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AN INVESTIGATION OF THE IMPACT AT MIDDLE AND HIGH LATITUDES OF TROPICAL FORECAST ERRORS

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CONTENTS

PAGE

Abstract 1

1. INTRODUCTION 1

2. THE RELAXATION SCHEME 2

2.1 The forecast model 2
2.2 The analyses 3
2.3 Finite difference scheme 3
2.4 The relaxation coefficient 4

3. THREE CASE STUDIES 5

3.1 Case 1: 14/11/79 5
3.2 Case 2: 16/10/79 12
3.3 Case 3: 11/6/79 20

4. IMPACT AT MIDDLE AND HIGH LATITUDES 28

5. CONCLUSIONS 36

REFERENCES 40

Abstract

A series of forecast experiments, designed to assess the impact at middle and high latitudes of tropical forecast errors, is described. A control set of forecasts with the ECMWF global grid point model is compared with a series of forecasts in which the predicted values are replaced by analysed data in the tropics. The largest impact is seen when tropical features interact with deep middle latitude troughs. Modification of the phase tilt of these troughs leads to significant differences in the evolution of the flow at middle and high latitudes.

1. INTRODUCTION

In the tropical region, the limit of useful predictability of the ECMWF forecasting system is generally reached within the first few days of the forecast. This report describes a series of experiments which were designed to try to assess the impact of errors in the tropics on the quality of the subsequent forecast at middle and high latitudes.

A relaxation scheme was developed for the ECMWF global grid point model. In this scheme, predicted values may be replaced by analysed values in selected regions. Seven cases were selected. These were all taken from the FGGE year (December 1978 - November 1979), in view of the availability of analyses based on above-average data coverage in the tropics. For each case, two forecasts were run: a standard control run and a forecast which was relaxed towards the uninitialized FGGE analyses in the tropics.

Uninitialized analyses were used, because the nonlinear normal mode initialization scheme has a tendency to damp the divergent part of the flow, particularly in the tropics. Bengtsson (1981) showed that the intensity of the tropical divergent wind can be reduced by up to 50% by the ECMWF initialization scheme. Even the uninitialized analyses used here are likely to have some errors in this respect. The first guess field for each analysis within the data assimilation system is a 6-hour forecast from the previous initialized analysis, and in only 6 hours, the forecast model does not have time to restore fully the divergent part of the flow.

Of the seven cases selected, one showed a dramatic improvement with the relaxation scheme , three showed a small but significant improvement, and two showed very little impact, while one case was made worse. Three cases will be presented in more detail below, together with a discussion of what appears to be the principal mechanism by which the tropics influence middle latitudes in these forecasts. This mechanism involves the interaction between the tropical circulation and deep mid-latitude troughs. The interaction influences the meridional phase tilt of the extratropical wave, and thus its subsequent evolution.

Much theoretical attention has recently been concentrated on models of the effect of localized tropical forcing on stationary wave motion in middle latitudes (e.g. Egger, 1977; Opsteegh and Van der Dool, 1980; Hoskins and Karoly, 1981; Webster, 1981; Simmons, 1982). The present results demonstrate that the tropics may sometimes also have an important influence on transient mid-latitude features.

2. THE RELAXATION SCHEME

2.1 The forecast model

The operational ECMWF grid point model (Burridge and Haseler, 1977; Tiedtke et al, 1979) was used, with the standard resolution (1.875°for the regular latitude/longitude grid in the horizontal, 15 σ-levels in the vertical and a 15 minute timestep). The relaxation scheme was applied to all the model's predicted variables (temperature, horizontal velocity, specific humidity, surface pressure, surface temperature, soil wetness and snow depth).

2.2 The analyses

The uninitialized FGGE III-b analyses (Bjorheim et al, 1981), interpolated to the model's σ-levels, were used by the relaxation scheme in the tropics. The analyses were available at 6 hour intervals, except for one case in December, 1978 when they were only available at 12 hour intervals. The relaxation scheme required analysis values at each model timestep, so a linear combination of the nearest two analyses was used at intermediate times.

2.3 Finite difference scheme

Let the model equations, without the relaxation scheme, be expressed generally as

$$\frac{\partial \underline{x}}{\partial t} = \underline{\underline{M}}\ \underline{x}$$

where $\underline{\underline{M}}$ is a non-linear finite different operator

and $\underline{x}$ is a vector of the model dependent variables

Then with the relaxation scheme , the equations become

$$\frac{\partial \underline{x}}{\partial t} = \underline{\underline{M}}\ \underline{x} - K(\underline{x} - \underline{x}_a)$$

where K is the spatially variable relaxation coefficient, and

$\underline{x}_a$ is a vector of analysis variables.

With the model's leap-frog time scheme, with semi-implicit correction, this gives

$$\underline{x}^{n+1} = \underline{x}'^{n+1} - 2\Delta t\ K(\underline{x}^{n+1} - \underline{x}_a{}^{n+1})$$

where $\underline{x}'^{n+1}$ is the vector predicted without the relaxation scheme

giving

$$\underline{x}^{n+1} = \frac{1}{1+2K\Delta t}\,\underline{x}'^{\,n+1} + \frac{2K\Delta t}{1+2K\Delta t}\,\underline{x}_a^{n+1}$$

2.4 The relaxation coefficient

The relaxation coefficient K is defined to be of the form

$$K = K_\lambda\ (\lambda)\ K_\theta\ (\theta)\ K_\sigma\ (\sigma)$$

where λ = longitude and θ = latitude

Although the formulation allows K to vary with longitude and height, in all these experiments, K varied only with latitude:

$$K_\lambda\ (\lambda) = 1,$$

$$K_\sigma\ (\sigma) = 1$$

$K_\theta(\theta)$ was chosen to give pure forecast values at high latitudes, pure analysis values in the tropical belt, and a smooth transition between forecast and analysis values in the intermediate zones;

i.e.

$K_\theta\ (\theta) \quad = 0$ at high latitudes

$\frac{1}{1+2\Delta t\ K_\theta(\theta)} \approx 0$ in the tropical belt

$\frac{1}{1+2\Delta t\ K_\theta(\theta)} = \frac{1}{2} + \text{SIGN}.\ \frac{1}{2}\tanh\ (20(\theta-\theta_{\frac{1}{2}}))$ in the intermediate zones

where θ is given in radians

and

SIGN = +1 in northern hemisphere

= −1 in southern hemisphere

In these experiments, the intermediate zone was taken to be a latitude band of width 10°, centred on latitude $\theta_{\frac{1}{2}}$.

3. THREE CASE STUDIES

3.1 Case 1: 14/11/79

This case showed a dramatic improvement with the relaxation scheme. The operational forecast from 14/11/79 produced the worst forecast of November, 1979 over Western Europe at days 5-6. Its poor performance was traced back to its failure to reproduce the interaction of a tropical feature over the Caribbean with a mid-latitude trough at day 3, so it seemed to be a good case to repeat with the relaxation scheme.

The relaxation experiment, which will be denoted F68, started from the initialized 12Z operational analysis, and was relaxed towards 6-hourly FGGE analyses in the tropics, with pure analysis values in the band 15°N-15°S, pure forecast values to the north of 25°N and to the south of 25°S, and smoothly mixed values in the intermediate zones. It was compared with the operational forecast from the same initial data.

The two forecasts were very similar for the first 2 days. Between days 2 and 3, a high level vortex developed over the Caribbean. This can best be seen in the 200 mb wind field shown in Fig. 1. In the FGGE analysis, a maximum wind speed of 58 m/sec occurred to the east of Florida in a tight westerly jet, which extended for approximately 30 degrees of longitude where the vortex and a high latitude trough reinforced each other. In the relaxation experiment, F68, the vortex and jet were correctly positioned, but with a maximum wind speed of 66 m/sec. However, in the operational forecast the Caribbean vortex was barely detectable, the maximum wind speed was only 47

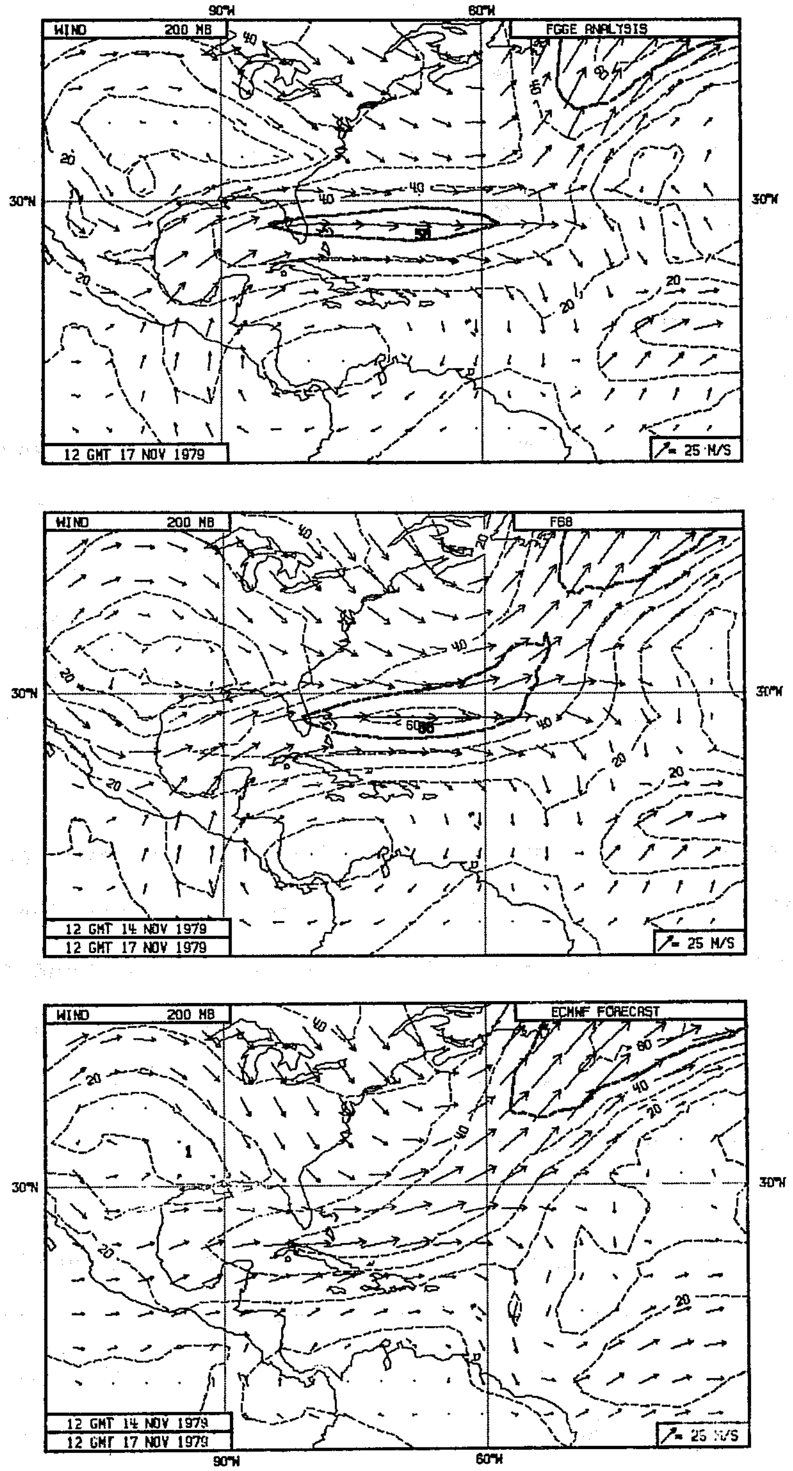

Fig. 1 Day 3: 200 mb wind field at 12 GMT 17 November 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).

m/sec and the area of maximum wind did not extend far enough to the east. As a result, the southern tip of the trough was moved approximately 15° further east in the analysis and the relaxation experiment than in the operational forecast. This can be seen in Fig. 2a, which shows the northern hemisphere 500 mb geopotential fields for the 3 cases.

Over the next 3 days, this trough was treated very differently by the two versions of the model. At day 4 (see Fig.2b) the amplitude of the trough in the operational forecast was too small, and its southern tip was again retarded. By days 5 and 6, the operational forecast was showing almost zonal flow across the Atlantic at 500 mb (see Fig. 3). With the relaxation scheme however, the trough was retained (though positioned 10° too far to the east) and the ridge over the Eastern Atlantic was developed. The cut-off low over Southern Europe was also captured. At the surface (Fig. 4) the operational 6-day forecast was of very poor quality for Western Europe. With the relaxation scheme, the high extending from the Azores to Southern Scandinavia and the low over Italy were captured quite successfully.

