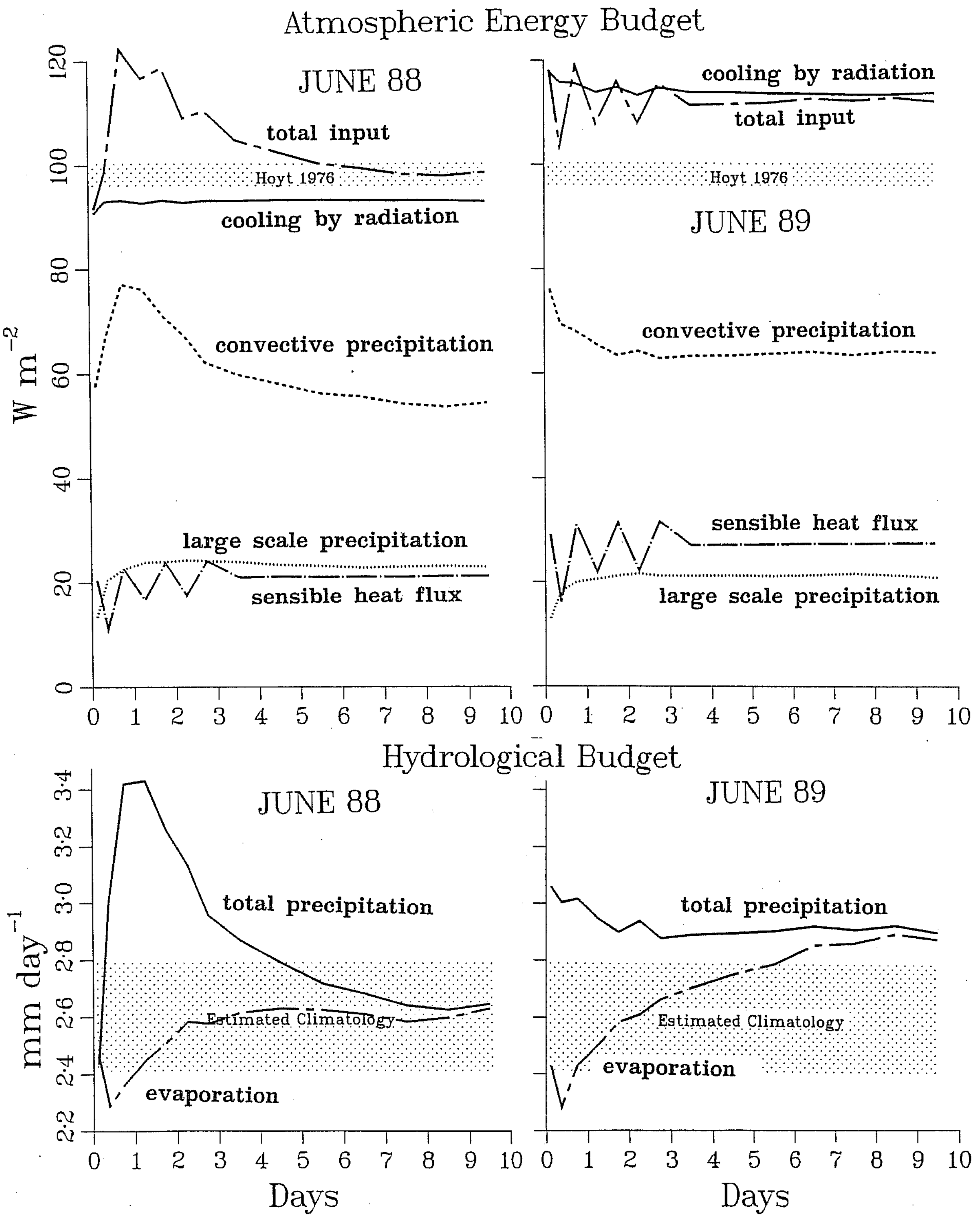

Fig. 21: Global budgets of latent and sensible heat during the course of forecasts in June 1988 and June 1989. Estimated climatological values of net radiative cooling and evaporation by Hoyt (1970) are indicated by stippled areas.

evaporation in the model with estimates by Oberhuber (1988) carried out by Arpe and Esbensen (1989) have shown that for June the evaporation in the short-range forecasts was too low over oceans. Evaporations in the day 9-10 forecasts with the new model agree better with estimates by Oberhuber. iii) Comparisons of precipitation in the model with estimates by Jaeger (1976) carried out by Arpe (1987) suggest too much precipitation in the tropics by the 1985-1987 model but too little precipitation when comparing them with estimates from OLR measurements.

