OROGRAPHIC MODIFICATION OF CYCLOGENESIS AND BLOCKING

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Summary: The interaction of atmospheric transients with localized orography can give rise to modifications of "average" circulations ("weather regimes"). In this lecture a simple example of orographic modification of transients and one of non-linear feed-back on average circulation are analyzed. A model is used capable of reproducing some of the basic mechanisms operating in the real atmosphere, but still simple enough to allow for controlled experimentation and physical interpretation.

1. INTRODUCTION

In this presentation I will concentrate on a very specific topic: the interaction between large scale (in particular "baroclinic") atmospheric transients and localized orography. The studies I will refer to have nothing to do with "multiple equilibria" theories in which topography of global scale excites a global resonance of atmospheric circulation. They should rather be considered an extension of the "theory of lee cyclogenesis" (see Speranza 1986b for a summary and critical discussion) to the regime of finite amplitude, nonlinear growth of orographically modified atmospheric transients.

The basic purpose of the studies discussed here is very simple and worth formulating explicitly from the start: if atmospheric transients are the physical manifestation of a turbulence, characterized by an attractor developed on the manifold of some instability, we have to understand what the modifications induced by the orography on the attractor are and compute them (perhaps as modifications induced on the unstable manifold).

Atmospheric transients are traditionally interpreted in terms of baroclinic conversion and we shall therefore concentrate on baroclinic instability. However, most of our considerations would apply to other types of transients as well.

In order to keep the presentation as clear as possible we shall limit mathematical complications to a minimum by adopting the classical two-layer, quasi-geostrophic model. However most of the conclusions here presented, including the relevant ones, are fairly general and could be tested with much more complex models: the use of a two-layer, quasi-geostrophic model should not be felt as a methodological limitation.

The basic equations are, in standard notation (see Pedlosky, 1964):

$$\partial_t q_{1,2} + J(\psi_{1,2}, q_{1,2}) = 0 \qquad (1)$$

$$q_1 = \nabla^2\psi_1 + F(\psi_2 - \psi_1) + \beta y$$

$$q_2 = \nabla^2\psi_2 + F(\psi_1 - \psi_2) + \beta y + \frac{h'}{Ro}$$

where shallow topography enters through the slope effect of h'.

2. BAROCLINIC INSTABILITY (CYCLOGENESIS) AND LOCALIZED OROGRAPHY

2.1 Baroclinic instability and cyclogenesis

Baroclinic instability is traditionally considered as the basic physical process operating in cyclogenesis. Although from time to time alternative interpretations of this or that type of cyclone growth appear in literature, I am personally convinced that the energetic interpretation of atmospheric cyclonic "eddies" in terms of baroclinic conversion is well posed. I have more problems (expressed, for example, in Speranza 1986a) with the calculations (including my own!) that appear quite often in literature. Essentially I do not believe that the ensemble properties of "baroclinic noise" can be represented in terms of the instability (linear or nonlinear) of one single flow pattern (stationary solution, time-average, etc.). It is with this "caveat" in mind that I pose, in this section, the problem of orographic modification of transients in terms of a linear stability analysis of a stationary (time - independent) zonal flow. We will concentrate on the modification induced by topography on a baroclinically converting basic flow.

2.2 The model

We assume topography as an infinite East-West ridge h'(y). Any stationary zonal flow is consistent with the boundary conditions imposed by such topography; for simplicity we consider $\bar{u}_1 = \text{const} = \bar{u}$, $\bar{u}_2 = 0$.

The set of equations resulting from a linearization of equations (1) under the above conditions is:

$$\partial_t\,[\nabla^2\psi_1' + F(\psi_2' - \psi_1')] - \partial_x\psi_1'\,(F\,\bar{u} - \beta) + \bar{u}\,\partial_x[\nabla^2\psi_1' + F(\psi_2' - \psi_1')]=0$$

$$\partial_t\,[\nabla^2\psi_2' + F(\psi_1' - \psi_2')] - \partial_x\psi_2'\,(F\,\bar{u} - \beta) + \partial_x\psi_2'\,\partial_y(h'/Ro) = 0 \qquad (2)$$

By introducing solutions of the form:

$$\psi'_{1,2} = \phi_{1,2}(y)\; e^{i(\kappa x - \omega t)} \qquad (3)$$

the linear set (2) can be transformed into the eigenvalue problem:

$$\begin{aligned}&\{-i\omega + \bar{u}\partial_x\}\;\{\nabla^2 - F\}\;\phi_1 + (\beta+F\bar{u})\;\partial_x\phi_1 + \{-i\omega + \bar{u}\partial_x\}\;F\phi_2 = 0\\ &\{-i\omega F\}\;\phi_1 - i\omega\;\{\nabla^2 - F\}\;\phi_2 + (\beta-F\bar{u})\;\partial_x\phi_2 + \partial_x\phi_2\;\partial_y(h'/Ro) = 0\end{aligned} \qquad (4)$$

The parametric dependence on the transversal coordinate y of this problem makes its solution not straightforward. We need to have recourse to either numerical or perturbation techniques. Outlined here is the perturbation approach since, in some of its aspects, it is physically instructive. If topography is small we can expand the eigenvalues and eigenfunctions of the problem (4) in terms of the small parameter ε (we pose $h'/Ro = \varepsilon h$):

$$\begin{aligned}\phi_{1,2} &= \phi_{1,2}^{(0)} + \varepsilon\;\phi_{1,2}^{(1)} + \ldots\ldots\ldots\\ &= \omega^{(0)} + \varepsilon\;\omega^{(1)} + \ldots\ldots\ldots\end{aligned} \qquad (5)$$

By substituting (5) into (4), reordering terms in powers of ε and assuming different orders of expansion to vanish independently, we obtain a sequence of linear problems.

