DIAGNOSTIC AND PREDICTABILITY STUDIES USING FGGE DATA

L. Bengtsson, M. Kanamitsu(1), P. Kållberg and S. Uppala
ECMWF

ABSTRACT

A presentation of diagnostic and predictability studies using FGGE data is given. An excellent data coverage in areas previously practically void of observations have made it possible to analyse synoptic features in the Tropics and in the Southern Hemisphere in great detail. The studies strongly suggest that the winter circulation in the Southern Hemisphere is more intense than previously assumed. The tropical circulation show several examples of episodes of very active interhemispheric exchange. The large scale circulation in the Tropics is dominated by a giant ascending cell over the western Pacific having a particular strong component in the equatorial plane. This circulation is particularly pronounced during the Northern Hemisphere summer. Prediction experiments show increased skill in particular in the Southern Hemisphere and in the Tropics. Comparison with operational forecasts performed at ECMWF after FGGE as well as by observing system experiments shows that this is due to the improved data coverage during FGGE.

1. INTRODUCTION

The observational and data collection phase of the global experiment is now finalized and the research activity is rapidly gaining momentum as the observations are becoming available to the scientific community. FGGE has for the first time provided a truly global data set and the experiment has supplied the most complete set of atmospheric data ever obtained. It will give the scientists an exceptional data base for research directed at improving methods for weather forecasting and understanding of climate and thereby justify the cost and efforts spent on the experiment.

The main research objectives of the experiment as formulated by the Joint Organizing Committee (JOC) for GARP are as follows:

- To obtain a better understanding of atmospheric motion for the development of more realistic models for weather prediction
- to assess the ultimate limit of predictability of weather systems

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(1) Electronic Computation Center, Japan Meteorological Agency, Tokyo, Japan.

- To design an optimum composite meteorological observing system for routine numerical weather prediction of the larger-scale features of the general circulation
- To investigate, within the limitation of a one-year period of observation, the physical mechanisms underlying the fluctuations of climate in the time range of a few weeks to a few years and to develop and test appropriate climatic models.

This very broad, general and extensive research programme will undoubtedly be pursued over several years and it will clearly take a long time before the final scientific summary of FGGE can be made. Nevertheless as has been demonstrated by the operational data exchanged during the experiment, some of the results are so spectacular and striking that certain basic opinions about the experiment can already be expressed at this time.

ECMWF has had the great advantage, in the capacity of a III-b producer, to have a very early access to the data. Furthermore, the main objective of ECMWF, namely large-scale medium range forecasts, is consistent with the fundamental objective of the Global Weather Experiment. Proper resources in computers and technical expertise have therefore been available. Four-dimensional data assimilation systems and models developed for operational global prediction for medium and extended time scales are being applied in the FGGE research programme. It was certainly very timely and of mutual benefit for ECMWF and the Experiment that ECMWF entered its operational phase in August 1979 in the middle of the Global Weather Experiment.

The research programme of ECMWF is already drawing advantage, and will continue to do so even more, of the tremendous material compiled during the Experiment. The observations will be used in the testing and development of numerical models and to assess the predictability of the atmosphere for different time- and space scales. Furthermore, a joint programme with the ECMWF Member States has been launched towards the formulation of an optimum meteorological observing system necessary for medium and extended range forecasting. Section 2 of this paper summarizes the atmospheric circulation during January and July 1979. Section 3 will present results of some prediction experiments which show that a considerable improvement in forecasting skill is obtained in particular in the Tropics and in the Southern Hemisphere. The data-assimilation system development to produce the FGGE analysis is more or less identical to the Centre's operational system. A description can be found in Bengtsson et al (1982).

2. MEAN ATMOSPHERIC CIRCULATION DURING FGGE

The extensive observational coverage during the FGGE has not only provided excellent initial conditions for numerical weather prediction experiments, but also invaluable information on the circulation over the normally data void Tropical and Southern Hemisphere ocean areas.

During the course of operational FGGE analyses at ECMWF, we have been preparing several types of monthly mean maps. These maps show considerable deviations from published climatologies in the Southern Hemisphere, which hardly can be regarded as a year to year variation. Since the space is limited in this paper, we have confined ourselves to the description of the monthly mean field in the Tropics and Southern Hemisphere during the two extreme months, January and July, which show the most significant deviations from normal climatologies. A more complete description of the monthly average fields is in preparation and will be published soon at ECMWF.

The improvement of the Southern Hemisphere analysis is most apparent in the zonal cross section of the zonally averaged wind field. In Fig. 1 and 2 zonal cross sections of the zonally averaged zonal wind and meridional wind for January and July are shown on the left side of the figures. The most striking difference with long time averages in the Southern Hemisphere is the intensity of the polar night jet in July. The zonally averaged wind speed at 10 mb was greater than 95 m/sec, nearly twice the values shown by Newell et al (1972). The southern polar night jet is analyzed primarily from temperature data from TIROS-N, but the few available wind data from radiosondes reaching 50 mb and above confirm the analyses. Although the difference is less significant, the tropospheric jet in January is also stronger than in the normal climatology and extends further up into the lower stratosphere. The wind at the surface is also generally stronger, indicating a more intense cyclonic activity. Polar night jet intensities of the same order as those analysed over the Southern Hemisphere during FGGE have been obtained in general circulation simulation studies (e.g. Manabe and Mahlman 1976) although these authors tended to consider the intensities "unrealistic".

Thus in some respect numerical simulations by general circulation models carried out before FGGE have in all likelihood provided a more accurate picture of the Southern Hemisphere circulation than has been possible to hitherto analyze from the sparse conventional observing network.

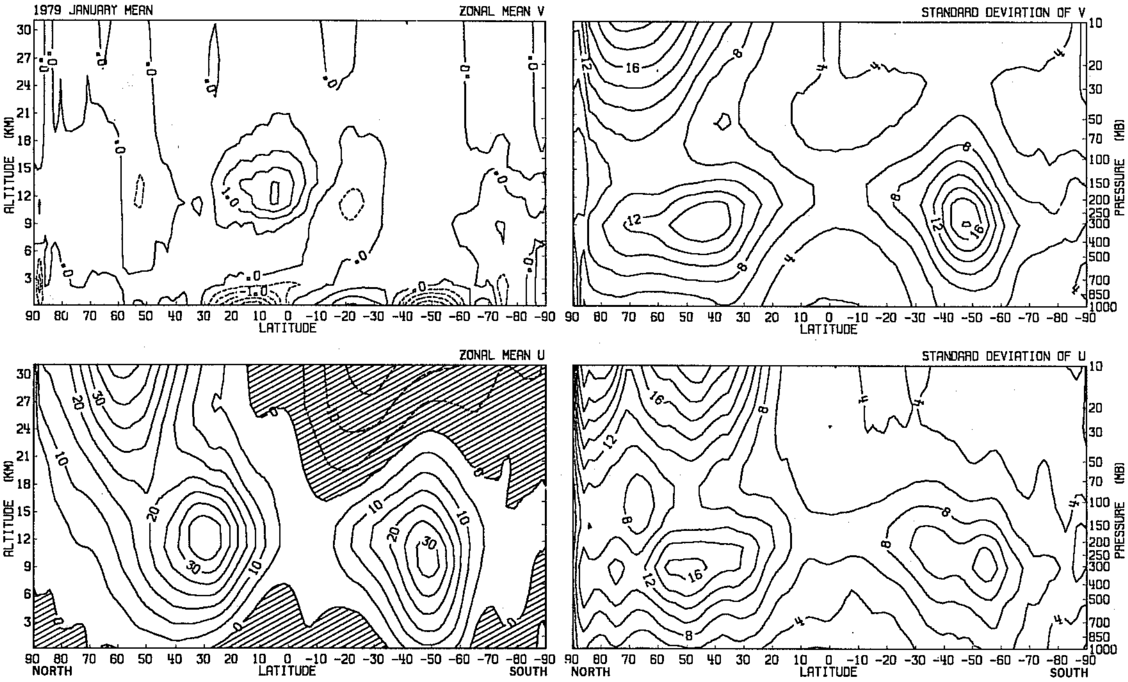


Fig. 1 Monthly zonal averages for January 1979. Zonal wind, hatched in areas with easterlies, (bottom left) and standard deviation in time (bottom right). Meridional wind (top left) and standard deviation in time (top right).

