A SOLAR ESCALATOR ON MARS: SELF-LIFTING OF DUST LAYERS BY RADIATIVE HEATING

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Abstract

The Light Detection and Ranging (LIDAR) instrument on the Phoenix Mars mission detected layers of dust in the atmosphere of Mars . These layers could be explained using an atmospheric general circulation model with high vertical resolution and dynamically and radiatively active dust [Daerden et al., 2015]. They were traced back to observed dust storm activity near the edge of the north polar ice cap where simulated surface winds exceeded the threshold for dust lifting by saltation. Heating of the atmospheric dust by solar radiation caused buoyant instability and mixing across the top of the planetary boundary layer (PBL). It was differential advection by wind shear that created detached dust layers above the PBL. The layers continued to ascend due to radiative heating, and arrived at the Phoenix site at heights corresponding to the LIDAR observations. The self-lifting of the dust layers is similar to the "solar escalator" mechanism for aerosol layers in the Earth's stratosphere. This work contributes to understanding why the Martian atmosphere is dusty up to large heights.

1. Introduction

Measurements by the Phoenix LIDAR [Whiteway et al., 2008, 2009] of the vertical distribution of dust in the atmosphere of Mars [Komguem et al., 2013] were very similar to measurements above the Australian Desert within the planetary boundary layer (PBL) [Dickinson et al., 2011]. However above the top of the PBL the atmospheric dust content on Earth drops rapidly, while on Mars dust continues to be approximately well mixed and proportional to atmospheric pressure up to heights above 20 km [Heavens et al., 2011; Komguem et al., 2013].

The present study addresses the mechanisms for transporting dust from the surface to heights above the PBL on Mars. On Earth it has been shown that radiative heating will result in self-lifting of layers containing particulate material, with the aerosol playing an active role in its vertical transport [Boers et al., 2010; de Laat et al., 2012]. This process was called the "solar escalator" since the diurnal cycle in solar radiative heating causes vertical steps in dust layers[de Laat et al., 2012]. Because the molecular density on Mars is a factor of 100 less than on Earth, the radiative heating of dust is potentially more significant in the atmosphere of Mars [see e.g. Fuerstenau, 2006; Heavens et al., 2011; Spiga et al., 2013]. Our study finds that radiative self-lifting was playing a substantial role in explaining the layers and that the "solar escalator" analogy is also applicable on Mars.

2. Measurements

The LIDAR instrument on the NASA Phoenix Mars mission measured optical extinction coefficients that were enhanced within the well-mixed PBL around summer solstice [Komguem et al., 2013]. Interestingly this was also the time when distinct layers were observed at and above the top of the PBL (Fig. 1). These layers are considered to be dust rather than water ice clouds since they were observed during the warmest part of the day (in the afternoon) as well as at night. Prior to our study there was no explanation for the formation of layers at the top of the PBL.

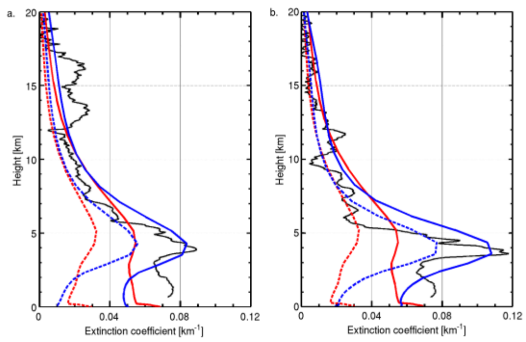

Figure 1: Vertical profiles of optical extinction coefficient derived from the Phoenix LIDAR measurements (black) showing separated dust layers peaking at height 4 km on mission sols (a) 20 (Ls=85.6°) and (b) 30 (Ls=90°). The added lines are simulated profiles above the Phoenix site (red) and for a site along the back trajectory that is shown in Fig. 2 (blue). Dashed lines indicate the contribution coming from wind-lifting. Figure from Daerden et al. [2015].

3. The GEM-Mars GCM

The GEM-Mars General Circulation Model for the atmosphere of Mars is based on the Canadian Global Environmental Multiscale (GEM) model for weather forecasting on Earth [Côté et al., 1998]. The model has undergone considerable improvements including an active dust cycle, carbon dioxide with surface exchange, a multi-layered thermal soil model including subsurface ice, turbulent transport in the atmospheric surface layer, convective transport inside the PBL, and a low level blocking scheme including gravity wave drag. Dust is represented in the model by a particle size distribution with 3 size bins and was lifted from the surface by saltation following the "KMH" method [Kahre et al., 2006]. A detailed roughness length map was applied [Hébrard et al., 2012]. D ust was also lifted in dust devils with a mass flux that is proportional to the surface turbulent heat flux and the height of the PBL [Renno et al., 1998]. Sedimentation of the dust particles was taken into account using the Stokes settling velocity with Cunningham slip-flow correction. To represent the active role of dust in the atmosphere, we did not apply a simple convective adjustment, but instead wherever heating of airborne dust by absorption of solar radiation created regions of convective instability, the temperature, momentum and constituents (including dust) were vertically mixed over the unstable model levels in order to regain stability.

