TECHNICAL MEMORANDUM

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Changes is the ECMWF analysis-forecasting scheme and the systematic error of the model

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August 1989

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ECMWF/SAC(89)6
SHINFIELD
21 August 1989

Subject: Systematic errors of the ECMWF model

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 into 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 is discussed. Table A gives an overview of those changes which produced the largest 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.

Before going into detail the differing importance of analysis/forecasting system changes at various forecast ranges will be discussed.

Fig. 1 shows the squared errors of 500 mb height fields of the forecasts averaged for the globe at forecast day 1 and 5. The squared error is separated into two contributions, one

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), replacement of Kuo by mass-flux convection (Tiedtke, 1989), revised gravity wave drag.

for monthly mean fields (shaded) which are termed systematic errors, and the other, which is the difference between the total error and the systematic error termed the random error. At day 1 the largest improvement of the total error occurred in May 1984 with the revision of the analysis scheme, but only the random errors were reduced. The T106/convection model change in May 1985 is marked by a reduction of the systematic error. A further reduction of systematic errors is due to the handling of tides in the initialization scheme from March 1986 onward. The revision of the analysis scheme in September 1986 led again to a reduction of random errors. There is another reduction of random errors around October 1988. At this time there have been no analysis/model changes which are expected to have contributed to this reduction but NOAA/NESDIS changed their method of retrieving the vertical temperature profiles from satellite measurements.

In the day 5 forecasts the impact from changes in the analysis scheme are less obvious. The following model changes coincide with marked variations in the error curves: In April 1983 (T63/envelope orography) there is some increase of systematic errors in the large scales and some reduction of random errors can be seen later in the year; the change in the radiation scheme in December 1984 reduced random and systematic errors; in May 1985 (T106/convection) the systematic errors are reduced; a reduction of random errors in the day 5 forecasts between November 1985 and July 1986 is difficult to assign to a single model change; lower systematic errors for the period from spring 1987 (change to surface parametrization) to summer 1988 (introduction of a finer scale analysis) could also be due to natural variability. In the day 10 forecasts (not shown) one finds an increase of random errors at the beginning of 1988. As there is only little predictive skill in the day 10 forecasts, this increase could reflect an increase of spatial variance in the forecasts arising from the reduction in vertical diffusion (January 1988) though this increase of error comes one or two months after this model change.

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 which was introduced together with a modification of the radiation and the gravity wave drag scheme in May 1989.

2. ZONAL MEAN OF ZONAL WIND

One of the most persistent components of the systematic error can be found in the zonal mean of the zonal wind. Fig. 2 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 the years but since DJF 87/88 there is more a strengthening of the jet. 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 which 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 relative to 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 have been found also in the NMC model (Tracton et al, 1988).

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. 3.

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. One has to do a considerable amount of experiments or to wait at least for JJA 89 to decide if this change in the annual cycle is due to natural variability or due to analysis/forecasting scheme changes which have been introduced in December 87/January 88. The slight poleward shift of the analysed subtropical jet for DJF 87/88 and JJA 88 is anomalous, which helped to reduce the DJF 87/88 day 10 forecast error. The weaker subtropical and a stronger polar jet for DJF 88/89 is also anomalous. Both anomalies are not only features of the ECMWF analyses but have also been found in the NMC analyses (White, pers. comm).

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 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 be correlated with the stratospheric QBO i.e. tropical storms are stronger when the QBO is in the westerly phase (W. Gray, pers. comm.). This may give a clue to the source for this systematic error of the model. 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. The dominant reduction of systematic errors is 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., 1987). 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 mainly to a general improvement of the forecast through improved analyses but also improved the mean forecasts, especially 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. This change has not been in long enough in operations to give an impact in Fig. 3. The impact of this change is illustrated in Fig. 4 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 considerably different analyses with up to 1.2 m/s weaker easterlies in the tropical middle troposphere and up to 1 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. This question will be further addressed in the following sections.

The reduction of westerlies equatorwards of the subtropical jet stream which is accompanied by a decrease of easterlies at the same latitudes in the lower troposphere with the new model compared to the old model may, for this short period, be partly explained by the introduction of a cumulus friction parametrization in the massflux scheme.

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. 5 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 of 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 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 error.

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. 5. 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. Unsurprizingly 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. 6. 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 GMT 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 but its growth is slow during the first 5 days. The relatively large errors in the day 5½ forecasts shown in Fig. 6 compared to the day 10 forecast in Fig. 5 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 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 (not shown), one finds that they have a barotropic nature. 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.

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 1988. 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 the May 1989 model change has brought a considerable improvement (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. At 200 mb 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 the JJA 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 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 the marked westerlies over the eastern Pacific in the analysis are weakened in the forecasts.

Similar errors were found during the parallel run at the end of April 1989. In Fig. 8 the old and the new model for the May 1989 model change 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.

The increase of errors of zonal means of zonal wind in the new model, discussed above, has been found between 15°N and 15°S (see Fig. 4). The main contribution for this comes in the northern hemisphere from the area over west Africa and the eastern Pacific and in the southern hemisphere from nearly all latitudes. Another deterioration in the 200 mb wind field of the new model can be found over north India/south China where the subtropical jet is much weaker in the new model. 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 disappears during summer. 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 15°S and 15°N while they were of different signs before.

5. DIVERGENT WIND

The driving force for the atmospheric circulation is the convective activity in the tropics whose integrated strength can be measured by the large scale divergent or vertical wind component. Fig. 10 illustrates the variability of the Hadley circulation during recent years as shown by the meridional wind component at 850 mb as well as by 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 whole period which could reflect 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 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 more dramatic change in the Hadley circulation than is indicated by Fig. 10 and therefore zonal mean cross-sections of the vertical velocity during the parallel run in April 1989 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 updrafts in the forecasts did not penetrate high enough, this has now been clearly improved. Time series of vertical velocities at 500 mb (not shown) reveal also that the Hadley circulation in the day 10 forecasts was weakened with the December 1984 radiation modification which is not exhibited in Fig. 10. Below it will be shown that at this time the lower troposphere was considerably stabilized. The vertical velocity field reveals also an increase of the Hadley circulation in the analysis during Spring 1986 probably due to the use of satellite humidity observations scheme but 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 forecasts, which will be discussed below. This spin-up feeds information into the analysis since the model is used to provide a first guess field.

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 last 4 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 which was already pointed out above for zonal means.

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 but a larger sample is needed for a definite statement. 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).

In Fig. 13 the change over from climatology as analysed to the model's climatology 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 uninitialised 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 possible 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 from a forecast for 2 hours after the analysis while the first guess and the real atmosphere are forced diabatically only from processes up to the analysis time, which could mean a difference in the phase of the diurnal cycle by $\frac{1}{6}$ to $\frac{1}{8}$ of the full 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 88 and DJF 88/89 are shown. The middle and upper tropical troposphere is warmed by up to 2K during the 10 days and the lower troposphere is generally cooled. 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.2, correspond to meridional 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 also the analysis of the temperature in the tropics.

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 which increased the diurnal cycle of the 850 mb temperatures and could 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 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 during 1982, but the main increase occurs between January and March 1983. This is too late to be explained by the ENSO even 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. 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 difficult to assign to a particular event.

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 analyses as well as 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 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. 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. 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.

For the extratropics the same model changes are important in this regard also, 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 much larger improvement in the extratropics, than in the tropics.

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. 17 for the tropics at the 850 and 700 mb levels.

The largest impacts both on the analyses and the forecasts 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. This model change 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.

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 (not shown) 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).

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. 18 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 1988 is a drop of eddy kinetic energy (KE) and an increase in 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 the eddy kinetic energy in Fig. 18 results from 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 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.

Fig. 19 (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 the main 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 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 January 1988 model change is compensated by worse performance with respect to the conversion from eddy available potential energy to eddy kinetic energy, shown in Fig. 19 (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 which is that there 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 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.

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. 20 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 above. 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 above 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.

Fig. 20 contains also estimates of climatological values for the radiative cooling and the evaporation by Hoyt (1976) which for this season 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. This problem is highlighted by the following three examples: i) It is expected from experiments that the new model will better agree with Hoyt's estimates for the DJF means. ii) Comparisons of evaporation in the model with estimates by Oberhuber (1988) carried out by Arpe and Esbensen (1989) have shown that for June the evaporation with the old model was too low over oceans. 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. 21 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.

A major problem with the distribution of precipitation had been the disappearance of precipitation within the south Pacific convergence zone (SPCZ) (see e.g. Arpe, 1987). During June 1989 the SPCZ was retained during the course of the forecast.

10. CONCLUSION

It has been shown that the systematic error of the ECMWF model has been reduced considerably in recent years. It was 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 impact 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 analyses and forecast values.

