THE MARTIAN DUST CYCLE AT DIFFERENT ORBITS AND OBLIQUITIES

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Introduction:

Observations and simulations of present-day Mars have demonstrated the local and large-scale feedbacks of radiatively active atmospheric dust on the dynamics and meteorology. It can be useful to investigate extreme cases under which these feedbacks can arise and potentially generate more significant impacts on planetary climate. Here we present two series of simulations. The first set explores the Martian dust radiative feedback as Mars is moved closer to the sun and therefore experiences stronger solar forcing. This set of simulations is representative of a Mars-like land exoplanet in the habitable zone of a sun-like star. A second set of simulations explores dust feedbacks at different Mars obliquities. As surface wind speeds and therefore wind stress dust lifting increases, the accumulation of large amounts of atmospheric dust acts as a significant driver of dynamical change in both sets of simulations. We explore the conditions under which a new tide-dominated dust lifting regime is generated.

Methodology:

We use the new NASA Ames Mars Global Climate Model (GCM), which incorporates the NASA Ames Legacy GCM physics parameterizations [1] into the NOAA/GFDL cubed-sphere finite volume dynamical core [2]. To test the impact of orbital parameters (radius and obliquity) on dust lifting, we implement a fully interactive dust lifting scheme wherein dust is lofted from surface reservoirs via dust devil or wind stress lifting (as described in 4-7). Atmospheric dust is transported in two moments (the number and mass mixing ratios) with an assumed log-normal size distribution. Dust is advected by simulated winds and is removed via gravitational sedimentation. In simulations with radiatively active dust, dust heating and cooling rates are calculated using a two-stream, correlated-k radiative transfer scheme with dust refractive indices from [8]. We perform 6 simulations to investigate the impact of radiatively active dust on Mars climate at closer orbits and higher obliquities. For high obliquity simulations we also modify the aerocentric longitude of perihelion in order to remove the impact of the hemispheric asymmetry on the zonal mean circulation (ZMC). Simulations are summarized in Table 1.

		R_{orbit} [AU]	Isolation [Wm^{-2}]	Obliquity	Perihelion L_s
Vary Orbit	1	1.53	589	24°	241°
	2	1.0	1372	24°	241°
Vary Obliquity	3	1.53	589	35°	241°
	4	1.53	589	45°	241°
	5	1.53	589	35°	70°

Table 1: Simulation List

Mars as an Exoplanet:

We simulate a Mars-like land exoplanet at present-day Earth orbit to investigate the impact of solar insolation on the simulated dust cycle and dust internal feedbacks. As described in [9], we identify two major outcomes driven by dust radiative heating at Earth orbit: 1. Dust accumulates in and is vertically mixed throughout the atmosphere. Atmospheric dust acts as a greenhouse agent that warms the planetary surface above the freezing point of water (Fig. 1), while at the same time greatly reducing the surface flux of visible light. 2. Dust is exclusively lofted via wind-driven lifting. The most active dust lifting

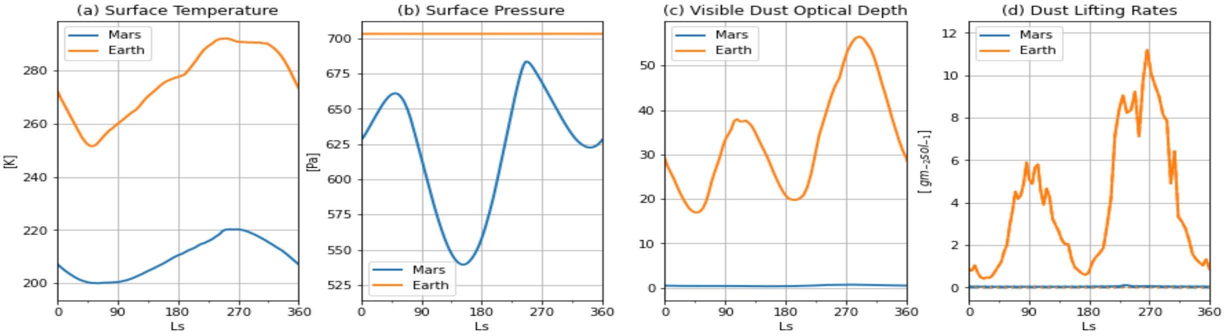

Figure 1: Global average (a) surface temperature, (b) surface pressure, (c) visible dust optical depth, and (d) cumulative (dust devil + wind stress) dust lifting rates vs time of year for simulations with active dust at Mars (blue) and Earth (orange) orbit.

