Reports

Interannual Variability of Global Dust Storms on Mars

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Global dust storms on Mars occur in some years but not in others. If the four Mars years of Viking data are representative, some distinguishing characteristics can be inferred. In years with global dust storms, dust is raised in the southern hemisphere and spread over much of the planet by an intensified Hadley circulation. In years without global dust storms, dust is raised in the northern hemisphere by relatively active mid-latitude storm systems but does not spread globally. In both cases the dusty season is winter in the north. Assuming that the cross-equatorial Hadley circulation plays a key role in the onset of global dust storms, it is shown from numerical simulations that a northern hemisphere dust haze weakens its intensity and, hence, its contribution to the surface stress in the southern hemisphere. This, in turn, reduces the possibility of global dust storm development. The interannual variability is therefore the result either of a competition between circulations in opposite hemispheres, in which case the variability has a random component, or it is the result of the cycling of dust between hemispheres, in which case the variability is related to the characteristics of global dust storms themselves.

THE CLIMATE OF MARS IS CRITICALLY influenced by the presence of suspended dust particles in its atmosphere (*1, 2*). Such particles enter the Martian atmosphere when surface stresses due to winds become strong enough to lift dust by saltation or other means (*3*). The resulting dust storms are generally short-lived (about a day) and of limited scale ($\sim 10^4$ km^2). Occasionally, however, a local dust storm will expand to global proportions, particularly when Mars is near perihelion (*4, 5*). It was thought that such global-scale storms might occur once or twice each Martian year (*1*), however, it is now known that in some years they do not occur at all (*6*). Understanding why global dust storms occur in some years but not in others is a major unsolved problem in Martian climate studies.

A potentially important clue can be found in the analysis of 4 years of Viking meteorology data by Leovy *et al.* (*6*). Using pressure, temperature, and wind data from the Mutch memorial station (*7*) they identified two distinct regimes that characterize Martian weather during northern winter (Fig. 1). In the first, one or more global dust storms occur that raise dust primarily in the southern subtropics. At these latitudes insolation is strong and mean vertical motions are upward. Haberle *et al.* (*8*) have shown that dust introduced into the atmosphere at these latitudes can be carried to high altitudes and rapidly transported into the northern hemisphere by a cross-equatorial Hadley circulation that is greatly intensified because of absorption of solar energy by the suspended dust. During these events, traveling baroclinic wave activity in the north is suppressed. In the second regime, no global dust storms occur, but baroclinic wave activity in the northern hemisphere is high, and winds associated with these systems raise dust. From the behavior of the diurnal and semidiurnal tides, Leovy *et al.* concluded that the dust so raised produced solar optical depths of about 1 and remained confined to a relatively shallow layer (<10 km) throughout a broad belt of northern mid-latitudes.

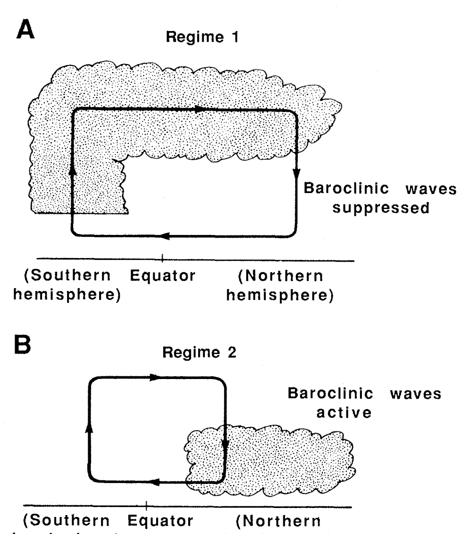

Fig. 1. Schematic illustration of the difference between (A) years with global dust storms and (B) years without global dust storms.

This is consistent with the weak insolation and general sinking motion that is expected for these latitudes at this season.

As pointed out by Leovy *et al.*, there is a straightforward connection between the reduction in baroclinic wave activity and the occurrence of global dust storms. During these storms the cross-equatorial Hadley circulation expands, the zone of maximum vertically integrated meridional temperature gradients moves poleward, and the static stability increases. These changes suppress baroclinic wave growth and shift the storm track northward (*9*).

