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Model calculations on the structure of planetary waves in the upper troposphere and lower stratosphere as a function of the wind field in the upper stratosphere

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ABSTRACT

The influence of variations of the mean zonal wind in the upper atmosphere on the structure of planetary waves in the upper troposphere and lower stratosphere has been investigated by means of a two-dimensional stationary wave-propagation model. It is found that the amplitude and phase at altitudes between 5 and 20 km, where the refraction index was left unchanged, are very sensitive to the mean zonal wind in the upper stratosphere. The reason for this dependence is the reflection of the planetary wave at the polar night jet. In the region above 20 km the structure of planetary waves depends strongly on the mean zonal wind as was previously found by Schoeberl and Geller (1976). Our calculations corroborate the conception that anthropogenic modifications and extra-terrestrial effects in the middle stratosphere can lead to consequences in the troposphere, as previously discussed by Bates (1977) and Grieger and Schmitz (1978).

1. Introduction

The propagation of planetary waves in the stratosphere and mesosphere was investigated by Matsuno (1970) and Schoeberl and Geller (1976, 1977) by means of a two-dimensional model. The latter found that the amplitude and phase of planetary waves show a great variability in the stratosphere and mesosphere when the mean zonal wind is changed in these heights. The reason for this is the dependence of the refraction coefficient on the mean zonal wind.

In this study we show the variability of planetary waves and associated meridional transport of sensible heat in lower atmospheric levels where the refraction coefficient is unchanged, whereas the mean zonal wind field is only changed in the upper levels.

Bates (1977) and Grieger and Schmitz (1978) (in the following denoted by I) have investigated this problem by means of one-dimensional models. Bates solved the equation of quasigeostrophic theory of type 2 for analytical wind profiles, and the Newtonian cooling coefficient was assumed zero in the stratosphere below about 45 km. In (I) the equation for geostrophic motion of the first kind was solved up to 100 km with a real mean zonal wind profile and a constant Newtonian cooling coefficient.

Both papers showed that the variation of the zonal wind maximum in the high stratosphere, while the tropospheric and lower stratospheric wind field remained unaltered, produced major fluctuations in the amplitude and phase of the planetary waves and the corresponding transport quantities in troposphere and lower stratosphere, respectively. The investigations showed that this result is due to the reflection of planetary waves at the west wind maximum. Attention was drawn by Bates (1977) and, independently, by (I) to the fact that this major dynamic process indicates how anthropogenic modifications and extra-terrestrial effects in the middle stratosphere can lead to consequences in the troposphere.

This paper continues the studies of the problems presented in (I), this time using a two-dimensional wave propagation model, since the simple β-plane model reproduces only qualitative aspects of planetary wave propagation.

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2. The model

The calculations are based on the linearized quasi-geostrophic equations of motion, Dickinson (1968b), and take the Newtonian cooling and Rayleigh friction into account:

$$\bar{d}_\beta \Delta\psi + \sigma^{-1}(\sigma - [\sigma^{-1}(\sigma\bar{U})_\varphi]_\varphi)\psi_\lambda + \mu\Delta\phi = 0,$$

$$h - \mu\psi = 0,$$

$$\bar{d}h_z - 0.5\mu\omega_z\psi_\lambda + Sw = -\alpha h_z,$$

$$\Delta\phi + w_z - w = 0.$$

ψ, ϕ are the stream function and velocity potential, φ, λ are the latitude and longitude, Δ is the Laplace operator, h is the geopotential height, $\omega = \bar{U}/\Omega a\sigma$, $\bar{U}$ is the zonal wind, a is the radius of the earth, Ω is the angular velocity of the earth, S is a non-dimensional statical stability term, α is the Newtonian cooling coefficient, β_R Rayleigh friction, $\bar{d} = (\partial/\partial t + 0.5\omega\partial/\partial\lambda)$, $\bar{d}_\beta = \bar{d} + \beta_R$, $z = \ln p_0/p, p_0 =$ 1000 mb, $w = dz/dt$, $\mu = \sin\varphi$ and $\sigma = \cos\varphi$.

At the meridional boundaries, it is assumed that

$$\psi = 0 \quad \text{for} \quad \varphi = 0, \quad \pi/2.$$

At the bottom boundary, in 5 km, the experimentally determined disturbances, as shown in Fig. 1, based on the results from Van Loon et al. (1973), are given.