Objective verification confirms the considerable improvement of the forecast with the relaxation scheme over the operational run. Figure 5 gives the anomaly correlation of height for the 2 forecasts and persistence, averaged over all longitudes, all latitudes between 30°N and 82.5°N and all levels between 1000 mb and 200 mb.

The forecast with the relaxation scheme, labelled F68, is seen to be clearly better than the operational forecast, labelled ECM, for the wavenumber groups 1-3 and 4-9. Taking the 60% anomaly correlation level as a guide to the limit of usefulness of a forecast, the relaxation scheme extended this from 5 1/2 to 9 days.

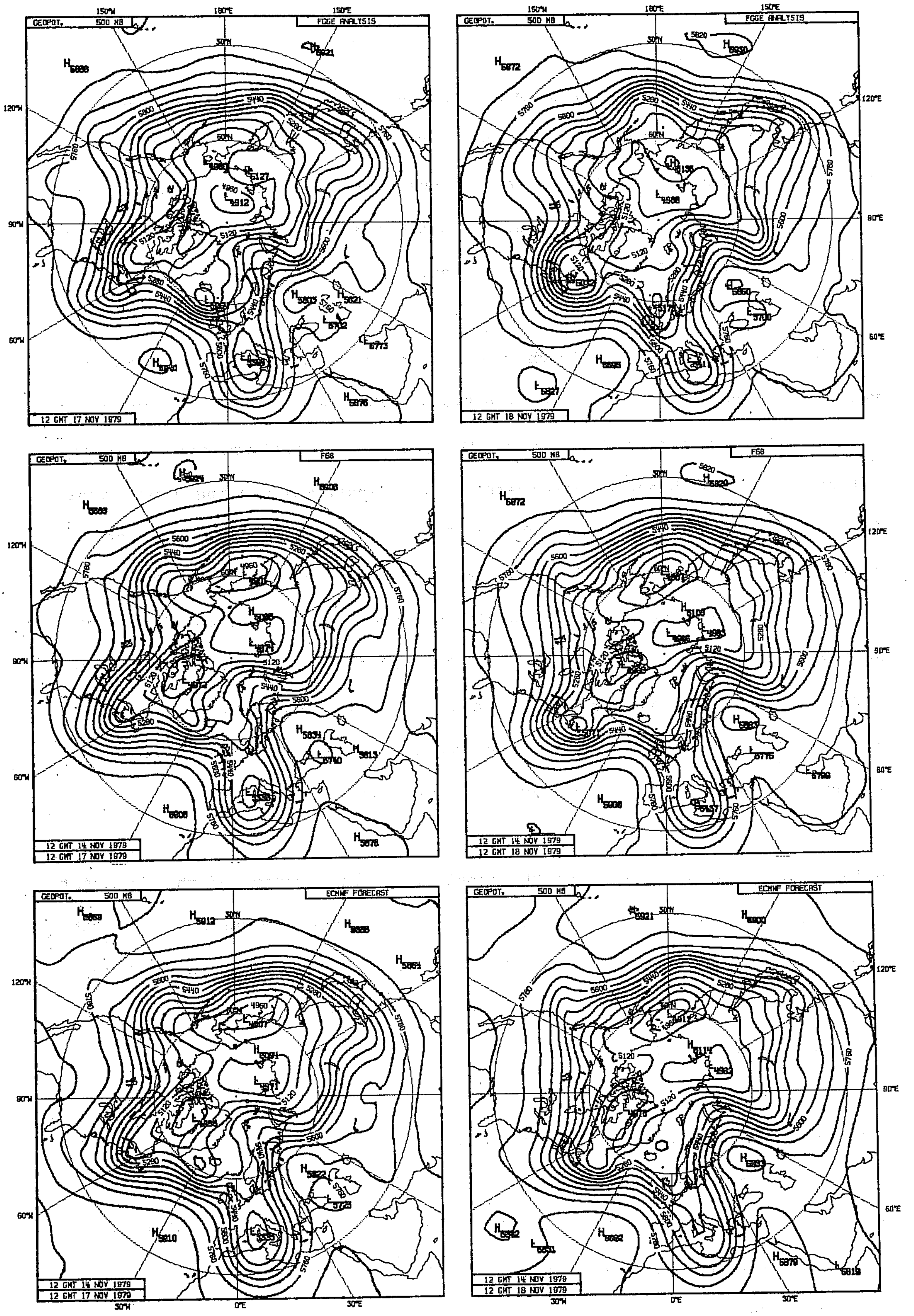

Fig. 2 Left column: Day 3: 500 mb geopotential field at 12 GMT 17 November 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).
Right column: Day 4: 500 mb geopotential field at 12 GMT 18 November 1979.

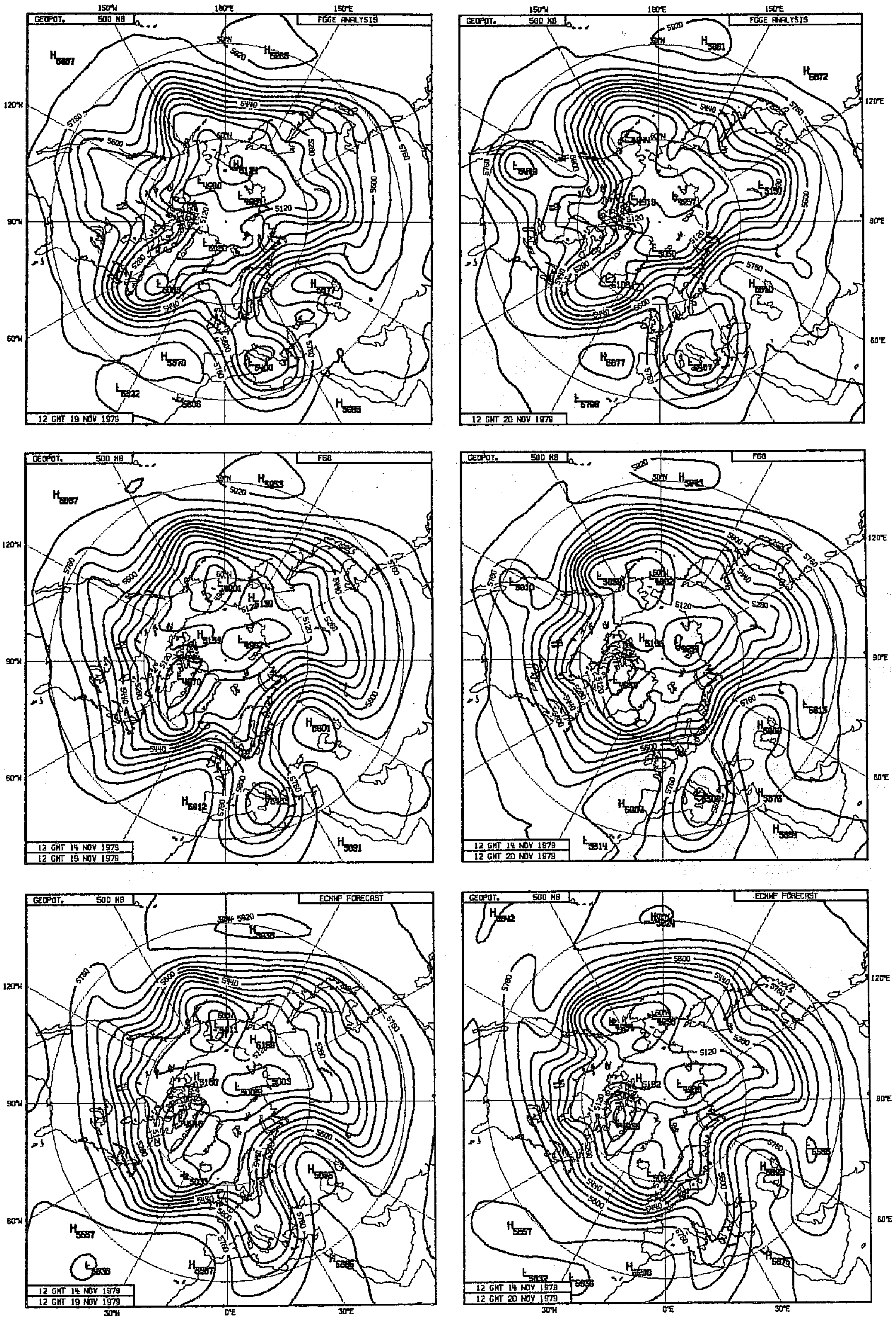

Fig. 3 Left column: Day 5: 500 mb geopotential field at 12 GMT 19 November 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).
Right column: Day 6: 500 mb geopotential field at 12 GMT 20 November 1979.

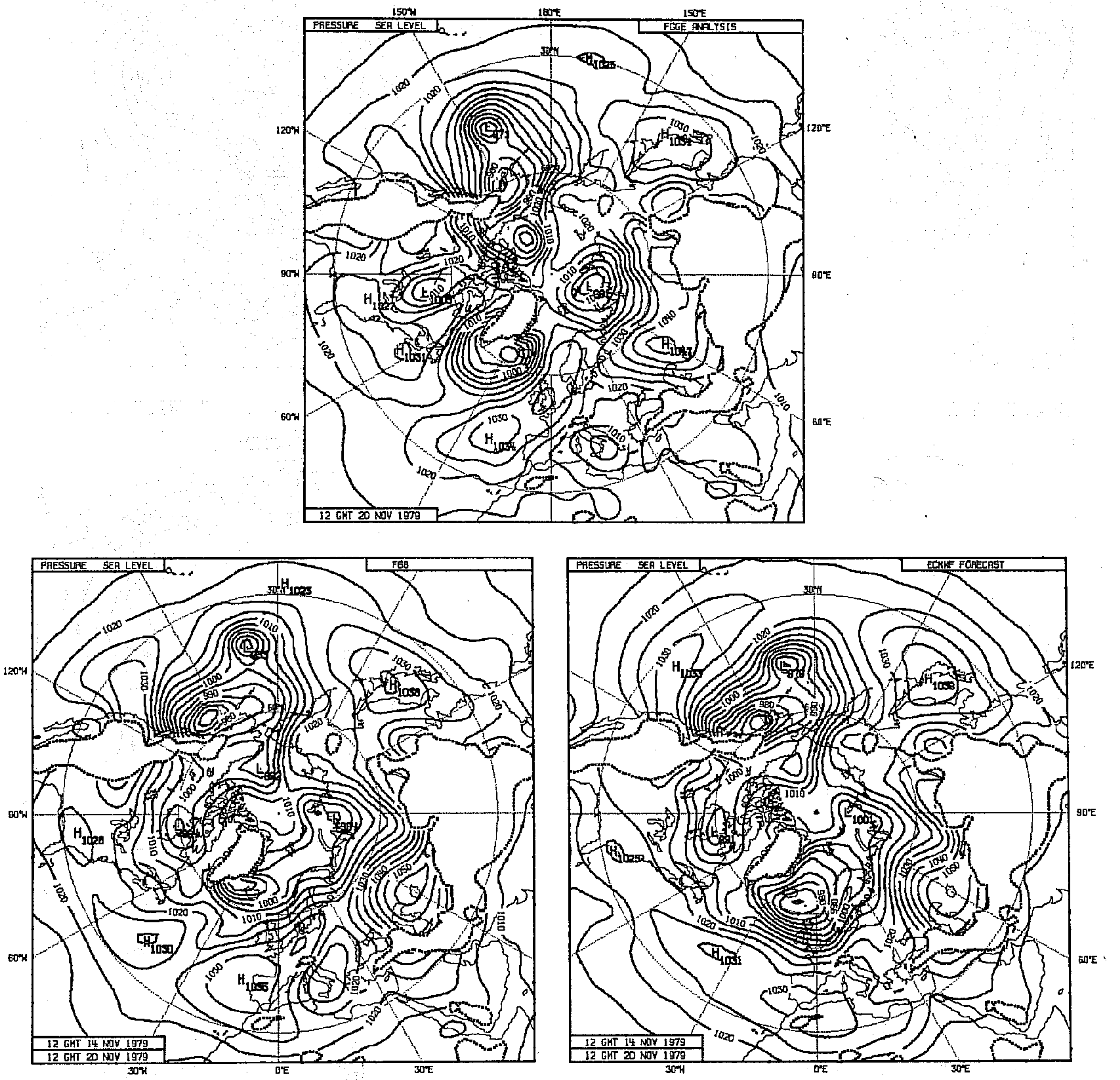

Fig. 4 Day 6: mean sea level pressure at 12 GMT 20 November 1979 for FGGE analysis (top), relaxed forecast (bottom left) and control forecast (bottom right).