The only variable directly linked to diabatic forcing which is globally available for verification is the outgoing longwave radiation (OLR). Arpe (1987) found large differences between model and observations over central Africa, Indonesia and central south America, areas with strong tropical convection mostly covered by high clouds. Morcrette (1989) has explained this deficiency by an insensitivity of the then operational radiation scheme to clouds and showed the improvements gained from the new radiation scheme which was introduced in May 1989.

Fig. 22 compares the observed OLR with that from the model during May 1989. The much better structure in the OLR of the new model is obvious. When comparing the fields one has to take into account that the observed values were only available with about half the resolution of the model values. However, the model OLR values over cloud free areas in the subtropics are clearly higher than the observed values which is to some extent due to the observed data which are not measured continuously for the whole spectrum but had to be extrapolated from a number of narrow band measurements. Also the parametrization scheme still has known defects which can now be addressed after the overall problem has been solved (Morcrette, pers. comm.). In the day 9-10 forecasts one finds clear reductions of extreme values, especially at the ITCZ. These are due to changes in the flow and may not be problems directly related to the radiation scheme.

In Fig. 23 the day 9-10 precipitation forecasts are compared with short range forecast values and with estimates from OLR measurements by satellite (Meisner and Arkin, 1987). The latter precipitation distribution is prepared operationally by the Climate Analysis Center (CAC), Washington D.C. The smoother appearance of this data set results from a coarser grid used by CAC compared to the ECMWF forecast model. Many similarities between all three distributions can be found. However much lower values by CAC for the Ethiopian Highland and for the ITCZ around Central America seem to be more realistic than the values by the model. A major problem in the day 9-10 forecasts is the disappearance of precipitation over India and the development of a new precipitation band in the southern tropical Indian Ocean. Arpe (1987) reported about a disappearance of precipitation within the South Pacific Convergence Zone during the course of the forecast. In Fig. 23 there is no such problem evident, but this is mainly due to the different season which is displayed here.