The radiation condition applies to the upper boundary.

The differential quotients in the model equations are replaced by finite difference quotients and the resultant system of algebraical equations is solved numerically by the method described by Lindzen and Kuo (1969). The numerical results depend largely on the number of grid points, and we have investigated this dependence for different Newtonian cooling coefficients. Our results described here are based on a vertical resolution of about 2.5 km and a latitudinal resolution of $\Delta\varphi = 2.5°$.

Fig. 2 shows the used Newtonian cooling profile which is based on a profile given by Cunnold et al. (1975). The Rayleigh friction parameter is

$$\beta_R = 1.10^{-8}\,\text{s}^{-1}.$$

At the upper boundary we assume that there is no vertical wind-shear.

We have not solved the correct meridional eigenvalue problem, but assume a constant atmospheric rotation and have calculated the eigenvalue with a mean zonal wind value as described by Dickinson (1968a).

Fig. 3 shows that the vertical stucture of the planetary wave does not critically depend on the chosen eigenvalues. With this boundary condition we can show in Fig. 4 that our numerical results are in agreement with experimental data from Schmitz and Grieger (1979).

3. Wind models

The wind profiles M, $M_{0.8}$, $M_{1.2}$ shown in Fig. 5a and based on a profile given by Matsuno (1970) were used as a basis for the model calculation of

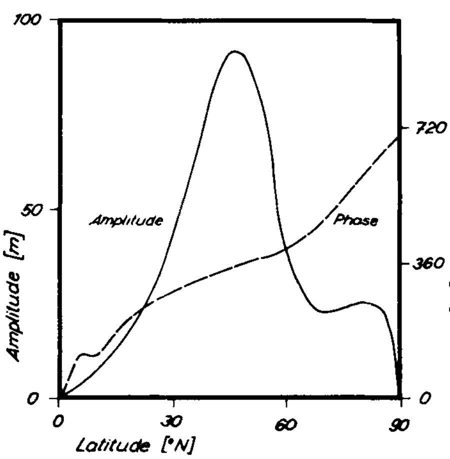

Fig. 1. The amplitude and phase of geopotential for wave number 1 at 5 km, the lower boundary, after Van Loon et al. (1973).

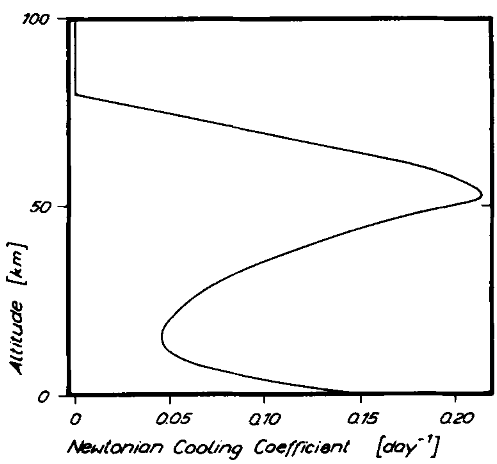

Fig. 2. The Newtonian cooling profile based on Cunnold et al. (1975). We assume a linear decreasing from 60 to 80 km.

