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Global impact of Mars dust storms on the plasma environment and implications for atmospheric carbon loss

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Abstract

We present the first attempt to globally investigate how the dust impact transfers from the upper atmosphere to the ionosphere and the induced magnetosphere. This is achieved by running a multifluid magnetohydrodynamic model under nondusty and dusty atmospheric conditions for the 2017 regional storm and the 1971-1972 global storm. Our results show that the dayside main ionospheric layer (below ~250 km altitude) undergoes an overall upwelling, where photochemical reactions dominate. Controlled by the day-to-night transport, the nightside ionosphere responds to the dust storms in a close connection with what happens on the dayside but not apparently with the ambient atmospheric change. At higher altitudes, dust-induced perturbations propagate upward from the ionosphere to the magnetosphere and extend from the dayside to the nightside, within a broad region bounded by the induced magnetospheric boundary. It is found that the global dust storm is able to dramatically enhance the CO_2^+ loss by a factor of ~3, which amounts to an increase of ~20% or more for total carbon loss (in the forms of neutrals and ions). Strong dust storms are a potentially important factor in long-term atmospheric evolution at Mars.

1. Introduction

Today's Mars is a dry and dusty planet, on which dust storms frequently occur mainly during southern hemisphere spring and summer seasons. Mars regional and global dust storms are able to significantly impact the lower and upper atmospheres through dust aerosol radiative heating and cooling and atmospheric circulation. Unlike extensive studies on the neutral atmospheric effectiveness of dust storms, their impact on the charged particle radiation environment near Mars remains poorly understood. Figure 1 shows a 3-D view of the global distribution of the column dust optical depth (CDOD) at a solar longitude (Ls) cadence of 30º during Martian Year 34. The CDOD is derived using combined infrared radiance observations from numerous Mars orbiters, applying essentially the same approach as described before [1] with specific data processing [2]. The 2018 planet-encircling dust storm is readily seen in the dramatic dust opacity increase, in both magnitude and spatial extent.

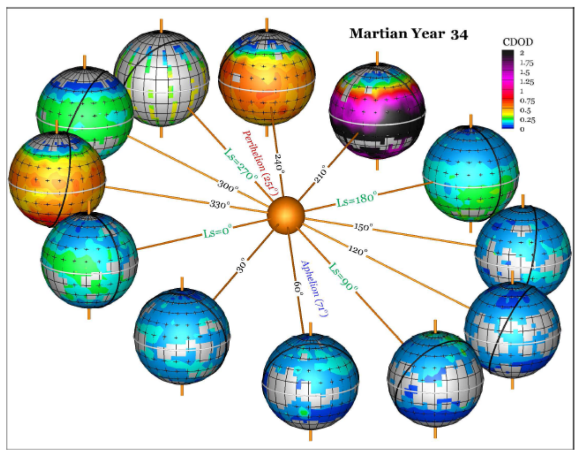

Figure 1. Global distributions of column dust optical depth at the wavelength of 9.3 µm during Martian year 34. The dust opacity has been scaled to the atmospheric pressure of 610 Pa.

2. Method

The primary research tool for this study is a 3-D multifluid magnetohydrodynamic (MHD) model [3, 4]. The state-of-the-art global MHD model self consistently solves the interaction between the impinging solar wind and the Mars conductive obstacle, covering a broad spatial domain at all altitudes higher than 100 km. For our case studies, we select the relatively weak regional dust storm in 2017 and the strong 1971-1972 global dust storm for numerical simulation. Considering that it is the plasma regime rather than the neutral atmospheric regime that our study focuses on, we adopt previously published works on atmospheric changes from nondusty to dusty scenarios, which serve as direct inputs to our model. The comparison of the MHD solutions under nondusty and dusty atmospheric conditions gives a first-order assessment of how dust storms disturb the near-Mars space environment globally. Figure 2 presents a 3-D view of the ionospheric and magnetospheric disturbances during the 1971-1972 global dust storm, clearly demonstrating that dust storms may effectively extend their impact into high altitudes through plasma processes.

3. Results

This is the first time the impact of dust storms on the ionosphere and the induced magnetosphere is modeled on a global scale, from 100 km altitude up to many Martian radii away from the surface. It is found that the dayside main ionospheric layer is lifted in accordance with dust-induced atmospheric expansion. During the overall ionospheric upwelling, the peak electron density remains unchanged. The ionospheric composition is basically stable during the regional storm but is significantly altered during the global storm. Driven by the plasma transport process, dust-induced perturbations are not confined in the dayside ionosphere but propagate upward from the ionosphere to the magnetosphere and extend from the dayside to the nightside. Our numerical results suggest that strong dust storms may enhance ion loss of CO_2^+ by a factor of ~3 and increase total carbon loss (neutrals and ions) by ~20% or more. Considering that global dust storms are an event over a time scale of months and their disturbances on the upper atmosphere may last even longer, it is implied that strong dust storms at Mars play a potentially important role in long-term atmospheric evolution.

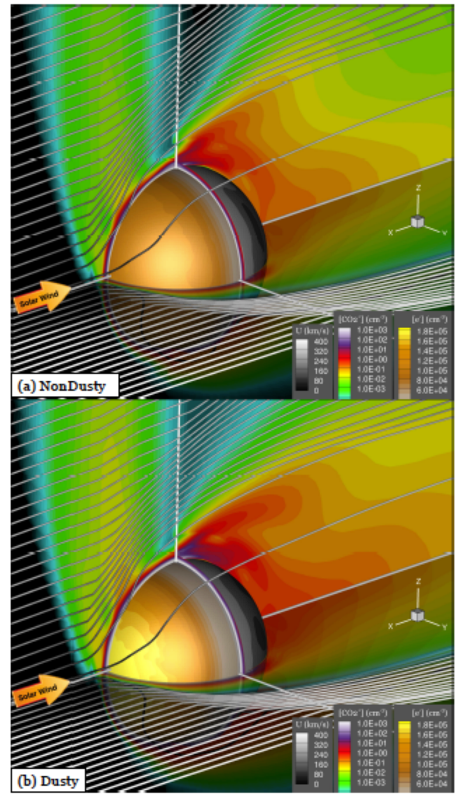

Figure 2. The 3-D view of the ionospheric and magnetospheric disturbances during the 1971-1972 global dust storm. The spherical surface shows the ionospheric electron density at 140 km altitude. On the meridional and equatorial planes, the CO_2^+ density is superposed.

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