GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L19S04, doi:10.1029/2006GL026188, 2006

Role of dust devils and orbital precession in closing the Martian dust cycle

R. M. Haberle,[1] M. A. Kahre,[2,3] J. R. Murphy,[2] P. R. Christensen,[4]
and R. Greeley[4]

Received 2 March 2006; revised 19 May 2006; accepted 14 July 2006; published 12 September 2006.

[1] We use a general circulation model to simulate the role of dust devils on the Martian dust cycle as a function of orbital precession. We focus specifically on the two most recent epochs of 22,500 and 72,500 years ago when perihelion occurred near northern summer solstice. We find that dust devils dominate the dust cycle at these times and that while orbital precession does modulate the exchange of dust between the hemispheres, the integrated effect is a net transfer of dust from north to south. The low thermal inertia continents of Tharsis, Arabia, and Elysium are the main regions that contribute to the net loss in the Northern Hemisphere and this loss is primarily due to dust devils. These results suggests that the dust cycle is closed on time scales longer than those associated with orbital precession (∼50,000 years) and that obliquity variations must also play an important role in the long-term dust cycle.

Citation: Haberle, R. M., M. A. Kahre, J. R. Murphy, P. R. Christensen, and R. Greeley (2006), Role of dust devils and orbital precession in closing the Martian dust cycle, *Geophys. Res. Lett.*, *33*, L19S04, doi:10.1029/2006GL026188.

1. Introduction

[2] Dust devils are ubiquitous on Mars and appear to play an important role in the present seasonal dust cycle. They have been shown to be efficient mechanisms for raising dust from the surface on Mars and Earth under wind conditions that are otherwise too benign to set dust into motion; this is due in part to the "vacuum cleaner" effect of the low pressure core of the vortex [*Greeley et al.*, 2003]. On Mars, dust devils help maintain the low background dust loading during the aphelion season [*Newman et al.*, 2002; *Basu et al.*, 2004], they are a potentially important resupply mechanism for regions with high surface wind speeds [*Kahre et al.*, 2005], and they can significantly affect the spatial patterns of net annual deposition/accumulation [*Kahre et al.*, 2006].

[3] Recent general circulation model (GCM) studies suggest that regionally the dust cycle is not closed on annual time scales [*Kahre et al.*, 2005]. These studies indicate a stable, annually repeatable, spatial pattern in net accumulation/loss of dust. Regions experiencing net loss or gain do so year after year implying that the dust reservoir in the regions experiencing net loss must be quite large ($\gg$ several meters), and that the regional dust cycle must be closed on time scales much longer than a year.

[4] A natural time-scale to consider for closure of the dust cycle is the 10^5-10^6 year time scale associated with orbital variations. *Christensen* [1986] first suggested this possibility and argued that the low thermal inertia continents (LTIC) of Mars - Elysium, Arabia, and Tharsis - are presently accumulating dust as a result of a net transport from the Southern Hemisphere to the Northern Hemisphere. He estimated the age of the deposits by dividing their apparent thickness (several meters) by the sedimentation rates estimated from Viking observations (∼25 μm/yr). The result, 10^5 years, is commensurate with orbital time scales.

[5] He further envisioned a reversal in the net meridional transport of dust associated with the ∼50,000 year precession cycle. On present-day Mars, the strongest winds and maximum dust activity occur in the southern hemisphere during southern summer, which occurs during the perihelion season when the planet is warmest and the circulation most intense. However, ∼25,000 years ago the season of perihelion would reverse and the strongest winds and highest dust activity would occur during northern summer causing a net transport from north to south. *Christensen* [1986] further speculated that dust devils could be the most important process eroding the surface. Thus, he hypothesized that the LTIC's alternately build-up and erode, moving between hemispheres on precessional time scales. Here we test this hypothesis with a general circulation model that reproduces the present day dust cycle reasonably well, and which includes dust lifting by winds and dust devils.

2. The Model

[6] The model we use was developed, tested, and validated by *Kahre et al.* [2005, 2006]. It is based on version 1.7.3 of the NASA/Ames GCM. This version runs with the *Pollack et al.* [1990] heating algorithms, is based on the Goddard C-grid, and has a second-order tracer transport scheme that treats advection as it does potential temperature. *Kahre et al.* [2006] describe the treatment of dust lifting and transport. Briefly, lifting occurs by two mechanisms: surface stresses associated with the simulated large-scale wind field, and convection associated with dust devils. Both schemes are parameterizations: the large-scale lifting scheme is based on the model of *Westphal et al.* [1987]; while the dust devil scheme is based on the thermodynamic

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[1] Space Science and Astrobiology Division, NASA/Ames Research Center, Moffett Field, California, USA.

[2] Department of Astronomy, New Mexico State University, Las Cruces, New Mexico, USA.

