Forced motion in the tropics

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Abstract

ECMWF analyses and forecasts are investigated in terms of planetary scale Rossby modes. Particularly poor forecasts are found for the second internal, gravest symmetric Rossby modes of zonal wavenumber one and two. They are quasi-stationary in the analysis, whereas they are travelling westward in the forecast. It is shown that the lack of an appropriate physical forcing leads to the erroneous propagation of these slow moving modes. The forcing required to keep the modes stationary is derived and compared to the forcing resulting from the parameterisation schemes. The sensitivity of the erroneous model forcing to different physical processes and to variations of the initial state is discussed.

1. INTRODUCTION

The correct treatment of the planetary scale waves is one of the most important problems in medium range weather forecasting. However, the ultralong waves are the "pride and sorrow of numerical weather prediction" (Sommerville,1980). From predictability theory, we should expect the best forecasts for the long waves (Lorenz,1969). Unfortunately, practical experience does not live up to these expectations (Baumhefner and Downey, 1978; Cullen et. al, 1981).

Recently, the barotropic parts of these errors have been investigated by Daley et. al. (1981). They showed, that one cause of model long-wave errors might be the erroneous excitation of large-scale, external Rossby modes by the use of unsuitable data in the tropics or by the imposition of tropical boundary conditions for non-global models.

The systematic errors of the ECMWF model are discussed by Arpe (1982). As the model is global and uses analysed data in the tropics, the arguments of Daley et al. (1981) do not apply directly. However, as Cats and Wergen (1982) showed, the ECMWF optimum interpolation scheme might not make proper use of the data. For example, it aliases an external Rossby mode on a number of external and internal Rossby and gravity modes. In particular, it cannot properly distinguish between a Rossby mode and a Kelvin mode. The relevance of these results for the model performance is still to be established.

In the present study, model normal modes are used to investigate the dependance of the planetary scale forecast errors on the parameterised physical forcing terms. Normal modes are particularly suited for this purpose, because they are truly global and they combine three-dimensional structures of mass- and wind-field. As they are the free solution of the linearised model equations, they can easily be interpreted physically.

2. PLANETARY SCALE FORECAST ERRORS

After the predicted and analysed fields have been projected on the Rossby modes of the model, the time evolution of the modes can best be shown on harmonic dials. (For details of the derivation of the normal modes of the ECMWF model, see Temperton and Williamson, 1981). Fig. 1 presents two such dials for the gravest symmetric, external Rossby modes for zonal wavenumber one (top) and two (bottom), corresponding to the operational forecast (heavy lines) from 1.7.81, 12Z and the verifying analyses (light lines). Numbers indicate days of forecast. Clockwise rotation indicates westward propagation. All modes are normalised in the same way, so that the amplitudes can be compared.

For the zonal wavenumber one, the forecast shows a westward travelling wave with a period of 5 days. This wave has also been identified in observations (Madden and Stokes, 1975). However, the analysis does not clearly show such a wave. For zonal wavenumber m=2, both analysis and forecast show a westward travelling wave (Fig.1, bottom). Generally, as Cats and Wergen (1982) indicated, analysed amplitudes of the largest scale normal modes should be interpreted with some reservation.

The picture changes dramatically, if we go to the second internal Rossby mode. Fig. 2 shows the dial for the zonal wavenumber one (top) and two (bottom) gravest symmetric Rossby modes. Big forecast differences are immediately evident. The forecast shows large amplitude, westward moving waves, whereas the analysis shows them to be quasi-stationary. In fact, some of the non-stationarity of the analysis is probably due to erroneous wave activity in the first guess. Interestingly enough, the forecast for these modes becomes almost stationary after seven days.

The vertical structure of the first three vertical modes is given in Fig. 3 for an isothermal (300K) atmosphere. The external mode does not change sign in the vertical. The second internal mode has a sign change near 50 mb and near 400 mb. It reaches its maximum amplitude around 150 mb.

The horizontal structure of the sum of the two modes plotted in Fig.2, at the initial time, is shown in Fig. 4 at the third model level (150 mb) for the variable

$$h = \phi + R\bar{T} \ln p_s \qquad (1)$$

R is the gas constant, $\bar{T}$ the basic state temperature (300K), p_s the surface pressure and ϕ the geopotential. This very large scale field bears already some resemblance to the climatologically dominant features in July (Newell et. al., 1975): warm air over the Tibetian plateau, cold air over the oceans, especially over the Atlantic. The meridionally anti-symmetric components are not discussed here, because they are better predicted by the model. The monthly mean observed wind field at 200 mb for July 1981 is given in Fig. 5. As Fig. 6 shows, the sum of these two components can already explain some of the main features, such as the anticyclonic circulation around the Tibetian high and over the southern Indian ocean together with the tropical easterly jet.

3. PHYSICAL FORCING

In order to understand the reason for the big forecast errors, it is helpful to project the model equations into Rossby mode space.

$$\frac{\partial c_R}{\partial x} = i\nu_r \; c_R + d_R + \; p_R \qquad (2)$$

Here, c_R is the amplitude of a particular Rossby mode, ν its associated free frequency, d_R the Rossby mode projection of all nonlinear dynamical tendencies and p_R the projection of the parameterised physical tendencies (radiation, diffusion, convection, phase changes of water vapour). If we require stationarity for a specific mode, Eq. (2) for these modes can be written

$$p_R = i\nu_R \, C_R - d_R \qquad (3)$$

It means, that the sum of the linear and nonlinear adiabatic tendencies on the right hand side must be compensated by the diabatic physical forcing terms on the left.

In the following, it will be assumed that the linear and nonlinear adiabatic tendencies are correctly computed by the model. In particular, the orographic forcing will be treated as "correct". It was, however, established, that the following conclusions are largely independent of the type of orography chosen.

Using Eq. (3), the "balancing" physical forcing that is necessary for stationarity can easily be computed for the large scale modes we have been discussing. It is shown in Fig.7. The variable contoured is R^{-1} dh/dt in K/day. In order to keep the structure in Fig. 4 stationary, we need upper tropospheric heating in the western Pacific and East-Asia. Over Africa we need upper tropospheric cooling and lower tropospheric heating. In terms of physical processes, one might think of convection over East-Asia. In the African region, the required pattern might be accomplished by radiative cooling in the upper troposphere. In lower levels, sensible heat fluxes might be important.

It is easy to understand, why this pattern is required. Fig. 8 shows the linear tendency caused by the waves in Fig. 4. Travelling westward, they would lead to a heating over Africa and a cooling over East-Asia. The physical tendencies then have to compensate this linear tendency and the (smaller) nonlinear adiabatic tendencies.

The actual physical forcing obtained from the present ECMWF parameterisation scheme is shown in Fig. 9. Compared to Fig. 7, it has a phase error of 90°. The amplitudes are too big by a factor of two. The dominant feature is the excessive upper-tropospheric heating over Africa. With this configuration, a westward propagation is inevitable. In order to keep the modes stationary, the physical forcing must be already correct in the early stages of a forecast.

The results obtained so far have been found for a number of cases, both during the FGGE period and during operational forecasting in 1981/82. Practically every forecast shows these planetary scale modes moving westward, whereas they are stationary in the analysis. The same systematic error shows also up in monthly mean forecasts.

4. SENSITIVITY STUDIES

The erroneous physical forcing can be due to errors in the intial fields (such as static stability, moisture distribution, divergence) and/or errors in the parameterisation schemes themselves. In order to test the sensitivity to different parameterisations, the physical forcing was re-computed with some processes switched off. Fig. 10 shows the physical forcing when radiation is switched off. There is hardly any difference to Fig.9, which suggests, that radiation does not directly contribute to this type of forecast error. In the next experiment, the moisture was set to zero (Fig.11). Now the pattern is closer to the required one. However, the cooling is not quite in the right place and the amplitude is too small. Furthermore, the heating over the western Pacific is much too small. On the whole, Fig.11 shows that the moist processes are the biggest contributor to the erroneous physical forcing. As convection forces not only Rossby waves, but also gravity waves, large forecast errors - both on a slow and a fast time scale- might be expected over Africa, where the present forcing is not correct. This is indeed shown by Heckley (1982).