The 0-th order expansion gives:

$$\begin{aligned}&\phi_{1,yy}^{(0)} - \kappa^2\;\phi_1^{(0)} + F(\phi_2^{(0)} - \phi_1^{(0)}) + \frac{\beta+F\bar{u}}{\bar{u}_1 - c^{(0)}}\;\phi_1^{(0)} = 0\\ &\phi_{2,yy}^{(0)} - \kappa^2\;\phi_2^{(0)} + F(\phi_1^{(0)} - \phi_2^{(0)}) + \frac{\beta-F\bar{u}}{-c^{(0)}}\;\phi_2^{(0)} = 0\end{aligned} \qquad (6)$$

which is the classical baroclinic instability problem (on a flat bottom boundary). The eigenvalue problem (6) has solutions of the form:

$$\phi_1^{(0)} = A \cos \lambda y \quad ; \quad A = \frac{F(\bar{u} - c^{(0)})}{(\lambda^2+\kappa^2)(\bar{u}-c^{(0)}) - \beta - Fc^{(0)}}$$

$$\phi_2^{(0)} = \cos \lambda y \tag{7}$$

$$c^{(0)} = \frac{\bar{u}}{2} - \frac{\beta(\kappa^2+\lambda^2+F)}{(\kappa^2+\lambda^2)(\kappa^2+\lambda^2+2F)} \pm \sqrt{\frac{\beta^2F^2}{(\kappa^2+\lambda^2)^2(\kappa^2+\lambda^2+2F)^2} - \frac{\bar{u}^2(2F-\kappa^2-\lambda^2)}{(\kappa^2+\lambda^2+2F)}}$$

which can be found in any textbook on the subject (see, for example, Pedlosky, 1979). We interpret this solution as a "primary" baroclinic wave (primary cyclone).

Topographic effects appear in the first order expansion:

$$\phi_{1yy}^{(1)} - \kappa^2\phi_1^{(1)} + F(\phi_2^{(1)} - \phi_1^{(1)}) + \frac{\beta+F\bar{u}}{\bar{u}-c^{(0)}}\,\phi_1^{(1)} = -\frac{c^{(1)}(\beta+F\bar{u})}{(\bar{u}-c^{(0)})^2}\,\phi_1^{(0)}$$

$$\phi_{2yy}^{(1)} - \kappa^2\phi_2^{(1)} + F(\phi_1^{(1)} - \phi_2^{(1)}) + \frac{\beta-F\bar{u}}{-c^{(0)}}\,\phi_2^{(1)} = \frac{h_y}{c^{(0)}}\,\phi_2^{(0)} - \frac{c^{(1)}}{c^{(0)2}}(\beta-F\bar{u})\phi_2^{(0)} \tag{8}$$

From the solvability condition of (8) we obtain the 1st order "topographic" correction to the eigenvalue:

$$c^{(1)} = \frac{1}{D}\int_{-L_y/2}^{+L_y/2} |\phi_2^{(0)}|^2\, h_y\, dy$$

$$D = -\left[\frac{(\beta+F\bar{u})c^{(0)}}{(\bar{u}-c^{(0)})^2}\int_{-L_y/2}^{+L_y/2} |\phi_1^{(0)}|^2\, dy + \frac{\beta-F\bar{u}}{c^{(0)}}\int_{-L_y/2}^{+L_y/2} |\phi_2^{(0)}|^2\, dy\right. \tag{9}$$

The first order correction vanishes if topography is symmetric in latitude. It is only at the second order that we obtain:

$$c^{(2)} = \frac{1}{D}\int_{-L_y/2}^{+L_y/2} \phi_2^{(0)*}\,\phi_2^{(1)}\, dy. \tag{10}$$

This represents the topographic effect we are interested in.