[3] Now at Space Science and Astrobiology Division, NASA/Ames Research Center, Moffett Field, California, USA.

[4] Department of Geological Sciences, Arizona State University, Tempe, Arizona, USA.

0094-8276/06/2006GL026188$05.00

Table 1. Orbit Parameters for the Last Two Time Periods When Perihelion Occurred Near Northern Summer Solstice[a]

Years Ago	Longitude of Perihelion (L_s)	Eccentricity	Obliquity
22,500	91.51°	0.0757	23.4°
72,500	90.29°	0.1173	24.9°

[a] L_s = 90°, where L_s is an angular measure of the Mars' orbital position measured with respect to northern spring equinox (L_s = 0°). Values are taken from the model of *Laskar et al.* [2004].

model of *Renno et al.* [1998] and is dependent upon the vertical sensible heat flux and the depth of the planetary boundary layer. Both wind stress lifting and dust devil lifting compare favorably with the observations of *Cantor et al.* [2001] and *Fisher et al.* [2005]. (see *Kahre et al.* [2006] for a detailed discussion.)

[7] These parameterizations predict a lifted dust mass per unit area per unit time, which is distributed into a log-normal particle size distribution with an effective radius of 2.5 microns, and a standard deviation of 0.64. That distribution is represented by three particle sizes of 0.1, 1.4, and 10 microns. Once dust enters the atmosphere it is carried away in suspension by winds and turbulence, where it interacts with the solar and infrared radiation fields. Thus, the model is fully interactive: surface wind speeds (stresses) and convection (heat fluxes and PBL depths) determine dust lifting, and the dust is radiatively active so that dynamical feedbacks are permitted. The model threshold stress and lifting efficiency factors are first tuned to reproduce the present day annual dust cycle for years without major dust storms. (Runs that are tuned to simulate years with major storms do not significantly change the mass balance of the LTIC, which is the focus of this work. See *Kahre et al.* [2006]). We then run the model for orbital conditions appropriate for 22,500 and 72,500 years ago when the longitude of perihelion occurred near northern summer solstice. Table 1 lists the orbit parameters. For each period we perform simulations with and without the dust devil parameterization activated in order to assess the effect dust devils have on the dust cycle.

3. Results and Discussion

[8] The results of the two runs with perihelion occurring near northern summer solstice are very similar. We therefore concentrate on the 72,500 year ago case which has the highest eccentricity and therefore the strongest northern summer forcing. Figure 1 shows how the simulated dust cycle for that period compares to the present day dust cycle. For the present day, the global mean opacity undergoes significant seasonal variation. During northern spring and summer, the global mean 9 μm opacity remains relatively constant at ~0.1 and this is maintained mostly by dust devil lifting with very little lifting by the large-scale wind field. But as fall and winter approach and the planet nears perihelion, lifting by the large-scale wind field increases and eventually dominates dust devil lifting causing the global mean opacity to increase by a factor of four. No such strong seasonal variation is seen for the 72,500 year ago simulation. This is because lifting by large-scale winds does not ramp up during northern winter as it does today. Consequently, the dust cycle is dominated by dust devils all year long. The reason for this is related to the control topography has on the strength of the mean meridional circulation [*Richardson and Wilson*, 2002]. The hemispheric asymmetry in topography – the southern hemisphere is significantly elevated with respect to the northern hemisphere - amplifies the response of the mean meridional circulation when perihelion occurs near southern summer solstice (as it does today), but it mutes the response when perihelion occurs near northern summer solstice (as it did 72,500 years ago).

[9] It is also evident from Figure 1 that without dust devils, the atmosphere would be relatively clear all year long in the 72,500 year ago simulation. This is not the case for present day Mars where even without dust devils, the atmosphere would become quite dusty during the fall and winter seasons because of lifting by large-scale winds [*Basu et al.*, 2004; *Kahre et al.*, 2006]. Thus, it is clear that the large-scale winds never contribute much lifting when perihelion occurs near northern summer solstice. Again, this is due to the fact that the mean meridional circulation at northern summer solstice is not as strong as it would be if the surface in the northern hemisphere – where the sub solar heating is now strongest – was located at a higher elevation than it is. Conversely, at northern winter solstice when the sun is now positioned over the higher elevations of the southern hemisphere, the planet is at aphelion and the amount of energy available to drive strong large-scale flows is greatly reduced.

