TROPICAL INFLUENCES ON STATIONARY WAVE MOTION IN MIDDLE AND HIGH LATITUDES

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ABSTRACT

The influence of the tropics on the stationary wave motion of middle and high latitudes has been examined using idealized model calculations and a preliminary forecast experiment.

A steady, linear, primitive-equation model illustrates the sensitivity of extratropically-forced wave motion to tropical boundary conditions, and indicates the extratropical response to tropical forcing. In the latter case an isolated tropical region of diabatic heating may excite a wavetrain with a substantial poleward direction of propagation. Specifying the tropical forcing by means of a relaxation towards climatology results in a large extratropical response.

Barotropic experiments have been performed in which an isolated tropical forcing is superimposed on a constant forcing which maintains a climatological basic flow with zonal variation. In these cases a large response is found in the North Pacific region, particularly when the forcing is located to the south of the region of strongest flow. Nonlinearity amplifies or damps this response depending on the sign of the forcing. Maintenance of a region of tropical westerly wind of limited zonal extent results in a substantial cross-equatorial propagation.

The forecast experiment involves comparison of a control forecast with a forecast in which the atmosphere in the tropics and subtropics is set equal or relaxed towards analyzed states. The largest high-latitude impact is found for the larger scales of motion in the winter hemisphere, in broad agreement with the results from simpler models.

1. INTRODUCTION

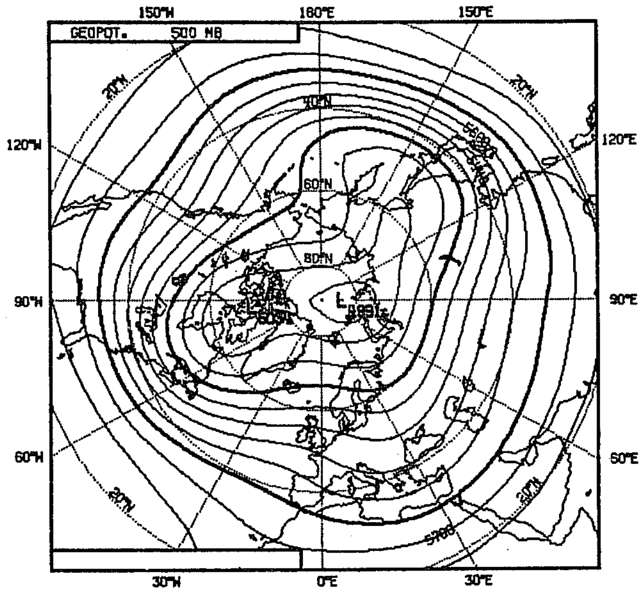
Two idealized models have been used to investigate tropical influences on the response in middle and high latitudes to a stationary wave forcing. A series of forecast experiments aimed at quantifying tropical influences on medium-range weather forecasts for extratropical latitudes has also recently been started. In this paper we summarize results to date. A much more detailed account will be given in a forthcoming ECMWF Technical Report.

In general, this investigation confirms and extends several previous theoretical studies (Egger, 1977; Opsteegh and van den Dool, 1980; Hoskins and Karoly, 1981; Webster, 1981). The resulting theoretical picture is in broad agreement with results from observational studies of teleconnections (e.g. Wallace and Gutzler, 1981) and general circulation model studies of the response to sea surface temperature anomalies (e.g. Rowntree, 1976). It clearly indicates that tropical influences may significantly affect the extratropical standing wave pattern, both in the climatological mean, and in deviations from this mean.

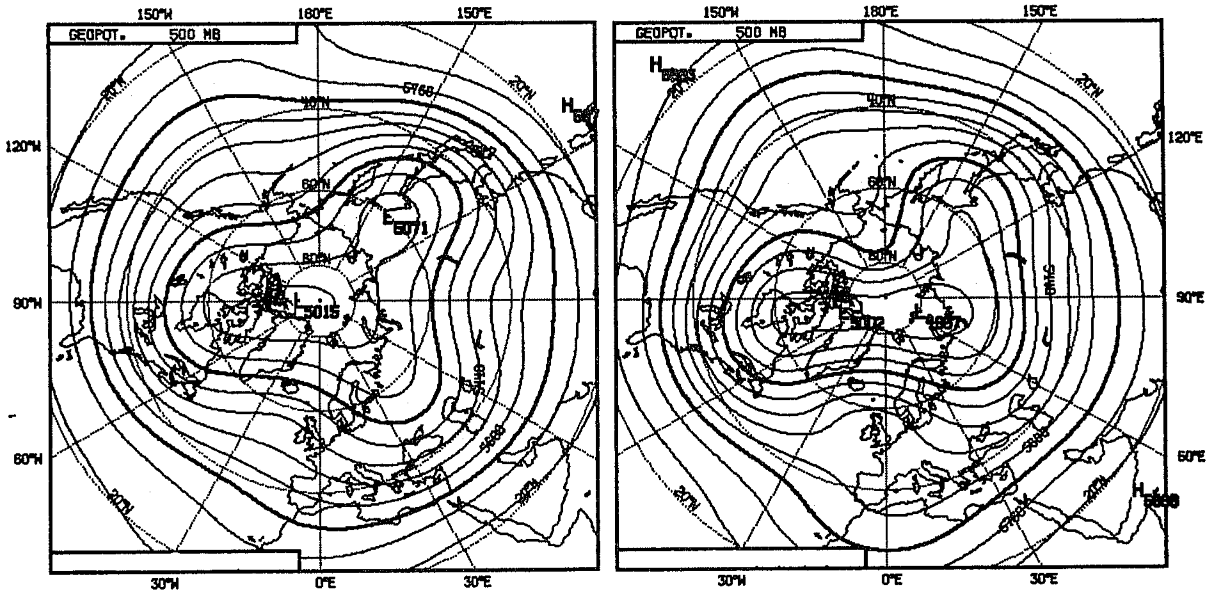
2. MIDDLE-LATITUDE FORCING

A linearized steady-state version of the ECMWF, adiabatic gridpoint model has been developed. Stationary wave solutions are determined from a set of linearized equations with forcing by a prescribed distribution of orography and/or diabatic heating, or by relaxation of a limited area of the atmosphere towards a prescribed state. The model includes a simple boundary-layer dissipation and Newtonian damping, together with a friction near critical latitudes (singular lines), where the zonal-mean flow vanishes. The latter is necessary in order to ensure well-behaved solutions. Fixed climatological zonal-mean flows are used. The resolution employed is that of the operational model.

