MIGRATING DIURNAL TIDE IN THE MARTIAN ATMOSPHERE: NUMERICAL INVESTIGATIONS.

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Introduction

The existence of the thermal tides in the Martian atmosphere was established by spacecraft observations [e.g., *Conrath et al.*, 1973; *Leovy and Zurek*, 1979]. These observations revealed that the amplitudes of thermal tides in the Martian atmosphere are very large. These thermal tides with large amplitudes are considered as important components of general circulation. Therefore, these have been studied in detail not only by the observations but also by the theoretical method.

The past theoretical studies on the thermal tides in the Martian atmosphere were mainly based on the classical tidal theory. For example, *Zurek* [1976] extended the classical tidal theory to include the orographic effect, and investigated the nature of diurnal tides excited by idealized heat sources. He showed basic structures of diurnal tides and implied the turbulent mixing which would be caused by diurnal tides with large amplitude. Based on the results of classical tidal theory, Hamilton [1982] and *Zurek* [1986] showed that large amplitude thermal tides may cause strong zonal accelerations during dust storms.

Recently, several Martian atmospheric General Circulation Models (GCMs) have been developed, and were used to investigate thermal tides in the Martian atmosphere. *Wilson and Hamilton* [1996] showed the structure of migrating diurnal tide at northern winter solstice obtained from their GCM. They implied that Doppler shift by the mean wind may cause the wave structures asymmetric with respect to the equator.

Past studies based on classical tidal theory only examined the diurnal tides excited by idealized heat sources. The nature of thermal tides excited by realistic heat sources is not understood. The effects of dissipations and mean wind cannot be understood by the classical tidal theory. Because many processes are included in GCM, it is difficult to understand the effect of each process on the wave structures. In terms of effects of thermal tides on the meridional circulation, almost all past studies were also based on classical tidal theory. The effects of thermal tides on the meridional circulation under the condition with a lot of heat sources, dissipation and mean wind may be different from those expected from classical tidal theory.

In this study, we focus our attention on migrating diurnal tide. Using numerical models, we investigate 1) the excitation sources and the propagation characteristics under realistic conditions, and 2) the effects of migrating diurnal tide on the meridional circulation and dust transport. We use Mars GCM and linear response model to investigate these issues. To understand the basic characteristics of migrating diurnal tide, we perform the numerical experiments using linear response model as well as we analyze the GCM result. Furthermore, we diagnose the force balance in the meridional circulation to reveal the importance of migrating diurnal tide in the meridional circulations.

Models

Martian atmospheric general circulation model (GCM)

The Martian atmospheric general circulation model (GCM) used in this study is a spectral model based on the primitive equation system. The horizontal resolution is spectral triangular 10 (T10), roughly equivalent to a $11.25^\circ \times 11.25^\circ$ latitude-longitude grid. The vertical domain extends from the ground up to 9.3×10^{-7} hPa pressure level, which is located around 120 km altitude. This vertical domain is divided into 35 layers. As for the radiative process, the effects of CO_2 and dust suspended in the atmosphere are considered in the model. Except for some dust transport experiments, we assume horizontally uniform dust distribution with the vertical profile of *Conrath* [1975]. In the model, the surface temperature is calculated from the heat balance equation at the ground surface and the thermal conduction equation of the subsurface soil. Through the radiative heating and diurnal variation of surface temperature, migrating diurnal tide automatically excites in the model.

Linear response model

The linear response model used in this study is based on the linearized primitive equation system. This equation system is solved by spectral method similar to that used in our GCM. In the linear response model, we neglect the effects of zonal mean zonal wind, zonal mean meridional temperature gradient, and topography. This framework of linear response model is the same as classical tidal theory except for the inclusion of transience and dissipations. The horizontal resolution and the vertical extent of the model are same as those of the GCM. The vertical resolution is 1/10 scale height.

