1.4A A NUMERICAL ANALYSIS OF TRANSIENT PLANETARY WAVES AND THE VERTICAL STRUCTURE IN A MESO-STRATO-TROPOSPHERE MODEL

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ABSTRACT

The structure of unstable planetary waves is computed by a quasi-geostrophic model extending from the surface up to 80 km by means of eigenvalue-eigenfunction techniques in spherical coordinates. Three kinds of unstable modes of distinct phase speeds and vertical structures are identified in the winter climate state: (1) the deep Green mode with its maximum amplitude in the stratosphere, (2) the deep Charney mode with its maximum amplitude in the troposphere, and (3) the shallow Charney mode which is largely confined to the troposphere. Both the Green mode and the deep Charney mode are characterized by very slow phase speeds. They are mainly supported by upward wave energy fluxes, but the local baroclinic energy conversion within the stratosphere also contributes in supporting these deep modes. The mesosphere and the troposphere are dynamically independent in the summer season decoupled by the deep stratospheric easterly. The summer mesosphere supports the easterly unstable waves 1-4. Waves 3 and 4 are identified with the observed mesospheric 2-day wave and 1.7-day wave, respectively.

INTRODUCTION

Since the discovery of the spectacular natural phenomena of stratospheric sudden warmings, interest in planetary waves has been increasingly enhanced. After satellite observations became possible, along with previous observations by meteor radar, partial-reflection radar and rocket sounding, many transient wave activities in the upper atmosphere have been documented, such as 2-day waves in the summer mesosphere (RODGERS and PRATA, 1981), 4-day waves in the upper stratosphere (VENNE and STANFORD, 1982), the slowly moving planetary waves in the winter stratosphere and mesosphere (HARTMANN, 1976), and a wide wave spectrum in the lower stratosphere (YU et al., 1983). Some wave activities, mainly in wave 1 and 2, are intimately related to the sudden warming phenomena, which extend from the stratosphere well into the mesosphere. The planetary scale waves possess deep vertical structure in winter, but vertically decoupled in summer (LABITZKE, 1981a,b).

The purpose of the present study is to investigate those transient planetary waves based on instability theory. The growth rate, phase speed, meridional and vertical structure of unstable modes are examined for the winter and summer solstice climate states. A comparison study of stabilities for the basic states before and after the 1976/1977 sudden warming event is also discussed.

METHOD OF ANALYSIS

(a) Governing Equation

Assuming the large-scale wave motions are adiabatic and nondissipative, we use the linearized quasi-geostrophic, spherical model formulated by MATSUNO (1971):

$$\left(\frac{\partial}{\partial t} + \frac{\overline{U}}{ac}\frac{\partial}{\partial \lambda}\right)\mathcal{L}(\phi) + \frac{2\Omega}{s^2}\phi_\lambda - \frac{\phi_\lambda}{cs^2}\left[\frac{(\overline{U}c)_\theta}{ac}\right]_\theta = 4\Omega^2 a^2 \frac{\partial \omega}{\partial p} \tag{1}$$

$$\left(\frac{\partial}{\partial t} + \frac{\overline{U}}{ac}\frac{\partial}{\partial \lambda}\right)\phi_p - \frac{\phi_\lambda}{ac}U_p + S\omega = 0 \tag{2}$$

where

$$\mathcal{L}(\phi) \equiv \left[\frac{1}{c}\frac{\partial}{\partial \theta}\left(\frac{c}{s^2}\frac{\partial}{\partial \theta}\right) + \frac{1}{s^2c^2}\frac{\partial^2}{\partial \lambda^2}\right]\phi$$

Equations 1 and 2 are vorticity and thermodynamic equations, respectively, where λ denotes the longitude, θ the latitude, $c = \cos\theta$, $s = \sin\theta$, Ω the angular velocity of the earth, a the radius of the earth, ϕ the perturbation geopotential, U the basic zonal flow, and S the static stability.

(b) Grid Point Arrangement and Boundary Conditions

The model is discretized vertically by ten computation levels covering from the surface up to 80 km and it is referred to as an MST model (M for mesosphere, S for stratosphere and T for troposphere). The computation levels are arranged at p = 0.01, 0.04, 0.2, 1 mb in the mesosphere; at p = 3, 10, 30, 100 mb in the stratosphere and at p = 250, 750 mb in the troposphere. The vertical boundary condition $\omega = 0$ is assumed at p = 0 and p = 1000 mb. In the meridional direction the model is bounded by the fixed boundary conditions $\phi' = u' = v' = 0$ at the pole and the equator with 10° meridional mesh sizes. The grid point arrangement is shown in Figure 1.