One experiment performed with this model was designed to illustrate the role of the tropics as the boundary condition on wave motion forced from extratropical latitudes. Figure 1 compares the climatological 500 mb height field for January with model results showing the response to a realistic extratropical forcing for two cases. In the first the model is global, and there is a dissipative critical latitude at all levels in the tropics. In the second the reflecting boundary condition $v = 0$ is applied close to 15 ^{o}N. The differences in the extratropical response suggest that an accurate representation of the tropics is important for an accurate simulation of the middle latitude circulation, even in the absence of explicit tropical forcing. They also provide further evidence for the importance of acquiring an improved theoretical understanding of singular-line effects, since the extent to which singular lines act to dissipate or nonlinearly reflect is currently far from clear.



January climate



Global model

v = 0 at 15°N

Fig. 1 The climatological mean 500 mb geopotential for January (upper) and calculations using a global model (lower left) and a model with a reflecting boundary condition close to 15°N (lower right). The contour interval is 8 dam.

3. THE STEADY, LINEARIZED RESPONSE TO TROPICAL FORCING

The same model as used in Sect. 2 has been employed, with forcing here provided solely by an isolated source of tropical heating. In agreement with a number of recent studies by others, notably that by Hoskins and Karoly (1981), a significant extratropical response is found. For the January climatology, the response is largest for a forcing at 15 ^{O}N, and appears as an approximately barotropic train of waves with a substantially poleward direction of propagation (Fig. 2). The amplitude of the response is halved for forcing at 5 ^{O}N or 25 ^{O}N, as shown in Fig. 3, and phase differences are also evident. A very weak steady Northern Hemispheric response is seen for a forcing at 15^{O}S on account of wave trapping in the equatorial region of easterly winds. Figure 4 shows a weak response due to forcing at 15^{O}N for a July flow, for similar reasons.

Figure 4 also illustrates a marked difference for the Southern Hemisphere response to a forcing at 15^{O}S. In this case there is an inhibition of poleward propagation south of the jet maximum, with a clear zonal and then equatorward direction of propagation. This is consistent with the theory of latitudinal planetary wave propagation which shows waves in westerly flow to be reflected by a region of negative poleward gradient of absolute vorticity. Such a gradient occurs on the poleward flank of the climatological jet in the Southern Hemisphere. Since climatological vorticity gradients are inevitably smoother than day to day values, it is likely that similar results may commonly hold for actual propagation in the Northern Hemisphere. Application of these ideas to the diagnosis of forecast results is currently being carried out.

Additional sensitivity studies show that results are not particularly sensitive to the detailed vertical structure of the tropical diabatic heating, a result of some significance from the viewpoint of the parameterization of convection. Little sensitivity to the meridional scale of the forcing is also found, while the high latitude (low wavenumber) response increases with the longitudinal scale of the forcing region.

In a second set of experiments the forcing has been specified, not as a direct diabatic heating, but rather as a relaxation towards tropical climatology. If this relaxation is applied south of about 25 ^{O}N, with no explicit extratropical forcing, a substantial extratropical response is found. In particular, a pronounced (and surprisingly realistic) North American trough is evident, as shown in Fig. 5.

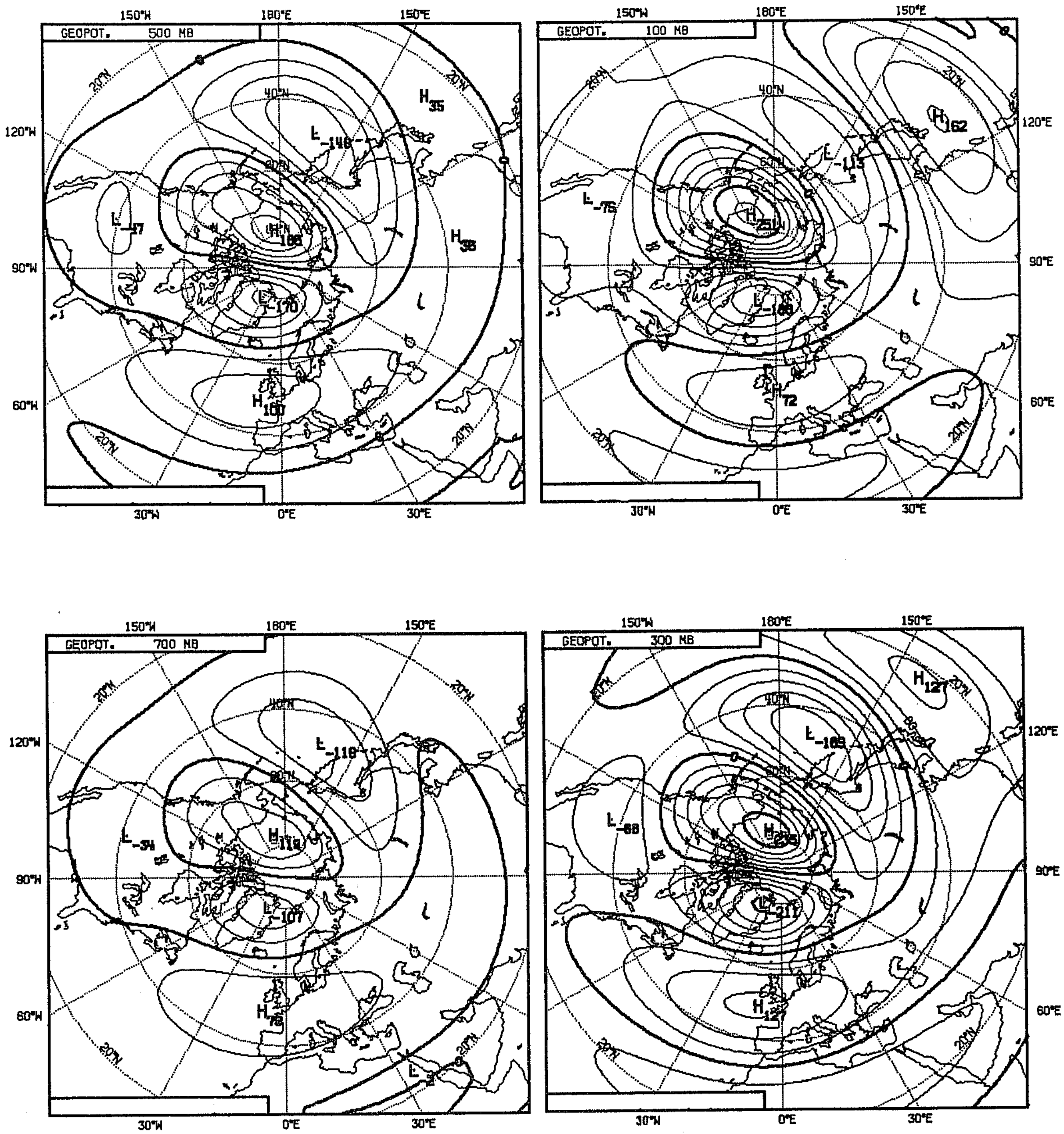
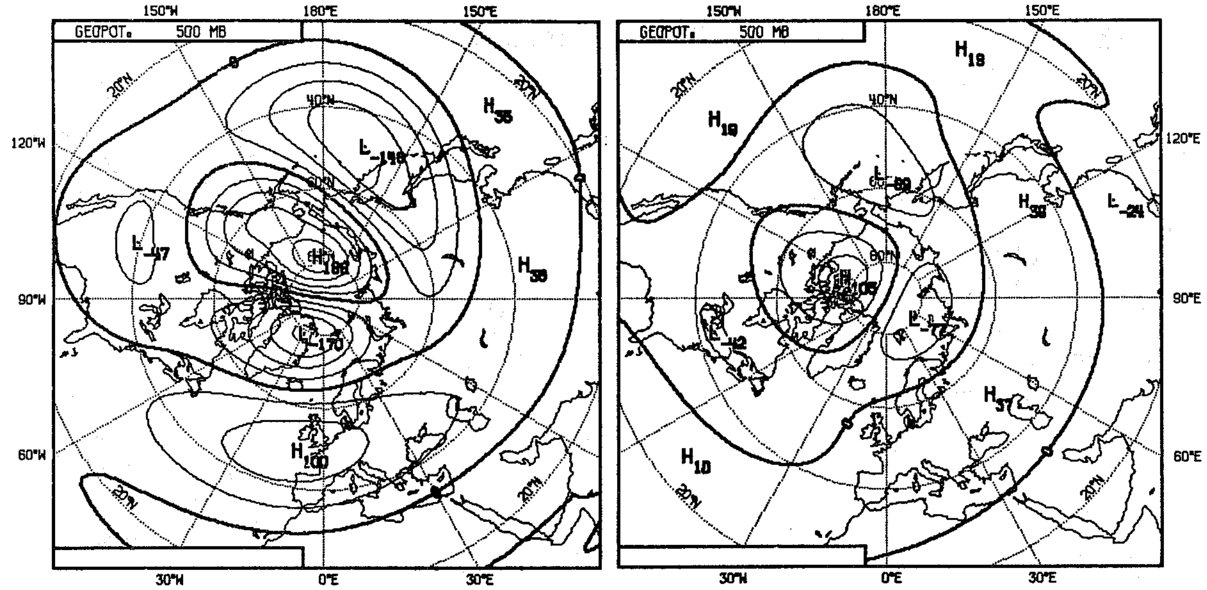