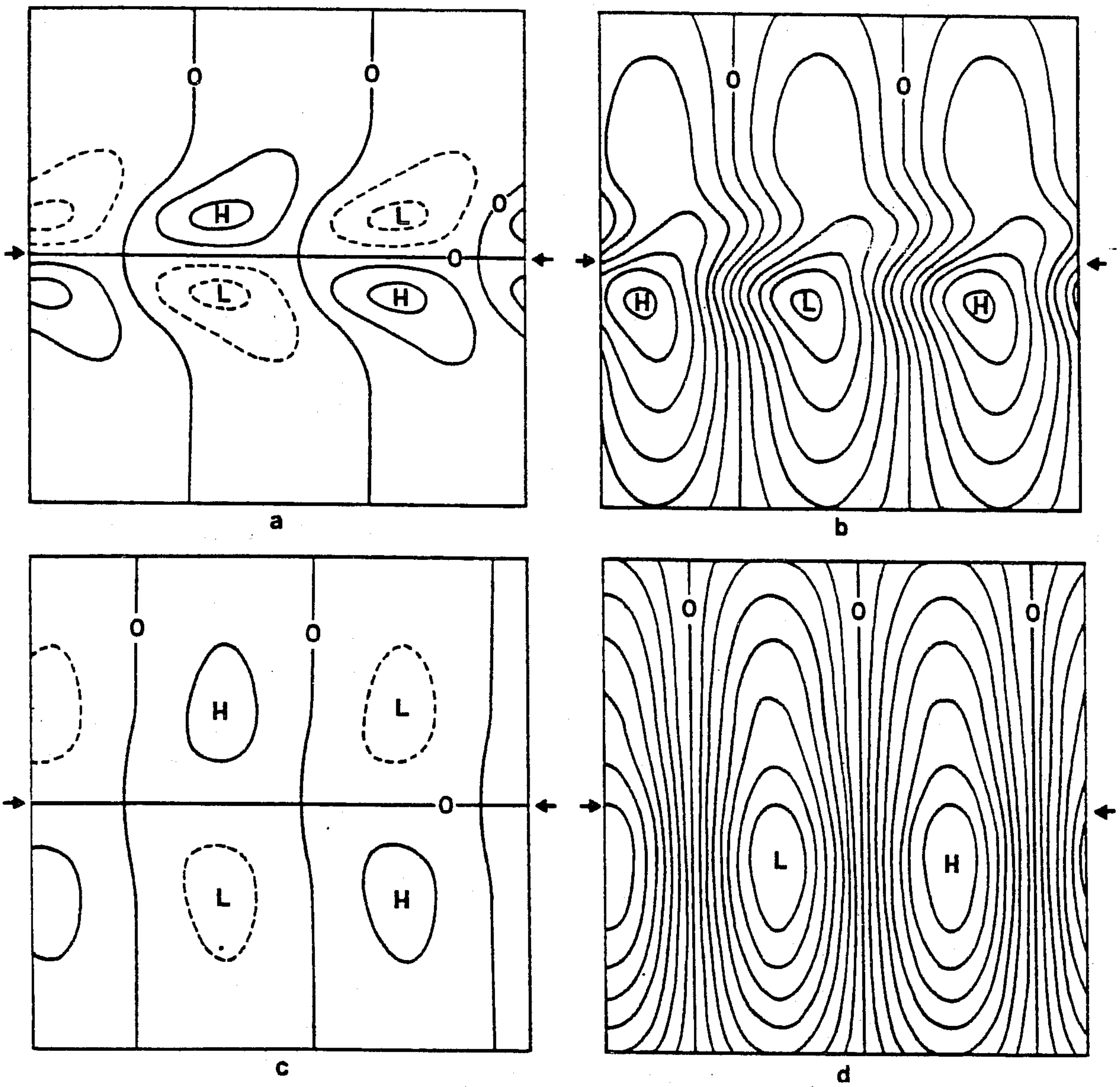

Fig. 1 Analytical solution for a baroclinic wave in the infinite β-plane two-layer model, with an east-west ridge. The arrows mark the position of the ridge crest. The parameter values are: $\bar{u} = 1.5$, $F = 2.0$, $\beta = 1.6$, $A = 1.0$, $k = 1.1$, $\lambda = 0.3$, $h_0 = 1.0$, $\bar{\lambda} = 3.0$, growth rate $\omega_1 = 0.29$. The contour interval is arbitrary. A portion of the domain of 8x8 non dimensional length units is shown.

(a) Streamfunction of orographic perturbation only, in the lower layer;

(b) Total streamfunction of modified baroclinic wave in the lower layer;

(c) and (d) as in (a) and (b), respectively, but in the upper layer, and with a double contouring interval. The basic zonal wind is not added. (From Speranza et al., 1985).

2.3 Topographically modified planetary waves

The field of topographic distortion can be shown to possess a "far-field" of large scale (of the order of the Rossby deformation radius) and an asymmetry as dictated by the h-term in equation (8) (see Speranza et al., 1985 for details). Fig. 1 shows the flow pattern obtained in the specific case of a ridge of cosine form in a limited latitudinal strip.

It can be noticed that the topographic correction, besides displaying the high-low symmetry required by observed phenomenology, extends to planetary scales in the horizontal and throughout the whole troposphere in the vertical. Note that the dipole structure is vertically coherent. This property is due to the particular symmetry of the problem here discussed: for non-symmetric mountains and/or basic flow the dipole axis rotates with increasing altitude.

We have learned from this simple example that the modifications induced by localized topography on a baroclinic wave are "global" in extent and more pronounced in the spatial structure of the wave than in the time behaviour: the growth-rate is only slightly decreased (the East-West mountain is a barrier for meridional flow and tends to inhibit baroclinic conversion).

3. THE BAROCLINIC JET IN THE PRESENCE OF OROGRAPHY

3.1 The baroclinic jet

It has been repeatedly proposed that the persistence of blocking is due to the statistical equilibration of transients with some large-scale, long-time pattern of the global circulation. I personally believe that this interpretation applies only to some specific blocking events which are not the ones that play a dominant role in the statistics of low-frequency variability.

I will try to explore here what type of physical mechanisms can lead localized orography to maintain a particular "equilibrium" through the modification of transients (of the type discussed in Section 2). For this purpose we need a model capable of reproducing the minimal statistics of baroclinic transients.

The simplest model representing the dynamics of interaction of baroclinic waves with a zonal flow and displaying earthlike statistics has a minimal vertical truncation (two layers or modes) of the equations of motion, with enough latitudinal resolution to guarantee adequate description of barotropic interaction between baroclinic waves and the zonal flow. I will describe here the quasi-geostrophic version in two layers, following the notation of Pedlosky (1979). Starting from the potential vorticity equations with Laplacian dissipation, written in terms of the barotropic, $\Phi=(\psi_1+\psi_2)/2$, and baroclinic, $\tau=(\psi_1-\psi_2)/2$, components of the streamfunction, and introducing a baroclinic forcing τ^*, we obtain:

$$\partial_t \nabla^2\Phi + J(\Phi, \nabla^2\Phi+\beta y) + J(\tau, \nabla^2\tau) = - \nu_E/2\ \nabla^2(\Phi - \tau) \tag{11}$$

$$\partial_t(\nabla^2\tau - 2F\tau) + J(\Phi, \nabla^2\Phi+\beta y) + J(\tau, \nabla^2\tau) = \nu_E/2\ \nabla^2(\Phi-\tau) - \nu_S\nabla^2\tau + 2F(\tau - \tau^*). \tag{12}$$

We separate now the symmetric and the asymmetric components:

$$\Phi(x,y,t) = - \int U(y,t)\, dy + \Phi'(x,y,t) \tag{13}$$

$$\tau(x,y,t) = - \int m(y,t)\, dy + \tau'(x,y,t) \tag{14}$$

and introduce the separated form:

$$\Phi'(x,y,t) = \sum_{n=1}^{+\infty} (A_n(y,t)\ g_n(x) + (*)) \tag{15}$$

$$\tau'(x,y,t) = \sum_{n=1}^{+\infty} (B_n(y,t)\ g_n(x) + (*)). \tag{16}$$

The main purpose of the assumptions (15-16) is to allow a simple representation of nonlinear wave-wave interactions: in fact, by inserting (15-16) into (11-12) and projecting onto the functions $g_n(x)$, equations in which nonlinearity is lumped into scalar products of g_n-functions can be obtained. Here, however, we shall concentrate on the wave-mean flow interactions. Consequently we assume:

$$g_1(x) = \exp(ikx)\ , \qquad g_n(x) = 0 \text{ for } n\neq 1 \tag{17}$$

which reduces (dropping superfluous indices) the equations of motion to:

$$\partial_t U + \nu_E/2\ (U - m) + 2k\ \mathrm{Im}(AA^* + BB^*) = 0 \tag{18}$$

$$\partial_t(m_{yy} - 2Fm) + \nu_s m_{yy} - \nu_E/2(U - m)_{yy} - 2F\nu_H(m - m^*) + \qquad (19)$$

$$+ 4kF\ \mathrm{Im}(A^*B)_{yy} + 2k\ \mathrm{Im}(AB^* + BA^*)_{yyy} = 0$$

$$\partial_t(A_{yy} - k^2A) + (\nu_E/2 + ikU)\ A_{yy} +$$

$$- [ik^3U + ikU_{yy} - ik\beta + \nu_E k^2/2]A +$$

$$- (ikm_{yy} + ik^3m - \nu_E k^2/2)B + (ikm - \nu_E/2)B_{yy} = 0 \qquad (20)$$

$$\partial_t\ [B_{yy} - (k^2 - 2F)B] + (\nu_E/2 + \nu_s + ikU)B_{yy} +$$

$$- [ik^3U + ikU_{yy} - ik\beta + \nu_E k^2/2 + k^2\nu_s + 2F\nu_H + 2ikFU]B +$$

$$- (ikm_{yy} + ik^3m - \nu_E k^2/2 - 2ikFm)A + (ikm - \nu_E/2)A_{yy} = 0 \qquad (21)$$

where any trace of wave-wave interaction has disappeared, except for the momentum and heat fluxes in the zonal flow equations. Since A and B are complex, (18-21) constitute a set of six field equations in latitude y and time t. Notice that when U and m are fixed, as in some cases of marginally unstable flow which we consider later, the wave amplitude vector (A,B) can be written explicitly in terms of zonal flow (U,m) as exp(Tt), where T is the matrix of the evolution operator in (20,21). In general though, the evolution operators of different instants T(t), T(t') do not commute and the generalized exponential solution cannot be written.