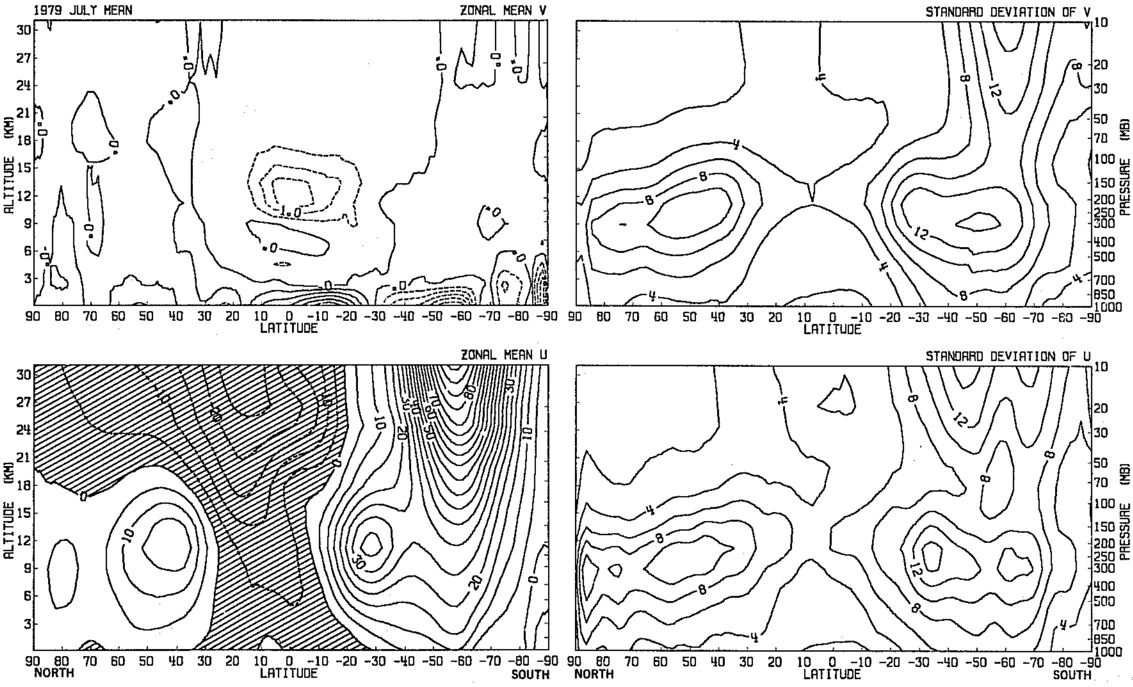


Fig. 2 As Fig. 1, but for July 1979.

The Northern Hemisphere circulation during the winter 1978 - 1979 was extreme. January was characterized by a persistent blocking over the North Atlantic. The Icelandic low was absent, and replaced by a high of 1017 mb at $52^{\circ}N/30^{\circ}W$. The Aleutian low, on the other hand, was 12 mb lower than normal. The winter of 1979 can only be compared with that of 1963, when the Atlantic blocking high was even more intense (Godbole and Shukla, 1981).

During 1963 a marked warm anomaly in the sea surface temperature (SST) was observed in the southern part of the North Atlantic from the Cap Verde Islands towards the Caribbean Sea. In a simulation study by Rowntree, 1976, it was shown that such an SST anomaly created an atmospheric anomaly similar in intensity and position to that observed during the winter of 1963. A preliminary analysis of the FGGE SST data for the Atlantic winter of 1979 shows a SST anomaly very similar to that of the winter of 1963.

In the Tropics, the zonally averaged winds are not significantly different from previously known long time averages. The absence of easterlies in the middle of the troposphere during January (Fig. 1) is not a persistent feature, and the easterlies return in February. Local details in the tropical analyses are reflected in minor irregularities of the mean zonal wind. For example, the dip in the lower tropospheric easterlies at $5^{\circ}S$ in January is due to a strong low level westerly flow over New Guinea, and the weak westerly maximum at the surface at $10^{\circ}N$ in July is a result of the south-westerly monsoon flow over the Indian Ocean.

The zonally averaged meridional wind, $\bar{v}$, is purely divergent and one of the most difficult quantities to analyze. The monthly mean of $\bar{v}$ in the Centre's analysis shows quite reasonably patterns and magnitudes, representing dominance of the winter hemisphere Hadley circulation in the Tropics, and it agrees well with other studies (Oort and Rasmussen, 1970, Newell et al, 1972). It is noted that in contrast to the Northern Hemisphere, the low level southward flow associated with the Southern Hemisphere Ferrel cell is very large and persistent in both January and July, corresponding to the large frictional convergence in association with the active cyclones.

As a measure of the time variability of the analysed wind field, zonally averaged standard deviations of u and v from respective monthly means are presented on the right side of Figs. 1 and 2. The values in the Northern Hemisphere and in the Tropics are very similar to those of Newell et al (1972) indicating reasonable performance of the analysis system to resolve time variability (transient disturbances), both in high and low latitudes.

The standard deviations of wind in the Southern Hemisphere troposphere have revealed quite interesting contrasts to those in the Northern Hemisphere. In the Northern Hemisphere, the variability of wind in winter is larger than in summer, which agrees with the synoptic experience of increasing cyclone activity in winter. On the other hand, in the Southern Hemisphere, as shown in Fig. 1 and 2, the variability of the wind does not vary very much with season (variance of u increases in winter but that of v decreases, while the area of large variability increases. From synoptic examination of the daily surface analysis in the Southern Hemisphere, we have noticed that the cyclones are not deeper in the winter than at other times of the year, lows with central pressures below 940 mb are analyzed during all seasons, which agrees with the above results. It is very interesting that the increase of the available potential energy in the Southern Hemisphere winter is accounted for by the increase of the latitudinal extention of the activity of the disturbances, and not by the increase of the activities themselves. The above analyses suggest the important role of the Antarctic continent as a mechanism of maintaining zonal available potential energy throughout the year in the Southern Hemisphere.

2.1 The Southern Hemisphere circulation

Among the various FGGE observation systems, drifting buoys, satellite derived cloud drift winds and satellite soundings provided most of the observations in the Southern Hemisphere. These observation systems have enabled us to examine longitudinal variations which previously have been considered to be very small. Figs. 3 and 4 show monthly averaged surface pressures and 500 mb height and their deviations from respective normal climatologies.

The zonally averaged sea level pressure during July 1979 reached a minimum of 976 mb at 66°S. This is 7 mb lower than the lowest July zonal mean from 16 years (1961 - 1976) of analyzed January and July monthly mean sea level pressure maps prepared by Godbole and Shukla, 1981. The average of their analyses was 990 mb at 70°S. Both during 1968, the most intense year in

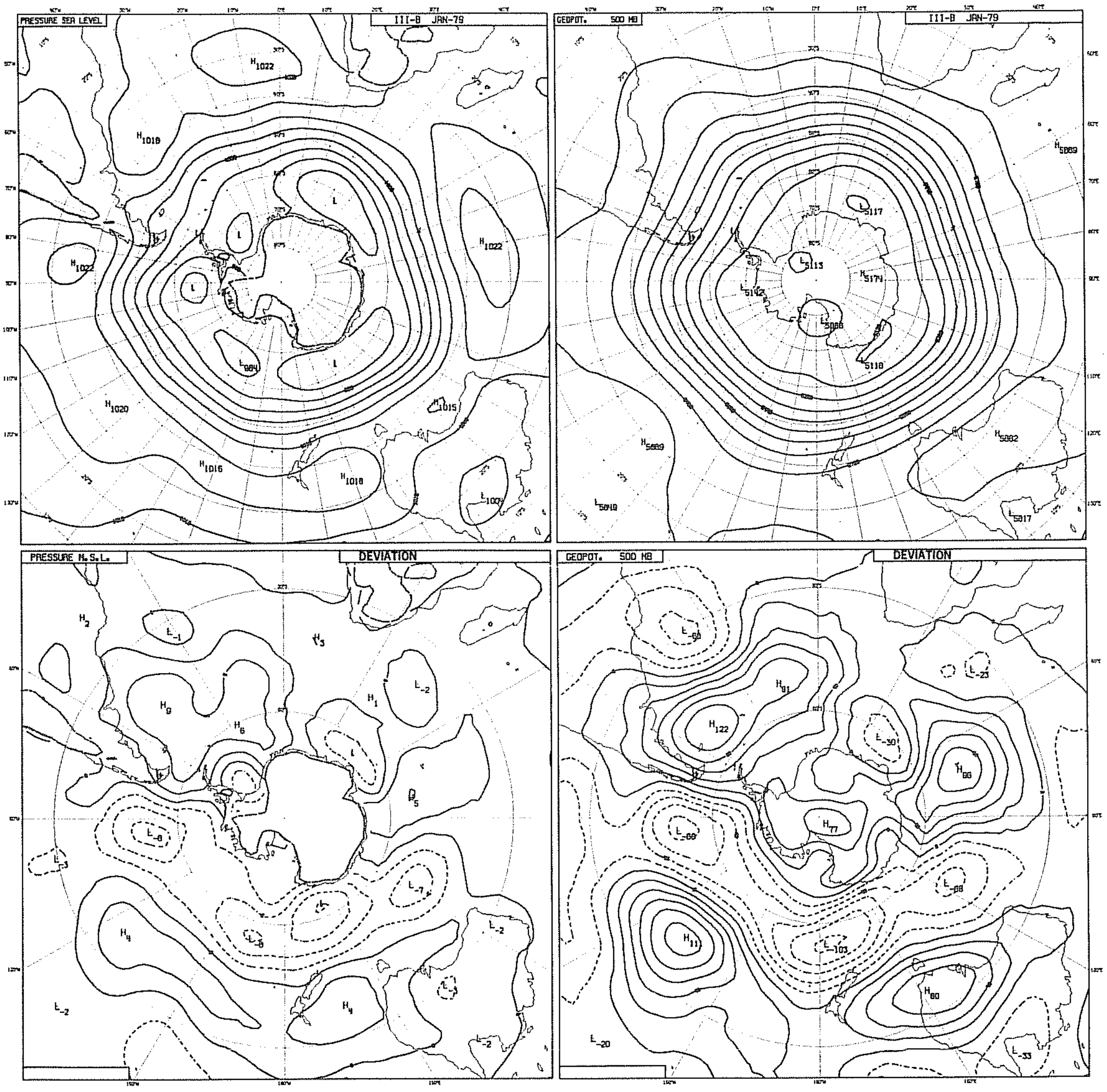


Fig. 3 Southern Hemisphere monthly average of sea level pressure (top left) and 500 mb geopotential (top right) for January 1979. The bottom left and right maps show deviations from climatology of the corresponding means. Full lines indicate 1979 values higher than normal. Dashed lines indicate 1979 lower than normal.