Fig. 2 The response to a heating centred at 15°N, 135°E with a meridional extent of some 20° latitude and a zonal extent of 60° longitude. The perturbation geopotential is shown at 700 mb (lower left), 500 mb (upper left), 300 mb (lower right) and 100 mb (upper right). The amplitude is arbitrary since the calculation is linear, but for a heating maximum of 5°C/day at 400 mb, the contour interval is 4 dam.

15°N forcing **25°N forcing**



5°N forcing **15°S forcing**

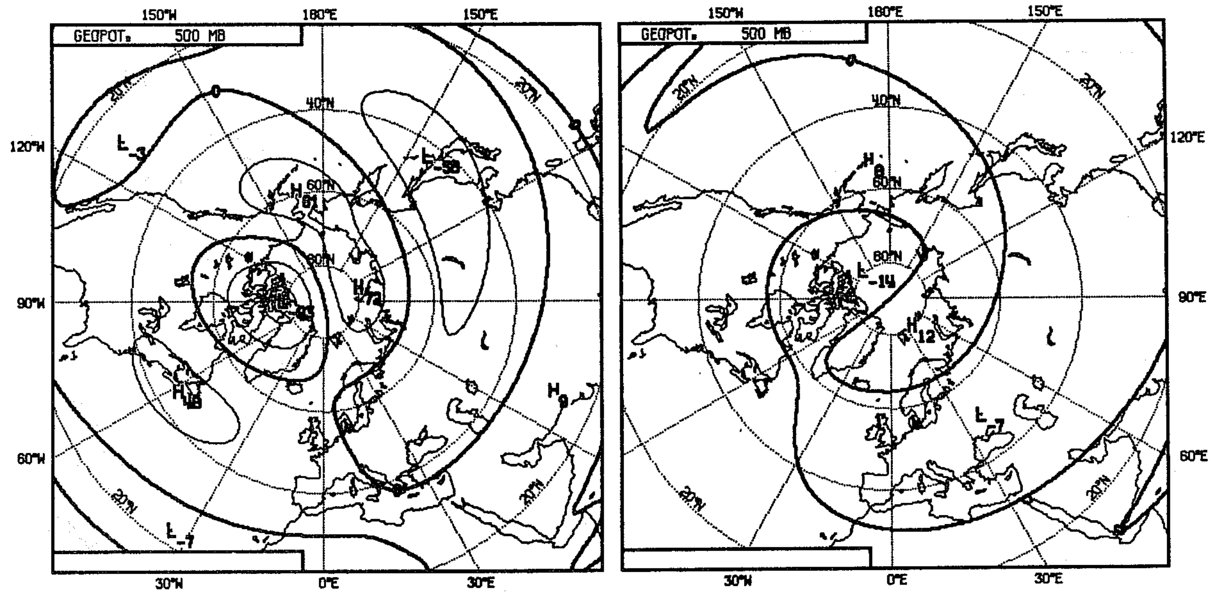
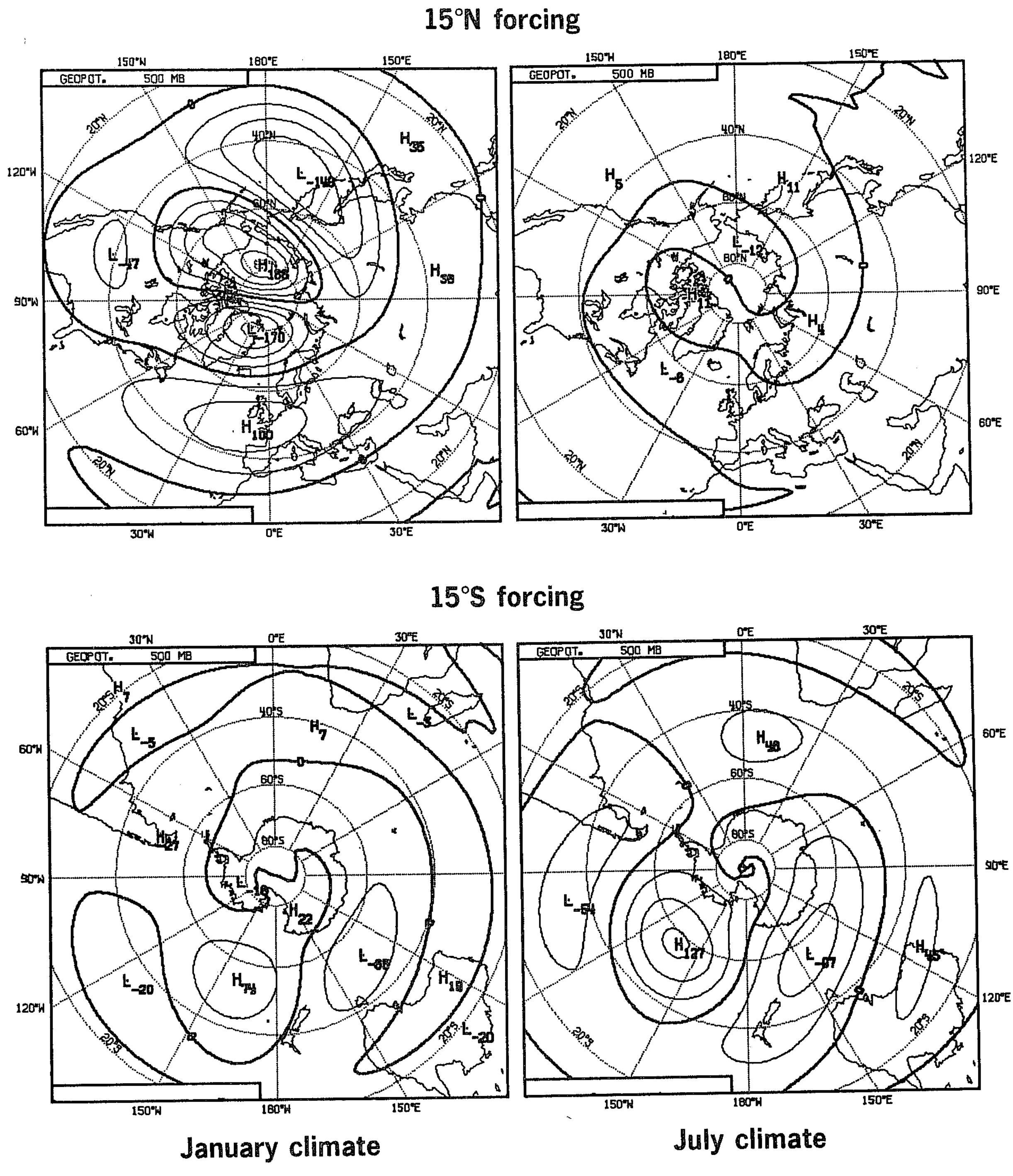