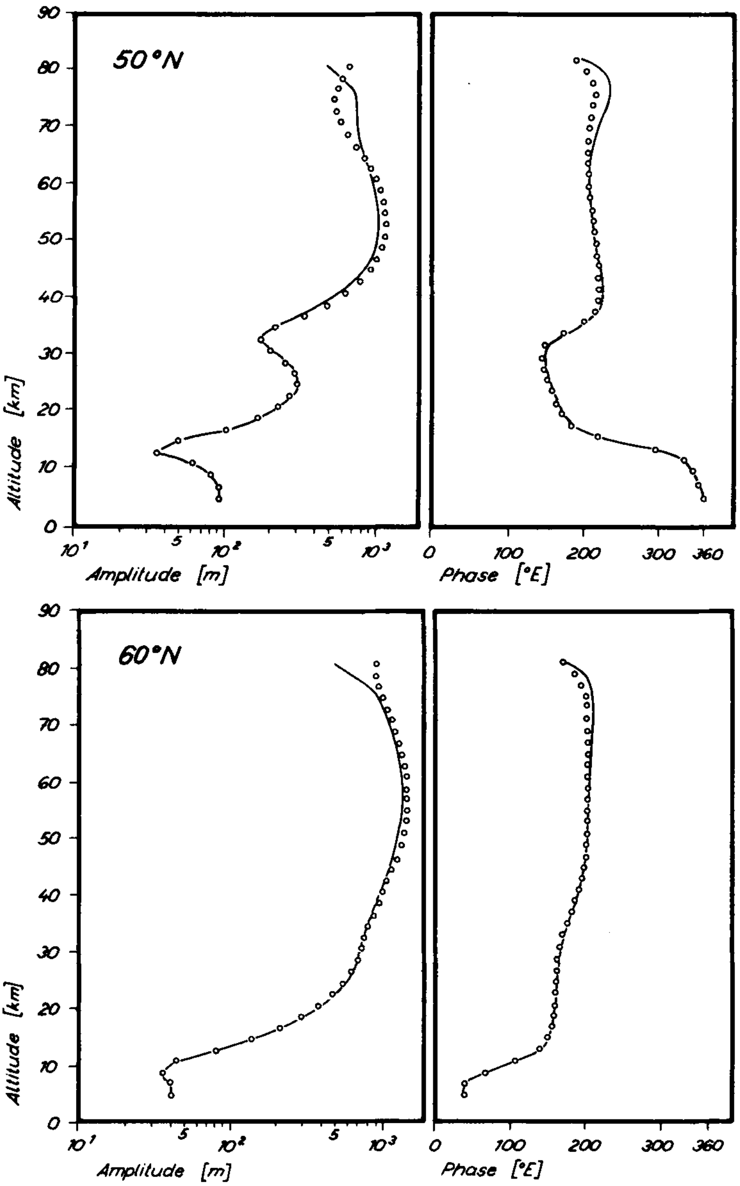

Fig. 3. The amplitudes and phases of the geopotential for wave number 1 in 50 and 60 °N of two-dimensional model calculations with Newtonian cooling and Rayleigh friction coefficient $\beta_R = 1.10^{-8}$ s^{-1} for different eigenvalues γ (after Dickinson 1968a) at the upper boundary condition ($\gamma_2^1 = 80.$, ——, $\gamma_2^1 = 600.\cdots\cdot$).

the propagation of planetary waves with the wave number one. The profiles $M_{0.8}$ and $M_{1.2}$ were obtained from the profile M by reducing or increasing the wind maximum in the stratosphere by factors of 0.8 and 1.2, respectively.

In the case of the modified profiles, the wind in the troposphere was left unchanged. The assumed fluctuations in the stratospheric winds lie within the normal range of fluctuation revealed by experimental results described in (I) (Fig. 2). To permit comparison of the different solutions obtained by our two-dimensional calculations, Fig. 5b shows the vertical wind profiles at the latitudes of 40, 50 and 60 °N.

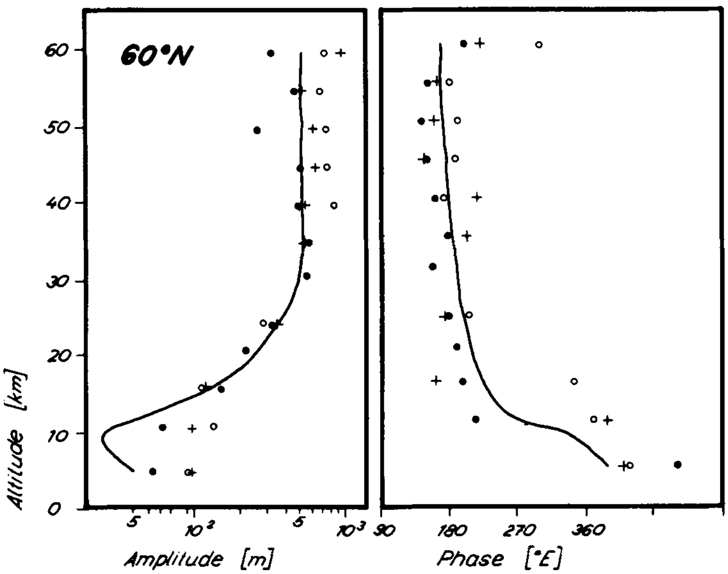

Fig. 4. The amplitudes and phases of the geopotential for wave number 1 in 60 °N for a two-dimensional model calculation with Newtonian cooling profile as shown in Fig. 2 and $\beta_R = 1{,}10^{-8}\ s^{-1}$ and the experimental data for different years based on Schmitz and Grieger (1979) (O January 1972, + January 1975, ● January 1976).