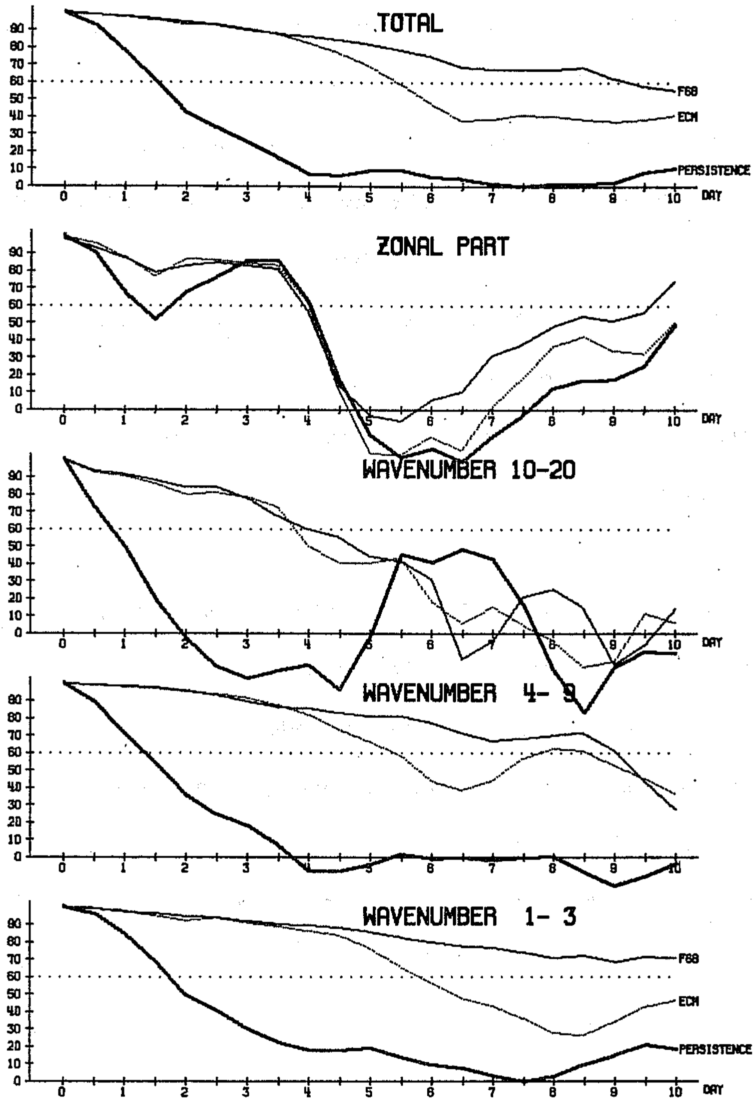

Fig. 5 Anomaly correlation of height averaged over all longitudes, latitudes 30°N-82.5°N and levels 200-1000 mb for the relaxed forecast (F68), the control forecast (ECM) and persistence.

3.2 Case 2: 16/10/79

This was one of the cases in which the forecast showed a small but significant improvement with the relaxation scheme. During this forecast, typhoon 'Tip' became extratropical in the region of Japan and deepened rapidly. In the control forecast, the typhoon moved too quickly to the north-east and deepened too fast. It was hoped that by inserting the typhoon in its analysed position and with its analysed central pressure, the high latitude forecast would be improved. In fact the relaxation scheme seemed to inhibit the development of the typhoon so that, though positioned correctly, it deepened a day late.

Two other forecasts were run with the relaxation scheme to investigate 'Tip', but starting from earlier dates. The forecast from 12/10/79 was the only case in which the relaxation scheme actually made the forecast worse. Here the typhoon collapsed instead of developing once it left the relaxation zone. The relaxed and control forecasts starting from 14/10/79 were equally poor. Neither forecast was able to represent properly the major trough downstream from the typhoon at day 4, and both were equally incorrect in their subsequent evolution of the flow.

The experiment G70 was a 10 day forecast from the initialized FGGE analysis for 00Z, 16/10/79, which was relaxed towards 6-hourly FGGE analyses in the tropics, with pure analysis values in the band 15°N-15°S, and pure forecast values to the north of 25°N and to the south of 25°S. The control forecast, G85, was a standard forecast from the same initial data.

At the surface, differences in the treatment of the typhoon were apparent at day 1. In the control forecast it was already too deep, and 5° too far to the north. Table 1 shows the central surface pressure in millibars of 'Tip' during the first 5 days of the forecast for the analysis, the relaxed forecast and the control forecast.

Table 1. Surface pressure of typhoon 'Tip', in mb.

Day	Analysis	Relaxed forecast	Control forecast
0	995	995	995
1	994	994	991
2	987	989	985
3	988	990	976
4	958	982	969
5	971	961	976

At day 3, 'Tip' was at 40°N 140°E in the control forecast , and 35°N 135°E in the analysis and the relaxed forecast. The differences between the two forecasts were becoming apparent at 500 mb (see Fig. 6a). The control forecast had a closed low at 140°E, while the analysis and the relaxed forecast had a trough at 135°E which extended further to the south.

At 200 mb a tropical circulation system had developed in the Eastern Pacific to the south-west of the major trough at 180°E (see Fig. 7). In the control forecast, the winds were stronger and the system extended over a larger area than in the analysis or the relaxed forecast. The control forecast had northerly winds of 30 m/sec at 10°N and easterly winds of up to 27 m/sec at the equator. In the analysis, the northerly winds extended only to about 20°N, while the easterly winds at 20°N had speeds of about 15 m/sec. In the control forecast , the shape of the high latitude trough at 180°E was slightly different, with a greater tilt to the north-east, especially in the northern part of the trough.

At day 4 (see Fig. 6b) a trough was maintained at 180°E in the analysis and the relaxed forecast, but not in the control forecast. The relaxed forecast did not develop the typhoon enough on day 4, and failed to produce a closed low in the geopotential field at 500 mb.

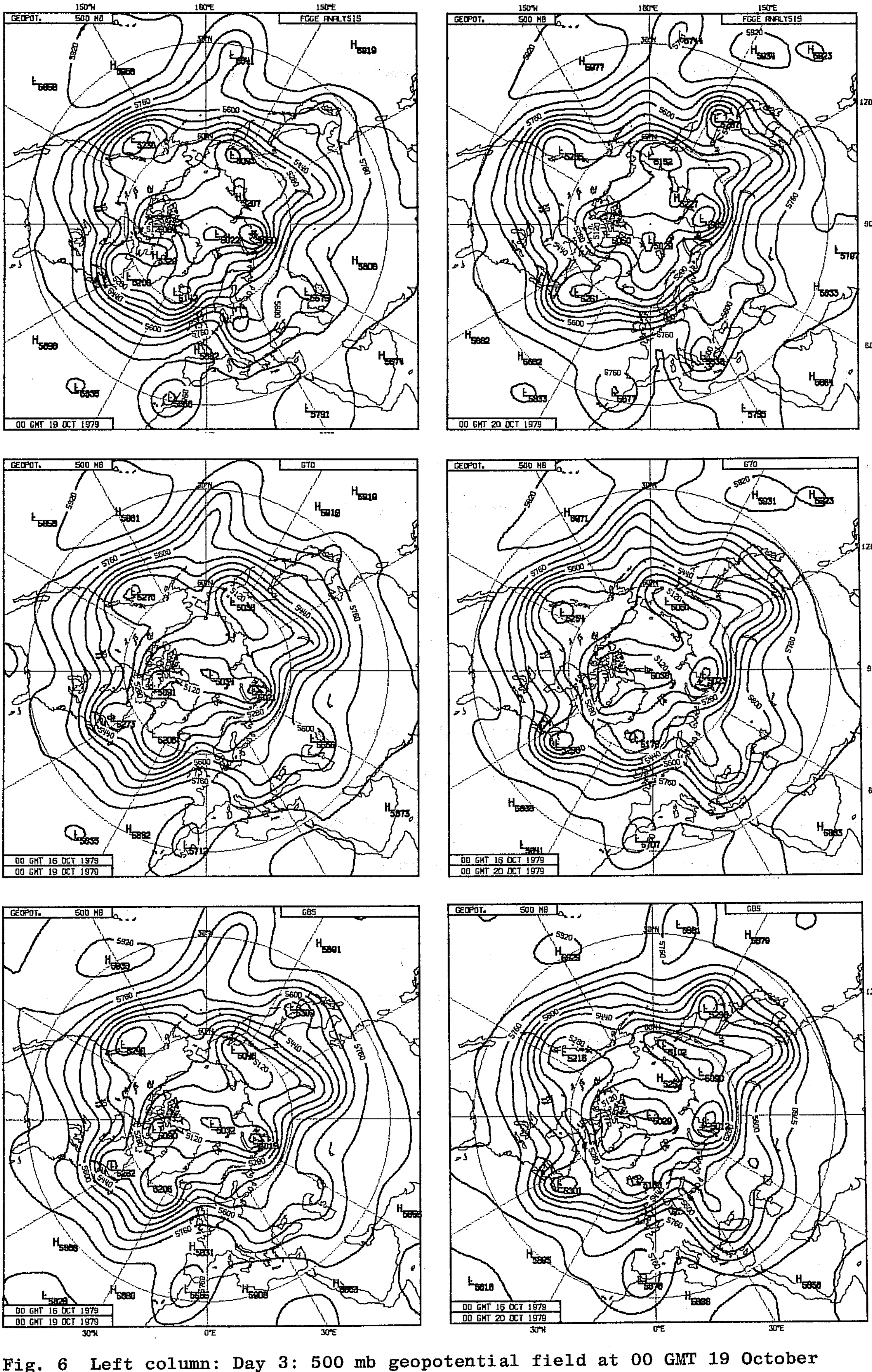

Fig. 6 Left column: Day 3: 500 mb geopotential field at 00 GMT 19 October 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).
Right column: Day 4: 500 mb geopotential field at 00 GMT 20 October 1979.

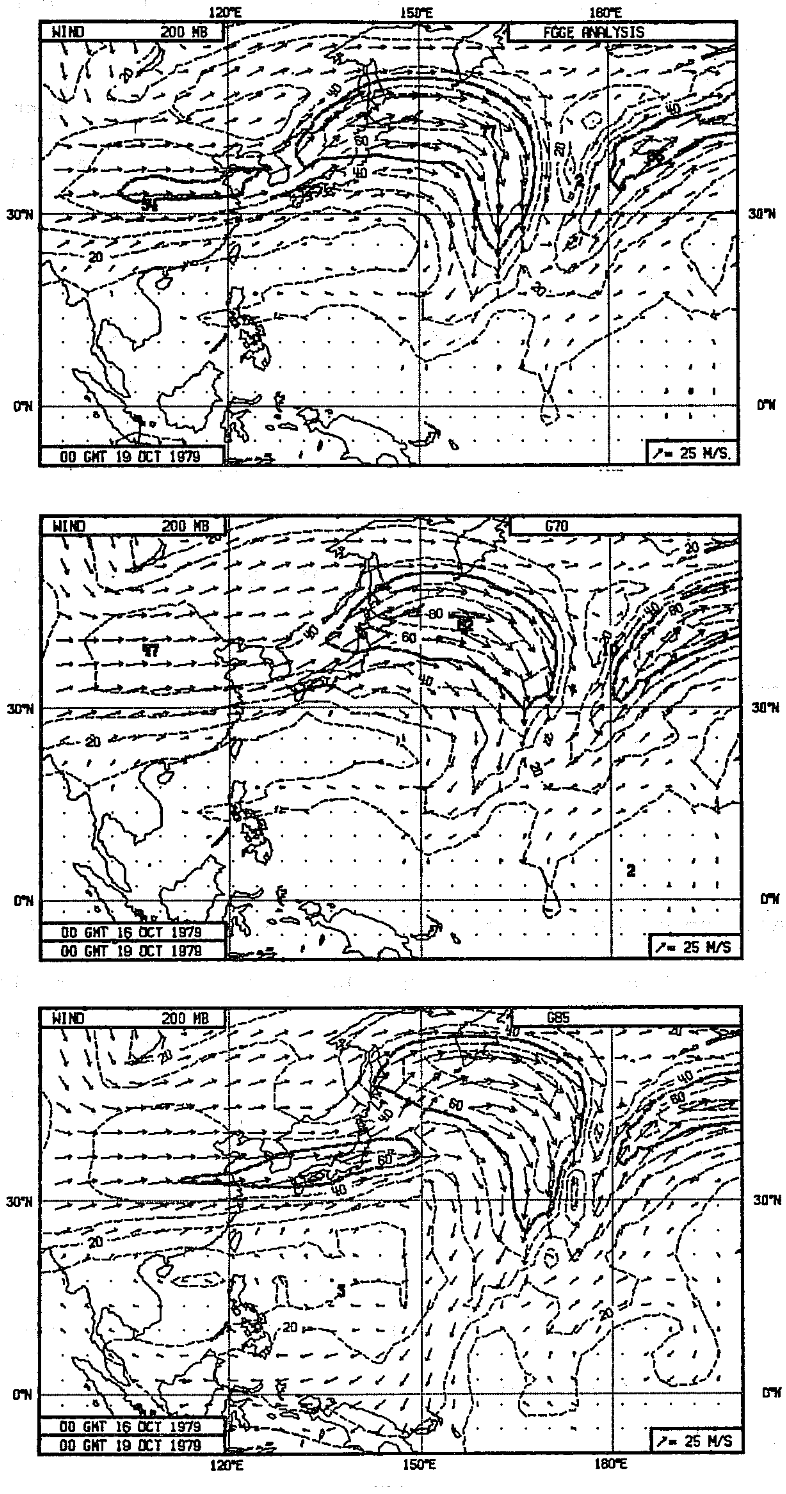

Fig. 7 Day 3: 200 mb wind at 00 GMT 19 October 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).