Fig. 3 The 500 mb response to an isolated heating centred at 135°E and 15°N (upper left), 25°N (upper right), 5°N (lower left) and 15°S (lower right).



15°N forcing

15°S forcing

January climate

July climate

Fig. 4 The 500 mb response for the Northern Hemisphere (upper, isolated heating at 15°N) and the Southern Hemisphere (lower, isolated heating at 15°S). Results are presented for the January (left) and July (right) climatological mean flows.

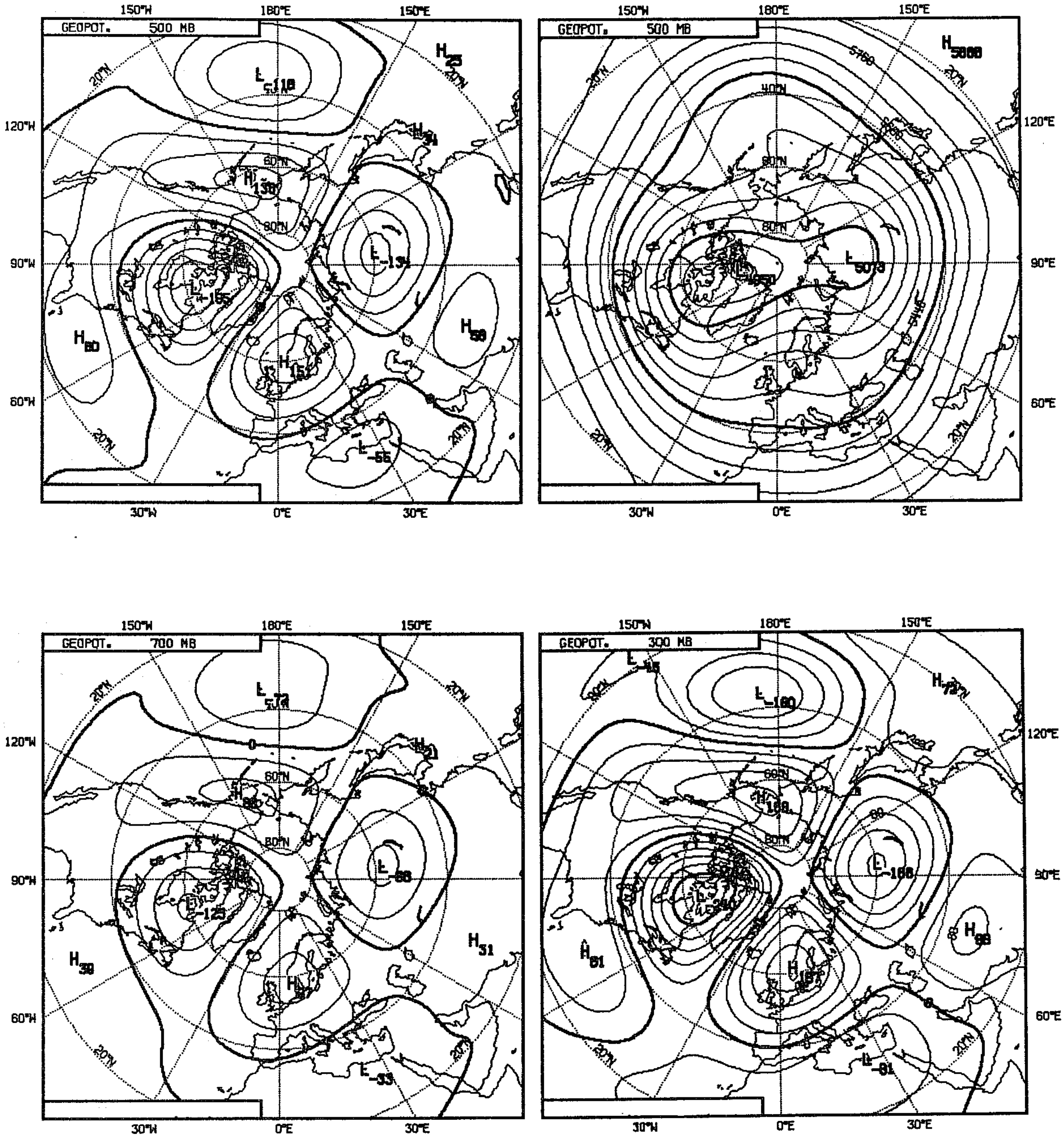


Fig. 5 The extratropical response forced by a relaxation towards tropical climatology. Perturbation geopotentials are plotted with a contour interval of 4 dam at 700 mb (lower left), 500 mb (upper left) and 300 mb (lower right). The total 500 mb field (contour interval 8 dam) is also shown.