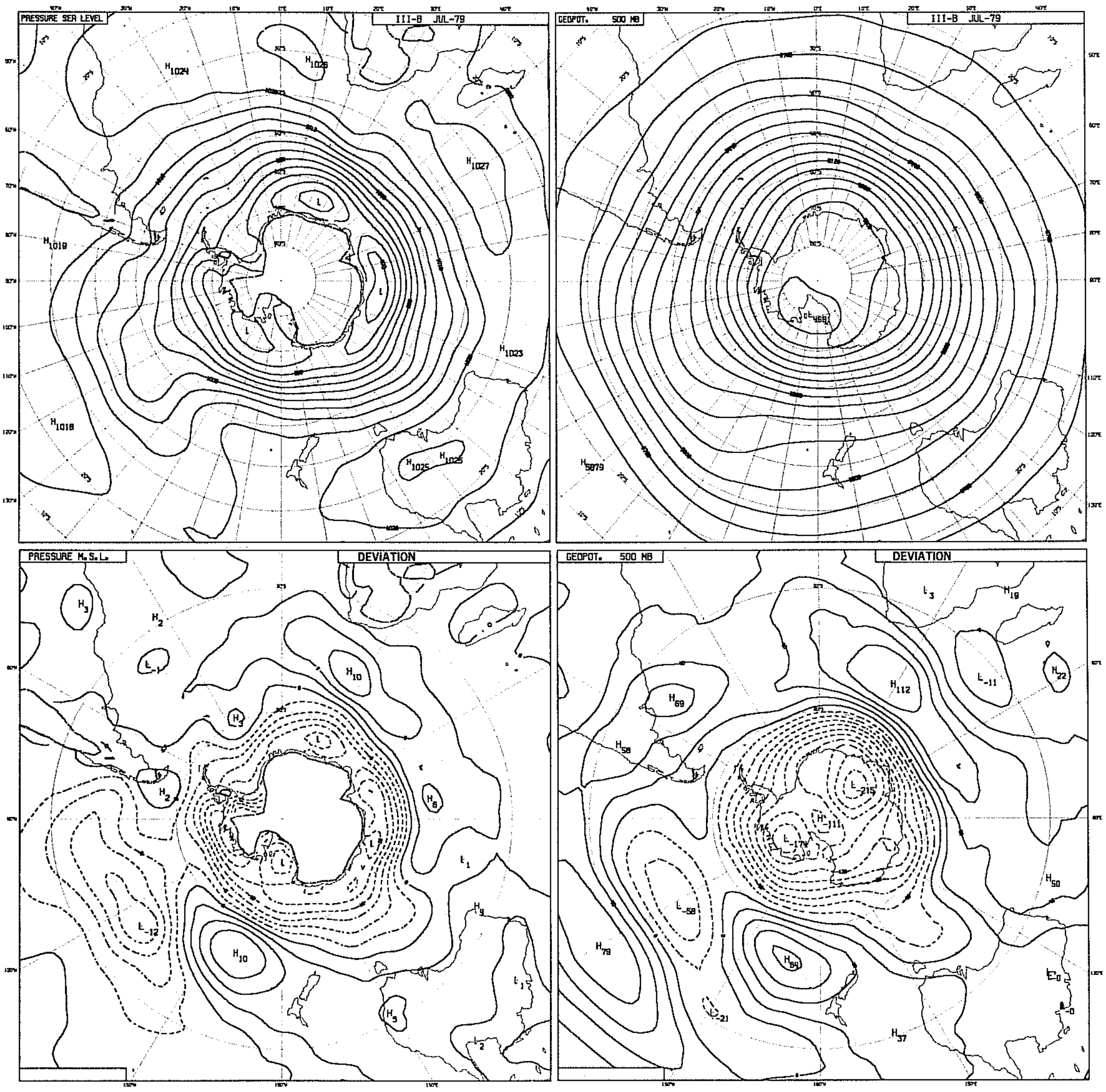


Fig. 4 As Fig. 3, but for July 1979.

Godbole's and Shukla' study, and during FGGE, the minimum pressure was analyzed around 20°E. The geostrophic gradient at this longitude was, however, about 40% stronger during 1979. It is unlikely that the discrepancy is entirely due to 1979 being an extreme year. The main explanation for the intensity of the Southern Hemisphere circulation must be found in the improved data coverage, primarily the drifting buoys. Similar results have been obtained by Guymer and Le Marshall (1981) using operational level II-a data. The most marked longitudinal deviation from the climate during FGGE is found over the Pacific, where a persistent trough-ridge system with clear indications of blocking near New Zealand developed. This blocking was observed on daily maps during July and August. In January, deviations from the normal as well as their longitudinal variations are less pronounced, except for a more intense circulation over the Pacific Ocean.

The most interesting difference between the Northern and Southern Hemispheres is found in the kinetic energy conversion processes between the different scales. Fig. 5 shows the kinetic energy conversions between zonal, and different scales of motion in the troposphere (1000 - 100 mb) during January over Northern (90°N - 24°N) and Southern (25°S - 90°S) Hemispheres. The numbers in the boxes indicate energy storage in each scale in units of 10^3 Joule/m^{-2}. The arrows connecting the boxes and the associated numbers indicate direction and conversion between the scales in units of 10^{-3} Watt m^{-2}. The energy storage values clearly show that the most dominant scales of motion in the Northern Hemisphere are the very long waves, while in the Southern Hemisphere the medium waves are the dominating ones. The dominance of the very large scale motion enhances energy conversions among the different scales, especially between the medium scale baroclinic waves and the very large scale motions which act partly as an intermediary for the maintenance of the zonal westerlies and also as an energy sink (Saltzman and Fleisher, 1960). In the Southern Hemisphere, on the other hand, interactions between the waves are much reduced and most of the conversions take place between the waves and the zonal motion. The baroclinic waves in the Southern Hemisphere are the direct energy source for the westerly jet and also for the large and small scale motions as expected from theoretical studies (Fjörtoft, 1953). In this sense, the general circulation of the Southern Hemisphere seems to be slightly simpler, at least during the Southern Hemisphere summer. However, the increased very large scale motions in July create a more complex circulation, similar to that of the Northern Hemisphere.