3.2 The statistical properties

Experience shows that the system (18-21) displays realistic statistical properties and these are conveniently modelled by means of a spectral representation in terms of a few tens of modes. The results shown here are relative to an integration with a leap-frog time-scheme (time-step ~1/10 day) and a pseudospectral representation of fields in terms of 32 latitudinal components. The integration is carried out for 10 years (~ 350.000 steps corresponding to about 1 hour of CRAY1).

The values of dissipation coefficients are respectively ν_E=0.45 (decay-time ~2.5 days in dimensional form) and $\nu_s=\nu_H$=.1157 (decay-time ~10 days in dimensional form). The external forcing, operating only on the gravest latitudinal mode, is m*=1.41. This corresponds to a thermal forcing ν_E=9. The zonal wavenumber is k=1.3 (~4800 km). The energy cycle is correctly closed and very realistic.

Fig. 2 displays the scatter of different components of states sequentially occupied by the system in time and Fig. 3 the relative probability densities. Fig. 4 shows the time average of the zonal flow; although characterized by a high degree of variability from year to year, the average is quite stable after ten years. The average of wave amplitude is obviously zero. Power spectra are shown in Fig. 5. It should be kept in mind that our dissipation is not scale-selective and that, therefore, we are not dealing with an inertial range: the -3 spectrum is not that of two-dimensional turbulence theory! The time spectra, shown in Fig. 6, confirm the "turbulent" nature of the system. Combined wavenumber-frequency spectra reveal the dominance of the lowest harmonics (Fig. 7). These statistical properties are in reasonable agreement with those of the real atmosphere. For comparison a typical histogram of short baroclinic waves is shown in Fig. 8 (see also Fig. 3).

3.3 Insertion of topography

The above described model of a baroclinic jet is particularly useful for studying orographic modification of transients along the lines discussed in Section 2. By inserting into eqs (18-21) terms of the form h_y we can represent the action of zonal topography h(y). This type of orography cannot change the time-mean, zonal flow directly: such a change can only take place through modification of transients of the type discussed in Section 2.

In fact, baroclinic waves like the one shown in Fig. 1 (*) display fluxes of momentum and heat which tend to modify the latitudinal structure of the jet. This effect is quite well displayed by the results of numerical experiments with the model including topography. 10 year runs have been performed under conditions identical to those discussed in Section 2, except for the presence of the East-West, infinite ridge. The statistics of transients (not shown here) does not seem to be suggestive of any major change. However, the distortions of the unstable "eddies" induced by topography seem to produce noticeable changes in the time-mean flow. Fig. 9 shows the new shape of the jet, to be compared with Fig. 4: the jet is displaced in latitude and one of the secondary jets if considerably attenuated, while the other is strengthened with respect to the case without topography.

(*) Although, I insist, linear stability analysis of Hadley circulations does not provide an adequate theory of atmospheric transients!