Here, it is suggested that a connection between enhanced baroclinic wave activity and the lack of global dust storms also exists. To make this connection, it is assumed that the combined strength of all wind systems in the southern subtropics (where global dust storms originate) is just barely able to reach the required value for dust storm initiation, and then only rarely. This assumption is supported by the observed low frequency of global dust storms. The major wind systems contributing to the surface stress in the southern subtropics are the mean meridional (Hadley) circulation, the thermal tides, and topographically driven circulations (*1, 10, 11*). A change in the intensity of any of these would therefore be decisive, especially if the affected system normally makes a significant contribution to the total stress. A change in the mean meridional circulation, but not in the tidal or topographic circulations, would occur if the baroclinic wave systems created an extensive dust haze in the north. Specifically, the mean meridional circulation would be weakened because dust in its descending branch would act as a heat source, thereby reducing the magnitude of the zonal-mean latitudinal heating gradient which drives meridional circulations in general (*12*). Since the mean meridional circulation contributes up to 50% of the required stress (*13*), its intensity is crucial. The tides would not be significantly affected in the presence of a northern hemisphere dust haze since latitudinally asymmetric heating excites modes with little surface pressure variation (*14*). Topographic circulations would not be affected because they are local in scale. Thus, the suggestion is that by creating a dust haze in the north, the baroclinic wave systems weaken the intensity of a key component of the dust-raising circulation in the south.

To test this hypothesis, the mean meridional circulation at northern winter solstice has been simulated for cases with and without a northern hemisphere dust haze by a zonally symmetric primitive equation model (*8*). The model computes a meridional circulation driven solely by zonally symmetric

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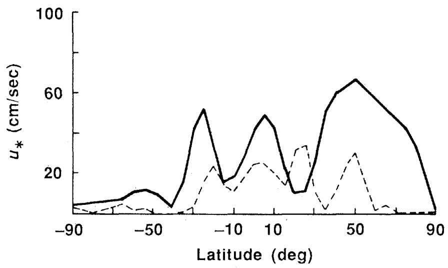

Fig. 2. Daily averaged friction velocities for model simulations without dust (solid line) and with dust (dashed line).

and daily averaged radiative heating. The radiative heating includes contributions from the absorption of solar and infrared radiation by dust and CO_2, as well as the exchange of sensible heat between the atmosphere and ground. In computing the latter, the model uses Deardorff's (*15*) boundary layer parameterization from which u^*, the friction velocity, is also computed. Since the friction velocity is related to the surface wind stress (*16*), its behavior is a useful indicator of the likelihood of dust raising.

A comparison of the model computed daily averaged friction velocities for simulations with and without dust is shown in Fig. 2. In both cases the circulations are approximately steady. For the dust case, the dust is fixed between 15°N and 35°N and distributed uniformly in height from the surface to 6 km with a solar optical depth of 1. This distribution and optical depth is consistent with that inferred by Leovy *et al.* Outside this region the atmosphere is clear. The presence of dust in the north clearly reduces surface stresses at almost all latitudes and especially the values of local maxima. The computed reduction in the north is probably overestimated by this model since it does not simulate or parameterize the effects of baroclinic waves and other types of large-scale eddy motions. On the other hand, the computed changes in the southern hemisphere should be reasonably well simulated, at least to the extent that the Hadley circulation is driven by radiative heating. There, the friction velocity is reduced at all latitudes with the greatest reductions occurring at precisely those latitudes from which global dust storms originate (10°S to 40°S). This result is particularly significant given the cubic dependence of the vertical dust flux on u^* (*17*). Since the magnitude of the effect will depend on the amount and distribution of dust, additional experiments were performed that vary these parameters. The results, however, are similar (Table 1).

Although these results are intriguing, they do not in themselves offer an explanation for why global dust storms occur in some years but not in others. Leovy *et al.* (*6*) suggested that Mars may exhibit a bifurcation phenomenon in which the alternative paths are determined by random fluctuations in the meteorology of the dust storm season. The results given here suggest that the random aspect is the result of a competition between circulations in opposite hemispheres—the baroclinic circulation in the north and the Hadley circulation in the south. If the baroclinic circulation is able to raise enough dust during winter, the Hadley circulation will be weakened and the tendency for global dust storms will be suppressed. Otherwise the Hadley circulation will be strong, global dust storms will occur, and baroclinic wave activity will be suppressed.

