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ZONAL DIAGNOSTICS OF THE ECMWF 1984 - 85 OPERATIONAL ANALYSES AND FORECASTS

by

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CONTENTS

1. INTRODUCTION

Various zonally averaged meteorological parameters (zonal mean diagnostics) are extensively used to assess the performance of analyses and forecasts of the atmospheric flow. In a relatively simple and straightforward way they give condensed information about either the instantaneous state of the real (analysed) atmosphere or the model atmosphere. When averaged over a sufficiently long period of time they define climatological properties of analysis or forecast. Moreover, the time averaged zonal diagnostics is very useful in displaying systematic differences between forecast and analysis, which can be investigated further by other diagnostic means.

The classical zonal diagnostics studies have been based on radiosonde data (e.g. Oort and Rasmusson, 1971; Newell et al., 1972, 1974; Oort, 1983). One of the shortcomings of such an approach is the unreliability of the analysis in the data sparse areas. Sophisticated analysis and data assimilation systems incorporate into the zonal diagnostics an immense amount of additional data from e.g. satellites, aircraft, buoys, etc., and many earlier data gaps are filled. However, these analysis systems are very often dependent on forecast models, which provide the first guesses and therefore analyses might be model biased. Moreover, the analysed fields might be smoothed to some extent by the initialization procedures. Oriol (1982) compared the zonally averaged energy budgets based on one year of the ECMWF analyses and found that they are in a good agreement with the results from earlier studies. Arpe et al. (1986) found that global integrals of kinetic and available potential energy have a smaller annual variability than estimated in some studies. They also demonstrated the existence of differences between energetics calculated from various data streams, i.e. from uninitialized analysis, initialized analysis, first guess and 12-hour forecast.

This paper can, in a way, be viewed as a continuation of Oriol's study. Zonal mean diagnostics of both ECMWF operational analyses and forecasts for the years 1984 and 1985 are presented. In contrast with Oriol (1982), more attention is paid to the basic fields, though the energetics are discussed as well. These two years are characterized by a number of changes introduced into the ECMWF operational analysis/forecast system. The paper highlights the positive impact of the changes on reduction of the model systematic errors and also draws attention to still existing and newly emerged problems as they have been revealed by the zonal diagnostics.

The data used were monthly and seasonal zonal mean quantities, averaged from routinely calculated daily diagnostics (see Oriol, 1982). The presentation will mainly be in a form of meridional cross-sections or time evolutions during the course of averaged ten day forecasts or of long series of analyses. Both zonal averages and mean variances along latitudinal circles will be shown. Contributions from various wavenumber groups are presented as well.

The monthly averages have statistical significance. However, the largest period between two subsequent major changes is only seven months and is therefore too short to show how a particular modification influences the model climate in terms of seasonal variability. On the other hand a change in the forecast model usually means a change in the assimilation model. Thus, before comparing the forecast for, say, the same month from two different years, the analyses should be compared in order to determine whether any significant change in analysed fields has taken place. In other words, errors in the forecast with a modified model will not only be reflected in the performance of the model itself but also in the analysis. These secondary effects could conceal some subtle impacts of the model major changes. However, as will be demonstrated, most of the effects of the modifications in the model are usually anything but subtle.

It is first necessary to have some idea of the natural interannual variability; some idea of this can be obtained by comparing the analyses for a particular month over several years. As the model is continually changing the variability will be part model and part naturally induced; it is not possible to separate wholly the two, but relatively large changes from one year to the next are likely to be model induced.

Changes in the system do not affect a single parameter or a single field alone. Some parameters are more or less directly influenced by a particular modification, but most of them are affected indirectly through a variety of physical and dynamical processes. On the other hand some of the modifications have differing impacts in different parts of the globe. Therefore it is difficult to define or to chose a single quantity which may be sensitive enough to detect impacts of all modifications. Experience shows that some of the basic fields are more sensitive to system changes than others. In particular this is the case with vertical velocity ω and temperature T. Sometimes the horizontal wind field might also be included, though, generally the impact in the temperature field is associated with an impact in horizontal wind. Humidity shows more inert behaviour.

We shall discuss the impact of the changes on the analysis and describe the differences (if any) between the forecasts and verifying analyses as found by the zonal diagnostics. In the following Section a brief account of the changes introduced during 1984 and 1985 is given. Section 3 deals with the impact of the changes on the analysis and Section 4 with the impact of the same changes on the forecast. Some of the forecast energy terms are discussed in Section 5. Concluding remarks are in Section 6.

It is hoped this study would shed more light on the effects both on analysis and forecast caused by changes in the analysis/forecast system. Also, it can be useful for some of a large number of users of the ECMWF products (e.g. for the FGGE community). As pointed out by Kanamitsu (1985) for predictability studies, it would be desirable to repeat this type of study each time a major change in the analysis/forecast system takes place.

2. CHANGES IN THE ANALYSIS/FORECAST SYSTEM IN 1984-85

During 1984 and 1985 several changes in the ECMWF analysis/forecast system took place. Some of them were major changes, such as re-formulations of dynamical and/or physical processes in the analysis/forecast system, which differed considerably from previous formulations. Besides these major modifications, some minor changes were made. From a number of changes within the latter group, only those which might have a noticeable effect either on analysis or on forecast are extracted. Chronologically, the changes which we consider are as follows:

(a) March 1984 The model horizontal diffusion was increased (reduced again in May 1985).

(b) May 1984 Diurnal cycle was introduced into the model.

(c) May 1984 The analysis was subjected to extensive revisions.

(d) July 1984 Correction to the moisture dependence of specific heat was introduced.

(e) December 1984 A modified radiation scheme and stratospheric drag were introduced.

(f) May 1985 The new T106 model became operational together with revised parameterization of convection and new representation of cloudiness.

The major changes are those listed under (b), (c), (e) and (f).

A brief description of the reasons for the changes in the analysis/forecast system, the changes themselves and the results of trials following their introduction are given in the following subsections. For most of the minor modifications the existing documentation is mainly in a form of internal memoranda and therefore not widely available.

(a) Enhanced horizontal diffusion on divergence (March 22, 1984 to May 1, 1985)

Operational experience with the spectral model revealed that in some extreme synoptic situations a spurious wavetrain of intense vertical velocity is developed. These situations have been identified as particulary strong jets or horizontal gradients of temperature and/or wind and very intense convection. An increase of diffusion on the divergence field proved to be sufficient to cure the problem. It had little impact on overall forecast quality, and was regarded as a temporary solution.

(b) Diurnal cycle (May 1, 1984)

A more realistic simulation of physical processes near the surface, a reasonable forecast of surface temperature range and a better first guess for the analysis were amongst the main objectives for introducing the diurnal cycle. A proper representation of the diurnal cycle also serves as a better framework for improvement of parameterization schemes.

The diurnal cycle was introduced through a variation in the local solar angle. In addition, an extra soil layer was added with reduced heat capacity so as to allow a realistic diurnal variation of soil temperature. The impact of the diurnal cycle on the forecast scores during the testing period was found to be small.

(c) Revisions to the analysis (May 22, 1984)

An extensive evaluation of the performance and properties of the data assimilation system and accumulated comprehensive statistics provided the basis for the following revisions in the analysis scheme (Shaw et al., 1984): revision of the data selection and data usage, revision of the optimum interpolation statistics, revision of the quality control criteria and revision of the method of analysing geopotential height in the upper levels.

One change was to disregard the land SYNOP winds and to abandon the extrapolations of the multi-level data. This has led to an analysis of surface pressure which fits the observations more closely and removes undesirable errors in the wind-field analysis.

Statistical properties of the observational errors, the rms first guess errors and the spatial correlations have been reviewed and revised using the assimilation statistics data base. The most dramatic change was a substantial increase in the ascribed rms error for PAOB data. SATOB errors have been reduced to have a greater impact in the analysis. TEMP geopotential errors were reduced in the troposphere and stratosphere and wind errors were increased in the lower troposphere. The ascribed first guess rms error estimate is reduced to be consistent with the predictive skill of the then current ECMWF model. The vertical correlations are separated into barotropic and baroclinic contributions.

Tolerances for quality control, which have been derived on the basis of revised optimum interpolation statistics, are, generally, tightened. A better fitting of the observed values was achieved by replacing the analysis of geopotential in the two upper slabs by an analysis of geopotential thickness. This means that the near-surface data are allowed to have an influence on the geopotential structure without the data being explicitly used.

Substantial gains have been made in the quality of the analyses as a result of the above revisions.

(d) Moisture dependence of specific heat (July 24, 1985)

An inconsistency in the application of the treatment of moisture terms in parameterization was found and subsequently corrected. Test results show only a very small impact on overall forecast quality. However, zonally averaged temperature deviation from analysis for the second half of the forecast reveals a significant reduction (about 2 degrees) in the erroneous warming near the tropical and subtropical tropopause.

(e) New radiation and stratospheric drag (December 4, 1984)

Some conceptual weaknesses in the radiation scheme, such as excessive cooling rates in the layers with small amounts of cloud and unrealistic treatment of upper tropospheric clouds, stimulated a different approach to the treatment of gaseous effects in the longwave radiative transfer. The new scheme incorporates gases directly in the solution of the corresponding broadband transmission function in a series of exponentials allowing the determination of 'pseudo-grey' gaseous absorption coefficients (Ritter, 1984; Slingo and Ritter, 1985). Experimentation with the new scheme shows that the greatest impact is found in the middle troposphere, particularly in the tropics, where a negative temperature bias is reduced. Wind errors are also reduced, though not as much as temperature errors. The predicted Hadley circulation is stronger when the new scheme is employed.

During the course of extended integrations an exaggerated polar night jet develops. It is caused by a coarse stratospheric resolution and a positive feedback between the enhanced zonal mean wind and the supression of planetary waves in the stratosphere, which account for the bulk of meridional energy transport in these layers. A weak drag applied in the two uppermost model layers has proved sufficient to cure the problem. The stratospheric drag has no significant impact on the forecasts.

(f) T106 model and revised parameterization (May 1, 1985)

The availabilty of the Cray X-MP/22 computer enabled an increase in the model spectral resolution to T106 (triangular truncation at total wavenumber 106) for upper-air fields, and consistently, an increase in the resolution of surface fields. The latter includes an envelope spectrally fitted orography which has been created from the mean orography by adding one standard deviation of the sub-grid scale orography. The horizontal diffusion was modified as well to enhance stability and allow use of a longer time step. For a detailed account of the above modifications the reader is referred to Jarraud et al. (1985).

Relatively large forecast errors in the tropics and subtropics are partially due to erroneous diabatic forcing in the pre 1985 versions of the model. A significant effort has been made to diagnose this forcing and to improve the parameterization of diabatic processes. Thus, substantial changes to the physical parameterization were made and they include revisions to the parameterization of convection (shallow convection and modified deep convection) and a new representation of cloudiness (Tiedtke and Slingo, 1985).

A number of experiments including both sets of changes was carried out and, generally, a positive impact on the forecast was found. In particular, there is an enhanced moisture supply from the surface to the PBL in the tropics. The tropical diabatic forcing leads mostly to an increase in temperature due to additional heat release which is related to a larger meridional transport of moisture (and therefore increased precipitation). The model's tendency to cool the tropical and subtropical troposphere is removed and the forecast of tropical zonal mean wind is improved. An intensification of vertical motion in the area of anticyclones is also apparent. There is an increase in the generation of zonal available potential energy due to tropical diabatic heating and an increase in conversion of eddy energies.

The revised parameterization has, through the shallow convection, a particular influence on a better distribution of the analysed humidity. The shallow convection deepens and dries the planetary boundary well mixed layer and intensifies the vertical transport of heat and moisture.

3. IMPACT ON THE ANALYSIS

The model changes described in the previous Section have an impact on the analysis through the first guess field. It seems suitable, therefore, to consider only the impact on the analysis of the more significant model changes. Some preliminary idea how a particular modification in the model affects the forecast can be obtained from the pre-operational trials. The change listed under (d) is regarded as having a little impact on the analysis. Other changes will be considered in chronological order. Impacts on some of the basic fields, i.e. temperature, horizontal wind components, vertical velocity, geopotential and humidity, will be shown first. Any difference in the energetics, when compared with the earlier analyses, will be presented too.

3.1 Enhanced horizontal diffusion on divergence

The increased diffusion has been tested in a several data assimilation experiments and results show much lower level of noise in the vertical velocity, ω, and horizontal wind fields when compared with the operational cases in which the noise occurs. The diffusion acts on the divergent wind and its effect on the vertical velocity can be seen as a direct consequence. We shall examine the impact of the increased diffusion on the ω-variance, because the variance is often more sensitive to the changes than the zonal average.

It would be desirable to examine the extratropical ω-variance since its magnitude is proportional to the eddy activity. However, the increased diffusion was introduced into the model on 22nd March 1984, i.e. in the transition season when the northern hemisphere eddies tend to diminish their activity. Thus, any expected reduction of the ω-variance due to increased diffusion may coincide with the seasonal trend of decreasing the northern hemisphere ω-variance.

Similarly, the southern hemisphere eddies have just reached their minimum activity in January. If they fail to show an increase in the ω-variance immediately thereafter, this may still be explained by the natural variability. Therefore, it seemed more appropriate to concentrate on the tropical ω-variance which is subject to a very small seasonal changes.

Fig. 1a shows a time series of monthly averaged 00Z analyses for the tropical upper troposphere area mean ω-variance. There is a sharp drop from March to April 1984 in waves with the wavenumber greater than 15. This decrease can be traced back before March. It can be explained by the fact that about one third of the analyses in March were affected by the increased diffusion. The longer waves are not affected much, though a reduction in the ω-variance magnitude can be seen. A similar behaviour in the short waves can be noticed in the extratropics of both hemispheres, but with a less intense damping (not shown). Therefore a certain care is required when comparing analyses of the smaller scale features before and after March 1984, especially those associated with the vertical velocity.

The conversion of eddy available potential energy to eddy kinetic energy, CE, which depends on the covariance between vertical velocity and temperature, is also, to some extent, affected by the increased diffusion. The northern hemisphere annual cycle of the CE calculated from the six-year data (Arpe et al., 1986) shows clearly less steep decrease from January to August and steeper increase thereafter. In Fig. 1b, however, a sharp drop from February to March 1984 can be seen, and it could be partly explained by the effect of increased diffusion. In the southern hemisphere the impact is not so obvious because the CE tends to rise relatively slowly in the first half of the year.

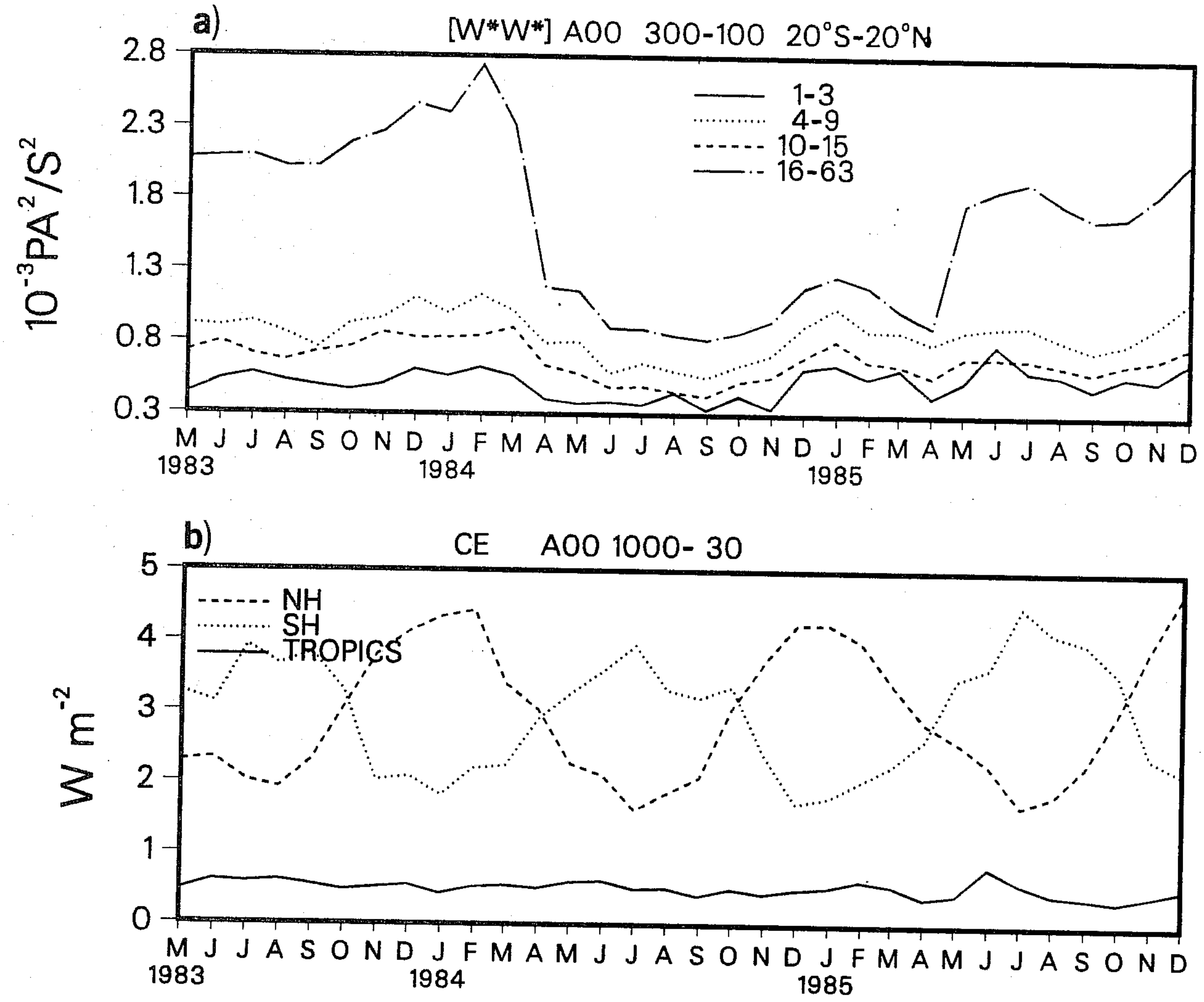


Fig. 1 Time series of monthly mean 00Z analyses for a) tropical ω-variance averaged beetwen 300 and 100 mb, and b) conversion of eddy available potential to eddy kinetic energy integrated between 1000 and 30 mb.

Other energy conversion terms which, among some other factors, depend on variability of the ω-variance, i.e. barotropic conversions from zonal available potential energy and from zonal kinetic energy to their eddy counterparts, CA and CK, are not affected so much by the modified diffusion. They depend mainly on other variables than the ω-variance, i.e. eddy temperature and eddy momentum flux respectively.

3.2 Diurnal cycle

The effects of the diurnal cycle might be expected mostly in the tropical and subtropical contineta1 regions and near the surface and in the lower troposphere. The most likely parameters to be affected are the near-surface fluxes. These effects have a strong longitudinal variability (or dependence) which may be reduced or even cancelled in the zonal mean. Thus, the impact of the diurnal cycle, as it might be revealed by the zonal mean diagnostics, on the quantities mentioned above is not as obvious as it is for other changes introduced in the analysis/forecast system.

However, some idea about an overall impact of the diurnal cycle on the analysis can be obtained from Fig.2. It shows the monthly mean diurnal cycle of the northern hemisphere tropical and subtropical variance of specific humidity, q, for four selected months at the two lowermost levels. The diurnal cycle was introduced into the operational model on 1st May 1984. The two successive months, April and May 1984, are chosen because they represent analyses without and with diurnal cycle, and because a relatively small seasonal variability between these two months in the tropical and subtropical regions can be assumed. The similarity between the same months in 1983 and 1984 shows that there was no great interannual variability.