In the extratropics the most important problem of the model seems to be the simulation and forecast of blocking events. It still has to be established if the latest (May 1989) model change, which had large impacts on many aspects of the systematic error, had also an impact on the performance of 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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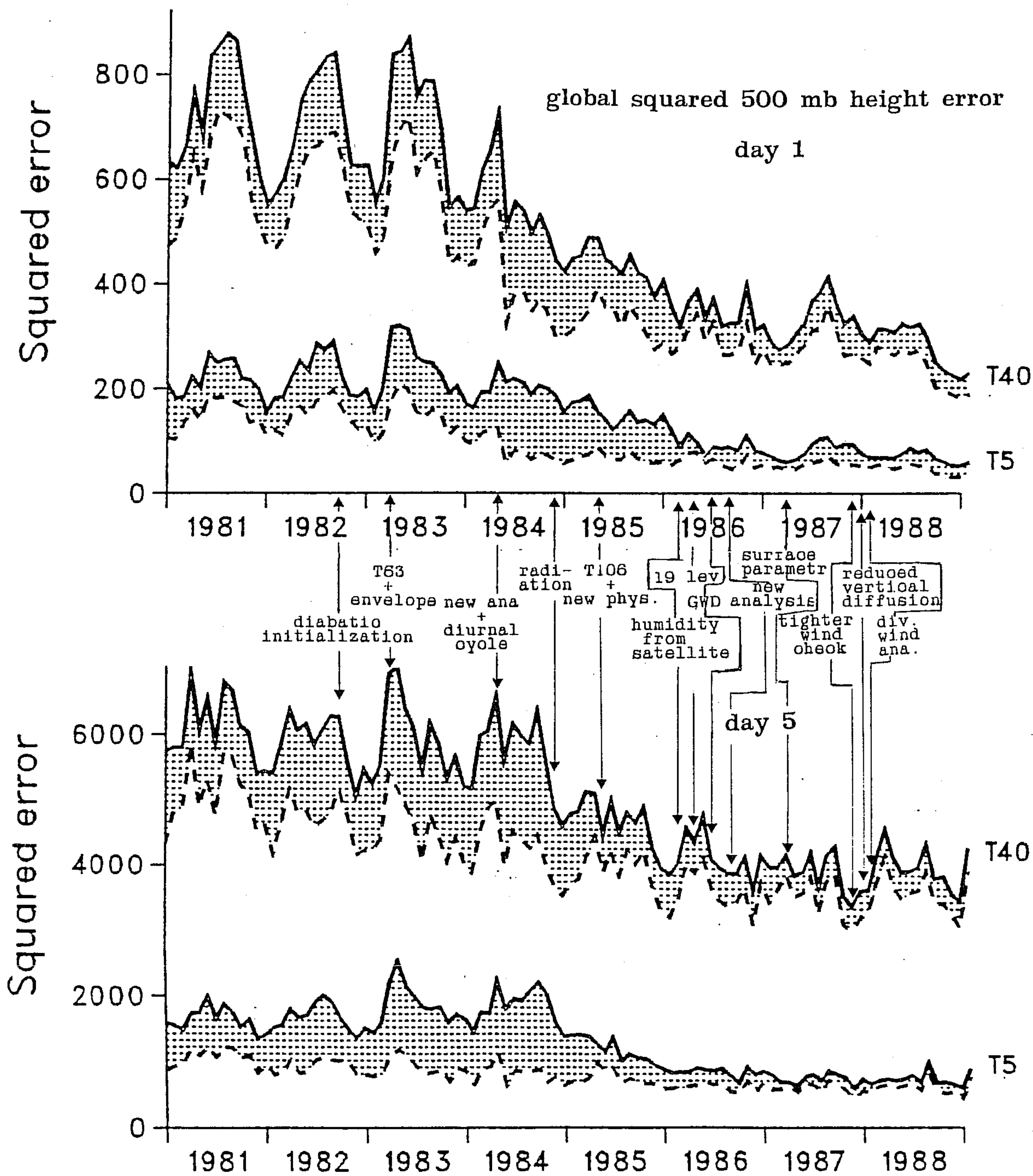


Fig 1: Squared 500 mb height field error for the globe since 1981 in the day 1 and day 5 forecasts. Two different truncations T40 and T5 have been used to calculate errors. Contributions of monthly systematic errors are shaded. (Figure by courtesy of R. Mureau).

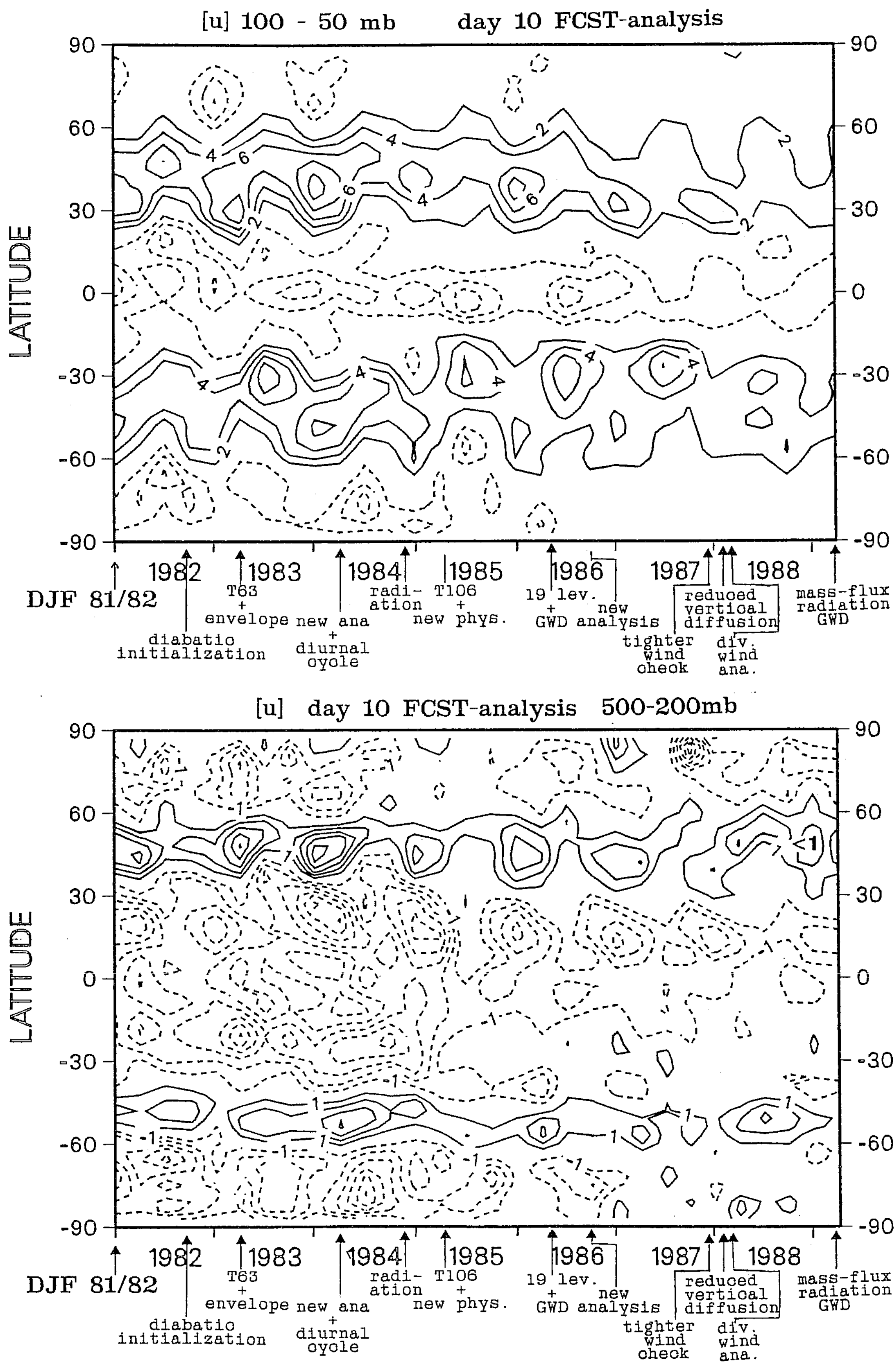


Fig. 3: Zonal and vertical means of zonal wind errors of the day 10 forecasts. Values represent seasonal means. Zero lines are suppressed. Upper panel : 100-50 mb mean; contour interval: 2 m/s. Lower panel: 500-200 mb mean; contour interval: 1 m/s. Ticks on the abscisse indicate the DJF season.

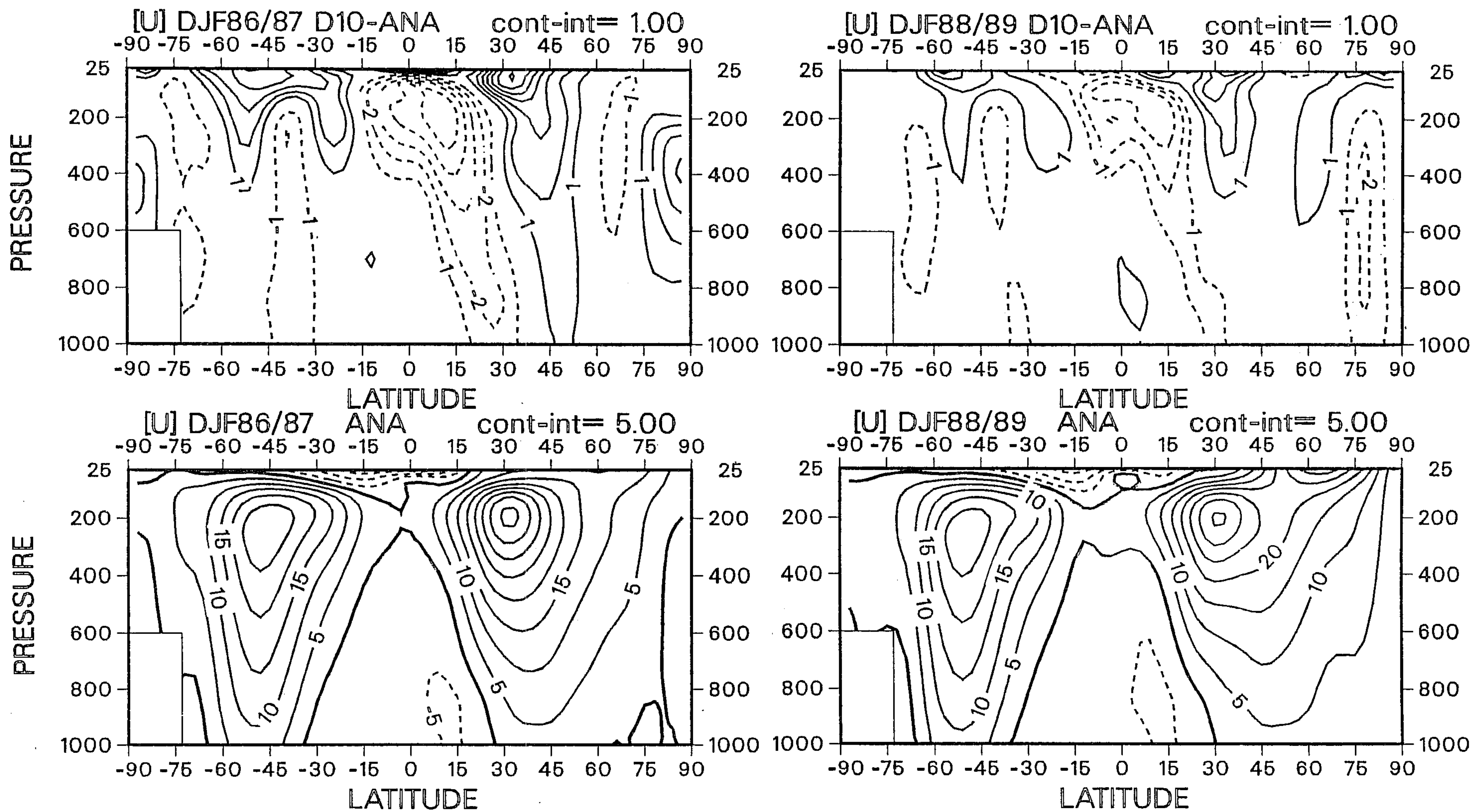


Fig 2: Zonal mean of zonal wind in the analysis during DJF 86/87 and DJF 88/89 (lower panels) and the day 10 forecast errors (upper panels). The zero contour in the error panels is suppressed.