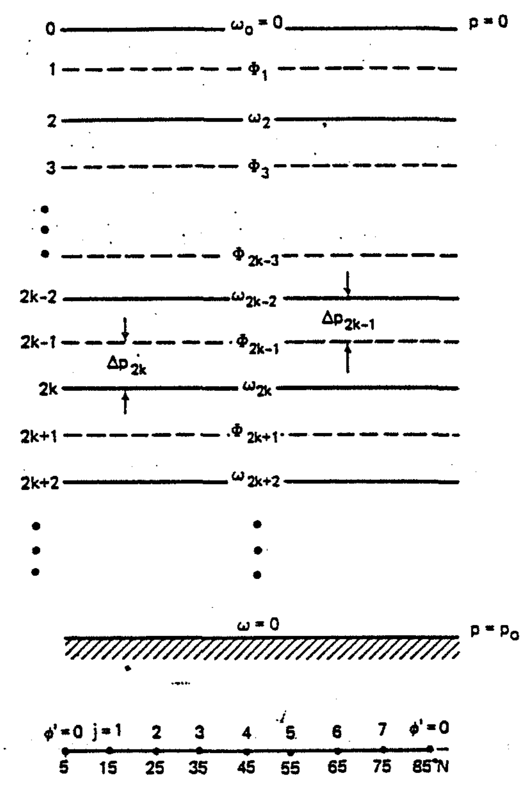

Figure 1. Vertical and meridional grid arrangement and boundary conditions used in the spherical model.

(c) Basic State Parameters

The winter and summer solstice climate basic flows are shown in Figure 2. The zonal-mean temperature field and the wind field consist of the parameter space (S, U), where the static stability is calculated from the temperature field.

