The Effect of Solar Tides on the General Circulation of the Martian Atmosphere

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ABSTRACT

The mean flow accelerations induced by solar tides in the Martian atmosphere have been calculated using separable tidal theory together with the thermal excitations of Leovy and Zurek (1979). The calculated accelerations are generally small in the dust-free Martian atmosphere, although they may be important in a small region near the surface. During global dust storms the tidally-induced mean flow accelerations are much larger and the tides probably play an important role in the general circulation.

1. Introduction

The effects of tidal heat and momentum transports on the zonally averaged circulation have been studied in both the terrestrial (Meyer, 1970; Fels and Lindzen, 1974; Miyahara, 1978a, 1978b) and Venusian (Fels and Lindzen, 1974; Plumb, 1975) atmospheres. It appears that in the Earth's atmosphere the solar diurnal tide forces significant mean zonal winds in the lower thermosphere (Miyahara, 1978a, 1978b) and may also be important in the general circulation of the mesosphere and upper stratosphere (Fels and Lindzen, 1974). The solar tides on Mars are known to be much stronger than those on the Earth (e.g., the ratio of the amplitude of the diurnal surface pressure oscillation to the mean surface pressure is typically 0.05% on the Earth and 2% on Mars) and thus their effect on the general circulation may be significant even at low levels in the Martian atmosphere. This is an issue of some importance since much of our understanding of Martian meteorology has come from experiments with comprehensive general circulation models (Leovy and Mintz, 1969; Mass and Sagan, 1976; Pollack *et al.*, 1981). While these models did include a diurnal cycle of incident solar radiation, they all employed very coarse vertical resolution (two or three levels) and a "rigid lid" upper boundary condition. These features may be adequate to simulate the structure of baroclinic waves, for example, but they are likely to present grave problems for the simulation of vertically propagating gravity waves such as the solar tides. Thus an understanding of tidal-mean flow interaction may be necessary in order to properly assess the validity of current general circulation models.

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The present paper reports the results of simple calculations of the tidally-induced mean flow accelerations in the Martian atmosphere. In Section 2 a description of the tidal calculations is given. The resulting mean flow accelerations are discussed in Section 3. Finally, in Section 4 an attempt is made to estimate the significance of these accelerations for the general circulation.

2. Tidal calculations

Calculations of the terrestrial tidal fields have usually been performed using "classical" tidal theory, i.e., the perturbations are assumed to occur about a mean state of no motion and the Earth is assumed to be a smooth sphere (e.g., Chapman and Lindzen, 1970). Unfortunately, the approximations made in the classical theory are less reasonable for applications to the Martian tides than they are for applications to the terrestrial tides. In particular the Martian surface topography may be sufficiently large to seriously affect the tidal fields (Zurek, 1976). However, Leovy and Zurek (1979) were able to simulate the observed diurnal and semidiurnal surface pressure oscillations at the two Viking lander sites reasonably well by using classical tidal theory together with simple thermal excitations.

The tidal fields used in the present work are very similar to those of Leovy and Zurek. They were calculated using the classical theory, and both the mean thermal structure and the thermal excitations were taken from Leovy and Zurek. The tidal fields were determined for clear and dusty atmospheric conditions. The "dusty" calculations employed Leovy and Zurek's heating profile III together with a value of their α_s parameter of 0.67 (which means that 67% of the incident solar beam is assumed to be directly absorbed by the atmosphere above the subsolar

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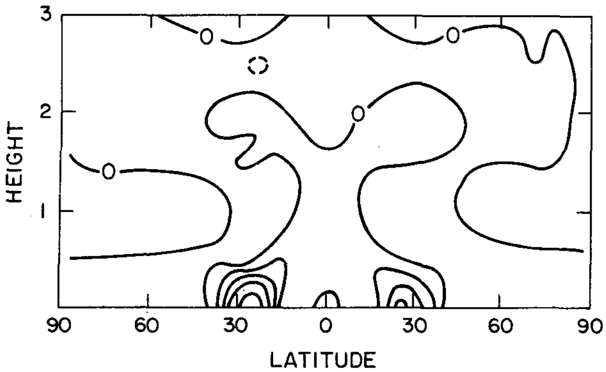

FIG. 1. The convergence of the Eliassen-Palm flux associated with the diurnal tide in the "clear" Martian atmosphere. The contour interval is 2 m s^{-1} (earth day)$^{-1}$ and dashed contours indicate easterly (westward) accelerations. The summer hemisphere is on the left. The solar declination in the calculations was 15°.

point). These calculations are appropriate for the mature stage of global dust storms. The "clear" calculations used Leovy and Zurek's heating profile I together with $\alpha_s = 0.10$ and are appropriate for a relatively dust-free atmosphere such as that which apparently existed during the early part of the Viking mission. The tidal fields were determined for a solar declination of 15° (corresponding to midsummer conditions).