4. EFFECTS OF TRANSIENCE, ZONALLY NON-UNIFORM BASIC FLOWS AND NONLINEARITY

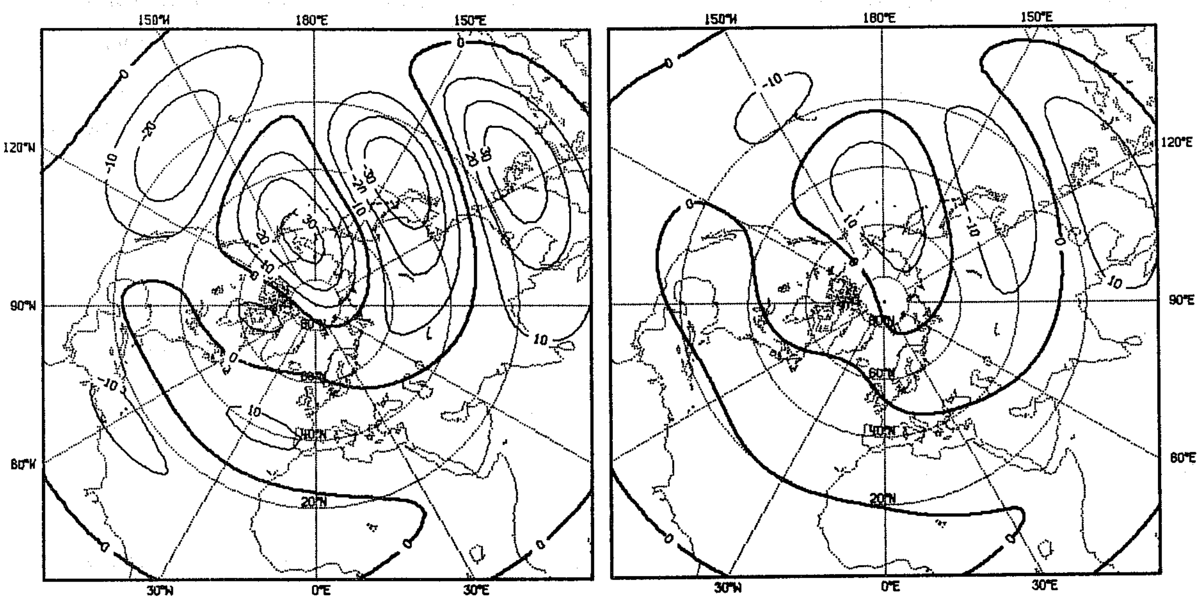
For these studies a spectral, nonlinear barotropic vorticity equation model originally developed at Reading University has been used. Initial conditions comprise either a zonal mean or a zonally-varying climatological basic flow, and in the latter case a vorticity forcing is included to keep the basic flow constant in time. An additional vorticity forcing is initiated over an isolated tropical region at t=0.

Results shown in Fig. 6 for a zonal-mean basic flow are in broad agreement with those of the steady, linear, three-dimensional model, pronounced wave trains being set up over the first 5 to 10 days, although a larger propagation across equatorial easterlies is found. This latter result is in agreement with similar calculations by Hoskins, Simmons and Andrews (1977) for time-dependent motion and mid-latitude sources.

Introduction of a zonally-varying basic flow gives rise to a marked sensitivity of the response to the longitude of maximum forcing (Fig. 7). In particular an especially large response is found when the forcing is located to the south of the strong climatological jet in the western Pacific. The nature of the response suggests that an isolated, very weakly dispersive, Rossby wave may exist in a region of decelerating basic flow. Although the wave amplitude varies significantly with the longitude of the forcing, in all four cases shown in Fig. 7 the largest response is found in the same region of the Pacific.

Nonlinearity can also play an interesting, and easily understood, role in this case. Figure 8 compares the linear and nonlinear response to cyclonic and anticyclonic vorticity forcing centred near 15 ^{o}N, 135 ^{o}E. The linear response is identical for the two forcings, apart from a change of sign, while nonlinearity results in a substantial weakening of the response in the case of cyclonic forcing, and a marginal strengthening for anticyclonic forcing. In the latter case, the large anticyclonic response in the North Eastern Pacific reinforces the climatological ridge, which is itself responsible for the anomalous response in the first place. A positive feedback thus occurs. Conversely, for cyclonic forcing the cyclonic response tends to reduce the climatological ridge, and thus damp itself.