[10] The dominance of dust devils on the dust cycle of 72,500 years ago is further illustrated in Figure 2, which depicts the spatial pattern of annual net deflation/accumulation of the surface dust reservoir. Dust devils have a major effect on this pattern. Without dust devils, the tropics and subtropics are largely accumulating dust mostly at the expense of Hellas, Argyre, and the northern midlatitudes. However, with dust devils, this pattern reverses and the lower latitudes lose dust, which ends up

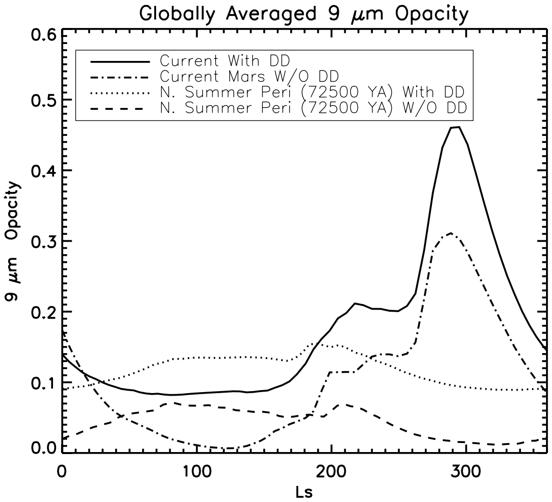

Figure 1. Simulated globally averaged 9 μm opacity as a function of season (Ls) for present day Mars with dust devils (solid) and without dust devils (dot-dashed); and for Mars 72,500 year ago with dust devils (dotted), and Mars 72,500 years ago without dust devils (dashed).

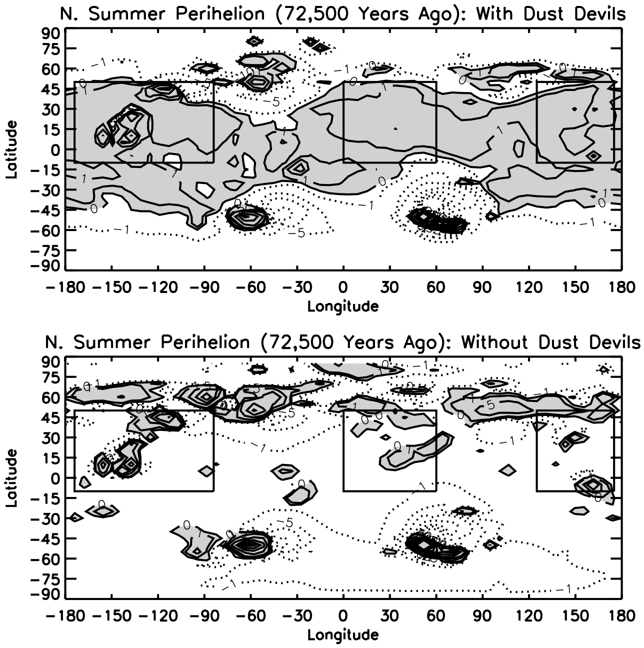

Figure 2. Net annual deflation (shaded) and deposition (white) regions for the 72,500 years ago simulation (top) with dust devils and (bottom) without dust devils. Contour intervals are 1 μm/year. Boxed regions are the LTIC of (left) Tharsis, (center) Arabia, and (right) Elysium.

accumulating instead at the middle and higher latitudes of both hemispheres.

[11] The net annual deflation specific to the LTIC for the 72,500 year ago case (the boxes in Figure 2) is shown in Figure 3. Without dust devils, Elysium and Tharsis are net sinks of dust and would therefore be expected to accumulate material at modest rates. However with the inclusion of dust devils, they become net sources of dust and lose about -1.55 and -2.40 μm/year, respectively. On the other hand, Arabia is a net source of dust with or without dust devils. However, its loss rate increases almost an order of magnitude when dust devils are included from -0.35 to -2.74 μm/year. Thus, the LTIC do experience significant net erosion with perihelion phased near northern summer solstice and it is mainly because of dust devils as *Christensen* [1986] suggested. With the exception of Arabia, the large-scale wind field is never strong enough to cause any significant deflation in these regions as was also found by *Haberle et al.* [2003]. The main regions where the large-scale winds do cause net deflation are Hellas and Argyre and northeast of Tharsis. In these regions, topography has a strong amplifying effect on the large-scale wind field.

[12] We can also assess the role of dust devils on the net annual meridional transport of dust between the hemispheres. According to Figure 4, for the past two epochs when perihelion was near northern summer solstice, the southern hemisphere was gaining dust at the expense of the northern hemisphere. All three of the LTIC contribute significantly to this exchange. While the simulations suggest this would be true even without dust devils, the magnitude of the exchange is increased by almost an order of magnitude with dust devils included. For present-day Mars, whose results are taken from *Kahre et al.* [2006], Figure 4 indicates that the large-scale wind field would transport $\sim 10^{11}$ kg of dust from the southern hemisphere to the northern hemisphere each year. However, dust devils reduce this by an order of magnitude. When expressed in terms of a percentage of the total amount of dust lifted annually, the exchange is $\sim$.2%. Since the model conserves mass to about 0.8% in this simulation, we interpret this to mean there is very little hemispheric exchange of dust on present-day Mars. For all other simulations, however, the percent exchange is above the model conservation uncertainty.