In order to test the influence of changes to the initial conditions, the operational physical forcing was computed for different variations of the analysis. As adiabatic initialisation, which was still in use in July 1981, suppresses diabatically driven circulations, the physical forcing was calculated from the uninitialised analysis (Fig. 12) The amplitudes are slightly reduced but the phase is not correct when compared to the required "balancing" forcing (Fig. 7). In the next experiment, the physical forcing was computed for the diabatically initialised analysis (Fig. 13). As convection is no longer suppressed, the physical forcing is even more in error now. This shows a problem with diabatic initialisation schemes, which use model-generated diabatic tendencies.

In order to establish the relevance of these results, a forecast was run, in which the physical tendencies for the modes in question were forced to be equal to the balancing forcing necessary to satisfy Eq.3 at the initial time. Fig. 14 shows the 850 mb RMS vector wind errors for the tropics. The light line is for the experiment, the dotted line for the operational forecast. For the long waves, the 30% improvement in the rms error makes the experimental forecast slightly better than persistence (heavy) between day one and seven. The operational forecast is worse than persistence throughout the whole period. For the other waves, the scores are very similar.

5. CONCLUDING REMARKS

The importance of a correct initial specification of the physical tendencies for tropical forecasting has been demonstrated. Within a data assimilation scheme this leads to serious problems. Even if the first guess is in the required balance, its modification by the analysis will usually distort the balance. Therefore, something like "initialisation of the physics" is required. Furthermore, it must be assured that the correct forcing is maintained throughout the forecast.

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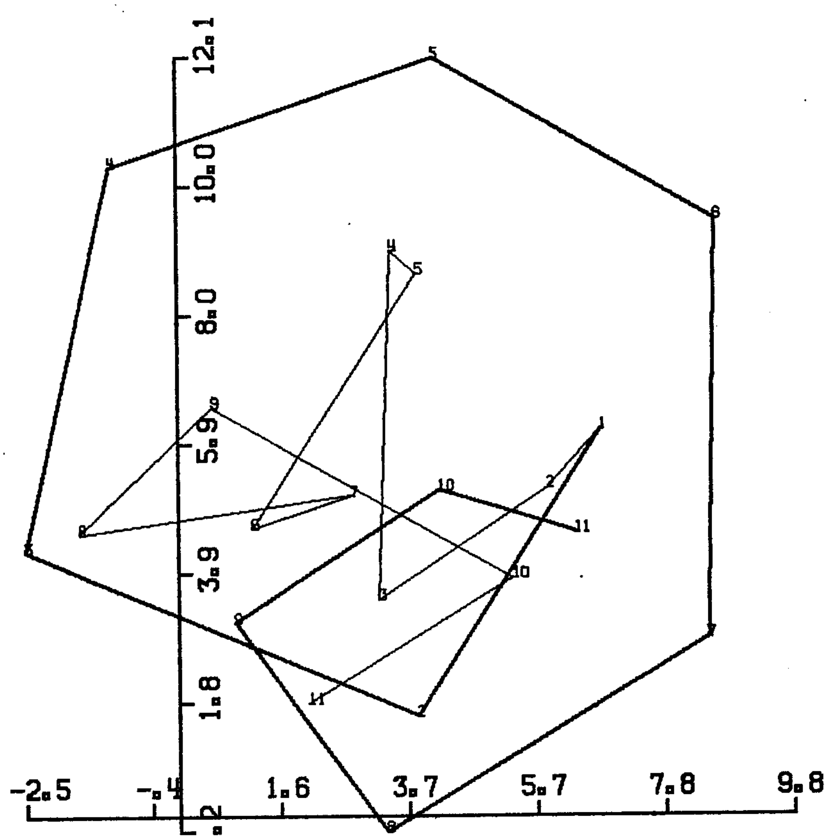
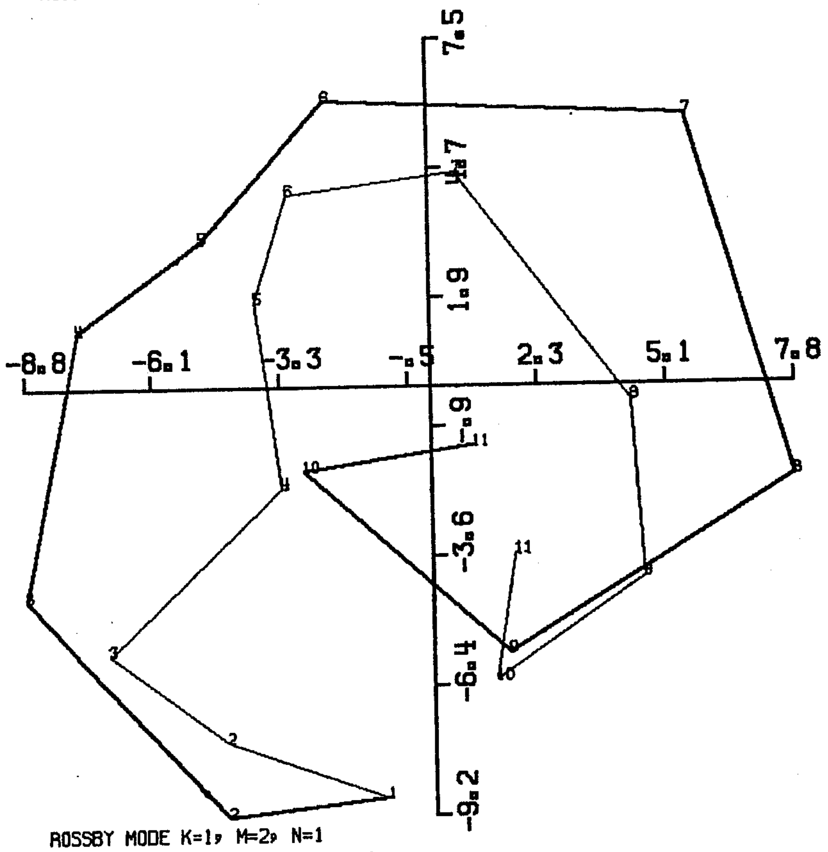


ROSSBY MODE K=1, M=1, N=1



ROSSBY MODE K=1, M=2, N=1

Fig. 1 Harmonic dial for the gravest symmetric, zonal wavenumber one (top) and two (bottom) external Rossby mode for forecast from 1.7.81, 12Z (heavy) and verifying analysis (light). Numbers indicate days of forecast. Clockwise rotation means westward propagation.