4. Results

Fig. 6a and b show how the amplitudes and phases of the planetary wave of wave number one of the geopotential depends on altitude at latitudes 40, 50 and 60 °N in the different wind models. The figure shows the following:

(1) At 50 °N and 60 °N, the amplitudes and phases of the planetary wave for the different wind profiles fluctuate considerably at altitudes from 5 to 20 km although the wind does not vary within this range.

(2) The amplitude and phase variations of the planetary wave of wave number one for the different wind profiles exhibit a pronounced dependence upon latitude at altitudes between 5 km and 20 km. These differences are shown in detail in Fig. 7 for the amplitude of the geopotential and the meridional transport of sensible heat. The influence of mean zonal wind variations in the upper stratosphere on the structure of planetary waves in lower layers is very sensitive to the Newtonian profile and is increased with decrease of the profile maximum.

The intensity minima in the lower stratosphere shown in Fig. 6a and b can, according to (I), be interpreted as the result of wave reflections. In order to illustrate this conception of reflection, Fig. 8 shows the vertical distribution of the kinetic energy of the zonal and meridional wind wave components. A pronounced intensity minimum can be seen at altitudes between 10 km and 20 km. This occurs at different heights for different wind profiles and is obviously determined by the reflection of the wave. Corresponding models of the reflection process were elaborated by Sato (1974) on the basis of observational results.

The results obtained with the β-plane and two-dimensional models, respectively, have been compared. At 50 °N the one-dimensional and two-dimensional models produce roughly the same variations in amplitude and phase at altitudes between 5 km and 20 km for the different wind profiles. The two-dimensional models thus also confirm the effect of the mean zonal wind in the upper stratosphere on the structure of planetary waves in the lower layers.