15°N forcing **5°N forcing**



5°S forcing **15°S forcing**

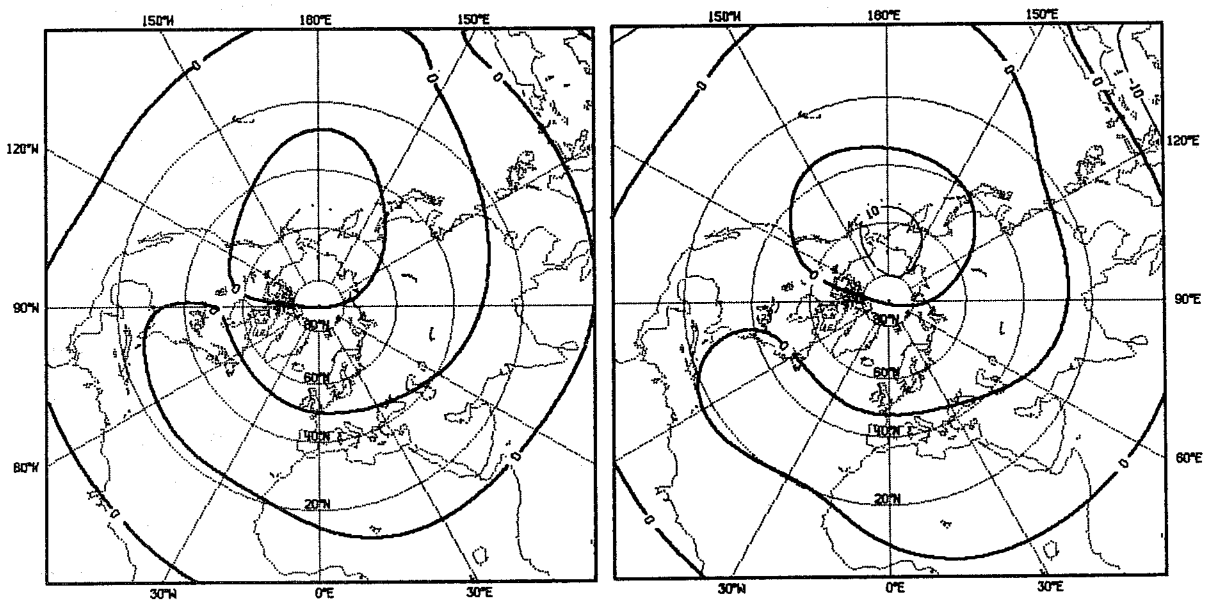


Fig. 6 The barotropic response of the stream function at day 10 to an isolated forcing centred at 135°E and 15°N (upper left), 5°N (upper right), 5°S (lower left) and 15°S (lower right). The January zonal-mean flow at 300 mb is used. The forcing corresponds to a maximum divergence of $2 \times 10^{-6} s^{-1}$. The stream function is non-dimensionalized by a factor $10^{-4} a^2 \Omega$, where a is the radius of the earth and Ω its angular rotation. The contour interval of 10 corresponds approximately to a height interval of 4 dam in polar latitudes.

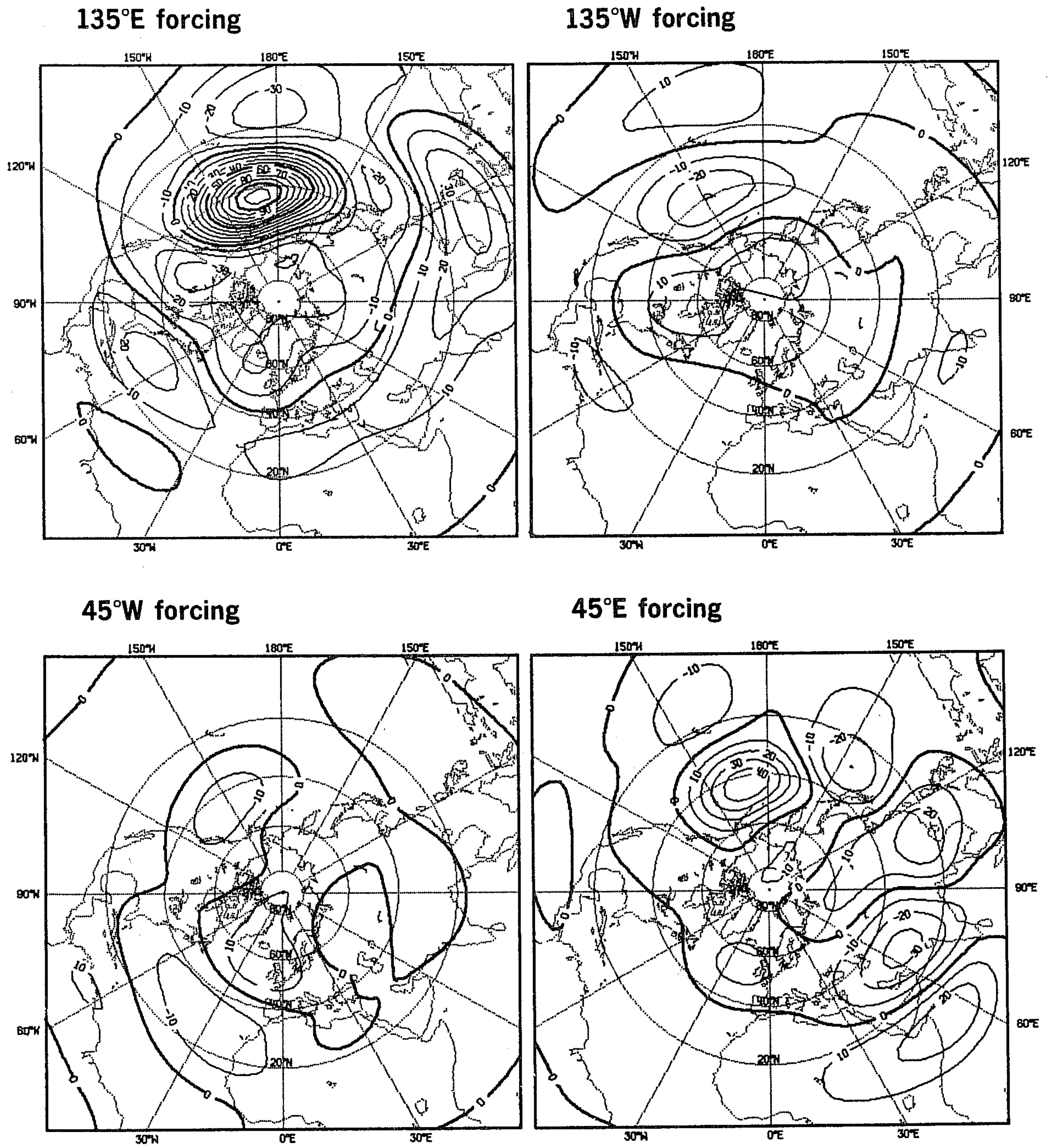


Fig. 7 The day 10 response for a basic flow derived from the zonally varying January climatology. The forcing is centred at 5°N and 135°E (upper left), 135°W (upper right), 45°W (lower left) and 45°E (lower right). Other details are as in Fig. 6.

