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WORKSHOP ON CLOUD PHYSICS AND CLIMATE

23 November - 20 December 1985

Technical Report No. 49

A STUDY OF THE PREDICTABILITY OF THE ECMWF OPERATIONAL FORECAST MODEL IN THE TROPICS

By
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European Centre for
Medium Range Weather Forecasts

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September 1985

Abstract

The predictability of the operational ECMWF forecast model in the tropics has been studied using the archived data for 1983 and 1984. The predictability of the very large scale quasi-stationary motions and the transient motions are examined separately.

The very large scale motion is predictable (as measured by the ratio of the root mean square error to the climatological standard deviation) only up to 2 days in the tropics. This is very short compared to about 6 days in the northern hemisphere mid-latitudes and about 4 days in the southern hemisphere. The largest part of the error is found to be due to the systematic error; about 70-90% of the total error can be explained in this way. The systematic error has a structure similar to the gravest internal symmetric Rossby mode of zonal wavenumber 1, but it grows without propagation. Several forecast experiments have been performed to isolate the cause of the systematic error. It has been shown that the error is most sensitive to the convective heating distribution in the tropics, indicating a major weakness of the convective parameterization in the model.

The predictability of the transient disturbances in the tropics is examined using the time filtering technique. The results indicate that the disturbances are predictable up to or beyond 4 days over the central Atlantic and over the central Pacific. However, the forecast skill is low over the far western and the far eastern parts of the Pacific ocean where disturbances develop into tropical storms. This is considered to be due to the resolution of the model being too coarse for predicting tropical storm development. The forecast is also not skillful in the Indian Ocean where satellite data is not available.

CONTENTS

1. INTRODUCTION

Shukla (1981) studied the theoretical short-range predictability of the tropical atmosphere by examining the growth rate of initial random errors in the GLAS climate model. He found that the predictability in the tropics is much shorter than that in mid-latitudes, i.e. the error grows to half of the climatological standard deviation in 2-3 days in the tropics while it requires 5-7 days in the middle latitudes.

The predictability of the real tropical atmosphere, using real data as input and verifying against real observations, can be much shorter than his results indicate. The major additional factors that may influence the practical predictability in the tropics are: (1) the poor observational coverage both in the horizontal and in the vertical, (2) difficulties in establishing dynamical and thermodynamical balance in the tropics in the analysis as well as in the initialization, and (3) insufficient accuracy in describing the diabatic heating processes in the model, which is crucial for tropical predictions.

The primary objective of this study is to examine the practical predictability of the tropical atmosphere by analyzing the forecast error of a large number of operational global forecasts carried out at ECMWF, and to find the essential factors for improving the tropical forecasts.

The tropical atmosphere is characterized by the dominance of very large scale (10000-40000 km) quasi-stationary systems with a time scale of 30-40 days. Embedded on these systems there are smaller scale (2000-4000 km) transient disturbances which have a life cycle of 3-4 days. Both these scales of motions are closely related to the major changes of the weather patterns in the tropics and are essential features to be predicted by the large scale numerical weather prediction models. Accordingly, in examining the predictability in the tropics, it is important to study both these scales.

Krishnamurti et al. (1983) subjectively verified the predictions of the very large scales in the tropics for the FGGE cases. They found that very large scale divergent circulations were not predicted well, and noted that the large scale forcing in the tropics was not properly handled in the model. A similar conclusion was reached by Heckley (1983a) who examined the systematic errors of the ECMWF operational forecast in the tropics using a large number of forecast cases, and focussed on the divergent circulations. He also pointed out that there are significant departures of the forecast divergent circulation from that observed, the largest error being situated over Africa and the Atlantic.

A number of subjective verifications of transient disturbance forecast in the tropics have been performed using case studies. Krishnamurti and Kanamitsu (1973), Krishnamurti et al. (1976), Chang (1982), and Sugi and Kanamitsu (1982) performed limited area predictions of typical tropical disturbances in various parts of the tropics, namely over the Caribbean, Africa, western Pacific and over India. These studies indicated that such disturbances are quite predictable, at least up to 3-4 days. Krishnamurti et al. (1983) also showed in their forecast experiment using a global spectral model that despite an unsatisfactory prediction of very large scale quasi-stationary systems, some of the transient disturbances (e.g. monsoon depressions) were reasonably well predicted even up to 6 to 8 days.

This paper discusses the predictive skill of the operational ECMWF model in the tropics, separating the very large scale motions and the smaller scale transient motions. The data used in this study is discussed in Section 2. Due to the dominance of the very large scale motions in the tropics, conventional measures of the predictive skill, such as the root mean square (RMS) error and the mean error computed over the global tropics provide a measure of the forecast skill for the very large scales. Section 3 deals with the results of such calculations; emphasis is placed on comparing the skill of the tropical forecasts with that in the northern and the southern mid-latitudes. The first part of Section 4 discusses the structure of the systematic error in the tropics, while the second part describes the results of the forecast sensitivity experiments performed to isolate the cause of the systematic errors in the tropics. Section 5 describes the predictive skill of the transient motions in the tropics by applying a time filtering technique to remove very large scale quasi-stationary motions. Conclusions and discussions are presented in Section 6.

2. DATA USED

The operational ECMWF forecast model has improved continuously since operational forecasting began in 1979. The increase in predictive skill during the period since then is apparent in the extratropics as well as in the tropics. Recent statistics of the forecast scores in the tropics reveal a continuous decrease of the 24 hour RMS forecast error of the 850 mb vector winds from 3.8 m/s in 1980 to 3.2 m/s in 1983 (Heckley, 1984).

The analyses and forecasts used in this study were taken from the most recent data available at the time the calculations were performed, i.e. from March 1983 to February 1984 (Nieminen, 1983). However, the forecast model and the analysis system went through several major improvements during the time of this study, and therefore, additional calculations were performed to examine the validity of this study using the very recent data archived after the major computations for this study had been completed (namely the data during the summer 1984). The general results did not change very much but it is certainly desirable to repeat this type of study whenever major changes in the analysis/forecast system take place.

With regard to the forecast models used during the period, a spectral model (Simmons and Jarraud, 1984) became operational on 24 April 1983 and this replaced a grid point model (Burridge and Haseler, 1977). Since February 1984, some additional changes have been introduced into the forecast system, namely the diurnal variation of solar radiation in early May 1984 and a revised analysis scheme in late May 1984. No significant changes have been made since May 1984.

The choice of parameters to be verified in the tropics needs some discussion. The forecasts of height and temperature in the tropics are not as useful as those in the extratropics, because of their small temporal variability. Therefore, for practical reasons, high priority is normally placed on the fields of wind and precipitation. In this paper we have concentrated on the wind field, and to some extent the mass field, because these are the fundamental dependent variables in the forecast equations. We consider that if these are not predicted with reasonable accuracy, examination of the predictability of other variables, such as moisture, precipitation and cloudiness, may not be very meaningful.

All the forecast verifications are made against the initialised analyses. The RMS differences between the analysed and the initialised fields are generally much smaller than the RMS forecast error. For reference, the zonally averaged RMS differences for the variables verified in this study are shown in Fig. 1. Note that the vertical scales of the figures are expanded compared to those shown later.

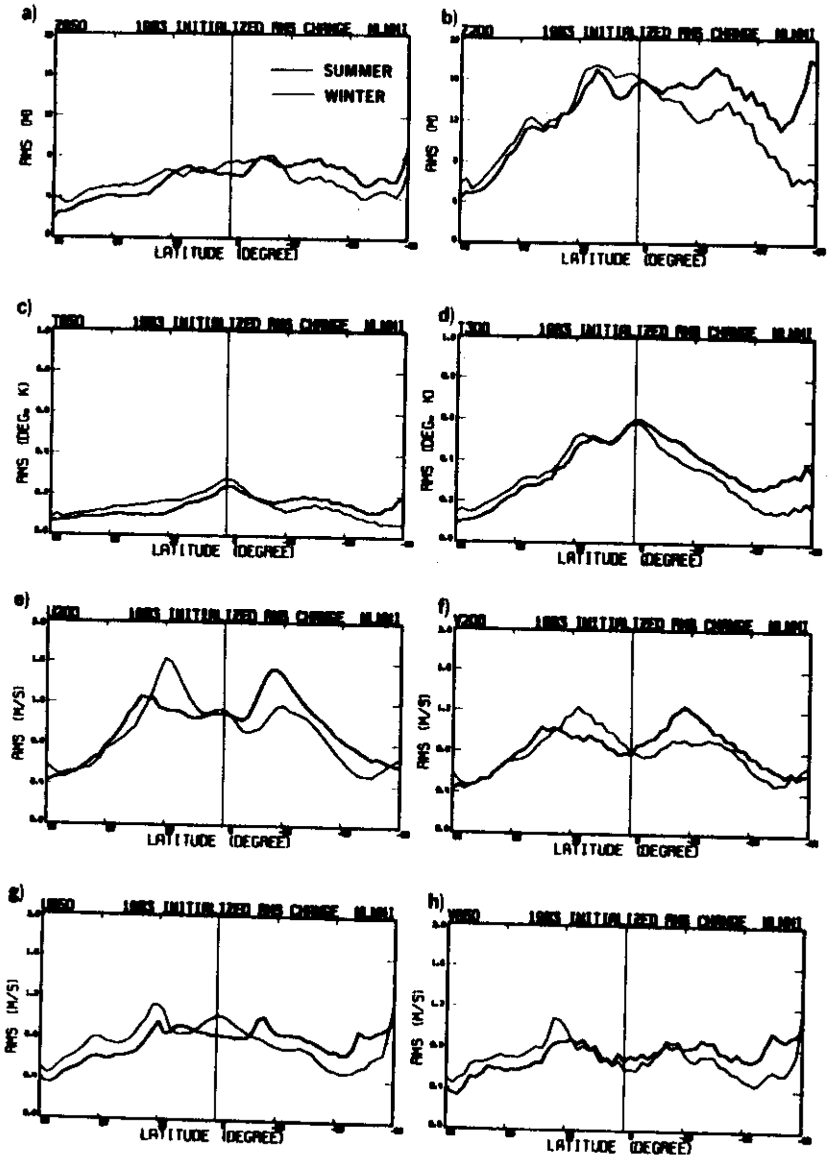

Fig. 1 Latitudinal variations of the root mean square difference between the analysed and the initialized fields for (a) 850 mb height, (b) 200 mb height, (c) 850 mb temperature, (d) 300 mb temperature, (e) zonal component of winds at 200 mb, (f) meridional component at 200 mb, (g) zonal component at 850 mb and (h) meridional component at 850 mb. Thick lines are for the summer 1983 and thin lines for the winter 1983/84.

3. PREDICTABILITY OF THE VERY LARGE SCALES

3.1 Zonally averaged scores for height and temperature

Fig. 2 shows the latitudinal variation of the RMS error of the 850 mb and 200 mb heights for summer 1983 and winter 1983/84 for the 24, 48, 72 and 168 hour forecasts. It is evident that the RMS error, as well as the growth rate of the error, are much smaller in the tropics compared to those in higher latitudes. The characteristics of the error in the tropics seem to be very different from those in the higher latitudes. The figure also shows that there is a much larger 24 hour forecast error in the southern hemisphere which indicates the effects of the poor observational coverage.

The small RMS error in the tropics does not necessarily imply better forecast skill because the temporal variability of the tropics is also small. To illustrate this the latitudinal variation of the climatological standard deviations for the period is shown in Fig. 3. It indicates that the temporal variability in the tropics is comparable to or even smaller than the RMS error. Seasonal variations of the standard deviations in the tropics are not very large, but slightly larger variability can be observed in the northern hemisphere winter. When the climatological standard deviation changes significantly from place to place, the ratio of the RMS error to the standard deviations provides a better measure of the predictive skill (Shukla, 1981). Fig. 4 shows the latitude versus forecast-day plot of this ratio. The shaded area indicates where the ratio is greater than 1.0, i.e. there is no forecast skill in terms of the RMS error. Clearly the predictability in the tropics is much less (less than 2 days) than that in the extratropics (5-7days) except for the 850 mb height in winter. The growth of 200 mb height error in the tropics is very large and is nearly linear in time; this suggests constant erroneous forcing in the model. Linear growth of RMS forecast error

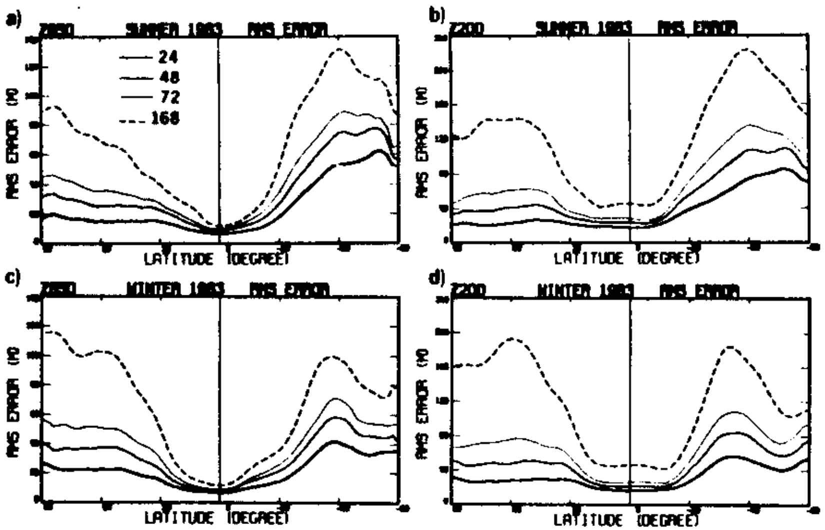

Fig. 2 Latitudinal variations of the root mean square error of height for (a) 850 mb in summer, (b) 200 mb in summer, (c) 850 mb in winter and (d) 200 mb in winter. Thick solid, solid, thin solid and dashed curves correspond to the forecast hours 24, 48, 72 and 168, respectively.

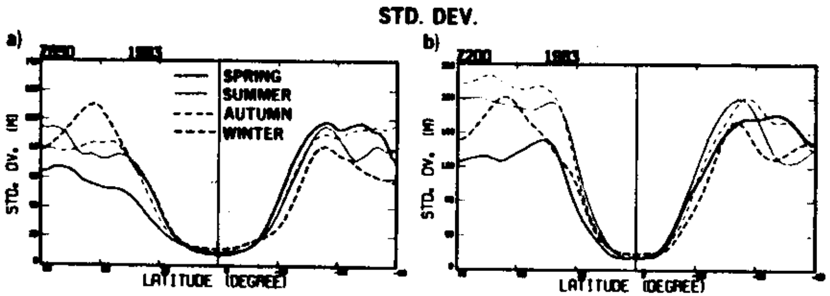

Fig. 3 Latitudinal variations of the climatological standard deviation of height, (a) for 850 mb and (b) for 200 mb for different seasons. Solid, thick solid, dashed and thick dashed curves correspond to spring, summer, autumn and winter, respectively.

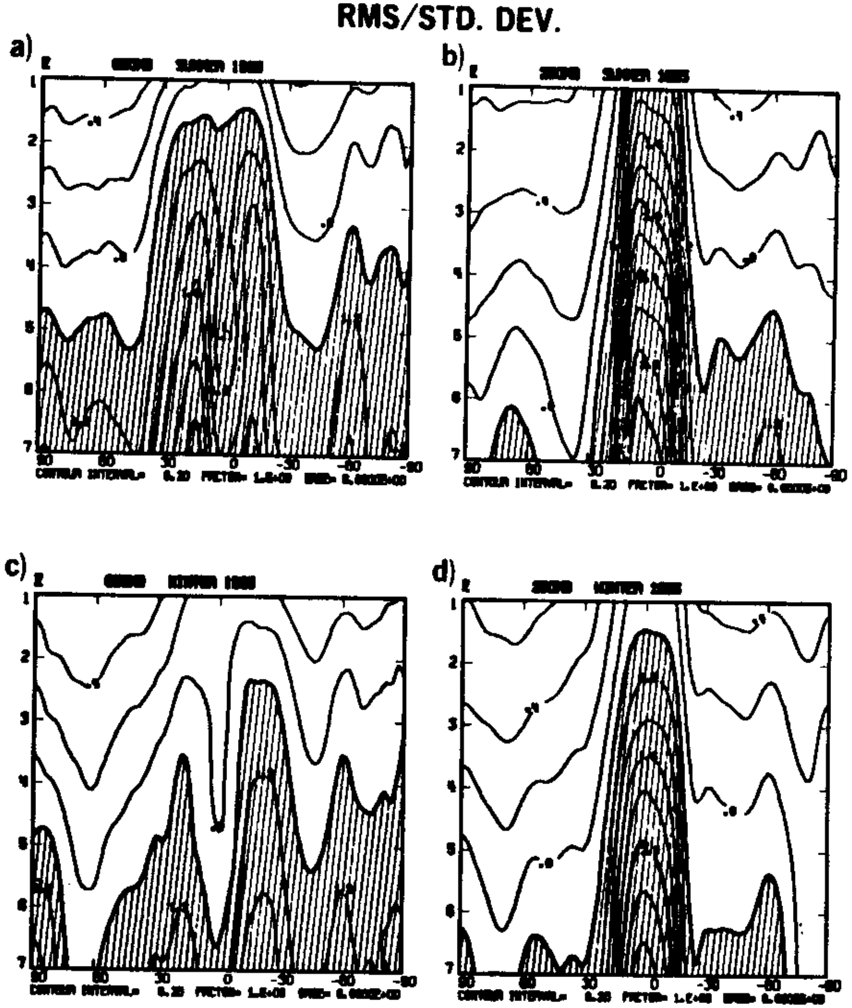

Fig. 4 The variations of the ratio of the root mean square error and the climatological standard deviation of height as a function of latitude (abscissa) and forecast time (ordinate) for (a) 850 mb in summer, (b) 200 mb in summer, (c) 850 mb in winter and (d) 200 mb in winter. The area of the ratio greater than 1.0 is shaded.

RMS/STD. DEV. (Filtered)

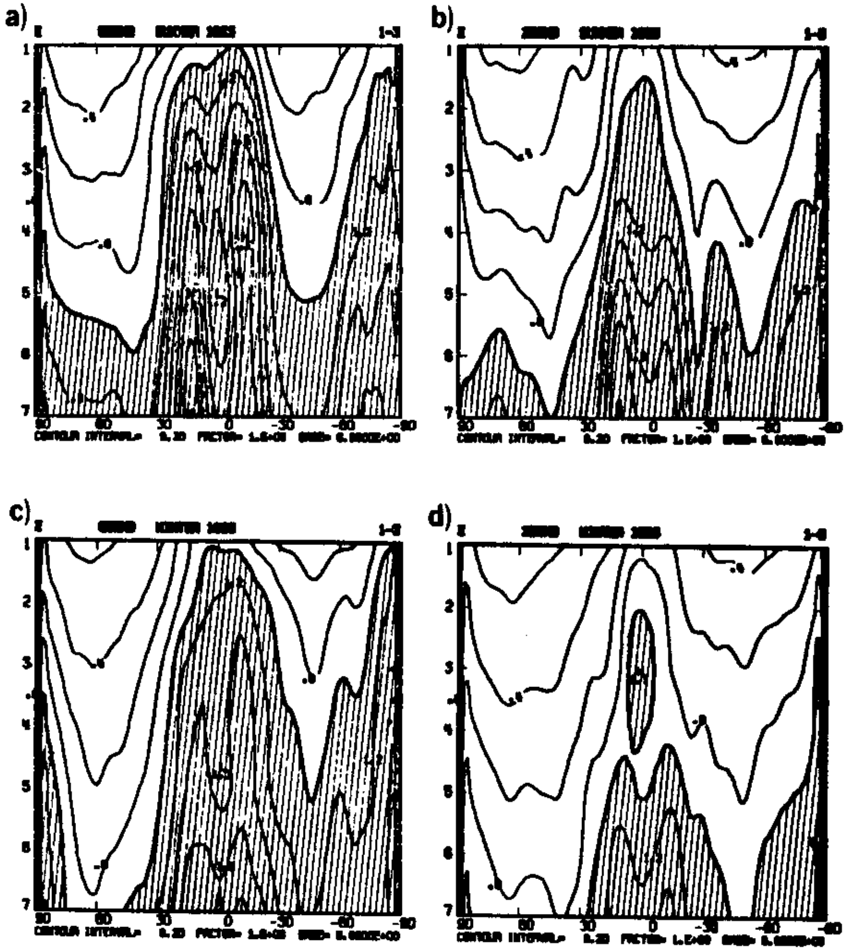

Fig. 5 Same as Fig. 4 except that the RMSE and the standard deviation are computed from zonally filtered (wavenumbers 1-3) data.

is also observed in middle latitudes (Arpe et al., 1985). The exceptionally good forecast of the 850 mb height in winter is unexpected. This may be simply due to the slightly larger climatological standard deviations in the winter as mentioned earlier, and may not necessarily indicate truly high predictability. Also note that the predictability of 850 mb height during the spring and the autumn are very similar to that in the summer.