Fig. 8 shows the 500 mb geopotential and mean sea level pressure fields for day 5. Although the typhoon at 170°E was too deep at the surface in the relaxed forecast, the shape of the double low structure was captured well. In the control forecast, the low at 140°E was too deep. At 500 mb, the control forecast had a trough of too great amplitude over the remains of the typhoon. The relaxed forecast correctly developed a surface low at 150°W, which the control forecast failed to do because the upper trough had moved too far to the east.

In the Atlantic, the surface low at 30°W had a central pressure of 994 mb in the analysis, 990 mb in the relaxed forecast and 975 mb in the control forecast. A spurious surface low had developed to the east of Florida at day 2 in the control forecast, and had then moved steadily north-eastwards. It started to deepen rapidly on day 4 when it came under the influence of the upper level trough.

At day 6, a major upper level trough started to move across North America. This was well described up to day 8 by the relaxed forecast, but missed completely by the control forecast (see Fig.9). Also at day 6 at 500 mb, the control forecast maintained a trough at 180°E, where the analysis and the relaxed forecast had more or less zonal flow.

Figure 10 contains objective verification scores for the two cases. Figure 10a shows the anomaly correlation of height, averaged over all longitudes, all latitudes betwen 30°N and 82.5°N and all levels between 1000 mb and 200 mb, for the relaxed forecast (labelled G70), and the control forecast (labelled G85). It can be seen that the improvement of the relaxed forecast came mainly from wavenumbers 4-9. For the long waves, the control forecast was better for days 4-7. Figure 10b, a pressure-time cross-section of the horizontally averaged height anomaly correlations, shows that the improvement of the relaxed forecast over the control forecast occurred mainly

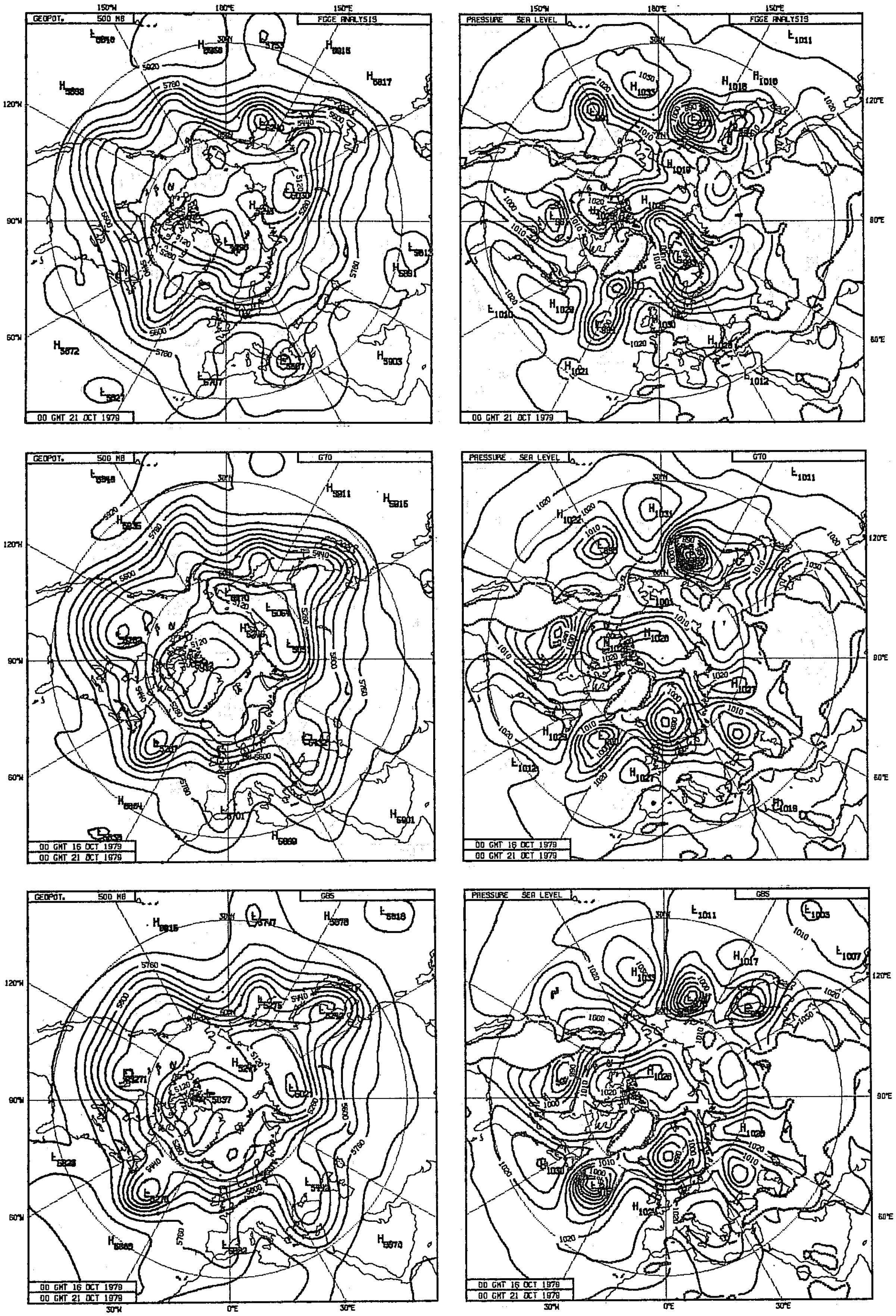

Fig. 8 Left column: Day 5: 500 mb geopotential field at 00 GMT 21 October 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).
Right column: Day 4: 500 mb geopotential field at 00 GMT 20 October 1979.

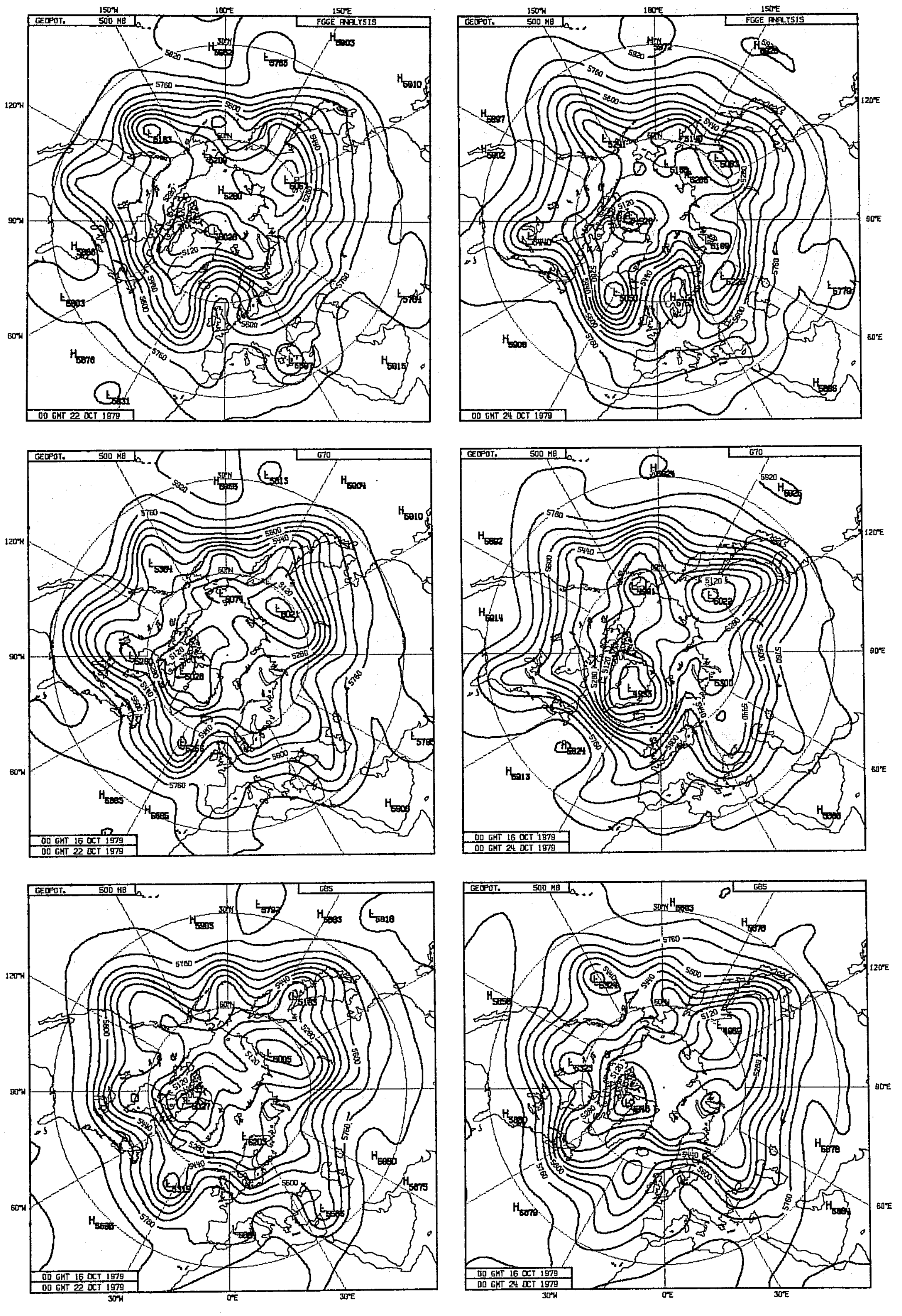

Fig. 9 Left column: Day 6: 500 mb geopotential field at 00 GMT 22 October 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).
Right column: Day 8: 500 mb geopotential field at 00 GMT 24 October 1979.