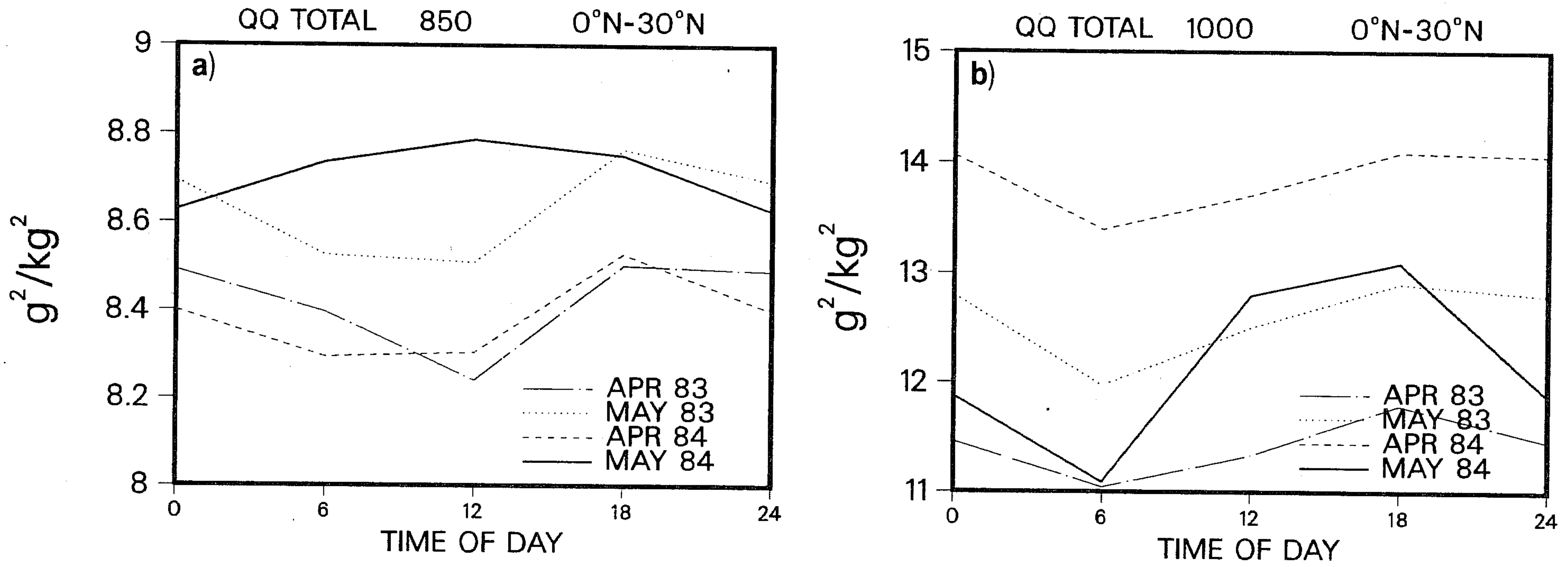


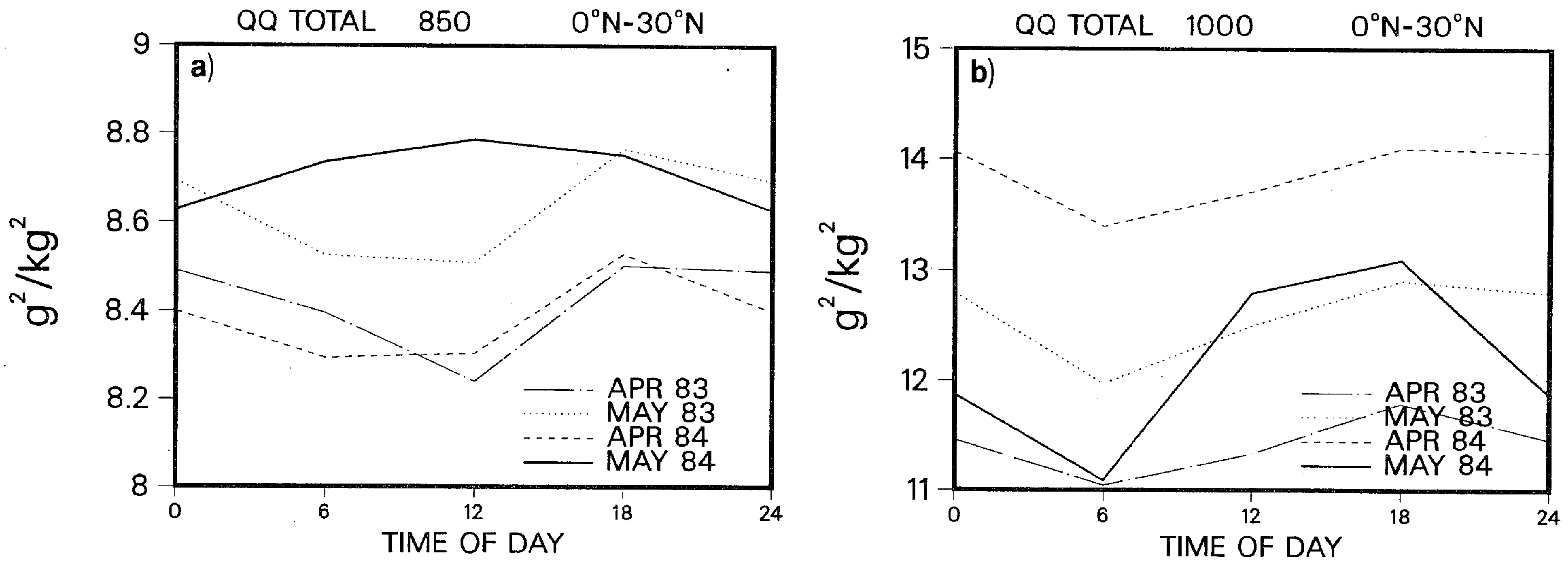
Fig. 2 Monthly mean analysed diurnal cycle of specific humidity variance between 0°N and 30°N for a) 850 mb, and b) 1000 mb.

From Fig. 2a it is obvious that the introduction of the diurnal cycle caused a change in trend of the May 1984 q-variance between 00Z and 18Z at 850 mb. The higher values of q or moistening at 06Z and 12Z in May 1984, when compared to April 1984 (and May 1983), can probably be associated with the increased transport of humidity due to a stronger lower-level fluxes over the continents. The latter can be indirectly confirmed by inspecting Fig. 2b, which shows drying from April to May 1984 at 1000 mb, whereas the opposite tendency in 1983 can be seen. This change is especially marked at 06Z analyses, i.e. at early morning over eastern Africa and late morning over India. The levels above 700 mb do not exhibit such a change; it could be said, even more generally, that as far as the zonally averaged quantities are concerned the free atmosphere is not affected significantly by the introduction of the diurnal cycle.

3.3 Revisions to the analysis

The revisions to the analysis scheme were introduced on 22nd May 1984 and therefore the May 1984 monthly mean data cannot be used to evaluate the impact of these revisions. To get an impression of what the impact of the revisions on the analysis might be, the 12Z analyses of the zonal mean temperature, [T], over a period of six months from June to November are averaged for years 1983 and 1984, i.e. prior to the introduction of the modified radiation. The averaging was performed to eliminate month-to-month variations. It was assumed here that we can speak about the impact of the revisions to the analysis only, since, as mentioned above, the effect of diurnal cycle on the zonally averaged data is not palpable, at least not in the free atmosphere.

Fig.3 shows the difference in zonally averaged temperature between these two periods. The greatest change can be seen in the extratropical stratosphere where 1984 is warmer by 1.5 K in the southern hemisphere and about 0.5 K in



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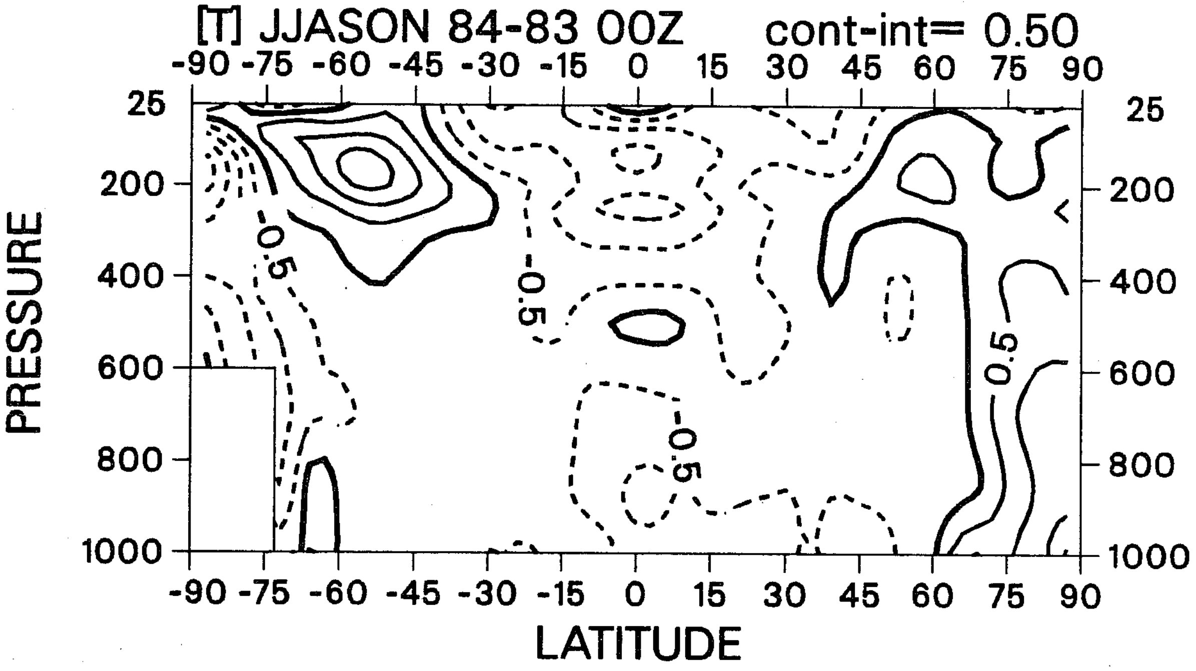

Fig. 3 Difference between 1984 and 1983 mean June to November 00Z analyses of zonally averaged temperature. Contour interval is 0.5 K. Dashed lines indicate negative difference.

the northern hemisphere. To find out whether these temperature changes owe their existence to the modifications imposed upon the system or to natural causes, we examine a six-year series of zonally averaged monthly mean temperature (Fig.4).

In the southern hemisphere stratosphere (Fig.4.a) the year 1984 was almost the coldest in the first four months, and was the warmest from June to September. The turning point coincides with the introduction of the revisions and one may hastily conclude that the trend displayed is caused by the system changes. A similar 'deviation' in the temperature behaviour can be seen in April 1980.

A detailed inspection of observed temperature for the station Casey, located on the edge of Antartica (66°S, 110°E), in the same period and for levels 200, 150, 100 and 50 mb (*) shows similar trends as those in Fig. 4a. This supports the view that the temperature behaviour discussed above was not caused (at least not completely) by the modifications in the system.

Also the warming of more than 1.0 K in the northern polar regions shown in Fig.3 is most likely the consequence of the interannual temperature variability. It can be seen from Fig. 4b that the zonal mean temperature in the slab between 850 and 500 mb in these regions is higher for most of the period June to November in 1984 than temperature in the same period of 1983. However, the 1984 temperature does not differ significantly from some previous years.

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* NOAA and WMO: Monthly climate data of the world.

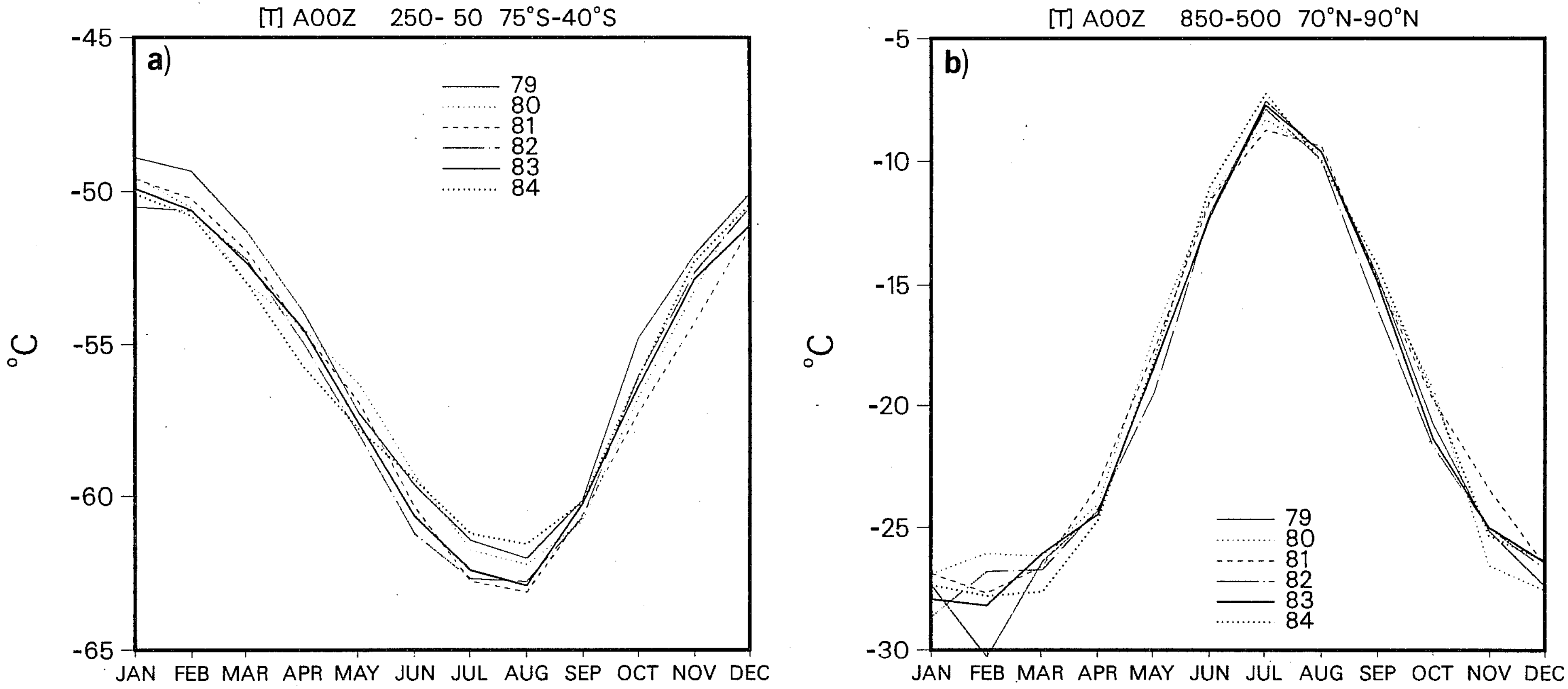


Fig. 4 Annual cycles of analysed (00Z) zonal mean temperature (degrees Celsius) averaged between a) 250 and 50 mb and 75°S and 40°S, and b) 850 and 500 mb and 70°N and the north pole.

Other parameters have also been examined, but, just as for the findings for the zonal mean temperature, no significant impact due to the revisions could be found. All the differences that emerge between the two periods in 1983 and 1984 and for various parameters are found to be within the limits defined by interannual variability.

Furthermore, no significant impact on the energetics could be seen. There is a slight decrease in the CE term for the period June to November 1984, and it can probably be attributed to the increased diffusion as discussed in Section 3.1.

3.4 Modified radiation and stratospheric drag

Since the new radiation and stratospheric drag were introduced early in December 1984, it is possible to assess their impact on the analysis by investigating the period December to February (DJF) 1984/85.

Fig.5 shows the difference between DJF 1984/85 and DJF 1983/84 of the zonally averaged temperature analysed at 00Z. The enormous difference in the northern hemisphere high-latitude stratosphere and upper troposphere is due to strong stratospheric warming in January 1985. According to Labitzke et al. (1985) January 1985 was the second warmest within the series of 30 years of data. The warming was so intense that it also affected significantly the upper polar troposphere. However, we are more concerned with the smaller differences that occur elsewhere.

A warming in the tropical mid-troposphere (Fig.5) could be at least partially explained by the interannual variability of the zonal mean temperature. In Fig. 6a vertical profiles of the zonal mean temperature differences between

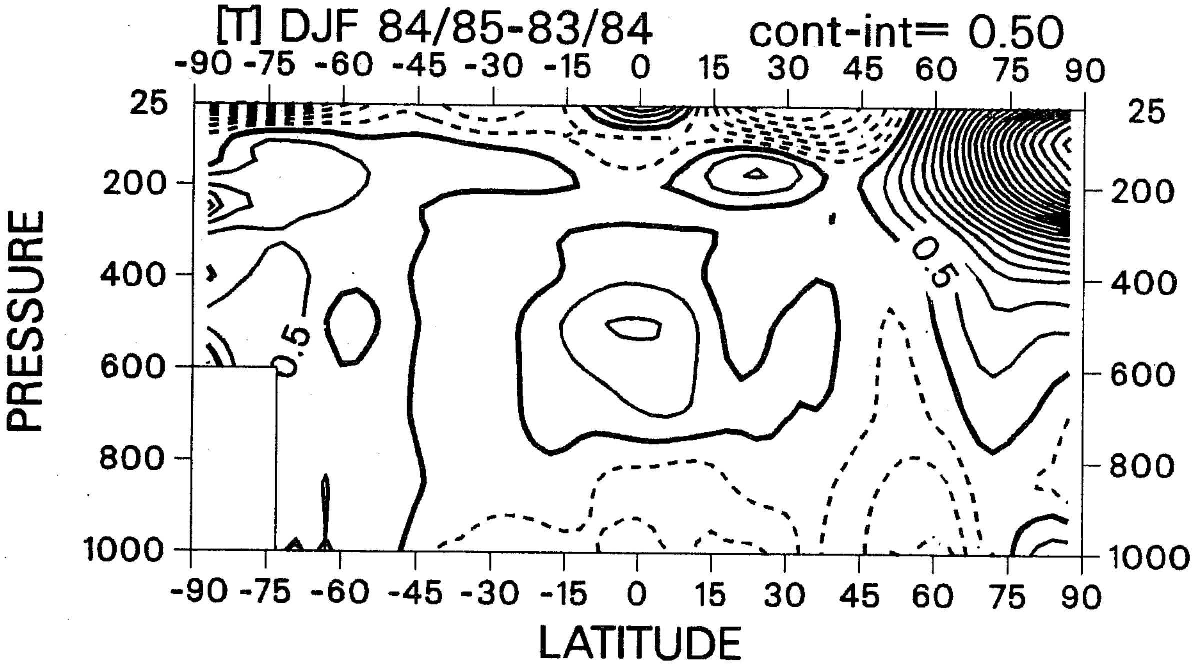


Fig. 5 Difference between DJF 1984/85 and DJF 1983/84 mean 00Z analyses of zonally averaged temperature. Contour interval is 0.5 K. Dashed lines indicate negative difference.

DJF seasons and the DJF 'climate' derived from the six-year data are displayed to enable much finer resolution on the temperature axis. The temperature departures at 500 mb in the tropical belt between 15°N and 15°S are 0.8 K in DJF 1984/85, and 0.1 K in DJF 1983/84. According to Oort's (1983) data, derived for the period from 1963 to 1973, the average DJF zonal temperature standard deviation at 500 mb in the same latitudinal belt is about 0.8 K. The 1984/85 departure is within one standard deviation, and we may assume, therefore, that the differences in the tropics shown in Fig.5 do not come solely because of the change in the radiation scheme. For 1984/85 one finds the coldest temperature at 850 mb, but again the value is within one standard deviation of the variance. A similar conclusion can be made for the differences in the tropical stratosphere.

A cooling in the northern hemisphere low-latitude stratosphere could be attributed again to the natural variability rather than to the change in the system. The 1983/84 DJF results for this part of the atmosphere were among the warmest in the seven-year period, and the 1984/85 was about the average (not shown).

In Fig. 6b vertical profiles of the DJF zonal mean meridional wind, [v], averaged between 18°N and 9°S are given. A difference in the vertical location of maxima of the upper branch of the Hadley circulation between DJF 1983/84 and DJF 1984/85 can be seen. A similar variation is also noticeable in earlier DJF seasons. Thus, the recent lowering of the [v] maximum cannot be exclusively related to the modified radiation. No plausible explanation for such a migratory behaviour of the [v] maxima was found.