The Newtonian cooling coefficient is given as a function of pressure and is obtained from *Forbes and Hagan* [2000]. The global mean temperature profiles, distributions of eddy diffusion coefficients, distributions of heat-

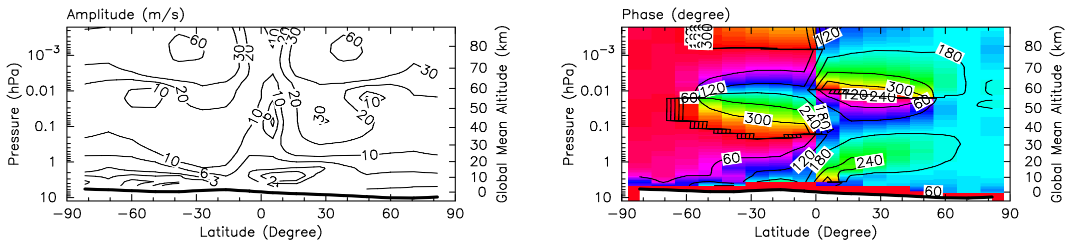

Figure 1: Amplitude and phase of northward wind component of migrating diurnal tide in the GCM at northern vernal equinox ($L_s \sim 0°$) under the typical dust condition ($\tau \sim 0.3$). Phase indicates the longitude of maximum at UT = 0.

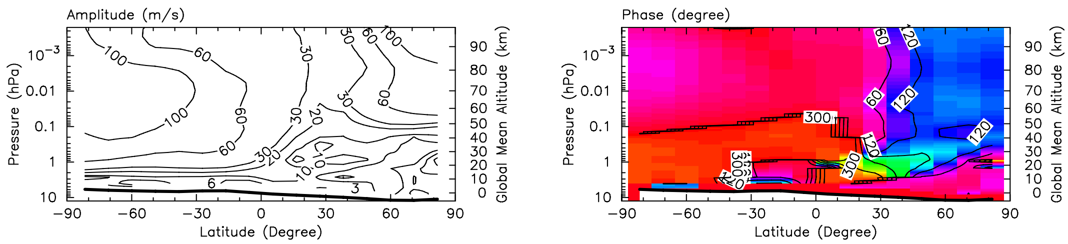

Figure 2: Same as Figure 1, except for the season, northern winter solstice ($L_s \sim 270°$) under dust storm ($\tau \sim 5$).

ing rates which correspond to migrating diurnal mode are obtained from GCM. In order to obtain steady state solution, this linear response model is run for 200 sols from an initial condition at rest. For first 100 sols from initial conditions, heating rates are gradually increased to avoid numerical instabilities as was done by *Miyahara* [1981].

Basic characteristics of migrating diurnal tide

First of all, basic structures of migrating diurnal tide in GCM are examined. The amplitude and phase of northward wind component of migrating diurnal tide at northern vernal equinox ($L_s \sim 0°$) under the typical dust condition (visible dust optical depth $\tau \sim 0.3$) show almost symmetric wave structure with respect to the equator (Figure 1). Vertically propagating mode dominates in the low latitude region, while evanescent mode dominates in the high latitude region. The vertical wavelength of propagating mode in the low latitude region is ~40-50 km, which is larger than that predicted by the classical tidal theory (~30 km). Detailed examination of amplitude reveals that the amplitude is much smaller than that expected when any dissipation processes are not present.

At northern winter solstice ($L_s \sim 270°$) under the typical dust condition, the wave structure is asymmetric with respect to the equator as is shown by *Wilson and Hamilton* [1996]. The asymmetric wave structure is more pronounced in the case under dust storm condition ($\tau \sim 5$, Figure 2). In addition, the amplitude of the wave is very large in the case under dust storm condition.