(d) Normal Mode Solution

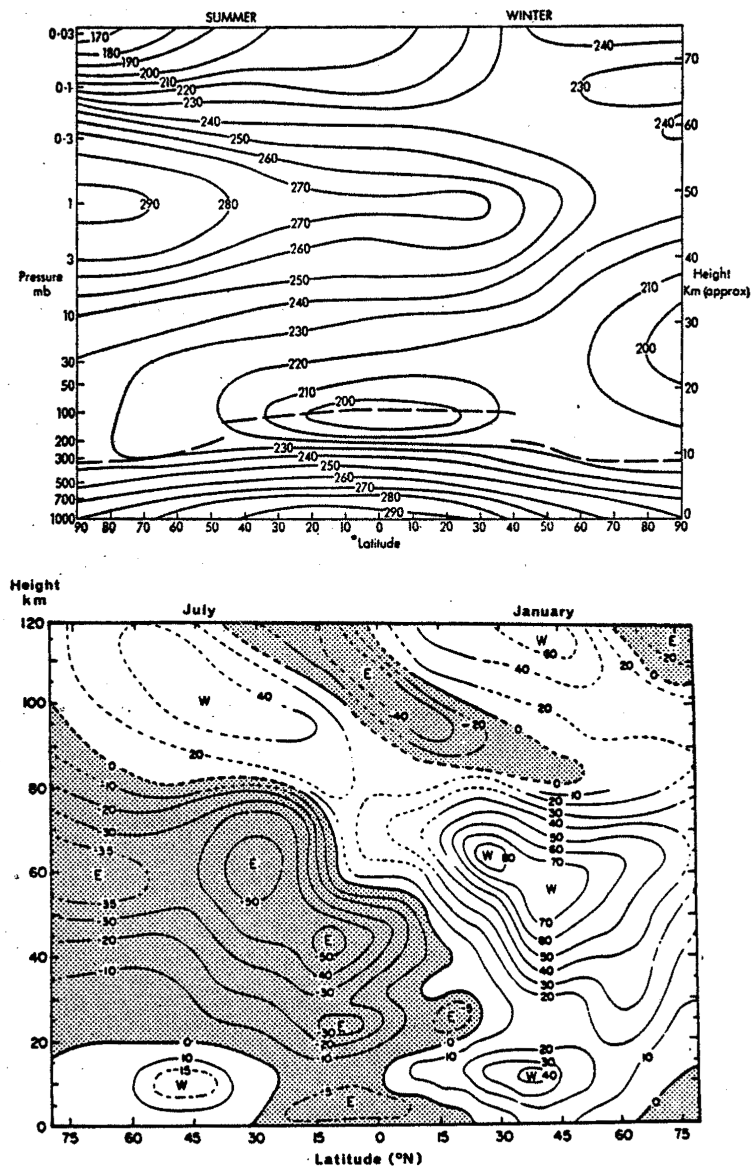

Figure 2. The solstice climate states. The upper panel is temperature (K) and the lower panel is the zonal mean wind in m/s.

We assume a normal mode solution:

$$\Phi = \Phi(\theta, p)e^{im(\lambda-ct)}$$

and calculate the phase speed C_r, growth rate $\sigma_i = mC_i$, and the eigenfunction $\Phi(\theta,p)$, where $C = C_r + iC_i$ and $\Phi = \Phi_r + i\Phi_i$ are complex numbers.

RESULTS

(a) Winter

Figure 3 shows the spectrum of the growth rates and phase speeds of the unstable waves computed for the winter basic flow. The values of α and α_s are representative for "dry" and "wet" tropospheric conditions. Both reveal the presence of three kinds of unstable modes:

1. Green mode, denoted by MST in Figure 3, for waves 1 and 2,
2. Deep Charney mode, denoted by ST in Figure 3, for wave 3, and
3. Shallow Charney mode, denoted by T in Figure 3, for waves 5-9.

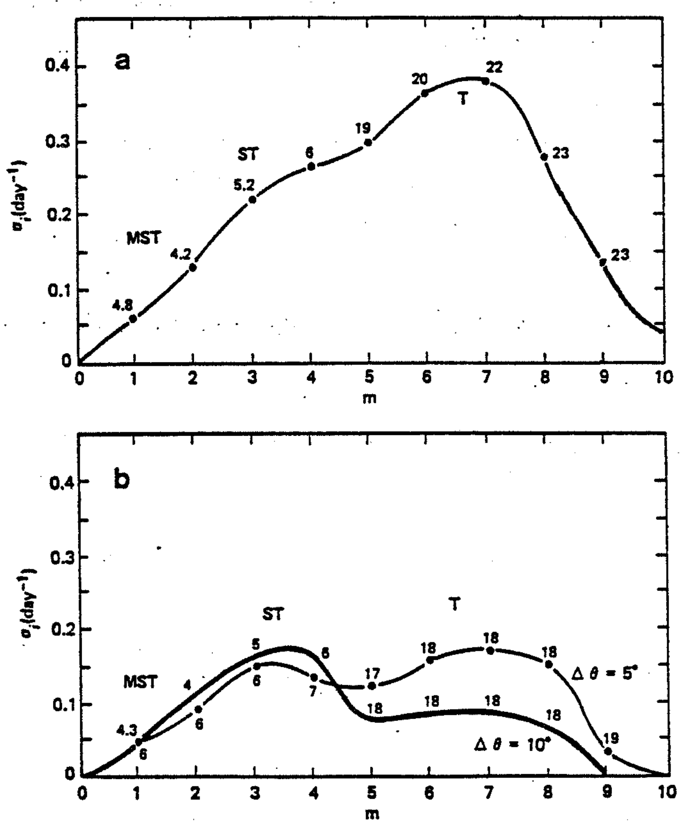

Figure 3. The growth rate (ordinate) and the phase speed at the equator (labeled in m/s) for winter solstice basic state: a) the dry troposphere; b) the moist troposphere.

The phase speeds given in Figure 3 reveal an interesting instability exchange between the slow modes (waves 1-4, including the Green mode and the deep Charney modes) and the fast modes (waves 5-9, all of which are confined to the troposphere). It implies some intrinsic relation between the phase speed and the vertical structure. The vertical wave energy fluxes (Figure 4) depict that the deep waves are vertically coupled as an entirety. They may be identified with the slowly moving waves 1, 2 and 3 in the real atmosphere.