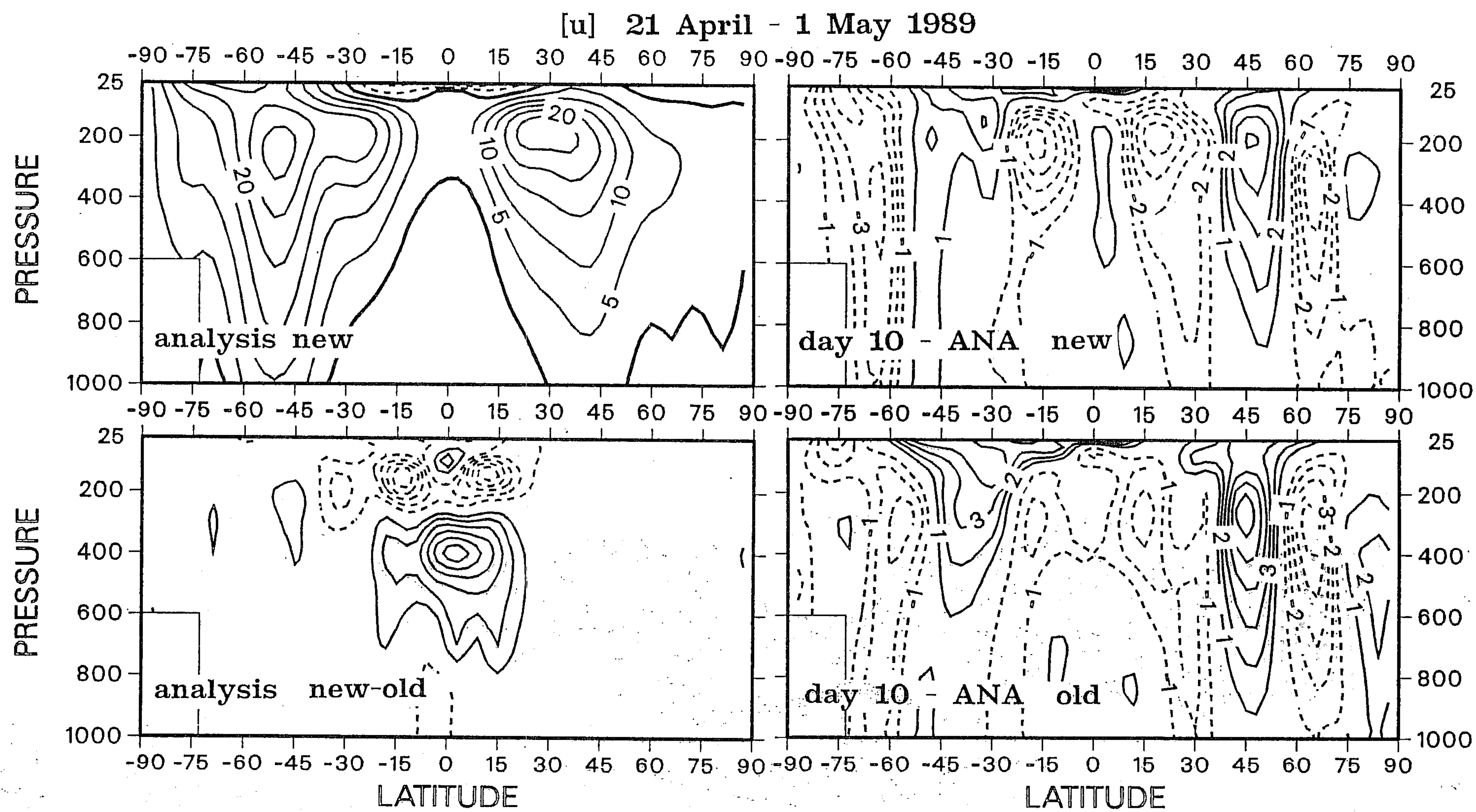


Fig. 4: Zonal mean of the zonal wind during the parallel run between 19 April and 1 May 1989 (mean of 13 cases)

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

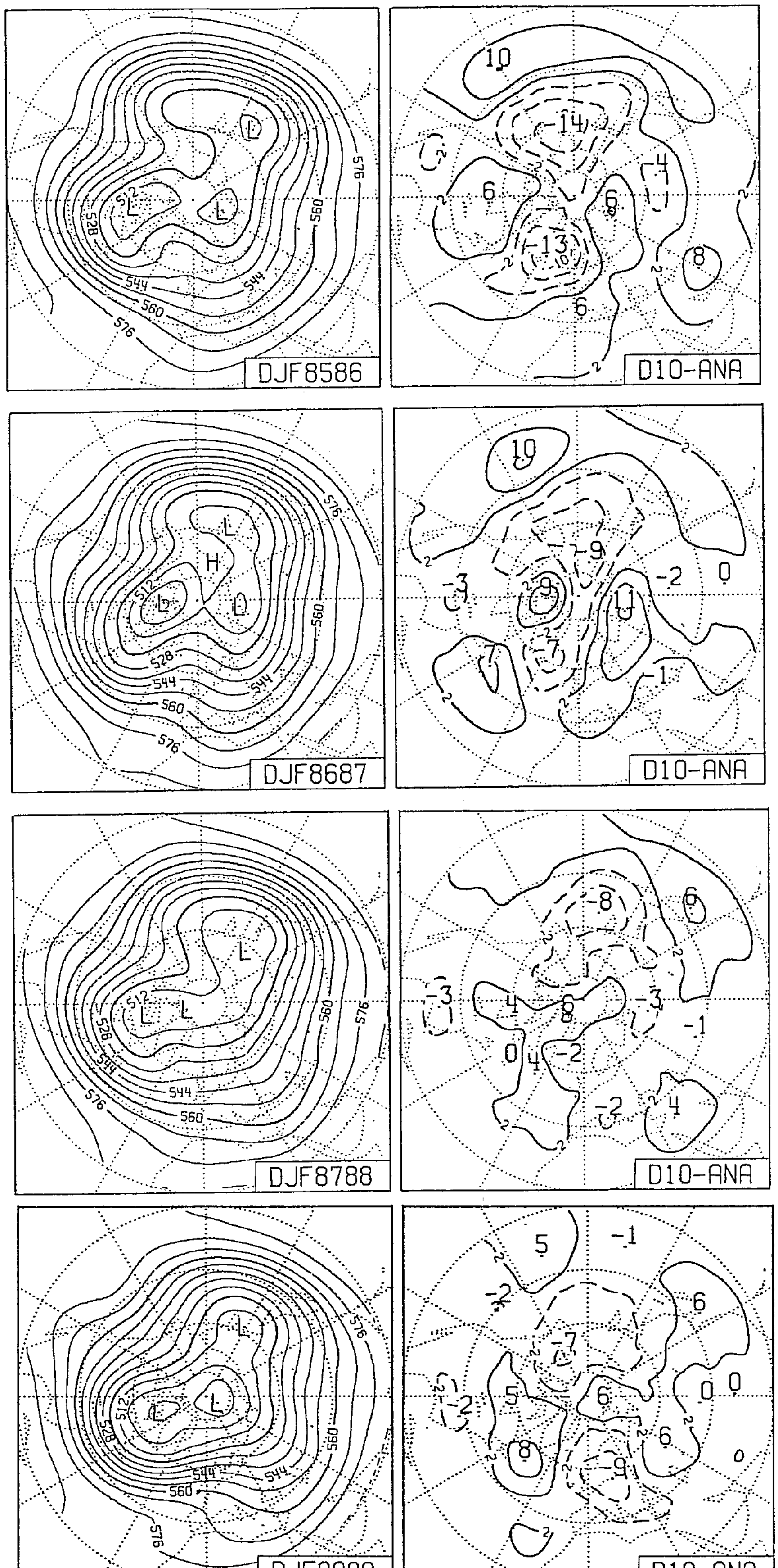


Fig. 5: 500 mb height fields and their day 10 forecast errors for the season DJF from 1985/86 to 1988/89. Contour interval is 8 dam for the mean heights and 4 dam offset by 2 dam for the errors.

mean day 5 500 mb height error 21 Dec.88 - 28 Febr.89

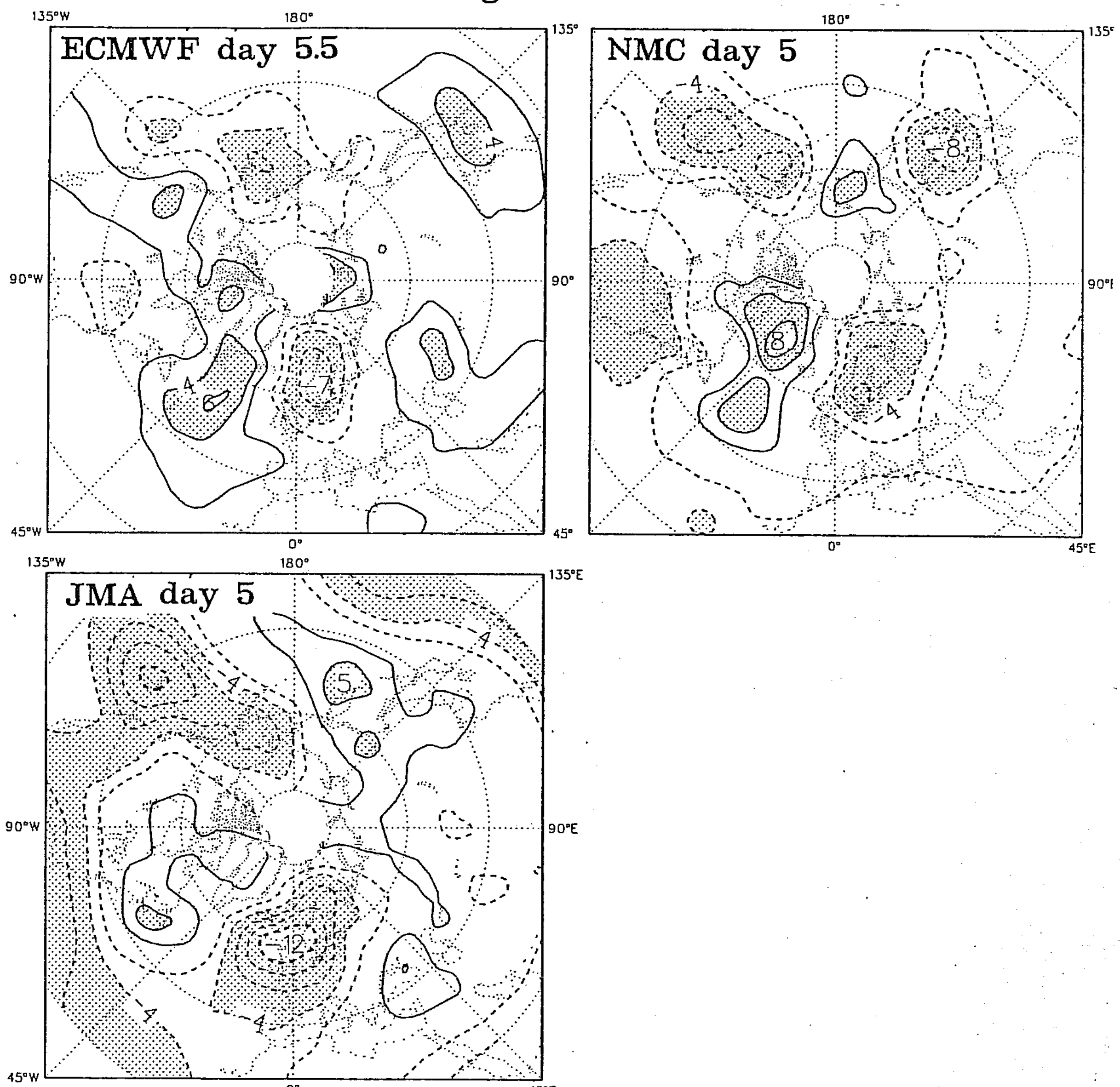


Fig 6: 500 mb height fields error of the day 5½ forecasts by ECMWF and the day 5 forecasts by NMC and JMA during the period 21 December 1988 to 28 February 1989 for those days when all 3 forecasts were available. Contour interval is 2 dam; the zero line is suppressed.