JANUARY 1979 MEAN 100 - 1000 mb

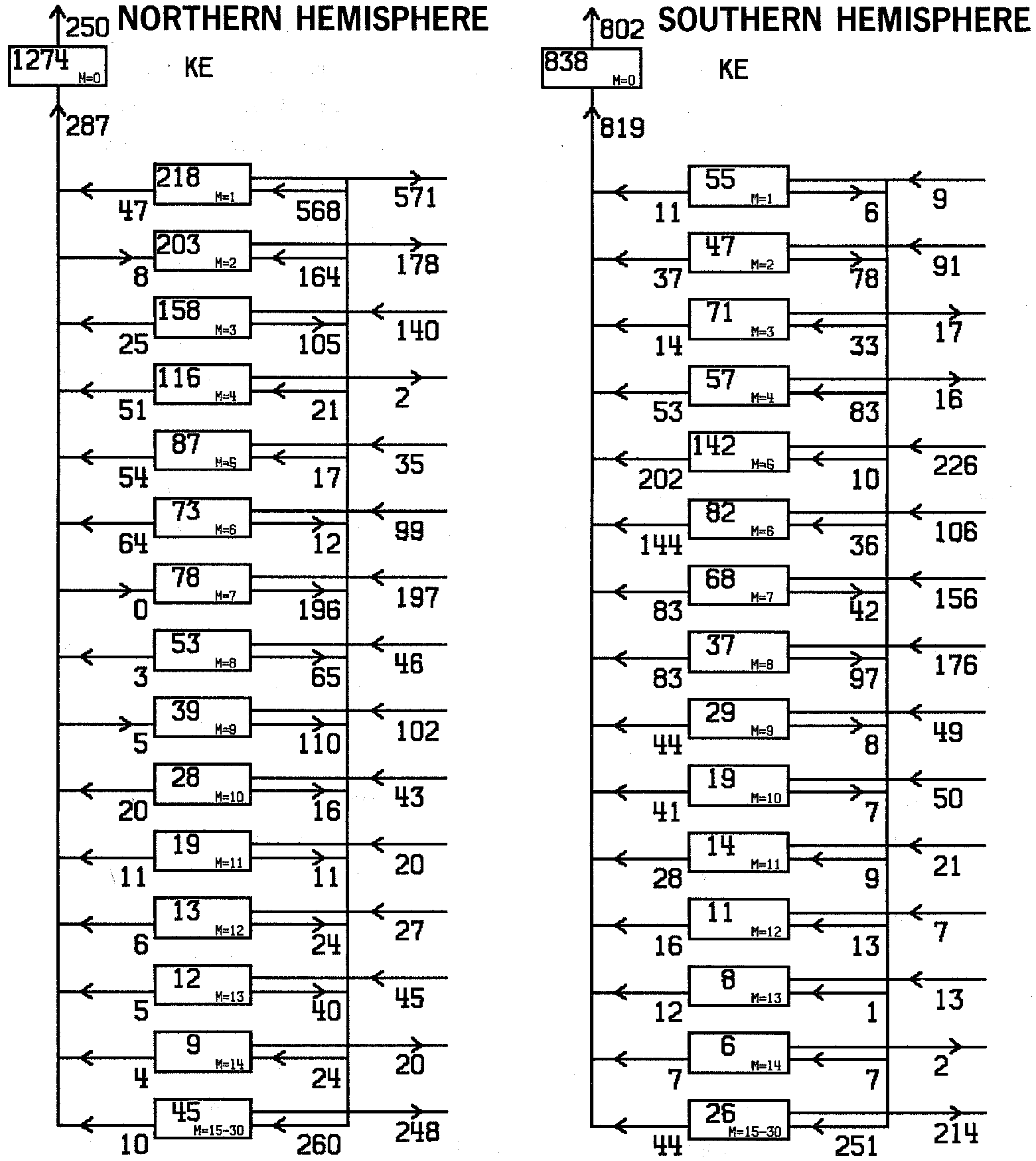


Fig. 5 Kinetic energy diagram in zonal wavenumber space for the troposphere (1000 mb - 1000 mb) between 90^{o} latitude and 25^{o} latitude during January 1979 for the Northern Hemisphere (left) and Southern Hemisphere (right). The boxes indicate different scales of motion, the zonal wavenumber, M, is indicated in the lower right corner of each box. The main numbers in the boxes and energy storages in 10^{3} J m^{-2}, and the numbers outside the boxes are conversions, in 10^{-3} w m^{-2}; zonal-wave to the immediate left, and wave-wave to the immediate right of column of boxes respectively. The numbers at the extreme right of each diagram are the residuals, comprising conversion from potential energy, dissipation and fluxes across the volume boundaries.

2.2 The Tropical circulation

The monthly averaged wind fields in the Tropics are also quite different from the normal climatologies obtained from conventional observations (e.g. Newell et al, 1972). Figs. 6 through 9 show streamlines and isotachs at 850 and 200 mb for January and July. The streamline patterns in the Tropics are generally similar to Newell's seasonal averages, particularly at 850 mb. Significant deviations are found at 200 mb over the tropical Southern Hemisphere ocean areas, especially over the eastern Pacific, where a strong westerly jet exists at around 5°S, decelerates towards South America causing subsidence over the west coast. This jet seems to be related to the trough located over Mexico, which extended across the equator.

Another noteworthy feature is the trough-ridge system strongly tilted from southeast to northwest over the central South Pacific, which seems to correspond to the frequently observed persistent cloud band over the same areas. Over the Southern Atlantic, an oceanic trough at the east coast of South America has significant amplitude in January and it seems that the area to be favoured for the formation of cut-off lows. In contrast to those areas, the Indian Ocean seems to be less active during January.

The circulation near the equator is very weak and does not seem to be of any significance.

The situation reverses in July due to the monsoon circulation over the Indian Ocean, and strong cross equatorial northerlies at 200 mb become most dominant over the area. Other areas in the Southern Hemisphere have some longitudinal variability with a smaller meridional wind component. The subtropical jet in the Southern Hemisphere also has significant longitudinal variations with a maximum over the Australian-Central Pacific area and minor maxima over South America and South Africa. The jet does not seem to be continuous at the west coast of South America. A similar discontinuous nature is noted on the Northern Hemisphere subtropical jet over the Atlantic during January. At 850 mb the wind speed is stronger, particularly in the Southern Hemisphere trade winds, both in January and July but the direction agrees with Newell et al (1972). The southwesterly monsoon flow over the Arabian Sea during July reaches 21 m/sec.

The large-scale circulation in the Tropics has a strong component in the equatorial plane as has already been demonstrated by Krishnamurti (1979).
The vertical circulation is very much dominated by a giant ascending cell over the western Pacific. The intensity of this cell varies through the year and moves slowly westwards during the first 6 months of the year. During June the

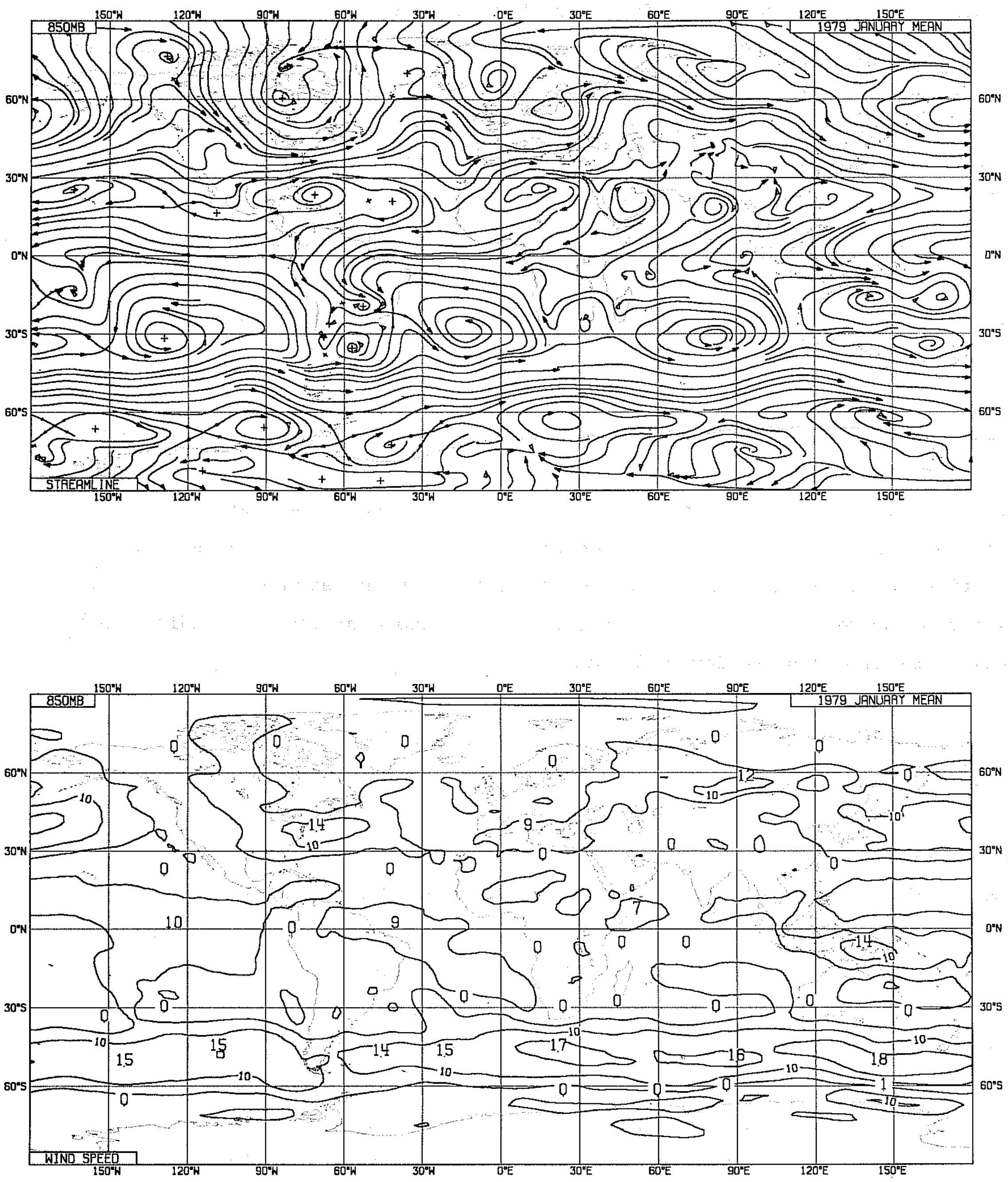


Fig. 6 Streamlines (top) and isotachs (bottom) of monthly mean wind analysis at 850 mb, January 1979. Windspeeds above 10 ms^{-1} shaded.