regions shifts from the summer to the winter hemisphere (Fig. 2).

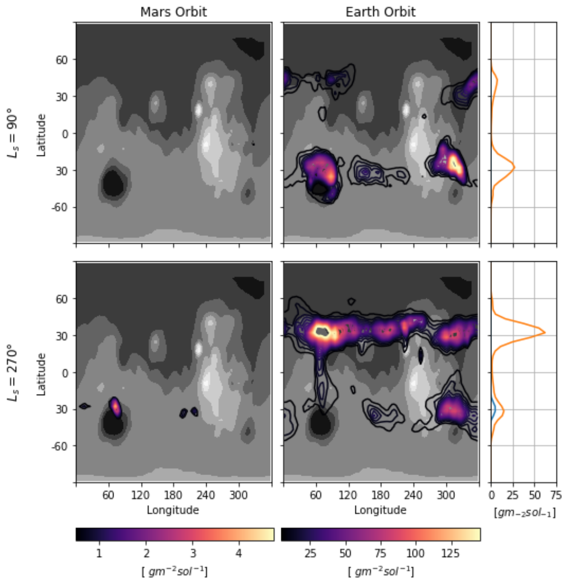

Figure 2: Solstitial wind stress dust lifting rates [g/m^2/sol] at Mars and Earth orbits. Line plots show the zonal average wind stress dust lifting rate.

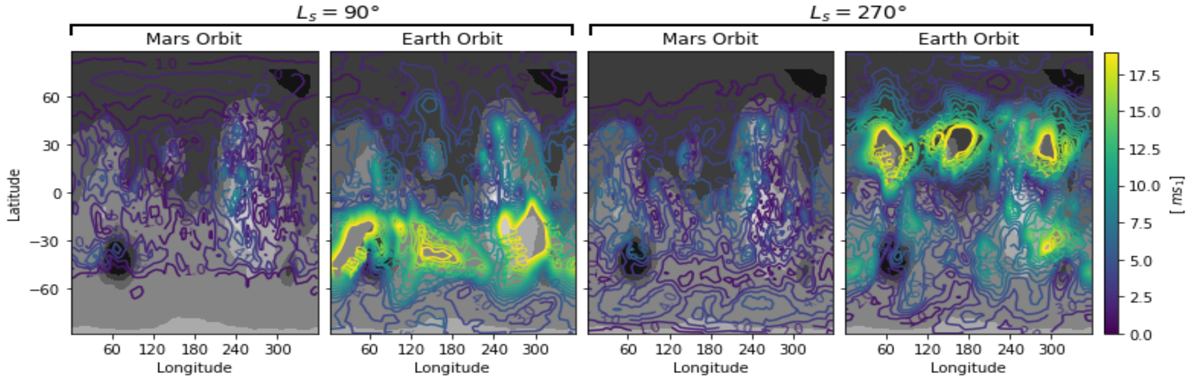

Figure 3: The amplitude [m/s] of the zonal wind solsticial semidiurnal tide for simulations at Mars and Earth orbits.