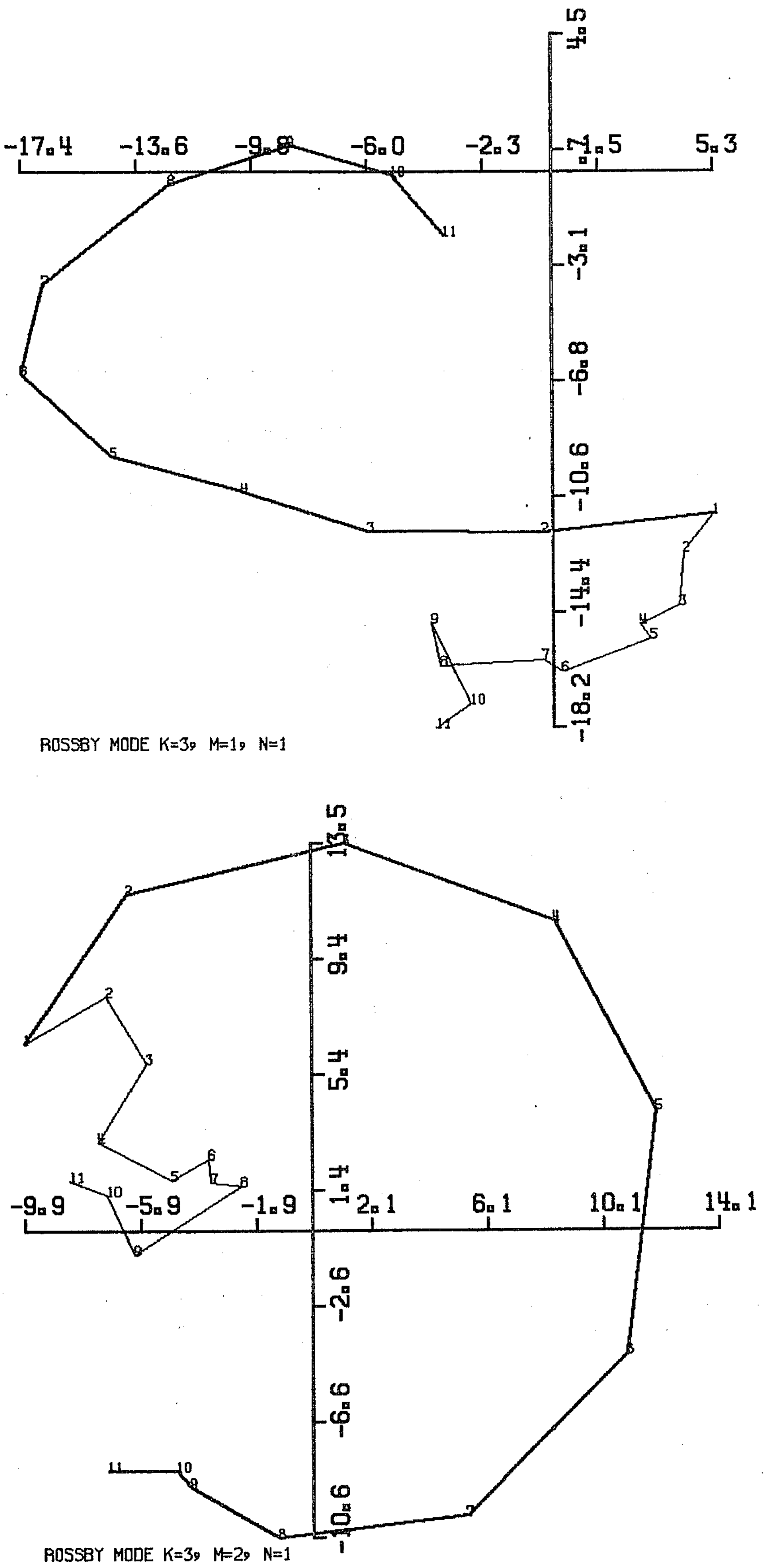


Fig. 2 As Fig. 1, but for second internal Rossby mode.

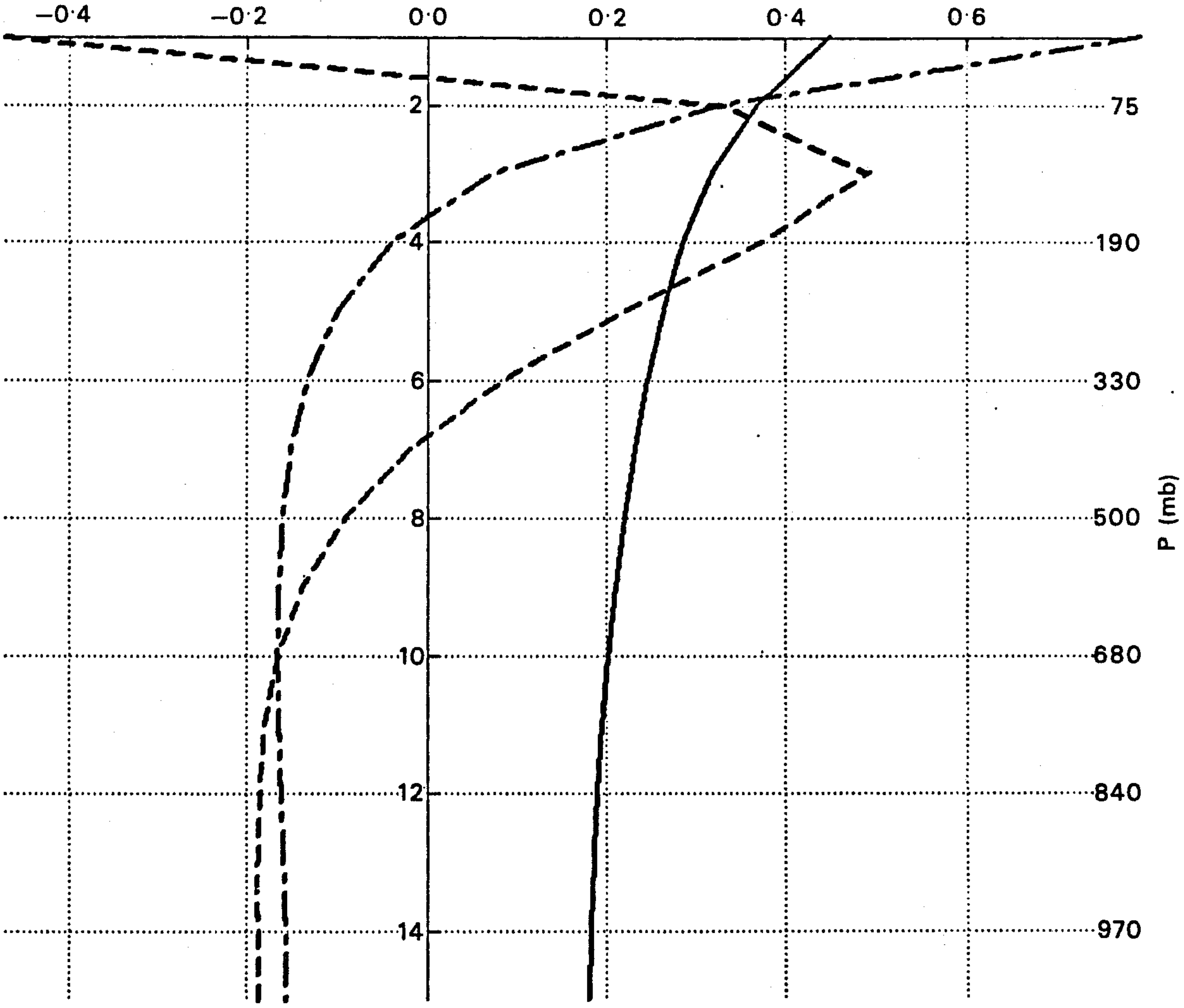


Fig. 3 First 3 vertical modes for isothermal (300 K) basic state. Rounded pressure values in mb are valid for p_s = 1000 mb.