(b) Summer

The spectra of the growth rates, phase speeds for the summer circulation are given in Figure 5. The mesospheric modes, with large negative phase speeds $C_r < 0$, and the tropospheric modes, with the positive phase speeds $C_r > 0$, exchange their stabilities at wave number 4. The computed most unstable mode is wave 3 with a period of 2 days which compares favorably with the observed 2-day wave. Figure 6 shows structures of the computed mesospheric waves with m = 1-4 and the tropospheric wave with m = 6. They are spatially separated by the easterly wind in the stratosphere. The planetary scale waves dominate in the mesosphere and the synoptic scale waves dominate in the troposphere.

VERTICAL COUPLING AND DECOUPLING

In order to understand the stability due to vertical coupling between the mesosphere, the stratosphere and the troposphere in the winter season, a case study is performed to compare the eigenmodes in the basic states before and after the 1976/1977 sudden warming event. Figure 7 shows the observed variation of geopotential amplitude for waves 1 and 2 during the warming phase.

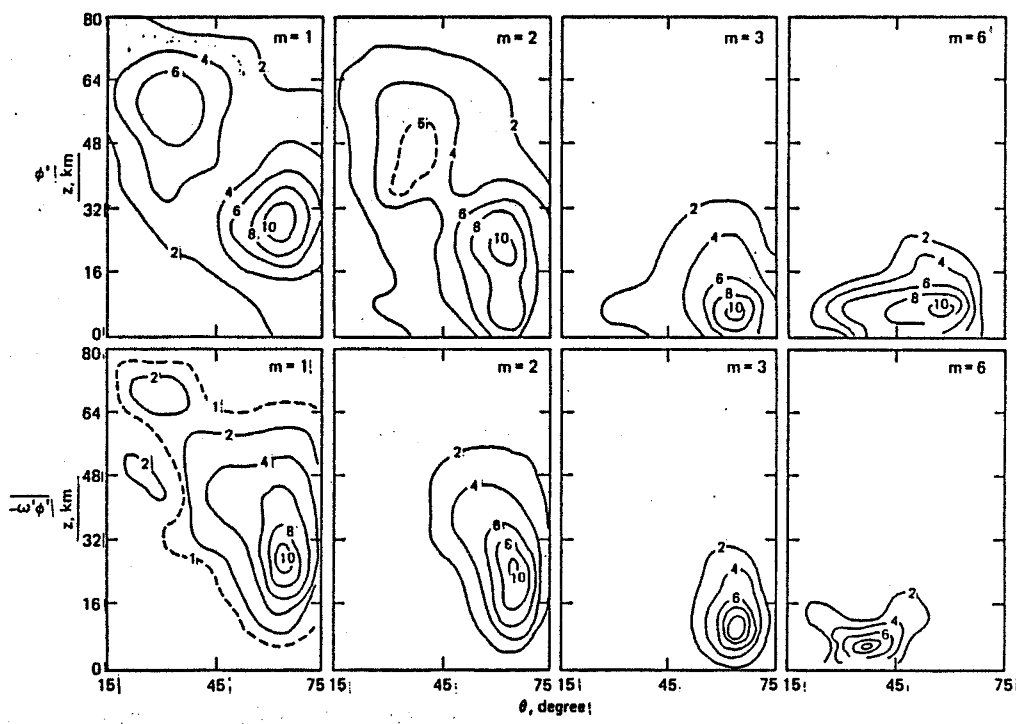

Figure 4. Geopotential eigenfunctions (upper and vertical wave energy flux (lower) in the NH winter basic flow with the "dry" troposphere. Units are arbitrary.