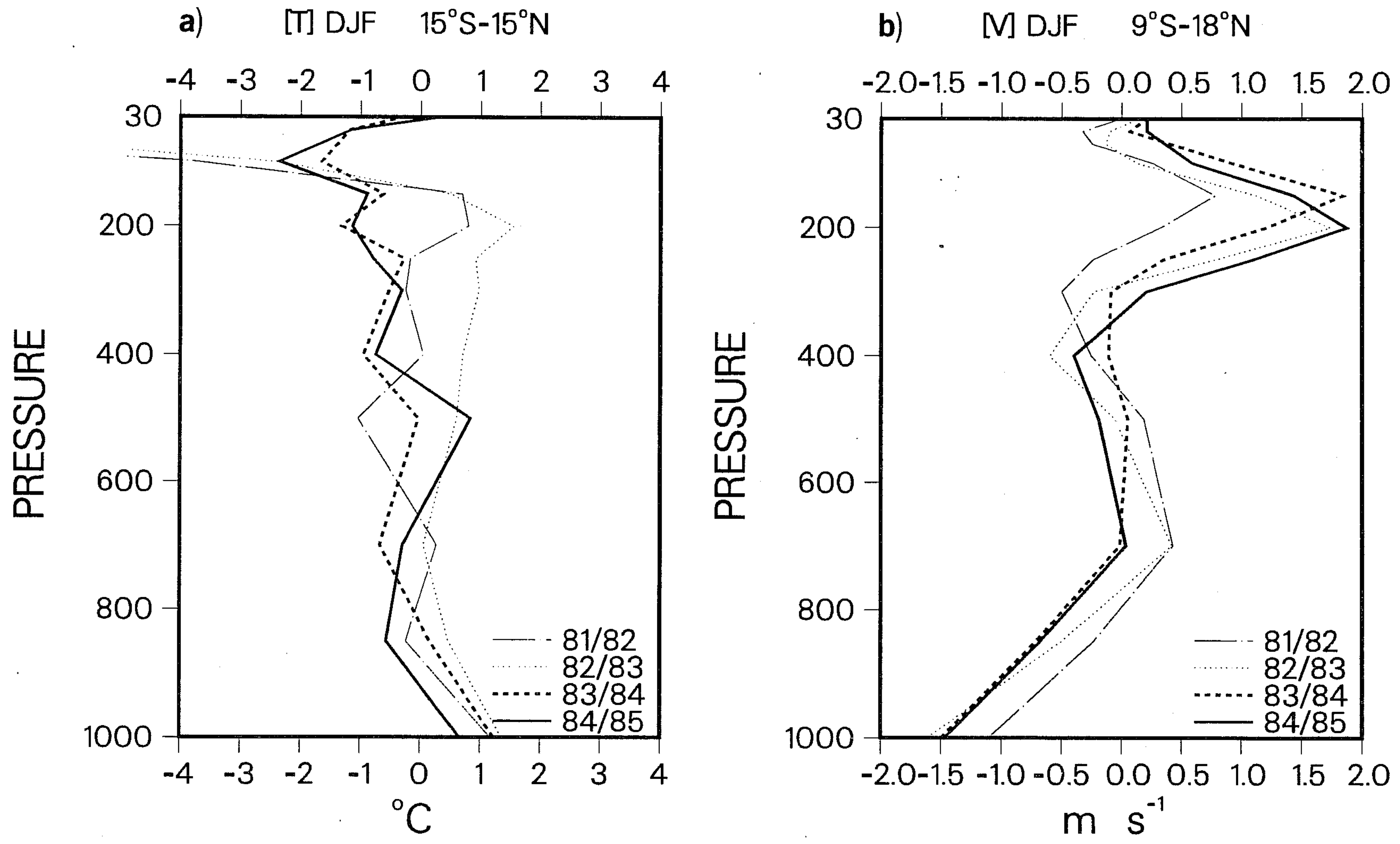


Fig. 6 Vertical profiles of DJF mean 00Z analyses for a) differences between zonal mean temperature and 'climate' temperature averaged in tropical belt 15°S to 15°N, and b) zonal mean meridional wind [v] averaged between 9°S and 18°N.

3.5 T106 model and revised parameterization

In the previous sections we have, apart from few exceptions, failed to produce more evidence that the changes in the analysis/forecast system, considered so far, have a significant impact on the zonally averaged analysed fields. In most cases the impact, if any, acts within the annual or interannual variability. In other words, zonal diagnostics was not affected beyond the expectations which one may assume because of the natural variability.

Now we turn to the modifications (f) as listed in Section 2. It was the most important and largest change undertaken during 1984 and 1985. Only the overall impact of these changes on zonally averaged diagnostics can be examined. The analysis has been affected much more by these changes than by any other modification previously considered. Since the high resolution, T106, model together with the revised parameterization became operational on 1st May 1985, we shall compare the period June to August (JJA) 1985 versus 1984.

Fig.7 shows the difference in zonally averaged analysed temperature between these two seasons. Most of the larger differences are found in the tropics and polar regions, while mid-latitudes exhibit less pronounced changes. In the tropics changes due to the May 1985 modifications can be summarized as follows. The analysis is warmer in the tropical stratosphere by about 1.5 K with a secondary maximum below the tropical tropopause. A slight cooling at 300 mb separates this upper atmospheric warming from an area of a relatively intense temperature increase in the middle troposphere with maximum of about 1.5 K at 700 mb. The 'warmer' analysis is not confined only to the tropical mid-troposphere. It is found also in the extratropics but here one finds variability in the pattern from month to month. Below 850 mb the tropical analysis displays a relative cooling when compared to the previous year.

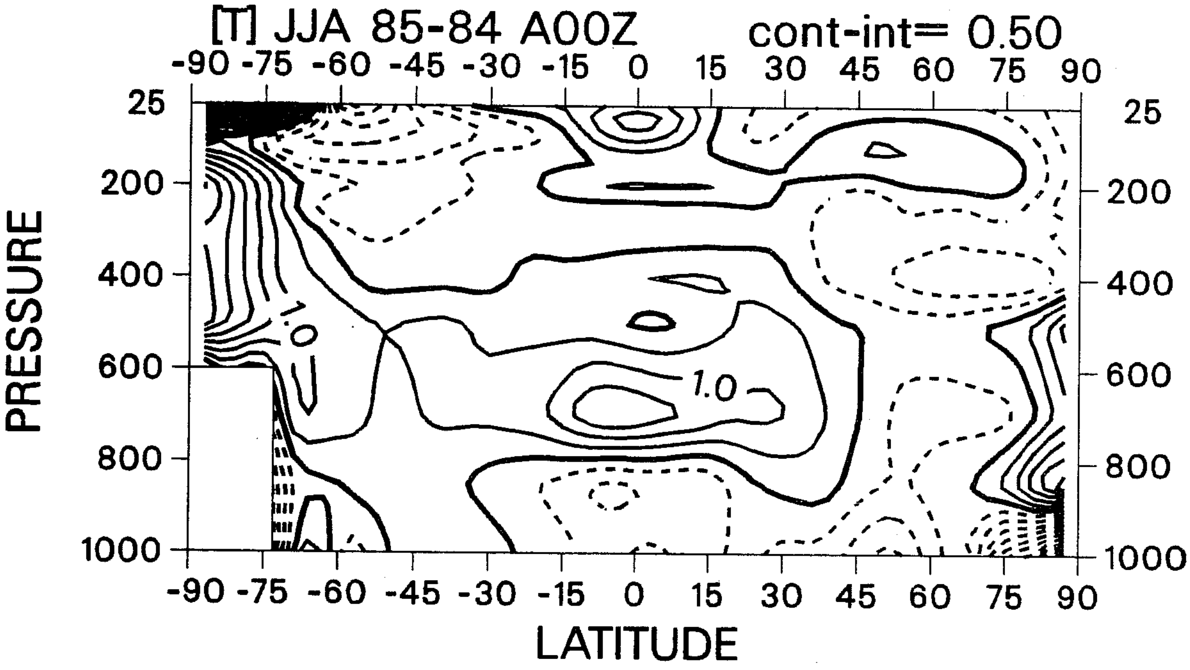


Fig. 7 Difference between JJA 1985 and JJA 1984 mean 00Z analyses of zonally averaged temperature. Contour interval is 0.5 K. Dashed lines indicate negative difference.

In addition to the above features in the tropics, June and July (but not August) show an intense temperature increase in the northern polar regions above 850 mb, which is reflected in the averaged differences in Fig.7. A strong lower troposphere cooling from 70°N poleward is due to the June and July data and probably can be ascribed to the erroneous use of sea surface temperature during that period. Due to an error the sea surface temperature in the assimilation for June and July 1985 was held fixed at the May 31, 1985 value. The polar cooling cannot be found in August when correct sea surface temperatures have been used.

Using the annual cycles of zonal mean temperature in Fig.8 we shall examine the temperature fluctuation within the seven-year period for the three tropical and two polar regions. In the tropical mid-troposphere temperature the season from June to August 1984 was the coldest of the seven (Fig. 8a), but was still within the range of variability which might be expected for this season. On the other hand, from May to December 1985 the temperature exhibits higher values than average. In particular, a sharp increase from April to May 1985 is noticeable. It seems that the May 1985 modifications tend to warm the tropical troposphere, but the real impact is probably smaller than that shown in Fig.7, because JJA 1984 was on the colder side.

The temperature increase in the tropics means that the negative temperature bias of the first guess (obtained when compared the first guess with the observations) is reduced. According to Tiedtke and Slingo (1985) the mechanism responsible for such a warming is the penetrative cumulus convection, which, through a modified moistening parameter, produces a more realistic thermal structure in the tropics. This parameter acts also towards producing less moistening in the tropical middle troposphere (see below).

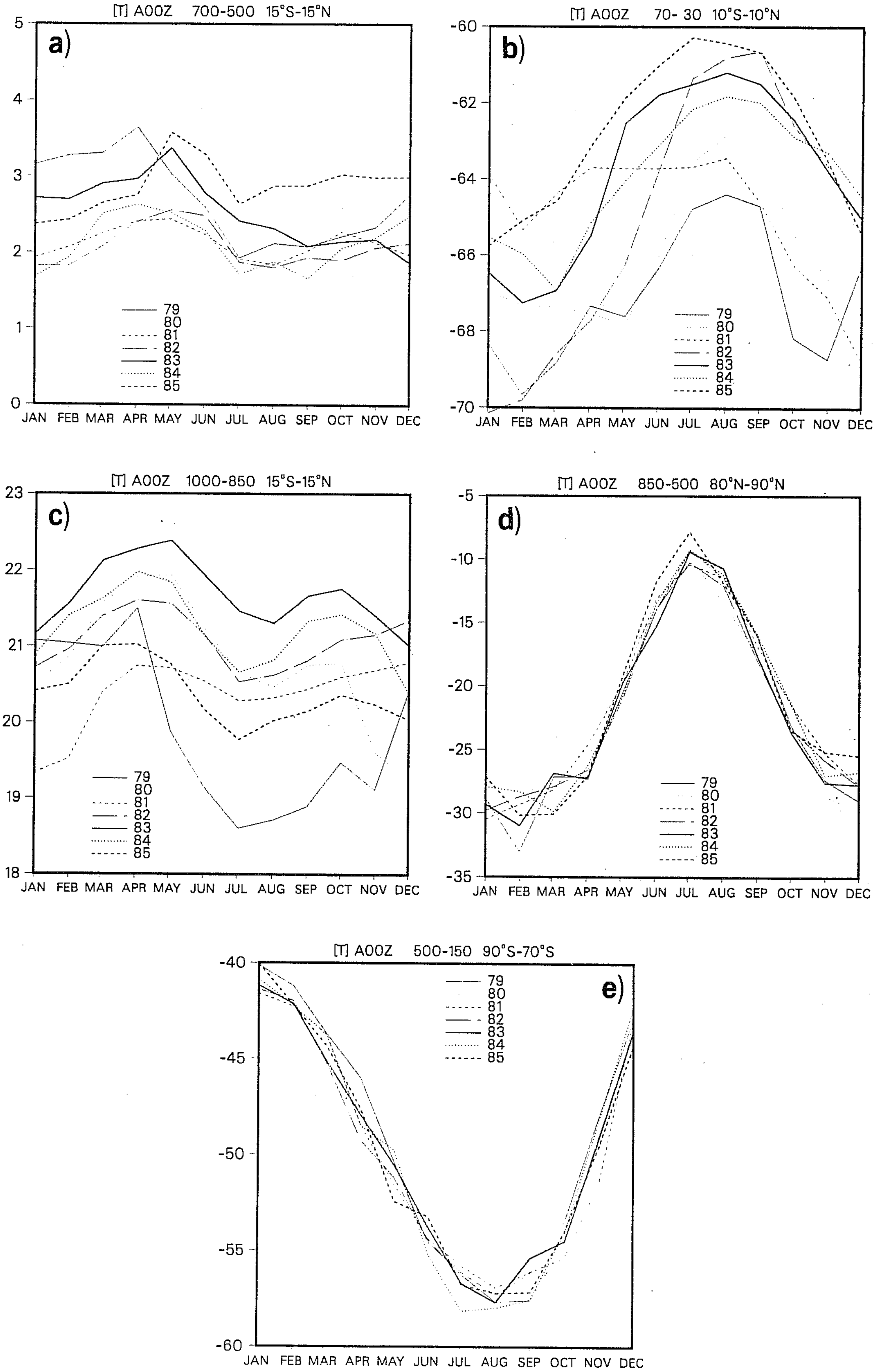


Fig. 8 Annual cycles of 00Z analyses of zonal temperature (degrees Celsius) averaged between a) 700 and 500 mb and 15°S and 15°N, b) 70 and 30 mb and 10°N and 10°S, c) 1000 and 850 mb and 15°N and 15°S, d) 850 and 500 mb and 80°N and the north pole, and e) 500 and 150 mb and 70°N and the south pole.

The impact of the modifications on the analysed temperature in the tropical stratosphere is less clear. Fig. 8b shows that in 1984 the tropical stratospheric temperature was well within the variability defined by the other years (except for the last two months), and the 1985 temperaure is the warmest for the most of the year. Since such a tendency already started in April 1985, i.e. before the introduction of the modifications, it is not obvious whether the warming in the tropical stratosphere in JJA 1985 is due only to the system changes.

The trend of being the second coldest in the lower tropical troposphere is seen from the beginning of the year 1985 (Fig. 8c). However, it seems that from May 1985 onwards the effect of the shallow convection scheme might be at least partially responsible for this trend. The shallow convection scheme intensifies heat and moisture transports within the PBL and reduces moisture in the lower layers (cf. Fig. 10c). The overall effect is cooling and moistening of the upper part of the PBL (cloud layer).

An increase in temperature in the polar regions of both hemispheres is more difficult to assess because of the large natural variability in these regions. In the northern polar region (Fig. 8d) there is a faster increase of temperature from April to May in 1985 than ever before. The very warm months of June and July 1985 are the continuation of that trend. Probably, the May 1985 modifications could partially be credited for such a behaviour. On the other hand, it seems that the temperature increase in the southern hemisphere polar region, as seen in Fig.7, owes little to the system changes. During JJA 1985 the temperature is within the limits of variability, but in JJA 1984 it was coldest in the seven-year period (Fig. 8e). This cold 1984 JJA season can be readily seen from the sequence of the 500 mb height anomaly maps for May, June and July 1984 (ECMWF, 1985). In May 1984 there was a positive anomaly of about 160 m from the climatological mean over the Antartica plateau; it drops to -110 m in June and -170 m in July 1984.

Fig.9 displays the mean meridional circulation in the JJA seasons of 1984 and 1985. This circulation is much stronger in JJA 1985 (lower panels). There is a substantial strengthening of the upper branch of the Hadley circulation in JJA 1985 when compared with the previous JJA seasons. An average increase of the extreme value from JJA 1984 to JJA 1985 is about 1.0 ms^{-1} or roughly more than 50%. It is unlikely that [v] is subject to such a strong interannual variability, though a certain amount of year-to-year difference should be assumed. The maximum in JJA 1985 is at 200 mb, but this positioning has already been noticed in DJF 1984/85 data (Section 3.4). A secondary tropical minimum, which in JJA 1984 and previous years, appears at about 700 mb (Fig. 9a) is replaced by positive values (Fig. 9c). A secondary tropical maximum at about 400 mb is stronger in JJA 1985 than in JJA 1984. The alternating flow in the tropics, which has been a typical feature of the analysed mean meridional wind (Arpe, 1985), is replaced by a simpler structure. Positive [v] dominates in JJA 1985 almost throughout the tropical troposphere, while negative [v] is confined to a region around the tropical tropopause and to the tropical stratosphere.

A strengthening of the tropical (subtropical) ascending (descending) motion (Fig. 9d) is closely related to the first guess field, because ω-velocity is highly affected by the model. It is still not clear to what extent the increased model horizontal resolution and reduced diffusion, contribute to a considerable boost in the ω-field. This increase of the ω-velocity in the

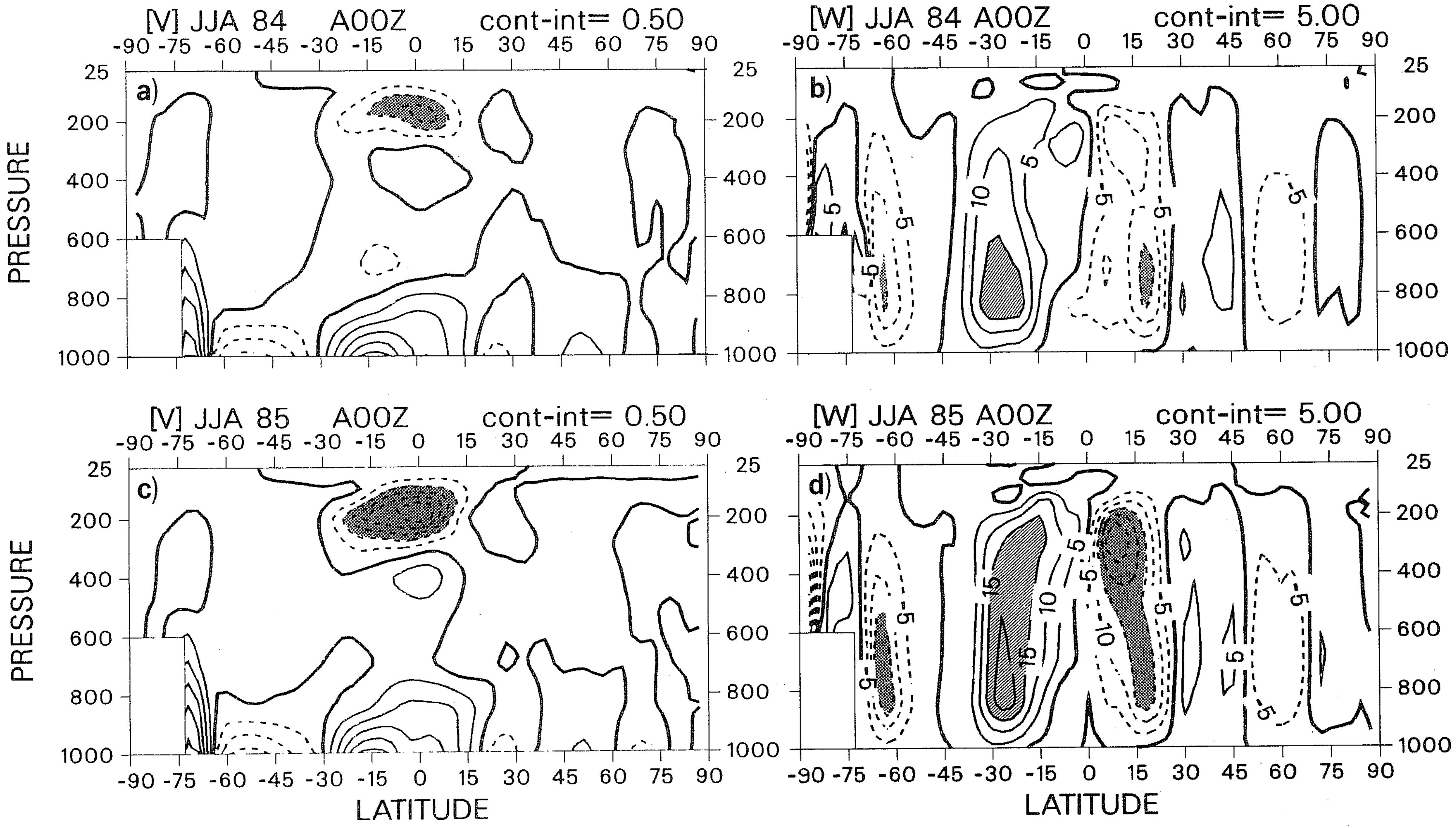


Fig. 9 Mean meridional circulation for JJA 1984 (top) and JJA 1985 (bottom). Unit for mean meridional wind (left) is m/s and for mean vertical velocity mPa/s.

early stage of the forecast is known as the model spin-up. The spin-up can be defined as the adjustment of the model away from observed data towards its own climate. In Fig. 1a a jump in the ω-variance from April to May 1985 indicates an increase of the spin-up in the 6-hour forecast with the high resolution model. Thus, the change in the analysed ω-field might be regarded as a part of a more general spin-up problem which will be discussed further in Section 4.4.

It has been pointed out by Tiedtke and Slingo (1985) that the revised parameterization has a particular influence on the analysed humidity. Fig.10 shows how a dramatic change in humidity field has occurred. Until May 1985 the analyses were too moist and had a too shallow planetary boundary layer (Heckley, 1985b). Above 850 mb the moisture was excesive in the tropics and insufficient in the subtropics by comparison with Oort's data (Fig. 10d). The shallow convection deepens and dries the PBL well mixed layer and improves the vertical transport of heat and moisture. The specific humidity is increased in the subtropics at 850 mb (Fig. 10c). The reduction in the zonal mean specific humidity, [q], in the tropical middle troposphere is mostly due to the revised penetrative cumulus convection which provides less moistening via modified moistening parameter. Thus, the moisture distribution in JJA 1985 becomes closer to Oort's climate data (Fig. 10d).