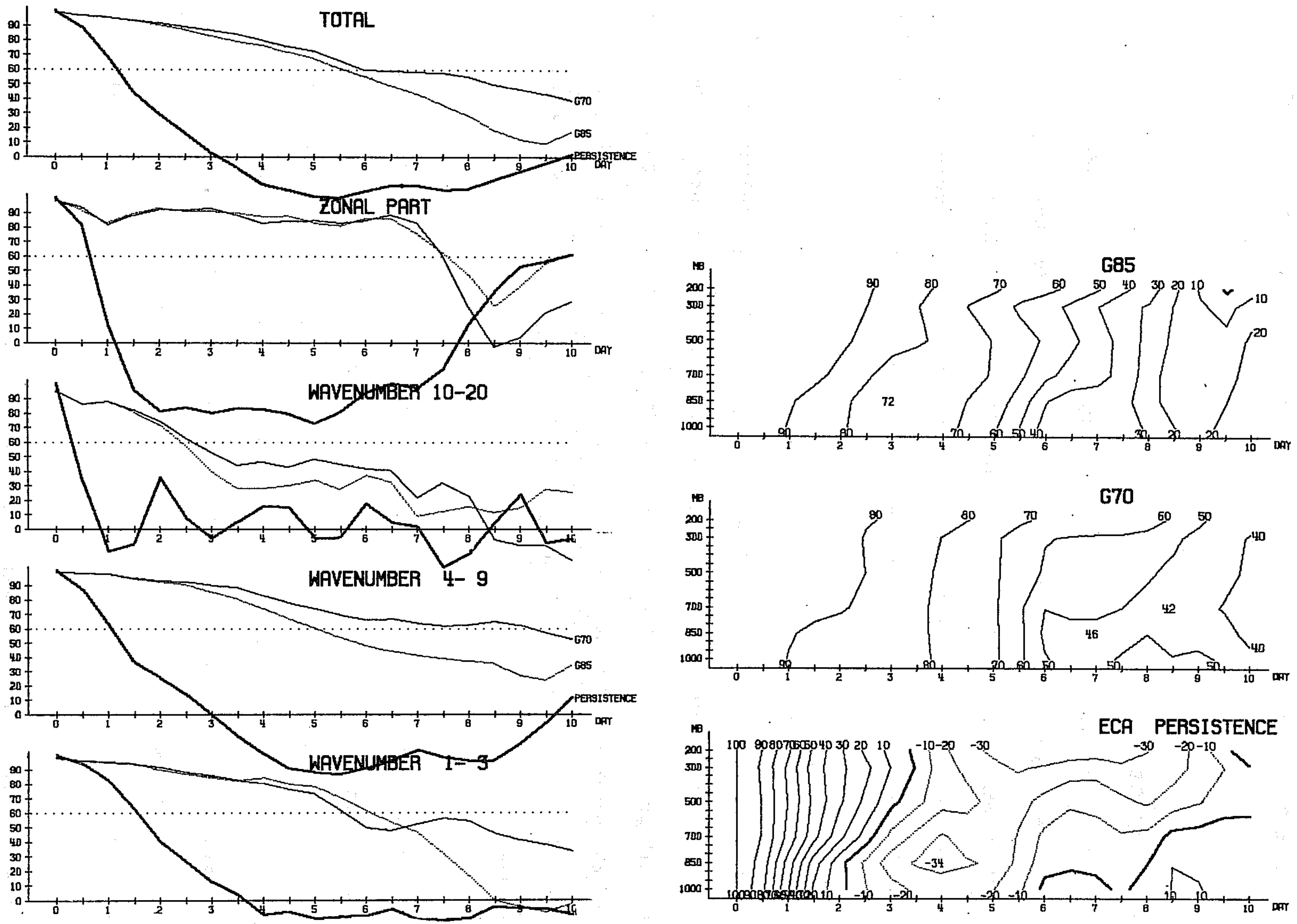

Fig. 10 Left column: anomaly correlation of height, averaged horizontally over the latitude band $30^{o}N-82.5^{o}N$ and vertically over levels 200-1000 mb for the relaxed forecast (G70), the control forecast (G85) and persistence. Right column: pressure-time cross-section of the horizontally averaged anomally correlation of height for the same experiments.

at the surface for days 2-5 and at 500 mb and above for days 6-10. The improvement at 200 mb in the second half of the forecast was particularly noticeable.

3.3 Case 3: 11/6/79

The relaxation scheme appeared to have little impact in this case, despite the fact that the control run gave a very poor forecast for the tropical region. The control forecast failed to predict the onset of the monsoon in the first few days of the forecast, and then went on to give a completely incorrect forecast for Central America and the tropical Atlantic from day 5 onwards.

The experiment E60, starting from the initialized 12Z FGGE analysis for 11/6/79, was relaxed towards 6 hourly uninitialized FGGE analyses in the tropics, with pure analysis values in the band 20°N - 20°S, pure forecast values to the north of 30°N and the south of 30°S and smoothly mixed values in the intermediate zones. The control forecast, E19, was a standard forecast from the same initial data.

The monsoon built up in the first 2 days of the forecast, and was well established by day 3. Figure 11 shows the 850 mb winds in the Indian Ocean region at day 3 for the FGGE analysis and the control forecast. The analysis had easterly winds with a maximum speed of 18 m/sec at 20°S, southerly winds along the East African coast and westerly winds with a maximum speed of 23 m/sec at 5°N. The control forecast underestimated the southerly flow along the East African coast, and failed to develop the easterly and westerly flows. The relaxed forecast portrayed the monsoon correctly, since it occurred within the relaxation scheme's band of pure analysis values.

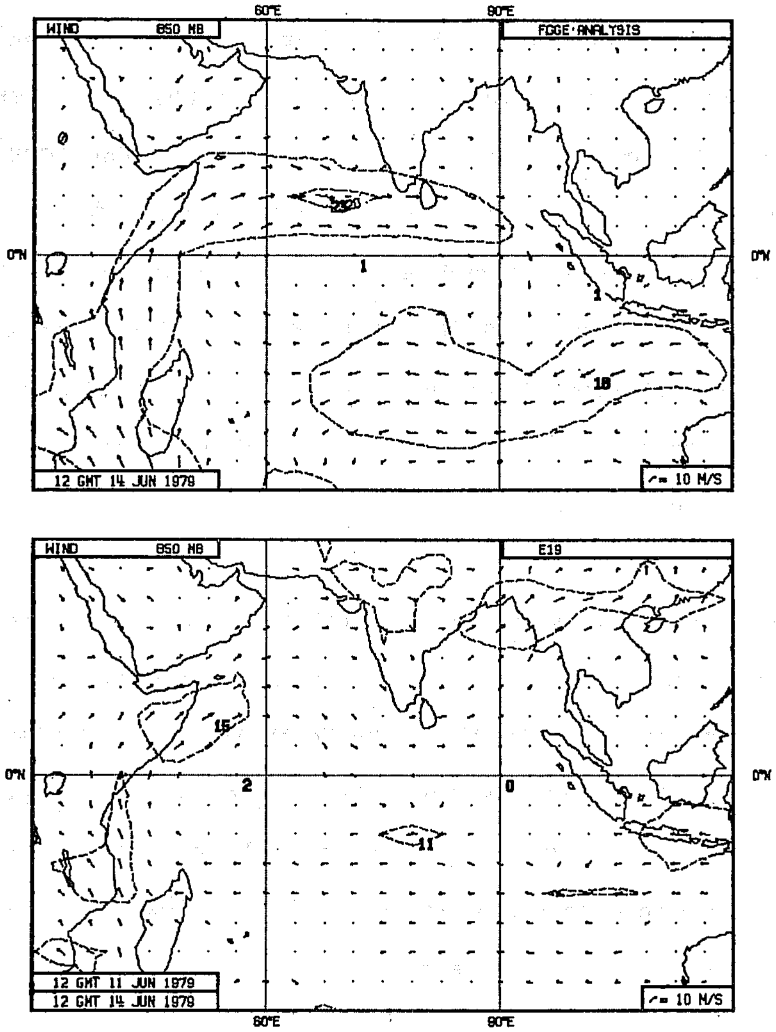

Fig. 11 Day 3: 850 mb wind field at 12 GMT 14 June 1979 for FGGE analysis (top) and the control forecast (bottom).

Outside the tropics, the 2 forecasts were very similar for the first 3 days. Figure 12 shows the 500 mb geopotential and mean sea level pressure maps for day 4. There were no obvious differences between the two forecasts in the Asian or East Pacific regions which could be attributed to the absence of the monsoon in the control experiment. Neither forecast had a deep enough 500 mb low at 180°E, and both positioned it too far to the west. The central pressure of the corresponding surface low was 988 mb in the FGGE analysis, 1004 mb in the control forecast and 1009 mb in the relaxed forecast. Neither forecast extended the 500 mb trough at 60°W far enough to the south, and neither had a ridge upstream at 80°W. Both forecasts had too low surface pressure over the south-eastern and north-western parts of the North American continent, while the relaxed forecast had too high surface pressure in the central Atlantic region.

By day 5, the winds at 200 mb in the tropical Atlantic region were beginning to be seriously wrong in the control experiment (see Fig. 13). The large circulation systems over the Caribbean and South America were missing, while the flow across the Atlantic was easterly instead of westerly. With the relaxation scheme the 200 mb wind field closely resembled the analysis, except that the closed circulation at 30°N 30°W was replaced in the relaxed forecast by westerly winds with a speed of more than 30 m/sec.

At higher latitudes the 2 forecasts were still very similar, with the largest differences over Eastern America and the West Atlantic. Neither forecast extended the 500 mb trough at 50°W far enough to the south, but in the control experiment it was also positioned 10° too far to the west. Where the analysis had a closed surface low of 1003 mb in mid Atlantic at 45°N 40°W, the relaxed forecast had uniformly high pressure. The control forecast had lower surface pressure here, but still with no indication of the closed low. The control forecast incorrectly developed a surface low of 998 mb at 50°N 65°W, and failed to develop a surface low of 1014 mb just to the east of

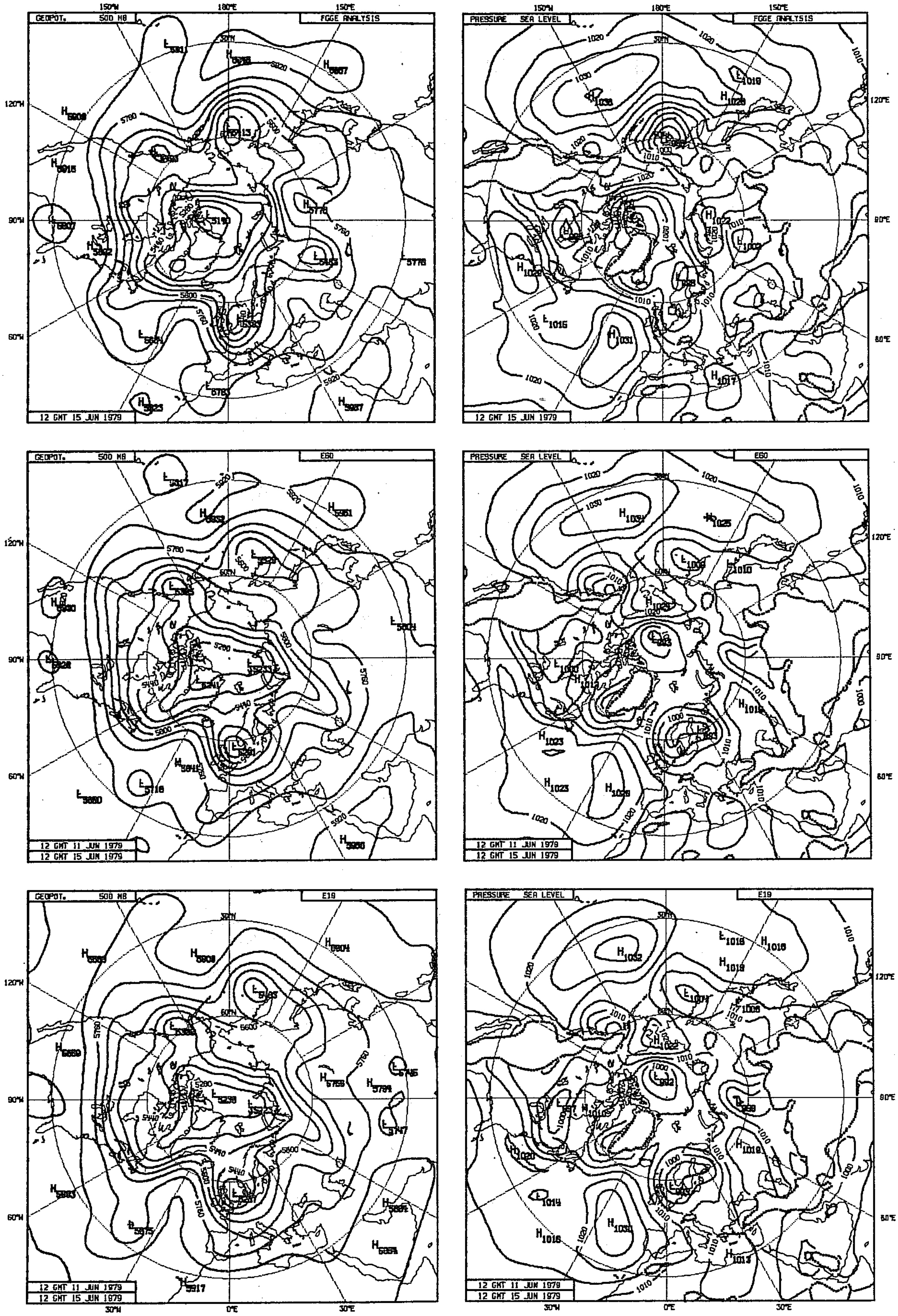

Fig. 12 Left column: Day 4: 500 mb geopotential field at 12 GMT 15 June 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).
Right column: Day 4: mean sea level pressure.