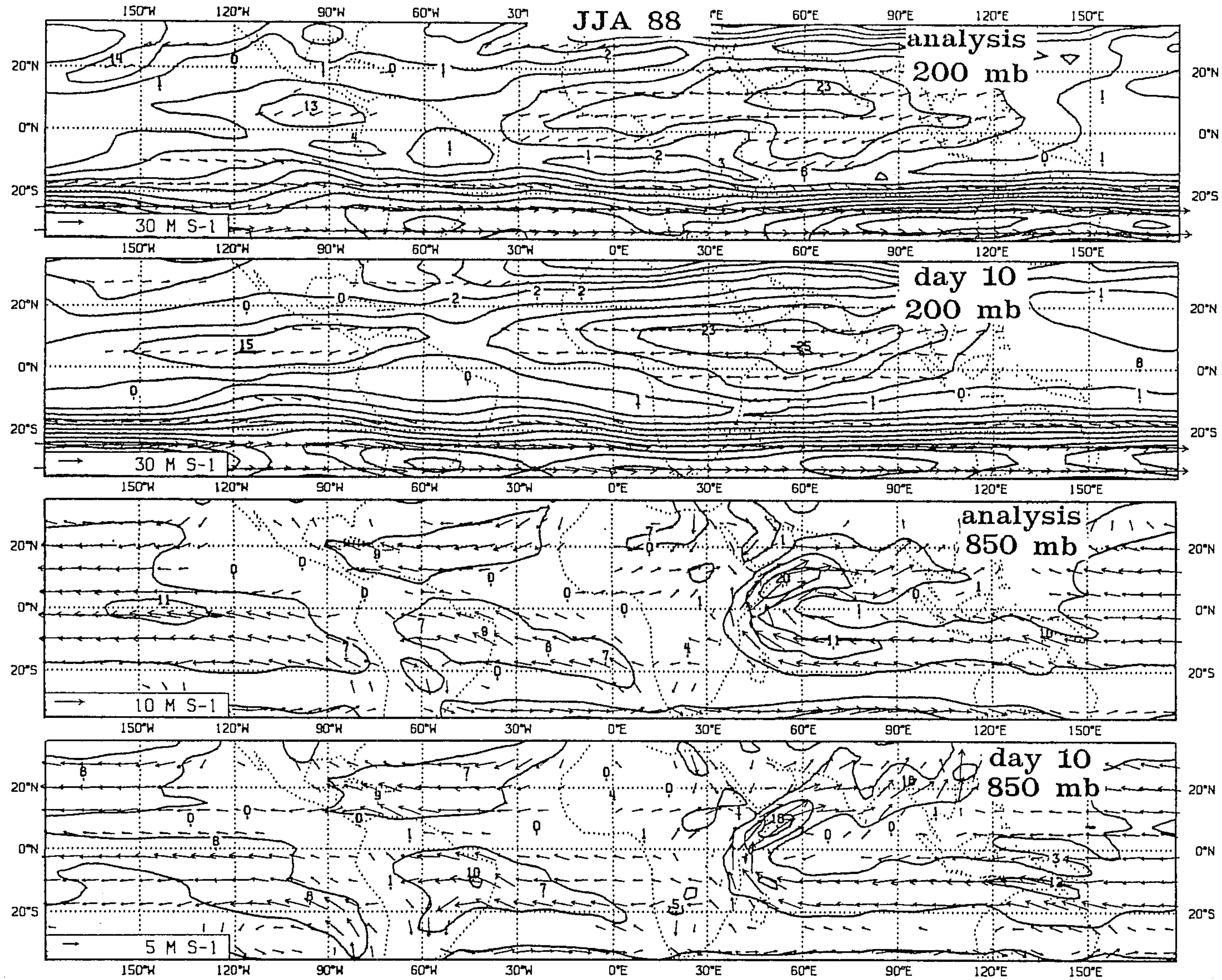


Fig 7: Mean 850 and 200 mb windfield during JJA 88 in the analysis and the day 10 forecast. Contour interval of isotachs: 5 m/s.

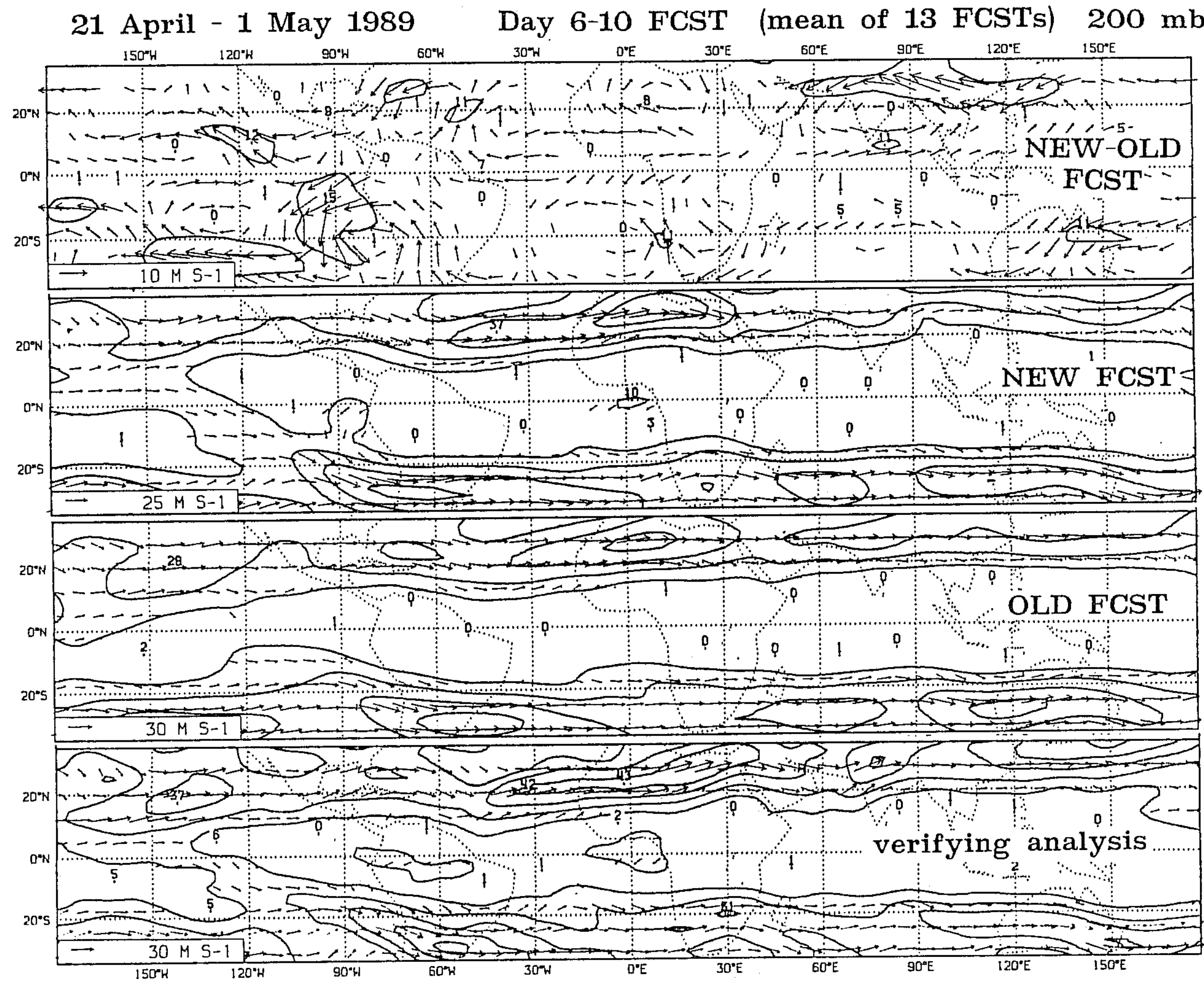


Fig 8: Mean 200 mb windfield for the parallel run between 19 April and 1 May 1989 (mean of 13 cases). Contour interval:10 m/s.

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.