3.6 Zonal wind in the tropical stratosphere

A long series of the zonal mean wind, [u], at 30 mb reveals a periodical wind regime in the tropical stratosphere, the quasi-biennial oscillation. Until December 1984 the analysed tropical [u] wind at 30 mb (Fig.11) was systematically weaker than Naujokat's (1985) data derived from observations. In December 1984 the ECMWF westerlies become significantly stronger (about

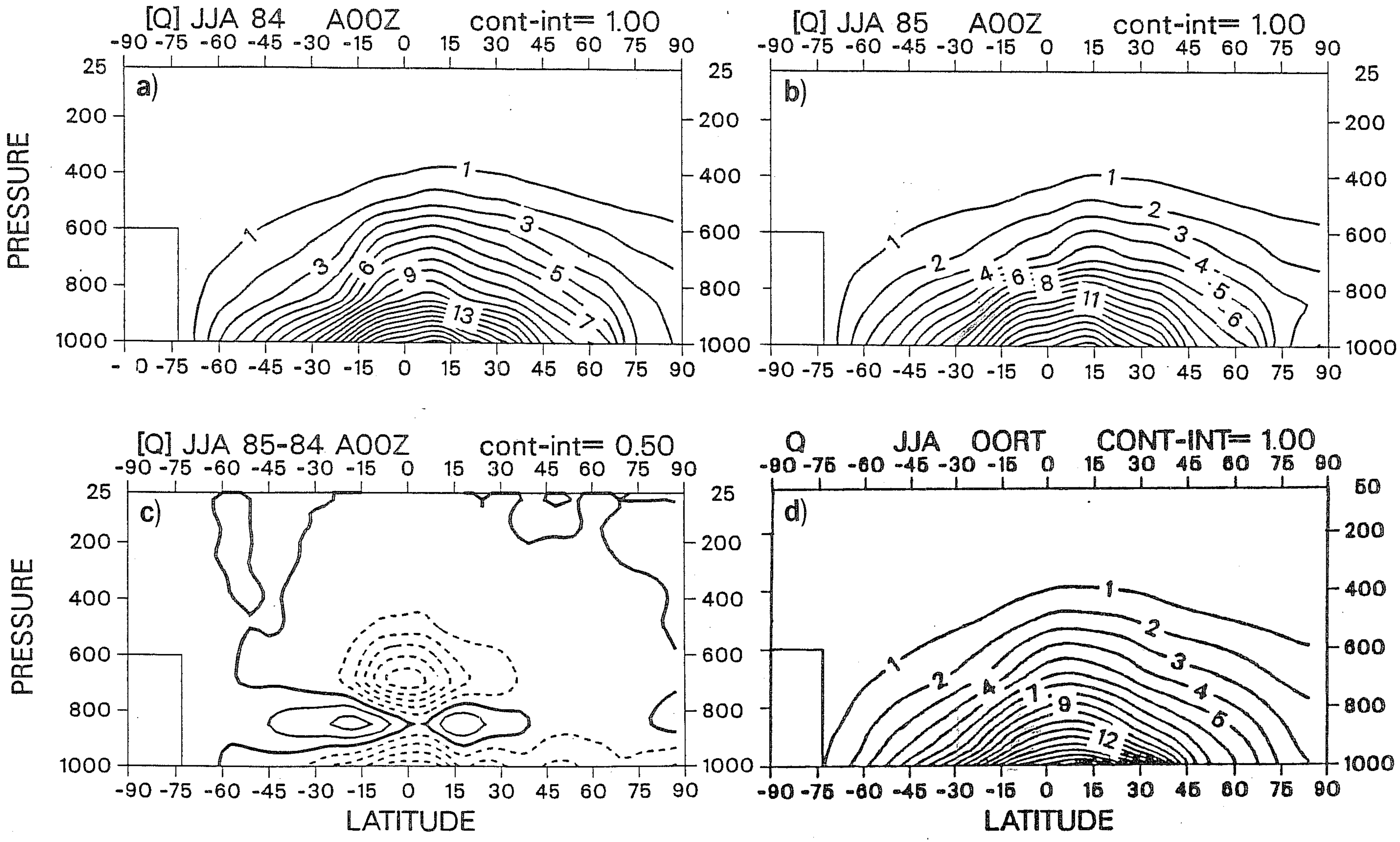


Fig. 10 Mean 00Z analyses of zonal mean specific humidity, [q], in g/kg for a) JJA 1984, b) JJA 1985, c) difference in analysis between JJA 1985 and JJA 1984 and d) Oort's climate for JJA.

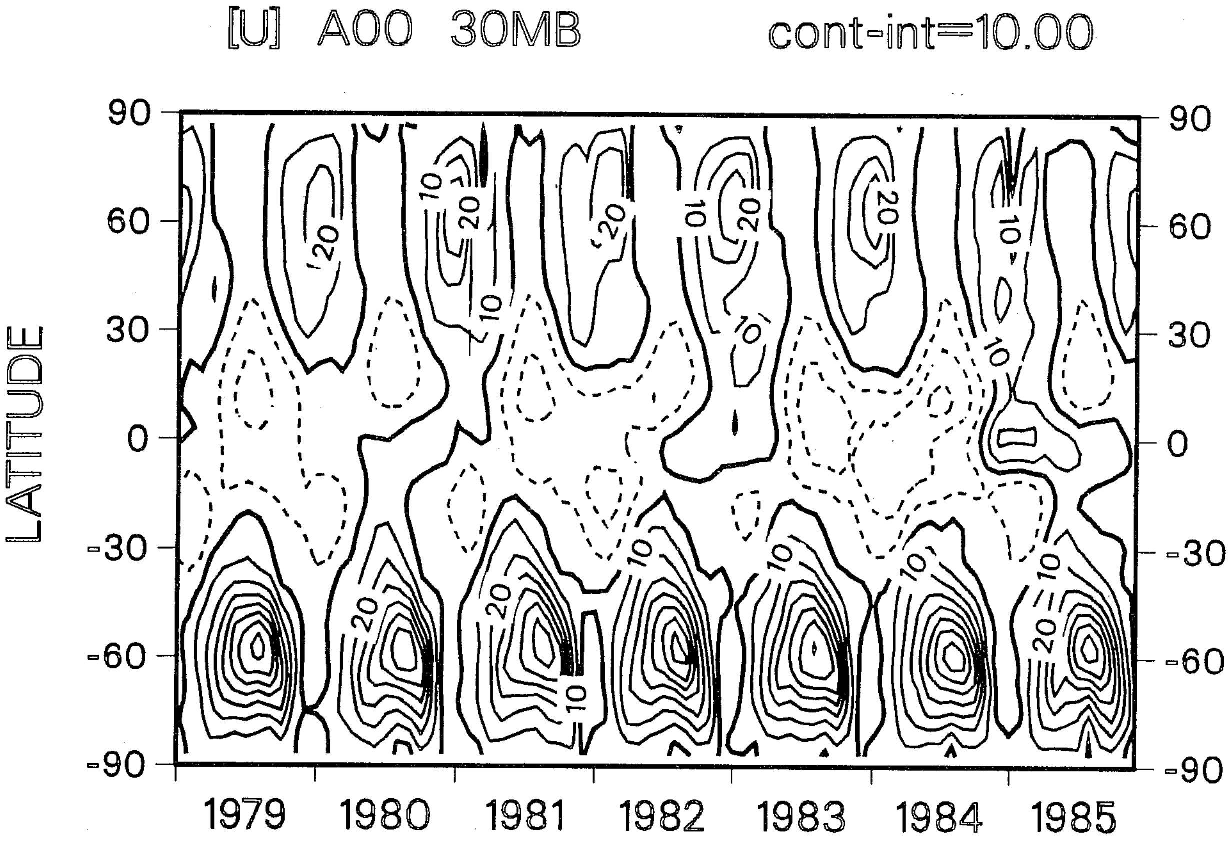


Fig. 11 Latitude-time diagram of monthly mean 00Z analyses of zonal mean u-wind (m/s) at 30 mb level. Dashed lines indicate easterlies.

20 ms^{-1}) than Naujokat's wind. Since this change in the [u]-wind occurs about the same time when the modified radiation and stratospheric drag were introduced, it was essential to investigate whether there is a relationship between the two.

Checking the 30 mb wind observations for the tropical stations between 10°N and 10°S yields no indication of any substantial change either in data quality or data density from November to December 1985 could be found. However, because of a large departures from the first guess, about 40% of wind reports have been rejected in December compared to about 8% in November. Thus, the 30 mb tropical wind field was chiefly determined by the first guess, and effectively the first guess is responsible for the stronger westerlies shown in Fig.11. The first guess at 30 mb is not a model generated field, but rather a blend of the climate, persistence and the first guess at 50 mb. The use of persistence makes it very difficult to remove an incorrect feature once it found its way into the analysis. The recent data assimilation experimentation with an increased number of levels in the stratosphere shows much improved analysis of the 30 mb wind (W.Wergen, personal communication).

Thus, an increase of the tropical westerlies at 30 mb simply coincides with the introduction of the modified radiation, but it has not been originated by this modification.

4. IMPACT ON THE FORECAST

The effects of the diurnal cycle on the operational forecasts will not be discussed here because, for the simplest assesment of that impact, at least 12-hour intervals are required. Since the zonal diagnostics for the operational forcasts is calculated in 24-hour intervals and because of its strong latitudinal dependence, it does not seem suitable to consider this modification.

The impact of the revisions to the analysis on the operational forecast will not be discussed as well. Inspection of time-diagrams of various zonally averaged parameters (see Fig.12 for an example) yields that no substantial changes in the parameters' behaviour since May 1984 could be found. It seems, therefore, that the revisions did not affect the zonal mean quantities very much, or at least such a change cannot be seen from the time-diagrams.

Thus, all modifications, except the diurnal cycle and revisions to the analysis will be considered in the same way as in the preceding Section.

4.1 Enhanced horizontal diffusion on divergence

To investigate the effect of the increased horizontal diffusion on the operational forecast in respect to zonal mean values, we shall, as in Section 3.1, concentrate on the ω-variance. Fig.12 shows the change in the ω-variance during the course of the forecast from January 1984 until December 1985. The ω-variance is averaged over the tropical middle troposphere. The forecasts are taken by verifying time and are averaged over a period of one month. The verifying monthly mean analyses are denoted by zero on the abscissa. This means, for instance, that one third of day ten (D10) forecasts commence in the previous month. This is important, because if a modification

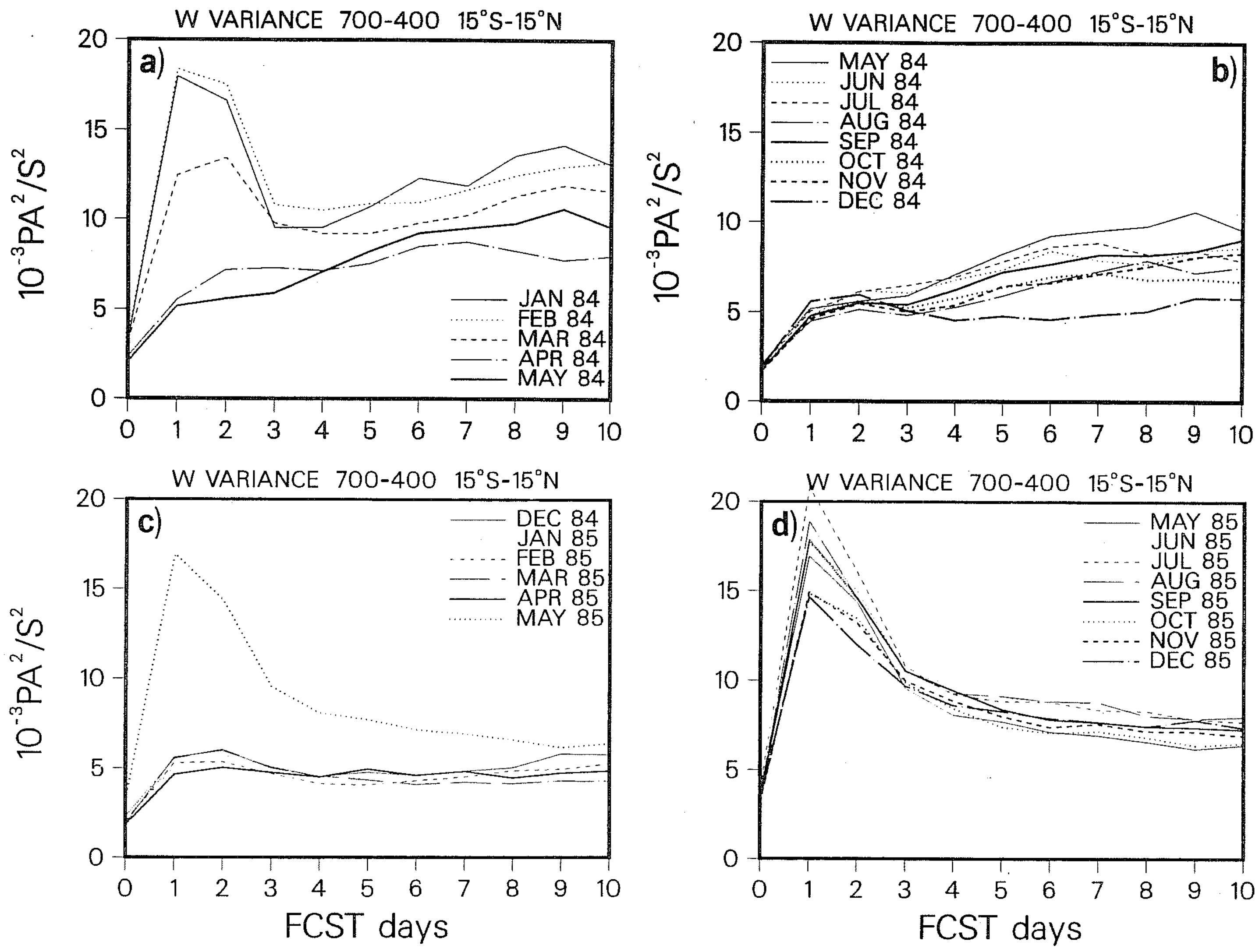


Fig. 12 Forecast time diagram of mean area ω-variance (10^{-3} Pa^2/s^2) for all waves averaged over the tropics, 15°S to 15°N, and between 700 and 400 mb for a) January to May 1984, b) May to December 1984, c) December 1984 to May 1985 and d) May to December 1985.

in the model was introduced on the 1st day of a month, one third of the D10 forecasts are unaffected by that change. Obviously, the ratio becomes smaller for shorter forecast times.

The figure is divided into four panels corresponding to four periods, each having at least one of the months in which major changes listed in Section 2 occur, either at the beginning or at the end of the period. The months May 1984, December 1984 and May 1985 overlap and are shown in pairs of successive panels.

From Fig. 12a it is clear that the increase in diffusion has a large impact on the variance of the tropical ω-field. The initial model spin-up in is damped in April 1984 and thereafter. Even March 1984 shows a different tendency compared to previous months; this is because the increased diffusion was introduced on 22nd March 1984 and there was a number of the March forecasts affected by this change. Despite initial damping an increase in the ω-variance during the course of the forecast can still be found, but it is eliminated with the introduction of a new radiation scheme (Figs. 12b and 12c). The behaviour of the ω-variance will be discussed further in Section 4.4.

4.2 Correction of moisture dependence of specific heat

This correction was introduced into the operational model on 24th July 1984. If, for instance, the mean D5 forecast is examined, only the last three days of the July mean D5 temperature are affected by this change. Therefore July 1984 is assumed to be representative as a month without correction. Fig.13 displays the upper tropospheric error in zonal temperature at D5 for July and August 1984. The D5 temperature error in August 1984, i.e. after the

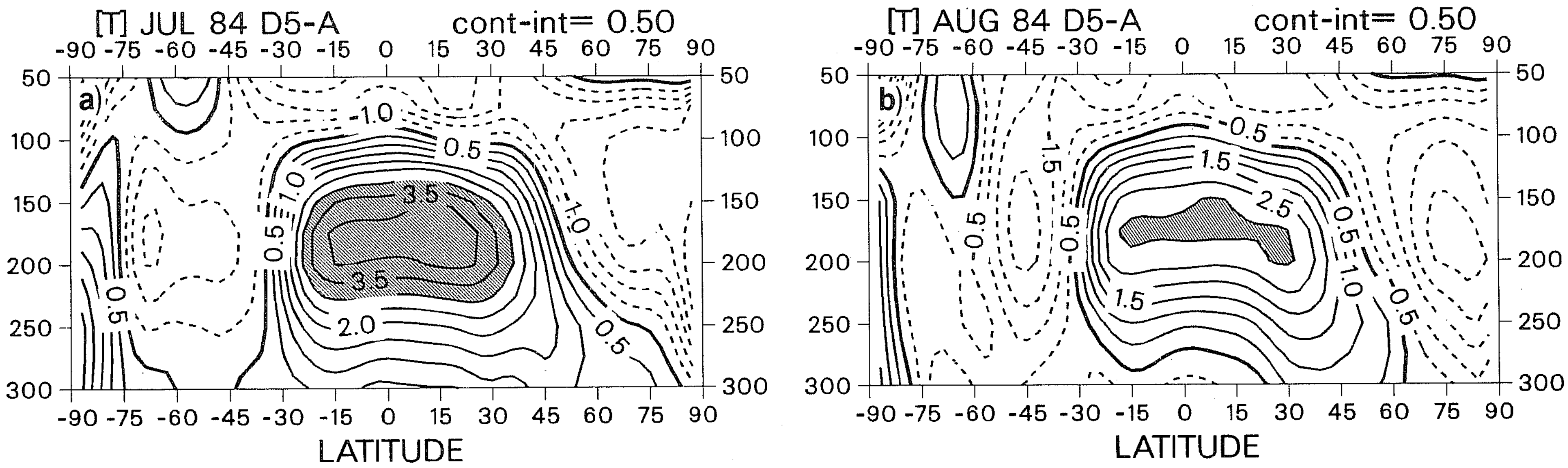


Fig. 13 Error in forecast of zonal mean temperature at D5 in a) July 1984 and b) August 1984. Contour interval is 0.5 K. Error greater than +3.0 K is shaded.

modification was introduced, is reduced by more than 1 K near the tropical tropopause. A similar tendency appears in the D10 temperature error field (not shown).

Although an apparently minor modification, the correction of moisture dependence of specific heat has a certain impact on the forecast. Therefore it has to be taken into account while examining the impact of the modified radiation (the next major system change) on the temperature field.

4.3 Modified radiation and stratospheric drag

It is not possible to assess separately the effects of the new radiation and stratospheric drag on operational diagnostics. The results presented here should be regarded as a joint impact of both modifications. For simplicity, these two changes will be referred hereafter to as the new radiation scheme.

The most likely parameter to be affected by the introduction of the new radiation is temperature. We shall consider the D5 temperature errors for the season DJF despite the fact that the first eight days in December 1984 are not affected by that change (modified radiation was introduced on 4th December 1984). In a seasonal mean those first eight days have a relatively small contribution. The spatial distribution of the temperature errors for the two successive DJF seasons is shown in Figs. 14a and 14b. The DJF 1984/85 errors are reduced in all areas, though they are still large. Cooling in the tropical stratosphere is removed, and in the extratropical stratosphere is substantially reduced. The strongest cooling now occurs at a much lower level of 850 mb. In fact the magnitude of the cooling in the tropical troposphere has not changed very much but the distribution of the cooling is different when compared to the previous DJF season. The magnitude of the intense

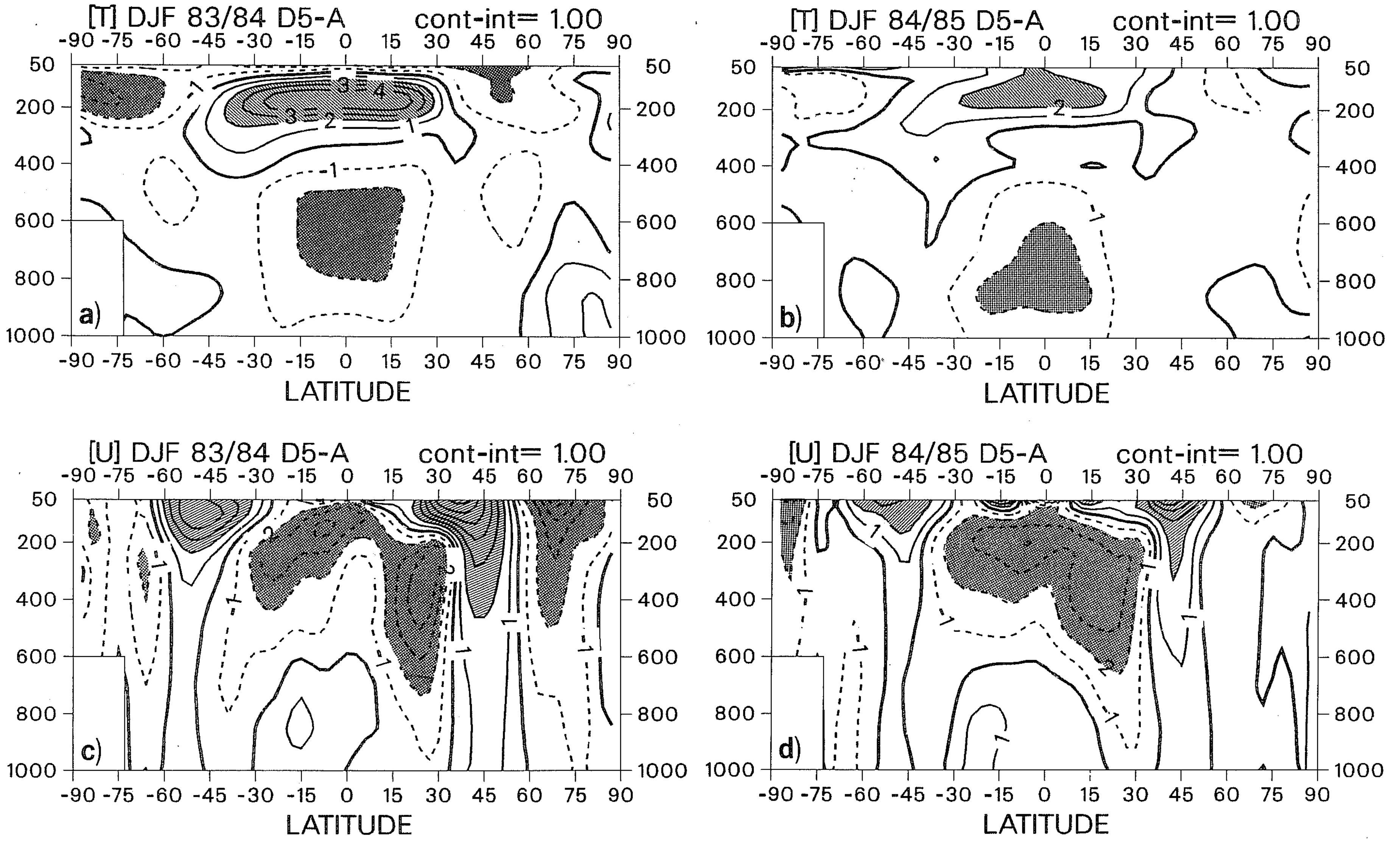


Fig. 14 Error in forecast at D5 of zonal mean temperature (top) and zonal mean u-wind (bottom) for DJF 1983/84 (left) and 1984/85 (right). Contour intervals are 1.0 K and 1 m/s respectively. Errors greater than |±2| K and |±2| m/s are shaded.

warming near the tropical tropopause is halved. A part of this reduction can be attributed to the correction of the moisture dependence of specific heat, as described in the previous Section. In the extratropical regions the temperature errors are also reduced.