The actual tidal computations were carried out using the method described in Chapman and Lindzen (1970). The vertical coordinate used throughout this paper is $z = \ln(p_s/p_0)$, where p_0 is the mean state pressure and p_s is p_0 evaluated at the surface ($z \times 12$ gives a rough estimate of the actual height above the surface in kilometers). The numerical solution of the vertical structure equation for each tidal Hough mode employed 2000 levels between $z = 0$ and $z = 25$, and provision was made for inclusion of Newtonian cooling.

3. Calculation of the mean flow acceleration

The acceleration of the zonal mean zonal wind induced by the heat and momentum transports associated with a wave cannot generally be written simply in terms of the local wave fields. However, Andrews and McIntyre (1976) showed that when certain scaling relations hold, the mean flow acceleration is approximately equal to the convergence of the Eliassen-Palm flux, i.e.,

$$\frac{\partial \bar{u}}{\partial t} = -\frac{1}{a\cos^2\theta}\frac{\partial}{\partial\theta}(\overline{u'v'}\cos^2\theta) - e^z\frac{\partial}{\partial z}(e^{-z}\overline{u'w'}) + fe^z\frac{\partial}{\partial z}(e^{-z}\overline{v'\phi_z'}/N^2),$$

where the notation is standard (e.g., Holton, 1975) and where effects of mean flow shear have been ignored. Andrews and McIntyre give the necessary scaling relations in detail. In particular they require that the vertical scale for variations in wave phase be much smaller than that for variations in the mean flow and that the mean flow Richardson number be much larger than one. Clearly these requirements are satisfied if, as has been assumed in the tidal calculations, the mean flow only negligibly affects the wave fields. In addition, Andrews and McIntyre require that the ratio of the vertical to meridional scales of the wave be close to the Prandtl ratio f/N. For an isothermal mean state with a temperature of 200 K (a reasonable approximation to the Leovy and Zurek temperature profile, at least above about a scale height in the atmosphere), the vertical wavelength associated with the main propagating diurnal tidal mode is ~35 km (and thus the vertical scale of wave phase variation is ~6 km). The meridional scale for this mode on Mars is ~1000 km and thus the ratio of vertical to meridional scales is $\sim 5 \times 10^{-3}$. This compares very well with the Prandtl ratio since $f \sim 7 \times 10^{-5}$ s^{-1} (at ~30° latitude) and $N \sim 10^{-2}$ s^{-1}. The agreement is less remarkable for the main semidiurnal mode since its vertical wavelength is over 150 km (even larger when a non-zero lapse rate is considered) and the meridional scale is only a little larger than that of the main propagating diurnal tidal mode.

Fig. 1 shows the convergence of the Eliassen-Palm flux as a function of height and latitude calculated from the "clear" tidal fields (which were determined with no Newtonian cooling).[2] The wave-induced accelerations in this figure are small everywhere except for two regions centered at ~ ±25° latitude and confined to about the lowest 5 km of the atmosphere. In the summer hemisphere the maximum accelerations exceed 8 m s^{-1} day^{-1}, while in the winter hemisphere they are slightly weaker. The significant accelerations are presumably confined near the ground because the thermal tidal forcing itself decays sharply with height in this case (Leovy and Zurek, 1979). When a Newtonian cooling profile similar to that used by Leovy and Zurek is included to damp the waves, the results are not greatly changed in the part of the atmosphere shown in Fig. 1 (at higher levels the Newtonian cooling has a considerable impact on the calculated accelerations). Calculations of the in-

[2] The results are shown only for $z < 3$ since Zurek (1976) found that the calculated diurnal tidal fields (with somewhat different thermal forcings) become gravitationally unstable at heights slightly above $z = 3$ in the clear case and slightly below $z = 3$ in the dusty case. Above these heights the linear theory used in the present study is presumably invalid.