The ratio of the RMS error to the climatological standard deviations has also been calculated for the very large scales (zonal wavenumbers 1-3). The predictive skill in these scales is somewhat different (Fig. 5) to that for all scales (Fig. 4). On this scale, the skill of the 850 mb height forecast in winter is reduced to only one day and for 200 mb it is increased to 2 days. This is mainly due to the error of the zonal mean field.

The growth of the forecast error is noteworthy. The error grows very fast in the tropics during the first 24 hours (the ratio reaches 0.7 to 0.8 in one day) compared to that in the extratropics (in one day the ratio barely reaches 0.4). The error growth slows down thereafter but continues in a nearly linear manner with a rate of about 1.0 in 5-7 days.

The latitudinal variation of the RMS error of the 850 mb and 300 mb temperature fields is shown in Fig. 6, the climatological standard deviations in Fig. 7 and the ratio of the RMS error and the climatological standard deviation in Fig. 8. In the tropics the predictive skill in the temperature field is similar to that of the heights. However, there is a major difference - the RMS error at the low level (850 mb) is larger than at the high (300 mb) level. Also the growth of the error again seems to be larger in the tropics, i.e. the 7 day forecast RMS error of the 850 mb temperature at the equator is 3.0 K which is approximately three times larger than the

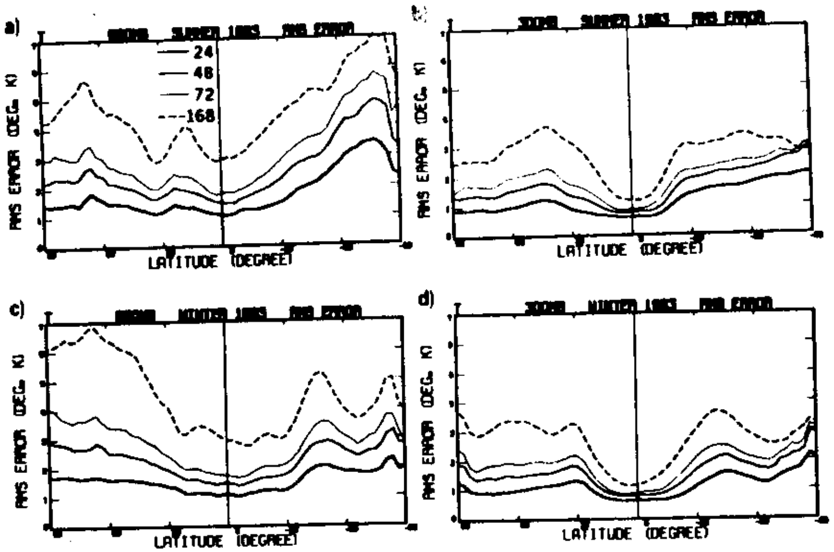

Fig. 6 Latitudinal variations of the RMSE of temperature for (a) 850 mb in summer, (b) 300 mb in summer, (c) 850 mb in winter and (d) 300 mb in winter. Thick solid, solid, thin solid and dashed curves correspond to the forecast hours 24, 48, 72 and 168, respectively.

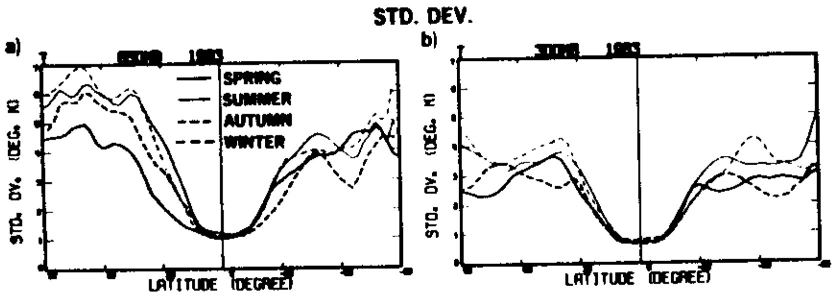

Fig. 7 Latitudinal variations of the climatological standard deviation of temperature, (a) for 850 mb and (b) for 300 mb for different seasons. Solid, thick solid, dashed and thick dashed curves correspond to spring, summer, autumn and winter, respectively.

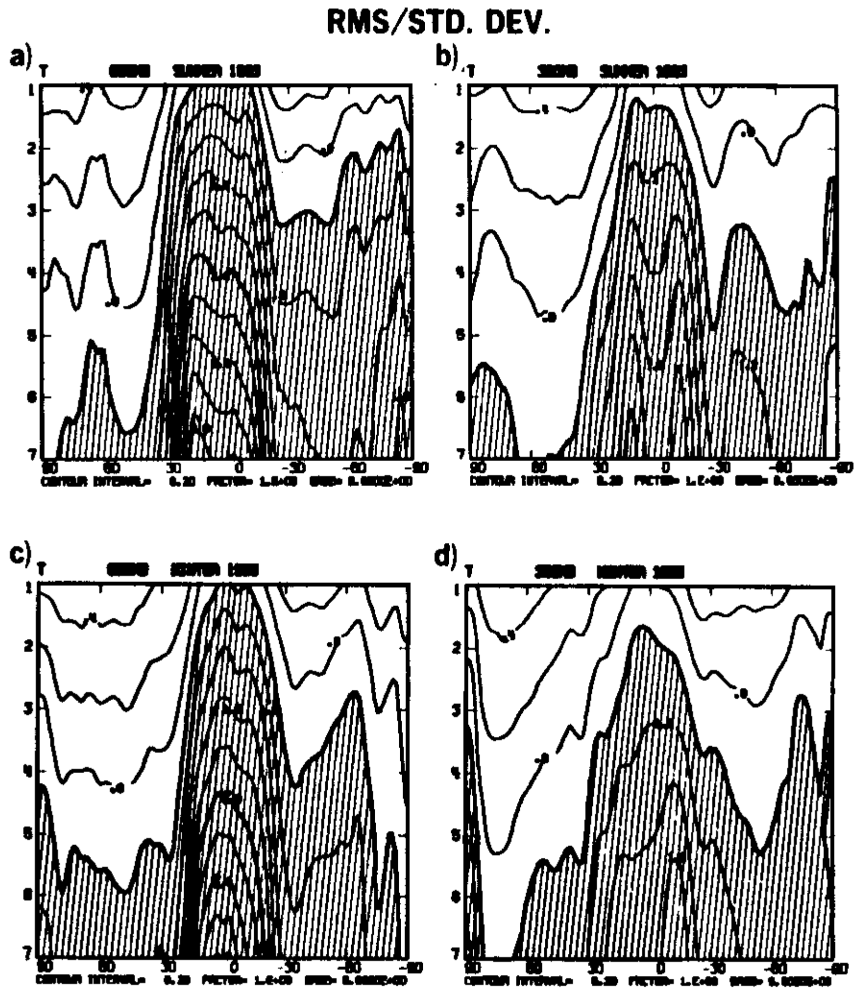

Fig. 8 The variations of the ratio of the root mean square error and the climatological standard deviation of temperature as a function of latitude (abscissa), and forecast day (ordinate), for (a) 850 mb in summer, (b) 300 mb in summer, (c) 850 mb in winter and (d) 300 mb in winter. The area of the ratio greater than 1.0 is shaded.

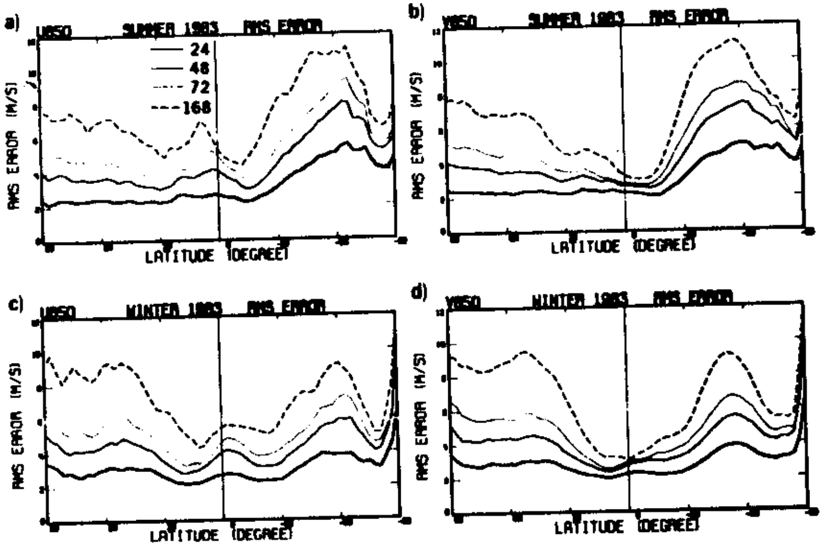

Fig. 9 Latitudinal variations of the root mean square error of wind at 850 mb for (a) zonal component in summer, (b) meridional component in summer, (c) zonal component in winter and (d) meridional component in winter. Thick solid, solid, thin solid and dashed curves correspond to the forecast hours 24, 48, 72 and 168, respectively.

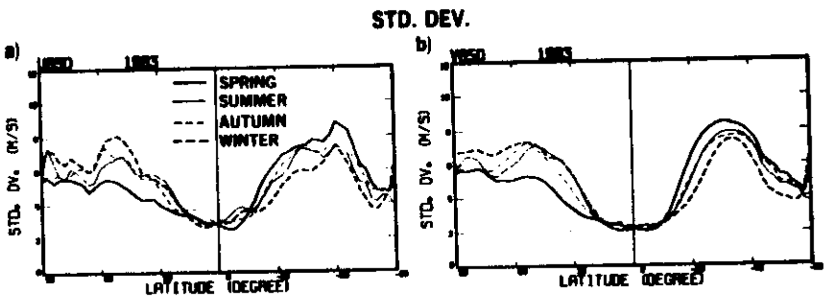

Fig. 10 Latitudinal variations of the climatological standard deviation of wind at 850 mb, (a) for zonal component and (b) for meridional component for different seasons. Solid, thick solid, dashed and thick dashed curves correspond to spring, summer, autumn and winter, respectively.

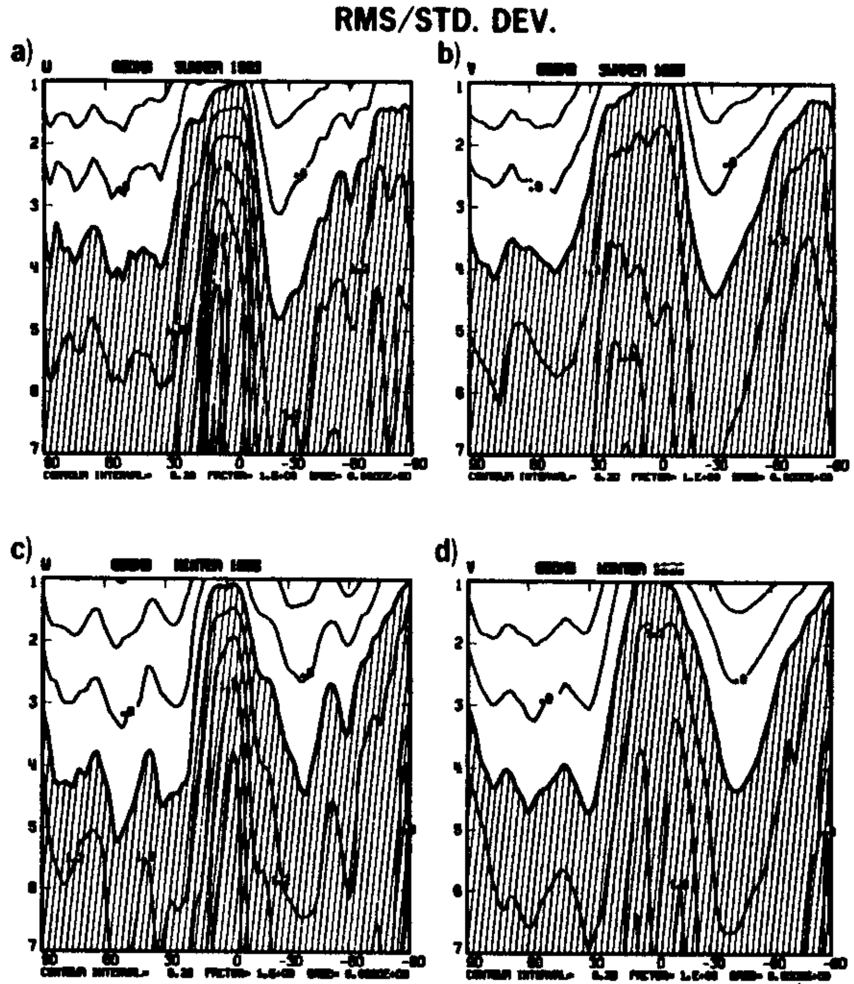

Fig. 11 The variations of the ratio of the root mean square error and the climatological standard deviation of winds at 850 mb as a function of latitude (abscissa) and forecast day (ordinate), for (a) zonal component in summer, (b) meridional component in summer, (c) zonal component in winter and (d) meridional component in winter. The area of the ratio greater than 1.0 is shaded.

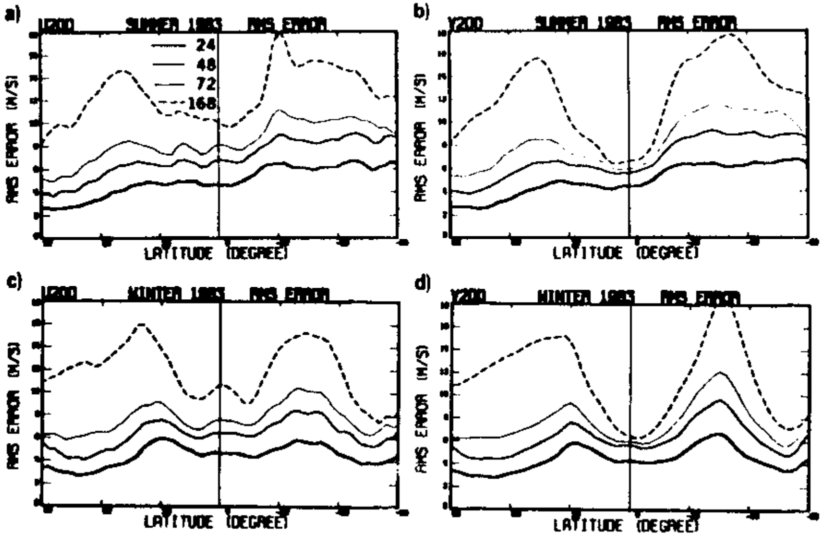

Fig. 12 Latitudinal variations of the root mean square error of wind at 200 mb for (a) zonal component in summer, (b) meridional component in summer, (c) zonal component in winter and (d) meridional component in winter. Thick solid, solid, thin solid and dashed curves correspond to the forecast hours 24, 48, 72 and 168, respectively.

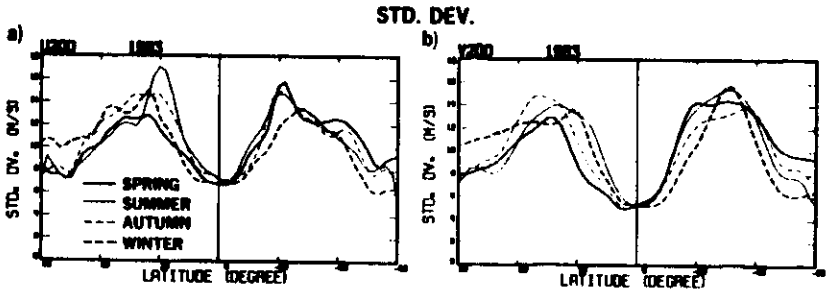

Fig. 13 Latitudinal variations of the climatological standard deviation of wind at 200 mb, (a) for zonal component and (b) for meridional component. Solid, thick solid, dashed and thick dashed curves correspond to spring, summer, autumn and winter, respectively.

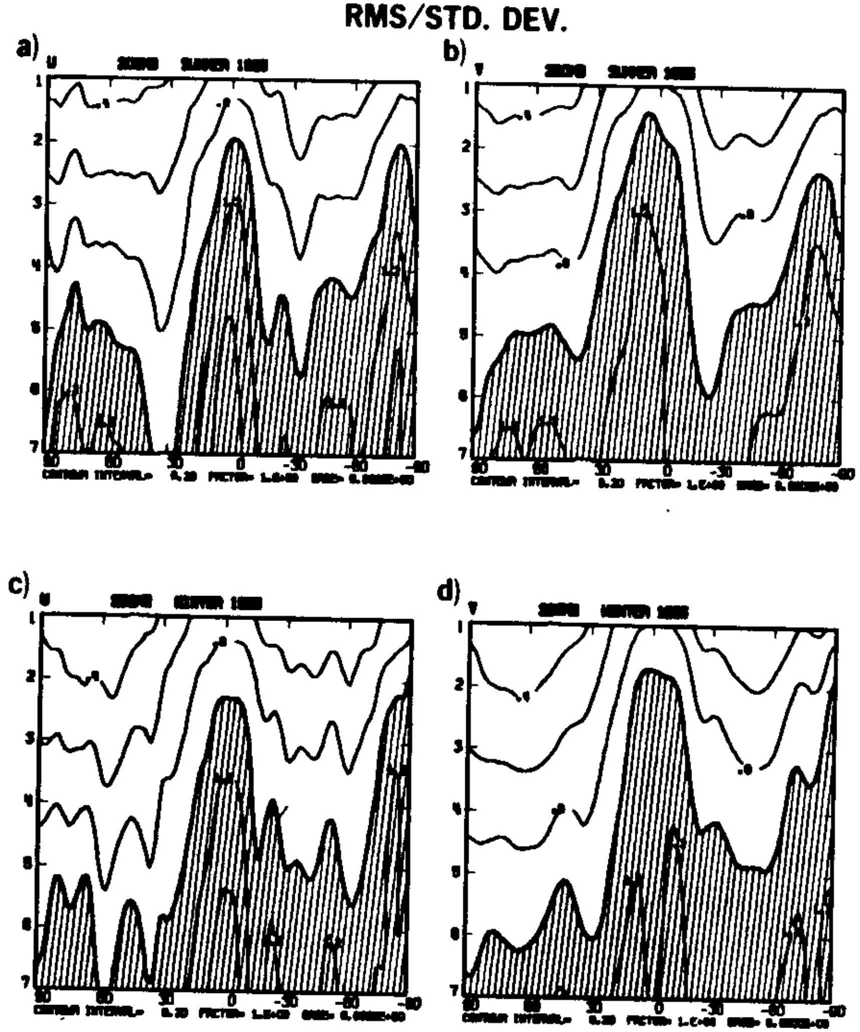

Fig. 14 The variations of the ratio of the root mean square error and the climatological standard deviation of winds at 200 mb as a function of latitude (abscissa) and forecast day (ordinate), for (a) zonal component in summer, (b) meridional component in summer, (c) zonal component in winter and (d) meridional component in winter. The area of the ratio greater than 1.0 is shaded.