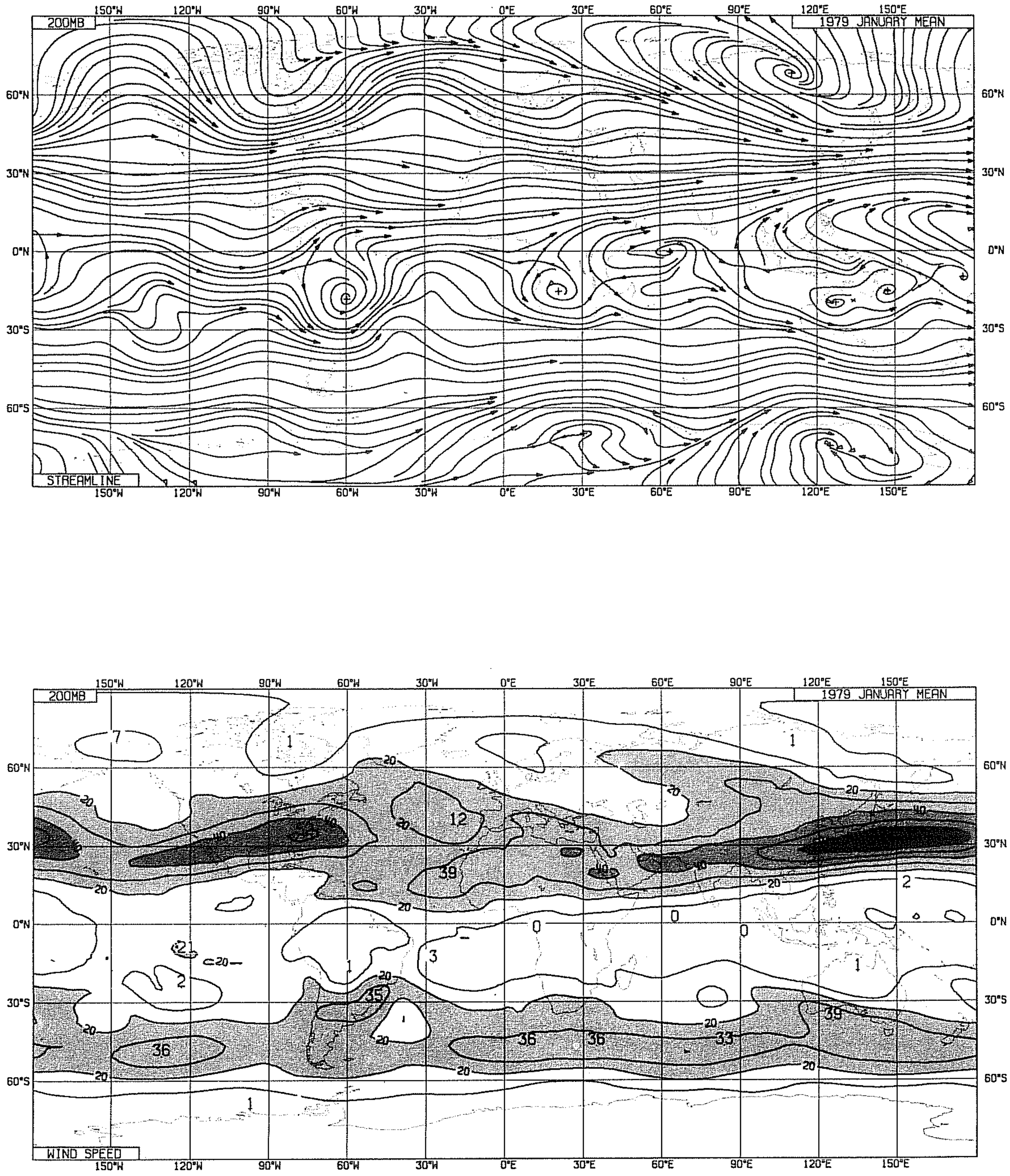


Fig. 7 As Fig. 6, but 200 mb. Shading for 20, 40 and 60 ms^{-1}.

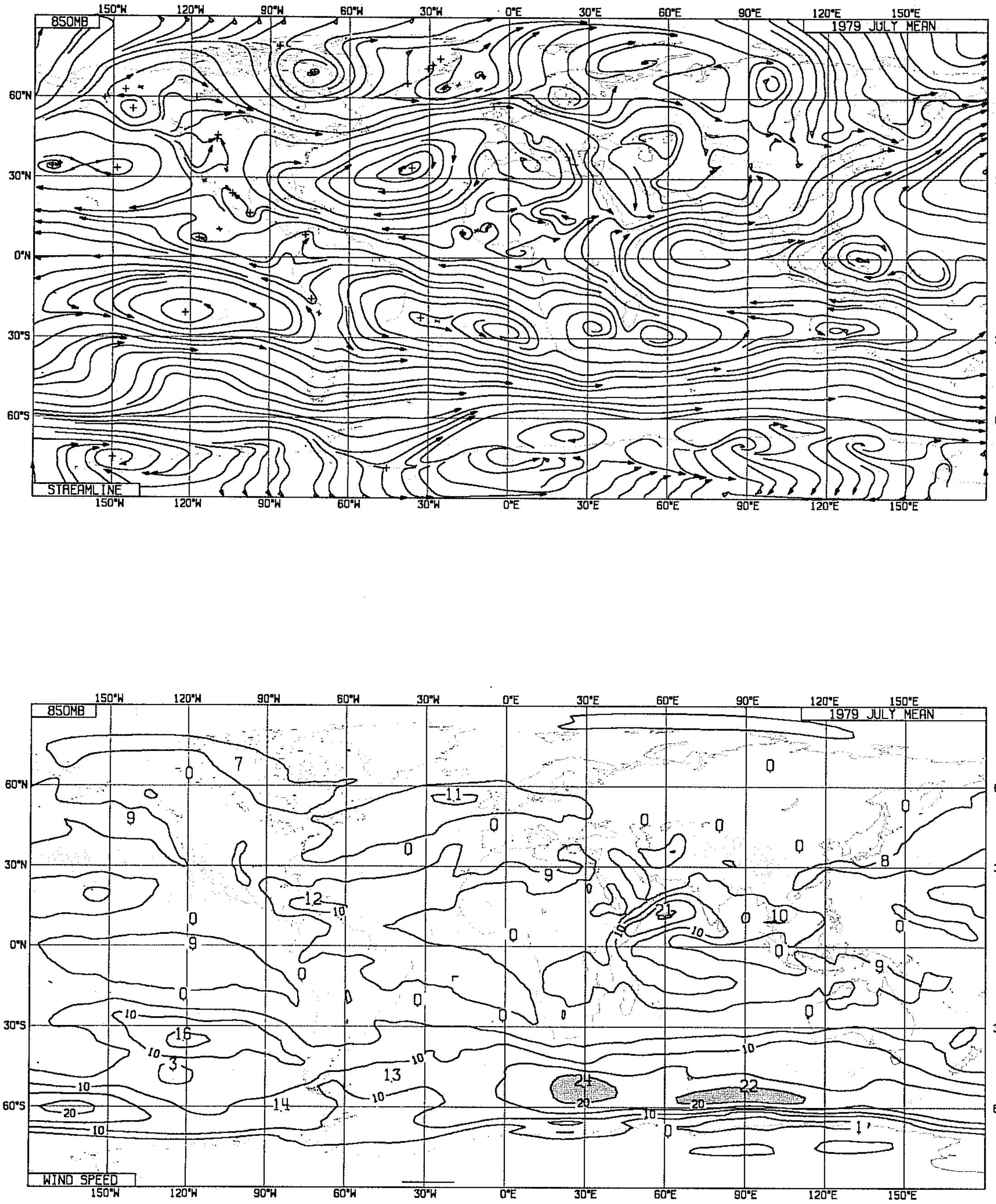


Fig. 8 As Fig. 6, but July 1979.