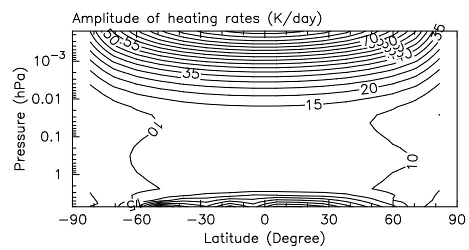

Figure 3: Amplitude of heating rates which corresponds to the migrating diurnal tide at northern vernal equinox ($L_s \sim 0°$) under the typical dust condition ($\tau \sim 0.3$). Contour interval is 5 K/day.

In order to understand the excitation sources of migrating diurnal tide, we examine the distribution of heating rates which corresponds to migrating diurnal mode. Figure 3 shows the amplitude of heating rates which corresponds to migrating diurnal tide at northern vernal equinox ($L_s \sim 0°$) under the typical dust condition ($\tau \sim 0.3$). The excitation sources are composed of 3 types of heating: 1) heating associated with surface (0–10 km), 2) dust heating (0–40 km), 3) solar near infrared heating (> 60 km). Heating associated with surface are caused by the radiative process and the sensible heat flux convergence. The magnitude of heating associated with surface is large (~40 K/day), but the vertical extent of that is limited just above the surface. We examine the distributions of heating rates at northern winter solstice ($L_s \sim 270°$) under the typical dust condition ($\tau \sim 0.3$) and that under dust storm condition ($\tau \sim 5$). In both cases, the excitation sources are also composed of 3 types of heating similar to those observed in the case at equinox condition. However, there are large asymmetric components with respect to the equator at solstice conditions.

Using the heating rates obtained from analyses of GCM results, we calculated linear responses to those heating using the linear response model. Migrating diurnal tide at northern vernal equinox ($L_s \sim 0°$) under the typical dust condition ($\tau \sim 0.3$) obtained from the linear response model show the symmetric wave structure with respect to the equator (Figure 4). As is the migrating diurnal tide in GCM, vertically propagating mode dominates in low latitude region, while evanescent mode dominates in high latitude region. The amplitude is also smaller than that expected when any dissipation processes are not present, as is observed in the GCM. The vertical wavelength of propagating mode in linear response model is different from that in GCM, and is ~30 km.

Migrating diurnal tides at northern winter solstice ($L_s \sim 270°$) under the typical dust condition ($\tau \sim 0.3$) and under the dust storm condition ($\tau \sim 5$) obtained from the linear response model show slight asymmetric wave structure with respect to the equator. However, the wave structures in the linear response model are much more symmetric with respect to the equator compared to those obtained from the GCM.

It is considered that the smallness of amplitude may be caused by dissipation processes in the models, e.g., Newtonian cooling and eddy diffusion. In order to understand the cause of small amplitude, we performed numerical experiments. The first case only includes Newtonian cooling as a dissipation process, and second case only includes eddy diffusion. The first case shows small amplitude similar to that observed in GCM, while the second case shows large amplitude compared to that observed in GCM. As a result of these numerical experiments, it is revealed that the radiative cooling plays an essential role for migrating diurnal tide in the Martian atmosphere.

The causes of differences in vertical wavelength at equinox condition and wave structures at solstice conditions are considered to be the effects of mean wind and the meridional temperature gradient. It is known that the mean wind and the meridional temperature gradient result in the mode coupling [*Forbes and Hagan*, 1988]. Our results imply that the effects of mean wind may be important and have important impact not only on the asymmetric structure of the tides but also on the vertical wavelength of the migrating diurnal tide in the Martian atmosphere.

Effects of migrating diurnal tide on meridional circulation

In order to examine the effects of migrating diurnal tide on the meridional circulation, we examine the contribution of the acceleration caused by migrating diurnal tide to the force balance in the meridional circulation. Transformed Eulerian Mean (TEM) diagnostics show that the acceleration caused by migrating diurnal tide play an important role to drive meridional circulation at northern vernal equinox ($L_s \sim 0°$) under the typical dust condition ($\tau \sim 0.3$). The importance of migrating diurnal tide can be realized when we compare the intensities of meridional circulations in two cases. In one case, the diurnally varying solar insolation is imposed, and diurnally averaged insolation is imposed in the other case. The meridional circulation obtained in the case with diurnally varying insolation is about 2–3 times stronger than that in the case with diurnally averaged insolation. Detailed examination of Eliassen-Palm (EP) flux divergence and wave structure of migrating diurnal tide revealed that the excitation and damping of migrating diurnal tide caused by dust heating result in the strong acceleration.