Tide-Dominated Dust Lifting:

High surface wind stresses in the winter hemisphere result from the combined influence of a much stronger zonal mean circulation and greatly augmented thermal tides. The zonal mean circulation is responsible for mixing dust into the middle and upper atmosphere. As a result, solar heating (via absorption by dust) become stronger and is distributed over a larger region of the atmosphere. Stronger dust heating rates strengthen the diurnal and higher harmonic thermal tides. While the diurnal tide is vertically trapped, the semidiurnal and higher harmonic tidal components increasingly dominate the near-surface winds. These components have the largest amplitudes in the winter hemisphere midlatitudes (Fig. 3). Enhanced surface winds increase dust lifting rates which further amplifies dust feedbacks on the circulation. We define a new dust lifting regime based on the tide-dominated winds described here. This represents a significant departure from dust lifting observed on present day Mars, which is associated with frontal activity in the winter hemisphere and is episodically amplified by further lifting in the southern (summer) hemisphere. Critically, the initiation of this regime requires heating by atmospheric dust and is not reproduced in clear sky simulations at the same orbit.

Mars at High Obliquity:

As at Earth orbit, simulations with higher obliquities experience greater dust lifting rates and higher atmospheric dust levels, in this case due predominantly to the poleward shift of the subsolar latitude and its impact on the ZMC [10,11]. However, at Mars current orbit and insolation, transitioning from topography-assisted wind stress lifting (Regime II) to the tidal mode discussed above. (Regime III) requires extremely high and possibly unrealistic atmospheric dust levels. In simulations with infinite surface dust reservoirs, tide-assisted wind stress lifting develops for both simulated obliquities, although it is not the dominant source of lifted dust (Figs. 4 & 5). As a present-day Mars, the highest dust lifting rates follow the seasonally migrating subsolar latitude.

Remaining Uncertainties:

The magnitude of simulated dust radiative feedbacks depends on dust optical properties and the total planetary dust budget. On Mars-like exoplanets, it is possible that a different geochemical history and planetary evolution could lead to dust with very different compositions. This dust could, for example, scatter incoming solar radiation more efficiently and absorb outgoing IR radiation less readily. In this case, the net impact of atmospheric dust would be planetary cooling rather than warming. Similarly, there is likely a great range of potential complications due to surface alteration (crust formation, reservoir depletion, etc.) as well as the influence of the water cycle (snow, cloud formation and dust scavenging. It is not obvious what the surface distribution and cumulative budget of surface dust should be on Mars-like land exoplanets or for simulations at different obliquities. If the total dust budget is significantly reduced or if atmospheric dust accumulates in reservoirs that do not coincide with the highest surface wind stresses, then dust feedbacks will be greatly reduced.

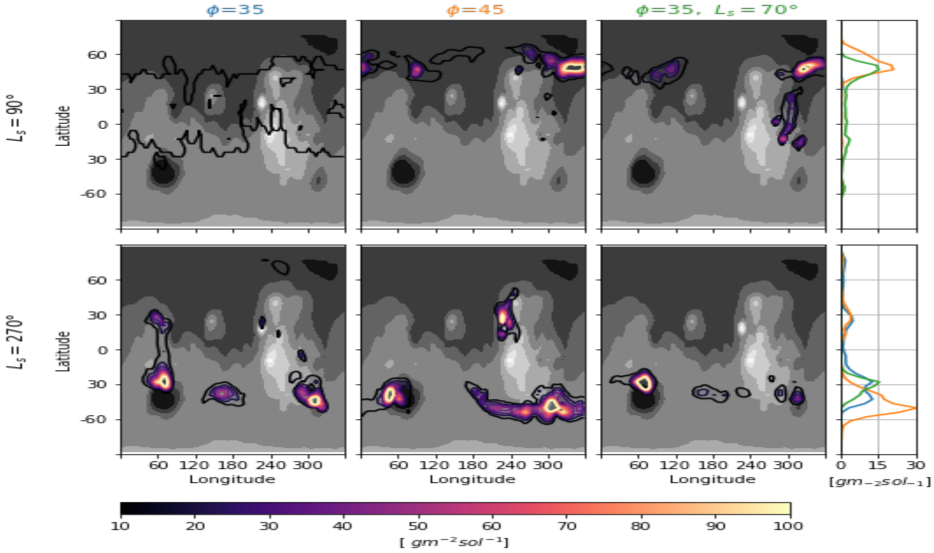

Figure 4: Solstitial wind stress dust lifting rates [g/m^2/sol] for simulations with (column 1) obliquity=35°, (column 2) obliquity=45°, and (column 3) obliquity=35°, longitude of perihelion=70°. Line plots show the zonal average wind stress dust lifting rate.