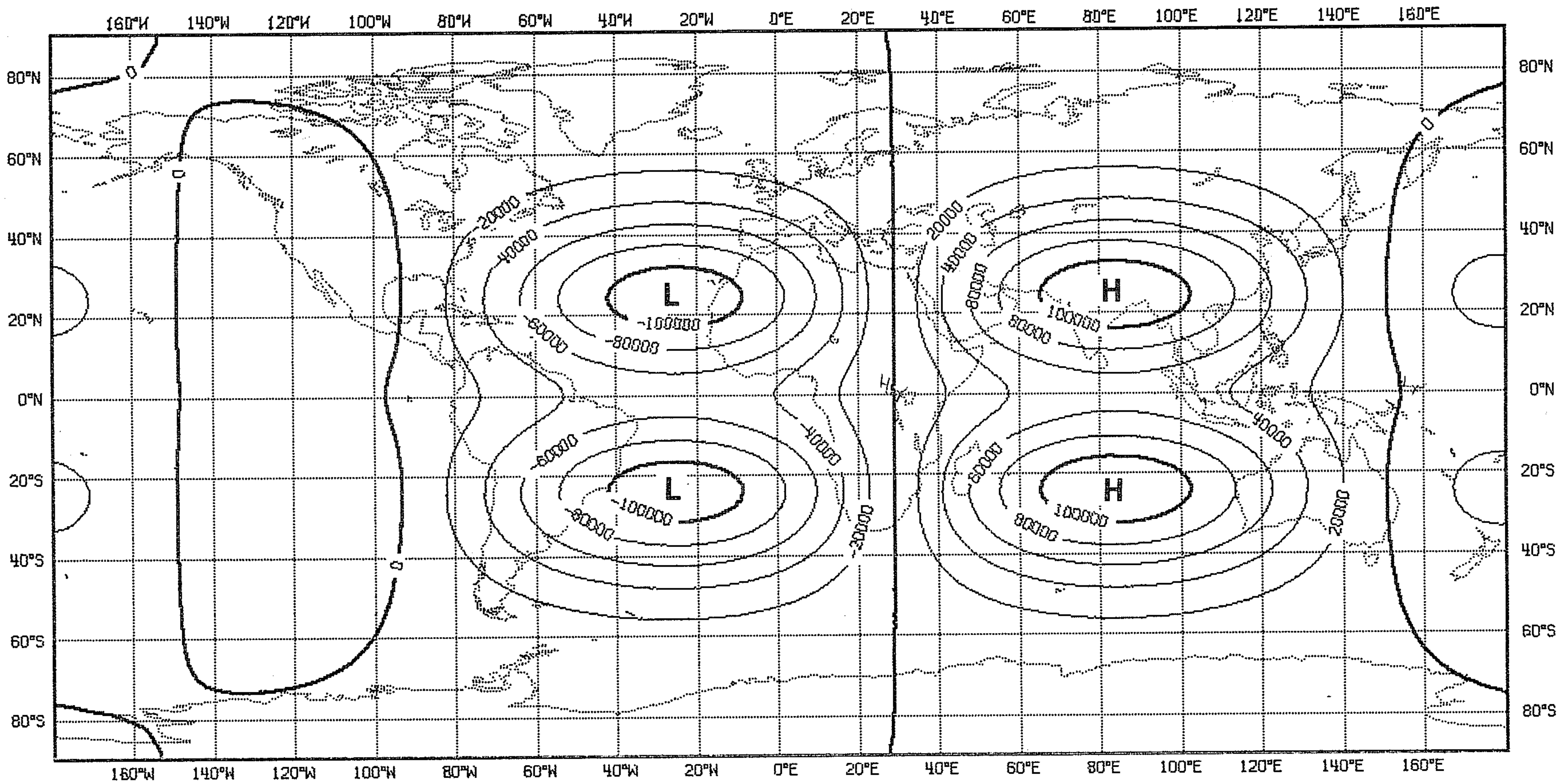


Fig. 4 Contribution of the second internal, gravest symmetric, zonal wavenumber one and two Rossby modes to mass-field analysis of 1.7.81, 12Z; valid at level 3 (≃150 mb).

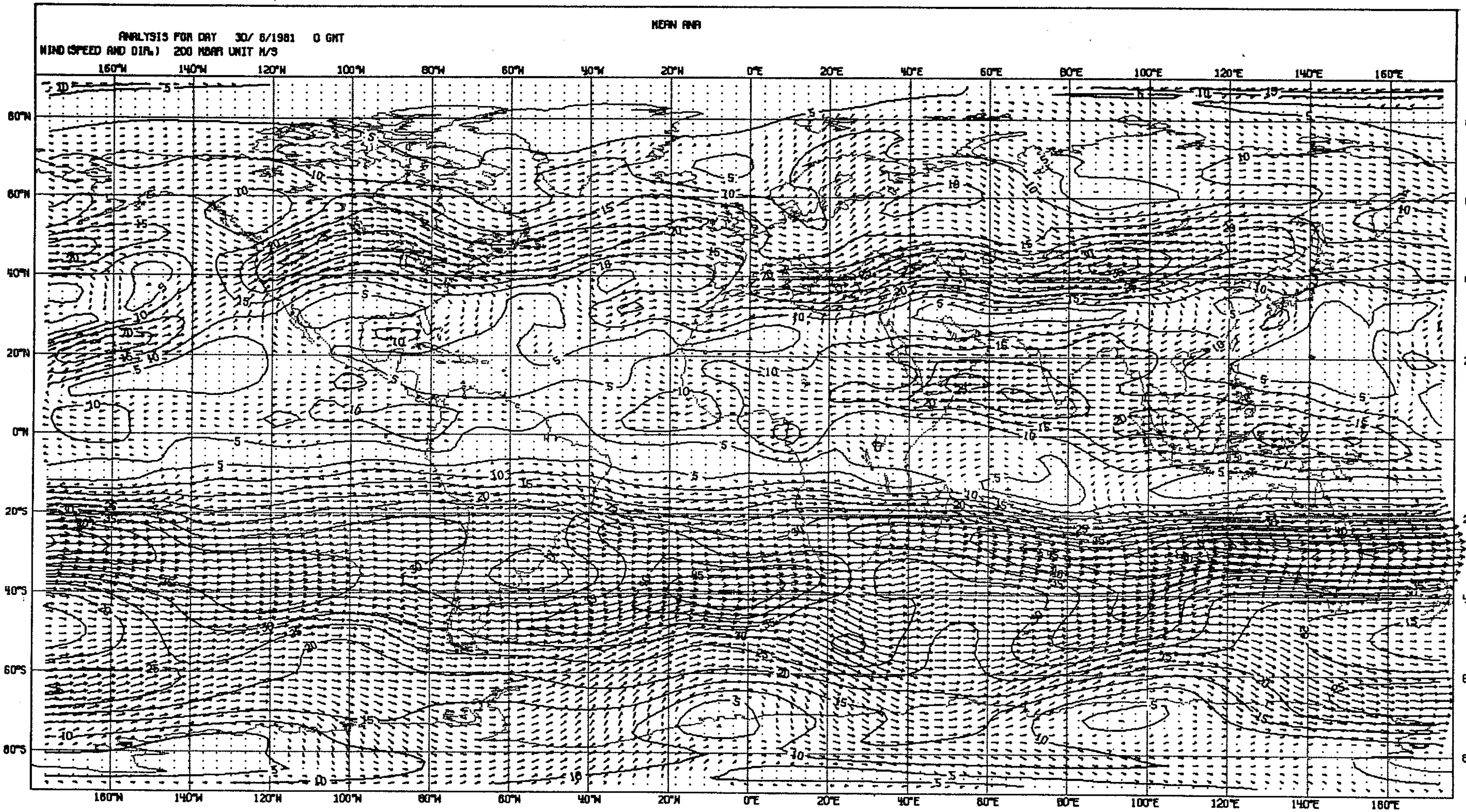


Fig. 5 Monthly mean wind field for July 1981 at 200 mb. Isotachs give wind speed in m/sec.