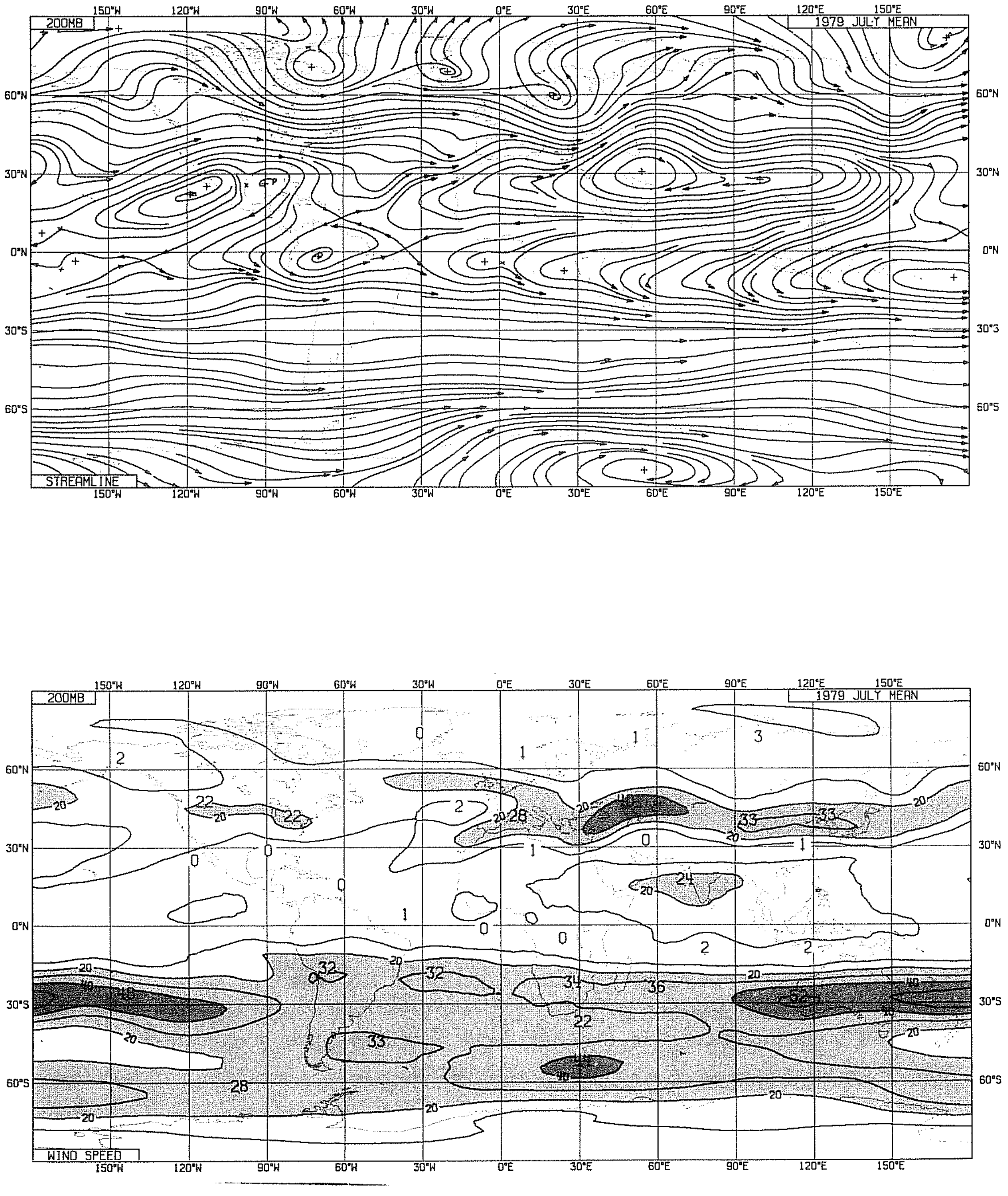


Fig. 9 As Fig. 7, but July 1979.

Centre is over south-east Asia. Connected to the onset of the monsoon a considerable increase in the intensity takes place as is shown from Fig.10. The large-scale structure of the mean vertical circulation and its dramatic change in the middle of June illustrates the global character of the monsoon phenomenon.

The examination of monthly averaged fields has revealed several major differences to the climatology which cannot be entirely explained by interannual variability. This indicates a significant positive impact of the FGGE observing systems for the study of the general circulation and the climate of the atmosphere.

3. RESULTS OF FORECAST EXPERIMENTS

To investigate the impact of the improved observing network during FGGE, a series of forecast experiments have been done. The quality of the forecasts can preferably be expressed as the number of days the anomaly correlation remains above 60%, when verified against the level III-b analyses (Bengtsson, 1981). This score varies widely from case to case and from one hemisphere to the other. For the ten cases run, the predictability ranges from 4 to 8 days in the northern hemisphere, and 3 to 6 days in the southern. The average predictability of 5 to 6 days in the northern hemisphere is comparable to that of operational forecasts at ECMWF during 1980. On the other hand, in the southern hemisphere there is an improvement of the order of a day, from about 4 days in the operational forecasts to about 5 days in the FGGE cases. The FGGE forecasts were verified against the level III-b analyses, while the operational forecasts are verified against the operational analyses, which during 1980, were based on much less data. If there are less data available for the verifying analysis, the verification is biased towards the forecast model, resulting in high verification scores for the operational 1980 forecasts. The one day improvement of the southern hemisphere scores can thus be considered as an underestimate. In the tropics, objective evaluation of the forecasts has not yet been done, but preliminary subjective evaluation of ten cases indicates a forecast skill of 2-4 days.

To illustrate the prediction experiments, we have chosen three cases of fairly successful forecasts, (i) in the southern hemisphere, (ii) in the tropics and (iii) in the northern hemisphere stratosphere.

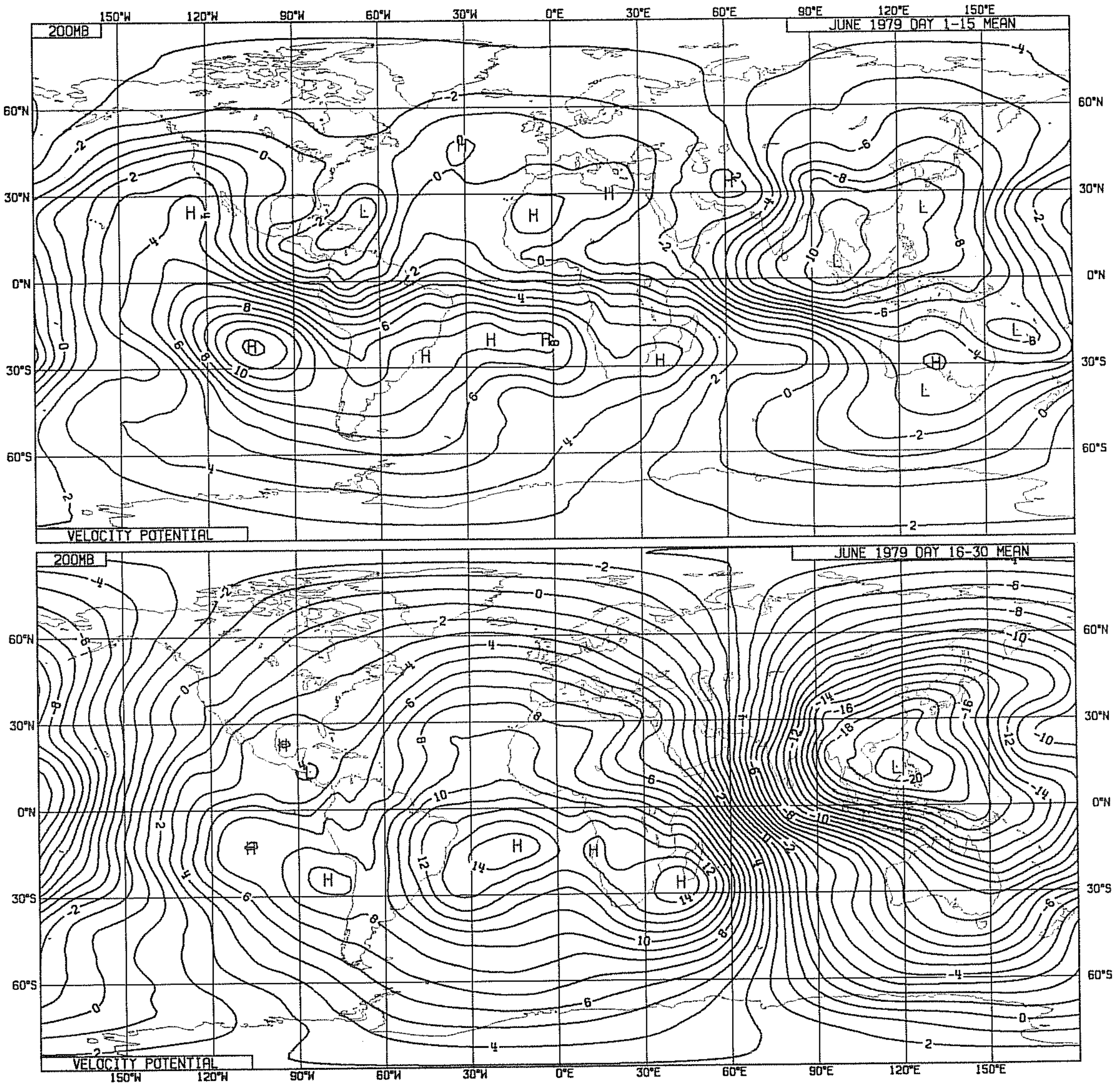


Fig. 10 Mean velocity potential, 200 mb, before monsoon onset, June 1-15, (top) and after monsoon onset, June 16-30, (bottom).