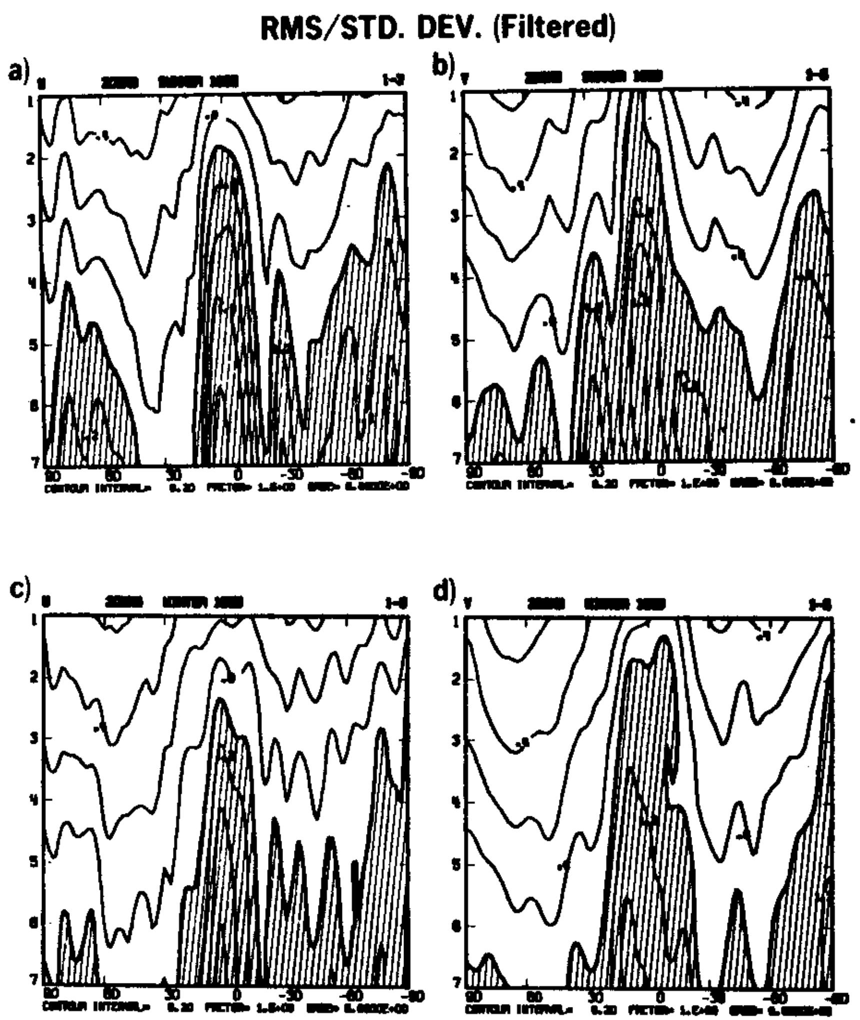

Fig. 15 Same as Fig. 14 but the root mean square error and the standard deviation are computed from zonally filtered (wavenumbers 1-3) data.

climatological standard deviation. The predictive skill in the temperature field in the tropics is less than 1 day at 850 mb and about 1.5 days at 300 mb.

3.2 Zonally averaged scores for winds

The RMS error growth of the zonal component of the wind in the tropics at 850 mb (Fig. 9) is comparable to that in the northern hemisphere; a typical RMS error is 2 m/s on day 1 and about 5-6 m/s by day 7. The error of the meridional component of the wind (Fig. 9) has a minimum in the tropics and its latitudinal variation is very different from that of the zonal component; the growth rate of the error is also different and smaller. Examination of the ratio of the RMS error to the climatological standard deviation (the ratio in Fig. 11 and the standard deviation in Fig. 10) again reveals that the predictability of the winds is about 1 day in the tropics with very fast error growth in the first 24 hours and even after 2-3 days.

The predictive skill of the wind field in the extratropics is less (about 4 days) than that of the height or the temperature (about 7 days). This is associated with the mass-wind relationships which leads to different scales being represented in the mass and wind field, with a higher weight to the shorter waves in the wind field. At 200 mb, although the RMS error is larger (Fig. 12), its ratio (Fig. 14) to the climatological standard deviation (Fig. 13) shows that the predictability is about 2.5 days in the tropics. The ratio computed for zonal wavenumbers 1-3 is shown in Fig. 15. It is very similar to the ratio of the total field, indicating that the error of these very large scales dominates.

The ratio of the RMS error and the standard deviation of daily values for the zonal wind component in the lower and the upper troposphere have been computed by Shukla (1981) for his initial perturbation experiments using the GLAS climate model. His results indicate that the ratio grows faster in the tropics than in middle latitudes, reaching 0.7 after day 7. Comparison with the present results in which a value of 1.0 is reached in less than a day for low level winds and in 1.5 days for high level winds, clearly shows that predictive skill of the winds of the ECMWF operational model in the tropics is much less than in the idealized experiments. It should, however, be noted that Shukla's study may have underestimated the error growth rate due to the initial perturbation used (Arpe et al., 1985).

3.3 Summary of the zonally averaged scores

Table 1 summarizes our estimates of the predictive skill in the height, temperature and wind fields in the lower and the upper troposphere determined from the number of days the RMS error remains below the climatological variance for the northern hemisphere, southern hemisphere and for the tropics.

Table 1. Predictability of the ECMWF opertional model, during summer (June, July, August 1983) and winter (December, January, February 1983/84). The predictability is defined as the number of days the root mean square error stays below the climatological variance.

	N.H. summer			N.H. winter		
	N.H.	Tropics	S.H.	N.H.	Tropics	S.H.
Z850	5.0	1.5	4.5	6.0	4.0	4.5
Z200	7.0	0.5	5.5	7.0	1.5	6.5
T850	6.0	1.0	3.0	5.5	1.0	3.5
T300	6.5	1.5	4.0	6.0	2.0	4.5
U850	4.0	1.0	3.0	4.0	1.0	3.0
V850	4.0	1.0	3.5	4.0	1.0	3.5
U200	5.5	2.5	4.5	6.0	2.5	5.5
V200	5.0	2.0	5.0	6.0	2.0	4.5

The general conclusions drawn from the table are [illegible]

(i) Predictive skill in the tropics is about 1-2 days for the mass field, 1 day for the low level winds and 2-2.5 days for the upper level winds. Also the winds are more predictable than the mass field in the upper troposphere in the tropics. In general, upper levels are more predictable than the lower levels, with the exception of the height field in the tropics. This may be due to the biased temperature forecast, whose accumulated errors appear in the upper level height field error. The longer predictability of winds compared to the mass field in the tropics seems to suggest that the mass-wind coupling is weak. This is possibly related to the degree of the coupling of the mass and the winds in the verifying analysis in the tropics.

(ii) Predictability in the northern hemisphere is 2-3 days longer than that in the southern hemisphere. The mass field is generally more predictable than the winds in the extratropics, since it generally represents larger scales of motion.

(iii) In the northern hemisphere, the winter season is more predictable than the summer season. Such seasonal variation is not very apparent in the southern hemisphere nor in the tropics (except in the 850 mb heights).

3.4 Geographical distribution of the RMS error

In the tropics there is strong zonal asymmetry and so the predictive skill is also expected to vary with longitude. For example, it is interesting to compare the RMS error of 24 hour forecast temperature during summer 1983 (Fig. 16a) with the corresponding RMS persistence error (Fig. 16b). Over the oceans it is clearly seen that the RMS error is generally less than the RMS error of persistence (over the Pacific and eastern Atlantic), indicating skill in the operational forecasts. On the other hand, a large RMS error of the order of 3-4 K is observed over the Sahara, India and over the Andes. Those areas also have large RMS persistence errors, but the RMS forecast error is equal to or even larger than the persistence error.

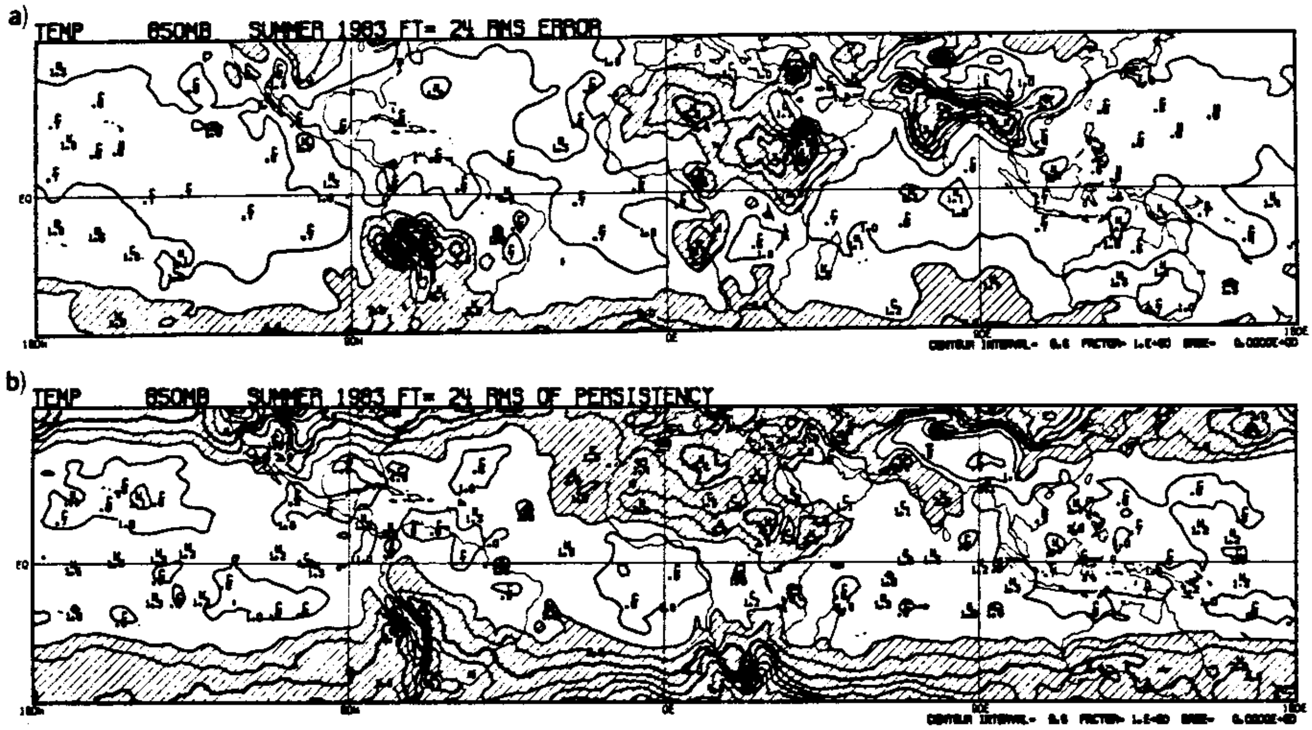

Fig. 16 Root mean square error (RMSE) and mean error of 24 hour forecast temperature at 850 mb. (a) RMSE of the forecasts, (b) RMSE of the persistence and (c) mean error. The areas of the RMSE greater than 1.5°K are shaded for (a) and (b). The areas of negative error is shaded in (c).

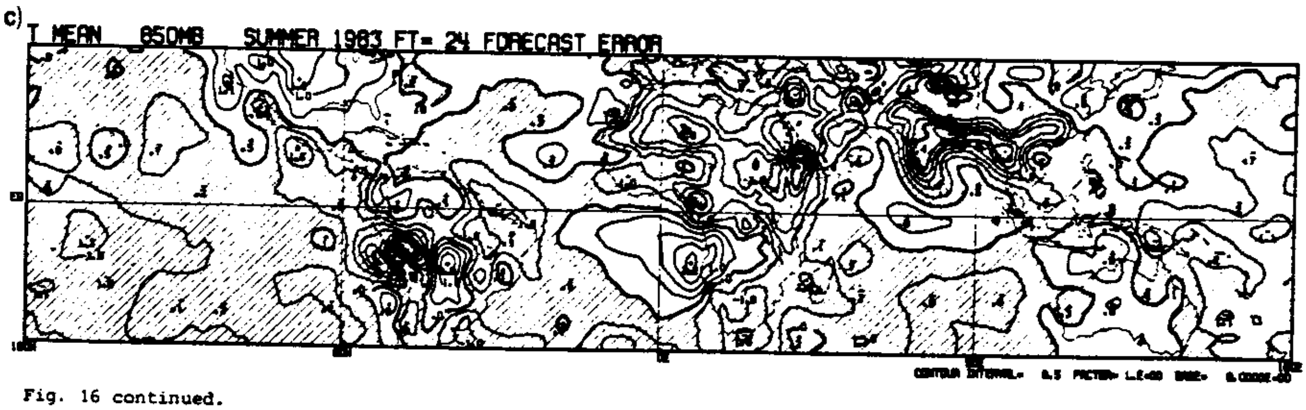

Fig. 16 continued.

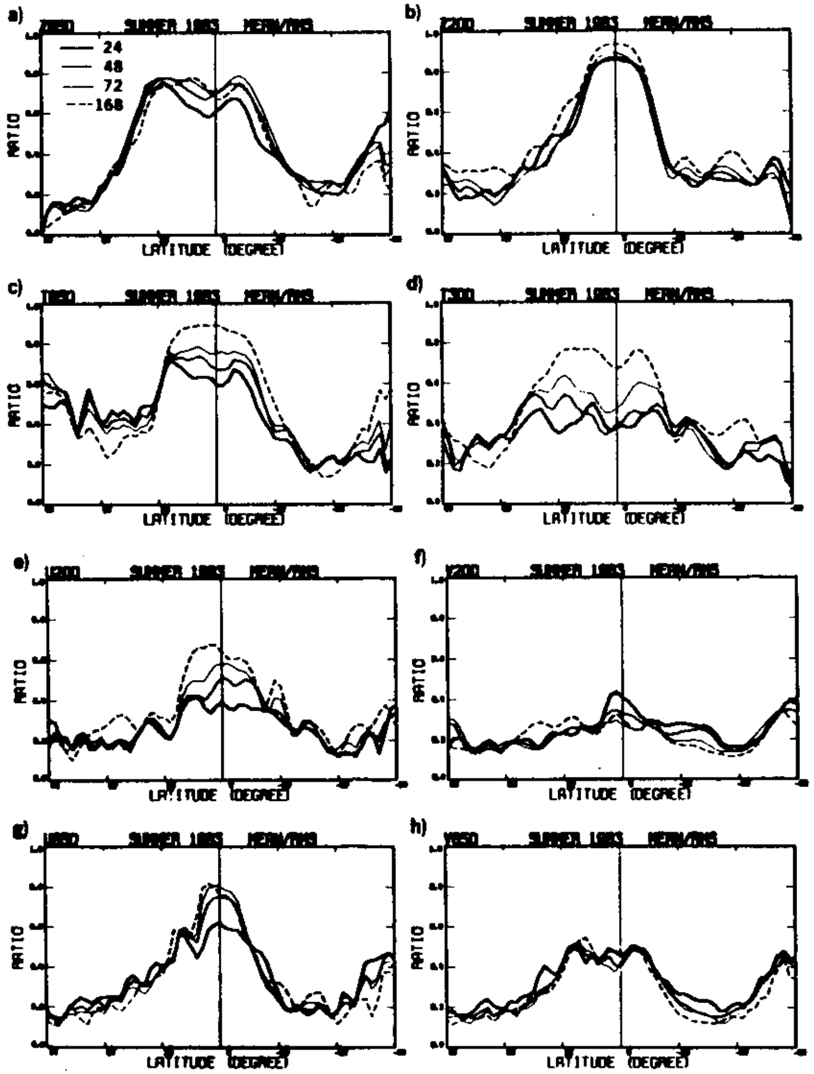

Fig. 17 Latitudinal variations of the ratios of the absolute mean error and the root mean square error in summer for (a) 850 mb height, (b) 200 mb height, (c) 850 mb temperature, (d) 300 mb temperature, (e) 200 mb zonal wind, (f) 200 mb meridional wind, (g) 850 mb zonal wind and (h) 850 mb meridional wind. The same figures for winter are shown in (i) to (p). Thick solid, solid, thin solid and dashed lines correspond to the forecast hours 24, 48, 72 and 168, respectively.

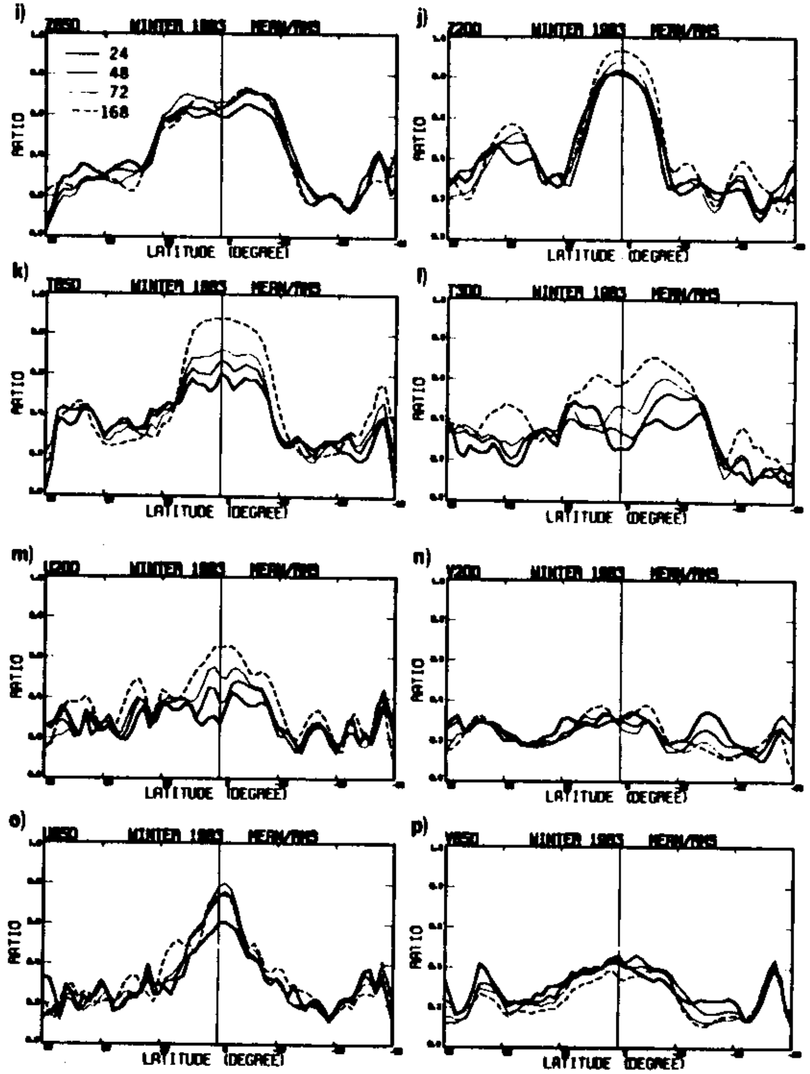

Fig. 17 continued.

The three month mean of the 24 hour forecast error of the 850 mb temperature is shown in Fig. 16c. Clearly the major part of the large RMS error is due to the mean error. This one to one correspondence between the large RMS error and the large mean error is observed in the tropics in almost all the parameters examined in this study.

3.5 Zonally averaged ratio of the systematic error and the total error

In order to make the relation between the total error and the systematic part of the error more clear, the ratios of the zonal means of the absolute values of the mean error and the corresponding RMS error are presented in Fig. 17 for the 24, 48, 72 and 168 hour forecasts. In the tropics the ratios are about 0.8 to 0.9 for the heights, 0.6 to 0.8 for the temperatures, 0.5 to 0.7 for the zonal component of the winds, and 0.3 to 0.5 for the meridional component of the winds. However, in the extratropics the ratios are between 0.2 and 0.3 for all the parameters (except 850 mb temperature) in the northern summer. This dominance of the systematic error in the tropics is an essential difference between the tropics and the extratropics.