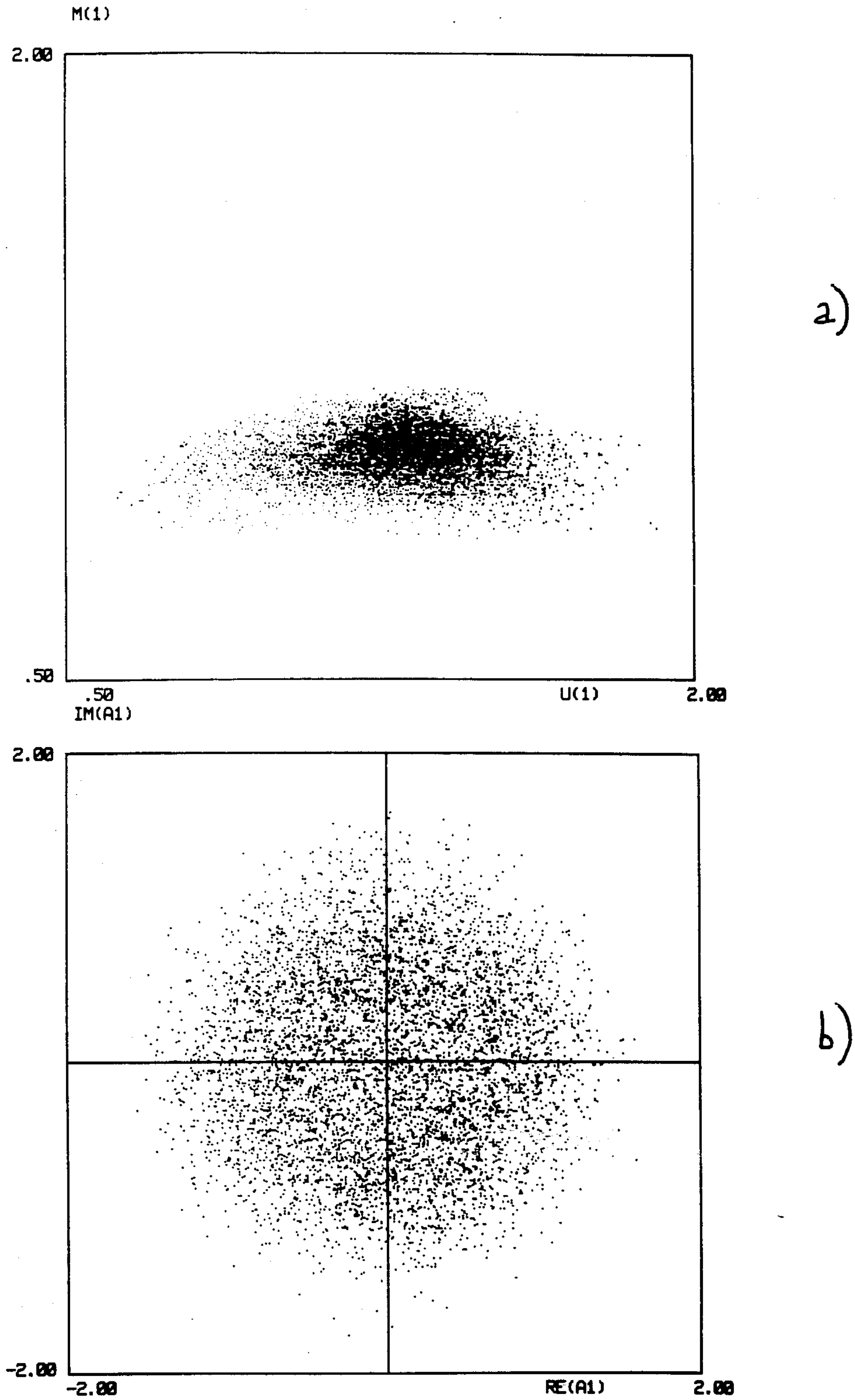

Fig. 2 (a) Scatter diagram of the first meridional component of zonal wind shear (m_1) versus the first component of zonal wind (U_1). Units are dimensionless (one unit corresponds to 10 m/sec). The total time of integration is about 10 years.

(b) Same as (a) but for the real and imaginary parts of the first barotropic meridional component of the wave-field (A_1).

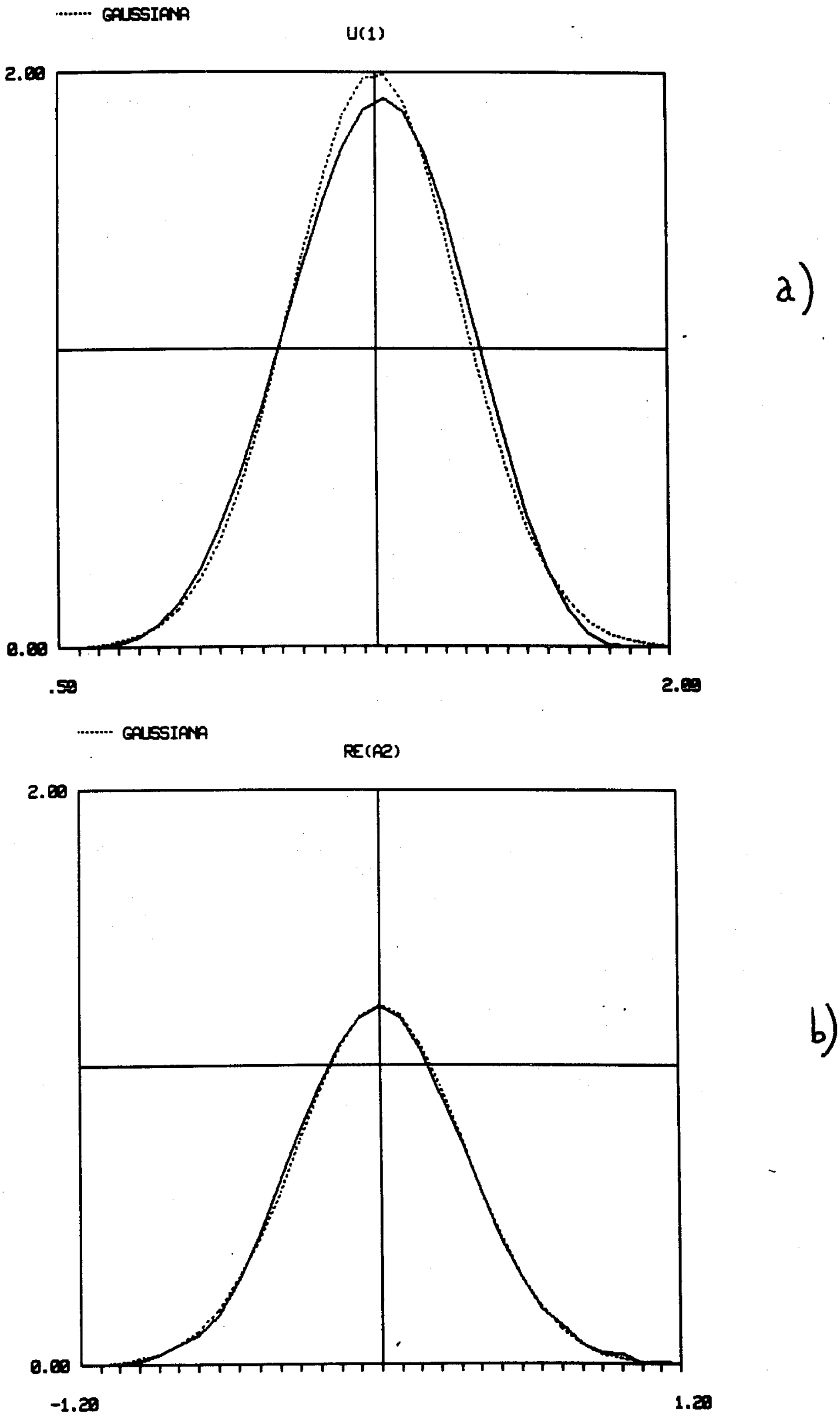

Fig. 3 (a) Histograms of U_1 (solid line). The dashed line represents a gaussian having the same mean and variance as the distribution of U_1.
(b) Same as (a) but for the real part of A_2.