3.1 Southern Hemisphere forecast (12 GMT, 11 June)

The forecasts in the Southern Hemisphere have higher correlation scores in winter than in summer. The case selected here is the best Southern Hemisphere forecast among the experimental predictions so far performed. The useful predictability (Bengtsson, 1981) of this case was found to be 6.0 days or in fact even 7 days when integrated with a high resolution spectral model (T63), using the same physics parameterization as the N48 grid point model used in all other experiments. Fig. 11 shows the analysis of surface pressure and 500mb height at 12 GMT on 11 June (initial) and at 12 GMT on 17 June (6 days).

Major large-scale features during this period are (i) change from a strong meridional flow to an intense zonal flow in the area south of South Africa between 0°E to 70°E, (ii) persistent ridge (weak blocking) over New Zealand (iii) new development of a trough to the east of New Zealand (at 155°W), which is associated with cyclone development that originated in low latitudes (20°S). The trough located at 150°W on the 11th moves steadily to 100°W during the course of the 6 days.

The 6-day prediction seems to be successful in predicting most of those features. Although the intensity and phase are not so accurate, the development of the low latitude cyclone and deep trough to the east of New Zealand has been well predicted. On the other hand, there are some places where the prediction is less good. For example, the trough over the Atlangic is too deep, which is also reflected at the surface. The prediction over Australia is also less satisfactory, in particular at the surface.

3.2 Tropical forecast (12 GMT 9 January)

The forecasts of the large-scale flows in the Tropics cannot be evaluated in the same manner as in the middle latitude because of the strong quasi-stationary nature of the tropical motion field. It is most essential that the prediction model maintains these quasi-stationary features throughout the forecast. Evaluation of transient features cannot be done without evaluating the preservation of the stationary features. Subjective evaluations of the prediction experiments indicate that the model preserves quasi-stationary features for the first 3 to 4 days, but gradually modifies them towards large scales. There is a tendency for these errors to start from tropical continental areas, which may suggest a weakness of the model in the physical forcing field, most likely in the convective heating.

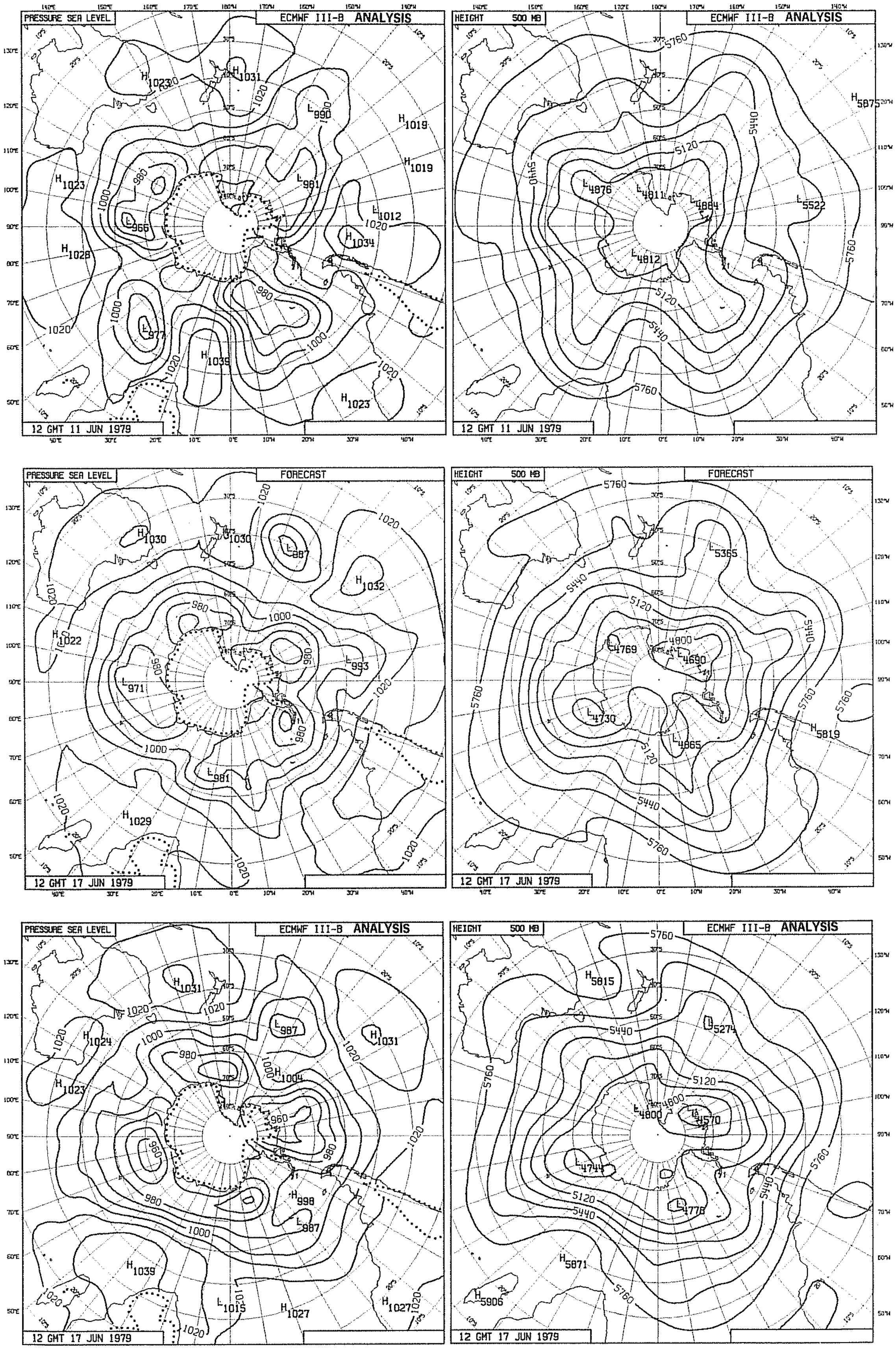


Fig. 11 Initial analysis valid 12 GMT 11 June 1979, (top).
6-day forecast valid 12 GMT 17 June 1979, (middle).
Verifying analysis valid 12 GMT 17 June 1979, (bottom)
Left column: Mean Sea Level Pressure in mb.
Right column: 500 mb Geopotential Height in gpm.

The example chosen here is a 4-day forecast starting from 12 GMT 9 January. The comparison of the initial and the verification analyses (Fig. 12) with the January climatology (Figs. 6 and 7) provides some idea of the quasi-stationary character. The trough penetrating from Mexico to the eastern equatorial Pacific, the anticyclonic circulation over South America and South Africa and the anticyclonic circulation over the western Pacific, are some of the quasi-stationary features at the 200 mb level.

In the 4-day forecast the semi-permanent features are fairly well preserved. Several transient phenomena are very well predicted, two examples are shown in Fig. 12. During the four days, the 200 mb subtropical jet over the Sahara was intensified considerably, and at the same time an equatorial, clockwise vortex near the Somali coast was weakened. Both these events were well predicted (Fig. 12, left). At 850 mb the forecast is somewhat worse, but also here the quasi-stationary features are preserved. One of the major transient events at this level was the marked intensification of the low level westerly jet over the southern Pacific ocean (Fig. 12, right). The very strong winds in the upper left corner of the verification (bottom map) are connected with a rapidly developing northern polarfront cyclone. This system was well analyzed from many surface ship reports on the verification day, but it was completely missed in the 4-day forecast.

3.3 Stratospheric forecast 00 GMT 12 February

Another example of successful predictions in this series of experiments is a forecast of the breakdown of the northern polar vortex in the stratosphere in February. The series of maps in Fig. 13 illustrates this dramatic event. The left column shows the time evolution (every other day) of the polar vortex starting from a rather circular pattern with three troughs on 12 February. As the trough over Scandinavia deepens and moves eastward, the entire polar vortex elongates (increase of wavenumber 2). Between the 18th and 20th, the elongated vortex breaks down to form two vortices over Hudson Bay and over central North Siberia. The highs developing over Scandinavia and over the Bering Sea (Aleutian High) are associated with an event of sudden warming.

The prediction during the period shown in the right column, shows the ability of the prediction model to forecast this development. The stretching and the eventual breakdown, and the sudden warming, are predicted very accurately with very few phase errors. It is noted that the trend of general cooling of the stratosphere during the prediction which is a characteristic systematic error of the model, lowered the mean height at 50 mb by 200 - 300 m, but it does not seem to affect the forecast in any other aspect.