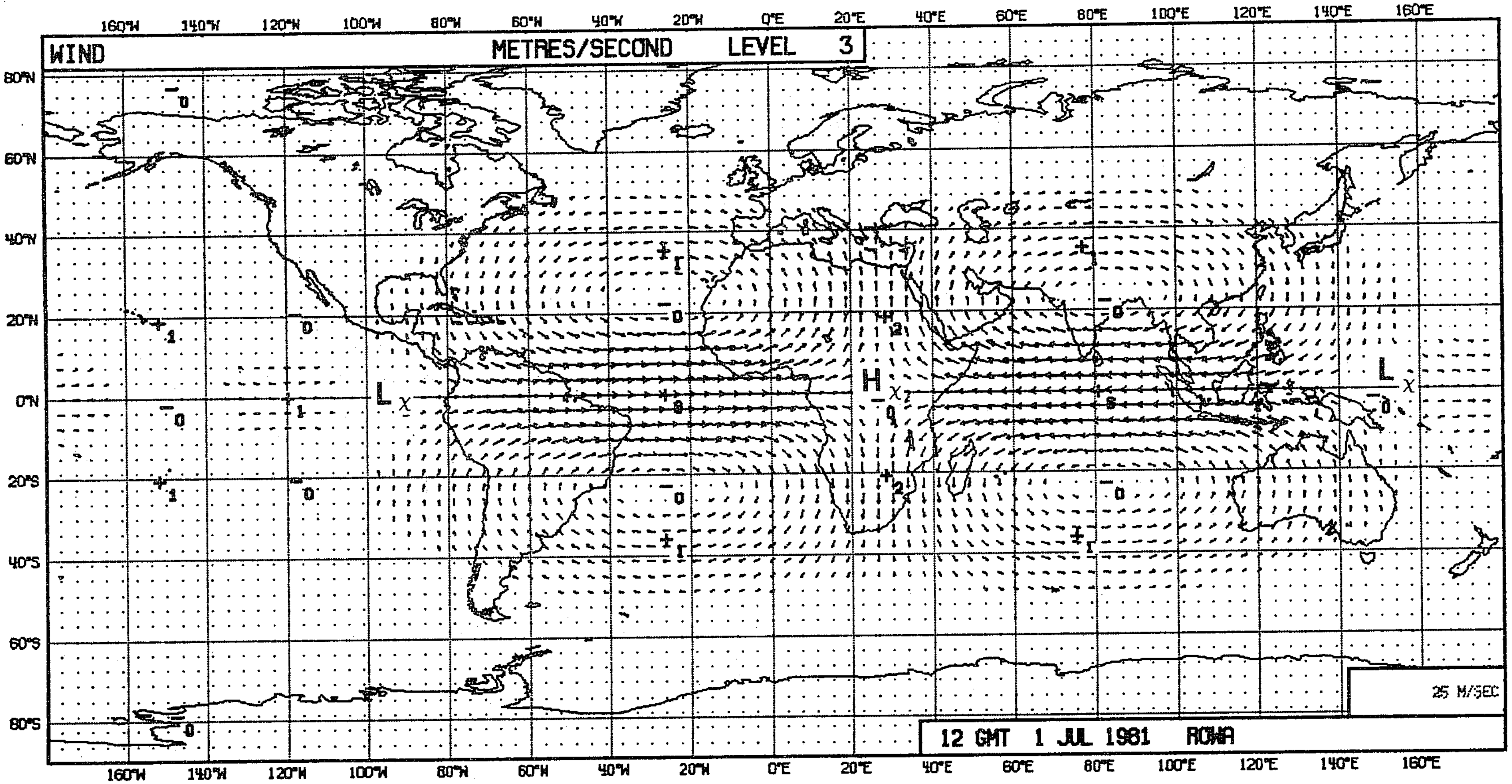


Fig. 6 Contribution of second internal, gravest symmetric, zonal wavenumber one and two Rossby modes to wind-field analysis of 1.7.81, 12Z; valid at level 3 ($\simeq$150 mb). Numbers give wind speed in m/sec. Centers of velocity potential are indicated by H_χ and L_χ.

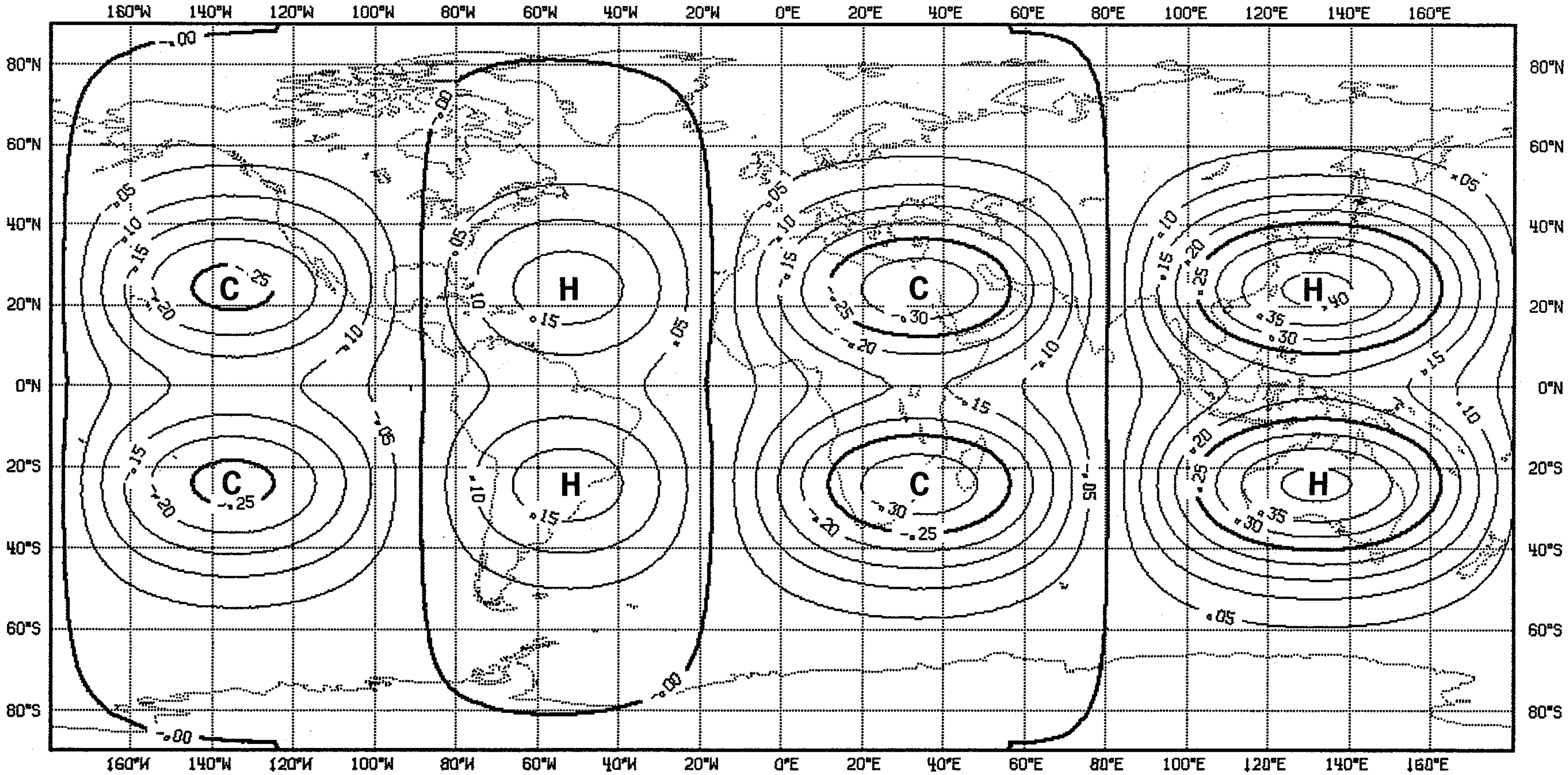


Fig. 7 Required "balancing" physical forcing in deg/day to keep the structures in Figs. 4 and 6 stationary. Valid at level 3.