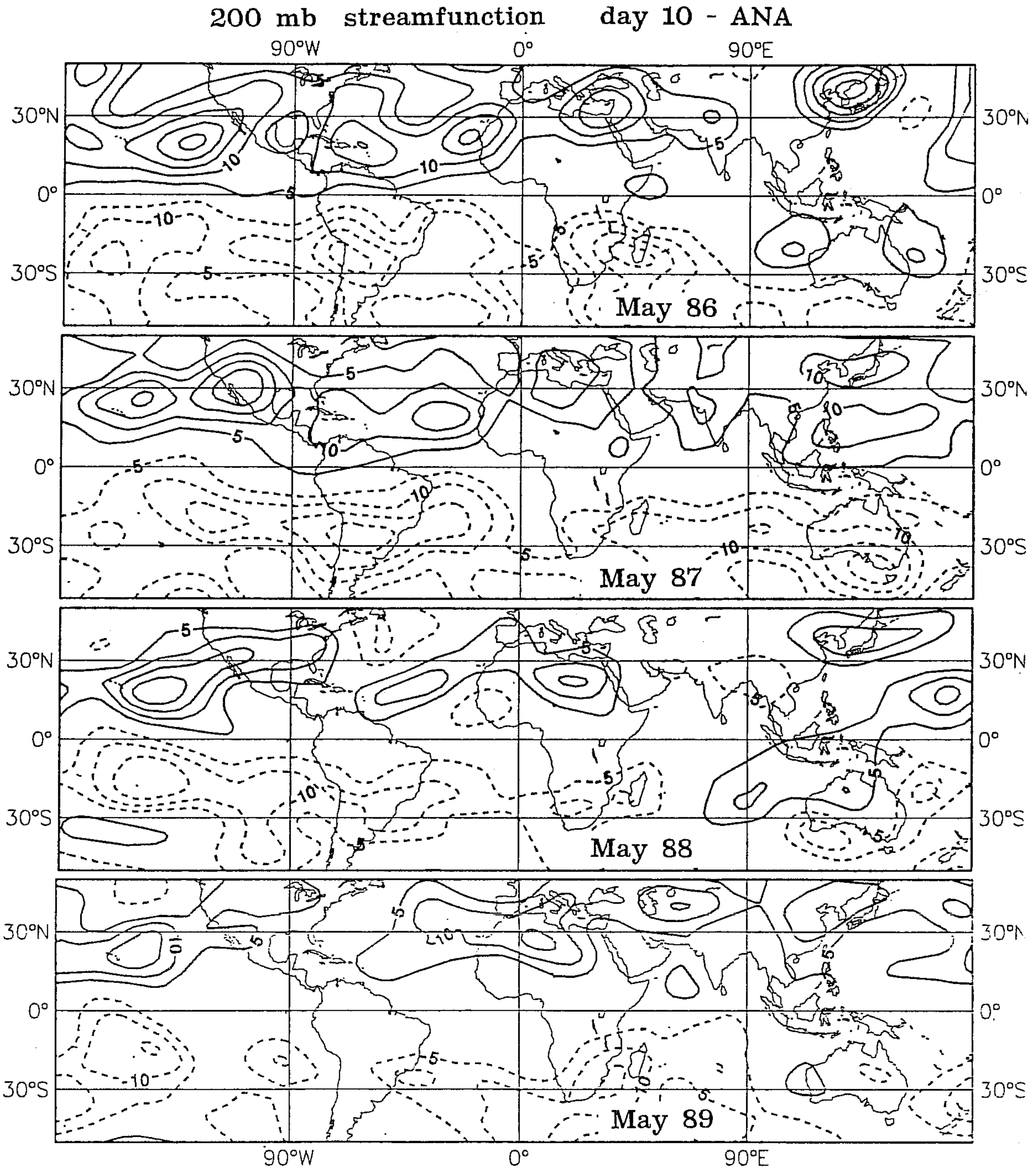


Fig. 9: Day 10 forecast errors of the 200 mb streamfunction (May 1986 - May 1989). Contour interval: $5x10^6$ m/s^2; zero line is suppresssed. One contour interval in 10° of latitude corresponds to 5 m/s.

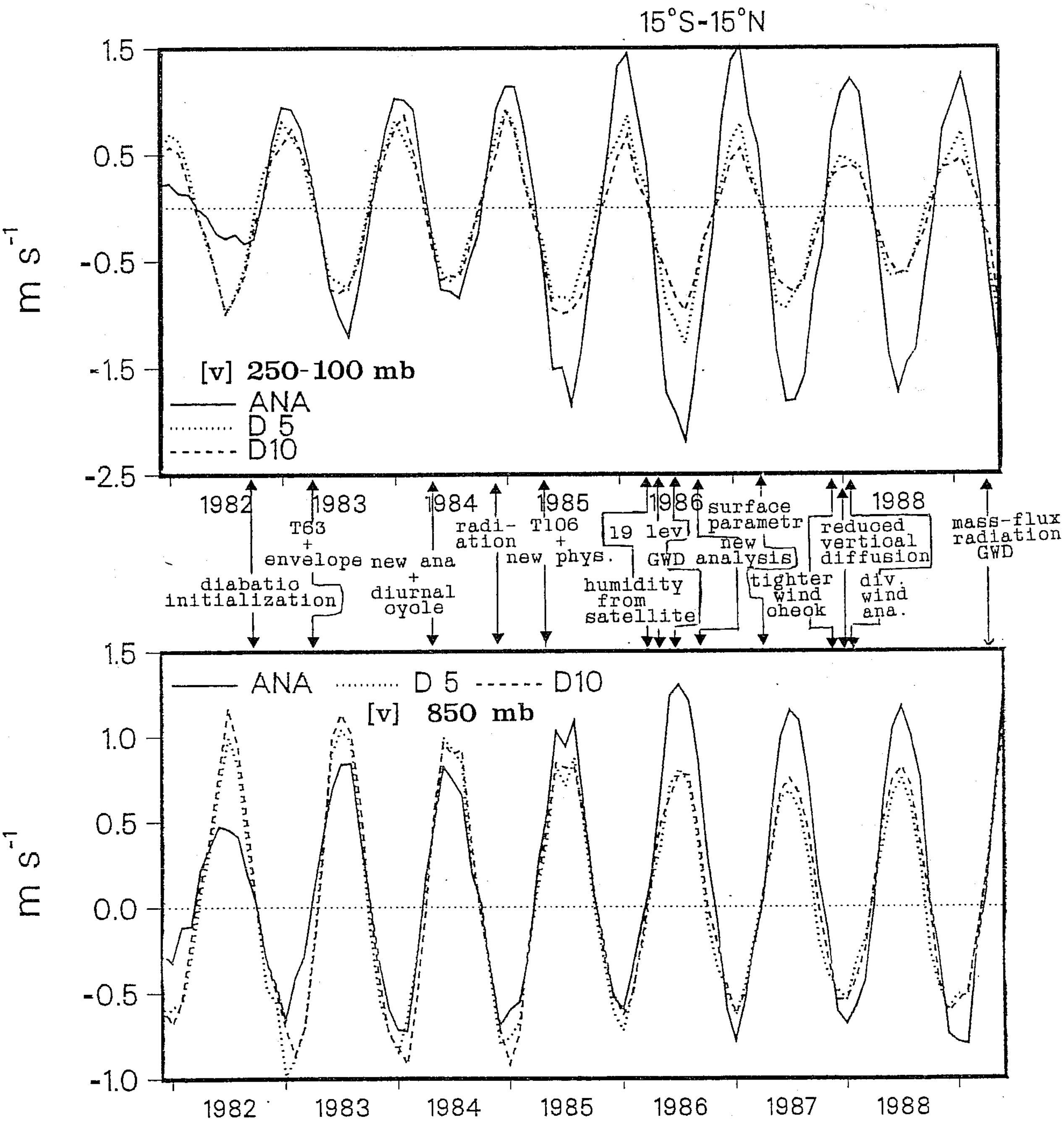


Fig. 10: Variability of the mean meridional wind (monthly averages) between 15°S and 15°N since December 1981. Forecasts and analyses are compared for the upper troposphere (250-100 mb) and for the lower troposphere (850 mb). Ticks on the abscisse indicate Januaries.

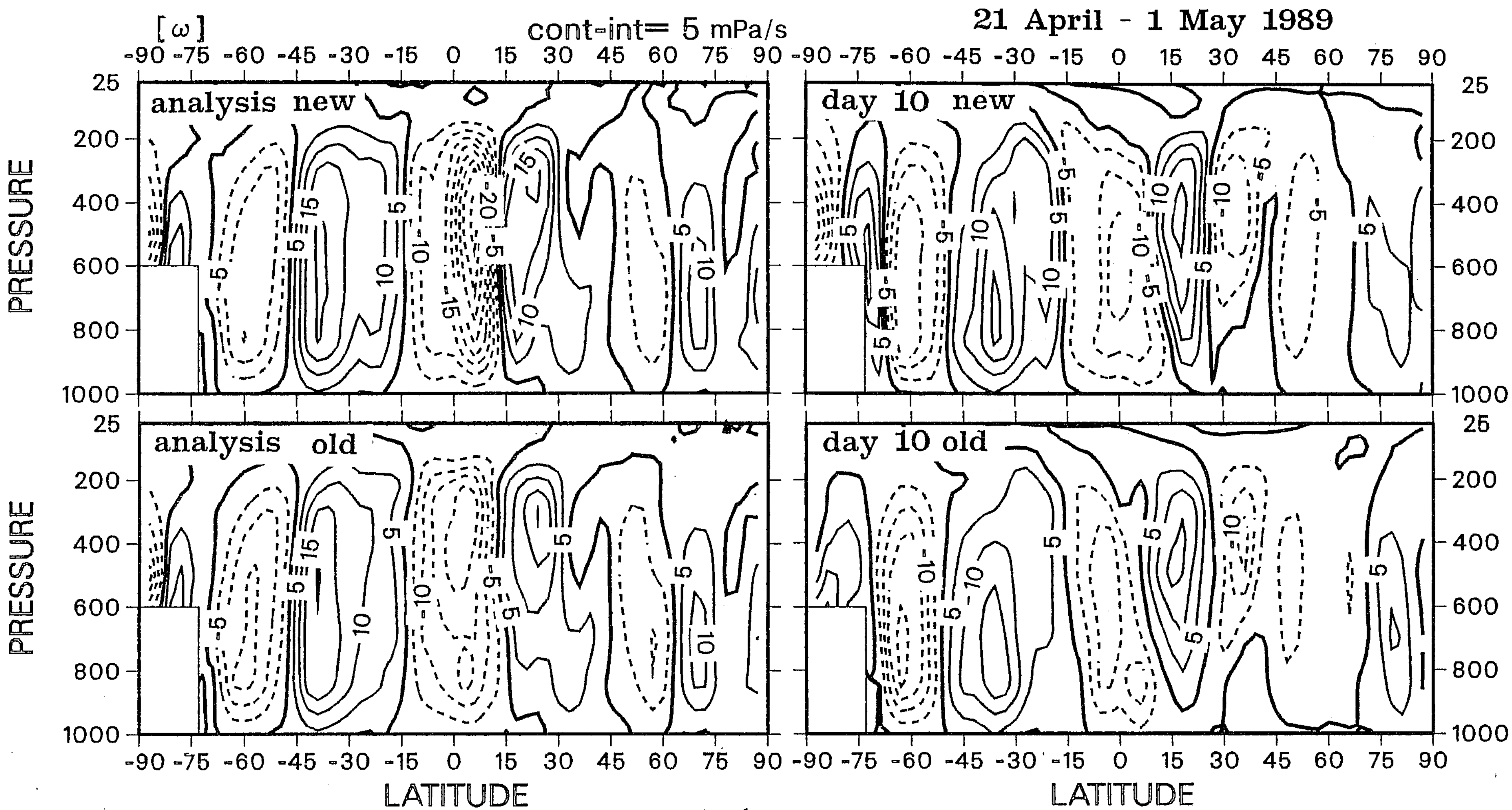


Fig. 11: Zonal mean vertical velocity ($\frac{dp}{dt}$) for the parallel run between 19 April and 1 May 1989 (mean of 13 cases). Contour interval: 5 mPa/s. Left panels: analyses; right panels: day 10 forecasts; upper panels: new scheme; lower panels: old scheme.

