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Review Article

Influence of dust on the dynamics of the martian atmosphere above the first scale height

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ABSTRACT

Dust suspended in the martian atmosphere strongly affects the radiative transfer. Diabatic heating and cooling it creates are prominent factors that drive the atmosphere at various scales. This paper provides a review of dust influence on the large-scale dynamics in the atmosphere of Mars above approximately 10 km. We outline the established properties of dust that influence the diabatic heating/cooling rates, and summarize the current knowledge of dust-related effects on the zonal-mean circulation and zonally asymmetric disturbances: planetary waves and tides.

Contents

1. Introduction

Airborne dust suspended in the dry atmosphere of Mars plays a role in many ways similar to the role of water on Earth. Being strongly radiatively active, dust absorbs solar radiation and emits in the infrared. The created local heating and cooling affects the atmospheric dynamics at various scales: from synoptic and meso-scale weather systems (martian meteorology) to the large-scale circulation and climate. A "dust cycle" on Mars with lifting from the surface, transport, and sedimentation back to reservoirs resembles the "water cycle" on Earth. Many martian weather

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phenomena are associated with dust: storms from local to regional and global ones, dust devils (Balme and Greeley, 2006), "cells" (Cantor et al., 2002), clouds (Clancy et al., 2003), and plumes (Fuerstenau, 2006). These similarities with the terrestrial hydrometeorology prompted Heavens et al. (2011b) to introduce the term "coniometeorology" (from the Greek word *konios* for "dust") to characterize the martian weather.

This paper is a review of the current knowledge of dust effects on the global-scale atmospheric dynamics of Mars. Most of meteorological phenomena are associated with the lower atmosphere where the influence of the surface is strong. In the dynamical meteorology of Earth, the definition of the "lower" atmosphere is vague, and most often means the troposphere. The martian troposphere, an atmospheric layer with vertically decreasing temperature, extends much higher, to 40–60 km. The martian middle atmosphere lies above, and covers the altitudes to 110–130 km. In this survey, the emphasis is placed on the layer which is little directly affected from below by convection, and, from above, by heating due to absorption of extreme ultraviolet and energetic particles. It corresponds to the altitudes between ~10 and 110–130 km, that is, coincides with the troposphere above approximately one scale height and the middle atmosphere of Mars. Therefore, we leave out of scope a large body of studies, which concern mechanisms of dust lifting and interactions with synoptic-scale disturbances, and focus on effects of the dust already injected in the air.

The most spectacular phenomena are the dust storms that regularly reach planetary scales. They sometimes obscure almost all the surface of the planet. Earlier observations of these storms on Mars started in the beginning of the 20th century with ground-based telescopes (Briggs et al., 1979, and references therein). Since the 1970s, landers and spacecraft inserted into the Mars orbit provided much more details. Orbital cameras and infrared spectrometers mapped the spatial and seasonal changes of the dust opacity (Thorpe, 1979, 1981; Martin, 1986). It was found that the storms occur systematically when Mars is near perihelion. Even during the clearest parts of the year, the dust optical depth remains relatively high: $\tau = 0.2–0.4$ in visible wavelengths. Absorption of solar radiation by dust is comparable with that of CO_2 gas, which the atmosphere of Mars mainly consists of. Thus, while heating/cooling by CO_2 maintains the martian climate, atmospheric dust determines a variability of the circulation and weather, very much like the water on Earth.

We begin with the overview of main features of Mars and martian atmosphere in Section 2, and then consider dust properties and observational constrains that control the dust-induced diabatic heating and cooling of the air in Section 3. An approach to analyzing the global-scale circulation is outlined in Section 4. The influence of dust on the zonal-mean circulation and zonally-asymmetric eddies are discussed in Sections 5 and 6, correspondingly.

2. Basic facts about the martian atmosphere

Mars is the second best-studied planet after the Earth. It is often called a "terrestrial-like" planet. Comparison of main physical parameters for Mars and Earth are given in Table 1. Martian radius is about a half, and gravity acceleration is ~0.38 that of Earth. However, its surface area is only slightly less than the total area of Earth's dry land. The martian atmosphere is very thin (the surface pressure is about 6 mbar, which is more than 150 times smaller than on Earth), and very dry (there is virtually no water except in subtropics in the northern summer and in polar regions). It consists mainly of CO_2 (95.3%) with other important constituents being N_2 (2.7%), Ar (1.6%), O_2 (0.15%) and H_2O (0.03%). Since the rotation period and orbit inclination of Mars and Earth are similar, the diurnal and seasonal variations are similar as well. Because martian atmosphere is less dense, the difference of temperature between day and night is significantly larger. For instance, the atmospheric temperature near the surface varies between approximately 200 and 260 K at the summer subtropics, according to the Mars Pathfinder observations (Schofield et al., 1997). Due to the colder temperatures, the atmospheric component of CO_2 condenses at the polar regions during winters (e.g., James et al., 1992), and the averaged surface pressure on Mars varies annually within the range of 25%. Although the atmospheric air is thin, winds on Mars are strong. They can lift in the air millions of tons of dust particles during planetary-scale dust storms, which make the atmosphere opaque.

Martian dust storms have been observed since the end of the 19th century. A comprehensive list of such activities from 1873 to 1990 is presented in Table 1 of Martin and Zurek (1993). Most of the global-scale dust storms occurred near or before southern summer solstice, which is close to the perihelion. They started as regional storms at elevated plateaus located in low- and mid-latitudes, and then expanded in the east-west direction to encircle the planet in 10–20 days, and to last for 50–100 days before decaying. Many regional dust storms have been observed at the edge of receding south polar cap (Briggs et al., 1979), and in northern mid-latitudes during equinoxes (James et al., 1999), all of them being associated with frontal systems. Various mechanisms of dust expansion processes, such as "dust hurricanes" (Gierasch and Goody, 1973), diurnal Kelvin tidal mode (Zurek and Leovy, 1981), have been discussed. In the recent decade, the processes of dust lifting and transport have been studied extensively using martian general circulation models (GCMs) (Newman et al., 2002a,b; Wang et al., 2003, 2005; Basu et al., 2004, 2006; Kahre et al., 2006, 2008).

3. Properties of the airborne dust

3.1. Seasonal and spatial distributions

Martian atmospheric dust consists of mineral particles eroded from rocks. It is continuously supplied from the martian surface owing to two physical processes: the near-surface wind stress (e.g., Greeley and Iversen, 1985), and small-scale convective vortices ("dust devils") clearly observed from the Mars Exploration Rover Spirit (Greeley et al., 2006). The amount of airborne aerosol is highly variable with most of the dust storm activity occurring in southern springs and summers. Because of the large orbit eccentricity (0.0934), the planet receives 1.3 times more of solar radiation near the perihelion, which almost coincides with the southern summer solstice (aerocentric longitude $L_s = 270°$). Therefore, the lower atmospheric convection and meteorological processes are more violent during this season compared to northern springs and summers. The scales of dust storms that occur in this period vary from year to year, and range from regional to planet-wide. In the southern spring and summer, the observed maxima of the mean dust opacity over the equator are between 0.25 and

Table 1
Comparison of physical parameters of Mars and Earth.

Parameters	Mars	Earth	Unit
Radius of planet	3397	6378	km
Acceleration of gravity	3.72	9.8	$m\ s^{-2}$
Rotational period	88,775	86,400	s
Amount of solar radiation	589.2	1367.6	$W\ m^{-2}$
Sols per a year	669	365	sol
Eccentricity	0.0934	0.0167	–
Angle of equator inclination	25.19	23.45	°
Mean surface pressure	6	1013	mbar
Mean surface temperature	230	288	K