The D5 zonal wind errors are reduced as well though the error pattern remains very much the same as in DJF 1983/84 (Fig. 14c and d). To summarize, some of the model systematic errors descibed by Heckley (1985a, 1985b) and which can be seen in Figs. 14a and 14c are reduced by the new radiation scheme and to a lesser extent by the correction of moisture dependence of specific heat.

The other basic fields are also affected by the change in the radiation scheme though to a much lesser extent than the fields considered above. The tropical specific humidity shows a somewhat reduced drop in the later stage of the forecast. The new radiation acts to decrease the model spin-up of the ω-field from D3 onwards (see Figs. 12b and 12c).

The reduction of the temperature systematic error in the middle and upper troposphere in DJF 1984/85 shown in Fig. 14b indicates a stabilizing effect in the lower troposphere (except in the lowermost layers) compared to DJF 1983/84. Thus, instead of having a strong increase in stability confined to a thin layer near the tropopause, the forecasts in DJF 1984/85 display a weaker tendency to stabilize the atmosphere but this stabilization is extended to the most of the troposphere. Bearing in mind that the zonal mean temperature has not been changed very much, we find that the net effect is an overall decrease of the zonal available potential energy, AZ, in DJF 1984/85 when compared with DJF 1983/84 (Fig. 15a). The difference in the verifying analysis between these two seasons agrees with a difference in static stability as shown in

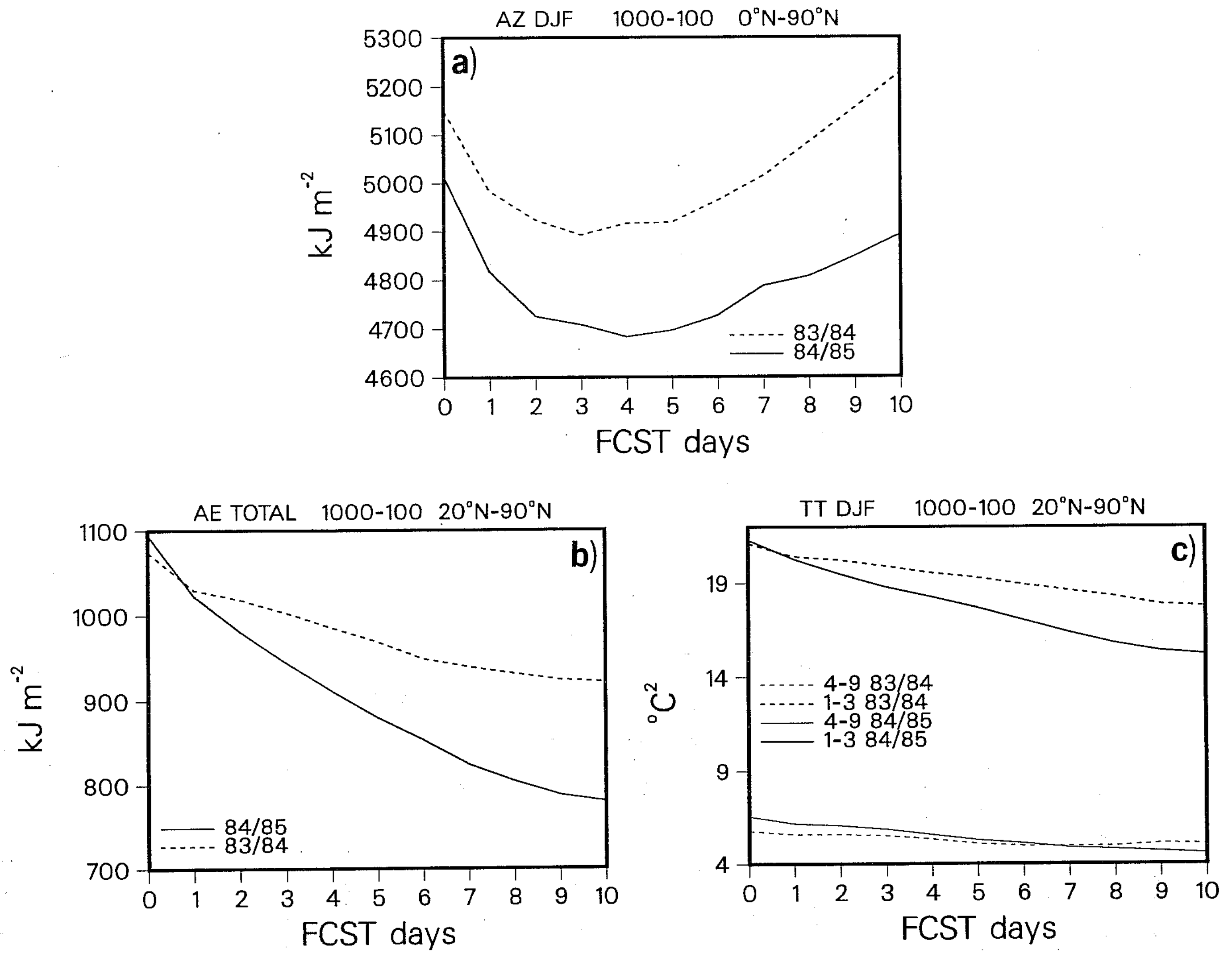


Fig. 15 Forecast time diagram for DJF season for a) zonal available potential energy (AZ) integrated between the equator and 90°N and between 1000 and 100 mb, b) total eddy available potential energy (AE) integrated between 20°N and the north pole, and c) total temperature variance for long and medium waves.

Fig. 6a, but it is not clear if this change is due to natural interannual variability or to the system change. However, this initial difference increases in the forecasts and is the consequence of the system change.

The eddy potential energy, AE, depends directly on temperature variance and on the reciprocal of the atmospheric static stability, which is calculated from the zonal mean temperature. In DJF 1984/85 the northern hemisphere AE exhibits a greater drop during the course of the forecast than in DJF 1983/84 (Fig. 15b). Changes in both stability and temperature variance caused the drop. It can be seen in Fig. 15c that the largest contribution to the drop in the temperature variance comes from the long waves (wavenumbers 1 to 3). Since the changes in static stability affect contributions by different wave groups in a similar way, we may assume, that the temperature variance has a greater role in the energy loss shown above. In fact, it is difficult to separate completely the impacts of the two factors to the total AE budget. Nevertheless, it has been shown that the effect of the new radiation has more far-reaching consequences than might be concluded by examining the zonal mean temperature field alone.

4.4 T106 model and revised parameterization

In order to assess the impact of the May 1985 modifications on the operational forecast we shall compare the JJA 1985 zonal mean diagnostics against the previous JJA seasons. Again, as mentioned earlier, there was no way to separate the effects of the high resolution and effects of revised parameterization; only an overall impact of these changes can be discussed.

(a) Temperature

The spatial distribution of the mean D5 temperature error in JJA 1985 (Fig. 16b) is very different from that in JJA 1984 (Fig. 16a). However, one has to bear in mind that modifications introduced earlier into the forecasting system contribute already towards reduction of the model systematic errors in the temperature field. Thus, what is seen in Fig. 16b is the joint impact of the correction of moisture dependence of specific heat, the new radiation and the May 1985 changes. If we take into account the effects of the modifications discussed in the two preceding sections, then the impact of the May 1985 changes on the temperature field can be summarized as follows. The revised parameterization corrects the earlier model's tendency to cool the tropical and subtropical middle and upper troposphere. In the new model cooling is confined mainly to the boundary layer and to the northern stratosphere. Taking the season DJF 1985/86 into account (but which is not considered here) we can speak about cooling of the summer stratosphere. A relatively weak cooling of the southern stratosphere in JJA 1984 is replaced by a stronger warming in JJA 1985. Overall, net warming now occurs in most of the atmosphere. Such an error distribution at D5 indicates a more stabilizing effect since May 1985. The region of relatively decreased stability is now confined mostly to the northern stratosphere (250-100 mb).

(b) Zonal wind

The assessment of seasonally averaged [u] field during the course of the forecast before the introduction of the modifications in May 1985 yields the following results (cf. Fig. 17a; Arpe and Klinker, 1986; Heckley, 1985a, 1985b). A decrease of westerlies (or an increase of easterlies) in the upper tropical troposphere was found in both winter and summer seasons. The subtropical jet cores were subject to an upward and poleward shifts. The maximum zonal wind speed was reduced already at D1 and the jets were broadened. The wind errors are related to the temperature errors according to the thermal wind relationship.

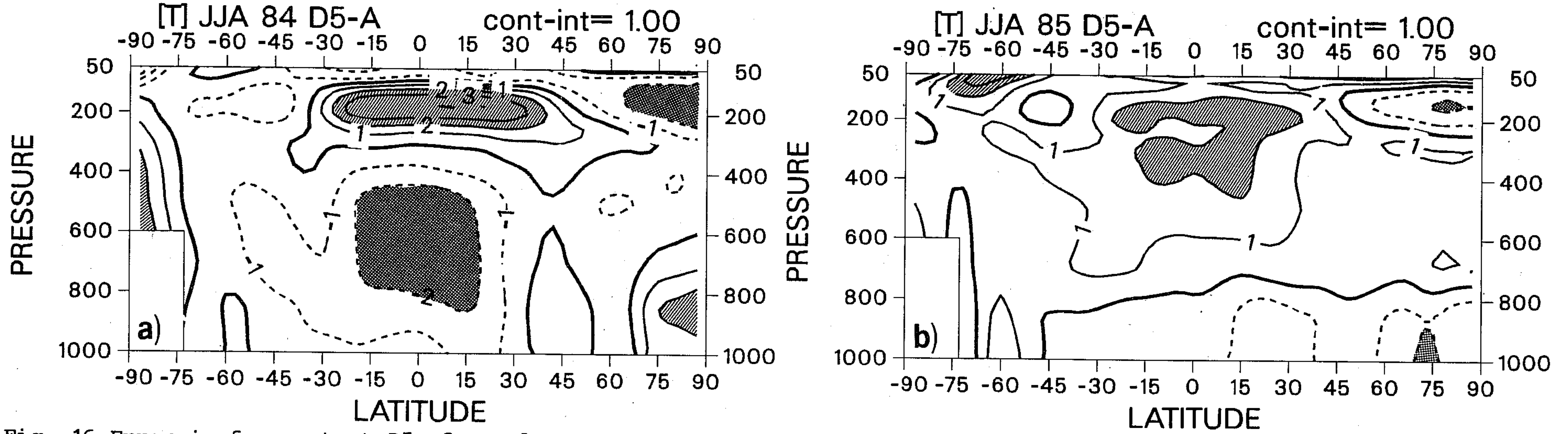


Fig. 16 Error in forecast at D5 of zonal mean temperature in a) JJA 1984 and b) JJA 1985. Contour interval is 1.0 K. Error greater than $|\pm 2|$ K is shaded.

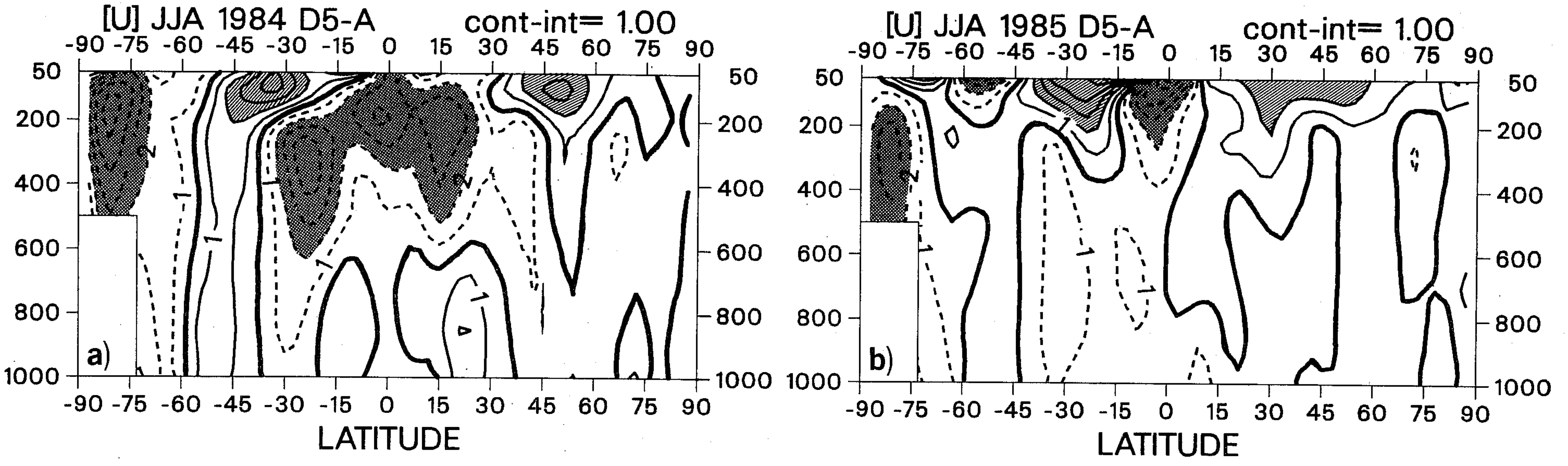


Fig. 17 Same as Fig.16 but for zonal mean u-wind. Contour interval is 1.0 m/s. Error greater than $|\pm 2|$ m/s is shaded.

From Fig. 17b a significant change in the [u] wind error in the upper tropical troposphere can be seen. The maximum positive errors (strengthening of the westerlies) are shifted equatorward in JJA 1985 and therefore a decrease in westerlies (or an increase in easterlies) in the tropics is no longer a dominant feature. These errors are related to the maxima of the horizontal wind shear in such a way that higher wind speeds at D5 can be found at the lower latitudes. In fact the subtropical jet cores are not shifted from their mean analysed positions very much. Such an error pattern means a decrease of the anticyclonic absolute vorticity equatorward of jet cores compared to the JJA 1984 forecasts and, as a consequence, a strengthening of inertial stability. This feature should be scrutinized together with an increase of vertical stability in the tropical stratosphere as discussed for temperature errors above. (However DJF 1985/86 is much nearer to DJF 1984/85 and therefore the above findings cannot be generalized.)

The effect of the strengthening of the forecast zonally averaged zonal wind in the subtropics is demonstrated in Fig.18, which shows the vertical profile of [u] at 24°S for two summer seasons. The 1984 analysis values are concealed by the 1985 analysis, i.e. the analysed seasonal [u] wind profile remained almost unchanged. Whereas in JJA 1984 the D5 wind at 200 mb has been weakened, in JJA 1985 it has been strengthened by almost the same magnitude.

Other features in the [u] wind error field (Fig. 17b) can be summarized as follows. There is an increase in wind speed above the subtropical jets but unlike JJA 1984 the increase is at lower subtropical latitudes. As mentioned by Heckley (1985a) the error is seasonally dependent, i.e. larger errors are to be found on winter hemisphere.

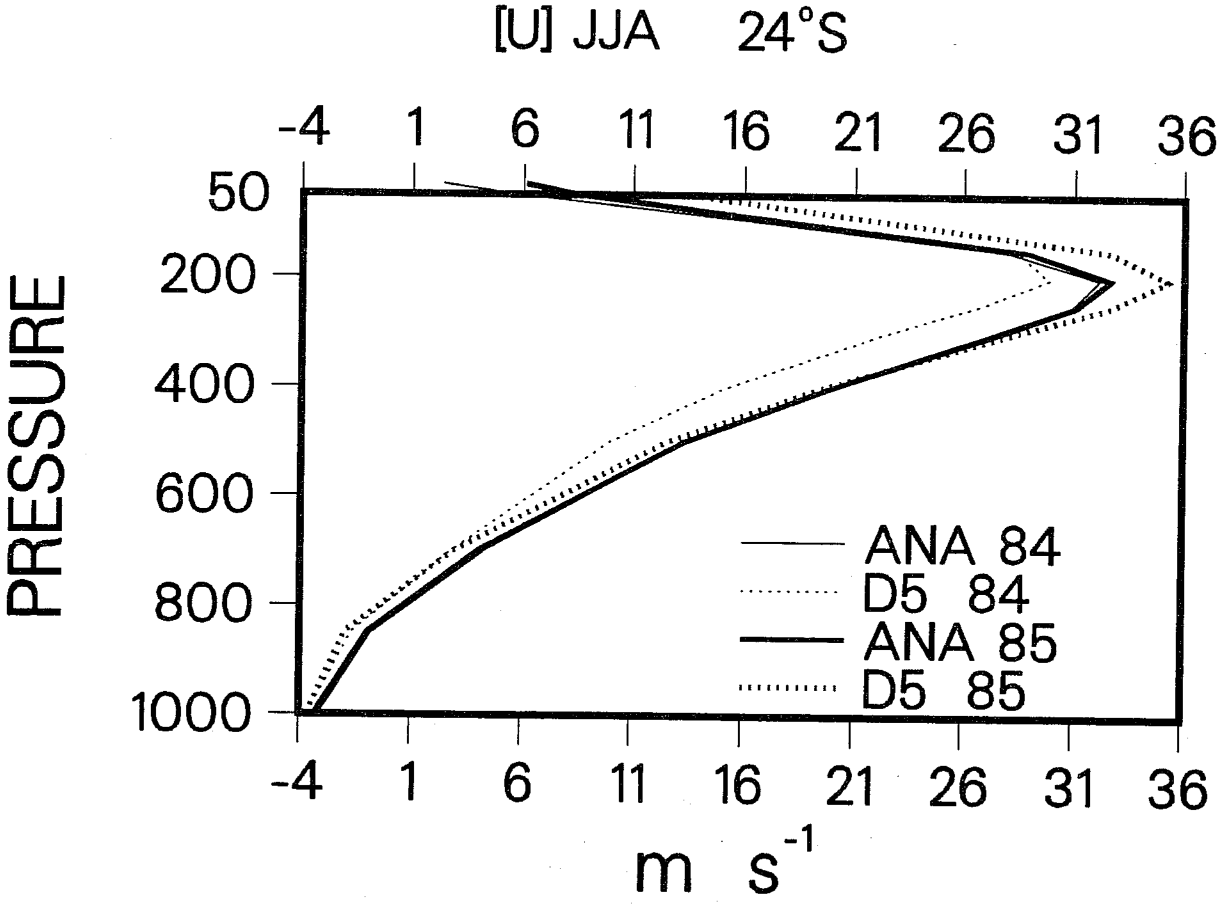


Fig. 18 Vertical profiles of the JJA mean zonal wind (m/s) at 24°S.