Also note that the ratio is higher in the extratropics in the northern hemisphere winter, exceeding 0.5 after 2 days for the 200 mb height; this indicates that systematic errors are also important in the higher latitudes.

The systematic error in the extratropics has been a central problem of numerical weather prediction for some time. Present statistics for the tropics shows that the reduction of the systematic error is even more essential for the improvement of tropical predictions. In the following section, some attempts are made to isolate the cause of the systematic error.

4. SYSTEMATIC ERROR IN THE TROPICS

4.1 Structure of the systematic error

The general systematic errors of the ECMWF operational model in the tropics have been discussed in detail by Heckley (1985). In this paper, we focus on one particular very large scale global tropical systematic error pattern in the northern hemisphere summer and investigate its horizontal and vertical structures.

The mean error of the winds of the day 7 forecasts in the tropics during the northern hemisphere summer are shown in Fig. 18. The most prominent large scale errors at 850 mb are the two pairs of cyclonic and anticyclonic circulations straddling the equator over the Atlantic and the Indian oceans; at 200 mb the circulations are reversed. These systematic errors are more clearly observed in the height field (Fig. 19). This height-wind relationship of the systematic error indicates that the error is in geostrophic balance even at very low latitudes. In fact, the pattern of the error resembles that of the gravest symmetric Rossby mode (see for example Kasahara, 1976). The zonally filtered error patterns (zonal wavenumbers 1-3) of the wind, height and the temperature are shown in Fig. 20. It is clear that the error is dominated by wavenumber 1 and the vertical structure between 850 and 200 mb indicates the dominance of the gravest internal mode in the troposphere.

The temperature error at 300 mb shows warming over the Atlantic and cooling over the Indian Ocean, corresponding to positive and negative errors in the heights. The relation between the height error and the temperature error at and below 850 mb is not simple due to the fine structure of the planetary boundary layer present in the verifying fields. Also note that the 1000 mb height forecast error is very similar to the 850 mb error suggesting a

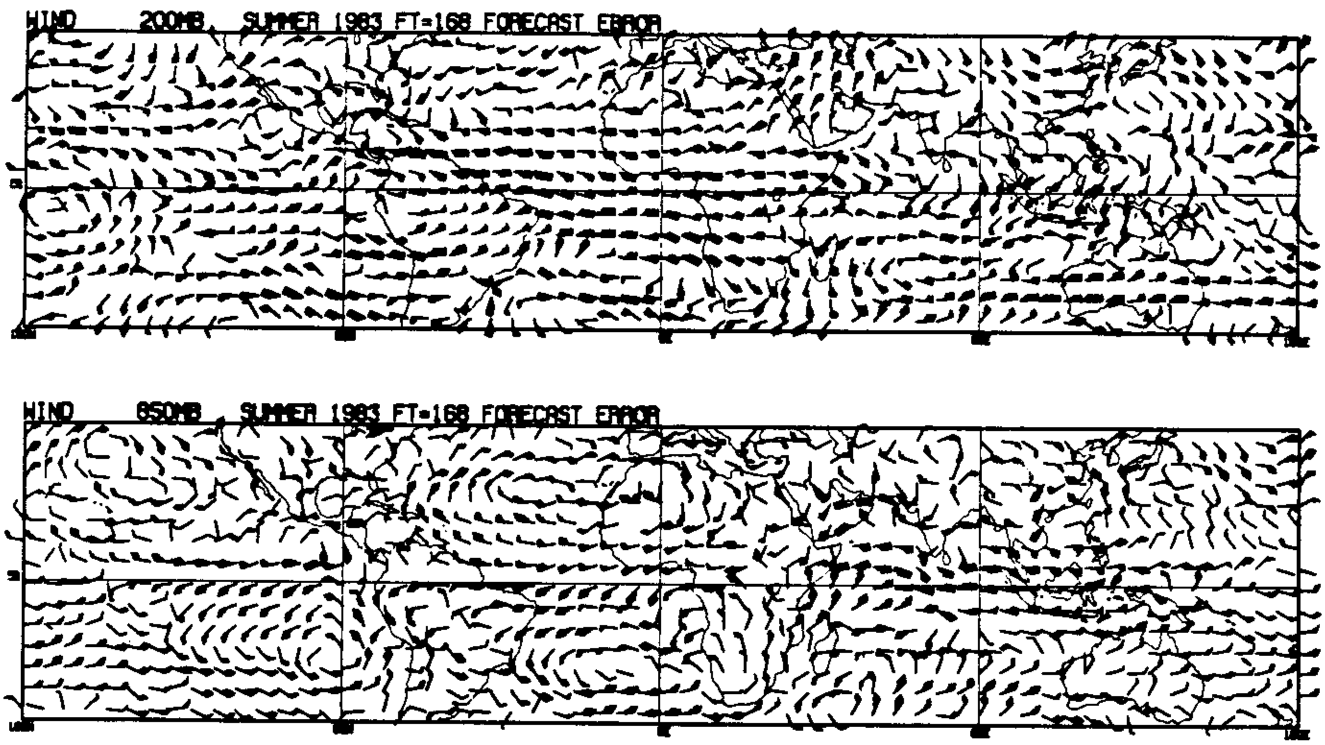

Fig. 18 Mean error of winds of day 7 forecast at 200 mb (upper panel) and 850 mb (lower panel). The error of wind speed is multiplied by 5 and expressed in knots by feathers in normal convention.

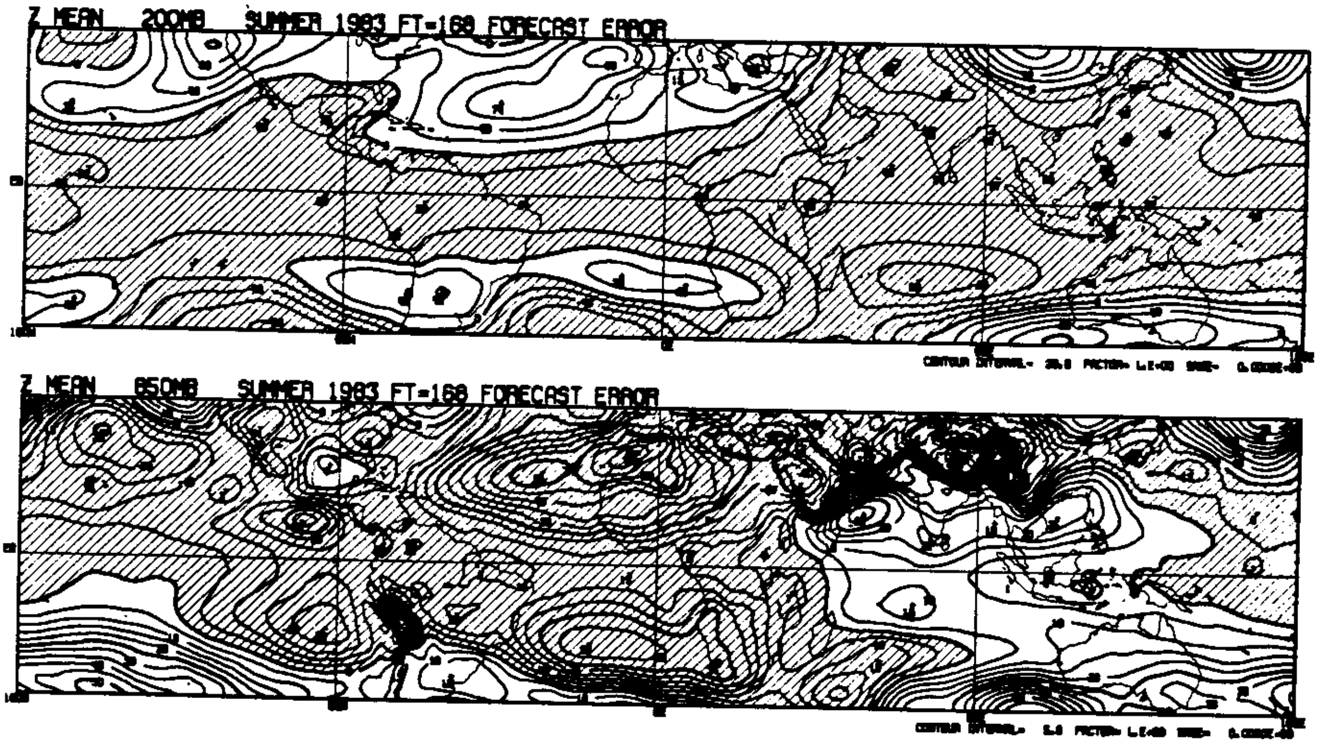

Fig. 19 Mean error of heights of day 7 forecast at 200 mb (upper panel) and 850 mb (lower panel). Units are metres and the negative areas are shaded.

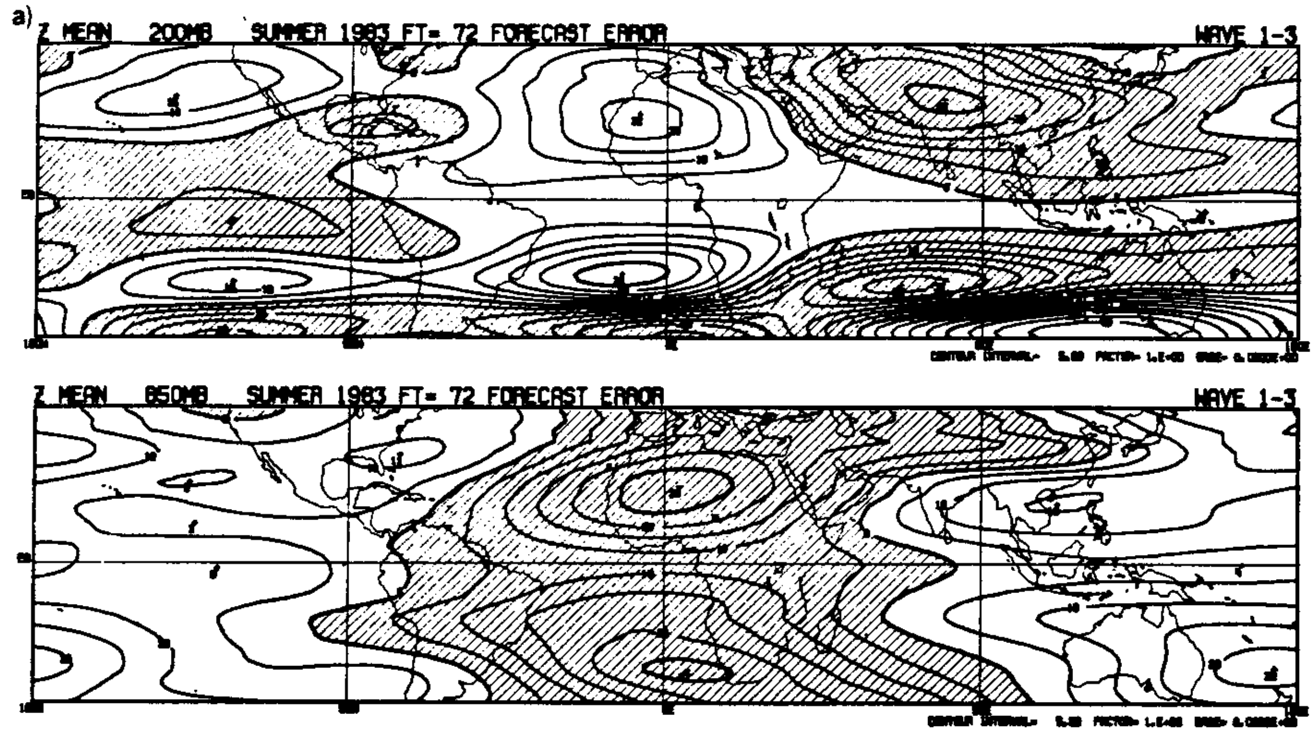

Fig. 20a Zonally filtered (wavenumbers 1-3) error of heights of day 3 forecast at 200 mb (upper panel) and at 850 mb (lower panel). Note the different contour intervals used here. Units are metres and negative areas are shaded.

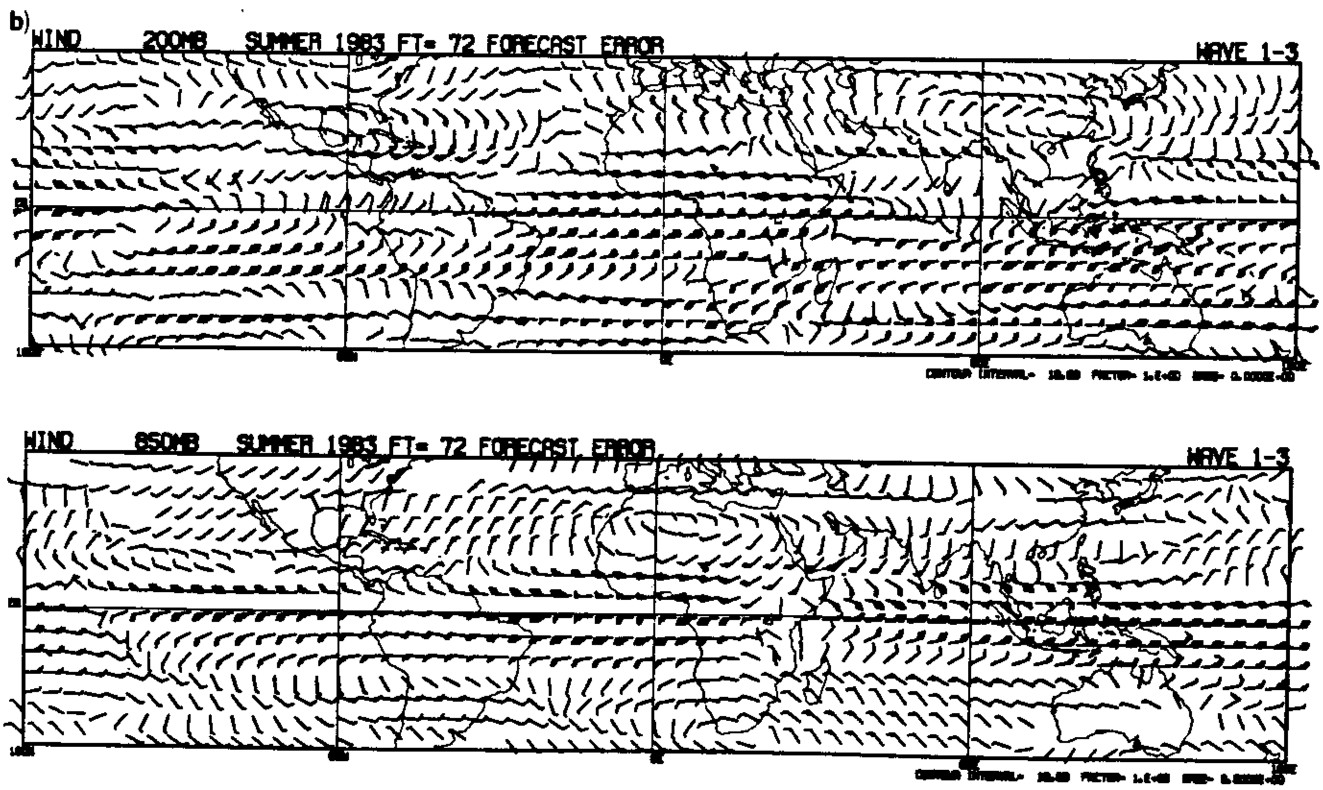

Fig. 20b Zonally filtered (wavenumbers 1-3) error of winds of day 3 forecast at 200 mb (upper panel) and at 850 mb (lower panel). The error of wind speed is multiplied by 5 and expressed in knots by feathers in normal convention.

c)

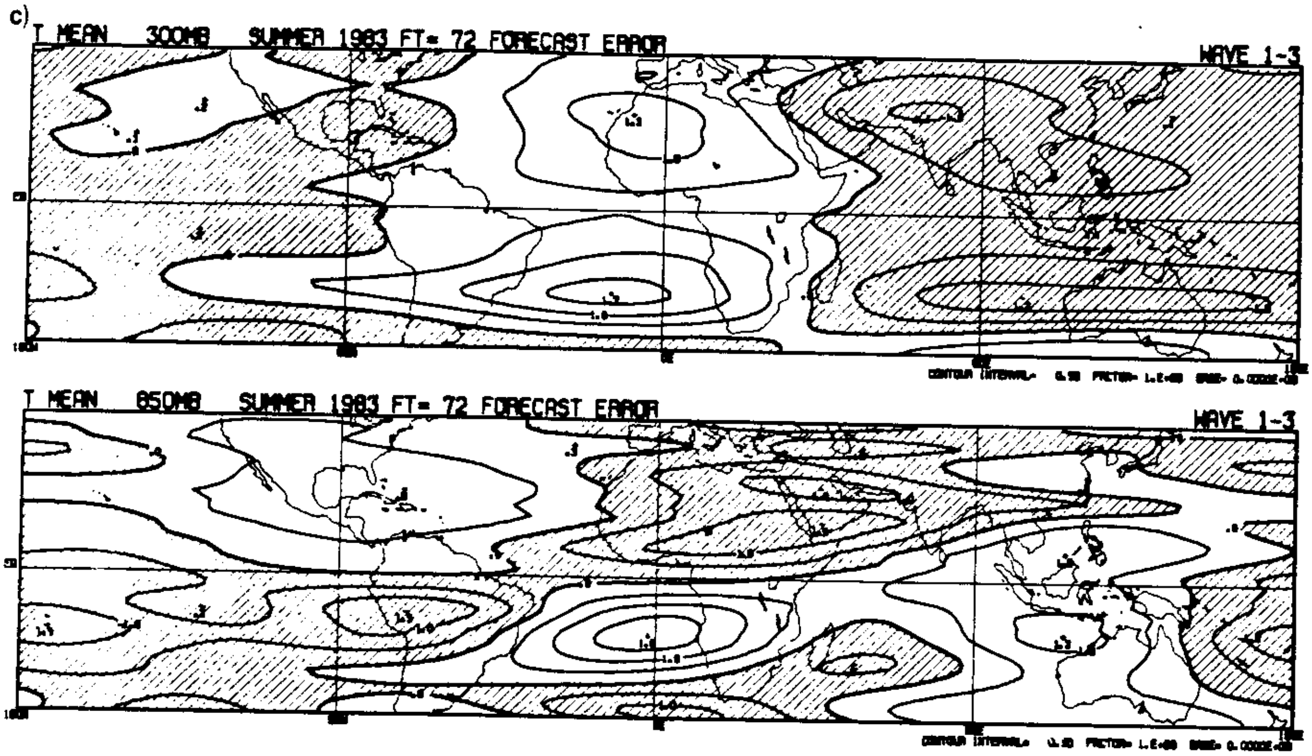

Fig. 20c Zonally filtered (wavenumbers 1-3) error of temperature of day 3 forecast at 300 mb (upper panel) and at 850 mb (lower panel). Units are °K and the negative areas are shaded.