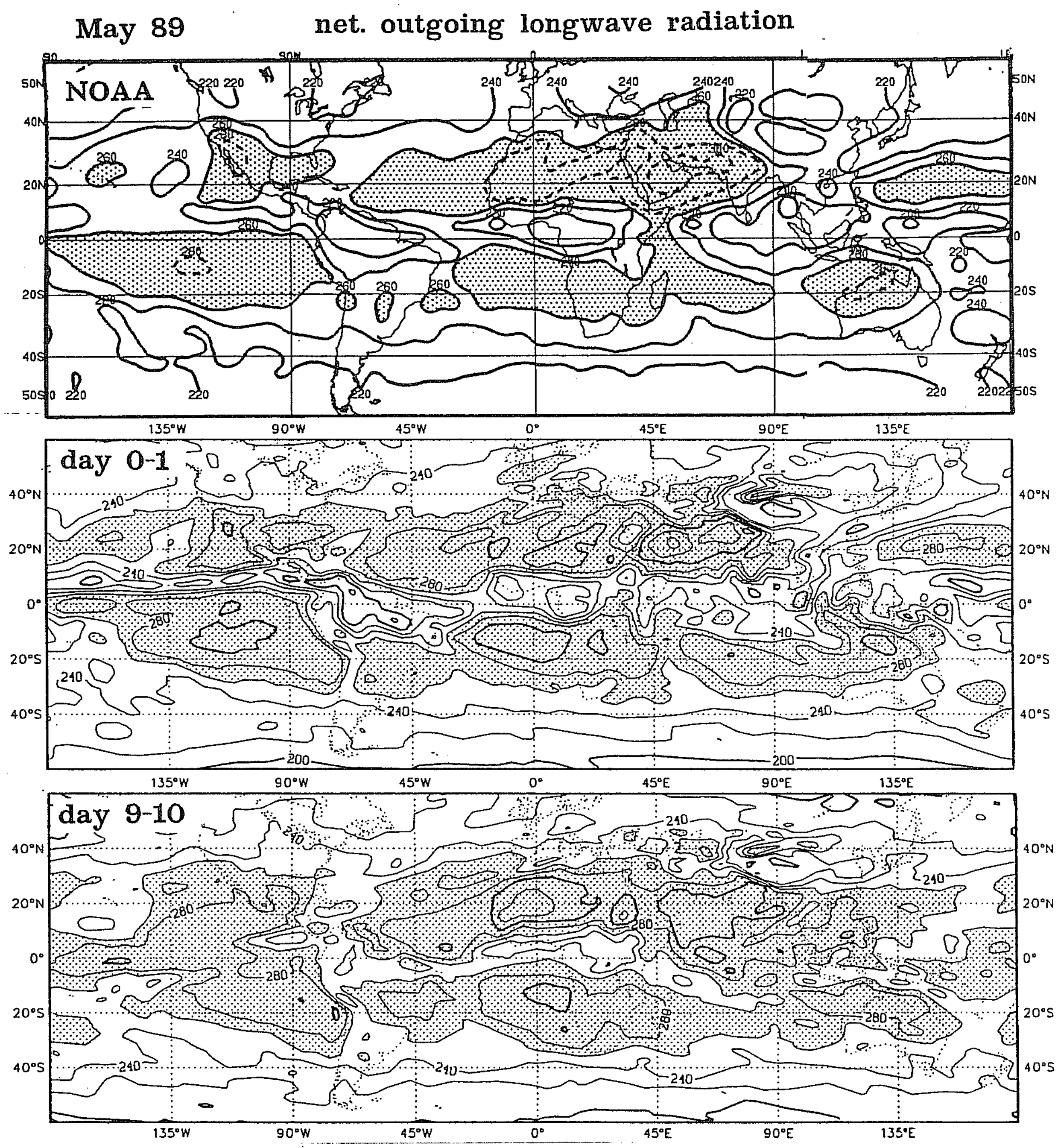

Fig. 22: Net outgoing longwave radiation during May 1989 as observed by NOAA (1989) from satellite and in the day 0-1 and day 9-10 forecasts. Contour interval: 20 W/m^2; areas with more than 260 W/m^2 are shaded.