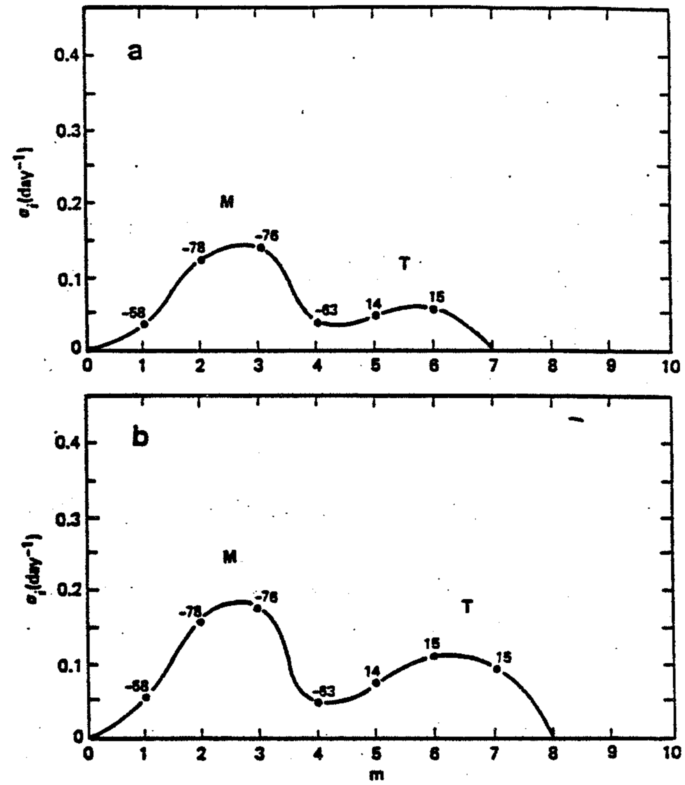

Figure 5. The growth rates (ordinate) and the phase speeds (labeled in m/s) for summer solstice basic state with a) the "dry" troposphere and b) the "moist" troposphere. m indicates the wave number, M the mesospheric mode and T the tropospheric mode.

Both waves 1 and 2 were growing during December 1976 and decreasing in January 1977. The basic flow in December 1976 is characterized by a broad, weak throughout the troposphere and the stratosphere, and in January 1977 is characterized by easterlies at high latitudes. Figure 8 summarizes the results of frequency computations for December and January.

Three significant changes occur after the sudden warming:

1. The maximum growth rate shifts from planetary scale (m = 2) to synoptic scale (m = 7) and the planetary scale waves are substantially stabilized.
2. Transition occurs from the slow modes to the fast modes at wave number 4 before the warming, but all waves change to the fast modes after it.
3. All the deep modes (MST modes and ST modes) are suppressed to the shallow, tropospheric modes after the sudden warming as shown in Figures 9 and 10.

Since the deep Green mode and the deep Charney mode have been calculated in the winter climate basic flow, we suspect that the deep modes exist in the whole season except in periods after sudden warmings, in which all deep modes are suppressed primarily by the reversed zonal flow at high latitudes.

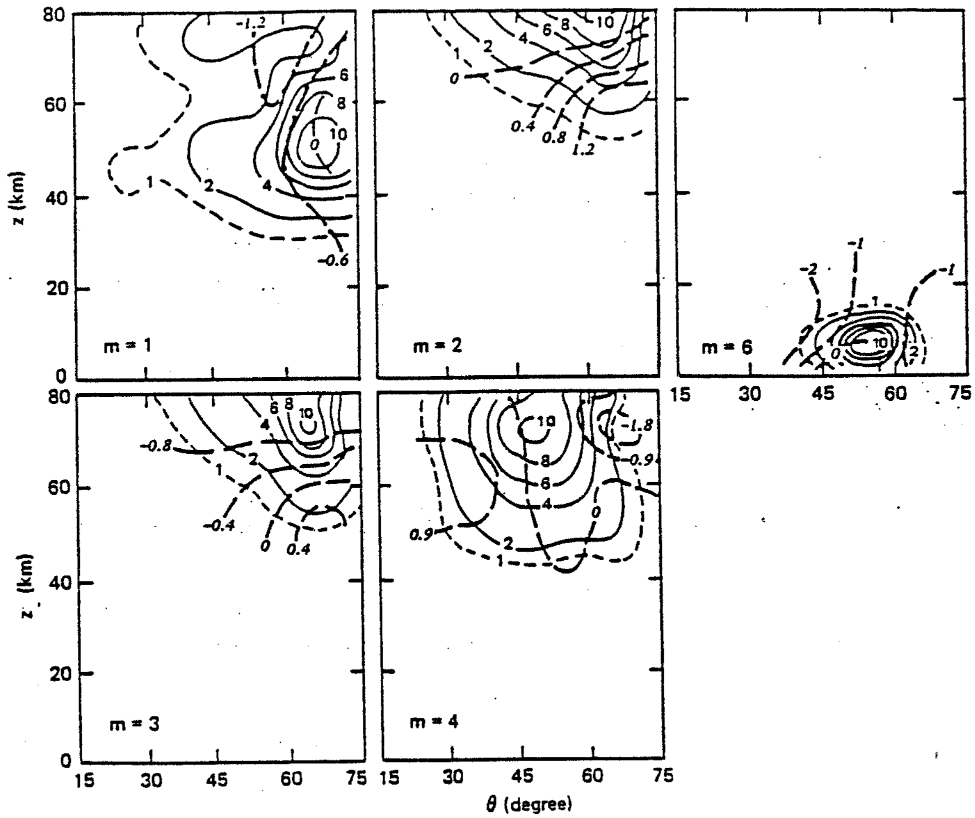

Figure 6. The geopotential eigenfunctions for waves m = 1 - 4 in the summer mesosphere, for wave m = 6 in the summer troposphere. The units of amplitude (solid line) are arbitrary. The phases (broken line) are in π radians.