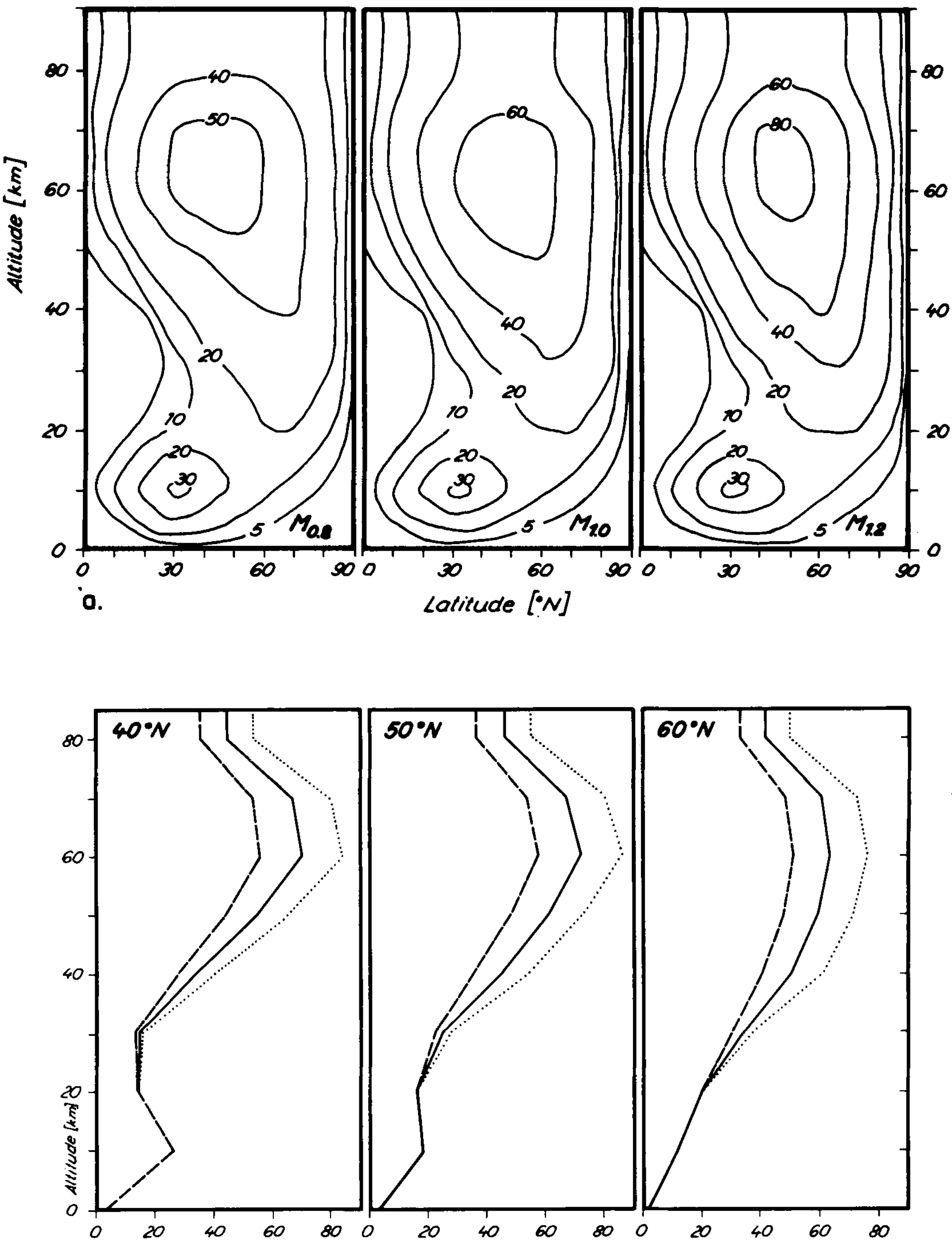

Fig. 5. The mean zonal wind field U, m s^{-1} (a), and the wind in different latitudes (b). (--- $M_{0.8}$, —— $M_{1.0}$, $\cdots$ $M_{1.2}$).