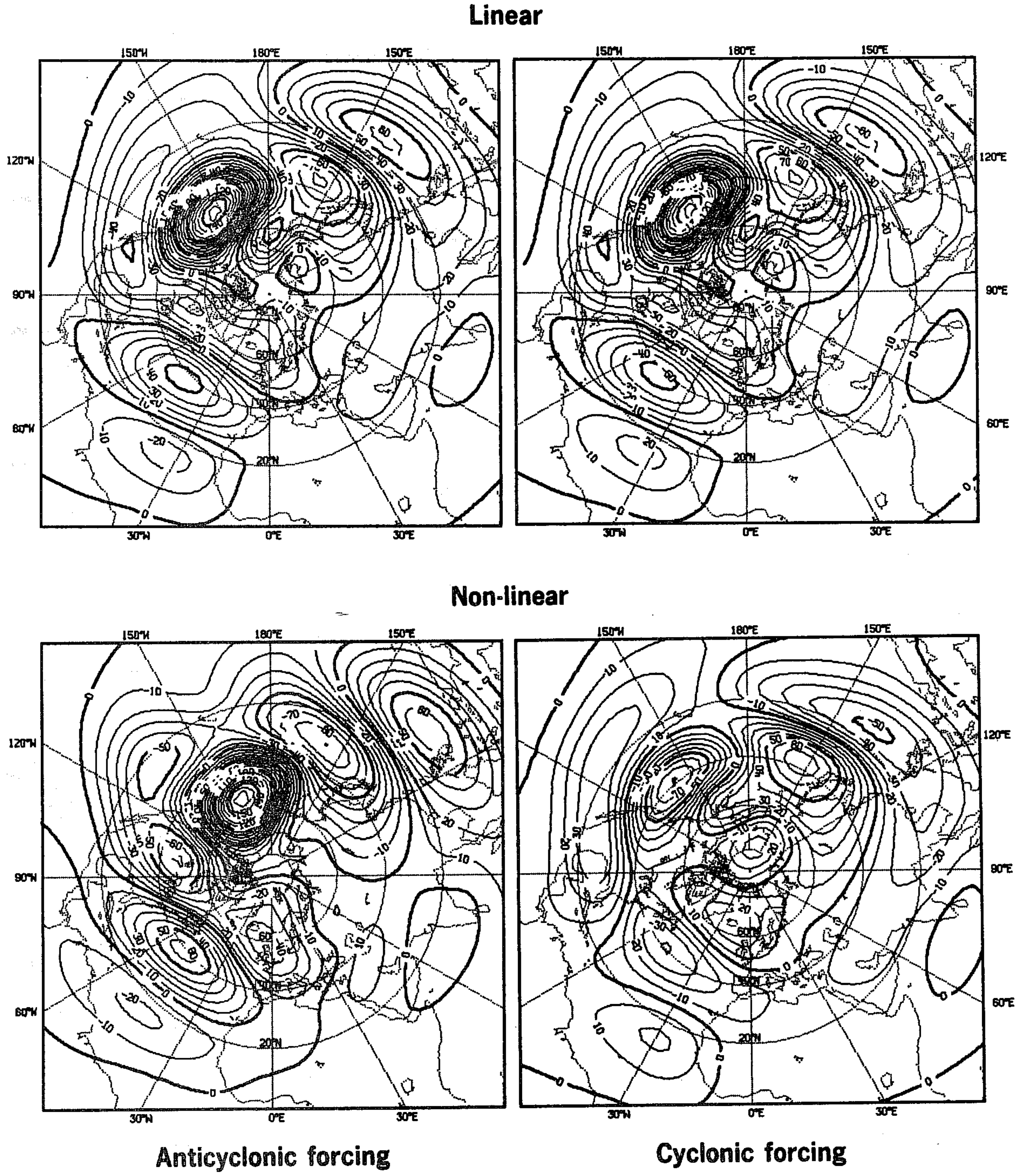


Fig. 8 The linear (upper) and non-linear (lower) day 10 response to anticyclonic (left) and cyclonic (right) vorticity forcing centred at 15°N and 135°E for the zonally varying January climatological flow. Other details are as in Fig. 6.

Another important effect of introducing a zonally-varying basic flow is a marked influence on the degree of cross-equatorial propagation. For the zonal-mean climatology, winds are easterly at the equator. The Northern Hemisphere response to a forcing at 15 $^{\circ}$S has been shown for day 10 in Fig. 6, and beyond this time its amplitude weakens to give the particularly small long-term response indicated by the steady-state calculations.

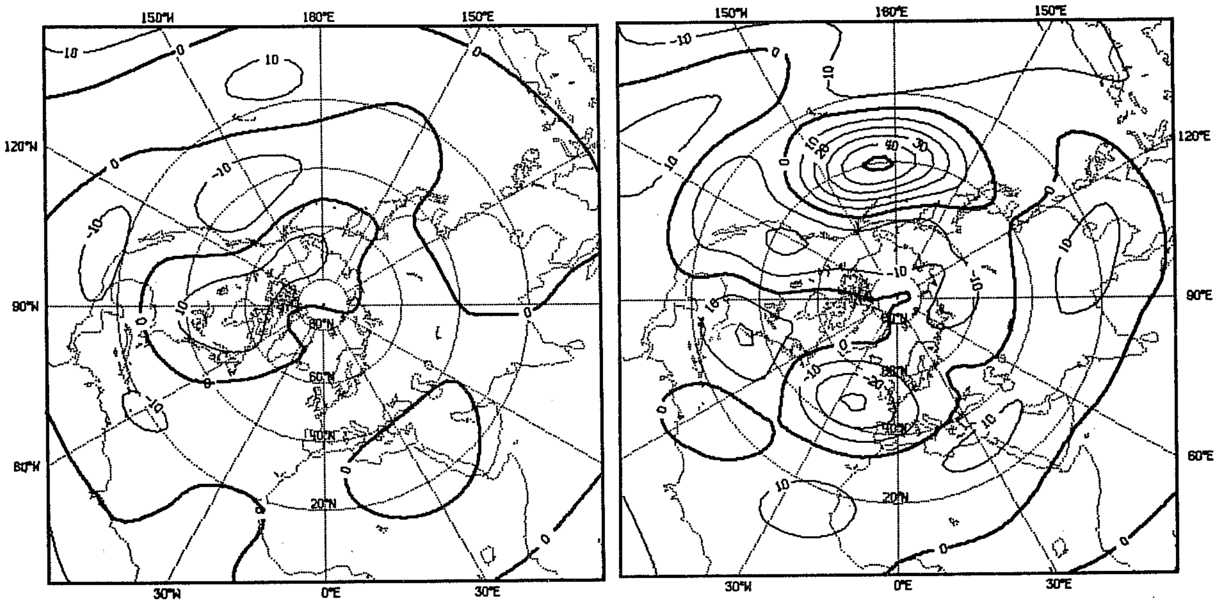


Fig. 9 **The Northern Hemisphere response at days 10 (left) and 30 (right) for a forcing centred at 15°S, 135°W for the zonally-varying basic flow.**

A quite different result is shown in Fig. 9 for the zonally-varying January flow and a forcing at 15 $^{\circ}$S, 135 $^{\circ}$W. At day 10 the maximum amplitude of the Northern Hemisphere response differs little from that in the case of the zonal-mean flow, but beyond this time the amplitude increases, rather than decays. Thus, by day 30 a substantial wave amplitude is found, particularly in the North Pacific region which we have already seen to be a favourable region for a large-amplitude response.

This result confirms a speculation by Webster (1981) that cross-equatorial propagation may occur through regions of westerly flow of limited longitudinal extent which appear in seasonal-means. Such westerly flow occurs over the East Pacific for the 300 mb level used for the calculations shown in Fig. 9.

5. A FORECAST EXPERIMENT

The forecast experiment involves comparison of a control forecast starting from the FGGE III(b) analysis for 12GMT, 11 June 1979 using the standard N48, 15-level ECMWF forecast model and a forecast in which the atmosphere in the tropics and subtropics is relaxed towards analyzed states. The impact of this tropical relaxation is summarized by the objective verification presented in Fig. 10. Although the standard area chosen for verification includes part of the forcing region, the contribution from the latter is small, and most of the differences shown in Fig. 10 arise due to changes in the forecast fields in middle and high latitudes.