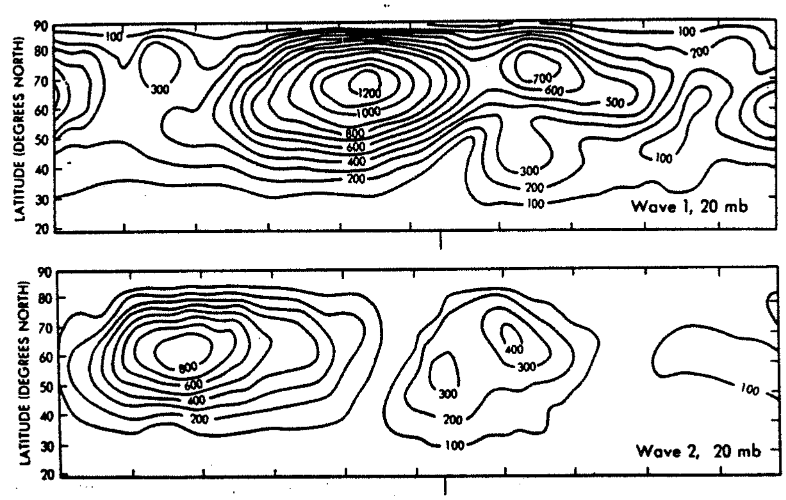

Figure 7. Latitude-time cross sections of geopotential height wave amplitude (meters) for waves 1 and 2 during the 1976/1977 sudden warming event (after O'NEILL and TAYLOR, 1978).

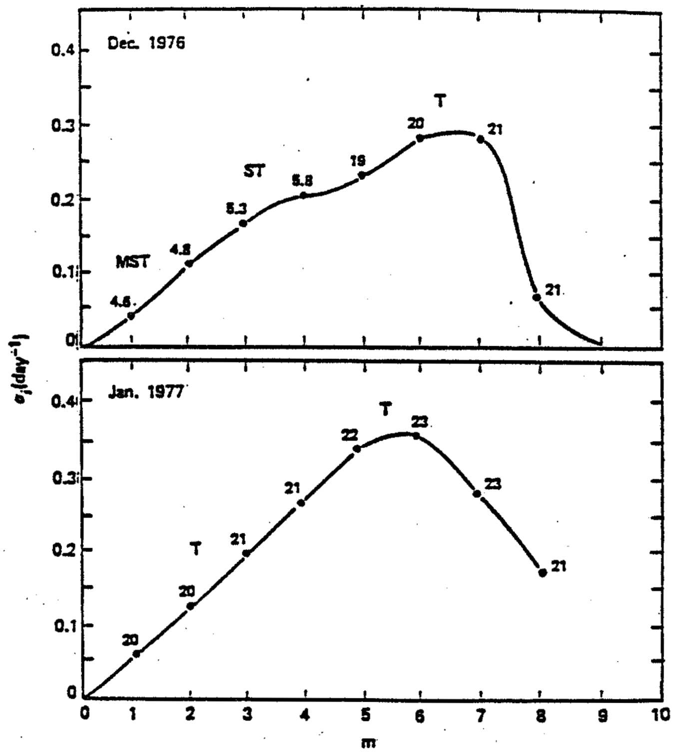

Figure 8. The growth rate (ordinate) and the phase speed at the equator (labeled in m/s) as a function of wave-number m.