On the other hand, it is possible that the interannual variability is related to the supply of dust particles available for lifting in the north (Fig. 3). Dust transported into the northern hemisphere during a year with global dust storms becomes available for lifting in the following year or years. During those years, the northern wave systems raise this dust, thereby weakening the Hadley circulation and preventing global dust storms. These systems further transport dust northward into the polar regions where it is permanently removed as part of the layered terrain formation process (*2*). Dust may also be permanently removed in regions with aerodynamically rough surfaces (*18*) or low thermal inertias (*19*). In addition, the mean circulation may recycle some dust back toward the southern hemisphere. In any case, once the supply has been diminished, dust raising in the north is reduced, the Hadley circulation regains its strength, and global dust storms develop anew. Deposition of dust following a global dust storm and its subsequent erosion during the following winters has been observed at the Mutch memorial station (*20*). If this feedback mechanism operates, it suggests that global dust storms are quasi-periodic, with a frequency determined mainly by the amount of dust transported into the northern hemisphere latitudes that experience greatest wave activity. It also suggests that mobile dust particles are more efficiently removed in the north compared to the south which is consistent with recent interpretations of Viking infrared thermal mapper data (*19*).

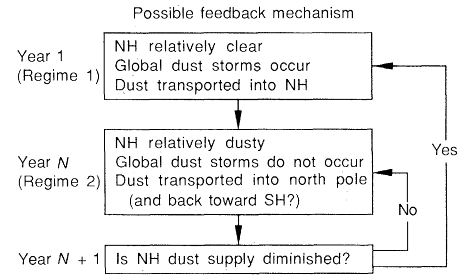

Fig. 3. Box diagram illustrating a possible feedback mechanism for interannual variability of global dust storms. NH, northern hemisphere; SH, southern hemisphere.

At present it is not possible to distinguish between these possibilities since only six well-documented cases of global dust storms exist (Table 2). In the (Mars) year following the 1956 and 1977 storms, no global dust storms were observed, in accord with the feedback hypothesis. However, a global dust storm was observed in the year following the 1971 storm, which is more in accord with the random hypothesis. The most recent storm occurred during late 1982 at the end of the Viking mission, but Mars was too far away during the following year to document a global dust storm from Earth (*21*). Thus, only three pairs of years exist to test these ideas; this is not sufficient to establish statistical significance.

Furthermore neither database, telescopic or spacecraft, is able to unambiguously determine if a northern hemisphere dust haze

Table 1. Sensitivity experiments.

Optical depth (τ)	Cloud top (km)	$\delta\lvert\psi\rvert$* (%)	$\overline{\delta u_*}$† (cm/sec)
1.0	6	−42	−16.2
0.5	6	−40	−13.9
0.1	6	−18	− 1.6
1.0	2	−28	−12.4
1.0	12	−23	−15.2

*$\delta\lvert\psi\rvert$ represents the change in the peak mass flux when dust was present. The mass flux is a measure of the intensity of the Hadley circulation. †$\overline{\delta u_*}$ represents the mean area weighted change in u_* between latitudes 10°S and 40°S.

Table 2. Well-documented global dust storms (*22*).

Year	L_s*	Initial location	Observation
1956	250°	30°S 31°E	Telescopic
1971	260°	29°S 38°E	Telescopic/Mariner 9
1973	300°	24°S 88°W	Telescopic
1977	204°	30°S 70°W (?)	Viking
1977	268°	?	Viking
1982	200°	?	Viking

*L_s is the areocentric longitude. It is an angular measure of the seasonal date. L_s = 0 corresponds to northern spring equinox.

exists in years with global dust storms and does not exist in years prior to them. Complicating this issue is the occurrence of early and generally less intense fall storms. Such storms were observed before the great storms of 1971 and 1977. The most recent storm listed in Table 2 falls in this category. These storms may also play a role in the observed variability.