For the present study the model was operated on a grid with a horizontal resolution of 4°×4° and with 102 hybrid vertical levels reaching from the surface to ~150 km. The vertical resolution was 35 m near the surface and increased gradually to ~1.2 km at height 10 km. At the latitude of the Phoenix landing site, the PBL was resolved with 17 vertical layers. The integration timestep was 1/48 of a sol (Martian day).

The model reproduced well the latitude distribution of dust as observed by the Thermal Emission Spectrometer (TES) instrument [Smith, 2004] on the NASA Mars Global Surveyor (MGS) at northern summer solstice [Daerden et al., 2015]. At high northern latitudes, the large optical depths measured by TES from orbit and by the Surface Stereo Imager (SSI) instrument on Phoenix [Tamppari et al., 2010] could only be reproduced by including wind gustiness and an increased efficiency factor for dust devils. This could be explained by the presence of a strong dust source such as the extended dune fields in the north polar region or the sublimation lag from the evaporating seasonal polar ice cap, or that the model's resolution may not be high enough for a detailed enough simulation of high friction velocities over ice-soil boundaries in the permanent polar cap.

4. Simulations

The simulated vertical profile of the dust optical extinction coefficient was compared with measurements from the LIDAR instrument and with measurements from the Mars Climate Sounder (MCS) instrument on the Mars Reconnaissance Orbiter (MRO) mission [Kleinböhl et al., 2009; Heavens et al., 2011] and were found to be within the range of variability and measurement uncertainty in the observations [Daerden et al., 2015, supporting information]. The simulations were also in agreement with the variation in the total atmospheric optical depth as observed by the SSI instrument on the Phoenix lander over the period around summer solstice when the dust loading was a maximum [Daerden et al., 2015]. A peak in optical depth just after summer solstice in the simulation was due to transport of dust that was originally lifted by saltation at the edge of the polar ice cap and then transported to the Phoenix site. The timing of this local dust storm was linked to the retreat of the seasonal CO_2 ice cap to within the north polar sand sea, when the albedo contrast between the cap and surrounding soil was maximal, leading to sharp thermal gradients, and strong near-surface winds causing dust lifting by saltation. The area of dust lifting in the simulation also roughly coincided with a large dust cloud observed from orbit by the Mars Color Imager (MARCI) instrument [Cantor et al., 2010] on MRO (Fig. 2b).

The simulation produced detached dust layers at the latitude of Phoenix at heights corresponding to those in the LIDAR detections (Fig. 1). In order to explain these layers, the model wind fields were used to calculate a back trajectory from such a detached layer (Fig. 3a). The air parcel containing the dust layer could be traced back to a region of enhanced dust abundance originating from strong wind-lifting events (local storms) close to the polar cap.

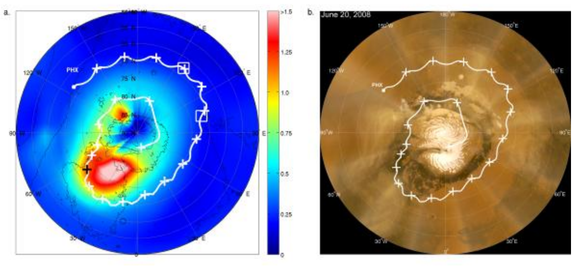

Figure 2: (a) Map of simulated dust optical depth at L_s=85°. The white line is a 20-sol back trajectory starting from a simulated detached dust layer over the Phoenix site at height 5 km. The markers on the back trajectory have a spacing of 1 sol. The location of the back trajectory at the time of the map is indicated by a black cross (+). (b) Mosaic image from MARCI images on June 20, 2008 (L_s=88)°, with a dust cloud visible at longitudes 30°-120°W. The simulated back trajectory from Phoenix is overlaid and passes through this observed dust cloud. Figure from Daerden et al. [2015].