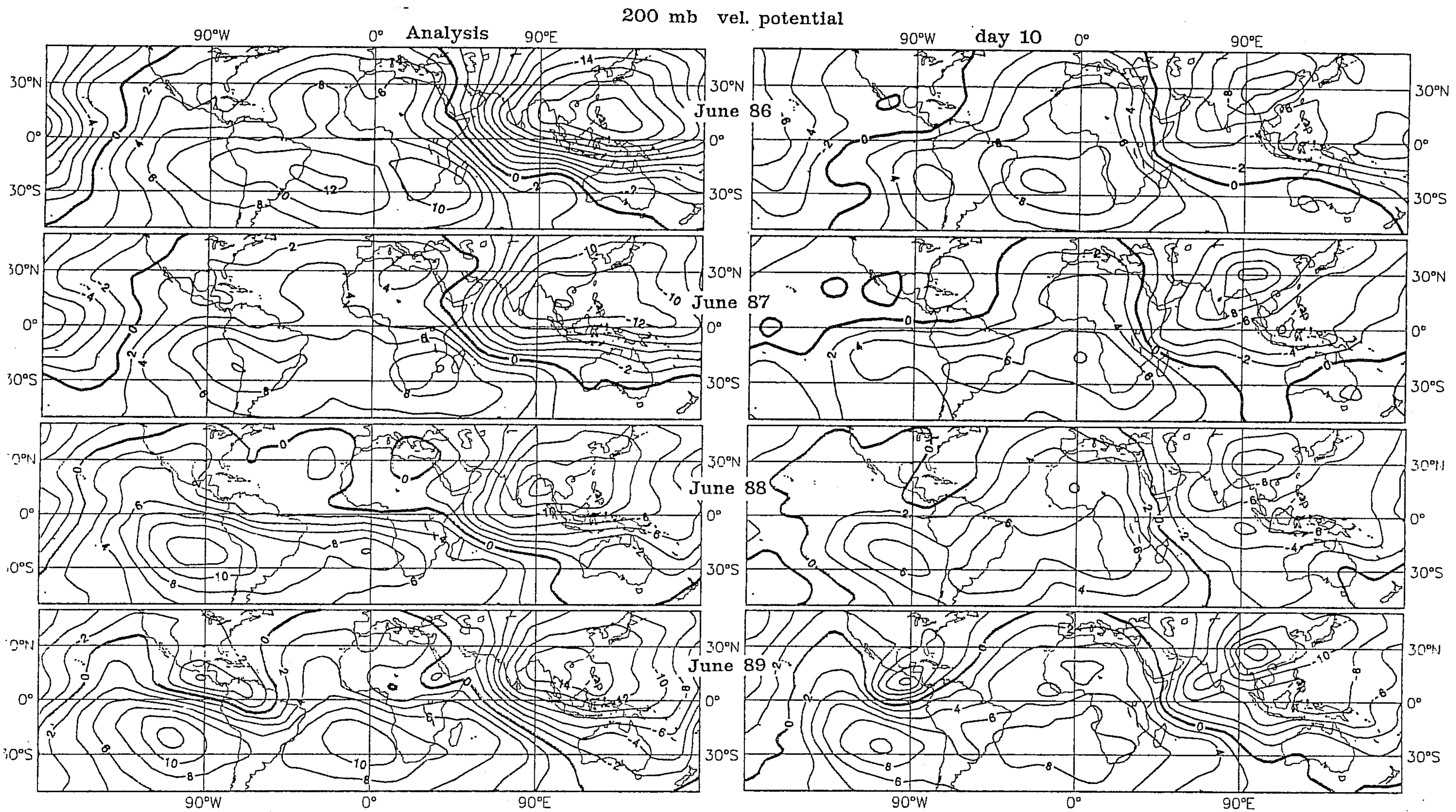


Fig. 12: Velocity potential during June at 200 mb in the analyses as well as the day 10 forecasts during 1986, 1987, 1988 and 1989. Contour interval: $1x10^6$ m/s^2. Left panels; analyses; right panels: day 10 forecasts.

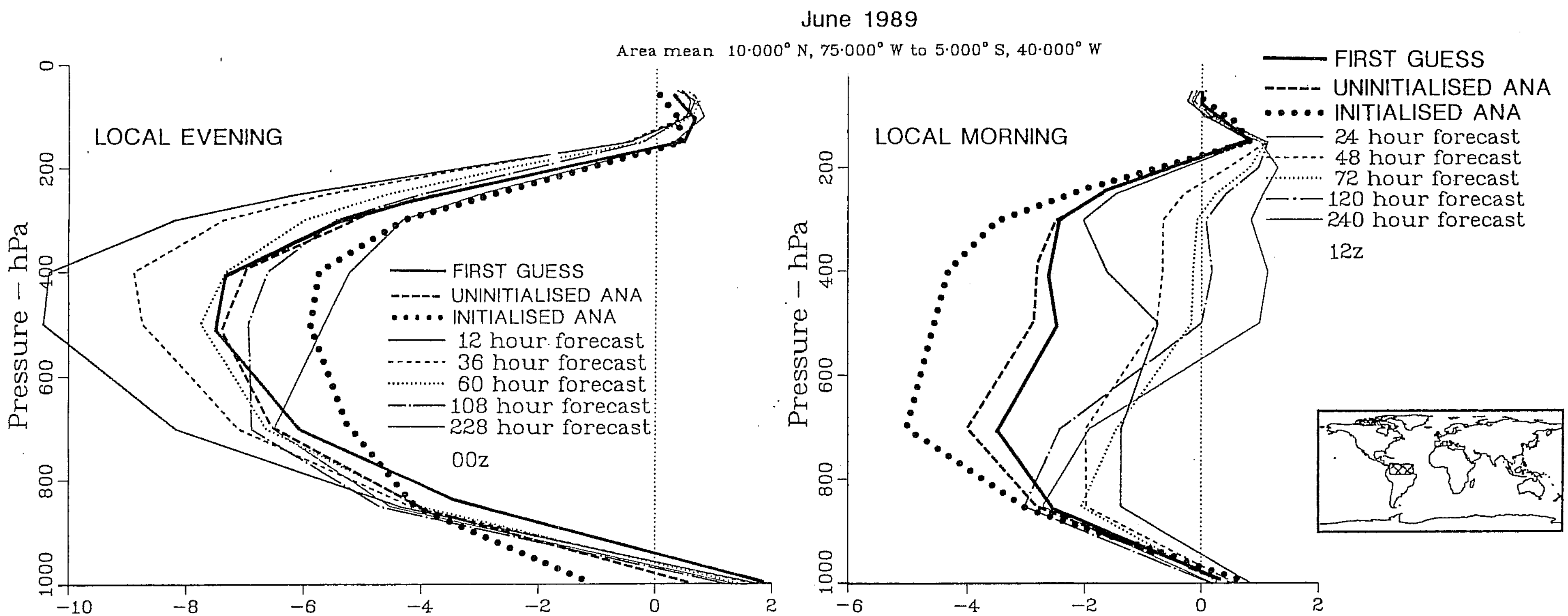
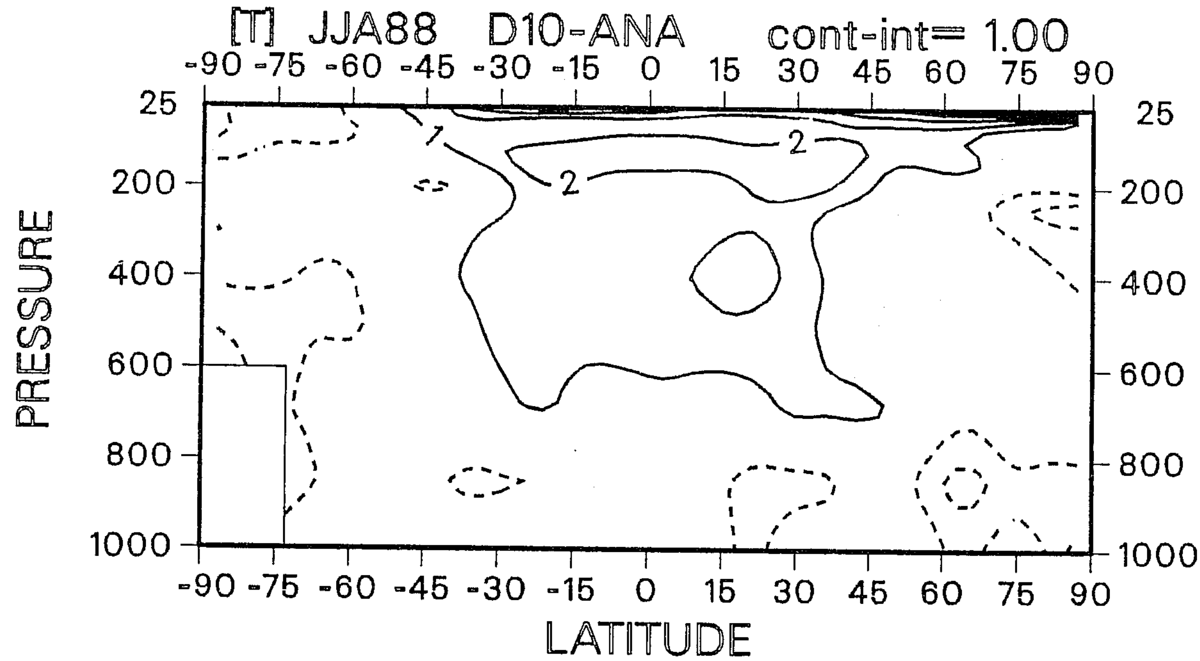


Fig. 13: Vertical profiles of vertical velocity over northern South America (5°S-10°N, 75°W-40°W). Initialized and uninitialized analyses as well as first guesses and forecasts of different ranges are compared for 00 UTC (left panel) and 12 UTC (right panel).



