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Dynamical processes of dust lifting in the northern mid-latitude region of Mars during the dust storm season☆

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A B S T R A C T

The general circulation model MarsWRF has been used to simulate the regular dust climate on Mars. In particular, the double-peak episodes of dust storm activities during the dust storm season can be captured with the use of an active dust lifting scheme in the model. This study focuses on the dynamical processes of dust lifting in the northern mid-latitude region during these episodic periods. Wavelet analysis to the time series shows that dust lifting activities are associated with three distinct modes of variability. The first is the high frequency signal with a period of 0.5 to 1 sol, which is generally associated with the thermal tide. The second mode has the period about 7 sols, which is generally associated with the mid-latitude planetary waves. The third mode has the period over 50 sols, which is basically the signal of seasonal change in the region. Further analysis on wave numbers suggests that the dust lifting processes are dominated by the mode around wave number three. Results of sensitivity experiments also suggest that topography in the northern mid-latitude region is important to the lifting of dust in the period around 1 sol.

1. Introduction

Previous observations (e.g., Montabone et al., 2015; Kass et al., 2016) show that the regular annual activity of Martian dust storms is concentrated in the second half of the Martian year (solar longitude Ls = 180 - 360°). However, even in this period of "dust storm season", dust storms are not prevailing all the time but are more active in two episodic periods (Ls = 220° - 260° and Ls = 310° - 340°). Between these two periods dust storms are significantly less. This double-peak occurrence of dust storms with a quiet period in between has been identified in some observational studies and is usually referred as the "solsticial pause" (e.g., Wang and Richardson, 2015; Kass et al., 2016; Lewis et al., 2016).

During the double-peak episodes, relatively frequent occurrence of dust storms can be observed over the northern mid-latitude region (e.g., Cantor et al., 2001; Wang, 2007; Guzewich et al., 2015; Lemmon et al., 2015; Wang and Richardson, 2015). In fact, Hollingsworth et al., (1996) has suggested that a storm zone as on Earth can also be identified on Mars. From these previous studies (e.g. Hollingsworth et al., 1996), the favorite originating regions include the Acidalia region, followed by the Utopia and Arcadia regions. In particular, the dust storms initiated over Acidalia are far more than the others (Wang and Richardson, 2015; Hinson et al., 2012; Guzewich et al., 2015). These three regions are all located downstream of three high topographic regions of Alba Patera, Syrtis Major and Elysium. In some occasions, the initiated dust storms may "flush" southward and cross the equator, and may strengthen again in the southern hemisphere (Cantor et al., 2001; Wang et al., 2003, 2005; Wang 2007). This southward transport of "flushing storms" would help distribute the dust to the southern hemisphere, and also affect the general circulation.

The frequent occurrence of dust storms over the northern mid-latitude region during the dust storm season has been suggested to be related to the transient mid-latitude wave activities (e.g. Barnes, 1980; Hinson and Wang, 2002; Banfield et al., 2004; Hollingsworth and Kahre, 2010; Kass et al., 2016). Therefore, many previous studies have been devoted to investigate the characteristics of these waves (e.g., Wang et al., 2005; Kuroda et al., 2007; Kavulich et al., 2013; Hinson and Wang, 2010; Hinson et al., 2012; Wang et al., 2013; Wang and Toigo, 2016). In the studies, wavelet or spectrum analysis were mainly focused on the zonal decomposition of the signals, and the results generally suggest that the dominant zonal wave number of the waves is 2 to 3 with the dominant period between 2 to 4 sols during the double-peak episodic periods of dust events, while they are suppressed during the solstice period. The dominated waves during the solsticial pause

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have a zonal wave number 1 with the period of 6 to 7 sols and are located at higher altitudes (Read and Lewis, 2004; Kuroda et al., 2007; Hinson and Wang, 2010; Read et al., 2011; Hinson et al., 2012; Wang and Richardson, 2015; Wang and Toigo, 2016; Lewis et al., 2016). Furthermore, some previous studies (e.g., Hinson and Wilson, 2002, Banfield et al., 2004) suggest that the strongest waves during the storm season (dominated by zonal wavenumber 2 ~ 3) are generally more significant in the lower level of the atmosphere, which may result in perturbations of the low-level temperature (up to ~7 K) and wind speed (10 - 15 ms^{-1}).

Since most observations show a high correlation between planetary wave activities and dust storms (e.g., Hinson et al., 2012), the above mentioned previous studies have focused more on planetary wave activities, particularly the zonal wave numbers. On the other hand, the processes of dust lifting with short period in the scale around one sol were generally not considered. This may be due to two reasons. First, most of these observations are based on remote sensing in Sun-synchronous orbits (such as MGS and MRO, Montabone et al. 2015), and so the temporal resolution are limited (no more than two times per day) at one location. As a result, some dust lifting process with short time scales might not be detected. Second, many previous numerical studies used the prescribed dust approach (actually the optical depth) to realistically simulate the observed general circulation (e.g., Kuroda et al., 2007; Mulholland et al., 2016), which is generally not well simulated by using the approach of active dust parameterizations. Although dust lifting processes with short time were usually not considered, their importance should not be ignored. In one recent simulation study by using a Mars GCM (with active dust parameterization), Hollingsworth and Kahre (2010) show that dust can be lifted by the nocturnal down-slop winds over the Tharsis volcanoes and Alba Mons, and then transported to the downstream regions along with the transient frontal systems.