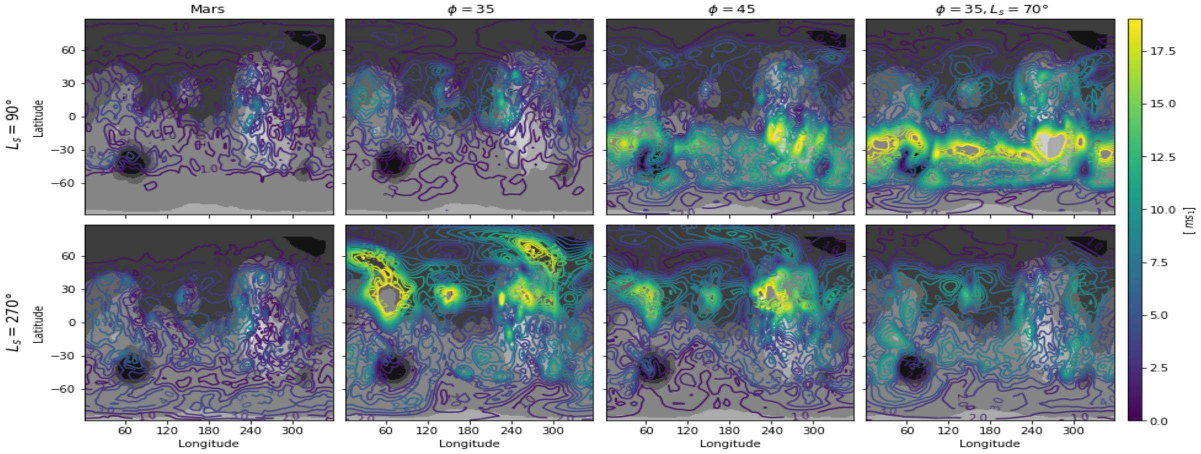

Figure 5: The amplitude of the zonal mean solstitial semidiurnal tide for simulations at Mars orbit and present-day obliquity (column 1), obliquity=35° (column 2), obliquity=45° (column 3), and obliquity=35° with longitude of perihelion=70° (column 4).

Conclusion: We explore the dust radiative feedback cycle under extreme orbital conditions (either at much closer planetary orbits or with higher planetary obliquities). We find that dust feedbacks have the potential to significantly modify simulated planetary dynamics and climate. In particular, as atmospheric dust with optical properties similar to dust on present-day Mars accumulates, the surface distribution of dust lifting is increasingly dominated by the surface amplitude and spatial distribution of the thermal tide. This shift from topographic slope-driven to tide-dominated lifting depends on both the level of atmospheric dust and the insolation, which together determine the total dust heating. At closer planetary orbits, this regime initiates even with relatively small levels of atmospheric dust. By contrast, at Mars present day orbit and high obliquity, this shift is initiated, but dust lifting remains predominantly in the summer hemisphere and likely requires more dust than can be realistically lofted.

References: [1] Haberle et al. (2019) Icarus, 333 [2] Kahre et al. (2022), 7th MAMO [3] Newman et al. (2002a) J. Geophys. Res., 107 [4] Newman et al. (2002b) J. Geophys. Res., 107 [5] Basu et al. (2004) J. Geophys. Res. 109; [6] Kahre et al (2006) J. Geophys. Res., 111 [7] Kahre et al (2008) Icarus, 195 [8] Wolff et al., (2010) Icarus, 208;[9] Hartwick et al. (2022) [10] Lindzen & Hou (1988) J. Atmos. Sci., 45 [11] Newman et al. (2005) Icarus, 174.