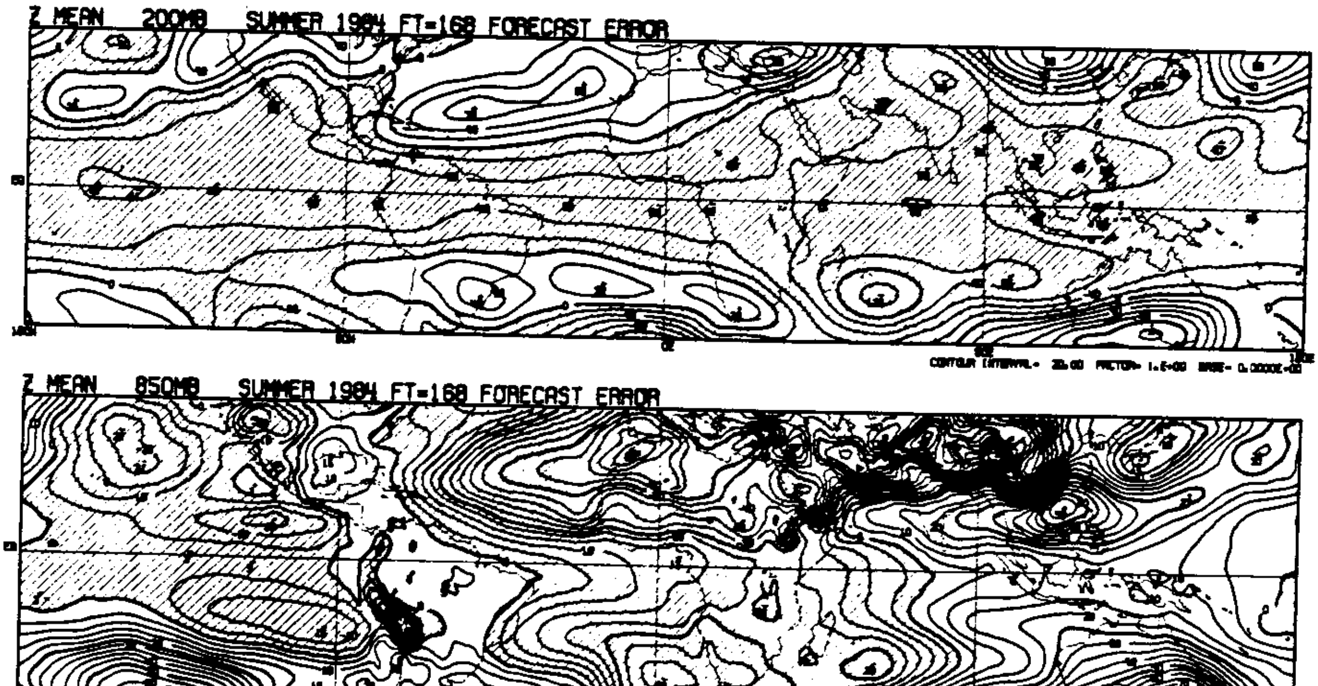

Fig. 21 Mean error of heights of day 7 forecast at 200 mb (upper panel) and at 850 mb (lower panel) additionally computed for 1984 summer. Units are metres and the negative areas are shaded.

barotropic nature for the error below 850 mb. The time evolution of the height error indicates that the error remains over the same area and grows as the forecast proceeds. In his case study Wergen (1983) showed that the gravest second internal mode in the model tends to move (about 180 degrees in 7 days) while it is nearly stationary in the analysis. However, such a movement of the error is not found in the present study. The relation between the error discussed by Wergen (1983) and the error presented here is not very clear at the moment.

There is some seasonal variation of the systematic error. The error is smaller and the maximum shifts slightly to the west in the winter compared to the summer.

The mean height error for the summer 1984 is presented in Fig. 21. The pattern and the magnitude of the height error at 168 hours is not very different from that in 1983. It may be argued that the improvements made to the 1984 model, namely the inclusion of the diurnal cycle and the improvement of the analysis scheme, did not contribute very much to the reduction of the systematic error in the tropics.

4.2 Forecast sensitivity experiment

The cause of the systematic error in the middle latitude has been studied extensively. In such studies the external forcing, particularly orography, is considered to be a primary source of the error (Wallace et al., 1983) in winter, although these authors point out that the tropics may also make a substantial contribution to the generation of the mean mid-latitude errors. Transient motions are also shown to be responsible for some of the systematic error of the JMA model in higher latitudes (Sumi and Kanamitsu, 1984). However, due to the strong interaction between the forcing and the motion fields, the causes of the systematic errors have not yet been clearly identified.

The systematic error in the tropics is also likely to be related to the erroneous forcing in the model, as suggested by Heckley (1983b) and Wergen (1983). Heckley (1983b) compared the climatological rainfall with the predicted rainfall in the tropics and, based on a simple linear model, suggested that the systematic error over the Atlantic and Africa is caused by excessive vertical mass flux over western Africa, possibly due to excessive rainfall. Using normal mode analysis, Wergen (1983) also showed that an erroneous heating distribution in the tropics is responsible for the erroneous forecast of the quasi-stationary modes. However, it is still necessary to confirm the importance of the physical forcing in the model in generating systematic errors since there are many other possible sources of error in the model and in the initial analysis.

The possible sources of error considered in this study are model resolution, orography, convective heating, sensible heating and the initial moisture analysis. These do not cover the entire range of possible error sources and more experiments are certainly needed.

It is a considerable advantage that the forecast errors of the tropics are dominated by the systematic errors. In the extratropics, the forecast error is normally dominated by the errors of the transients and a large number of cases or long runs are needed to study the systematic error. This places severe limitations on the interpretation of the forecast experiments in the extratropics. On the other hand, since the systematic error is observed in almost all forecasts in the tropics, forecast experiments carried out for one or two cases are sufficient to examine the sensitivity of the systematic error to changes in the model or the initial analysis.

The initial state for the experiment is chosen from a series of resolution experiments carried out at ECMWF by M. Jarraud and A. Simmons. In order to see a clear impact, a summer case (initial date 15 July 1983) is selected. As a measure of the systematic error, the forecast error of 850 mb height (zonally filtered by taking the first three waves) is used. The control run using the operational model (with diurnal cycle) shows that the error pattern (Fig. 22b) very closely resembles that of the mean forecast error during summer 1983 (Fig. 22a).

(a) Impact of the resolution

The resolution experiments performed here are T21, T42, T63(control) and T106, where T stands for triangular truncation and the number that follows indicates maximum retained planetary wavenumber. The filtered error patterns after 7 days, shown in Fig 22c-22e, indicate that the impact of the resolution on the systematic error is not very large. However, we observe that the magnitude of the error tends to decrease as the resolution increases. The experiment using the T21 model gives a somewhat different error pattern, particularly in the southern hemisphere. However, it is generally recognized that the T21 model is too coarse for large scale short and medium range prediction, and gives a quite inferior forecast compared to higher resolution models in many cases. The small impact of the resolution on the systematic error implies that the small scale transients are not responsible for the generation of the systematic error. Furthermore, it also suggests that the effect of physical forcing (including orography) is similar in models with different resolutions.

(b) Impact of the orography

An envelope orography (Wallace et al., 1983) has been extensively used to reduce the systematic error in middle latitude winter forecasts at ECMWF. Krishnamurti et al. (1983) noted the positive impact of the use of the envelope orography in the forecast of the onset of the monsoon. In the control experiment, an envelope orography with $\sqrt{2}$ times the standard deviation of the topography over the grid square (computed from 10'x10' tabulation of orography) is used. The impact test was performed by replacing the envelope orography by the mean orography. The error pattern shown in Fig. 22f indicates that the impact of the envelope orography is positive, as it reduces the systematic error in the tropics (compare Figs. 22b and 22f). However, the effect is not very large. This may be due to the fact that the impact of the orography on the very large scale motion in the tropics itself is not very large due to the lack of high mountains in the tropics. The main impact seems to come from the indirect impact of the orography in the extratropics which in turn influences the tropical large scale motion. This aspect of the impact of the envelope orography needs to be studied further.

(c) Impact of the model physics

Impact studies of the physical processes in the forecast model are complicated by the strong interaction among the various processes and by the interactions between the physics and the dynamics. Furthermore, it is not possible to verify the physical processes in the model against observations because such quantities (e.g. heating rate by convection) averaged over the large scale cannot be directly observed with reasonable accuracy. In order to minimize these complications, we compare forecasts made with the normal

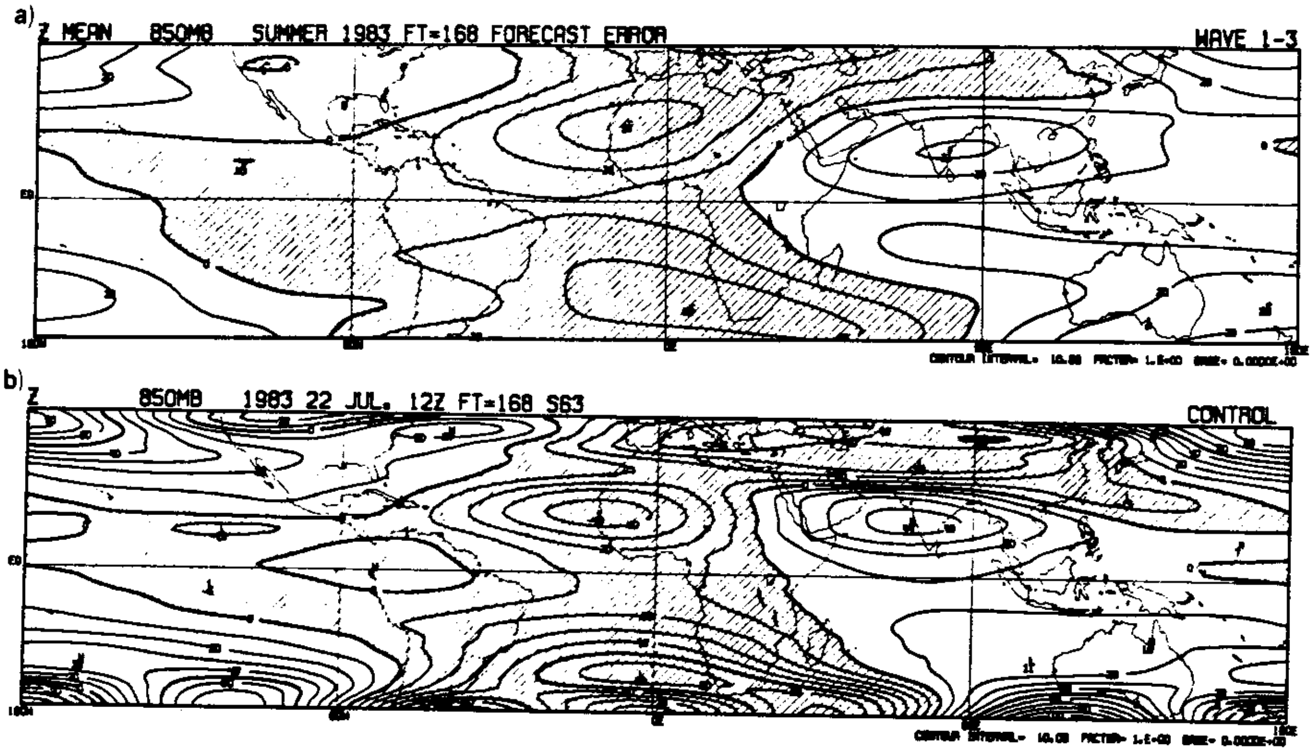

Fig. 22a Zonal Fourier filtered 7 day mean forecast error for summer 1983.
b Zonal Fourier filtered 7 day forecast error for the control experiment

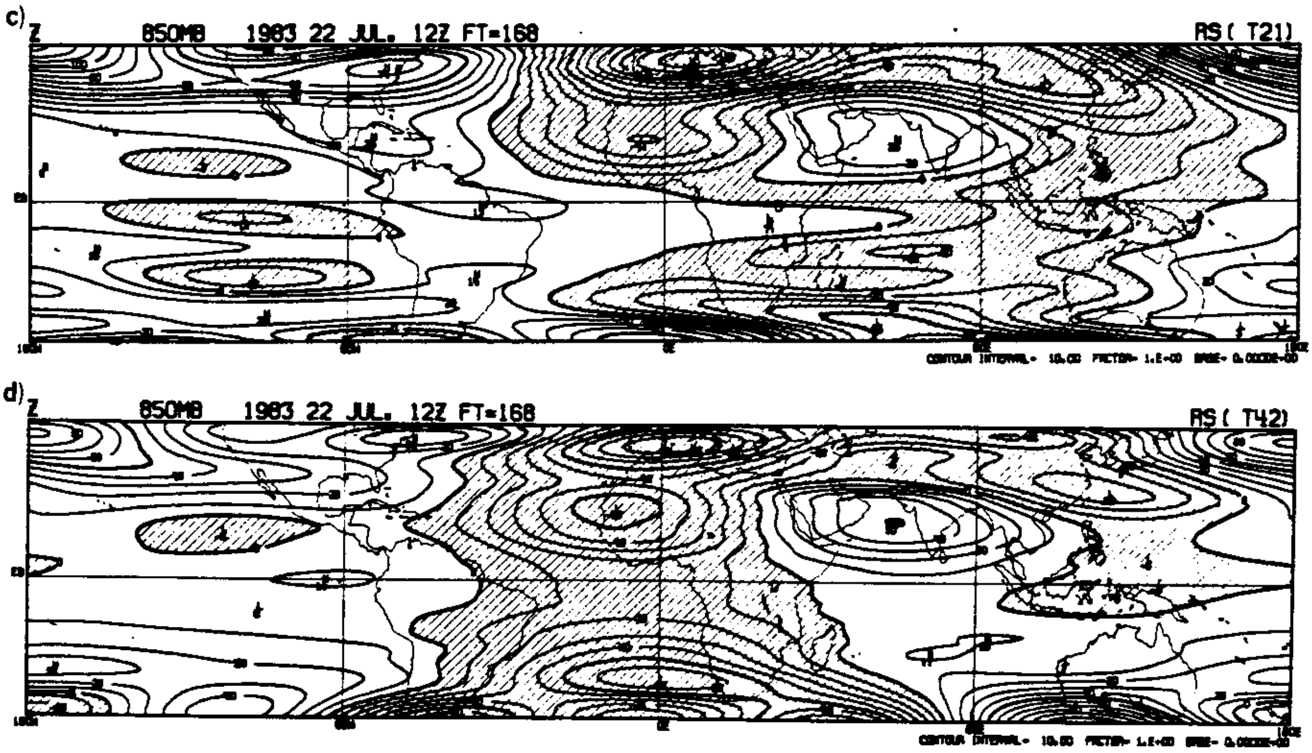

Fig. 22c Zonal Fourier filtered 7 day forecast error for the T21 resolution model.
d Zonal Fourier filtered 7 day forecast error for the T42 resolution model.

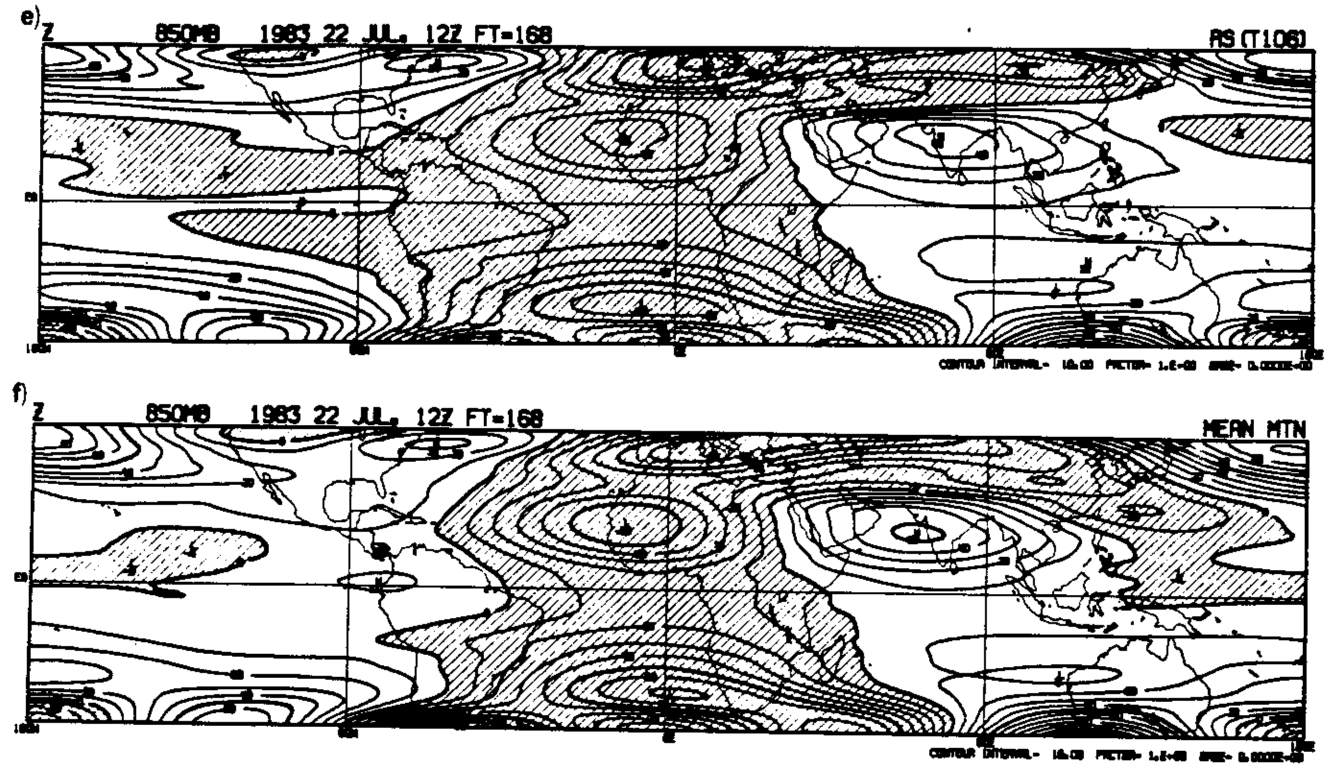

Fig. 22e Zonal Fourier filtered 7 day forecast error for the T106 resolution model.
f Zonal Fourier filtered 7 day forecast error for the mean mountain experiment.

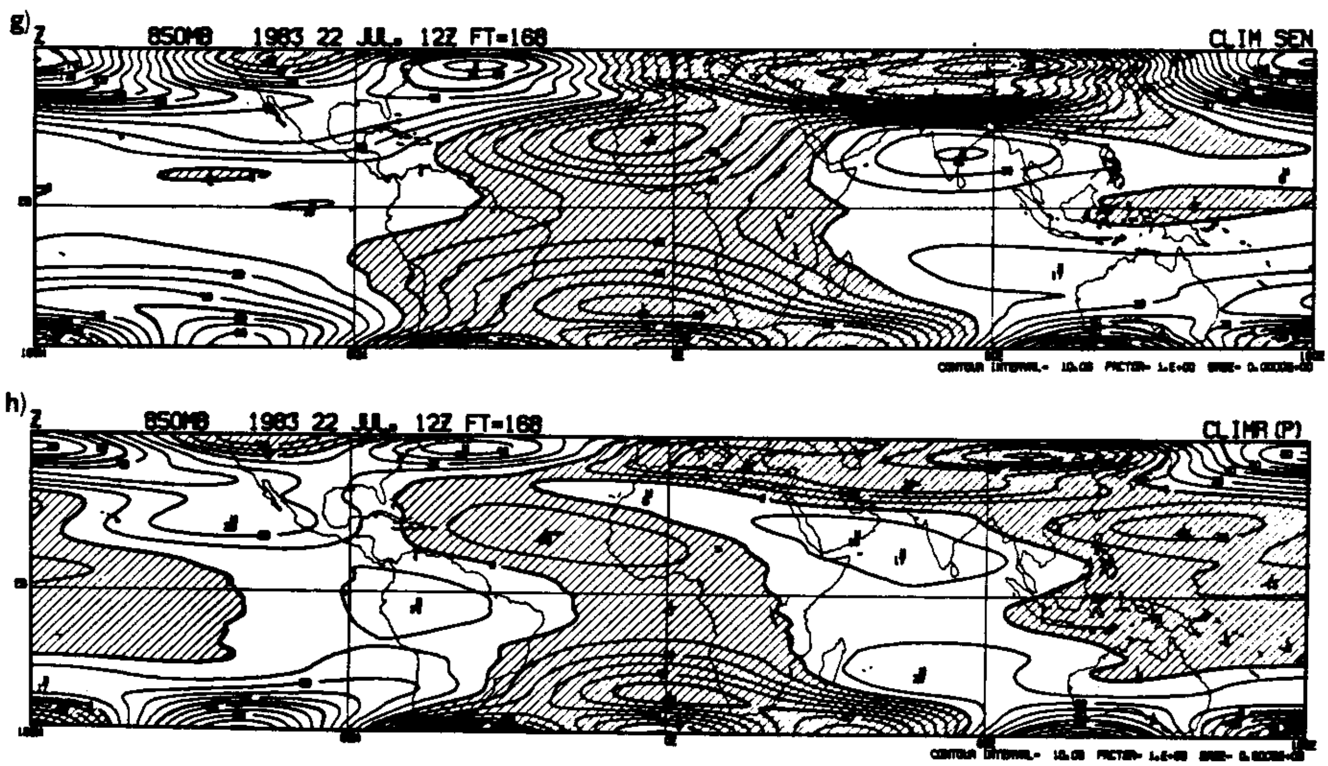

Fig. 22g Zonal Fourier filtered 7 day forecast error for the climatological sensible heat flux experiment.
h Zonal Fourier filtered 7 day forecast error for the climatological convective heating with the Pacific vertical heating profile.