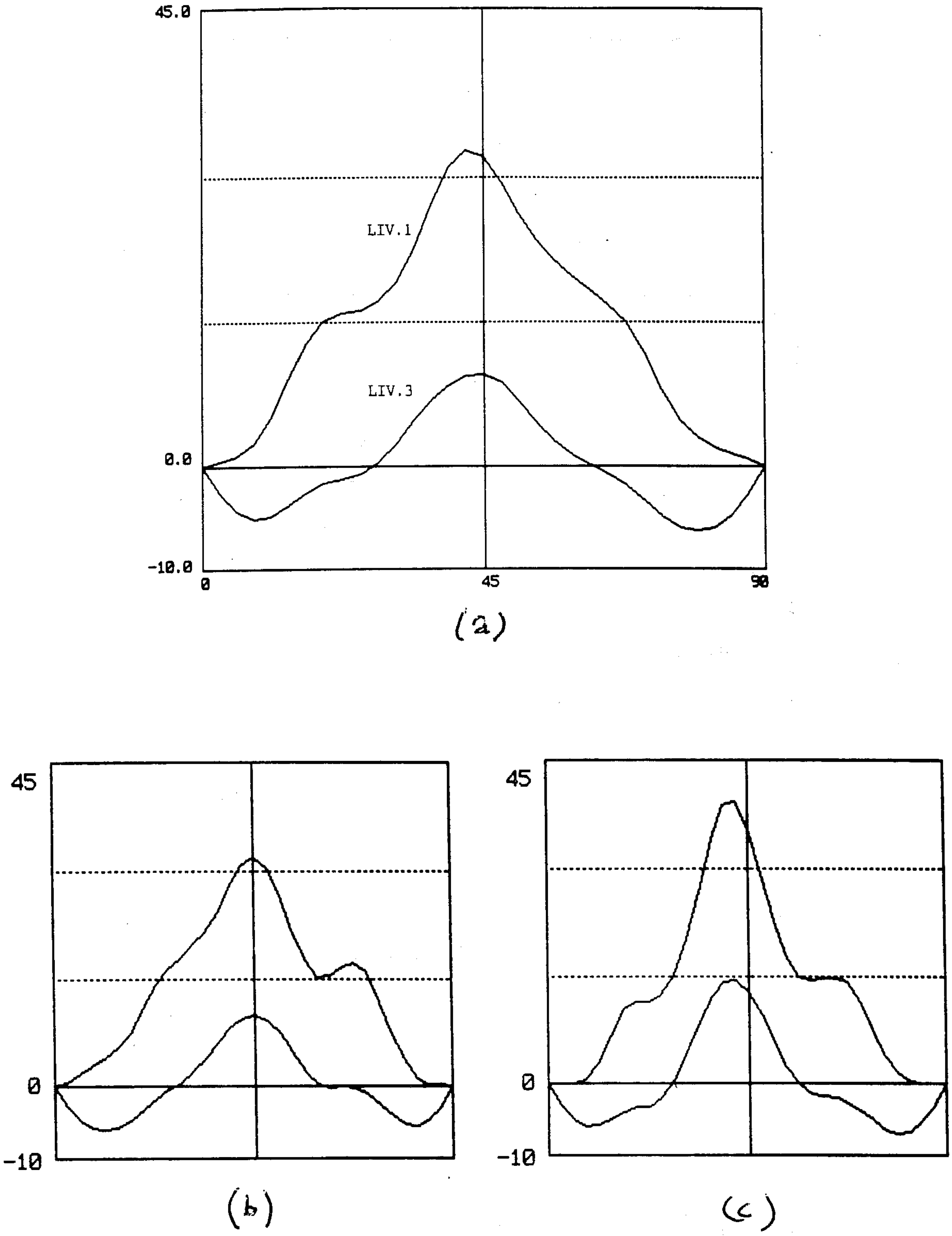

Fig. 4 (a) Ten year average of the zonal wind at the upper level (lev. 1) and lower level (lev. 3). Units are m/sec. Examples of averages over individual years are shown in (b) and (c).

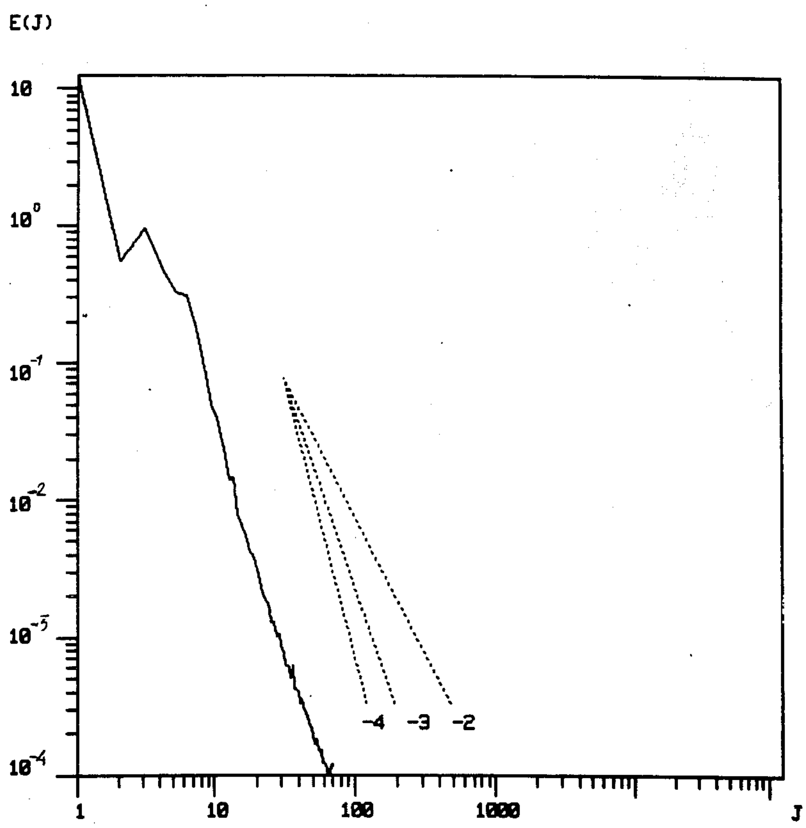

Fig. 5 Fourier spectrum of the total energy (kinetic + available) as a function of the meridional wavenumber $w_j=\pi j/Ly$, $j = 1, 2, 3,\ldots$ The slope of a w_j^{-n} law, $n = 2, 3, 4$, is also plotted for comparison.