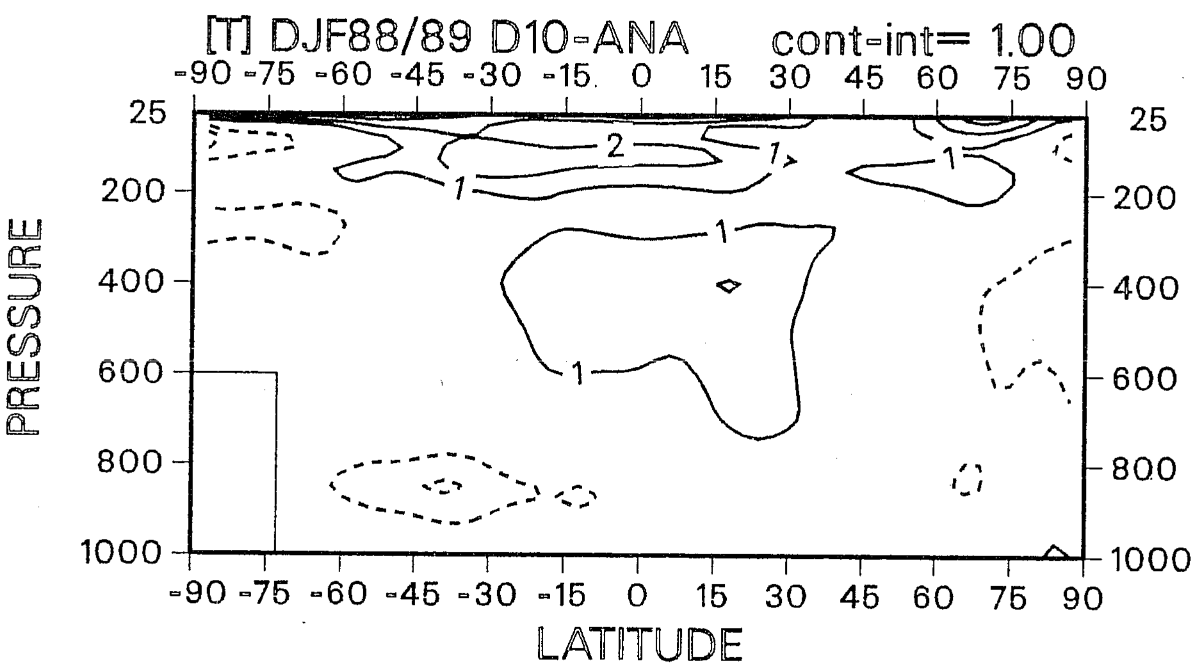


Fig. 14: Day 10 forecast error of zonal mean temperatures during DJF 88/89 (lower panel) and JJA 88 (upper panel). Contour interval: 1 K. The zero line is suppressed.

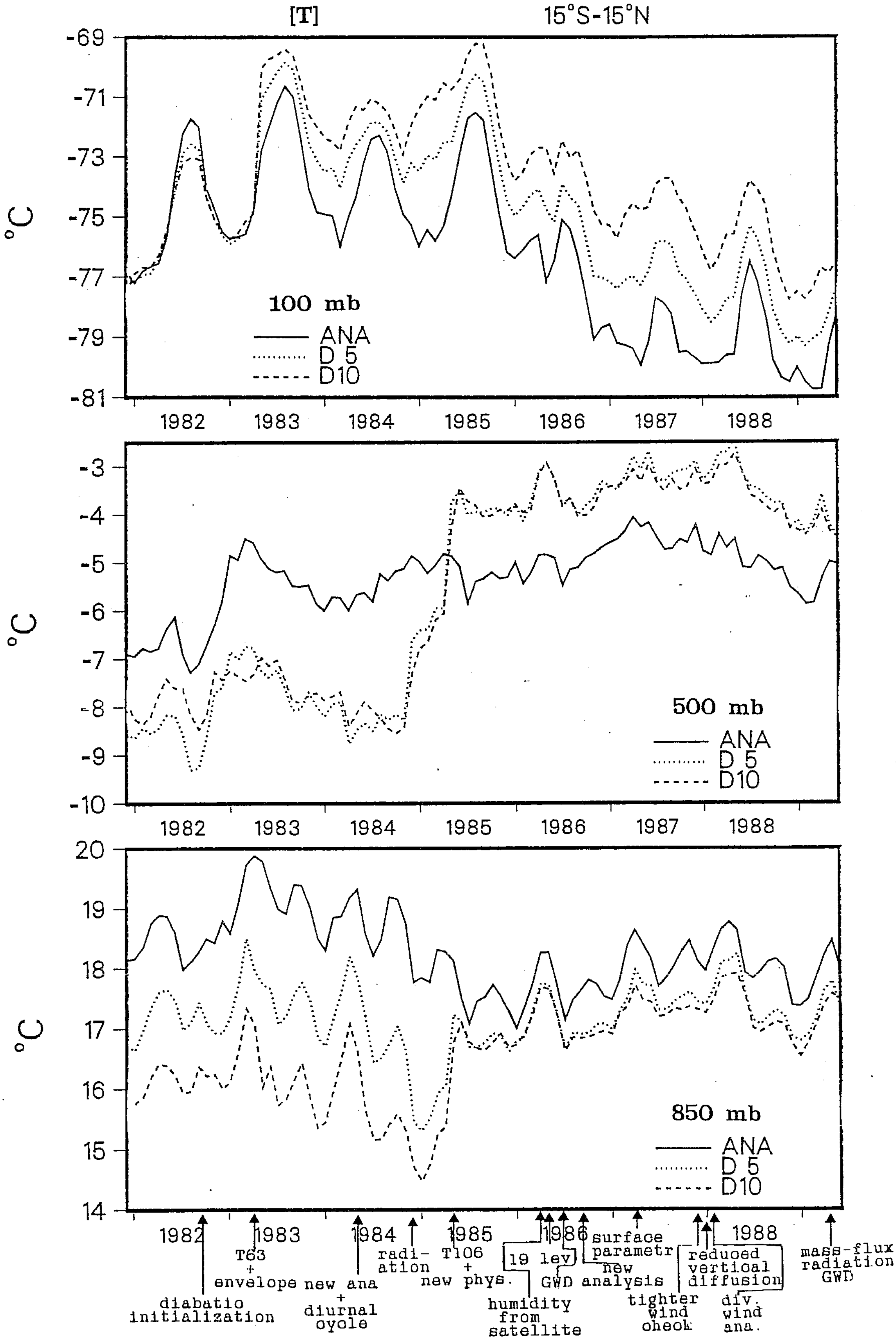


Fig. 15: Zonal mean temperature in the tropics (15°S-15°N) in the analysis, the day 5 and day 10 forecast at 850, 500 and 100 mb. Values represent monthly means. Ticks on the abscisse indicate Januaries.

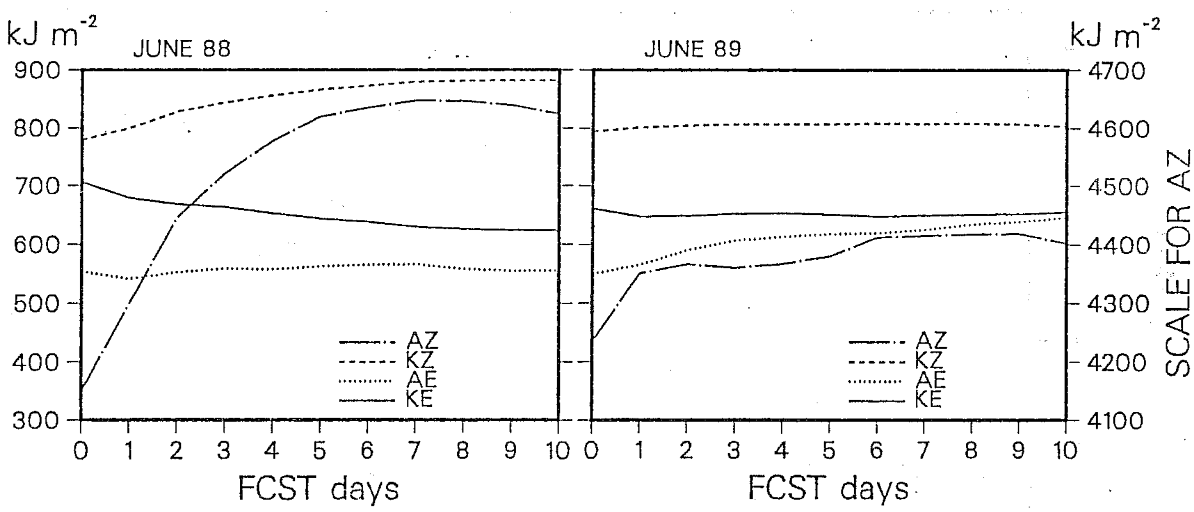


Fig. 18: Global averages of energy amounts during the course of forecasts in June 1988 and June 1989.
KE = eddy kinetic energy AE = eddy available potential energy
KZ = zonal kinetic energy AZ = zonal available potential energy.
Scale on the left refers to KE, AE and KZ while the scale on the right refers to AZ.