The standard forecast for this case was characterized in the tropics by a poor forecast of the onset of the South West Monsoon. Despite this the impact of relaxing towards tropical analyses is shown both by Fig. 10 and by examination of synoptic maps to be small in the Northern Hemisphere. This is in broad agreement with the results from the simpler models, which show little extratropical response to steady tropical forcing for the Northern Hemisphere summer.

A more substantial impact is evident in the Southern (winter) Hemisphere. This is only partly shown in the objective scoring of the total field because of a poor forecast of the medium scales of motion in both cases. For the longer waves, however, Fig. 10 shows a substantial improvement to result from the tropical relaxation, which prevents the sudden fall in anomaly correlation which occurs beyond day 6 in the standard forecast. This is confirmed by a synoptic assessment, which shows a clear improvement as far south as the $60^{\circ} - 80^{\circ}$ latitude band at day 8.

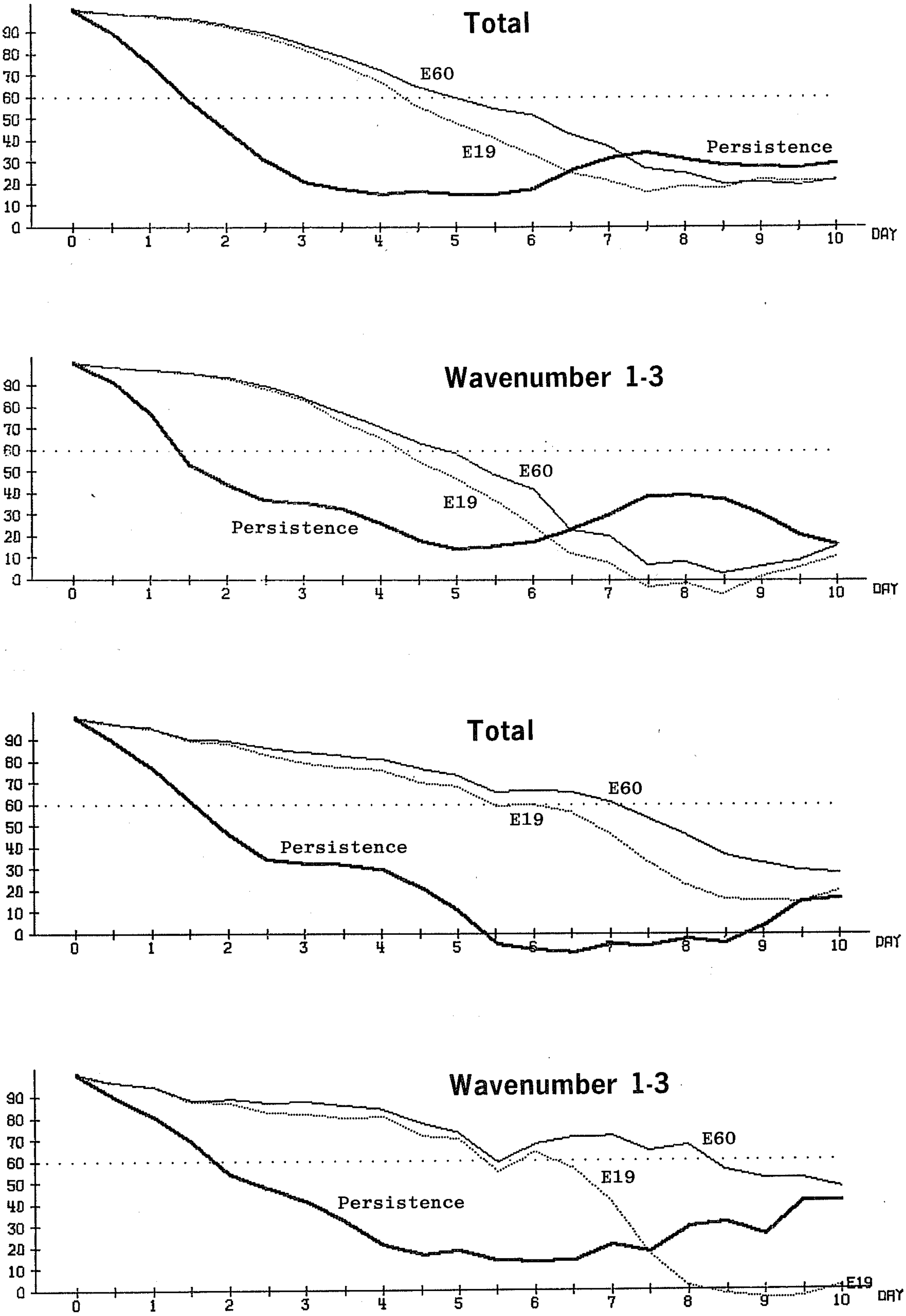


Fig. 10 Anomaly correlations of the height field averaged from 1000 to 200 mb and from 20 -82.5°N (upper) and 20 -82.5°S (lower). E19 denotes the standard experiment and E60 the experiment with tropical relaxation.

6. CONCLUDING REMARKS

It is difficult to assess quantitative aspects of the simple model results summarized here for a number of reasons, in particular because of the presence in reality of significant interactions between standing and transient waves and perhaps also because of the lack of any direct vorticity forcing or dissipation to accompany the imposed diabatic heating chosen to model the effect of an area of tropical convection. However, if results of studies such as this are combined with those of observational and general circulation model studies a coherent picture is obtained which shows a marked influence of the tropics on the standing wave pattern in the middle and high latitudes of at least the winter hemisphere. This is borne out to some extent by the single forecast experiment also reported here, but caution must of course be exercised in drawing conclusions from just one such experiment.

From the idealized model studies it is seen that it is important to simulate accurately the geographic distribution, the magnitude, and the temporal variability of the tropical convective heating in order to represent accurately its effect on stationary motion in middle latitudes. A particularly accurate vertical profile of heating does not appear to be as important in this respect. It is also important to represent the detailed structure of the mid-latitude jet in order to obtain the correct response to tropical forcing.

The barotropic solutions for a zonally-varying basic flow show that in favourable circumstances there can be a significant interaction between a pre-existing forced stationary wave and wave motion forced from an isolated tropical region. This raises the possibility that experiments with a general circulation model may substantially underestimate the effect of anomalous boundary conditions, for example sea surface temperature anomalies, if the model used underestimates the climatological standing wave pattern. A second result of these calculations is that substantial cross-equatorial propagation may occur in the presence of an equatorial region of westerly flow of limited longitudinal extent.

A possible deficiency of these barotropic calculations is that the zonally-varying basic flow is maintained by a constant forcing rather than by one which changes with the motion as the additional tropical forcing is introduced. Further study of the large response found in this case is evidently required.

Acknowledgements

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