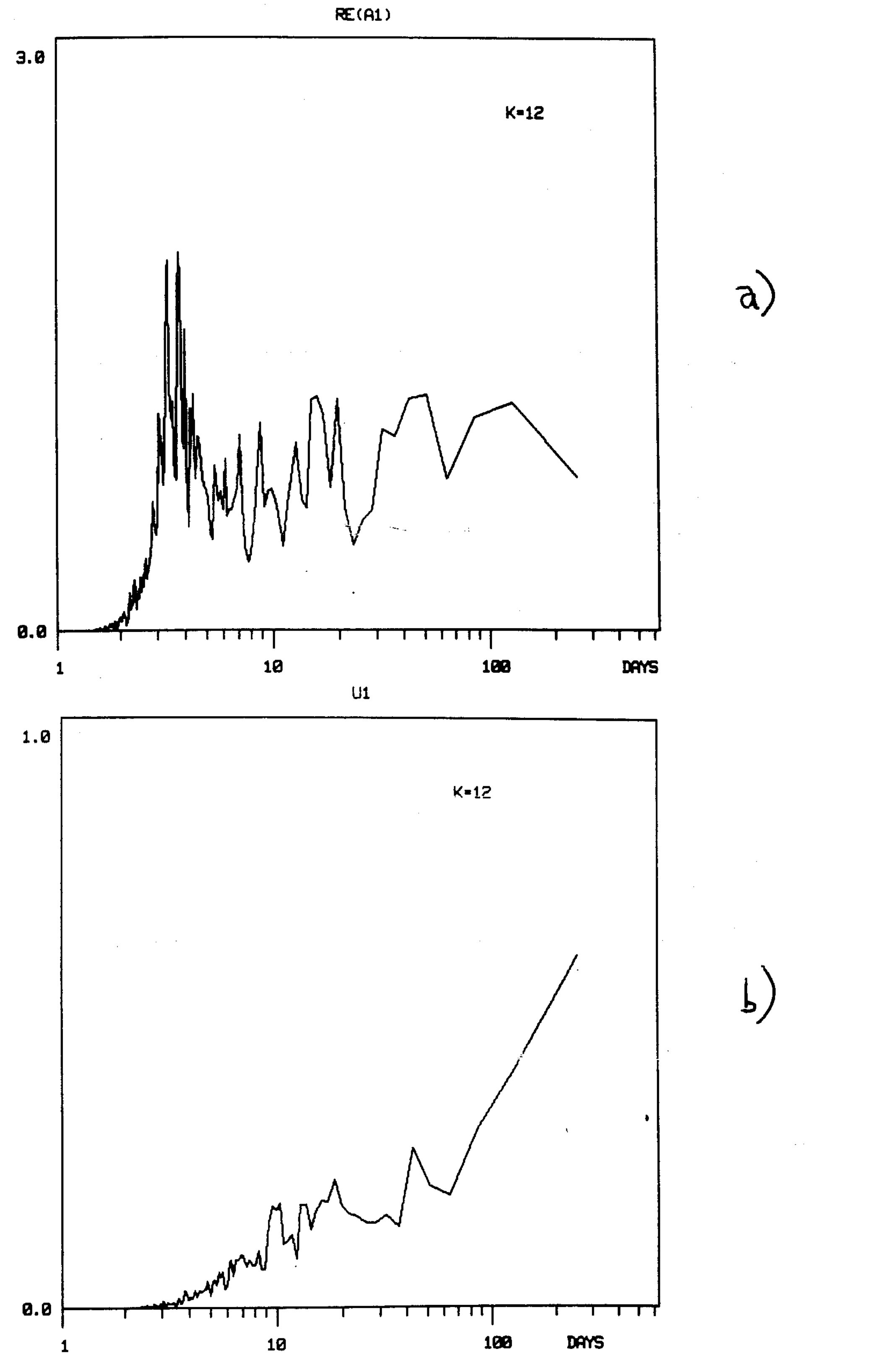

Fig. 6 Power spectrum of (a) real part of A_1 and (b) first component of the mean zonal wind U_1. In abscissa is the period (in days) on logarithmic scale.

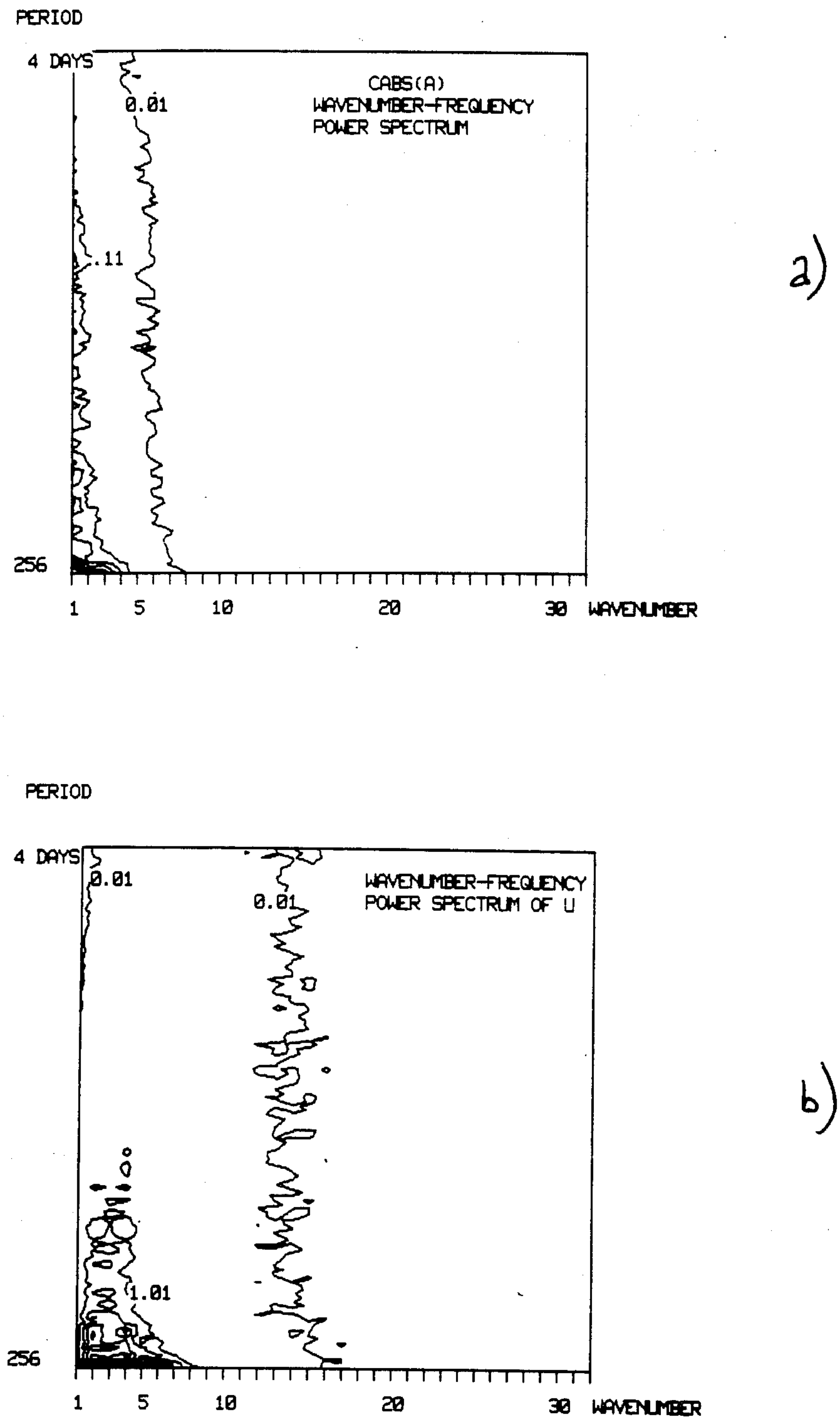

Fig. 7 Wavenumber-frequency power spectrum for (a) barotropic wave-component (contour interval .1) (b) mean zonal wind. On the y-axis is the period on logarithmic scale.