duced accelerations associated with the solar semidiurnal tide were also performed. It was found that these accelerations were generally at least an order of magnitude smaller than those produced by the diurnal tide.[3]

Fig. 2 shows the accelerations determined from the "dusty" diurnal tidal fields (once again no Newtonian cooling was employed). In this case the thermal tidal forcing has a large vertical extent (from $z = 0$ to about $z = 6$). These results indicate that the tidally-induced accelerations are very large over much of the atmosphere during global dust-storm conditions. The inclusion of Leovy and Zurek's Newtonian cooling profile in the tidal calculations has little effect on the results shown in Fig. 2 [although it appears from Zurek (1976) that considerably larger values of the Newtonian cooling coefficient might be appropriate for dust-storm conditions]. The mean flow accelerations induced by the semidiurnal tide in the dusty Martian atmosphere were found to be considerably smaller than those associated with the diurnal tide.

The pattern of alternating layers of easterly and westerly acceleration seen in Fig. 2 is similar to that found by Fels and Lindzen (1974) in the terrestrial stratosphere and mesosphere. This is a consequence of the large vertical extent of the excitation region and (as explained in Fels and Lindzen) is essentially an interference effect. The fact that the accelerations peak in the subtropics of both hemispheres apparently results from the strong thermal forcing of the tide in the lowest few scale heights of the atmosphere, which manifests itself in the term

$$fe^{z}\frac{\partial}{\partial z}(e^{-z}\overline{v'T'_0}/N^2),$$

in the Eliassen-Palm theorem of Andrews and McIntyre (1976). In this expression T'_0 is the value of ϕ'_z which would be produced by the forcing in the absence of a dynamic response. Even for an equatorially trapped symmetric tidal mode this term peaks off the equator since both f and v' are antisymmetric in θ. This tendency for the accelerations to peak off the equator is even more pronounced in Fig. 1. This seems to be related to the dominance of the main trapped diurnal mode (which has a temperature perturbation which peaks in mid-latitudes) in the response. This is particularly important since the Leovy and Zurek (1979) thermal excitation for

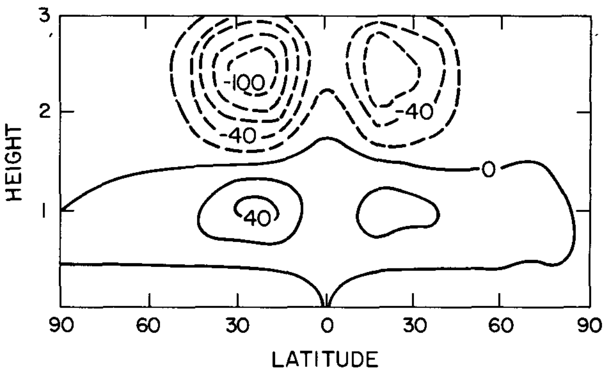

FIG. 2. As in Fig. 1, but for global dust storm conditions. The contour interval is 20 m s^{-1} (earth day)$^{-1}$.

the clear Martian atmosphere has a vertical phase propagation and thus the so-called trapped mode can actually transport momentum (even in the absence of propagating modes).

4. Discussion

It is difficult to determine the precise effects that the mean flow accelerations calculated in the previous section ought to have on the Martian general circulation. However, an estimate of the importance of the tidally-induced accelerations can be made by comparing them with the Coriolis torque $f\bar{v}$ associated with the mean meridional circulation simulated by the general circulation models mentioned in the Introduction. In particular Pollack *et al.* (1981) present the $\bar{v}$ distribution simulated by their model of the clear Martian atmosphere at solstice (see their Fig. 6). In the tropics and subtropics Pollack *et al.* obtained mean meridional winds with magnitudes as large as five or six m sec^{-1}. At 25° latitude such winds produce Coriolis torques of the order of 30 m s^{-1} day^{-1}, i.e., considerably greater than even the largest of the tidally induced accelerations found in the "clear" atmosphere. However, the mean flow accelerations calculated for global dust storm conditions are comparable to or even larger than the Coriolis torques in the model of Pollack *et al.* Although one might anticipate a stronger mean meridional circulation if their model were run with a dusty atmosphere, it still seems probable that the tidal heat and momentum transports play a significant role in the general circulation during global dust storms. It should be noted that even in the absence of a global dust storm there may at times be considerable dust in the Martian atmosphere (e.g., Leovy and Zurek, 1979; Pollack *et al.*, 1981) and the heating rates used in the "clear" calculations are probably something of an underestimate for these periods.