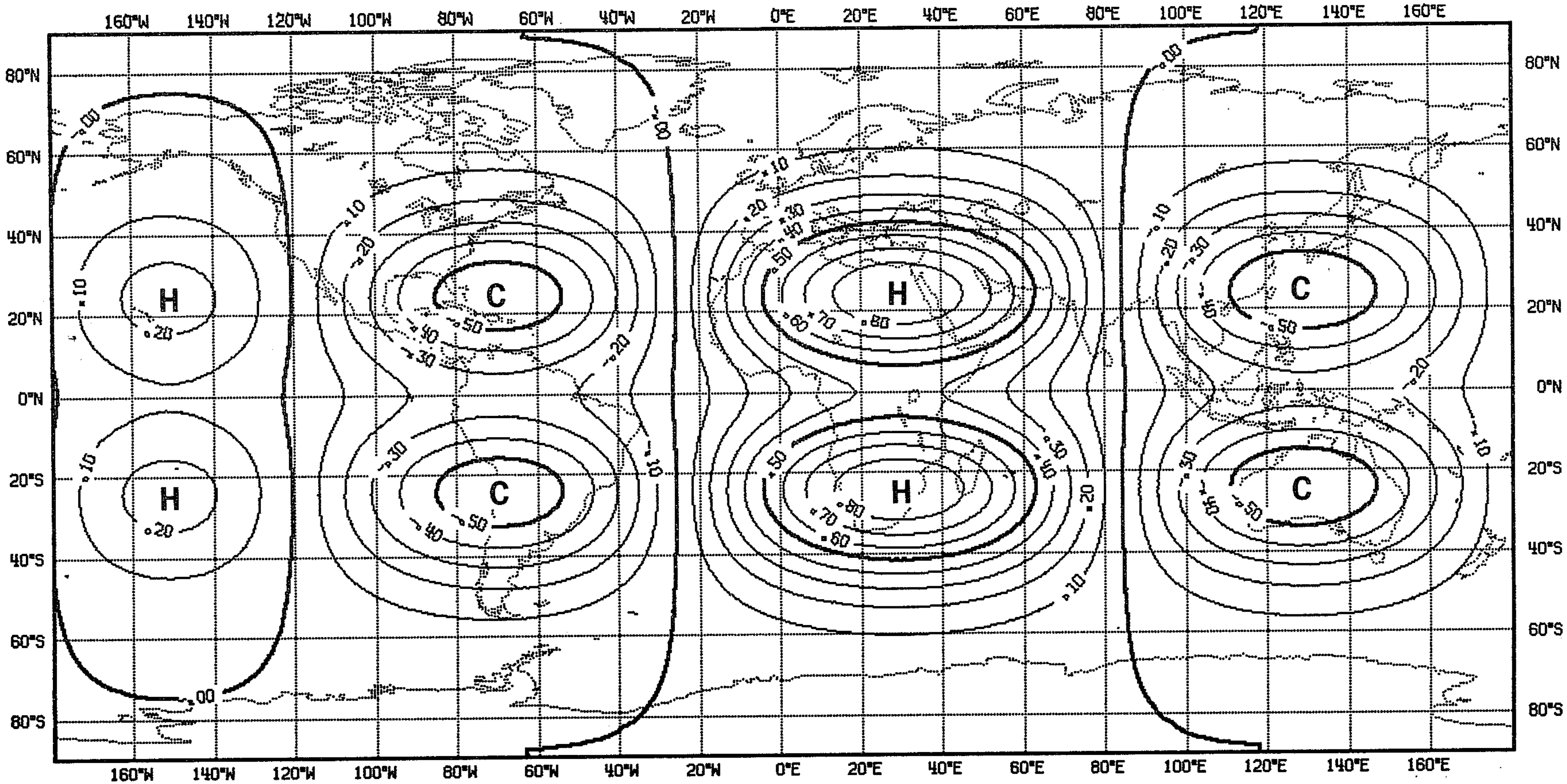


Fig. 8 Linear tendency in deg/day caused by the structure in Figs. 4 and 6. Valid at level 3.

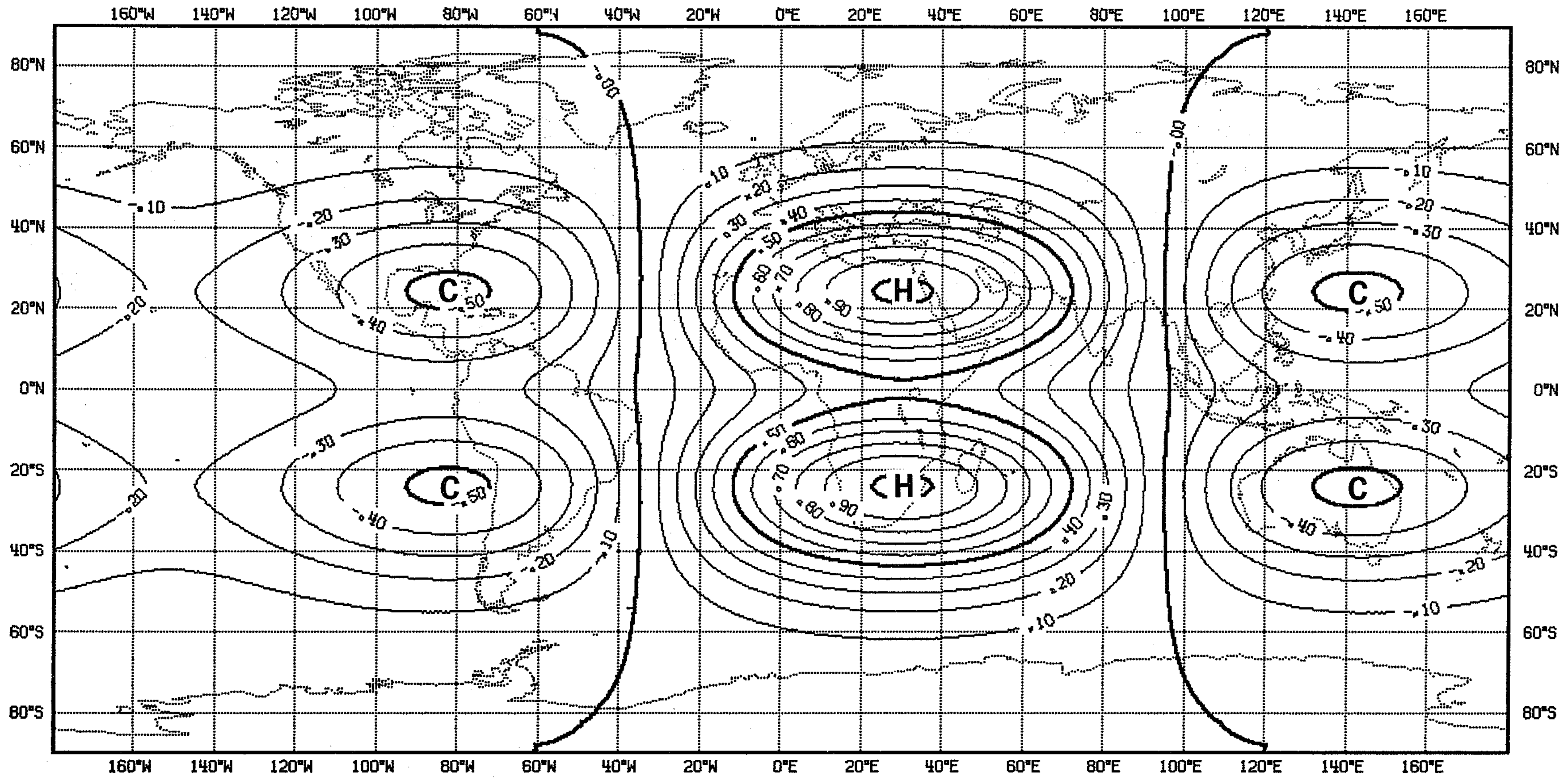


Fig. 9 Physical forcing in deg/day as computed with the current ECMWF parameterisation scheme from the adiabatically initialised analysis for the fields in Figs. 4 and 6. Valid at level 3 (≃150 mb).