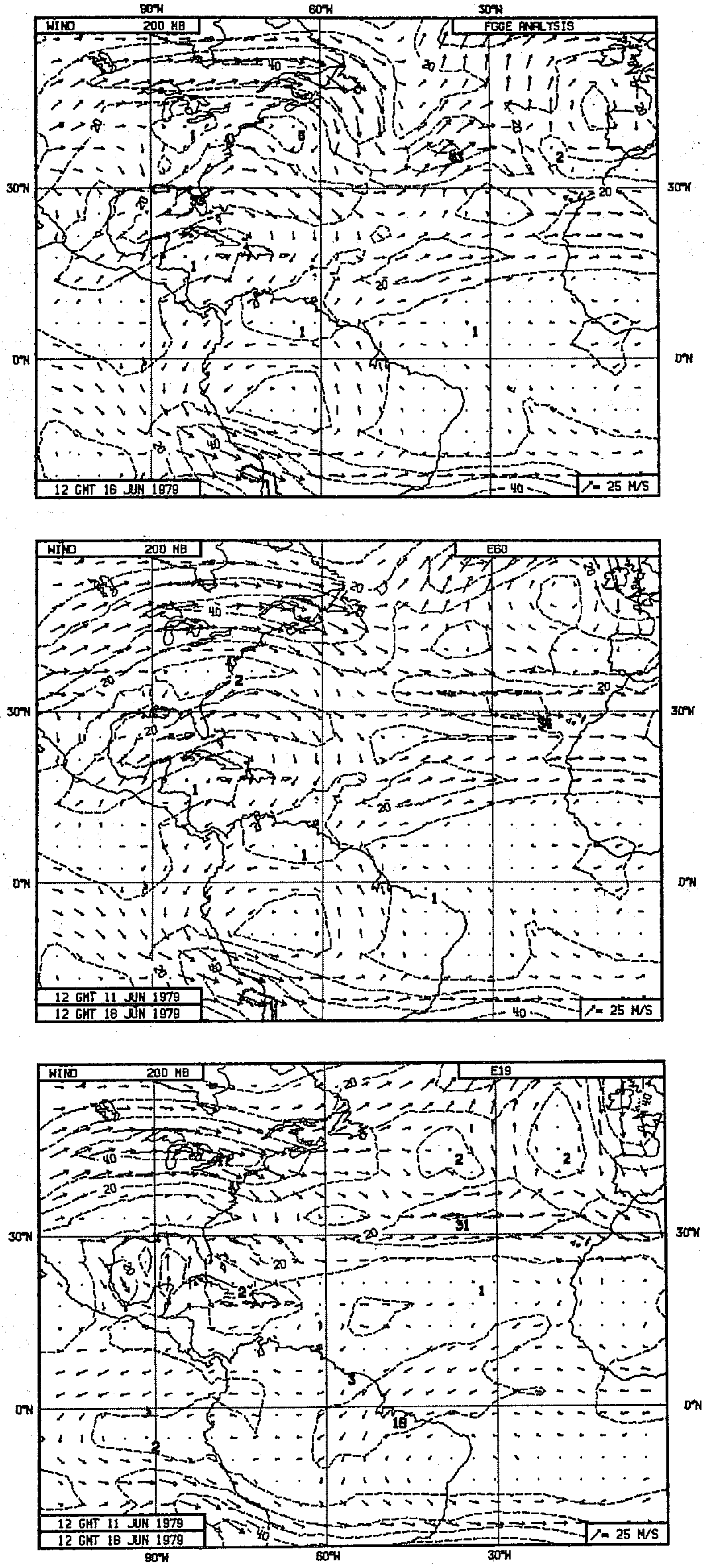

Fig. 13 Day 5: 200 mb wind at 12 GMT 16 June 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).

Florida.

Figure 14 shows the 500 mb geopotential and mean sea level pressure fields for day 6. The absence of the monsoon in the control forecast had still not led to any significant differences between the 2 forecasts in the Eastern Pacific region. Nor (with the possible exception of the 500 mb trough over south-eastern USA which the relaxed forecast only hinted at, but the control forecast missed altogether) had the poor Atlantic and Caribbean tropical forecast had any obvious impact on the forecast at higher latitudes.

Outside the tropics, the largest difference between the 2 forecasts was probably in the Newfoundland region, where the control forecast had a surface low of 996 mb beneath a 500 mb trough which had remained stationary at 60°W since day 4. In the analysis, the corresponding trough was at 35°W with a surface low to the south west of Iceland. In the relaxed forecast the trough was at about 45°W, with too small amplitude and no closed surface low.

Figure 15a shows the anomaly correlation of height, averaged over all longitudes, all latitudes between 30°N and 82.5°N and all levels between 1000 mb and 200 mb for the relaxed forecast (labelled E60), the control forecast (labelled E19) and persistence. The relaxed forecast showed a small improvement over the control forecast , particularly in wavenumbers 4-9. However, the relaxation scheme was not able to extend the useful limit of the forecast by more than half a day, and both forecasts deteriorated rapidly in the later stages, so that they were both worse than persistence by day 7.

Figure 15b shows the equivalent anomaly correlation diagram for the latitude band 30°S - 82.5°S. In this case, the relaxation scheme had a greater impact in the southern, winter, hemisphere than in the northern hemisphere. From day 2 onwards, the relaxed forecast showed a small improvement over the

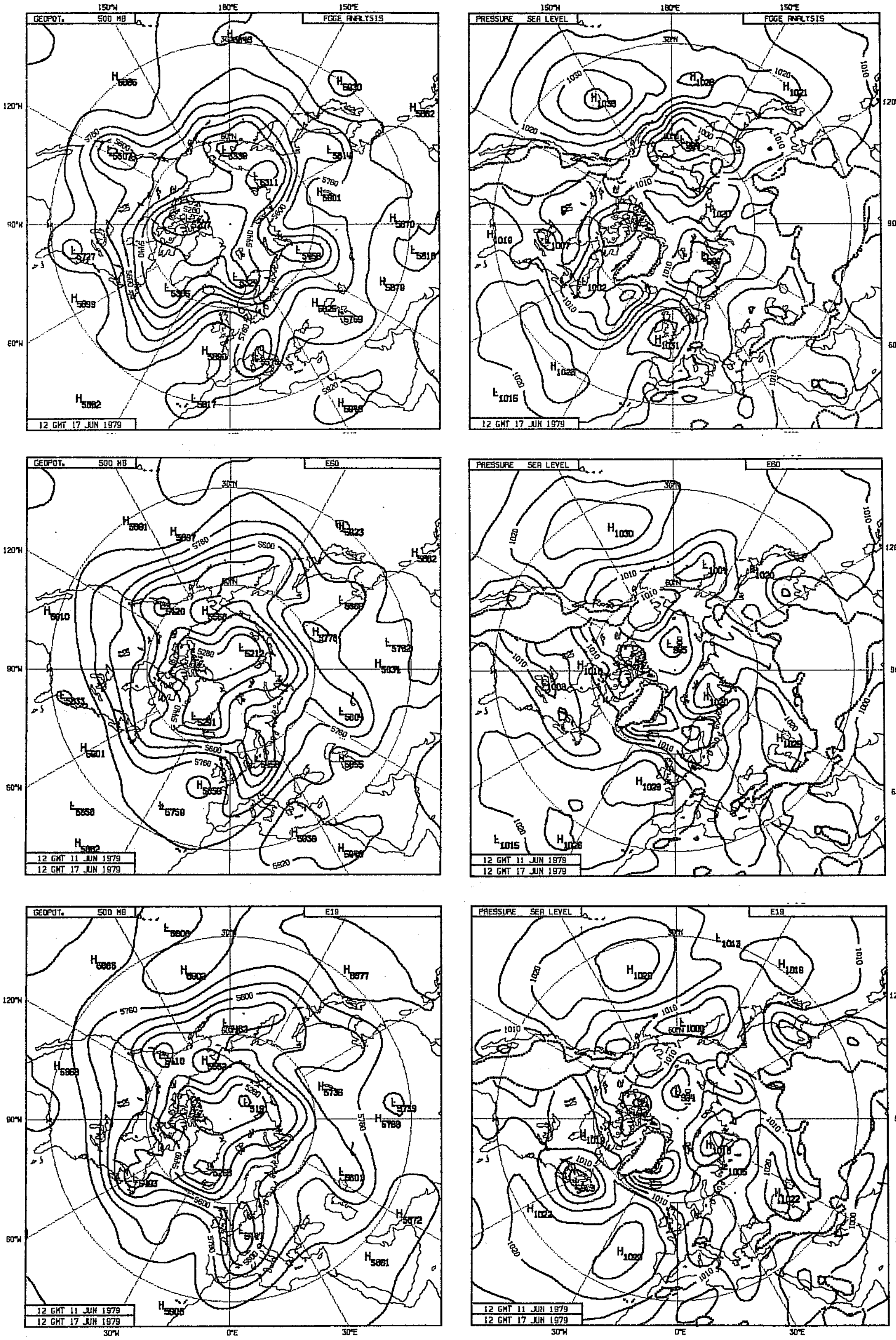

Fig. 14 Left column: Day 6: 500 mb geopotential field at 12 GMT 17 June 1979 for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).
Right column: Day 6: mean sea level pressure.

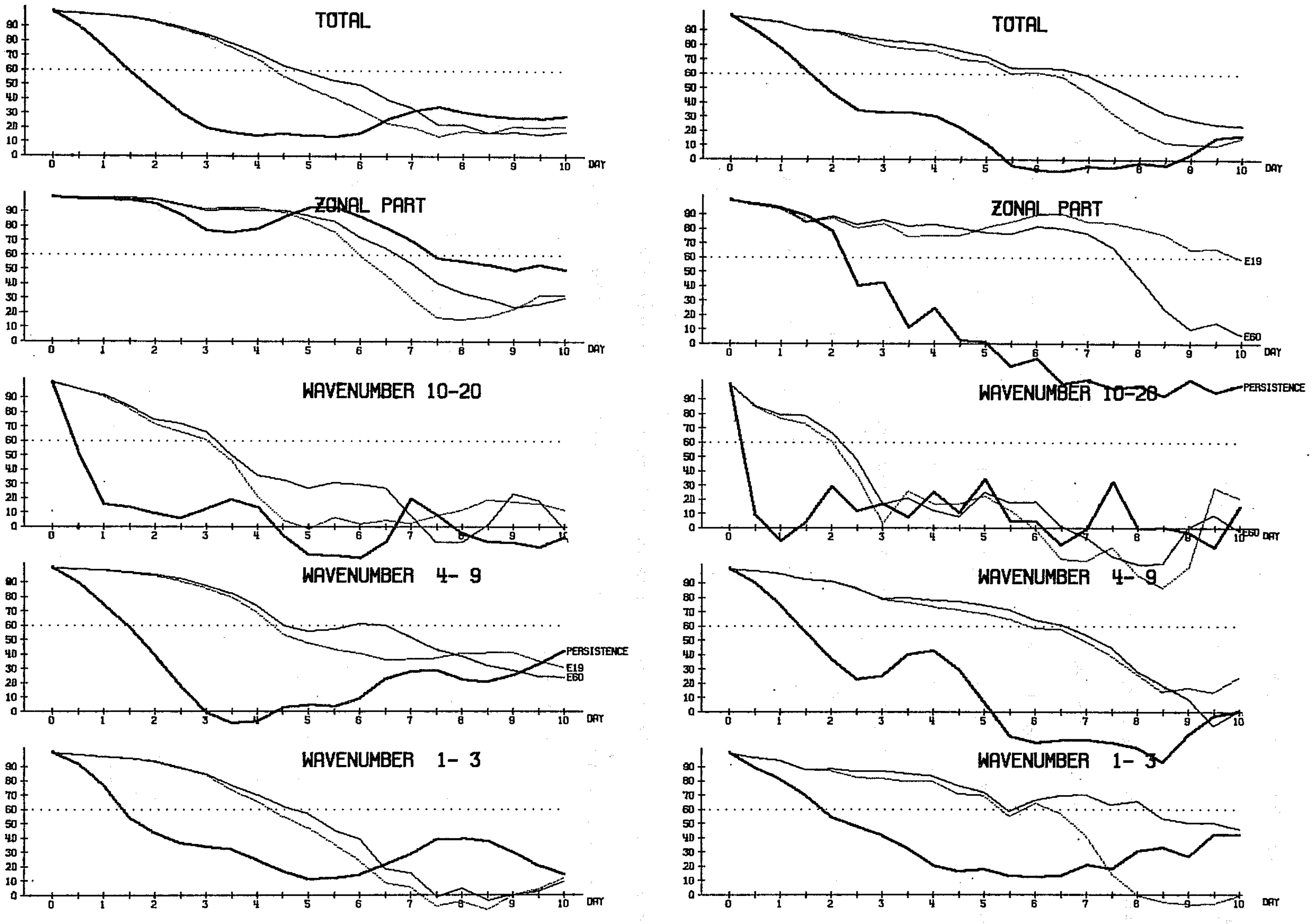

Fig. 15 Left column: anomaly correlation and height, averaged over all longitudes, latitudes 30^{o}N-82.5^{o}N and levels 200-1000 mb for the relaxed forecast (E60) and the control forecast (E19).
Right column: the same anomaly correlations but for the latitude band 30^{o}S-82.5^{o}S.

control forecast , and this improvement was maintained through to day 10. (By comparison, the relaxation scheme had little impact in the southern hemisphere in the forecast from 14/11/79, but gave a big improvement in objective scores for the forecast from 16/10/79).