Clearly, a longer observational record is needed. This record will be extended by Earth-based observations (the International Planetary Patrol Program, for example) and by viewing Mars from orbit during the forthcoming Mars Observer mission. Until a longer record can be established, however, the only firm conclusion is that enhanced dustiness in the north relative to the south during winter weakens the Hadley circulation and the likelihood of global dust storms.

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23. Helpful discussions with O. B. Toon, J. B. Pollack, D. L. Westphal, R. W. Zurek, P. R. Christensen, J. R. Barnes, C. B. Leovy, and L. J. Martin are gratefully acknowledged. Supported by funds from NASA's Mars data analysis program.

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Gap Junctional Conductance and Permeability Are Linearly Related

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The permeability of gap junctions to tetraethylammonium ions was measured in isolated pairs of blastomeres from *Rana pipiens* L. and compared to the junctional conductance. In this system, the junctional conductance is voltage-dependent and decreases with moderate transjunctional voltage of either sign. The permeability to tetraethylammonium ions was determined by injecting one cell of a pair with tetraethylammonium and monitoring its changing concentration in the prejunctional and postjunctional cells with ion-selective electrodes. Junctional conductance was determined by current-clamp and voltage-clamp techniques. For different cell pairs in which the transjunctional voltage was small and the junctional conductance at its maximum value, the permeability to tetraethylammonium ions was proportional to the junctional conductance. In individual cell pairs, a reduction in the junctional conductance induced by voltage was accompanied by a proportional reduction in the permeability of the gap junction over a wide range. The diameter of the tetraethylammonium ion (8.0 to 8.5 Å, unhydrated) is larger than that of the potassium ion (4.6 Å, hydrated), the predominant current-carrying species. The proportionality between the permeability to tetraethylammonium ions and the junctional conductance, measured here with exceptionally fine time resolution, indicates that a common gap junctional pathway mediates both electrical and chemical fluxes between cells, and that closure of single gap junction channels by voltage is all or none.

GAP JUNCTIONS ARE CLUSTERS OF specialized membrane channels that directly connect the interiors of adjoining cells (*1*). Communication via gap junctions can be quantified by measurement of junctional permeability (*2*) for a specific molecule (P_j) or by junctional conductance (g_j), which reflects the composite junctional permeability to small cytoplasmic ions, dominated in most cells by potassium (*3*). Both g_j and P_j are most easily measured in coupled pairs of cells, where voltage and concentration are uniform in each cell so that all junctions are subject to the same gradient. Determined qualitatively from tracer studies, the upper size limit for permeation of gap junctions is about 1.0 to 1.5 kD or 12 to 14 Å in diameter, which would allow inorganic ions and many metabolites, but not macromolecules, to pass between cells (*4*).

The conductance of gap junctions can be reduced by several physiological and pharmacological agents, most notably applied voltages and intracellular hydrogen and calcium ions (*5*). In some cases these treatments were reported to depress dye transfer to a much greater extent than electrical coupling or to block transfer of larger dyes preferentially (*6*). However, junctional permeability and conductance were not measured, and the apparent selectivity may have reflected a lower sensitivity in the measurement of the larger tracers (*7*). A more recent study reports proportional reductions in dye permeability and g_j for one treatment that decreases coupling in *Chironomus* salivary gland (*8*).

Quantitative correlation of g_j and P_j would help distinguish between two proposed mechanisms for gap junction gating. If closure is all or none and channels exist in open or closed states, a reduction in g_j (producing uncoupling) results from a reduction in the number of channels in the open configuration (Fig. 1). If closure is graded or in multiple steps and each channel behaves in the same way, a reduction in g_j results from decreased conductance and permeability of each channel. These two models of closure imply quite different relative changes in g_j and P_j. For all-or-none closure, g_j and P_j will be decreased proportionately and for graded closure, P_j for larger molecules will be decreased more than g_j, which is dominated by permeability to small ions.

We measured the junctional permeability to tetraethylammonium ions [P_j (TEA)] and g_j simultaneously in pairs of amphibian blastomeres. In these cells g_j is reduced by moderate transjunctional voltage (V_j) of either sign (*9*). We compared P_j (TEA) to g_j

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