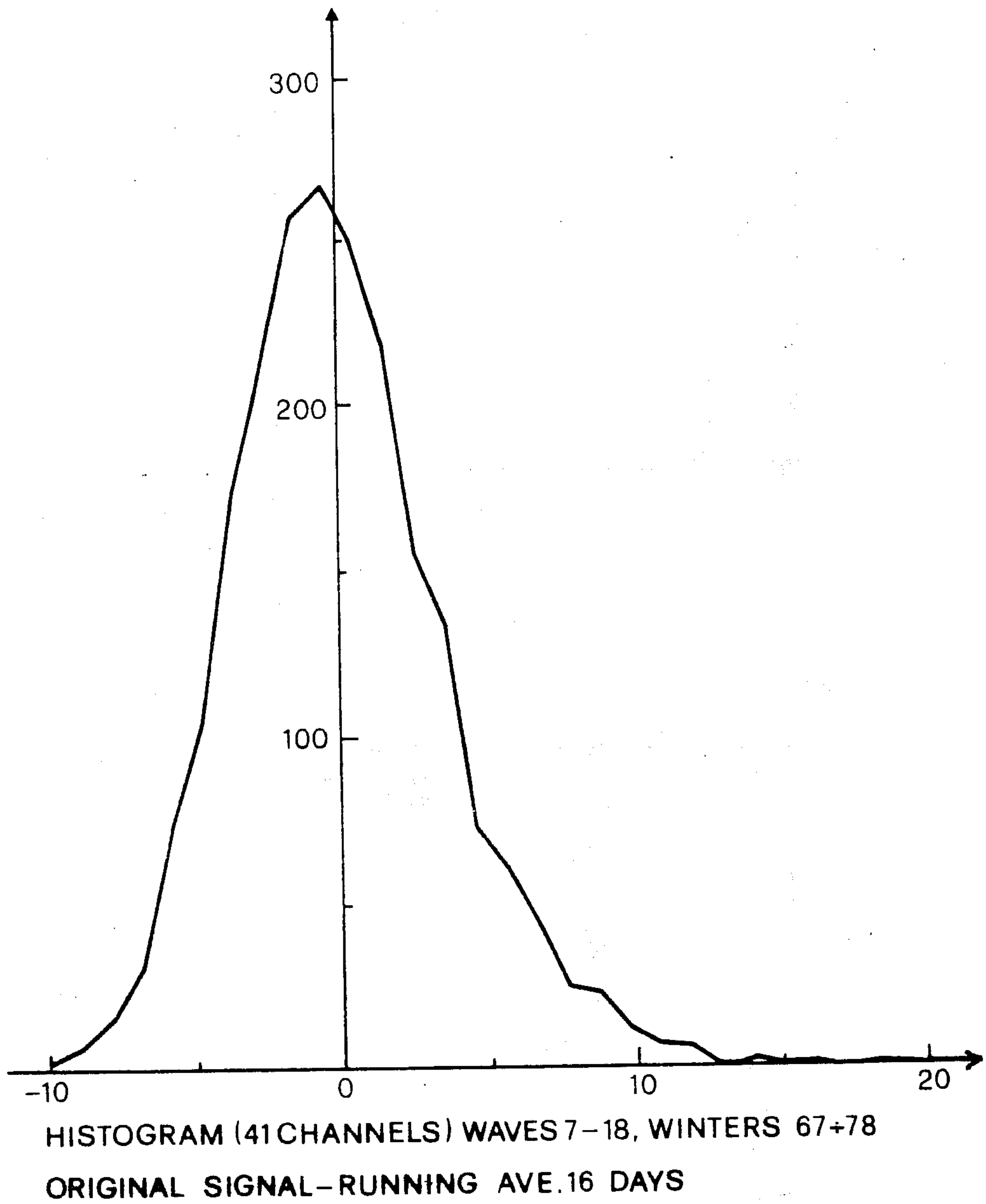

Fig. 8 Histogram of spectral power of short (zonal wavenumber s7-18) baroclinic waves in the northern hemisphere computed from 500 mb heights of winters 1966-1978. Heights are integrated in latitude between 30 and 75 degrees. The signal is detrended by applying a running average of 16 days.

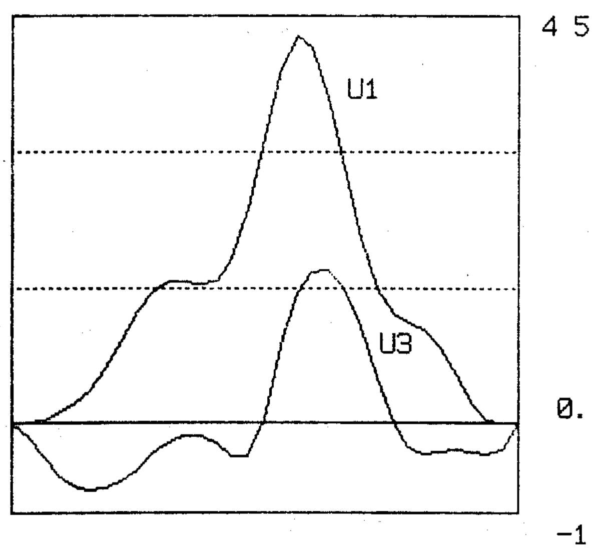

Fig. 9 Ten year average of the zonal wind at the upper and lower levels. Units are m/sec.

Apparently, small changes in the statistics can produce relevant changes in the time-mean pattern. How robust this property is will be tested in the future with more realistic models.

4. CONCLUSIONS

In this presentation I have tried to stress the fact that orographic modification of the transients shall be part of the final theory of general circulation, no matter what the physical nature of the transients is. I have also tried to exemplify the nature of orographic action on transients by means of a simple model of baroclinic instability that has been used in studies of orographic cyclogenesis.

With a similarly simple mode of a baroclinic jet I have shown how the orographic modification of transients can affect time-averaged circulations.

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