[13] One clear result of these simulations is that dust devils have a major impact on the inferred age of the LTICs. *Haberle et al.* [2003] showed that the large-scale winds never become strong enough to erode the LTICs regardless of orbital configuration. They suggested that if dust devils are not important, then the LTICs would be very old and the long-term net sedimentation rates would have to be very low in order to explain the observed thickness. Here we show that dust devils are, in fact, very important and that the LTICs must therefore be geologically young as suggested by *Christensen* [1986].

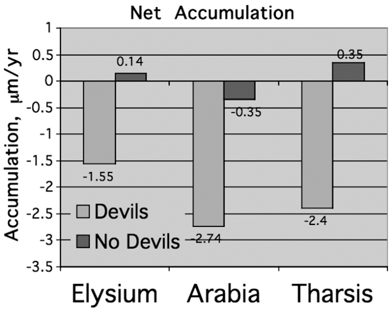

Figure 3. Net accumulation of dust (μm/yr) in the three LTIC for cases with (light shading) and without (dark shading) dust devils, and for the period 72,500 years ago.

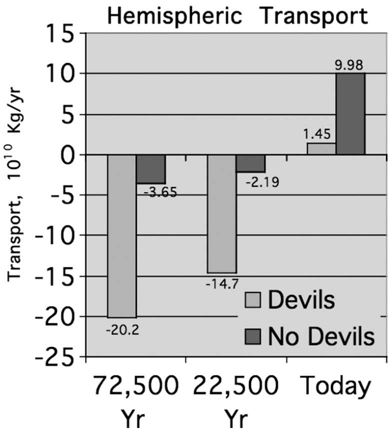

Figure 4. Net annual meridional transport of dust from the Southern Hemisphere to the Northern Hemisphere for periods of 72,500 years ago, 22,500 years ago, and for the present. Cases with dust devils are in light shading, without dust devils in dark shading.

[14] Another clear result of these simulations is that the dust cycle does not appear to be closed on time scales associated with the precession cycle alone. The simulations we've conducted suggest that the LTIC have been losing dust for the past 100,000 years or so and that dust devils greatly facilitate this loss. The obvious question, therefore, is under what conditions do the LTIC gain dust? We speculate that this re-supply occurs when the obliquity is higher than at present. In some preliminary simulations with a 35° obliquity, for example, we do find this to be the case as wind stress lifting dominates dust devil lifting [*Kahre*, 2006], a result consistent with that of *Newman et al.* [2005]. Further modeling of the high obliquity regime should provide more definitive estimates of the time scale for closure.

4. Conclusion

[15] The main conclusion of this work is that dust devils play a very important role in the long-term dust cycle. Their presence greatly affects the overall pattern of dust accumulation and removal, both for present day Mars [*Kahre et al.*, 2006], as well as Mars when perihelion occurs near northern summer solstice. Their general affect on the dust budget of the LTIC is to act as a removal mechanism and greatly accelerate the deflation process. For the past 100,000 years these regions have been losing dust to the middle and higher latitudes of both hemispheres.

[16] We also find that orbital precession does not lead to a balanced alternating pattern of hemispheric exchange. For obliquities and eccentricities similar to present day, precession modulates the net annual hemispheric exchange of dust, but over a precession cycle the integrated transport is north to south. The annual hemispheric exchange is weakest (∼zero) when perihelion occurs near northern winter solstice as it does today; and is strongest (north to south) when it occurs near northern summer solstice as it did 22,500 and 72,500 years ago. The integrated effect of the precession cycle does not, therefore, lead to a zero mass balance but instead causes a net loss in the north and gain in the south. Thus, it is clear that other processes are necessary (e.g., the obliquity cycle) to return dust to the Northern Hemisphere.

[17] **Acknowledgments.** This work was supported by NASA Mars Data Analysis Program, by NASA's Planetary Atmospheres program, and by NASA's Graduate Student Researchers Program.

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P. R. Christensen and R. Greeley, Department of Geological Sciences, Arizona State University, Tempe, AZ 85287, USA. (phil.christensen@asu.edu; greeley@asu.edu)

R. M. Haberle and M. A. Kahre, Space Science and Astrobiology Division, NASA/Ames Research Center, MS 245-3, Moffett Field, CA 94035-1000, USA. (robert.m.haberle@nasa.gov; kahrema@nmsu.edu)

J. R. Murphy, Department of Astronomy, New Mexico State University, Las Cruces, NM 88003, USA. (murphy@nmsu.edu)