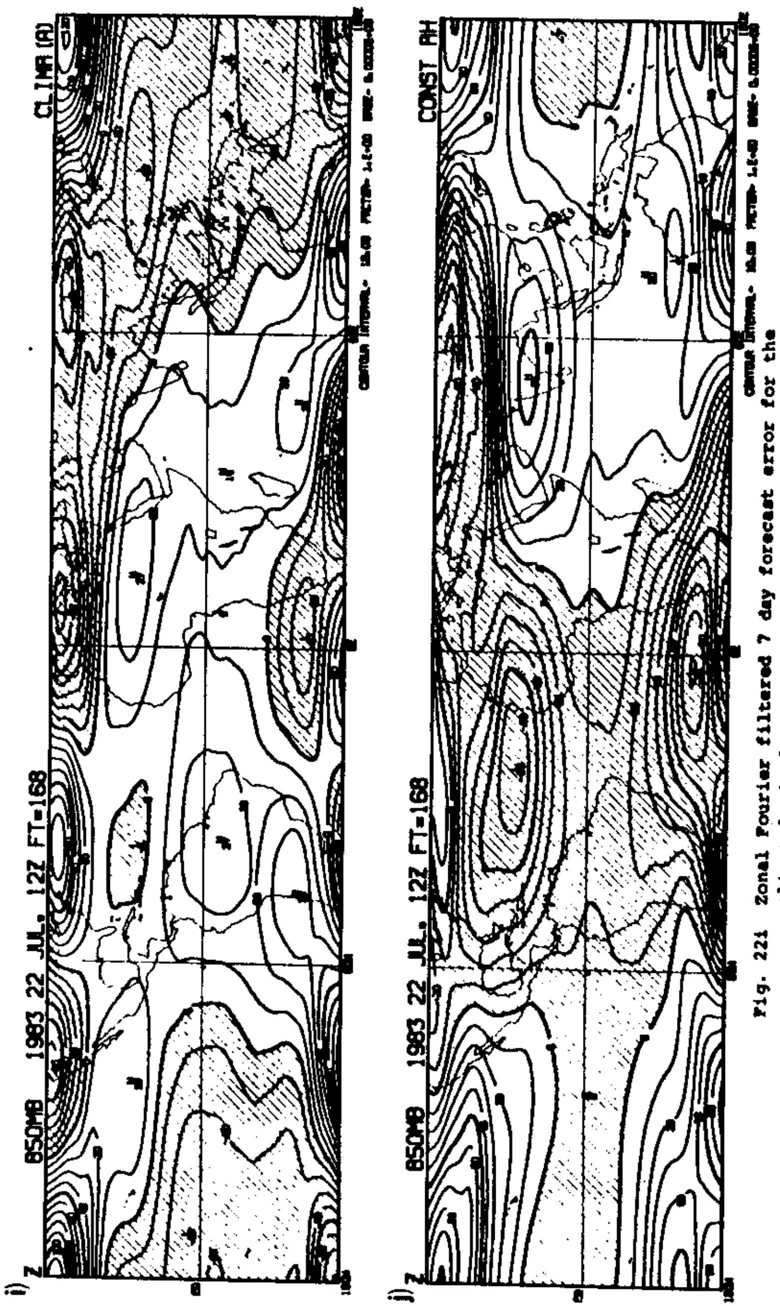

Fig. 22 i) Zonal Fourier filtered 7 day forecast error for the climatological convective heating with the Atlantic vertical heating profile.
j) Zonal Fourier filtered 7 day forecast error for the constant initial moisture experiment.

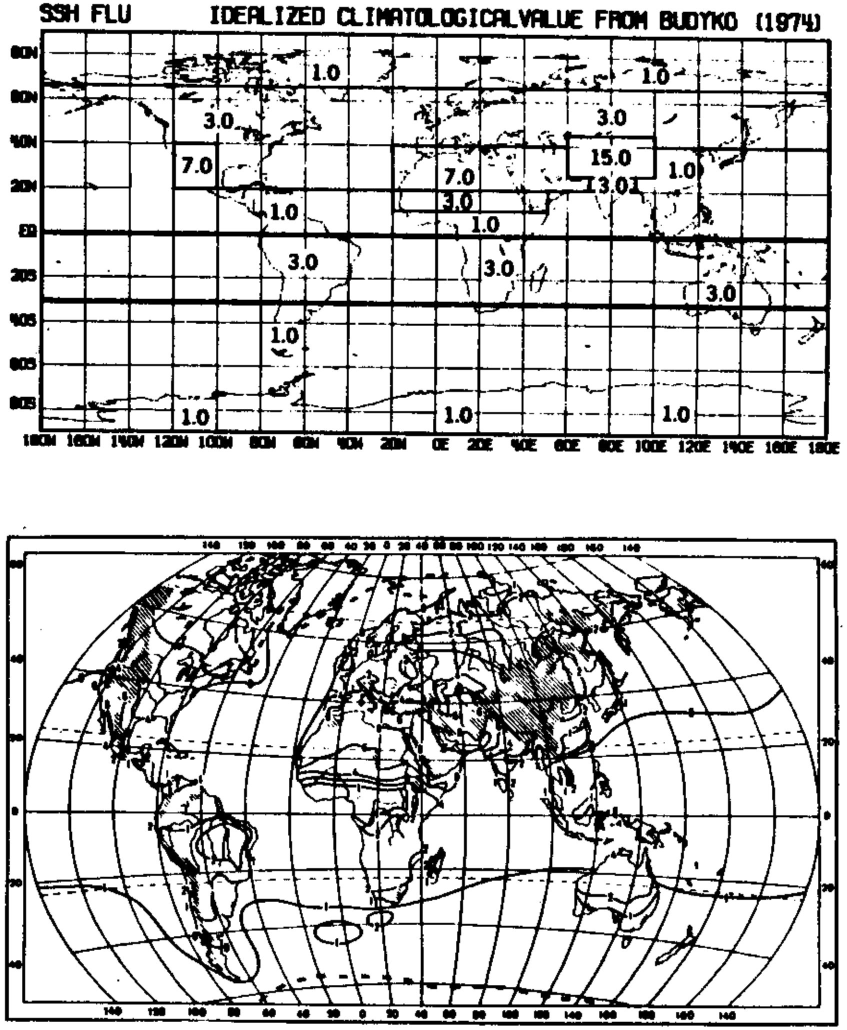

Fig. 23 Idealized climatological sensible heat flux used in the experiment (upper panel). These values are used only over land area. The original climatological value from Budyko (1974) are also presented (bottom panel). Units are Kcal cm^{-2}/month.

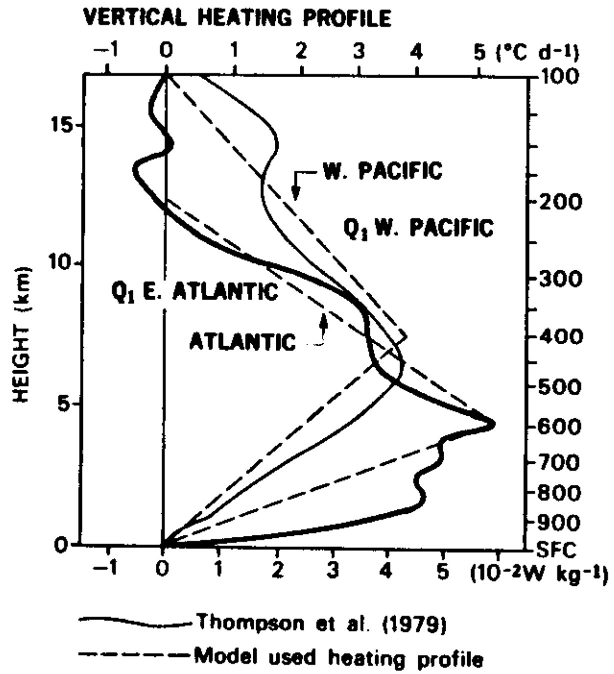

Fig. 24 Vertical profile of the convective heating used in the experiment. The vertical profile of the apparent heat source by Thompson et al. (1979) are also shown by the thin curves.

model physics with forecasts using prescribed climatological forcing. A heating function which varies in space but is constant in time greatly simplifies the sensitivity tests, but it should be noted that there are errors in determining climatological values. In addition, instantaneous values of the heating are not likely to be close to the climatological values. In this sense, the use of the climatological heating may detect only large deviations of the model physics from reality.

Sensible heating over the continent

The seasonally averaged sensible heat flux over the Sahara predicted by the ECMWF model is found to be 1/3 less than that of the climatological value given by Budyko (1974), i.e. 80 W/m^2 for the forecast compared with 120 W/m^2. Furthermore, the sensible heat flux over the Tibetan Plateau is about 1/2 to 1/3 of the climatological value (about 100 W/m^2 compared to 240 W/m^2) obtained by Yeh and Gao (1979). In order to detect the impact of this difference of sensible heating between the forecast and the climatology, an experiment with fixed and somewhat idealized climatological sensible heating over the continents is performed. The distribution of climatological heating used in the experiment is presented in Fig. 23. For simplicity, we have assumed that the heating by the sensible heat flux is constant in the boundary layer.

The error pattern (Fig. 22g) shows that the impact is rather small and tends to make the error worse, though the systematic temperature error at 850 mb over the Sahara has decreased (not shown). It is expected that the dynamical response to low level heating will not be very large because of the inhibition of vertical motion near the ground and because the weak horizontal gradient of temperature in the tropics prohibits compensation by horizontal advection. This experiment indicates that the systematic error is caused by the dynamical response to some erroneous forcing, and not by the direct response to local heating. In other words, improvement of the boundary layer may cure the systematic error of temperature at the lower troposphere but it may not influence the dominant very large scale systematic error in the model.

The strong response to the sensible heating over the Tibetan Plateau is considered to be due not only to the change of the surface heat flux but also to the change of convective activity over the area. Comparison of the rainfall between the control and the sensible heating experiment indicates that a significant change of precipitation pattern took place only over and near the Tibetan Plateau.

Impact of convection

The climatological heating used here is based on the precipitation climatology of Jaeger(1976), and the vertical heating profile over the tropics has been taken from the budget study by Thompson et al. (1979). Two different profiles (Fig. 24) are tested in the experiment, i.e. one with the level of maximum heating at about 400 mb corresponding to the western Pacific profile, and the other with the maximum heating occurring at about 600 mb corresponding to the Atlantic profile. The convective heating in the model is switched off and the climatological heating is introduced, but the moisture is still predicted by the convection scheme in the model. It is expected that the motion field should respond to the climatological heating and hence cause the moisture to respond to the heating in a reasonable manner. Note that the moisture in this experiment influences only the radiative processes (and to some extent the motion field through the virtual temperature correction). The climatological heating is applied only in the tropics, i.e. between 30°N and 30°S. The large scale condensation processes in the model are not modified

but this is not important for the tropics. In the first few experiments, Jaeger's precipitation is smoothed in space (taking zonal Fourier components 1-4) to remove the small scale response. In later experiments the unsmoothed rainfall is used, but the results are not very different as far as the large scale systematic error is concerned.

The systematic error pattern using the Pacific heating profile case (Fig. 22h) demonstrates that the error is drastically reduced not only over the Atlantic but also over India. Clearly the role of the convective heating associated with the ITCZ is essential. A comparison of the rainfall between the control and the climatological rain experiment (Fig. 25a,b) indicates that major differences are the absence of ITCZ rain (particularly over the Atlantic and central Pacific) and the general tendency for too much rain to occur in the small scales in the operational model. The relation between the systematic error and the above mentioned differences requires further investigation.

The experiment with the Atlantic heating profile gave a completely different error pattern, as shown in Fig. 22i. Examination of other parameters revealed that the response of the model to the heating is extremely large and the forecast drifts further away from climatology. We now examine zonal cross-sections of the forecast temperature deviation from observed (Fig. 26a) and the cross-sections of the mean meridional circulation (Fig. 26b) for the three experiments: the control and the cases with the Pacific and Atlantic heating profiles. From these figures, it is clear that the forecast of the zonally averaged temperature has less error for the Pacific heating case than the control experiment. The pattern of the meridional circulation is not much different. On the contrary, too much warming at the lower troposphere is apparent in the low level heating case. Furthermore, large cooling (compared

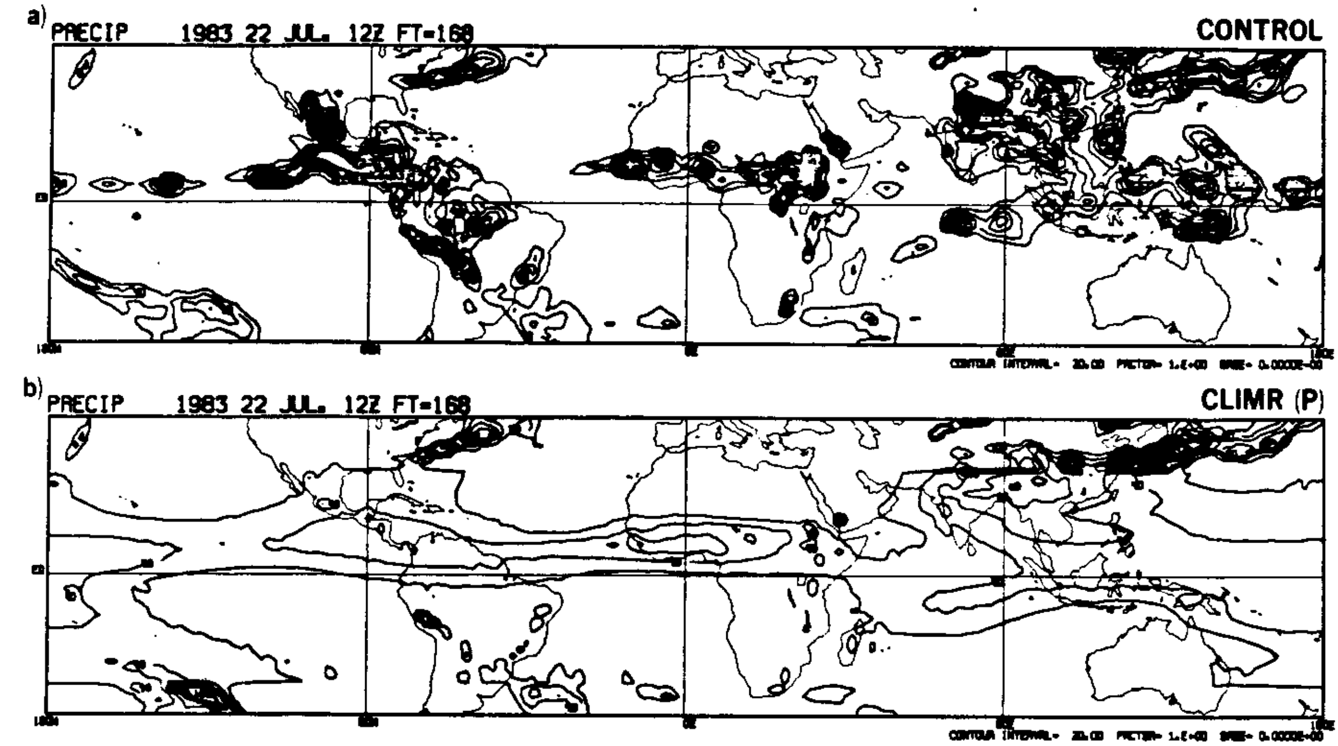

Fig. 25 Predicted precipitation accumulated for the 7 day forecasts, (a) for the control experiment, (b) for the climatological rain experiment and (c) for the constant initial humidity experiment. Note that in (b), the rain in the tropics is the specified climatological value plus small contribution from the model produced large scale condensations. Units are mm.

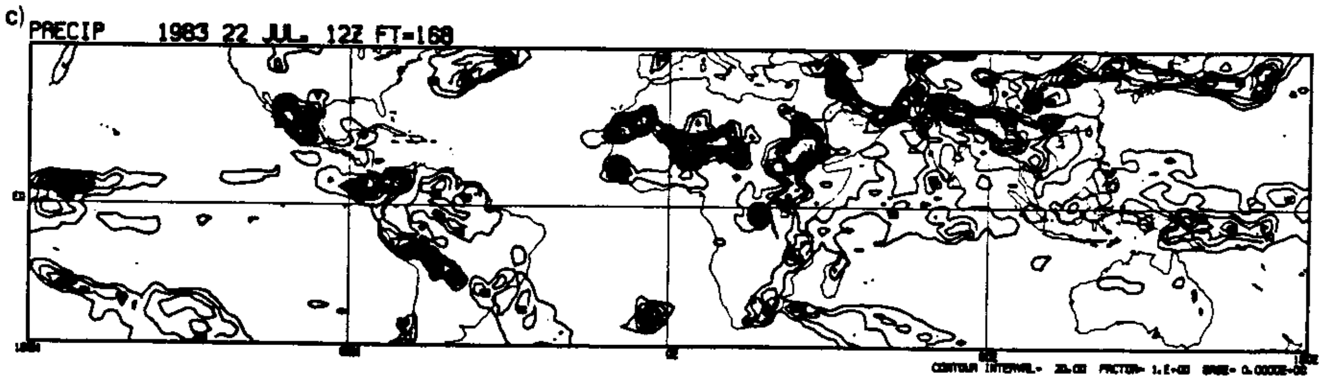

Fig. 25 continued.