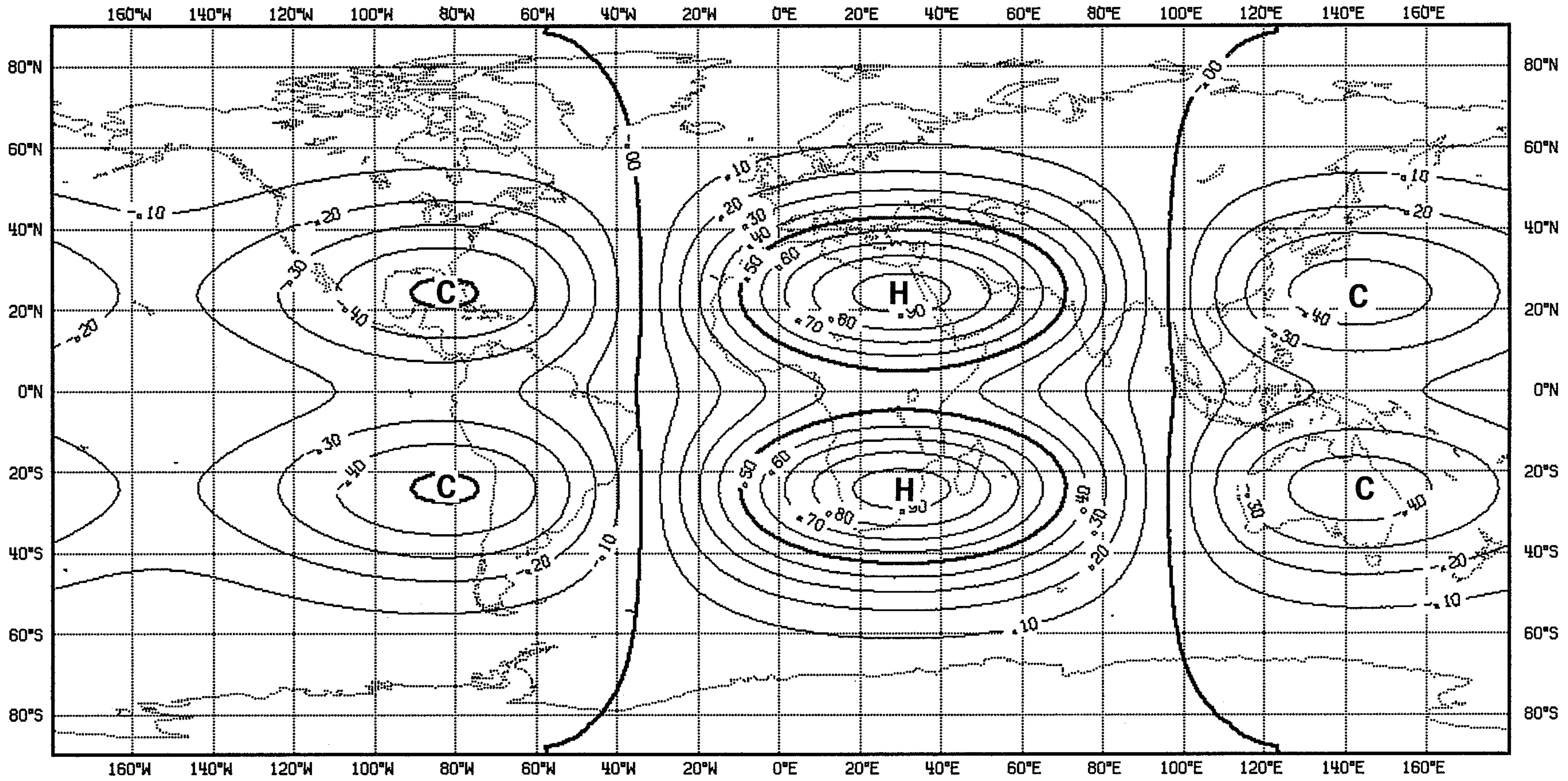


Fig. 10 Same as Fig. 9, but without radiation.

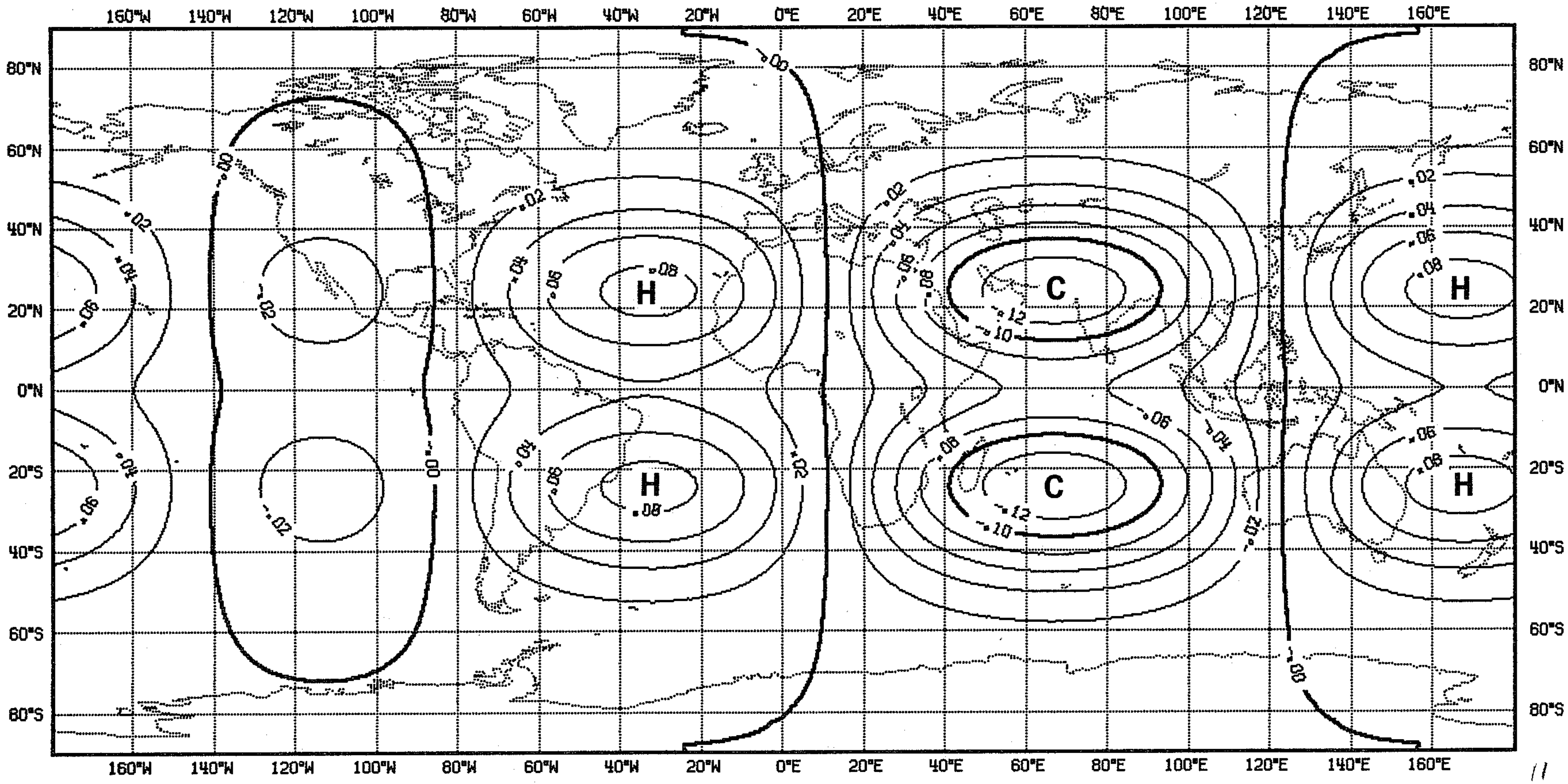


Fig. 11 Same as Fig. 9, but for dry atmosphere.