From the above considerations one can conclude that there has been a definite improvement of the [u] wind prediction in JJA 1985 in the tropical troposphere. This effect can be attributed mostly to the May 1985 modifications, since the DJF 1984/85 mean errors (Fig. 14d), although not exactly the same as the errors shown in Fig. 17a, display a number of similarities to the JJA 1984 errors and therefore a relatively weak impact of the new radiation on the [u] field might be assumed.

(c) Vertical velocity

It was shown in Section 3.5 that the model spin-up affects the analysed vertical velocity and this impact comes through the first guess field. An increased diffusion of divergence, introduced in March 1984, prevents a large increase of the ω-variance in the early stages of the forecast (Section 4.1; Fig. 12a). With the introduction of the T106 model the diffusion of divergence was reduced and the model spin-up, as revealed by the ω-variance, increases (Fig. 12c). Similarly to the over-shooting found before the increasing in diffusion of divergence in March 1984 (Fig. 12a), the model needs about three days to build up a sort of balance which is reflected in a steadier tropical ω-variance pattern towards the end of the ten day forecast period. The largest contribution to the enhanced ω-variance in the tropics in JJA 1985 comes from very short waves - zonal wave numbers from 16 to 63 (Fig.19). Contributions from other wave groups are much smaller though a weak spin-up in both medium (4-9) and short waves (10-15) can be seen. Here one has to be cautious since the wave with, for instance, zonal wave number 16 in the tropics has a wavelength of about 2500 km, even though it falls into the group of 'very short' waves.

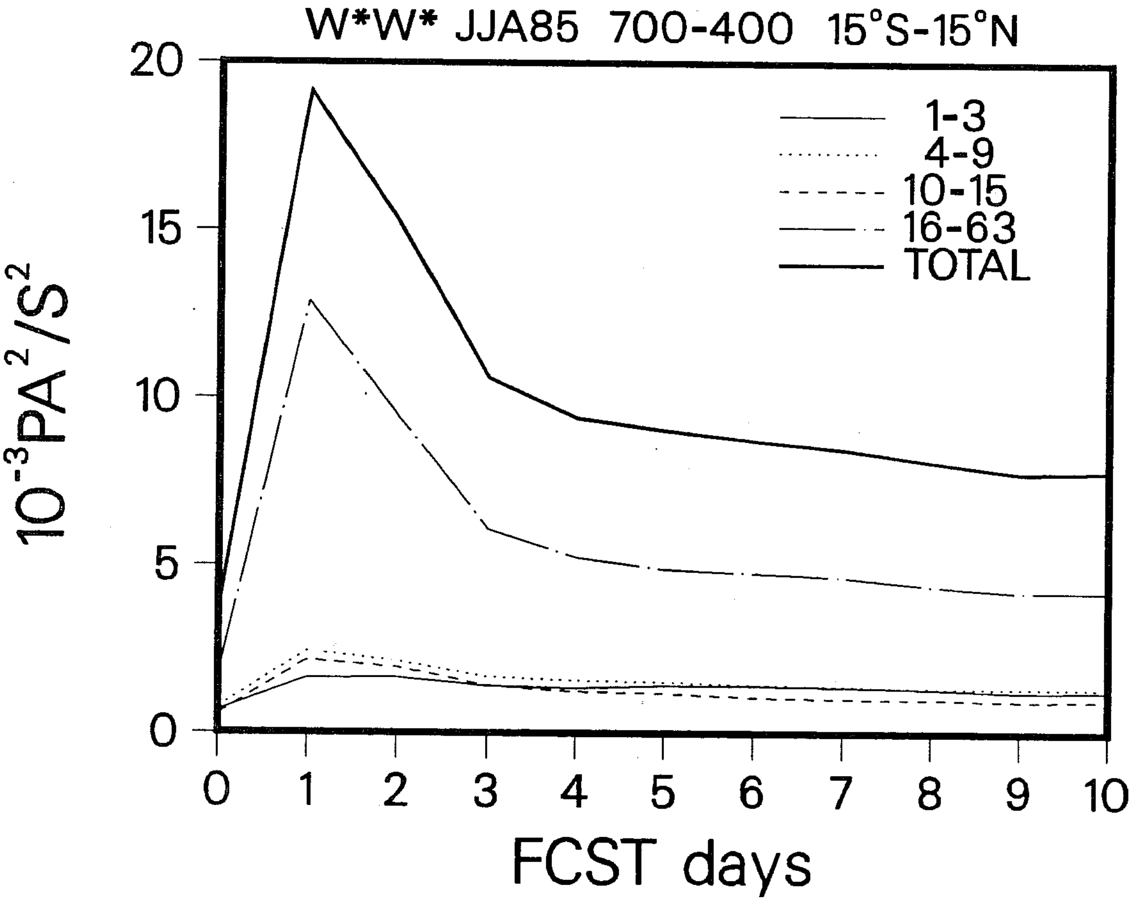


Fig. 19 Contribution of various wave groups to the tropical (15°N to 15°S) ω-variance averaged between 700 and 400 mb in JJA 1985.

The time-sequence of the ω-variance cross-sections (Fig.20) reveals that the spin-up is not confined to the tropics only. In the extratropics of both hemispheres one can see an increase in ω-variance at D1 and decrease thereafter. This may indicate that the model spin-up may be due both to the higher resolution and lower diffusion. In JJA 1984 less indication of the tropical spin-up can be found (not shown) since the stronger diffusion damps the changes in the divergence field. In the extratropics the role of longer waves becomes relatively important, i.e. the contribution of the model generated baroclinic activity to the total spin-up is almost as large as from the vertical motion on a smaller scale. This enhanced vertical motion at D1 lies between 700 and 300 mb in the extratropics. The tropical smaller scale vertical motion spreads over almost entire troposphere. The latter fact may support the view that the tropical spin-up in the ω-variance is mostly due to deep convection, since this type of motion dominates on smaller scales in the tropics and penetrates high up to the tropical tropopause. An example of the model tropical spin-up in the 500 mb vertical velocity field is shown in Fig.21 for a randomly chosen case, 15th July 1985. The verifying analysis is shown at the top and successive forecasts of 12-hour intervals are shown below. Rising motion is depicted by solid and sinking by dotted contours. It is clear that rising motion dominates in both quantitative sense and intensity. The spin-up is strongest between 24 and 36 hours and shows a tendency of weakening thereafter. The large tropical ω-variance is strongly related to the spin-up in the tropical precipitation (see paragraph (e) below).

(d) Meridional wind

As discussed in Section 3.5 the May 1985 model changes contribute to a strengthening of the analysed mean meridional circulation (Fig.9). However, the initial great similarity between verifying analysis and D1 and D2

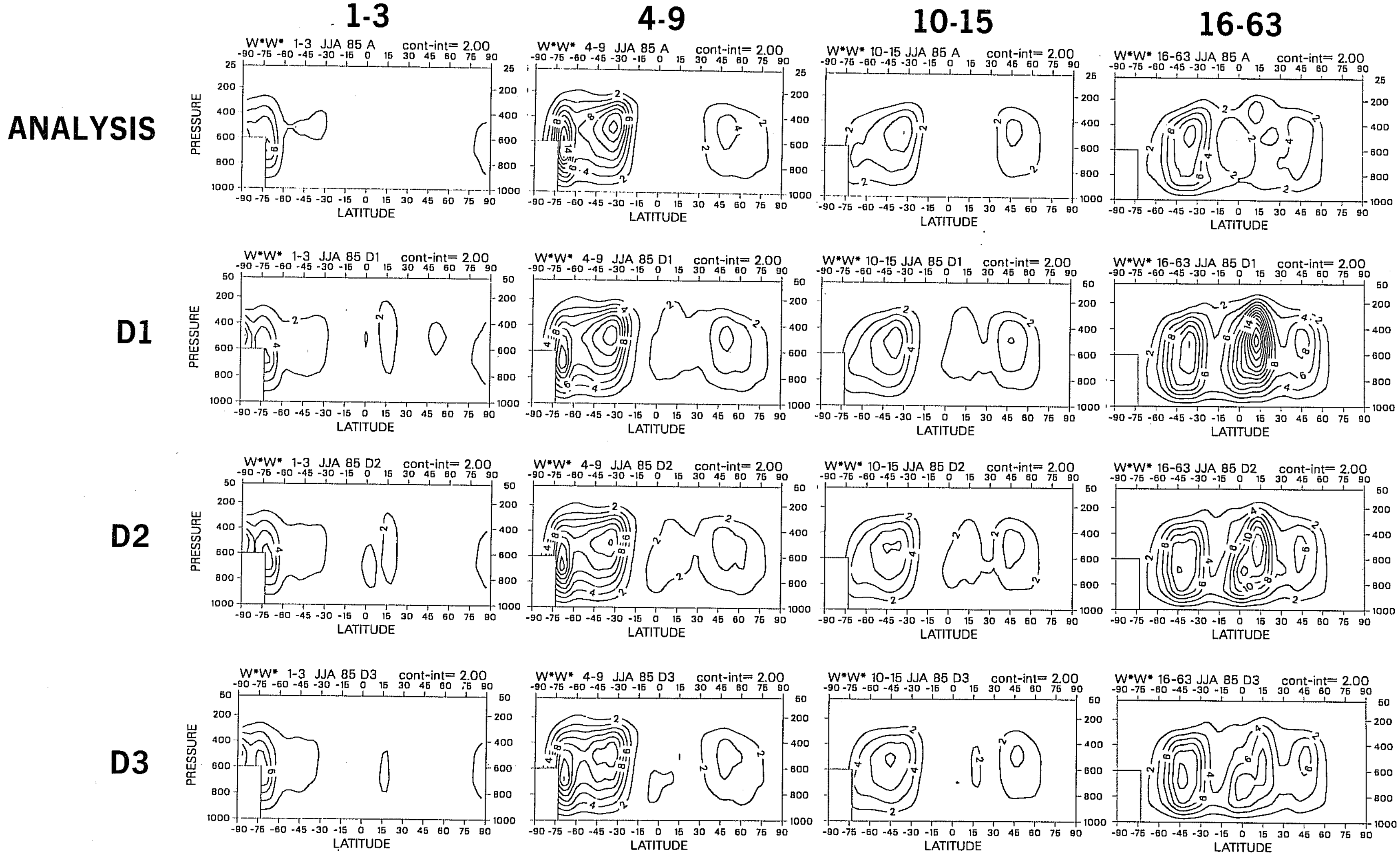


Fig. 20 Forecast time sequence of ω-variance for long (wavenumber 1 to 3), medium (4 to 9), short (10 to 15) and very short (16 to 63) waves in JJA 1985.

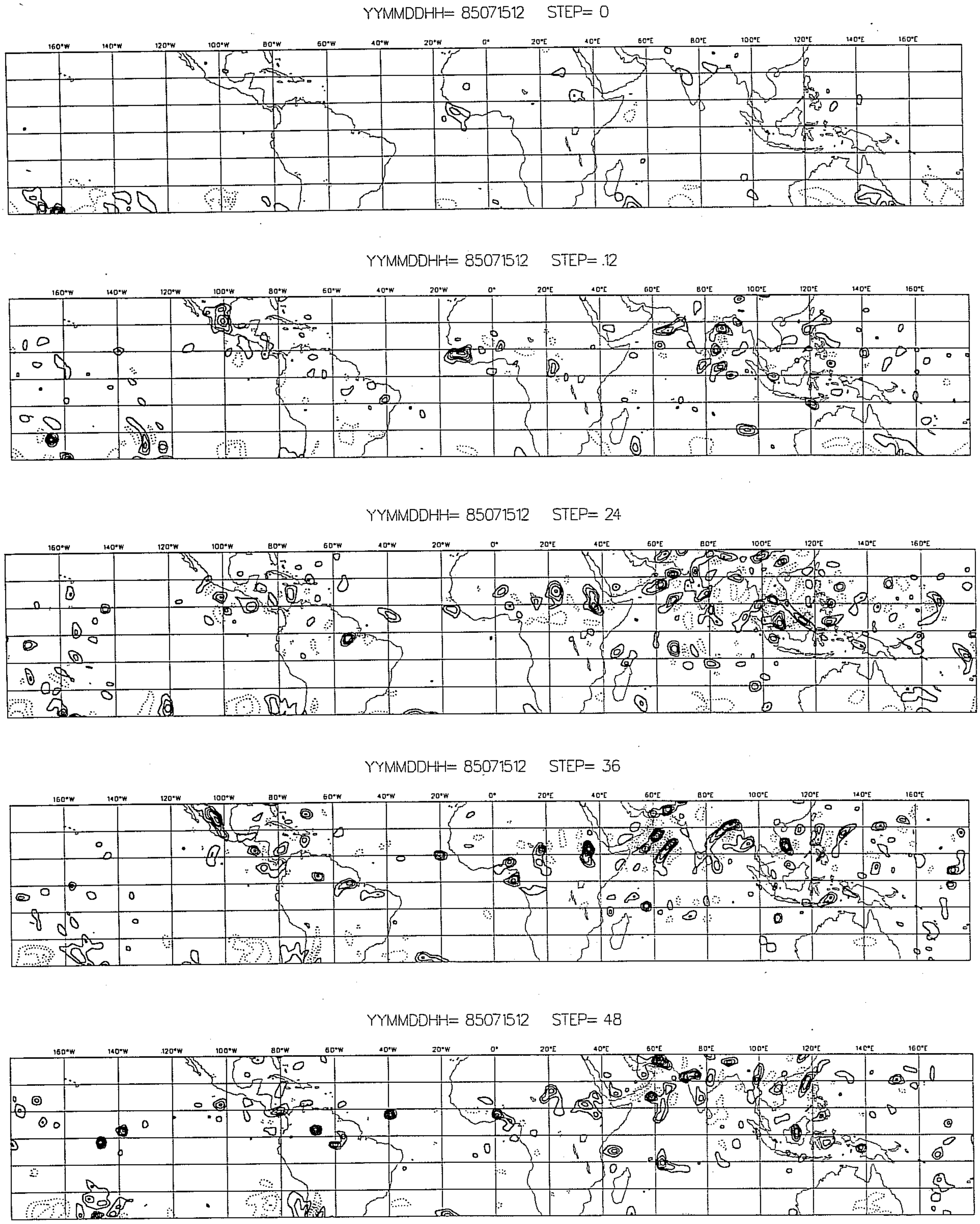


Fig. 21 Forecast time sequence of vertical velocity at 500 mb and between 30°N and 30°S. Solid lines indicate rising motions.

forecasts (Fig.22) is lost rapidly after D2. At D3 the upper tropospheric outflow is reduced by about 50%. An explanation for this model behaviour requires consideration of the zonally asymmetric part of the flow which is not discussed here.

(e) Humidity

We have seen in Fig.10 that the shallow convection scheme makes the analysed PBL generally dryer, particularly in the tropics. This is further confirmed in Fig.23 where the tropical and subtropical specific humidity in the lower half of the atmosphere (1000 to 500 mb) has a smaller magnitude since May 1985 (cf. Figs. 23b and 23d). A relatively uniform decrease of humidity during the course of the forecast before May 1985 has been changed to a sharper drop in the first three days and a very small decrease thereafter.

This sharp decrease in the zonal mean humidity, [q], since May 1985 can be associated to a strong model spin-up in early stage of the forecast. The drying is very intense in the first three days because of large difference between precipitation and evaporation (Fig. 24c). In the same figure the February and June 1984 monthly mean values are shown, and they correspond to the periods before and after the increased diffusion on divergence in March 1984 was introduced. Thus, the increase in precipitation in June 1985 is closely related to the spin-up in vertical velocity field as discussed in the paragraph (c) above. In the tropical region (15°N - 15°S) the maximum excess in precipitation over evaporation in June 1985 is 2.5 mm/day at D1.5, while in June 1984 it reaches 1.4 mm/day at D5.5. The global hydrological budget displays a similar qualitative pattern. From the global budget it can be concluded that hydrological balance, i.e. the balance between precipitation and evaporation, is established earlier (between D5 and D6) with the new

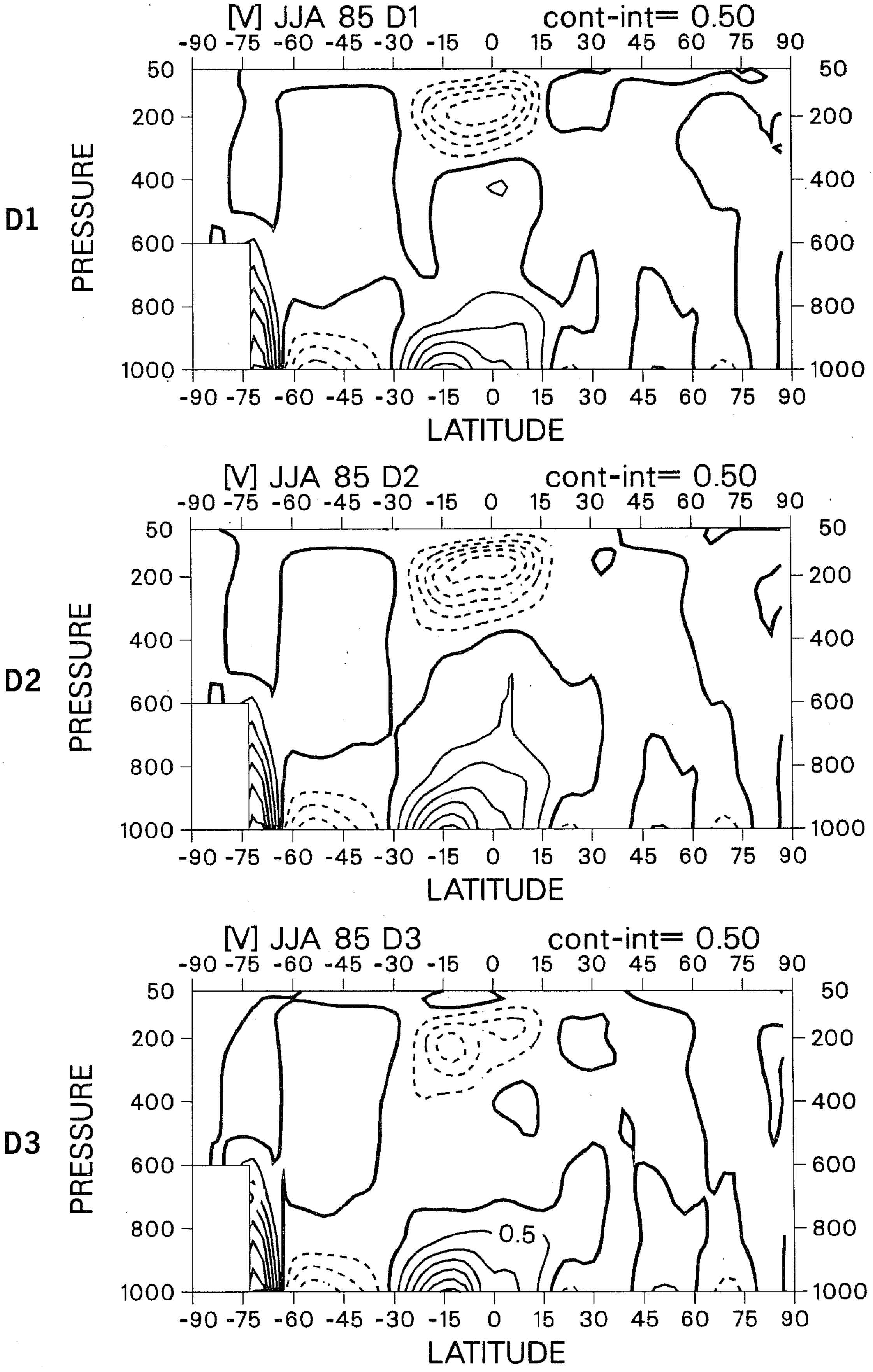


Fig. 22 Forecast time sequence of cross-sections of mean meridional wind (m/s) in JJA 1985. Contour interval 0.5 m/s.