We examine the force balance in meridional circulation at northern winter solstice ($L_s \sim 270°$) under dust storm condition ($\tau \sim 5$). TEM diagnostics show that the acceleration caused by migrating diurnal tide plays an important role in the southern hemisphere below ~40 km altitude. This strong acceleration drives meridional circulation with rising blanch around 60° S and descending blanch in the southern high latitude. In order to examine the effects of this meridional circulation on the dust transport, we performed two passive dust transport experiments. In one case, the diurnally varying insolation is imposed, and the diurnally averaged insolation is imposed in the other case. In the case with diurnally varying insolation, dust amount southward of ~60° S is about 2 times smaller than that in the case with diurnally averaged insolation (Figure 5). This reduction of dust in the southern high latitude region is caused by the meridional circulation driven by the acceleration caused by migrating diurnal tide mentioned above. This result implies that the migrating diurnal tide in the Martian atmosphere may play an important role to determine the dust distribution during dust storm condition.

References

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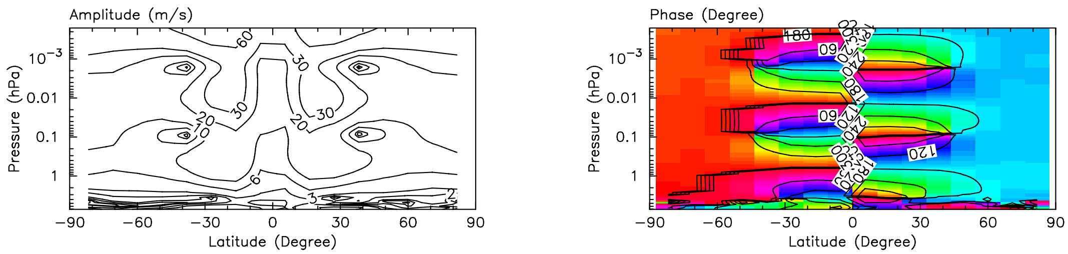

Figure 4: Amplitude and phase of northward wind component of migrating diurnal tide obtained by the linear response model at northern vernal equinox ($L_s \sim 0^\circ$) under the typical dust condition ($\tau \sim 0.3$). Phase indicates the longitude of maximum at UT = 0.

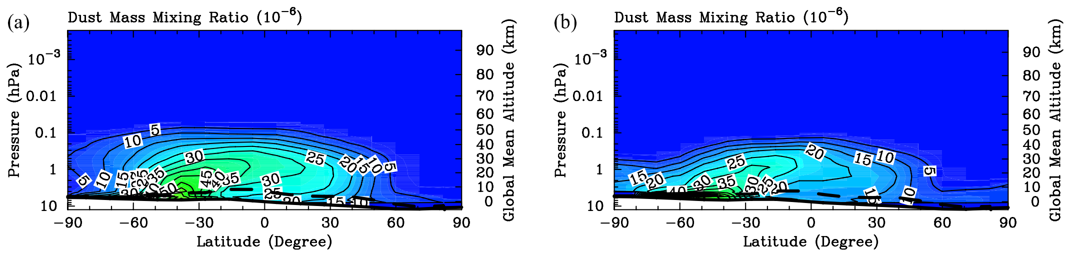

Figure 5: Distribution of dust mass mixing ratio at northern winter solstice ($L_s \sim 270^\circ$) under dust storm condition ($\tau \sim 5$): (a) the case with diurnally varying insolation, (b) the case with diurnally averaged insolation.

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