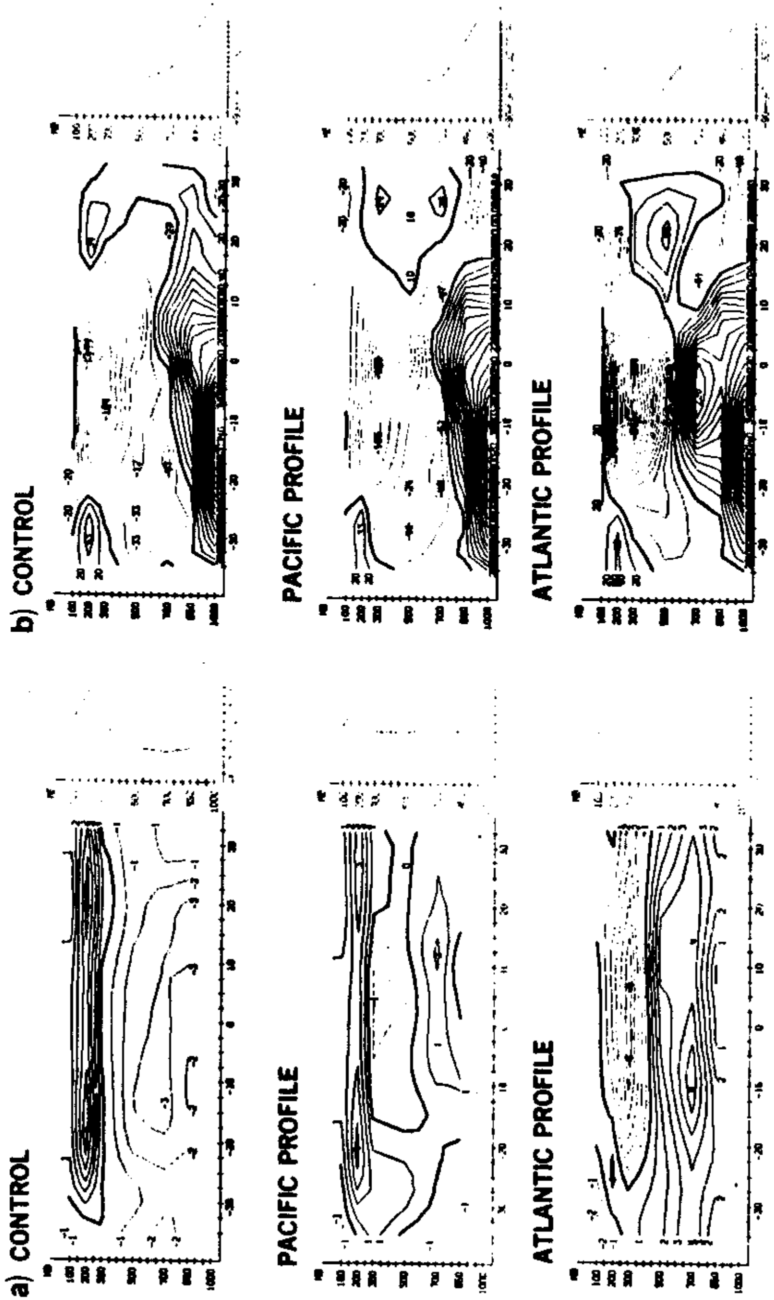

Fig. 26 Zonal cross-sections of (a) the temperature deviation from observed and (b) the meridional winds, for the control (top), for the Pacific profile convective heating experiment (middle) and for the Atlantic profile convective heating experiments (bottom). Contour intervals are 1°K for temperature and 20 cm/sec for the meridional winds.

to warming in the high level heating case) is observed in the upper troposphere, which is very likely a consequence of a dynamical response. The meridional circulation of the low level heating experiment produces an unrealistically strong and deep return flow of the Hadley circulation. This experiment indicates that the response of the tropical atmosphere is very sensitive to the vertical heating profile. The Atlantic heating profile seems to be not appropriate for the ITCZ type rain treated here. However, it is desirable to perform additional experiments with varying vertical heating profile in the different tropical oceans.

(d) Impact of the initial moisture

To test the impact of the initial moisture on the systematic error, a somewhat unrealistic experiment was performed to enhance the effect. The initial moisture of the entire atmosphere is set to 70% and the forecast is then made with the control model. If the dynamics controls the large scale moisture distribution in the tropics, as it does in the extratropics, we should expect little impact. The rainfall pattern of this experiment indicates that this is not the case (Fig. 25c). The rain, especially over the Sahara and the Middle East, is very unrealistic. In this sense the initial moisture distribution has a strong impact on the forecast. However, the 850 mb height error pattern of this experiment still resembles that of the control experiment (Fig. 22j). Comparing the rainfall pattern for the control and the constant humidity experiment, we may speculate that the absence of the ITCZ over the Atlantic is related to the generation of the systematic error over the area. Since this experiment is excessively unrealistic, further experiments are needed to refine the present conclusion.

5. PREDICTABILITY OF THE TRANSIENT DISTURBANCES

There have been several attempts to perform case studies of the analysis and forecast of the tropical transient disturbances in the ECMWF operational forecast system. Shaw (1983) has shown that easterly waves are well analysed and predicted in some individual cases; also Hollingsworth and Datta (1984) looked at disturbances over India and showed useful skill in some cases. However, no extensive evaluation of the predictability of the transient disturbances in the tropics has been performed. This is due mainly to the relatively weak intensity of the disturbances in the tropics compared to that in the extratropics.

As a preliminary examination of the problem, several x-t diagrams of the 850 mb meridional component of the wind at 15°N have been prepared. This latitude is known to be a region of marked activity for the tropospheric transient disturbances (Chang, 1970). The x-t diagram for the analysis is shown in Fig. 27 and covers the period from May 1983 to October 1983. During the last half of the period, westward propagating waves are apparent over the Pacific (90°E-210°E) and over the Atlantic (300°E-0°E), whereas stationary patterns dominate the flow over the continents in the regions 0°E to 90°E (Africa/Asia) and 240°E to 270°E (central America). Several strong systems are observed at around 120°E and 240°E; these are likely to correspond to the tropical cyclones (in fact, the westward moving intense disturbance at 120E° around day 75 has been identified as a typhoon). In order to see the transient wave activity more clearly, a time filter (Lanczos filter - see for example Duchon, 1979) has been applied to extract disturbances with a period between 3 and 10 days. The response function of the time filter used here is presented in Fig. 28. The x-t diagram of the time filtered data shown in Fig. 29 clearly indicates that the transient waves are dominant in this frequency range. The waves propagate very steadily with a speed of roughly 6

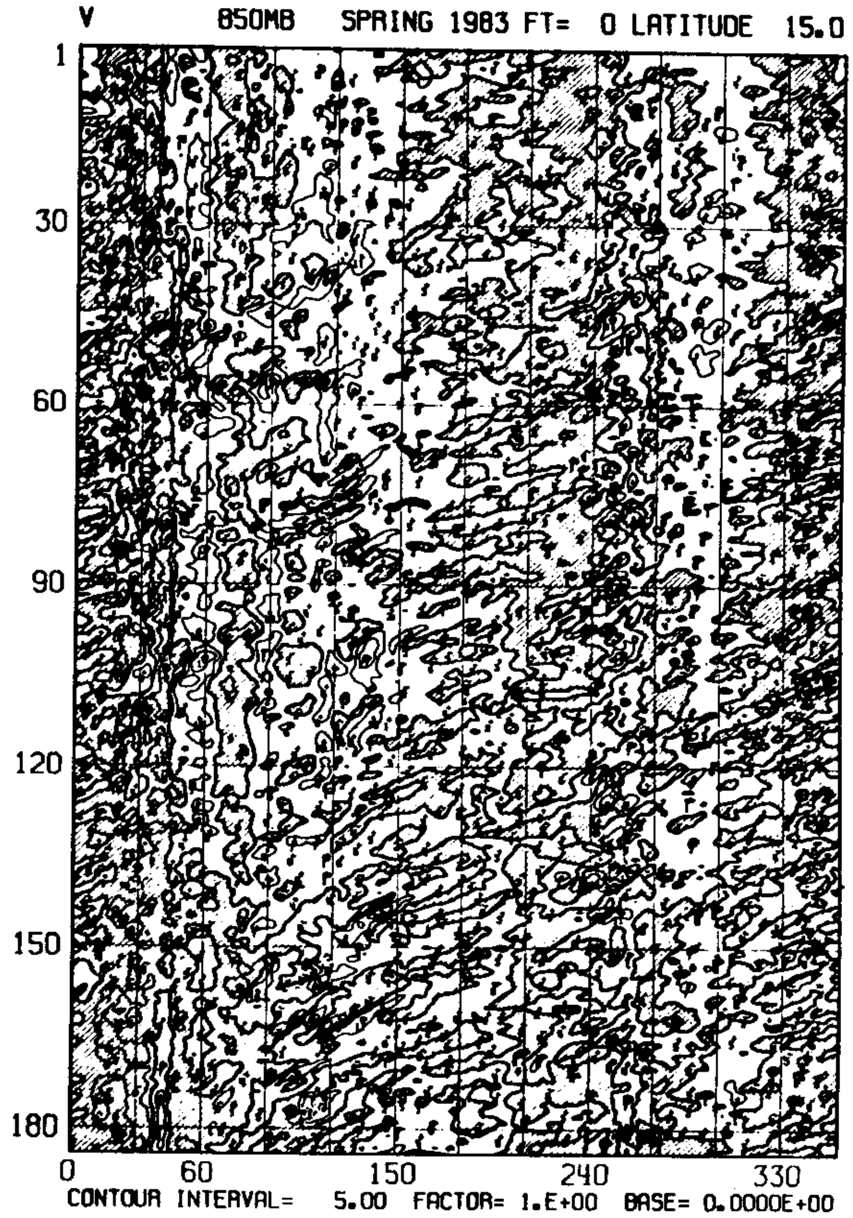

Fig. 27 x-t diagram of 850 mb meridional winds at 15°N from the operational analyses (initialized). Day 1 corresponds to 1 May 1983 and the last day to 31 October 1983. Units are m/s and negative areas are shaded.

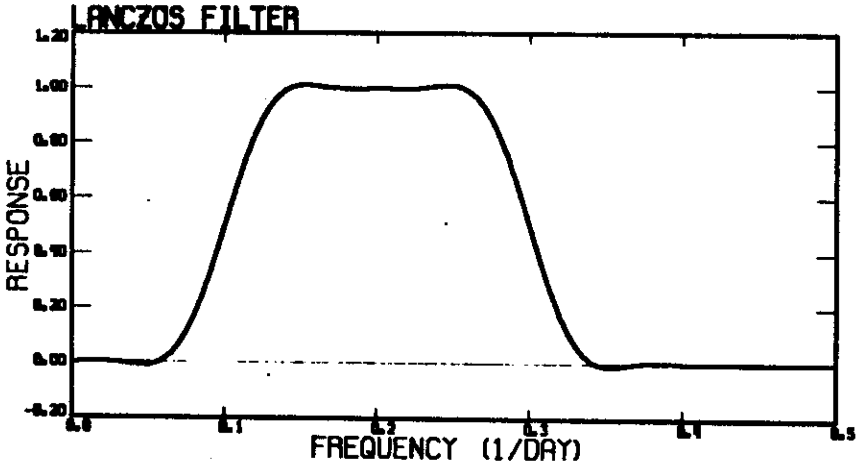

Fig. 28 Response function of the Lanczos filter used in this study.

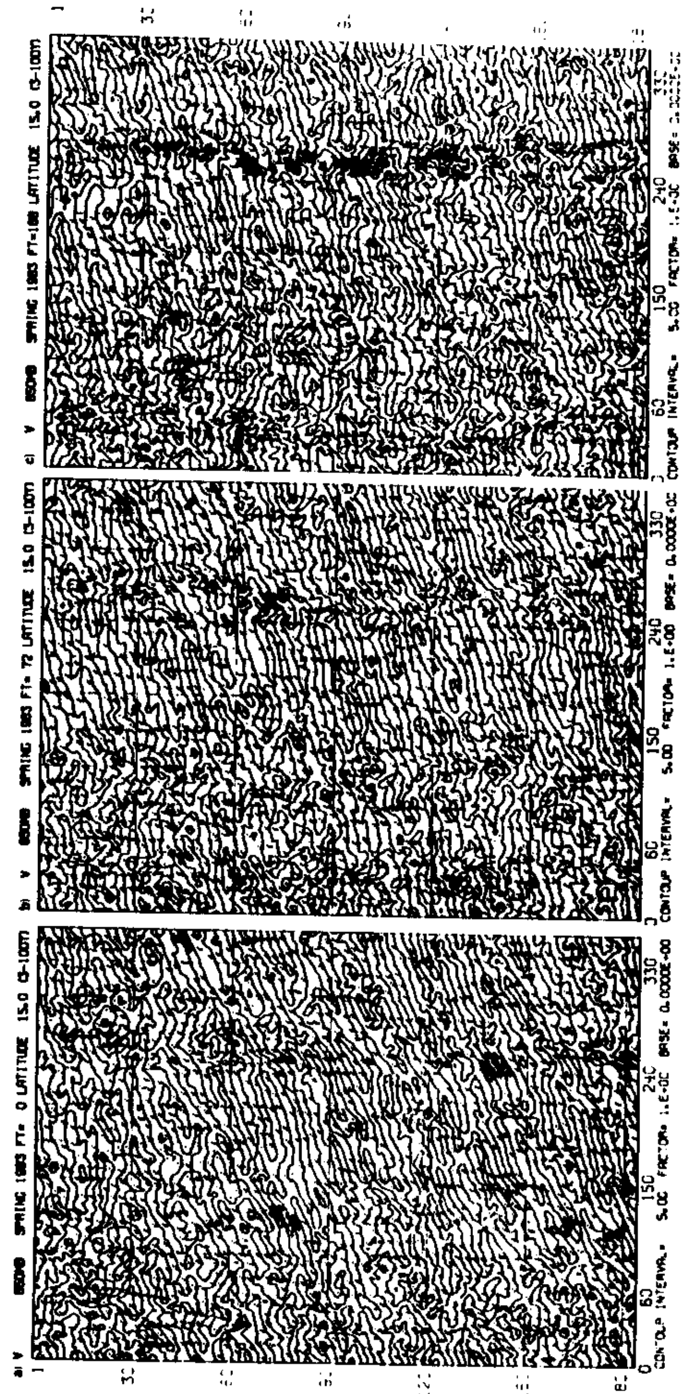

Fig. 29 Band pass filtered x-t diagrams of 850 mb meridional winds at 15°N constructed from the series of analyses and the forecasts. (a) analyses, (b) 72 hour forecasts and (c) 168 hour forecasts. The time filter is designed to extract the frequency range between 3.3 and 10.0 days. Units are metres and the negative areas are shaded.

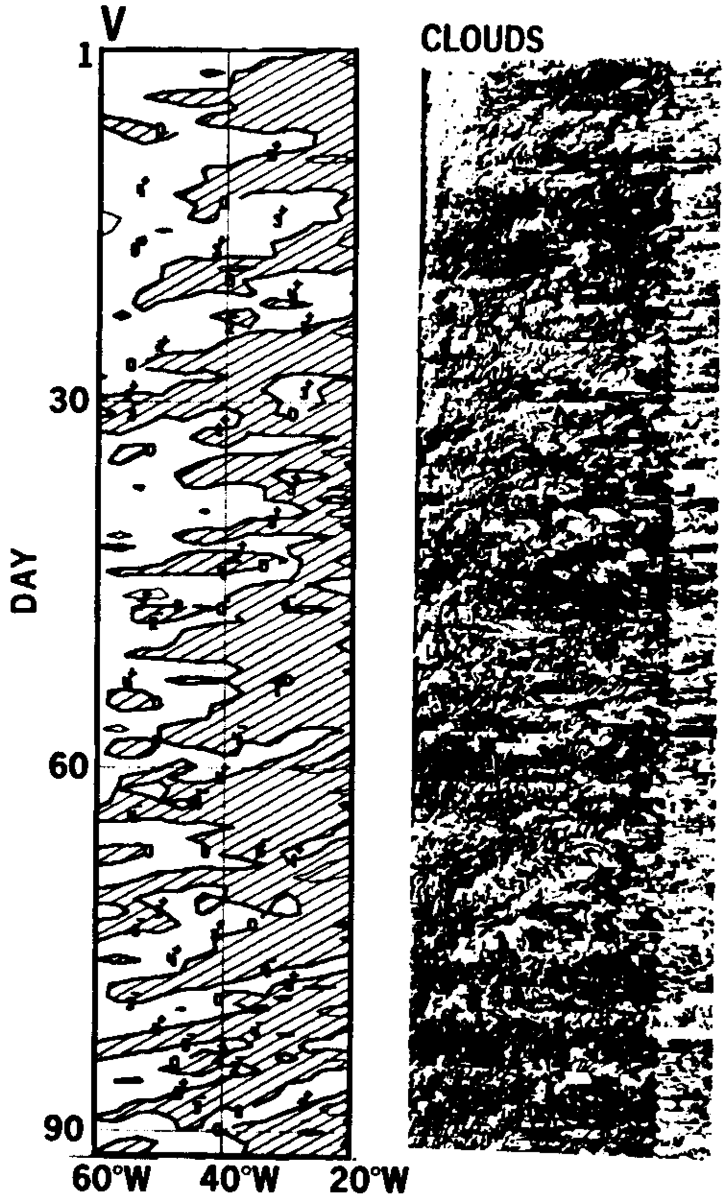

Fig. 30 x-t diagram of the analysed meridional winds (left) and the cloudiness (right) at about 15°N over the Atlantic (60°W-20°W). The diagram for cloudiness is obtained from the METEOSAT visible images (see detail in the text). The period covers from 1 June 1983 to 31 August 1983. The units of the meridional wind are m/s and the negative areas are shaded.

degrees longitude per day and the typical wavelength is about 3-4000 km. These properties of the transient waves correspond very well with the known properties of observed transient disturbances in the tropics. For example, the easterly waves have a wavelength, L, of roughly 2-3000 km and propagate westward with a phase speed, c, of 5-7 degrees of longitude per day (Riehl, 1954). Corresponding values for other disturbances are; L=3500 km and c=5-7 deg/day for African waves (Burpee, 1972), L=3500-4000 km and c=7 deg/day for ITCZ waves in the western Pacific (Reed and Recker, 1971), and L=2500-3000 km and c=5-6 deg/day for monsoon disturbances over India (Murakami, 1976).

It is interesting to note that some of the waves are very long lasting and even go around the earth. Furthermore, some of the waves are observed to develop into tropical cyclones.

The relation between the weather and the disturbances identified in the meridional wind component at 850 mb requires some investigation. A preliminary study was made using visible satellite images. Daily METEOSAT pictures were cut into thin strips (corresponding roughly to 5 degree latitude) centred at around 15°N, and mounted to form x-t diagram of clouds; this method was first applied by Chang(1970). Fig. 30 compares the two x-t diagrams (clouds on the right and the meridional wind on the left) over the Atlantic during the period, 1 June to 31 August, 1983. We observe some agreement between the two fields, around days 30, 65, 70 and 80. This investigation is very crude and requires further refinement, but clearly the use of digitized satellite information is vital to quantify the relations.

The time filtered x-t diagram constructed from a series of 72 hour forecasts is shown in Fig. 29b. There is a very good correspondence between the

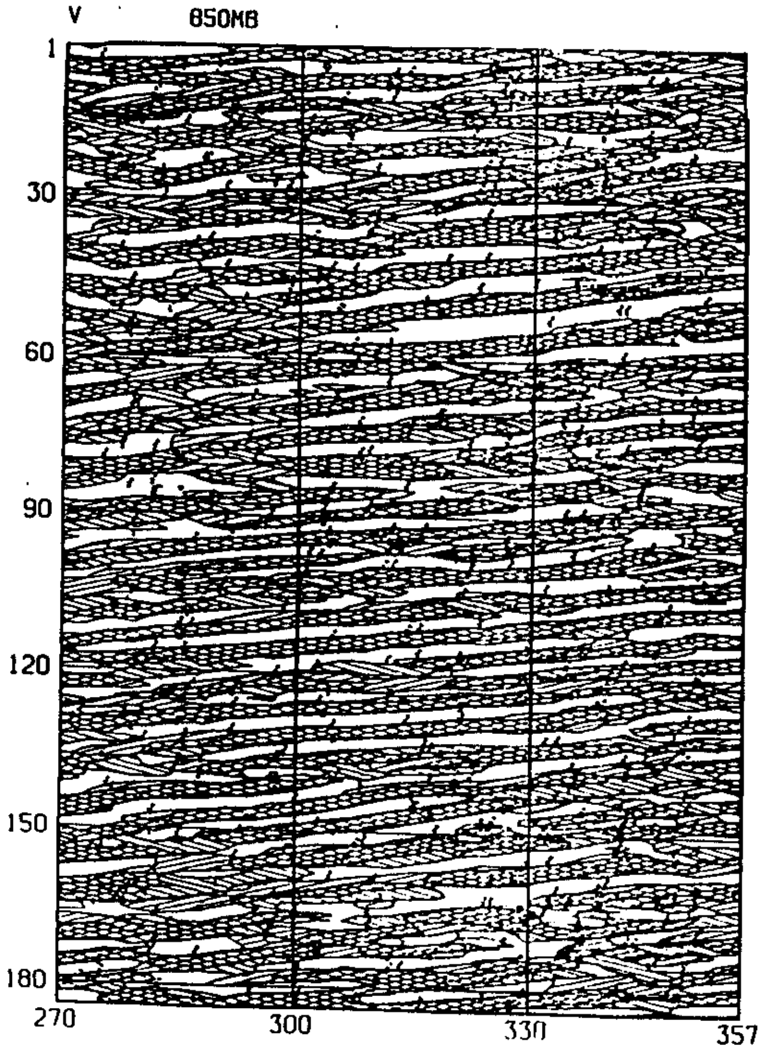

Fig. 31 x-t diagram of time filtered 850 mb meridional wind at 15°N over the Atlantic. The diagram for the analyses and the 72 hour forecasts are overlayed. The areas of crossed hatch and the areas of blank indicate that the sign of the meridional winds agree between the forecasts and the analyses. Units are m/s.

analysis and the forecast. To demonstrate the agreement more clearly, the band pass filtered x-t diagram over the Atlantic for the analyses and forecasts are overlayed and presented in Fig. 31. The cross-hatching indicates where the signs of the filtered meridional wind for the analyses and the forecasts are both negative, and blank areas are where the signs are both positive, indicating forecast skill. This method of verification of the transients seems to indicate that the transient disturbances in the tropics are predictable for more than 3 days.