The formation and transport of the layer can be further explained by plotting the contour of the vertical profile of dust optical extinction coefficient along the back trajectory (Fig. 3a). Moving forward in time (from the left side of Fig. 3a), the dust was first mixed above the PBL. Interestingly, at these high northern latitudes the PBL is shallow and any dust that is lifted would in principle mix only up to a few 100 meters by the surface layer turbulent mixing. But the atmospheric dust was heated by solar radiation and the temperature response of the atmosphere caused convective instability that triggered turbulent mixing in the model and transport of dust to heights above the PBL.

Consequently differential advection by wind shear produced a separated dust layer at height 2.7 km at L_s = 88.5°. The trajectory continued to rise to height 5 km before it arrived above the Phoenix site at L_s = 91.8° (right hand side of Fig. 3a).

The gradual lifting of the dust layer after L_s = 88.5° was caused by the radiative heating of the dust. The heating rate due to dust is plotted along the back trajectory in Fig. 3b. The ascent of the trajectory caused by heating due to solar radiation during daytime exceeded the descent caused by cooling due to IR radiation at night, leading to a step-like trajectory after L_s = 88.5°., i.e. the "solar escalator", similar to the process that was first identified on Earth for aerosol layers in the stratosphere of the Earth [de Laat et al., 2012].

The radiative heating resulted in a vertical displacement of the dust layer to an altitude where the increased potential temperature matched that of the environment. In the time period between when the layer became detached from the PBL and the time when the layer passed over the Phoenix site the integrated heating along the trajectory was 45 K in terms of potential temperature. This was slightly greater than the change in potential temperature in the background atmosphere between heights of 2.7 and 5 km, corresponding to the vertical displacement of the layer. (Fig. 3c). The difference was due to mixing.

The vertical profile of dust extinction coefficient from the simulation at L_s = 91.8° is compared to the Phoenix LIDAR observations in Fig. 1 (red line). The model simulation results in a layer of enhanced dust at heights 4 – 5 km that corresponds to the observations. Going back along the back trajectory, the simulated extinction profiles shown in Fig. 1 from L_s = 90° and 89° (blue lines) have even closer similarity to the measured profiles, i.e. the model reproduces the LIDAR measurements within the same latitude range.

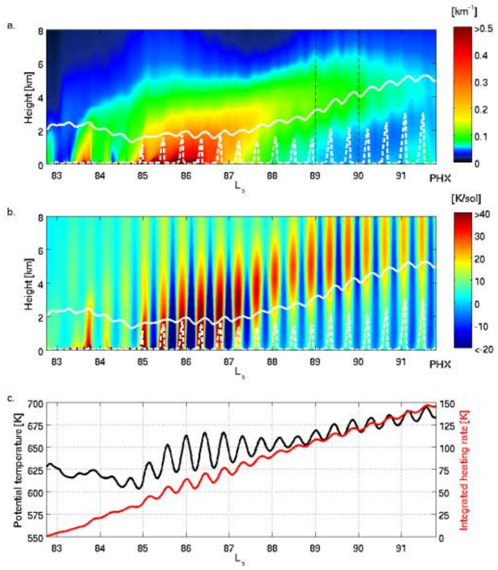

Figure 3: (a) Contour plot of the vertical profile of the simulated dust extinction coefficient along the back trajectory of Fig. 2. The right hand edge corresponds to the Phoenix site. The full white line represents the height of the trajectory shown in Fig 2. The dashed white line represents the local height of the top of the simulated PBL. The vertical black dashed lines indicate the times of the extinction profiles plotted in blue in Fig. 1. (b) Simulated net (solar + IR) dust heating rate along the back trajectory, in K/sol (solar day). (c) The potential temperature of the parcel of air followed along the back trajectory (black line), and the integrated heating rate along the trajectory (red). Figure from Daerden et al. [2015].

Conclusions

A general circulation model for the atmosphere of Mars has been applied to explain dust layers that were observed by the LIDAR instrument on the Phoenix mission [Daerden et al., 2015]. In the simulation the dust was lifted from the surface near the edge of the polar cap where strong winds were driven by the thermal gradients associated with the albedo contrast between bare land and ice. Heating due to absorption of solar radiation caused mixing of the dust to heights above the PBL where differential advection by shear drew the dust out into a layer. Heating of the layer by absorption of solar radiation then caused it to ascend further into the troposphere above the PBL. A similar process has been observed to occur in the stratosphere of the Earth and it has been called the solar escalator [de Laat et al., 2012]. This study provides evidence that the solar escalator mechanism can contribute to the sustenance of dust in the atmosphere of Mars at heights above the PBL. The different impact on the atmospheres of Earth and Mars can be attributed to this process being more effective on Mars due to the lower atmospheric density.

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