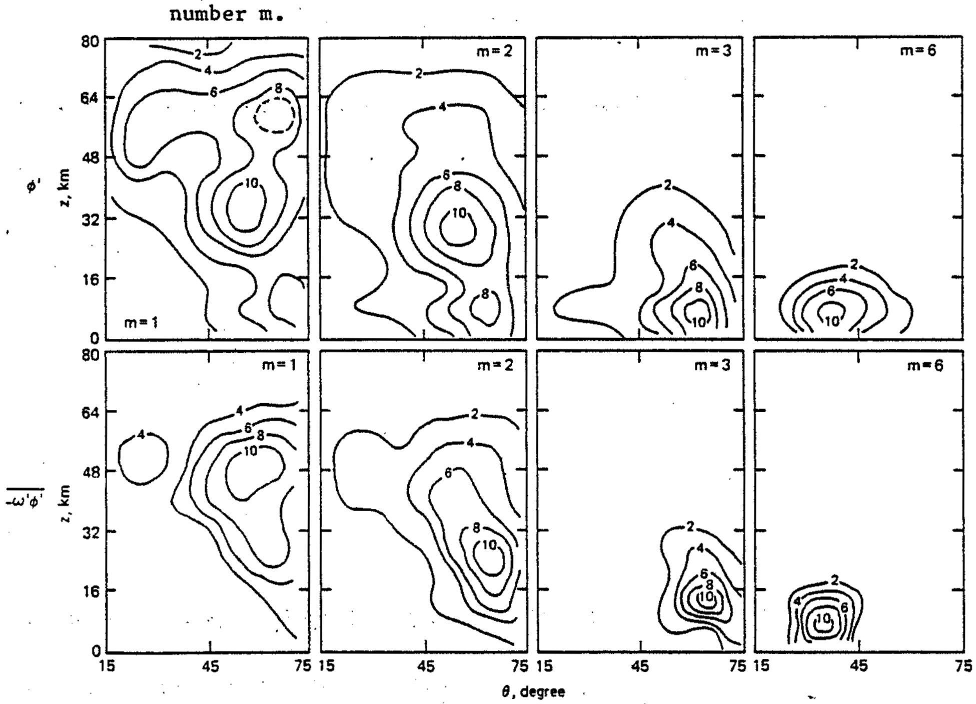

Figure 9. Geopotential (top) and wave energy flux (bottom) in December 1976. Units are arbitrary.

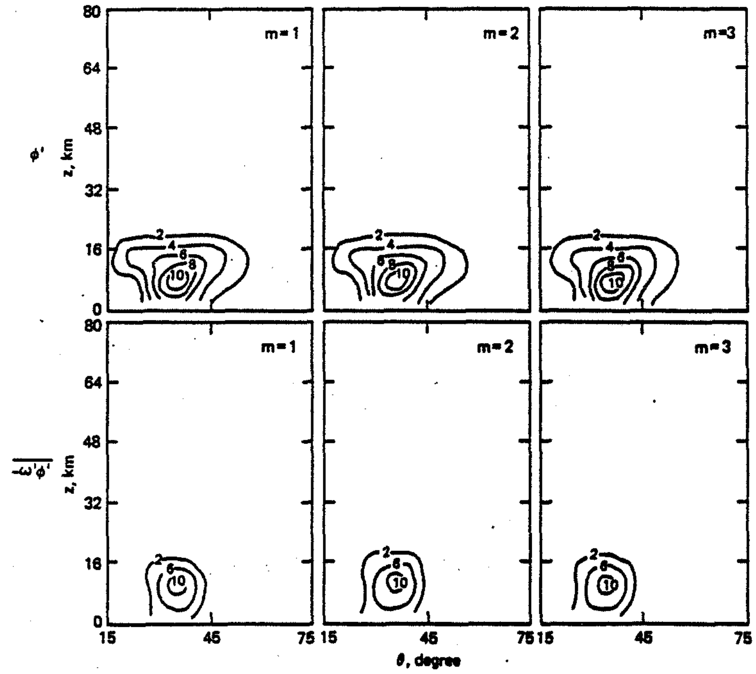

Figure 10. As in Figure 9 except in January 1977.

CONCLUSION

In conclusion, we propose a baroclinic instability for the generation of some planetary transient waves in the upper atmosphere. The usually observed transient waves 1 and 2 in the winter may have an origin of baroclinic instability in addition to the response to the external forcing. The mesosphere, the stratosphere and the troposphere are intimately coupled by the deep planetary waves in the winter circulation, while the summer circulation is vertically decoupled by the stratospheric easterly zonal wind. The computed unstable wave 3, confined to the mesosphere and the upper stratosphere, compares favorably with the observed 2-day wave.

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