4. IMPACT AT MIDDLE AND HIGH LATITUDES

In these experiments, two mechanisms by which tropical forecast errors could influence the quality of the forecast at higher latitudes were apparent. The most important effect was the interaction between real or spurious tropical features and major mid-latitude troughs. By altering the orientation and position of these troughs, the subsequent evolution of the flow at middle and high latitudes could be modified substantially. A smaller effect could be seen when surface lows developed in the tropics and then moved to higher latitudes.

The first case study described above contained the best example of a forecast which evolved incorrectly, after failing to simulate properly the interaction between a high latitude trough and a tropical system. The control run failed to develop properly a high level vortex over the Caribbean between days 2 and 3 of the forecast, and as a result did not have strong enough westerly winds advecting the southern part of the trough which lay to the east of the USA. In the analysis and the relaxed forecast, the trough remained symmetric with its axis lying approximately N/S, while in the control forecast it became tilted with a NE/SW orientation

The kinetic energy equations suggest that there should be a net conversion of eddy to zonal kinetic energy for the tilted trough, but not for the symmetric trough. Following Lorenz (1967), the kinetic energy equations are:

$$K_Z = \frac{1}{2} \int_{Atm} [\underline{u}] \cdot [\underline{u}] \; dm$$

$$K_E = \frac{1}{2} \int_{Atm} \underline{u}^* \cdot \underline{u}^* \; dm$$

where

K_Z = zonal kinetic energy

K_E = eddy kinetic energy

$[\underline{u}]$ = zonal mean wind, $[\underline{u}] = ([u], [v], [w])$

$\underline{u}^*$ = deviation of the wind from its zonal mean

$dm = \frac{a^2}{g} \cos(\theta) \; d\lambda \; d\theta$

θ = latitude

λ = longitude

p = pressure

a = radius of the earth

g = acceleration due to gravity

and the integrals above are over the earth's atmosphere.

Then the conversion from zonal to eddy kinetic energy, CK, is given by

$$CK = - \int_{Atm} \{\cos(\theta)[u^*v^*] \frac{1}{a} \frac{\partial}{\partial\theta} \left(\frac{[u]}{\cos(\theta)}\right) + [u^*w^*] \frac{\partial[u]}{\partial p} - \cos(\theta)[v^{*2}] \frac{1}{a} \frac{\partial}{\partial\theta} \left(\frac{[v]}{\cos(\theta)}\right)$$

$$+ [v^*w^*] \frac{\partial[v]}{\partial p} + \frac{\sin(\theta)}{a}[u^{*2} + v^{*2}] [v] \} \quad dm$$

Figure 16 shows plots of $-\cos(\theta)u^*v^* \frac{1}{a} \frac{\partial}{\partial\theta}\left(\frac{[u]}{\cos(\theta)}\right)$ at 500 mb in the Western Atlantic region at day 3 for the 3 cases. Assuming that the first term in Eqn.5 gives the major contribution to CK (see e.g. van Mieghem, (1973)), then latitudes with a net positive contribution from this term should have an overall conversion from zonal to eddy kinetic energy, and vice versa.

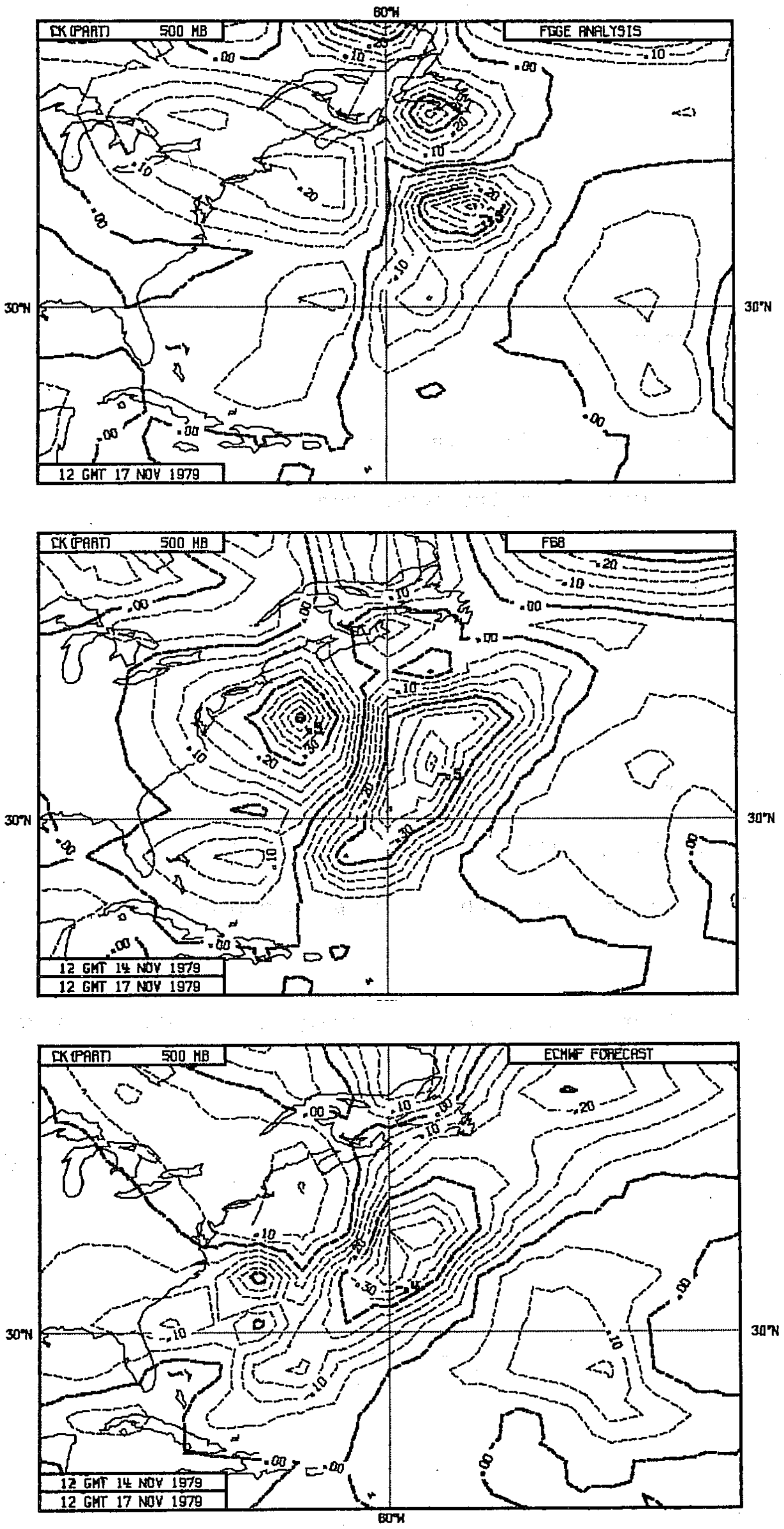

Fig. 16 $-\cos\theta . u^{*} v^{*} \frac{1}{a} \frac{\partial}{\partial\theta} \left(\frac{[u]}{\cos\theta}\right)$ (units: $m^{2}s^{-3}$) at 12 GMT 17 November 1979 at 500 mb for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).

For the analysis and the relaxed forecast, with a fairly symmetric trough at 60°W, this term was negative ahead of the trough and positive behind it, so that the net contribution to the zonal average from this region was small. For the control forecast with its tilted trough, this term was negative behind the trough as well as ahead of it in the area to the south of 40°N, while further north there was only a small positive contribution behind the trough. The net negative contribution to CK from this region implies a conversion from eddy to zonal kinetic energy.

Figure 17 shows the mean value of CK for the area between 30°N and 82.5°N, and for levels between 1000 mb and 200 mb. For wavenumbers 4-9, the control forecast had too large negative values from day 2 1/2 onwards.

Care must always be taken in interpreting local energy conversions. A large local contribution to CK does not necessarily imply a direct local change of zonal and eddy kinetic energy components, owing to the possible effects of potential energy conversions and boundary fluxes of energy. It is nevertheless noteworthy that in this case the 500 mb maps (see Figs. 2-4) show that the flow in the control forecast did indeed become too zonal in the Atlantic region during days 4-6. This behaviour is also in agreement with the results of some idealized studies of non-linear baroclinic waves (Simmons and Hoskins, 1978, 1980).

In the second case study described above, the set of forecasts from 00Z, 16/10/79, the interaction between a high latitude trough and a tropical feature appeared again to be important, but this time it was an overdeveloped rather than an underdeveloped tropical circulation system which gave problems for the control forecast.

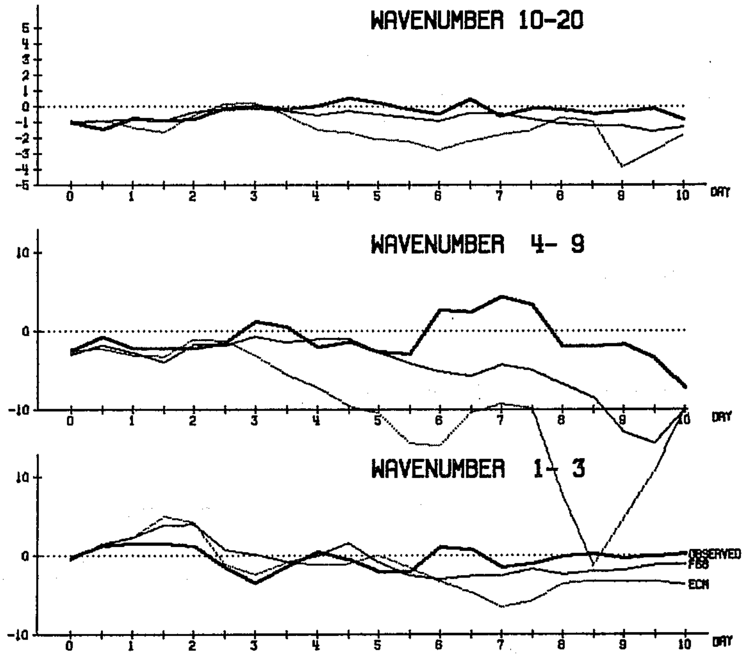

Fig. 17 Mean CK between $30^{o}N$ and $82.5^{o}N$ and between 200 mb and 1000 mb for the relaxed forecast (F68), the control forecast (ECM) and the analyses.

Between days 2 and 3, an anticyclonic circulation system became established at 200 mb in the control forecast (see Fig. 7). This extended south-westwards from the major trough at 170°E to the equator, then westwards for about 40 degrees of longitude. Smaller scale circulation systems were also present in the analysis and the relaxed forecast, but these extended southwards only as far as 20°N, and had much weaker winds associated with them.

As a result, the orientation of the trough was modified subtly in the control forecast. In the analysis at 200 mb, the winds in the rear portion of the trough at 170°E were northerly, while in the front portion they were south-westerly. In the control forecast , the winds had a significant easterly component in the back of the trough, especially in its southern part. The relaxed forecast was closer to the analysis than the control forecast.

Figure 18 shows that, with its slightly different orientation, the trough in the control forecast had a large negative contribution to CK, whereas the analysis and the relaxed forecast did not have a significant net contribution in this region. From this, one would expect conversion from eddy to zonal kinetic energy in the control forecast , but not in the relaxed forecast or the analysis. This did in fact occur over the next 24 hours, when the analysis and relaxed forecast maintained a trough at 180°E, while the control forecast developed zonal flow in this region. Subsequently the 2 forecasts evolved differently in the Pacific and North American sectors.