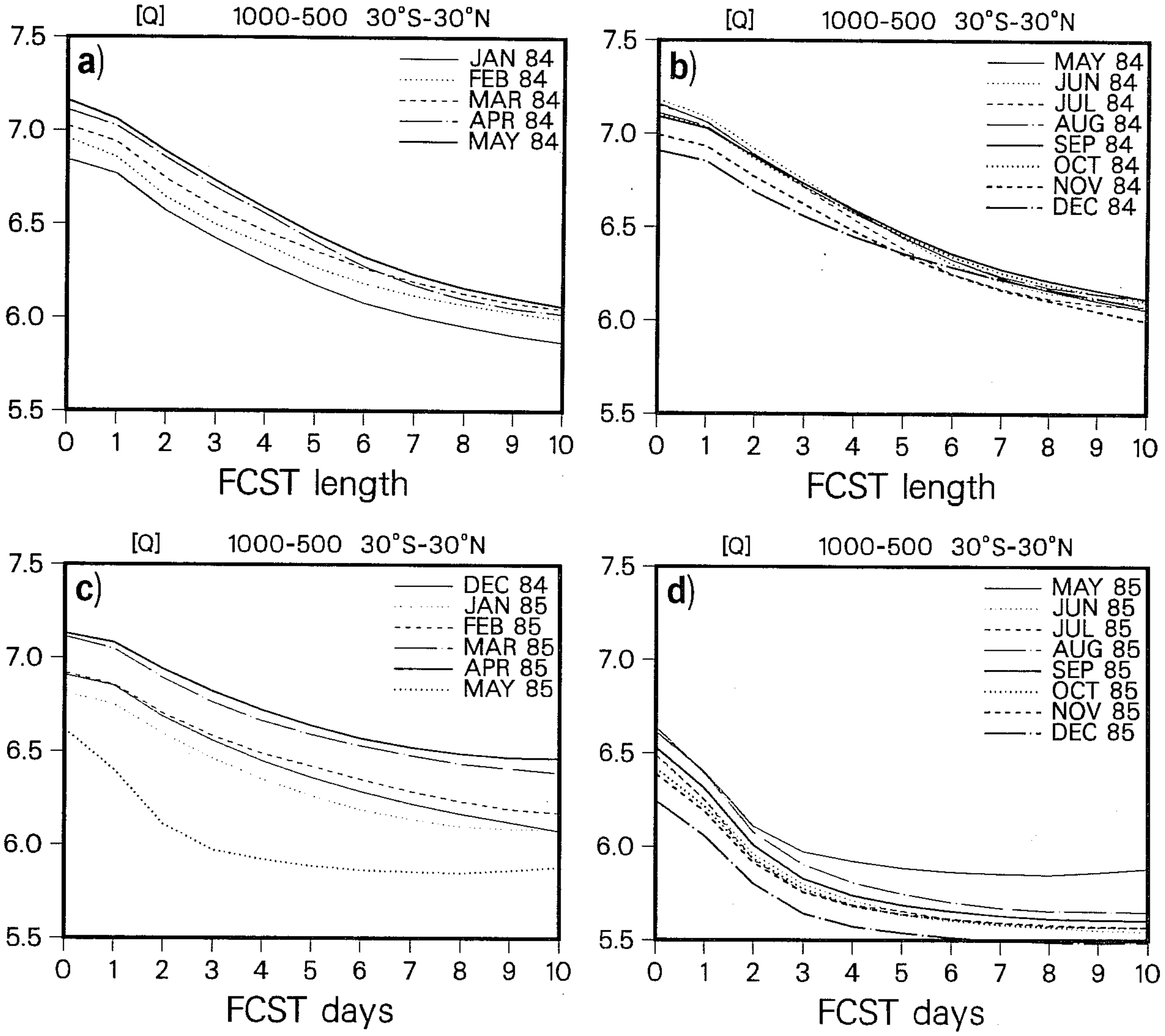
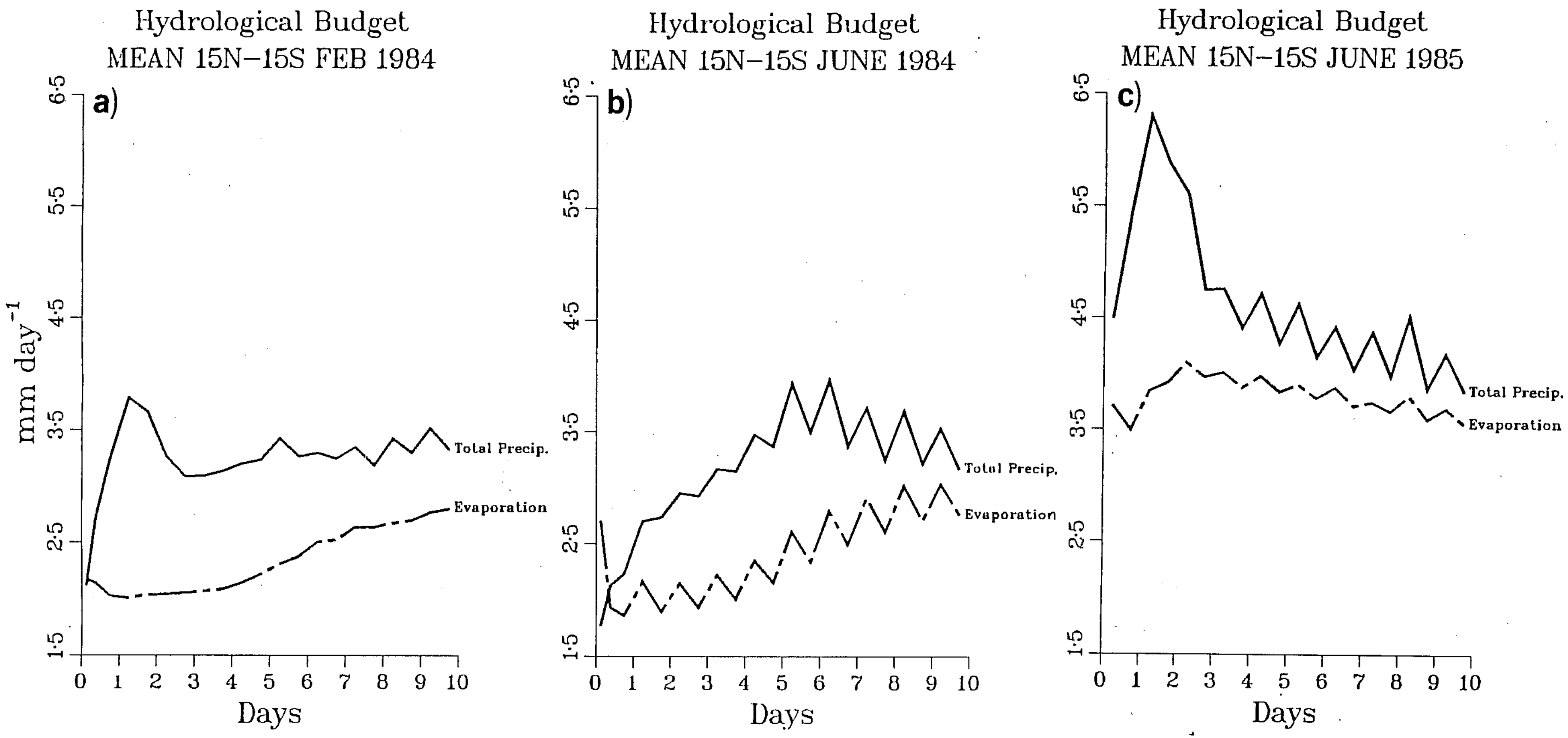


Fig. 23 Forecast time diagram of mean area zonal mean specific humidity (g^2/kg^2) over 30°S to 30°N, and between 1000 and 500 mb for a) January to May 1984, b) May to December 1984, c) December 1984 to May 1985 and d) May to December 1985.


Hydrological Budget
MEAN 15N–15S FEB 1984

Hydrological Budget
MEAN 15N–15S JUNE 1984

Hydrological Budget
MEAN 15N–15S JUNE 1985

Fig. 24 Precipitation and evaporation budgets (mm/day) in the tropics (15°N to 15°S) in a) February 1984, b) June 1984 and c) June 1985.

model. This can be seen in a leveling-off of the moisture mean field (Fig. 23d); this balance was reached by D10 in the earlier model (Heckley, 1985a).

It was shown earlier that the shallow convection and revised penetrative convection have a beneficial impact on the distribution of the analysed moisture. However, the moisture forecast error pattern looks very much the same as that before May 1985 (Fig.25). The largest forecast error is in the tropics at 700 mb and this error is made slightly worse with the new model.

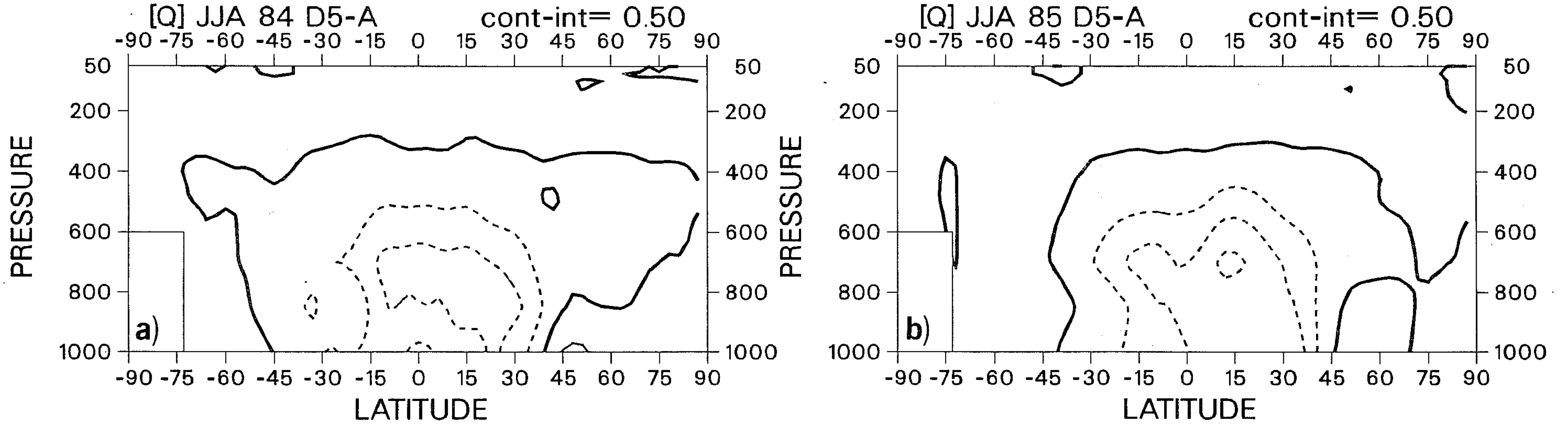


Fig. 25 Error in forecast of zonal mean specific humidity at D5 in a) JJA 1984 and b) JJA 1985. Contour interval is 0.5 g/kg.

5. ENERGETICS OF THE FORECAST

Some aspects of the model's energetics have been briefly discussed already in Section 4.3. It was concluded that, due to the impact of the modified radiation, there was a change in the atmospheric stability and partly because of this both zonal and eddy available potential energy have been reduced. In this section a further discussion on the energetics is given. The qualitative differences in most energy terms, arising from analysis or model modifications, are relatively small; they are mainly of a quantitative nature. In other words, apart from a few exceptions, the energy tendencies during the course of the forecast have not been changed dramatically during 1984 and 1985. However, in virtue of the nature of these tendencies, they need some more attention. No attempt to find causes for such an energy behaviour was made; we shall restrict ourselves merely to a description.

In Fig.26 some of the energy terms from the Lorenz energy cycle for the northern hemisphere are shown. Fig. 26a displays available potential and kinetic energies and Fig. 26b energy conversion terms. The conversion terms include conversion from zonal to eddy available potential energy, CA, from eddy available potential to eddy kinetic energy, CE, and from zonal to eddy kinetic energy, CK. Three winters (DJF) - 1983/84, 1984/85 and 1985/86, and two summers (JJA) - 1984 and 1985 are presented. Winter 1985/86 is in principle beyond the scope of this study but it is included to get an idea about the winter energetics after the introduction of the May 1985 modifications. The zonal and eddy terms are treated separately. The energy densities and conversions are given for the first two wave groups, since, according to Arpe et al. (1986), a major contribution to the total eddy energy budgets comes from wavenumbers 1 to 9.

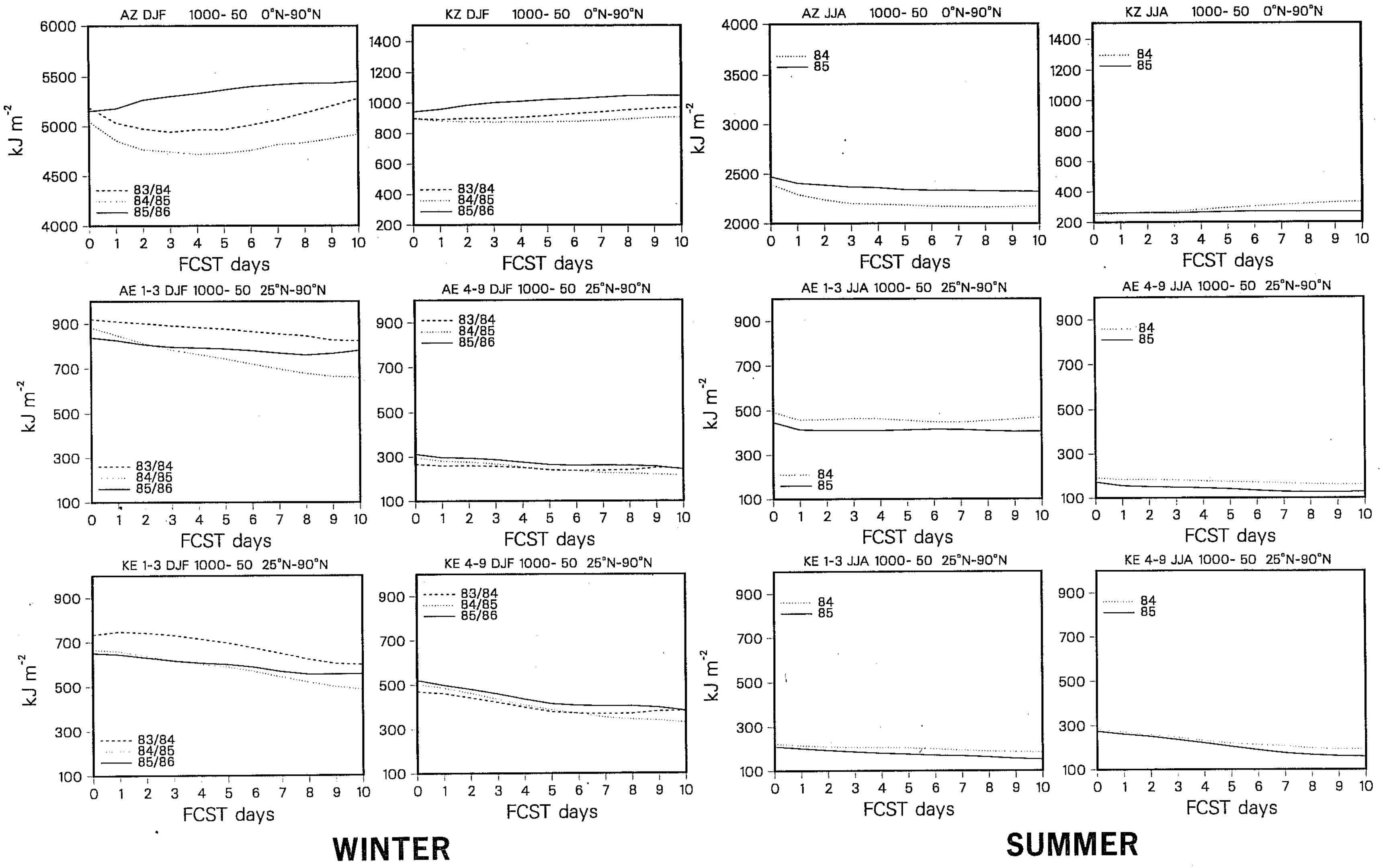


Fig. 26 Forecast time diagrams of a) energy terms and b) energy conversions in DJF seasons (left) and JJA season (right) for the northern hemisphere (AZ and KZ) and the northern hemisphere extratropics integrated between 1000 and 50 mb.

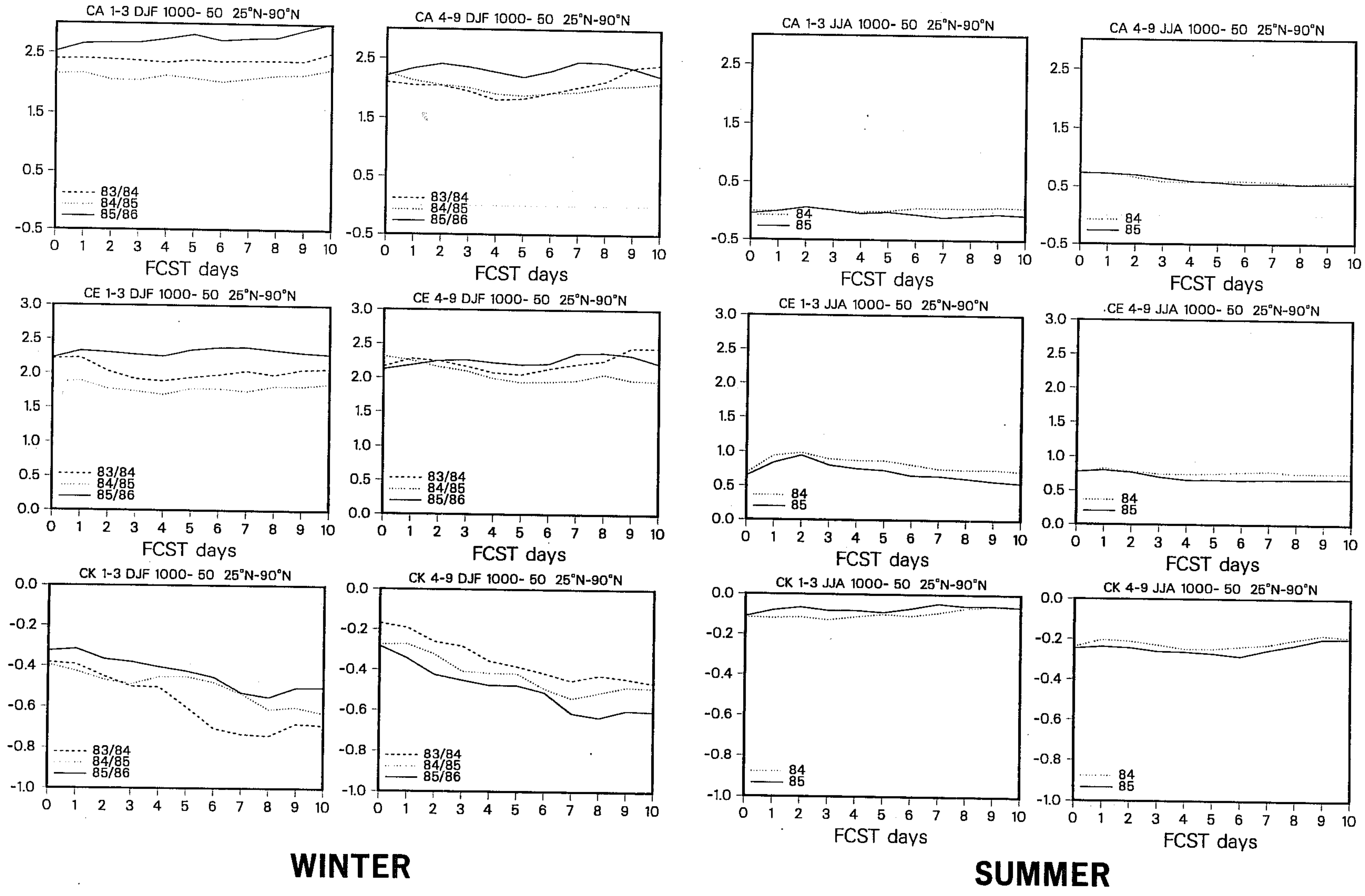

CA 1-3 DJF 1000- 50 25°N-90°N
CA 4-9 DJF 1000- 50 25°N-90°N
CA 1-3 JJA 1000- 50 25°N-90°N
CA 4-9 JJA 1000- 50 25°N-90°N
CE 1-3 DJF 1000- 50 25°N-90°N
CE 4-9 DJF 1000- 50 25°N-90°N
CE 1-3 JJA 1000- 50 25°N-90°N
.CE 4-9 JJA 1000- 50 25°N-90°N
CK 1-3 DJF 1000- 50 25°N-90°N
CK 4-9 DJF 1000- 50 25°N-90°N
CK 1-3 JJA 1000- 50 25°N-90°N
CK 4-9 JJA 1000- 50 25°N-90°N
83/84
84/85
85/86
84
85
FCST days
0 1 2 3 4 5 6 7 8 9 10
2.5
1.5
0.5
-0.5
3.0
2.0
1.0
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
WINTER
SUMMER

Fig. 26 b)

5.1 Zonal available and zonal kinetic energy

The magnitude of the analysed AZ has hardly changed in both winter and summer seasons. The existing differences are still within the interannual variability as it was found by Arpe et al. (1986).

The AZ is sensitive to the changes in the difference between zonal and global mean temperature (see Oriol, 1982 for definition of the energetics). It has lower values in winter 1984/85 after the introduction of a modified radiation scheme. This decrease can be found at almost all levels except the lowermost (1000 mb) level and 150 and 100 mb levels (not shown). The tendency in the forecasts remains the same as in winter 1983/84. The T106 model and revised parameterization affect the difference between zonal and global mean temperature and this is reflected in the changes of the AZ trend in the forecasts for DJF 1985/86 - there is a steady increase of the AZ during the course of the forecast. However, the trend in summer (JJA 1985) has not been changed significantly.