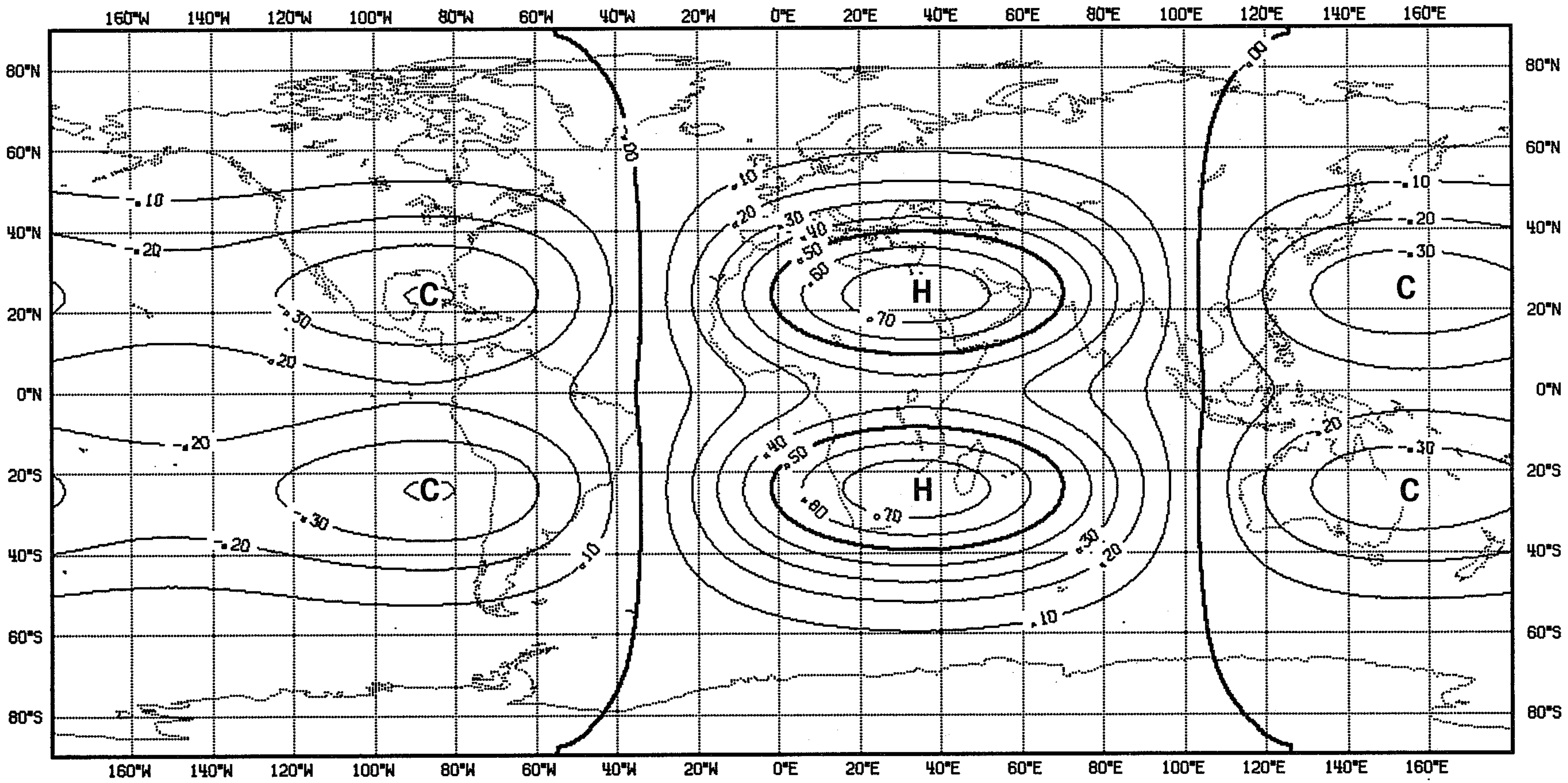


Fig. 12 Same as Fig. 9, but computed from the uninitialised analysis.

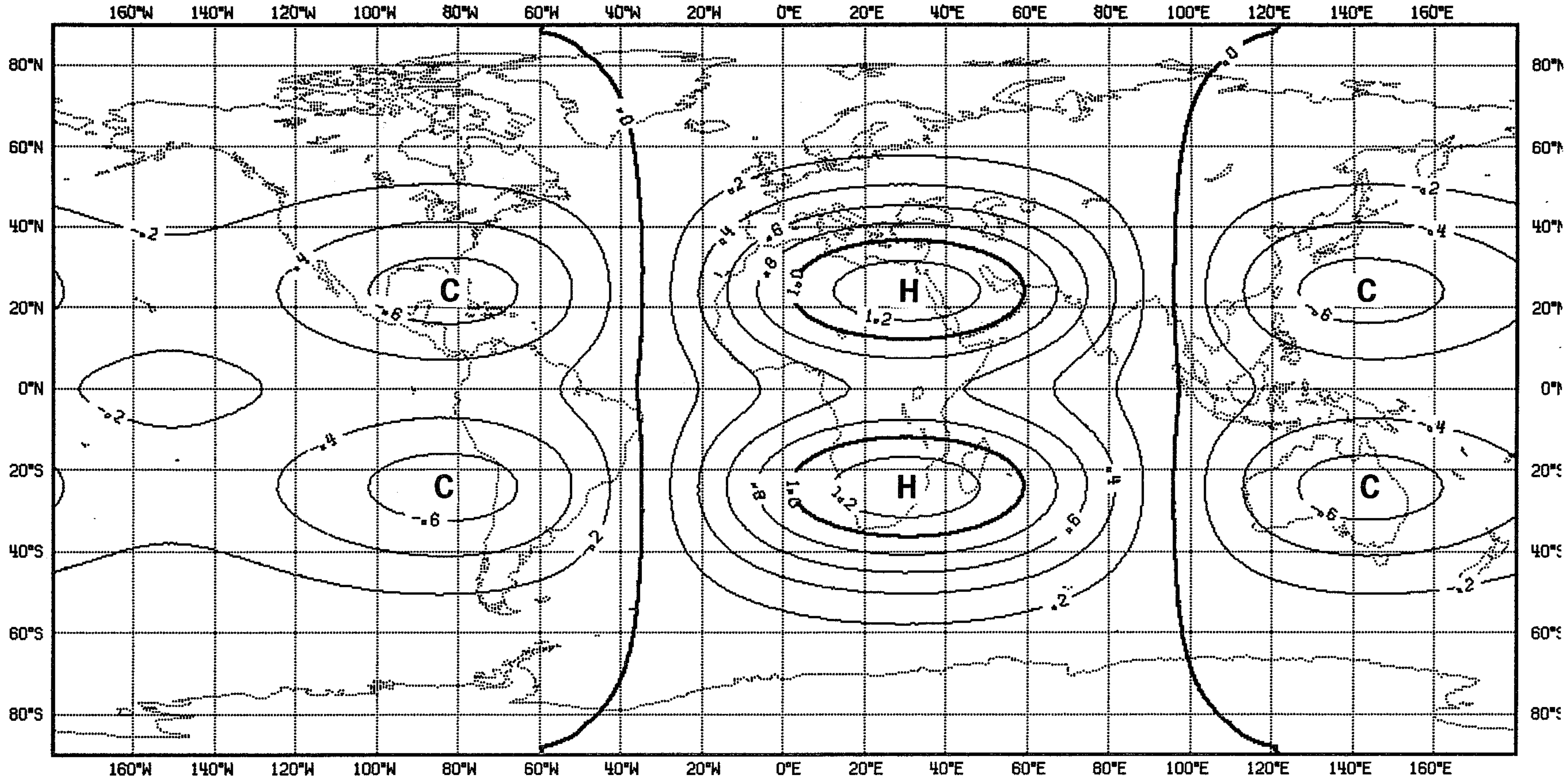


Fig. 13 Same as Fig. 9, but computed from the diabatically initialised analysis.

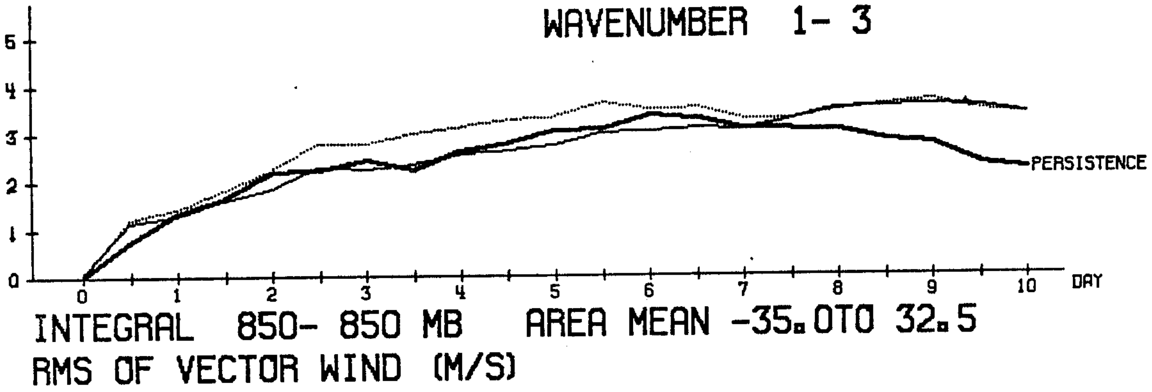


Fig. 14 RMS error of vector wind at 850 mb in the tropics for zonal wavenumber 1 - 3. Heavy line for persistence, dotted line for operational forecast and light line for forecast with corrected physical tendencies.