The present study focuses more on the dynamics pertinent to dust lifting, and the analysis is mainly on the dynamics near the surface. In addition, the effect of asymmetric topography in the northern mid-latitudes on the waves and dust lifting has been investigated. In this study, the general circulation model MarsWRF with active dust parameterization scheme is used to study the characteristics of the northern mid-latitude waves pertinent to dust lifting. In Section 2, the numerical model used in this study and the basic configurations of the simulations will be introduced. The dynamic processes contributed to the mid-latitude dust storms simulated by the model will be analyzed and discussed in Section 3. The effect of the northern mid-latitude topography on the waves and dust lifting will be discussed in Section 4, and the results of this study will be summarized and discussed in Section 5.

2. The numerical simulations

The general circulation model (GCM) MarsWRF has been used in this study, which is developed from the widely-used WRF model for Earth's weather research and forecasting (Skamarock and Klemp, 2008). MarsWRF is basically the Mars version of the PlanetWRF model (Richardson et al., 2007), and has been illustrated in Richardson et al. (2007) and Toigo et al. (2012) that it is capable of realistically reproducing most climate features such as the large-scale general circulation and temperature field on Mars. The basic configuration of the simulations is generally similar to that used in Chow et al., (2018), as described in the following. The global domain of the model has 36 latitude × 72 longitude grid points (horizontal spatial resolution of about 5° or 300 km in the equatorial region). There are 52 vertical levels in terrain-following hydrostatic-pressure vertical coordinate (Skamarock and Klemp, 2008), and the model top is set at 0.0057 Pa (about 80 km in altitude). Half of these 52 levels are located between the model top and the pressure level of 100 Pa. Non-hydrostatic dynamics is used for the model runs and the damping flag at upper levels is turned off. The 3rd order Runge-Kutta scheme is adopted for the time-integration. The advections of momentum and scalar variables have 5th order and 3rd order accuracy in the horizontal and vertical directions respectively. To deal with the turbulence and mixing processes, the 2nd order diffusion terms are evaluated on coordinate surfaces and the eddy coefficient is given by the horizontal Smagorinsky first order closure theory. In addition, some other filters like the divergence damping and external-mode filter are applied with typical strength.

The physical processes chosen in the simulations are suitable for the Martian environment. The radiation scheme for short- and long-wave radiation employed in these simulations is the "wide band model" scheme as described in Richardson et al. (2007), Toigo et al. (2012) and Newman and Richardson (2015). This scheme considers the heating/cooling effects of dust and the phase change of carbon dioxide (CO_2). The planetary boundary layer scheme and land surface scheme were largely adapted from existing terrestrial schemes in WRF (see Richardson et al., 2007 and Toigo et al., 2012). In particular, the friction velocities and exchange coefficients are calculated by the WRF SFCLAY Monin–Obukhov surface-layer scheme (Jiménez et al., 2012), which are then used to calculate the heat and moisture fluxes by the land-surface and boundary-layer models. The Martian 12-layer subsurface diffusion scheme is used as the land-surface model and the Medium Range Forecast Model (MRF) boundary layer scheme is employed to deal with an unstable boundary layer (Hong and Pan, 1996). The model also includes other physical process parameterizations specific to Mars, such as the carbon dioxide cycle (Guo et al., 2009) and the dust lifting process (Newman and Richardson, 2015). However, no parameterization of the water cycle is included in these simulations.

The parameterization of dust processes in the model includes two interactive dust schemes similar to those used in Newman and Richardson (2015), and dust is assumed to be available everywhere and at all times over the whole planet surface except those surfaces with ice cover. The first scheme is similar to some usual dust models on Earth, in which the lifting of dust is proportional to the surface wind stress. Dust lifting occurs over the surface when the local near-surface stress exceeds a particular threshold value (constant value 0.043 $N\ m^{-2}$ in this study). The second scheme provides most of the background dust, which is parameterized as dust lifting by dust devils. The amount of dust lifting is dependent on the temperature difference between the surface and the air above, as well as the sensible heat flux. The radiation scheme in the model is interactive with dust so that the suspended dust may change the atmospheric radiation and thus the circulation. Dust particle size may have important effect on the radiation and dust sedimentation processes. In this study, the model considers dust particles have two sizes of 1 and 2 μm. The averaged mixing ratio of these two kinds of dust particles is considered as the mixing ratio of the dust particles in the atmosphere. In general, the parameters in the two-size dust lifting schemes are adjusted to simulate the observed dust climatology.

The model was run for two Martian years, initially starting from the time of northern spring equinox (L_S = 0°), and the output interval is 2 h. The first year is considered as the spin up period. For the analysis of dust lifting dynamics discussed in the following sections, the simulation result of the second year of model run is considered. This single-year model run will be referred as the control experiment (CTRL) hereafter.

The vertical profiles of temperature and zonal wind (Fig. 1) from CTRL suggest that the model is capable of simulating the regular dynamic field of Mars during the solstice period (L_S = 265° - 275°). The temperature profile (Fig. 1a) has the maximum (over 240 K) near the surface in the middle to high latitude region in the southern hemisphere, while the minimum temperature (less than 140 K) is located at the altitude about 40 km near the north pole. The warm and cold polar air masses establish a strong meridional temperature gradient region in the latitudes between 30° to 70° N. The gradients are tilting northward with height similar to the polar front on the Earth. Corresponding to the thermal field, the global circulation contains a cross-equatorial overturning cell stretching from 60° S to 45° N, and a westerly jet (maximum