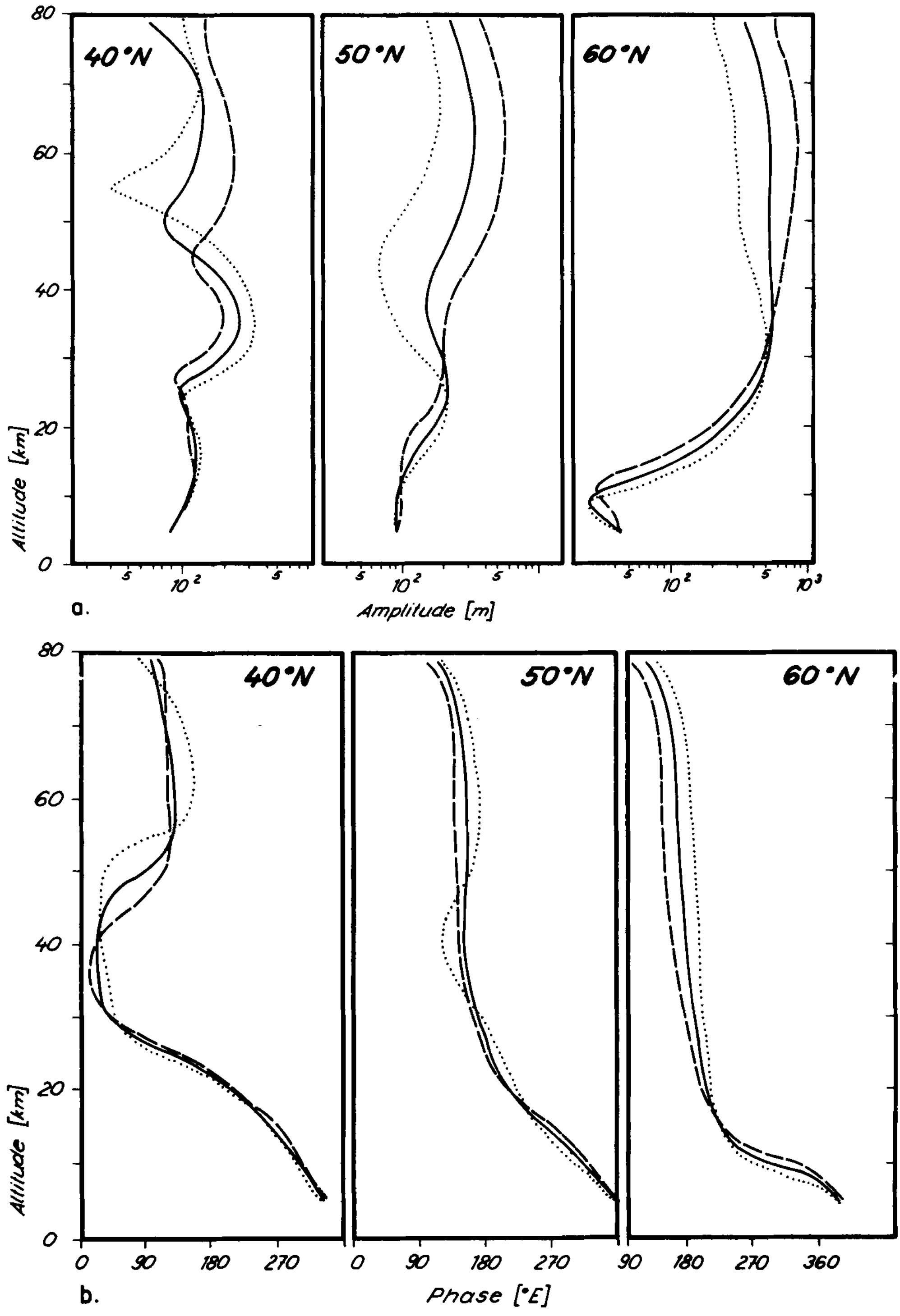

Fig. 6. The amplitudes (a) and phases (b) of the geopotential for wave number 1 of two-dimensional model calculations for different latitudes according to the wind fields. (--- $M_{0.8}$, —— $M_{1.0}$, $\cdots$ $M_{1.2}$).

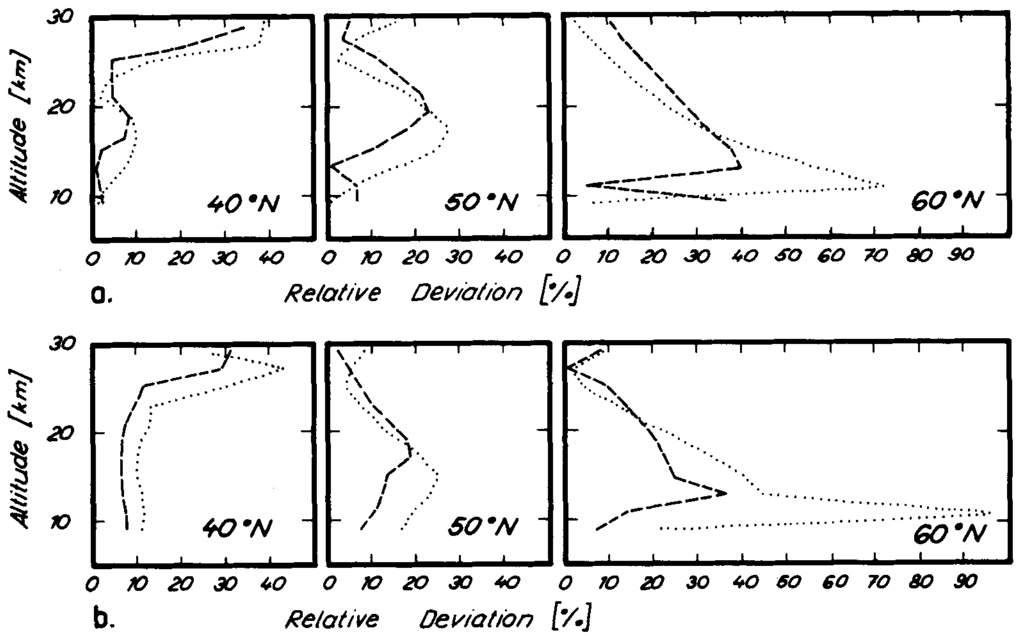

Fig. 7. The relative deviations between model calculations with changed wind profiles (---- $M_{0.8}$, ... $M_{1.2}$) and those with unchanged wind profile for the amplitudes (a) of the geopotential and the meridional sensible heat transport (b) for wave number 1 in different latitudes in the region where the wind profiles are approximately the same, see Fig. 5b.