The zonal kinetic energy, KZ, shows relatively small changes in behaviour in the forecasts. A characteristic feature is a steady increase during the winter forecasts. This increase is most marked in DJF 1985/86, i.e. since the T106 model was introduced. In JJA 1984, predicted KZ departs slightly from the verifying analyses, but this trend is corrected by the new model.

5.2 Eddy available and eddy kinetic energy

Eddy energy is shown for the northern hemisphere extratropics. The contribution of the long waves (wavenumber 1 to 3) to the total eddy available potential energy, AE, is larger than that of the medium waves (4 to 9). There is a slow but constant decrease of the AE in both wave groups in winter forecasts, which is reduced with the introduction of the new model. In summer, after a characteristic drop at D1 in the long waves, there is almost no significant change in the AE thereafter. The loss of the AE in the medium waves is stronger in JJA 1985.

The relative contributions of the first two wave groups to the total budget of the eddy kinetic energy, KE, vary with season: the long waves dominate in winter and medium waves in summer. The KE displays a similar trend during the course of the forecast in all five seasons shown. There is a steady decrease relative to the verifying analyses. An exception is DJF 1983/84 when there was a slight increase in the KE in early part of the forecasts. An improvement can be noticed in long waves in DJF 1985/86 when the drop in the second part of the forecast is less intense. However, no similar pattern in summer 1985 could be found.

Because of its importance in the energy cycle, the KE term will be considered in somewhat more detail. Fig.27 shows contributions of long and medium waves to the global mean of the KE in JJA 1985 and DJF 1985/86 at 250 mb (maximum wind level), 500 mb and 850 mb at D5 and verifying analyses. For the northern hemisphere the following can be concluded. In summer (upper panels), contribution from the long waves in both analyses and forecasts is largest in high latitudes. In winter, in addition to the above maximum, there is another maximum at about 35°N at 250 mb and 500 mb, and at 60°N at 850 mb. The largest contribution of the medium waves in the northern hemisphere summer is found at 50°N. In winter, the maximum at 250 mb is at about 40°N and is shifted poleward at lower levels. Similar patterns are found in other northern hemisphere summer and winter seasons.

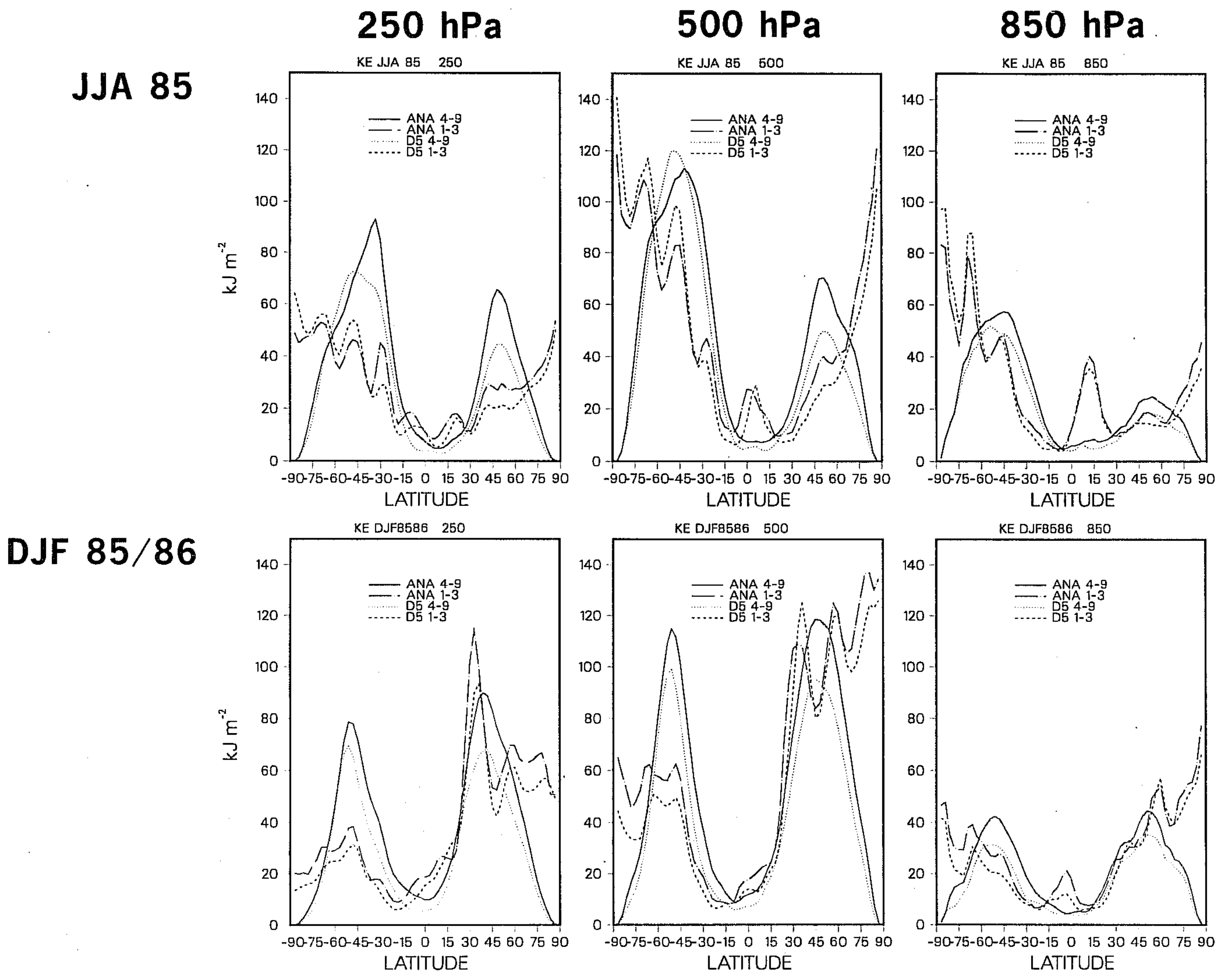


Fig. 27 Latitudinal distribution of analysed and D5 eddy kinetic energy for long (1 to 3) and medium (4 to 9) waves at 250 (left), 500 (middle) and 850 mb (right) in JJA 1985 (upper panels) and DJF 1985/86.

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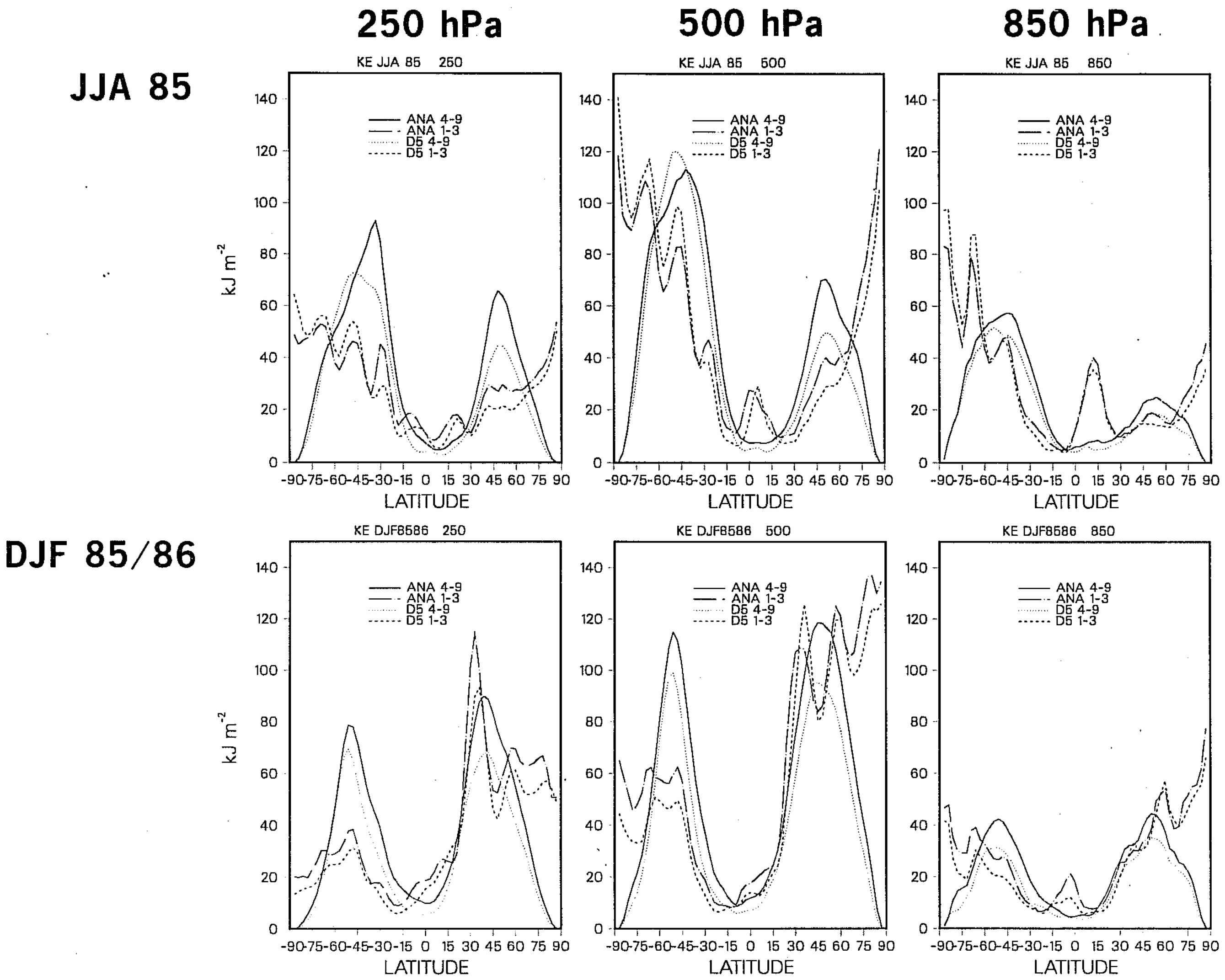

Fig. 27 Latitudinal distribution of analysed and D5 eddy kinetic energy for long (1 to 3) and medium (4 to 9) waves at 250 (left), 500 (middle) and 850 mb (right) in JJA 1985 (upper panels) and DJF 1985/86.

Apart of few exceptions, the loss in the KE at D5 is dominant feature at almost all northern hemisphere latitudes and all three levels. The latitudinal distribution of the largest loss in the KE during the course of the forecast is closely related to the largest values of the KE. The greatest drop of the KE in summer in both long and medium waves occurs in the latitudinal belt between 40°N and 65°N. In winter, the area of the largest drop is widened equatorward to about 30°N. Similar consideration can be applied to the southern hemisphere. By comparing the D5 maxima with the verifying analyses of the KE due to medium waves, one finds that they are shifted poleward at all three levels considered and in both summer and winter seasons. The shift is stronger in winter (JJA season). However, in the two previous DJF seasons (southern hemisphere summer) there was no such a shift and therefore it might be attributed to the new model introduced in May 1985. In winter (JJA) 1985, one finds an increase of the KE in long waves at D5 at higher latitudes and at all levels.

The KE term is calculated from the u and v-wind variances. At 250 mb the largest contribution to the drop of the KE in long waves comes from a decrease in the u-wind variance and there is almost no loss in the v-wind variance; in medium waves the drop in the KE comes mainly from the decrease of the v-wind variance, though the loss in the u-wind variance is considerable as well (Fig.28). A similar result, but with a smaller intensity, is found also for 500 and 850 mb. A larger decrease in the v-variance compared to the u-variance in medium waves in mid latitudes may indicate a gradual loss of amplitude of large eddies during the course of the forecast. A shift in the maximum of the KE in the southern hemisphere is due to a shift in the v-variance maximum.

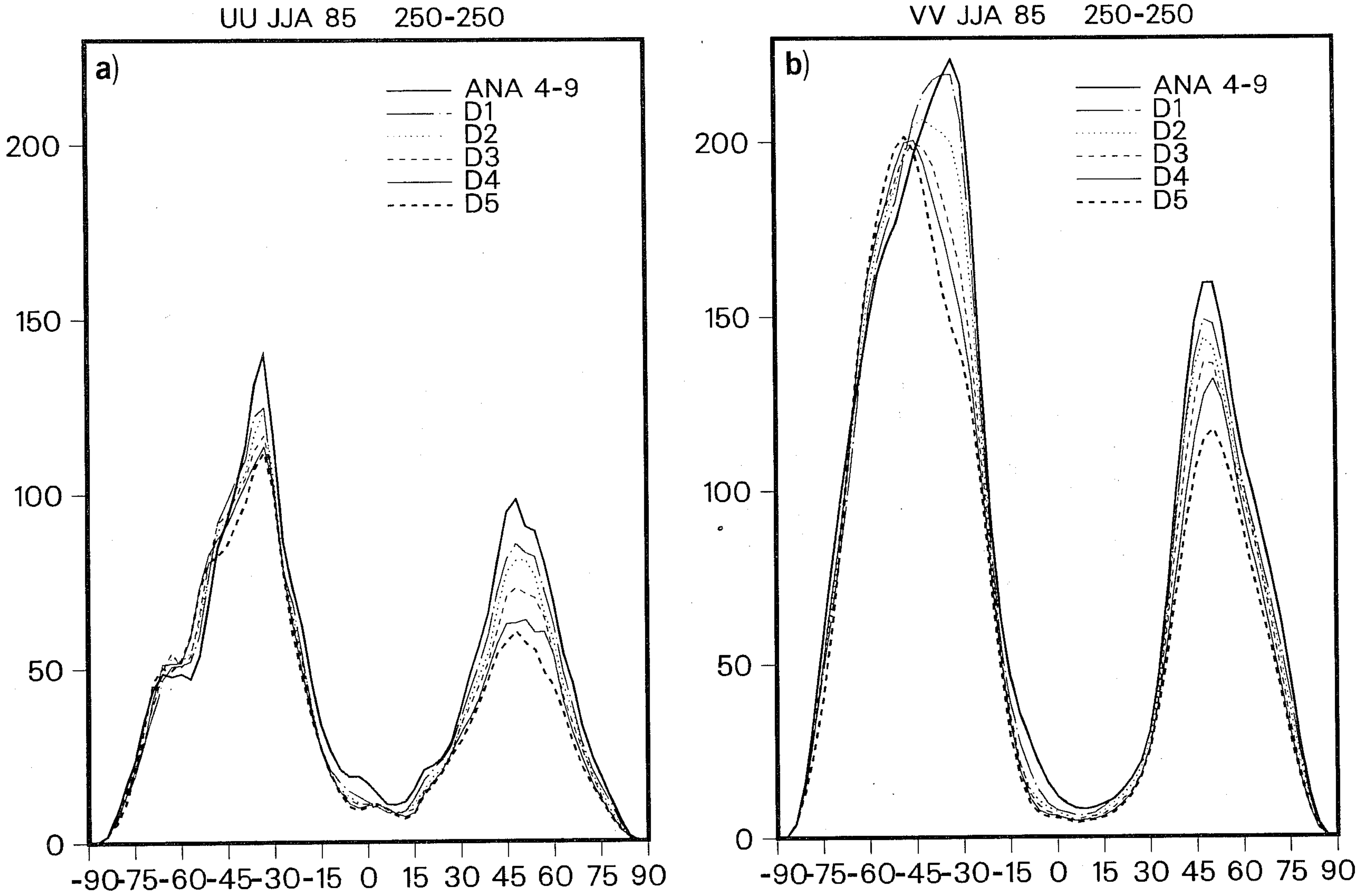

Fig. 28 Latitudinal distribution of the JJA 1985 variance of a) u-wind and b) v-wind at 250 mb for medium waves (wavenumbers 4 to 9) during the first five forecast days. Verifying analysis is depicted by a thicker solid line.

5.3 Energy conversions

The energy conversion terms (Fig. 26b) show the expected energy cycle in the winter season. In summer a negative CA in long waves is found, and generally much weaker conversions took place. There are no large differences in the CA trends during the forecast, but the magnitude increases significantly in winter 1985/86. The eddy baroclinic conversion CE becomes less changeable during the forecast in winter 1985/86 when compared with the previous winters, and with a higher values. In summer no difference in the CE trends can be seen but the intensity is decreased in JJA 1985. The CK in long waves is smaller in winter 1985/86 with a somewhat reduced increase during the forecast. By contrast, it is larger in medium waves during the same season. An increase in the CK is related to increased horizontal tilt of the waves (Arpe and Klinker, 1986). In summer, the same behaviour can be noticed: a weakening of the CK in long waves in JJA 1985 when compared with 1984 and an increase in medium waves.

Since there are no dramatic changes in the CE during the forecast in the wintertime, though some variations are obvious, than we can partially ascribe the decrease in the KE (Fig. 26a) to the CK conversion. The negative CK acts as a sink for the KE because the zonal flow is fed at the expense of eddy kinetic energy. An increase in the CK should therefore mean a decrease in the KE. The relationship is not, of course, straightforward but rather complex and this is only a rough estimate on the basis of the diagrams shown. A more complete assessment should include dissipation and non-linear interactions whose contributions to the KE budget are very important. It seems that these two factors play a more important role in the summer season, since the drop in the KE cannot be explained by simply looking at the conversion terms.

6. CONCLUDING REMARKS

We have discussed the effects of modifications, introduced during 1984 and 1985 into the ECMWF analysis/forecast system, on the ECMWF operational analyses and forecasts using zonally averaged diagnostics.

Most of the modifications affect the zonally averaged diagnostics of the analysis very slightly or their effects are masked by annual and interannual variability. The increased diffusion on divergence (operative between March 1984 and May 1985) damps the vertical velocity on a smaller scales and reduces conversion between eddy available potential and eddy kinetic energy (CE). The diurnal cycle has an effect limited to the lowermost troposphere. No siginificant change in the zonal mean diagnostics due to revisions to the analysis and modified radiation scheme was found. The largest impact on the analysis comes from the revised penetrative convection and shallow convection introduced in May 1985. It is seen as a warming of the tropical troposphere and as a strengthening of the mean meridional circulation. The distribution of moisture is improved - the planetary boundary layer is deepened and well mixed.

The impact on the forecast is much larger than that on the analysis. All basic fields have undergone a change of some sort and many of the model systematic errors are substantially reduced.

The temperature field exhibits constant improvements as modifications have been introduced. The correction of the moisture dependence of specific heat decreases the erroneous warming near the tropical tropopause. The new radiation formulation reduces this warming further and removes a cooling in the tropical stratopshere. The mid-tropospheric cooling was reduced as well, and by May 1985, i.e. when the new high resolution model and revised physics were introduced, this cooling is reduced even further. A slight warming of most of the atmosphere is now a dominant feature in the temperature field. The strong vertically 'layered' structure in the temperature error field has been removed.

The mean zonal wind sustains changes since May 1985 as well. In the season JJA 1985, the jets are subject to an equatorward instead of a poleward shift with strengthening instead of weakening of the core values. Thus, a decrease of westerlies or an increase of easterlies in the tropics is no longer a dominant feature in the northern hemisphere summer.

A stronger mean meridional wind as it was found in the analysis after the introduction of the May 1985 modifications is not maintained in the forecasts beyond day 3; thus a weakening in the [v] is still apparent, though a somewhat better predicition than before may be claimed.

The predicted distribution of specific humidity is much improved since May 1985. The planetary boundary layer and tropical mid-troposphere are less moist, and the subtropics are more moist. The error structure in the humidity forecasts has not been improved very much.

The new radiation scheme acts beneficially on the tropical ω-variance, especially in the later stage of the forecast. The May 1985 modifications, which restored a weaker diffusion on divergence, emphasize the model spin-up problem. This is one of the most marked deficiencies found in the zonal diagnostics data. Although the tropical ω-variance is linked with the deep convection it is not clear whether the spin-up is related to deficiencies in the initial state or deficiencies in the parameterization of deep convection or to some other cause. Besides a large increase in ω-variance in the first two days of the forecast, the spin-up is reflected in too much precipitation (which is closely related to vertical velocity) in the early stage of the forecast and therefore leads to a drying of the model atmosphere in the same period. The hydrological balance is established earlier than before.

The improvement of basic fields in the tropical forecasts is of special importance, because the model systematic errors in the tropics have been very large (Kanamitsu, 1985; Heckley, 1985a, 1985b).

It may be concluded, that the modifications of the analysis/forecast system give better analyses and predictions of zonally averaged basic fields. However, this is only partially reflected in the energetics. Eddy energies, and eddy kinetic energy in particular, still display large error growth. They are decreasing continuously during the course of the forecast and their contribution to the model's total energy is constantly reduced. The problem is most pronounced in wave numbers 4 to 9. Diabatic terms of energy cycle (energy generation and dissipation) could help to understand the energetic problems mentioned above. However, in the present calculation they are derived as residuals from other known energy terms and therefore their use is limited.

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