[3] Miyahara (1978a,b) also found that in the terrestrial atmosphere the effects of the semidiurnal tide were much smaller than those of the diurnal tide. This is presumably to be attributed to the smaller excitations and longer vertical wavelengths of the semidiurnal tidal modes.

It is interesting to note that zonally-symmetric model simulations of the Martian atmosphere during global dust storm conditions by Haberle *et al.* (1982) produce a temperature at the winter pole which is much less than that actually seen in the 15 micron brightness measurements of Martin and Kieffer (1979), which give temperatures representative of heights around $z = 2.5$. The easterly accelerations shown in Fig. 2 between $z \approx 1.5$ and $z \approx 3.0$ ought to be associated with a mean meridional circulation with sinking motion (and adiabatic warming) at the pole and this might help resolve the discrepancy between the calculated and observed polar temperatures.

A final point which should be considered is how well general circulation models might represent the tidally-induced mean flow acceleration. Fig. 3 shows a comparison of the equatorial accelerations in the dusty atmosphere determined from diurnal tidal fields calculated in the manner described in Section 2 with those determined from tidal fields calculated with a rigid lid upper boundary condition imposed at $z = 3$. If these calculations are performed without any damping of the tide the accelerations in the rigid lid case are identically zero. Thus, the calculations

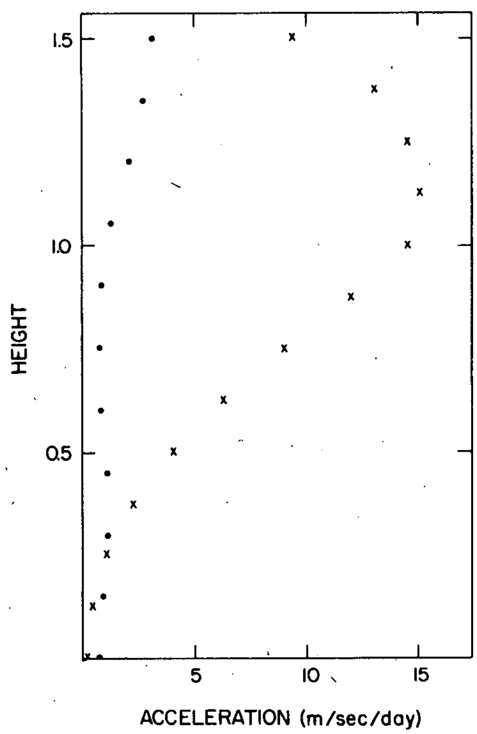

FIG. 3. The calculated mean flow accelerations at the equator obtained with a rigid lid (circles) and with a radiation condition (crosses). All accelerations are easterly. The solar declination was 15°.

TABLE 1. The equatorial mean flow accelerations induced by the diurnal tide at various heights as a function of the vertical resolution of the tidal calculations. The solar declination was 15° and no Newtonian cooling was used in the calculations. The units are m s^{-1} (Earth day)$^{-1}$.

Δz	$z = 0.5$	$z = 1.0$	$z = 1.5$	$z = 2.0$
0.5	−3.58	−9.25	−2.78	15.67
0.25	−5.02	−10.45	−3.31	12.66
0.10	−4.11	−11.28	−5.35	10.57
0.0125	−3.56	−11.16	−6.51	8.99

which produced the results shown in Fig. 3 included the Newtonian cooling profile of Leovy and Zurek (1979). It can be seen that the accelerations in the rigid lid case are still severely underestimated. This is presumably a reflection of the fact that the violation of the Eliassen-Palm theorem in this case is due mostly to wave forcing rather than wave dissipation.

Table 1 shows results for the equatorial accelerations obtained from tidal calculations performed with a radiation condition applied at a very high level, but with varying vertical resolutions. It can be seen that calculations employing vertical resolution comparable to that used in current models (i.e., $\Delta z \approx 0.5$) lead to accelerations which can be significantly in error. Thus it appears that general circulation models of the dusty Martian atmosphere ought to have fairly good vertical resolution and (more importantly) ought to avoid using a rigid lid boundary condition (although it is possible that the problems associated with the upper boundary condition may be largely eliminated by placing the upper boundary one or two scale heights above the level at which the tidal fields become gravitationally unstable).

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