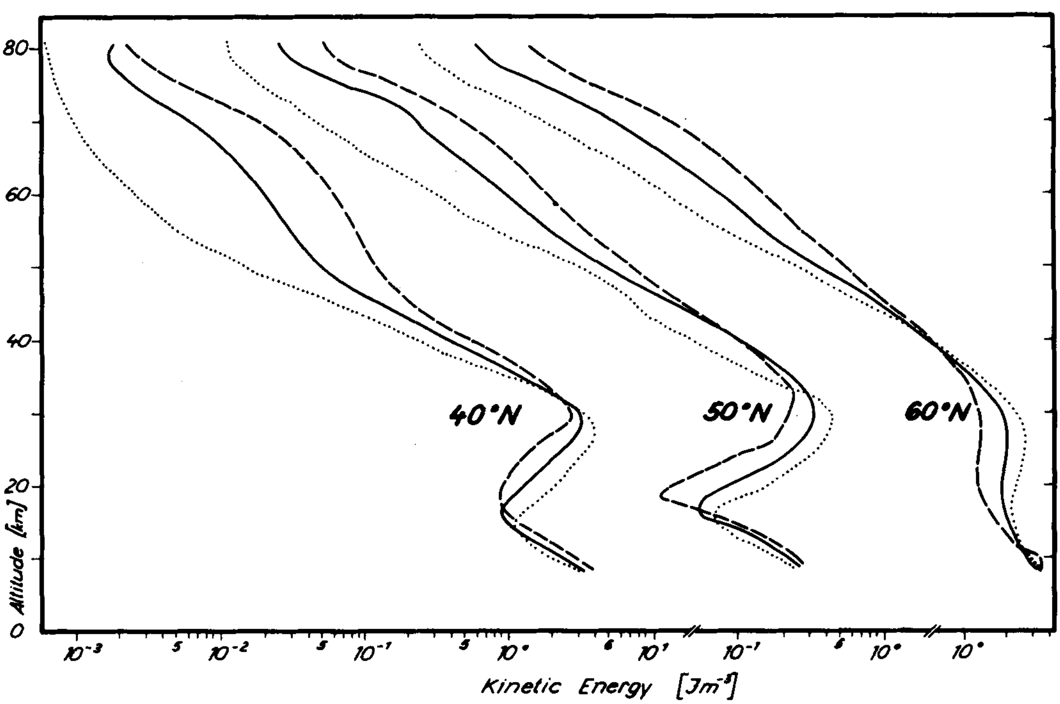

Fig. 8. The kinetic energy of the planetary waves of wave number 1 for the model calculations with different wind profiles, notation as in Fig. 6.

5. Conclusions

The two-dimensional results for wave propagation confirm the idea that the structure of planetary waves at upper tropospheric and lower stratospheric altitudes is influenced decisively by the reflection of planetary waves in the middle stratosphere. The calculations show that this process increases to higher latitudes. In order to cover any effects at altitudes below 5 km, it is necessary, by further studies, to describe the excitation processes for planetary waves in the troposphere, which is in preparation.

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МОДЕЛЬНЫЕ ВЫЧИСЛЕНИЯ СТРУКТУРЫ ПЛАНЕТАРНЫХ ВОЛН В ВЕРХНЕЙ ТРОПОСФЕРЕ И НИЖНЕЙ СТРАТОСФЕРЕ В ЗАВИСИМОСТИ ОТ ПОЛЯ ВЕТРА В ВЕРХНЕЙ СТРАТОСФЕРЕ

С помощью двумерной модели распространения стационарной волны исследуется влияние изменений зонального ветра в верхней атмосфере на структуру планетарных волн в верхней тропосфере и нижней стратосфере. Найдено, что амплитуда и фаза на высотах от 5 до 20 км, где индекс рефракции был принят постоянным, очень чувствительны к среднему ветру в верхней стратосфере. Причиной такой зависимости является отражение планетарной волны в области струйного течения полярной ночи. В области выше 20 км структура планетарных волн сильно зависит от среднего зонального ветра, как было ранее найдено Шоберлем и Геллером (1976). Наши вычисления подкрепляют концепцию о том, что антропогенные влияния и внеземные эффекты в средней стратосфере могут иметь последствия для тропосферы, как уже обсуждалось ранее Бейтсом (1977) и Григером и Шмитцем (1978).