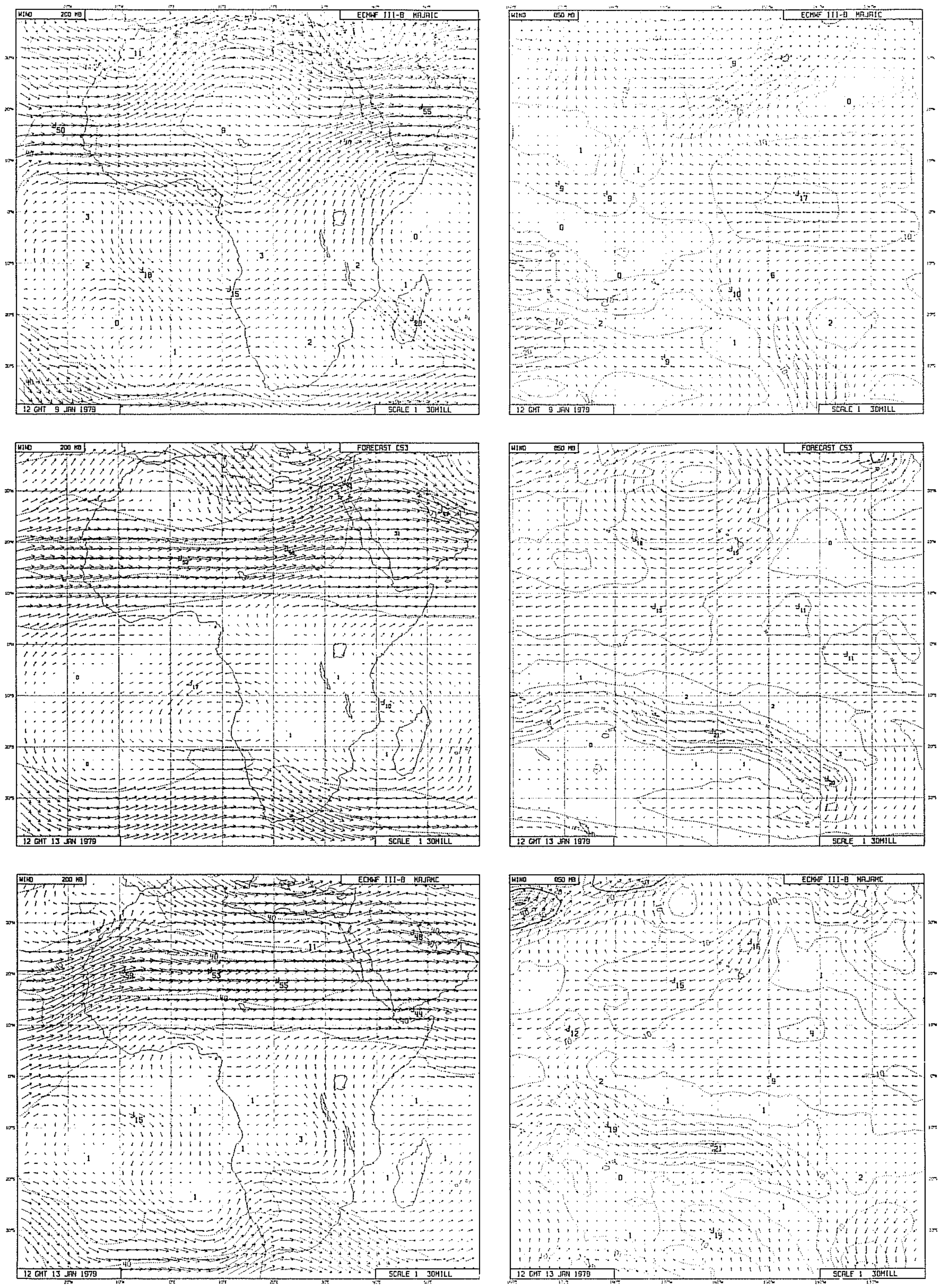
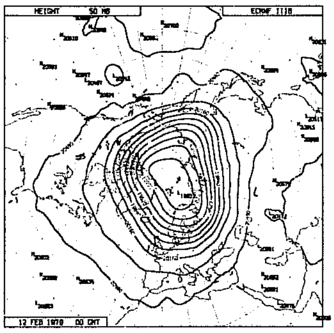


Fig. 12 Initial analysis valid 12 GMT 9 Jan. 1979 (top).
4-day forecast valid 12 GMT 13 Jan. 1979 (middle).
Verifying analysis valid 12 GMT 13 Jan. 1979 (bottom).
Left column: 200 mb windfield and isotachs. Africa.
Right column: 850 mb windfield and isotachs. S. Pacific Ocean.



INITIAL ANALYSIS 50 mb
00 GMT 12 FEBRUARY 1979

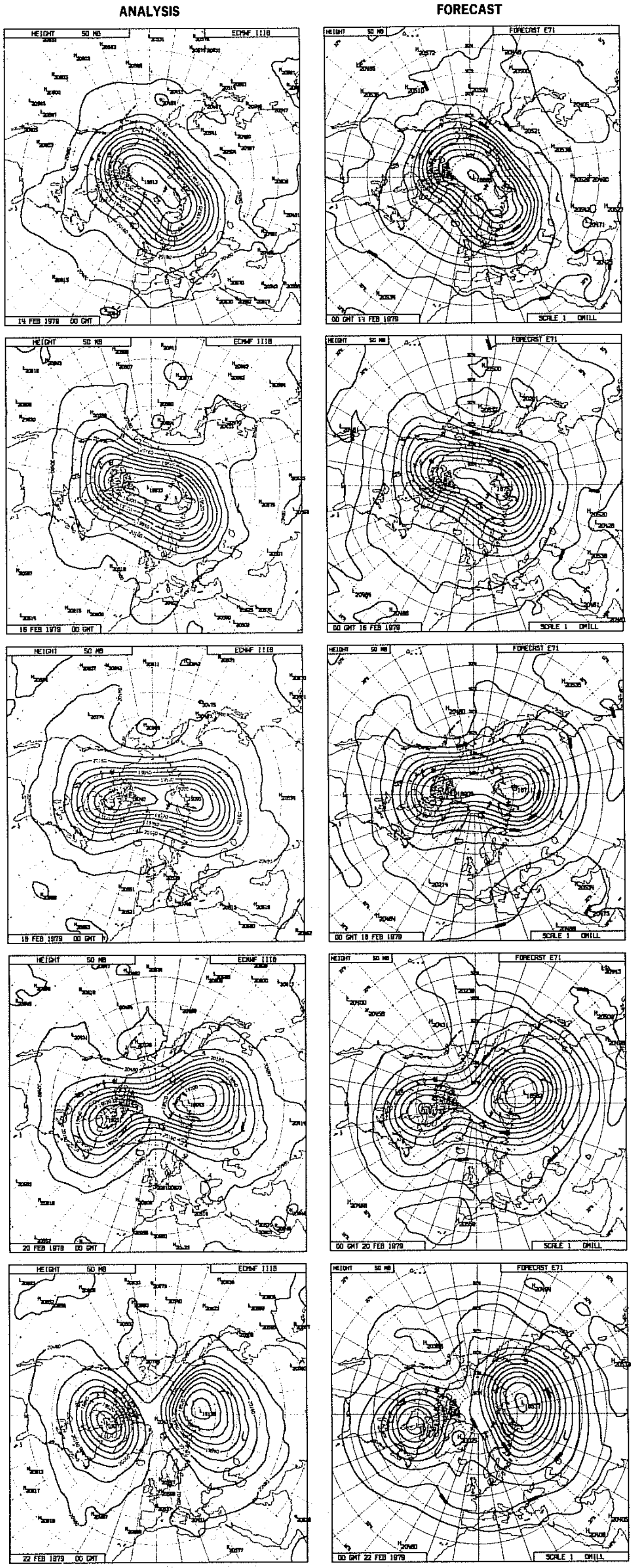


Fig. 13 Initial analysis 50 mb Geopotential Height, valid 00 GMT 12 Feb. 1979 (top left).
Left column: Forecasts for +2, +4, +6, +8 and + 10 days respectively.
Right column: Verifying analyses for the corresponding times.

The result of this prediction indicates that the major mechanism of the breakdown, i.e. forcing from the troposphere and successive dynamical processes in the stratosphere are all well handled by the forecast model.

We have presented only some synoptic descriptions of the predictions here. In order to make more definite comments on this case and on the stratospheric forecast in general, we need detailed physical and dynamical analyses which may also lead to the understanding of the phenomena itself. Such studies are in progress.

CONCLUSIONS

The preliminary results so far obtained from the global weather experiment are most encouraging and we may have confidence that the very ambitious objectives which were set up for the experiment will be met. The FGGE data consistutes an immense material and will possibly be the best meteorological large-scale dataset for the next 5 to 10 years. The data have confirmed that the large-scale circulation systems such as the Indian Monsoon, are interlinked globally. The strong circulation in the equatorial plane discussed by Krishnamurti et al(1979), as deduced from the GATE-data, is a fundamental feature of the Tropical circulation. The substantial increase in observations from the satellite observing systems and from the buoys has improved our knowledge of the general circulation of the Southern Hemisphere. The observations support the results from some general circulation simulation experiments suggesting that the circulation is significantly more intense than appeared from previous data, particularly during the winter. Prediction experiments for the Southern Hemisphere show improvements by at least 1 day compared to operational numerical forecasting at ECMWF after FGGE, and there are examples of exceptionally good forecasts from FGGE data during the Southern Hemisphere winter. The improvement of the forecasts in the Tropics is also impressive and is likely to improve even more when the models can cope better with the physical processes which are dominant in the tropical atmosphere.

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