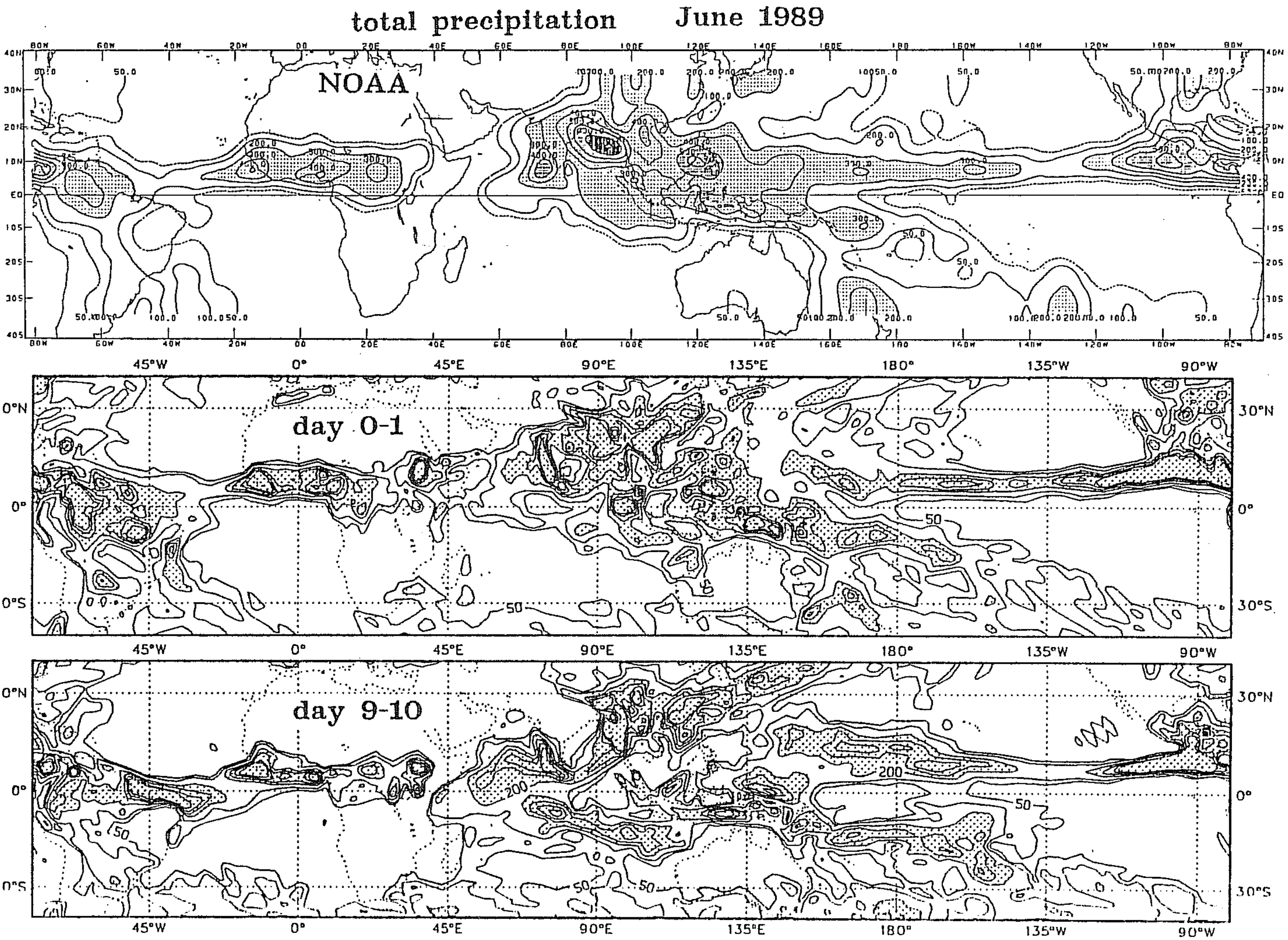

Fig. 23: Monthly mean precipitation for June 1989. Top panel: estimates from satellite measurements (NOAA, 1989). Lower panels: Day 0-1 and day 9-10 averages in the ECMWF forecasts. Contours at 50, 100, 200, 300, 400, 500 and 600mm, areas with more than 200mm are shaded.

10. CONCLUSION

It has been shown that the systematic errors of the ECMWF model have been reduced considerably in recent years. These improvements were clearest in the tropics. They were most sensitive to changes in parametrization schemes for convection and radiation and to a lesser degree to diffusion, GWD and the increase of vertical resolution in the stratosphere. These model changes had also impacts on the analysis data especially on the values of vertical velocity and humidity in the tropics. The analysed as well as the simulated vertical velocity (or divergent wind) is still an unreliable quantity even for seasonal means and more work has to be done to gain more confidence in the analysis and forecast values.

The geographical distribution of the mean errors of the geopotential height fields in the extratropics has maintained its pattern through the whole period of investigation. Only the amplitudes of these errors have been reduced. The standing waves in the forecasts have generally lower amplitudes than the verifying analyses and this problem can be connected with the failure of the model to simulate blocking events.

All changes in the operational model had been tested thoroughly before implementation but nevertheless due to many interactions also between the analysis scheme and the forecast model effects in the model performance have been found which were not expected.

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