In the third case study, the weaker summer circulation appeared to be less sensitive to errors in the tropics. Over the Asian continental region, the Himalayas formed an effective barrier, separating the monsoon flow from the high latitude circulation. Downstream in the West Pacific region, there were no significant differences between the forecasts which could be attributed to

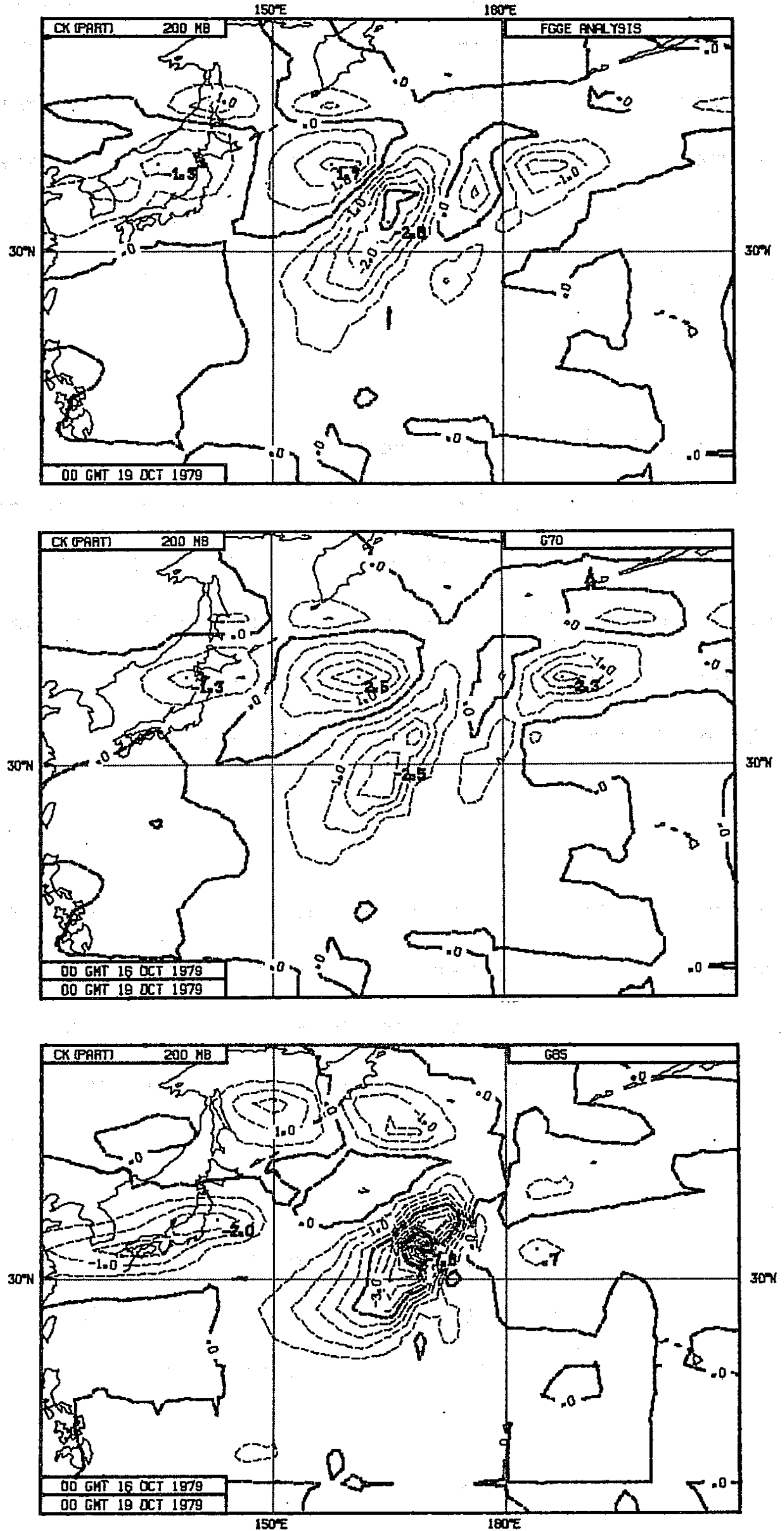

Fig. 18 $-\cos\theta . u^{*} v^{*} \frac{1}{a} \frac{\partial}{\partial\theta} \left(\frac{[u]}{\cos\theta}\right)$ (units: $m^{2}s^{-3}$) at 00 GMT 19 October 1979 at 200 mb for FGGE analysis (top), relaxed forecast (middle) and control forecast (bottom).

the absence of the monsoon in the control run.

Similarly, it is not easy to find differences between the forecast at middle and high latitudes which could be blamed on the very poor control forecast in the tropical Atlantic and South American regions from day 5 onwards. Figure 13, the 200 mb wind field at day 5 in this region, shows that the analysed mid-latitude trough at 45°W did not extend southwards beyond 30°N, while the major tropical forecast errors occurred to the south of this latitude. So neither in the Atlantic nor in the monsoon region was the tilting trough mechanism, with its resulting conversions between zonal and eddy kinetic energy, in evidence.

The second case study contained an example of the second, and less important, mechanism by which errors at low latitudes could effect the forecast at higher latitudes. A spurious surface low was developed to the east of Florida at day 2 in the control forecast. It moved north-eastwards, and deepened rapidly between days 4 and 5, when it came under the influence of an upper level trough at 45°W (see Fig. 8). The table below shows the central pressure of the surface low for the analysis, the relaxed forecast and the control forecast.

Table 2. Central pressure of Atlantic surface low in mb

	Analysis	Relaxed forecast	Control forecast
Day 2	-	-	1009
Day 3	-	1011	1005
Day 4	1010	1007	1000
Day 5	994	990	975
Day 6	983	980	983

The upper trough developed a little differently in the 2 forecasts from day 5 onwards. At day 5, both forecasts had the trough lying N/S at 45°W, while the analysis had the trough at 40°W. At day 6, (see Fig. 9), the control forecast had the trough at 30°W, while it was at 25°W in the relaxed forecast, and 20°W in the analysis. The gradients in the trough were a little slacker in the control forecast than in the relaxed forecast or the analysis. By day 7, however, both forecasts were treating the trough incorrectly. They both gave it a NE/SW orientation in its southern part, instead of N/S as in the analysis, and both had a ridge to the west, while the analysis had a second trough at 35°W.

Thus in this case, the spurious development of a low-latitude surface low had a clear impact at the surface in middle latitudes for about 3 days, with a possible impact at 500 mb for 1 or 2 days.

5. CONCLUSIONS

These experiments with the relaxation scheme indicate that interactions between tropical features and deep mid-latitude troughs can have a significant impact on the subsequent evolution of the flow at higher latitudes. In the first case study described above, the model failed to develop properly a high-level anticyclonic circulation system over the Caribbean between days two and three of the forecast. As a result, the major mid-latitude trough to the north of this region did not have strong enough winds advecting its southern portion eastwards, and it developed a NE/SW orientation, instead of the N/S orientation that was analysed. In the second case study, again between days two and three of the forecast, the model over-intensified a high level anticyclonic circulation system to the south-west of a major trough in the Western Pacific, and as a result this trough also acquired too much of a NE/SW orientation.

In both these cases, the incorrect orientation of the trough led to spurious conversion from eddy to zonal kinetic energy, and adversely affected the subsequent evolution of the flow. These results agree with diagnostics produced by Arpe and Oriol (1981) which show that for the 1981 January mean ECMWF operational forecasts and analyses, the zonal mean of the eddy meridional flux of zonal momentum, $\overline{u'v'}$, was almost twice as large in the 5 day forecast as in the analysis in the region 30-50°N (see Fig. 19).

The relaxed forecasts may have been better in this respect because by inserting the correct values within the relaxation zone (which extended to 25°N in the first 2 cases, and to 30°N in the third case) the bases of the deepest troughs were forced into the correct position. However, these experiments indicate that interaction with tropical features is one of the mechanisms which cause mid-latitude troughs to become incorrectly oriented in the first place.

It should also be pointed out that the three cases described in detail above were specially selected because it was thought they might be more likely to show an impact at higher latitudes from tropical forecast errors. The seven cases investigated can be grouped together as follows:
Dramatic improvement with relaxation scheme: 14/11/79
Small improvement with relaxation scheme: 16/10/79, 1/12/78, 9/2/79
Little or no improvement with relaxation scheme: 14/10/79, 11/6/79
Worse with relaxation scheme: 12/10/79
These results thus indicate that, at least for a small proportion of cases, errors in the tropics have a significant impact on the quality of the forecast at higher latitudes.

The experiments also show that the relaxation scheme is a useful tool for investigating the effect of errors in one region on other areas of the forecast. It must be kept in mind when using this scheme that any errors in

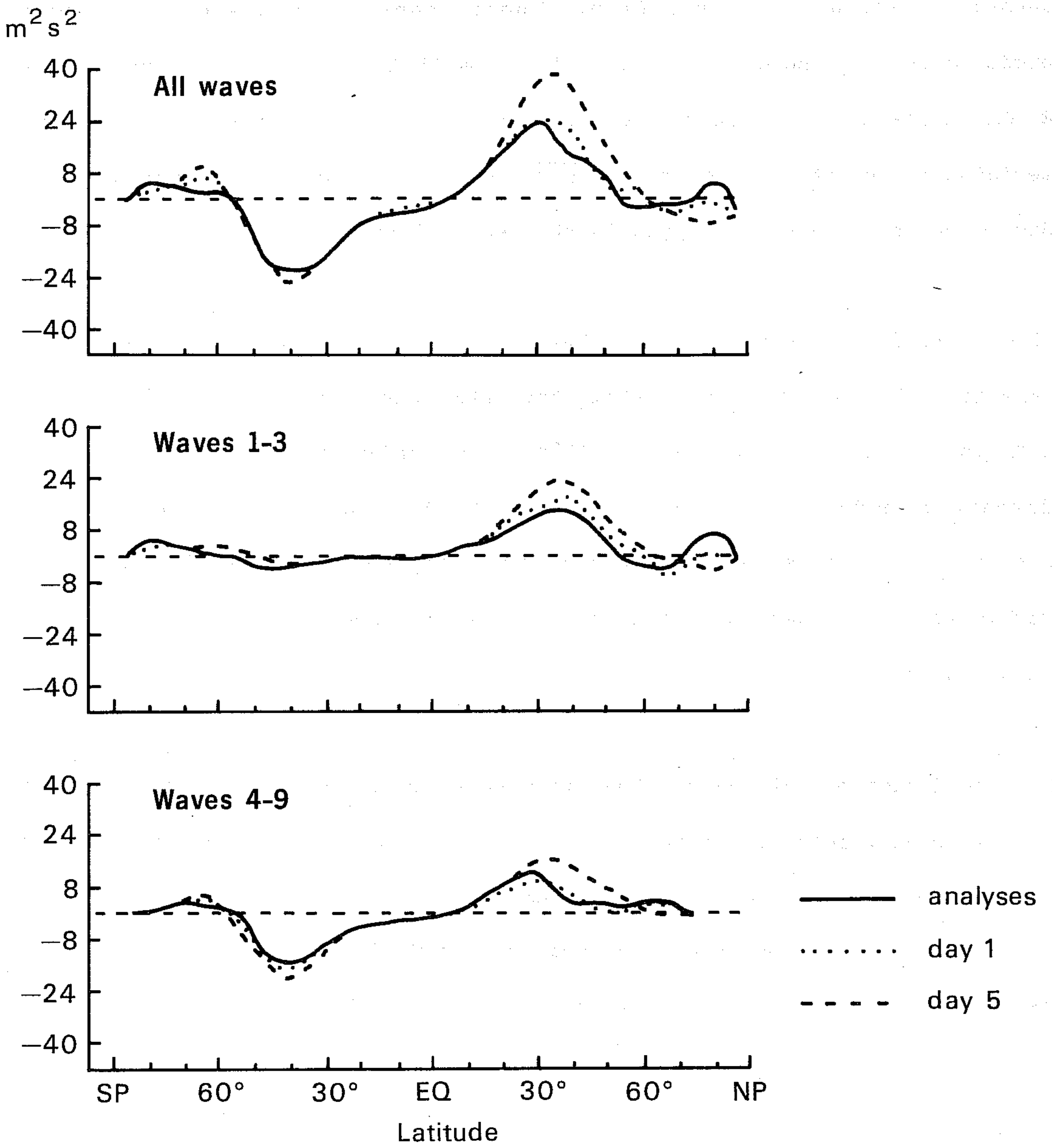

Fig. 19 Zonal mean of the eddy meridional flux of zonal momentum $\overline{u'v'}$. Vertical average between 500 and 1000 mb. January 1981 means of analyses and forecast days 1 and 5 are compared.

the analysis will be inserted directly into the forecast in the relaxation zone. In these tropical analyses, it is likely that the divergent part of the wind field was somewhat diminished, due to the effects of the initialization scheme within the data assimilation cycles. (This problem is likely to be considerably reduced by the introduction of diabatic processes into the initialization.) Errors in the forecast model's parameterization scheme can affect the analyses through the first guess field. Also, the analysis structure functions are designed primarily for mid-latitudes, rather than for the tropics. These analysis factors, together with model spin-up problems, may have been partly responsible for the difficulty which the relaxed forecasts experienced in treating Typhoon 'Tip' correctly.

It might be interesting in future to investigate other applications of the relaxation scheme. In these experiments, the analyses were inserted into a complete latitude band within the tropics. By restricting the relaxation zone to a smaller longitudinal extent, it should be possible to isolate the effects of individual tropical systems on the rest of the forecast. At higher latitudes, the relaxation scheme could perhaps be used to assess the influence of orographic forcing from a single mountain chain, such as the Rockies or the Andes. The scheme could also be used in the vertical, for example to investigate the influence of the troposphere on stratospheric flow.

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