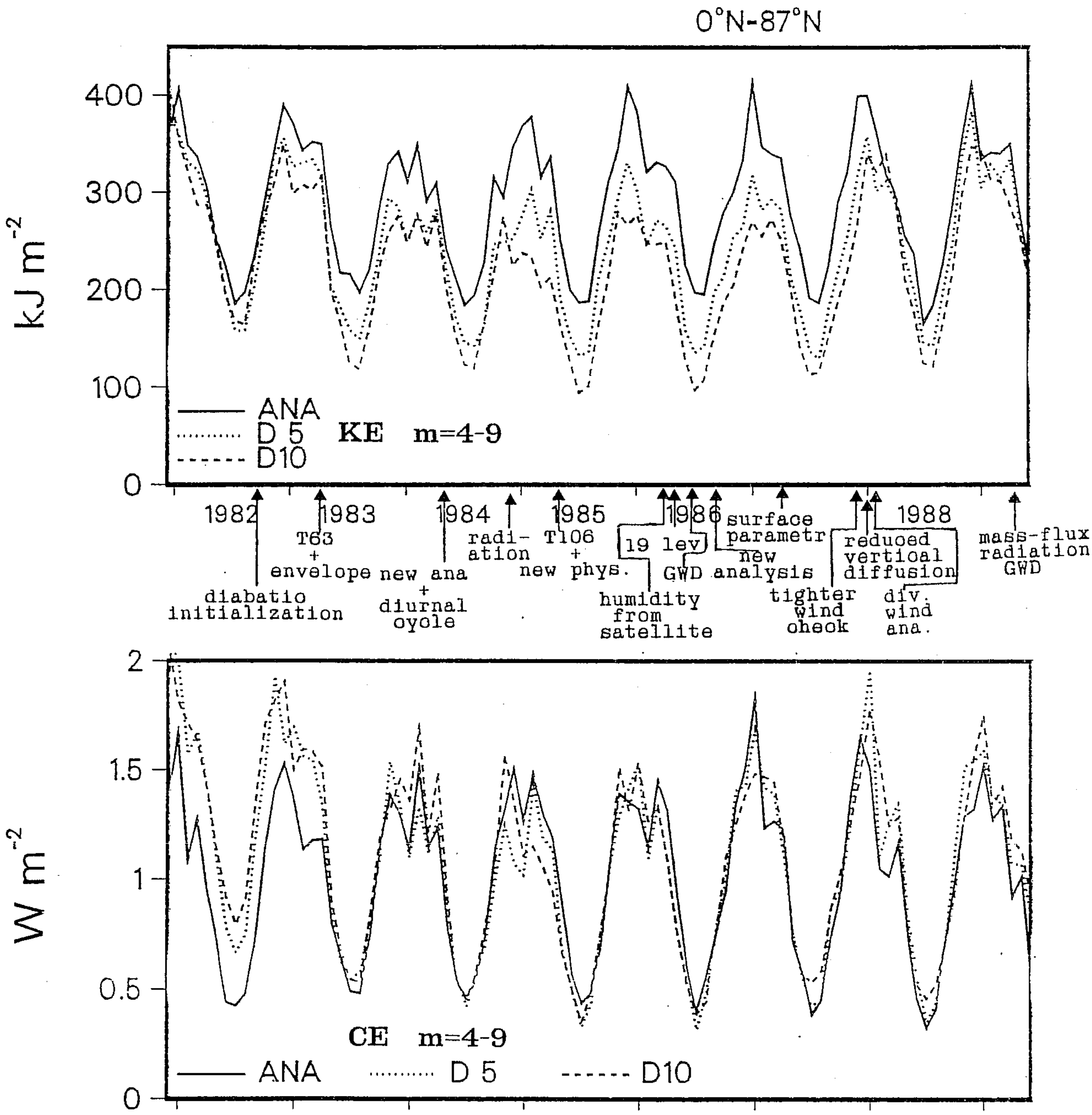


Fig. 19: Northern hemisphere mean eddy kinetic energy by synoptic (zonal wavenumbers 4-9) scale waves in the analyses, the day 5 and day 10 forecasts (upper panel) and the conversion from eddy available potential energy to eddy kinetic energy (lower panel). Values represent monthly means. Ticks on the abscisse indicate Januaries.

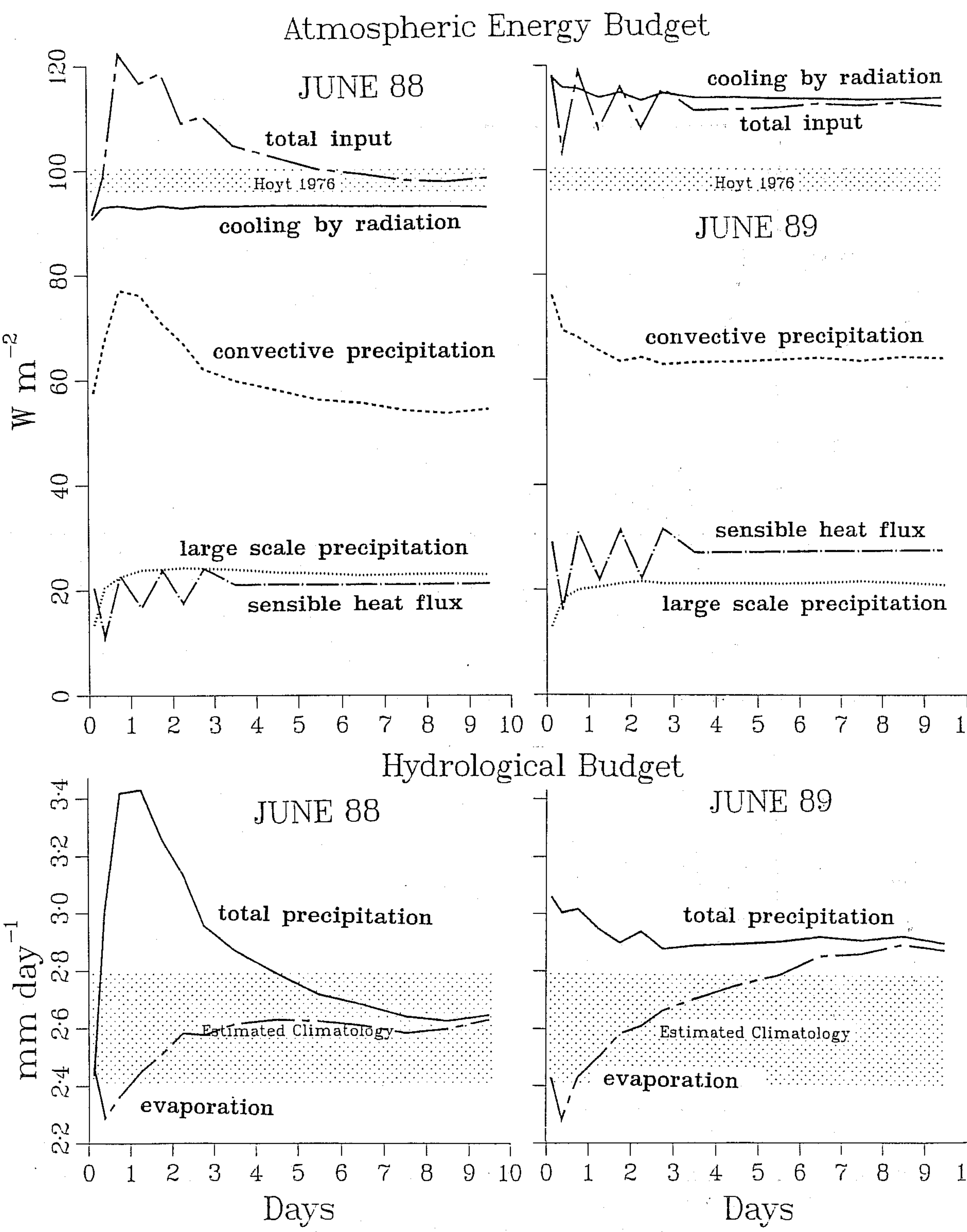


Fig. 20: Global budgets of latent and sensible heat during the course of forecasts in June 1988 and June 1989. Estimated climatological values of net radiative cooling and evaporation by Hoyt (1970) are indicated by stippled areas.

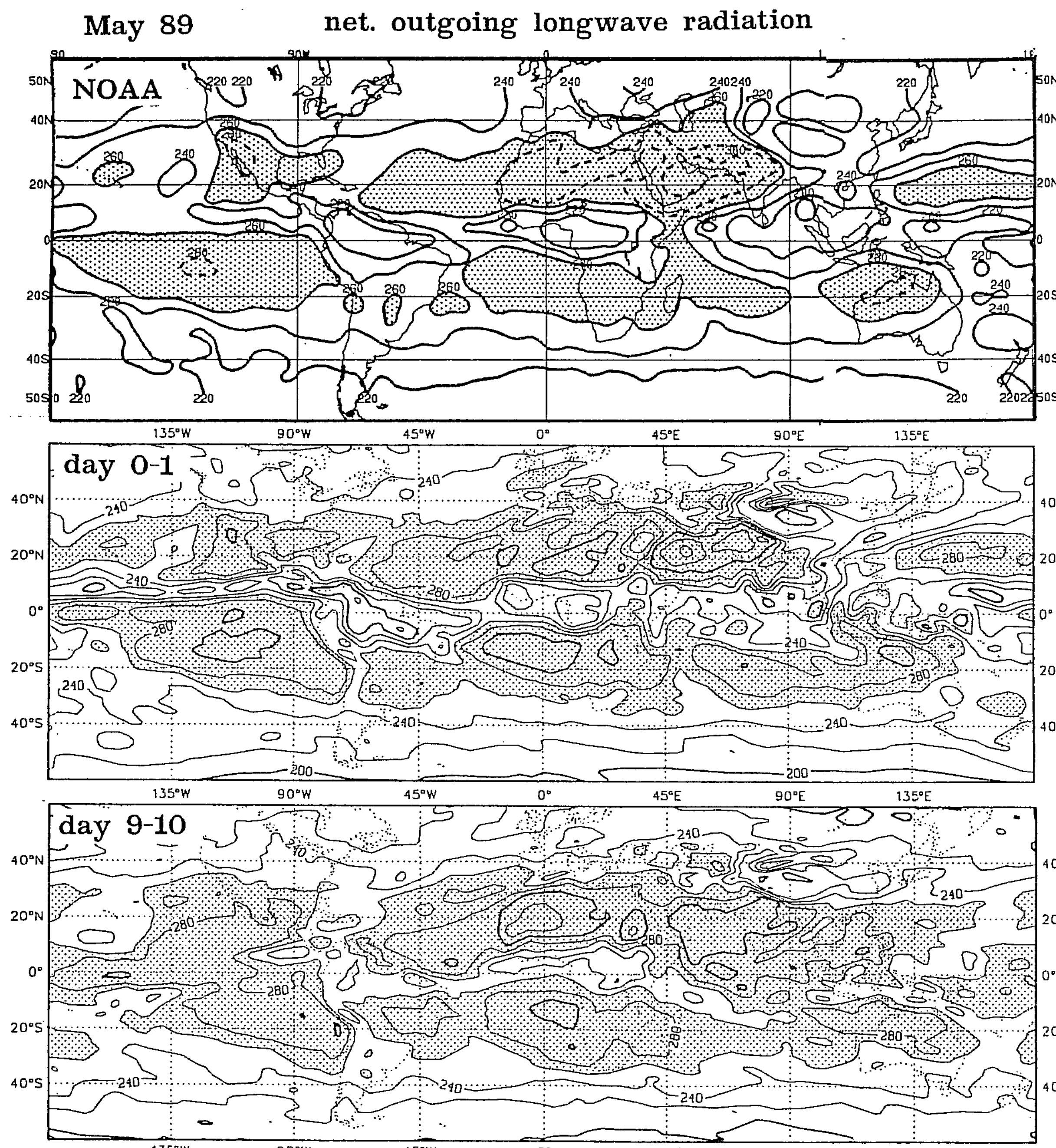


Fig. 21: Net outgoing longwave radiation during May 1989 as observed by NOAA (1989) from satellite and in the day 0-1 and day 9-10 forecasts. Contour interval: 20 W/m²; areas with more than 260 W/m² are shaded.