The x-t diagram for the 168 hour forecasts is shown in Fig. 29c. The agreement with observation is not very good. However, transient waves still exist and move westward with a reasonable phase speed. Considering the growth of the systematic error in the very large scales, and the consequent deterioration of the basic state on which the transient waves develop and propagate, the existence of the transient waves at the 7 day forecasts seems to suggest that in the tropics the predictability of the waves may be longer than that of the very large scale quasi-stationary motion.

In order to make the verification more quantitative, the correlation of the time filtered meridional component of the wind at 850 mb between the analysis and the forecast is computed from the summer 1983 data over the tropics covering 30°S to 30°N. For the verification of the time filtered data, it is not clear what ranges of correlation values can be regarded as providing useful forecasts. However we have somewhat arbitrarily shaded the area where the correlation is greater than 0.5. This value is chosen because the correlation of the persistence of the time filtered data drops to less than 0.5 in one day, becoming negative by day 2 over the entire tropics; thus in this sense, a correlation of 0.5 or more seems to indicates good forecast skill for the time filtered data.

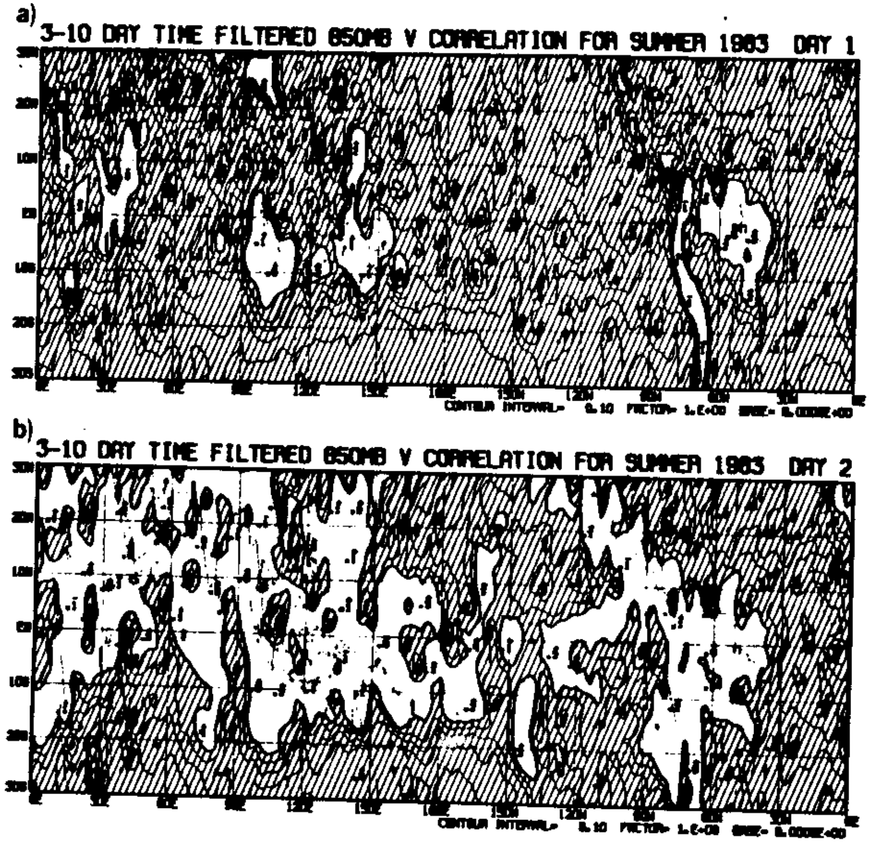

Fig. 32 Correlation between the time filtered analyses and the forecasts of the meridional component of wind at 850 mb. Contours are drawn where the values are greater than 0.5. The areas of correlation greater than 0.5 are shaded. (a) for 1 day, (b) for 2 day, (c) for 3 day and (d) for 4 day forecasts.

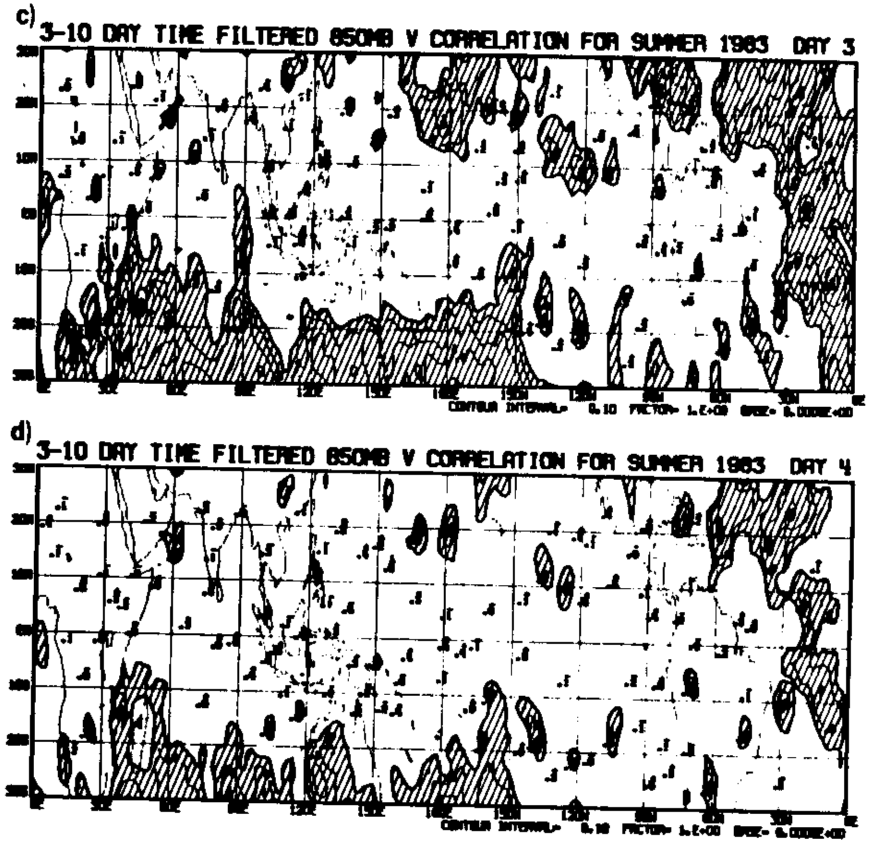

Fig. 32 continued.

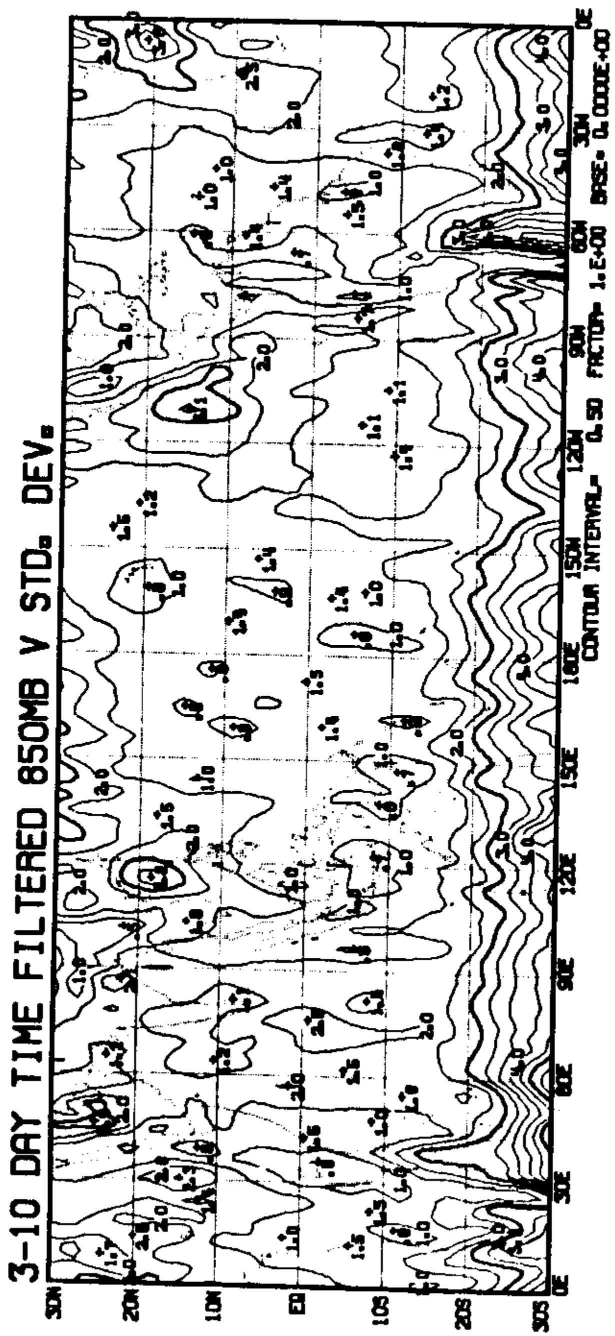

Fig. 33 Standard deviation of the filtered meridional component of the wind at 850 mb computed from the analyses. Units are metres.

The correlations shown in Fig. 32 indicate that over most of the tropical oceans, the model has good predictive skill. Over the Atlantic, in particular, the forecast seems to be skilful even beyond day 4. Note that the area is very well covered by satellite derived wind observations and the verifying analyses cannot be biased toward the model forecast initial guess fields. Therefore, the forecast is considered to be truly skilful. The forecast skill is found to be not very high over the Indian Ocean and over the western Pacific. The former region has no satellite wind observations and low skill is likely to be due to the lack of data. The western Pacific is, on the other hand, covered by satellite data and fairly good island station observations and so the low skill cannot be explained by the data problem. The characteristic feature of the area is strong activity of the tropical storms. This seems to imply that the model cannot properly handle the development of tropical disturbances into tropical storms. In order to examine the relation between the forecast skill and the tropical disturbance intensities, the climatological standard deviations of the time filtered meridional wind are presented in Fig. 33. This figure itself presents quite interesting observational evidence of tropical transient disturbance with periods of 3-10 days. In the Pacific, the transient disturbances are intense over the far western (South China Sea) and over the far eastern (west coast of Mexico) parts of the ocean, where typhoons and hurricanes are known to develop frequently (Gray, 1978). The disturbance intensities are also large over the Western Sahara and over the head of the Bay of Bengal where African waves and monsoon disturbances are occasionally observed. Recently, Nitta et al. (1985) analysed tropical transient disturbances in the lower troposphere over the globe using FGGE III-b data (during the summer 1979). The areas where they found transient disturbance active measured in terms of the power spectrum, agree very well with the present results. Returning to the forecast skill of the transient disturbances, comparison of the correlations (Fig. 32) and the standard deviations (Fig. 33) shows that the correlation is low where the disturbance intensities are large. This result seems to be fairly reasonable because the resolution of the model (triangular truncation at wavenumber 63) is known to be insufficient for predicting the development of the tropical storms. However, Bengtsson et al. (1983) had some success in predicting tropical storms by the ECMWF operational model, but they also pointed out the need for increasing the horizontal resolution for better forecasts.

6. CONCLUSIONS AND DISCUSSION

The predictability of the ECMWF operational model in the tropics during the 1983/84 period has been examined.

The RMS and the mean forecast errors of height, temperature, and wind in the lower and upper troposphere over the globe are calculated in order to examine the predictive skill of the very large scale quasi-stationary motions in the tropics. The results showed that;

(1) Predictability in the tropics (as measured by the time taken for the RMS forecast error to reach the climatological standard deviation) is about 1-2 days for the mass field, 1 day for the low level winds and 2-2.5 days for the upper level winds. This predictability is very short compared to that in the northern hemisphere mid-latitudes (7 days) and in the southern hemisphere (4 days).

(2) The errors in the tropics grow very fast in the first 24 hours. In most of the parameters, the error growth slows down after 24 hours but continues growing in a nearly linear manner. The departures from climatology grow very fast and become large.

(3) Predictability of the lower troposphere is generally shorter than that of the upper troposphere, except for the height field in the tropics.

(4) Seasonal variation of the predictability in the tropics is not very large.

(5) In the tropics the mean error (systematic error) forms a very large part of the total error (i.e. 80-90% for the height, 60-80% for the temperature,

50-70% for the zonal component of the wind and 30-50% for the meridional component of the wind) in the forecast time range of 24 to 168 hours. The percentage of the mean error to the total RMS error in the extratropics is much less.

(6) The structure of the predominant systematic error resembles that of the internal symmetric gravest Rossby mode. The error grows without any appreciable propagation.

Several sensitivity experiments on resolution, orography, sensible heat flux over the continents, convective heating and the initial moisture distribution indicated that convective heating was most closely related to the generation of the systematic error. The convective heating in the tropics estimated from climatological rainfall, assuming a western Pacific vertical heating profile, drastically reduced the systematic error. The sensible heating over the continent and orography showed little impact. Horizontal resolution was also shown not to be too closely related to the systematic error.

The present study indicates that the predictability of the very large scale quasi-stationary motions in the tropics by the ECMWF operational model is still disappointingly low. However, there is considerable scope for improving the forecast in the tropics since the systematic error is shown to be the major contributor to the total forecast error. Furthermore, it has been demonstrated that the error is essentially caused by the failure of the cumulus parameterization to produce the climatological distribution of rainfall in the tropics, particularly the rain associated with the ITCZ. The present convective parameterization used at the ECMWF is a version of the Kuo's scheme which was originally developed for tropical storm studies and is suitable for the prediction of transient disturbances. The performance

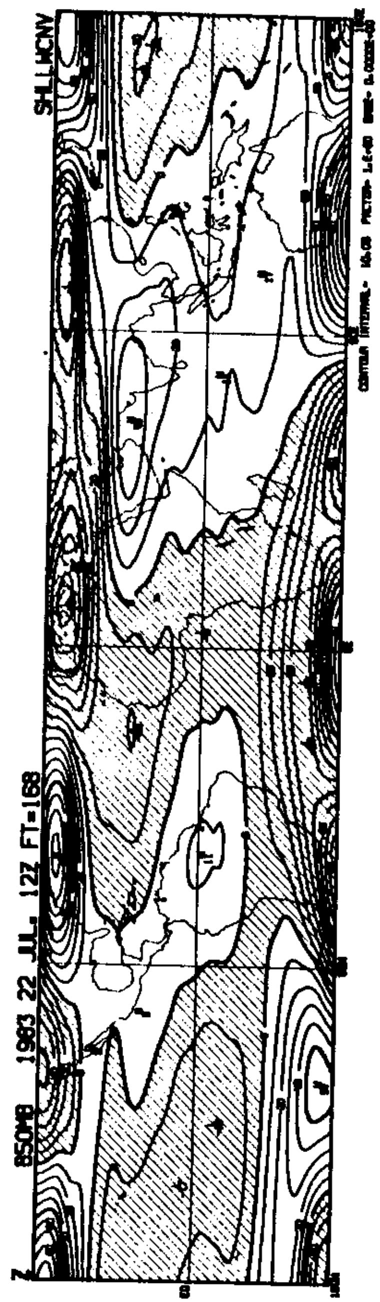

Fig. 34 Zonal Fourier filtered (wavenumber 1-3) forecast error of the 850 mb height at day 7 of the forecast using shallow convection scheme (Tiedtke, 1984). Units are metres and the negative areas are shaded.

of the scheme in simulating climatological rainfall has not been extensively studied, but present result seems to suggest that the scheme (together with the boundary layer parameterization) is not working very well in this context. The climatological rain experiment performed in this study suggests that the convective heating should depend more strongly on the geographically fixed forcing, such as the sea surface temperature. Research into the parameterization of convention seems to require some thought towards this direction. Recent experiments incorporating a shallow convention scheme Tiedtke (1984) greatly improved the precipitation distribution in the tropics and accordingly reduced the systematic error growth. Fig. 34 shows zonally filtered error of 850 mb height for the same case presented earlier. Comparison with Figs. 22 indicates that the incorporation of the shallow convection scheme significantly reduces the systematic error over the Atlantic in the northern hemisphere. The use of the adjustment type scheme being developed at ECMWF by Betts and Miller (1984) is also found to reduce the systematic error in the tropics significantly.

The predictability of the transient waves in the tropics was studied using a time filtering technique. The analysis scheme at ECMWF is found to be capable of detecting typical tropical tropospheric transient disturbances. The subjective evaluation of the forecasts of the transient disturbances using x-t diagrams indicated that the forecast model seems to predict these transient waves at 72 hours and even beyond. The change of the very large scale basic field due to the growth of the systematic error does not seem to strongly influence the properties of the transient disturbances in the model.

The objective verification of the forecasts using correlations between the time-filtered analyses and the forecasts has been performed. Over a large part of the oceans, the transient disturbances are predicted very well up to or beyond 4 days. However, the model seems to have difficulty in predicting the development of tropical storms, possibly due to insufficient horizontal resolution of the model. The forecast is also found to be not very skilful where satellite wind data are lacking.

The ability of the large scale model to predict transient waves in the tropics is very encouraging. Further research should be directed at extracting information on transient disturbances in the tropics from unfiltered forecast products. It has been observed that some tropical cyclones have apparently been initiated by the transient waves. In this connection, short to medium range prediction of the tropical cyclones may be possible by using high resolution models such as the one being developed at ECMWF. The reduction of the systematic error is expected to further improve the predictability of the transient disturbances.

Several other important aspects of tropical predictability have not been covered in this study. The sensitivity of the forecast to the initial state could be studied using the observing system experiment data performed at ECMWF. It can also be studied in relation to the analysis problem in the tropics. Recent studies of the performance of the optimum interpolation analysis scheme at ECMWF (Cats and Wergen, 1983; Daley, 1983; Hollingsworth and Lönnberg, 1985; Lönnberg and Hollingsworth, 1985) indicate that the normal modes with very large horizontal scale are not properly analyzed. The reasons are the decoupling of mass and wind at low latitudes used in the analysis scheme and the limitation placed on the scale of the analysis due to the horizontal structure functions used. This aspect needs to be studied extensively in future work.

The impact of the tropical forecast to the middle latitudes must be considered as an another important subject. The systematic error discussed in this paper, in fact, extends far into the extratropics. In this respect, the elimination of the tropical systematic error should provide an immediate impact on middle latitude forecasting. However, the large temporal variability in the extratropics makes it very difficult to isolate the impact particularly from a small number of cases. In this regards, it is necessary to perform a large number of such impact experiments such as the one performed by Haseler (1982).

Acknowledgements

The author wishes to sincerely thank Lennart Bengtsson (Director) and Dave Burridge (Head of Research) for their kind invitation to ECMWF. Also the author would like to thank the staff at the Centre who helped in performing the present study. Rauno Nieminen helped in using archived data; Michael Tiedtke's assistance was essential in carrying out many forecast experiments - furthermore, he provided an example of the forecast with the shallow convection under development; Adrian Simmons and Michel Jarraud kindly allowed the author to use their results from resolution experiments; Tony Hollingsworth and Bob Riddaway carefully read the original manuscript. The author also profited from discussions with Klaus Arpe, Bill Heckley and Ernst Klinker. Discussions with Dr. Krishnamurti were also very helpful in finalizing this paper. The graphics were done by Robert Hine.

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