INITIATION AND SPREAD OF MARTIAN DUST STORMS. J. R. Barnes, College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis OR 97333, USA (barnes@oce.orst.edu).

Introduction: Martian dust storms have been observed at least since the latter half of the 19th century. It was noted early on that the larger-scale obscurations by "yellow clouds" tended to occur near the perihelion season, though these clouds were observed in other seasons as well. A large ("planet-encircling") storm was observed extensively from Earth in 1956, but spacecraft observations have been associated with most of the best-known and largest Martian dust storms. In particular, the 1971 storm that essentially coincided with the arrival of Mariner 9 at Mars is the most extensive storm ever observed (and probably the only storm of truly global extent). Another very large storm was telescopically observed in 1973, the subsequent Mars year. Two large storms (the so-called 1977a and 1977b storms) were observed two Mars years later in 1977 by the Viking spacecraft - though these storms were not observed from Earth. Viking lander meteorological data indicate that another very large storm occured two Mars years later, in 1982. Earth-based microwave observations indicate that a large dust storm (with thermal effects approaching the magnitude of those observed by Mariner and Viking) occurred in 1994. Finally, again coincident with the presence of spacecraft at Mars, a large regional storm - close to planet-encircling size - was observed in late 1997 by MGS.

Our knowledge of the frequency of major dust storms is limited because of the coverage biases inherent in the Earth-based observational record. Careful analyses of this record have led to an estimate that the probability of a "planetary-encircling" storm occurring in any particular Mars year is roughly 1/3. The only confirmed such storms on record are the ones in 1956, 1971, 1973, 1977 (two), and 1982. It appears likely that a storm in 1924-25 was also planet-encircling, and the microwave data strongly suggest that the 1994 storm was of planet-encircling scale. It can be noted that all of the successful Mars spacecraft missions that have been at Mars during the perihelion season have observed large dust storms. It is somewhat difficult to attribute the apparent increased frequency of major dust storm activity starting in 1971 (essentially the beginning of the spacecraft era) to chance, but it is possible that the first half of the century was characterized by fewer large storms than the more recent era - something that would indicate substantial climate changes on Mars on decadal time scales.

A categorization of dust storms can be made on the basis of horizontal scale, with a breakdown into local, regional, and planet-encircling storms. The demarcation between local and regional storms has been placed at a scale of 2000 km, or about 40 degrees of longitude (for the long axis of the storm). Local storms then include all dust activity at smaller scales, extending down to the dust devils observed by Viking and Pathfinder. In this categorization scheme, the planet-encircling storms can range from storms that remain largely restricted to one - northern or southern - hemisphere to storms that are completely global like the 1971 event. Obviously, a more quantitative categorization of storm size would also be based upon a measure of the total amount of dust put into the atmosphere and on the magnitude and extent of temperature changes induced. Some such estimates can already be made using the available spacecraft observations, and future data should permit much better estimates to be made for major storms that are observed.

Mechanisms and Dynamics: Three sets of mechanisms are critical to the genesis and growth of dust storms in the Martian atmosphere: mechanisms for dust lifting from the surface and injection into the atmosphere, mechanisms for dust heating of the atmosphere, and mechanisms for dust lofting, suspension and horizontal transport at higher altitudes.

Dust lifting and injection into the atmosphere (suspension) can occur as a result of saltation processes, and these take place most readily on Mars for sand-sized particles ~

100 microns in diameter. In the absence of such particles, extremely high wind speeds are needed to move the relatively small (~ 1 micron) particles that appear to dominate the atmospheric dust loading in storms (as well as the normal, "background" dust loading). The existence of dunes together with thermal IR data indicate that sand-sized particles are present over much of the Martian surface. Saltation of these particles can act to "trigger" the injection of much smaller particles via impacts. Sand-sized aggregate particles can be raised and then broken down into much smaller particles by collisions. Volatile outgassing from surface layers has been suggested as a possible means of directly injecting smaller particles into the atmosphere. Finally, dust devils may be a very important mechanism (in which vertical pressure differences play a key role) for injecting small particles into suspension; the observations by Pathfinder certainly suggest that dust devils are frequent during summer.

Once dust is in the atmosphere, it provides a very potent source for heating which in turn constitutes a very powerful forcing for vertical and horizontal winds. The dust particles are relatively effective absorbers of solar radiation, and thus can generate very strong heating in the thin Martian atmosphere. The dust particles also absorb and emit IR radiation, producing both atmospheric heating and cooling. The impact of dust particles in producing strong solar heating can be substantially altered if there is condensation of ices on the dust, and this could be a significant factor in determining when and where large storms occur.

Vertical motions can loft dust particles to great heights in the atmosphere. In the planetary boundary layer, smaller-scale turbulent processes are almost certainly very important. Above this lower region, more organized flows appear to play a key role in lofting dust to high altitudes. Convective cells can rapidly transport dust to the top of any layer which is actively convecting (and such layers can be produced at high altitudes as a result of dust heating), and global modeling has shown that the planetary-scale Hadley circulation is capable of transporting dust quickly to very great heights in its ascending branch, as well as over large latitudinal distances - in particular, from the southern hemisphere well into the northern hemisphere during the dust storm season. Viking and MGS imagery of the early stages of large dust storms show cloud structures that indeed appear to be highly convective in nature.

Observations of large (regional and planet-encircling) dust storms reveal some fairly consistent features of their development. The storms are first seen as sizeable local storms, which then expand fairly rapidly to regional scales. The Noachis Terra storm seen by MGS expanded to a large regional size within 4 days. Typically, within 10-15 days a storm can become planet-encircling. The 1971 storm had reached an essentially global extent (obscuring almost all of the surface) within 20 days. Observations and modeling indicate that substantial amounts (corresponding to column visible optical depths of one or more) of dust can be transported well into the northern hemisphere (to at least 30-40 N) from a southern hemisphere source region very quickly - within ~ 3-10 days. Changes in northern hemisphere thermal structure and dynamical fields (e.g., surface pressure) can occur even more rapidly than this. MGS detected large changes in thermospheric densities in northern midlatitudes just two days after the observed start of the Noachis Terra storm.

Almost all of the planet-encircling storms have been observed to start in one of two basic regions on Mars: Syria Planum/Sinai Planum/Solis Planum/Thaumasia Fossae and Hellespontus/Noachis Terra, in the southern subtropics between ~ 15-40 S. All of the observed storms have begun within 50-60 degrees of L_s of perihelion (L_s ~ 250); the Noachis Terra storm began at L_s ~ 224. The observed locations and timing of the early stages of the large dust storms provide a strong clue that several components of the atmospheric general circulation play particularly important roles in their initiation and growth. Two of these are the thermal tides and the summer subtropical jet; others are the "western boundary currents" and slope winds.

Viking and Pathfinder have directly shown the prominence of thermal tides on Mars, and modeling studies show that these tides should have maximum wind amplitudes in the subtropics with these amplitudes tending to increase with the insolation (which peaks in the southern subtropics at perihelion) and the dustiness. The tides consist of both sun-following modes, and eastward propagating modes that can be excited by topography or dust loading having a zonal wavenumber 2 pattern. The interference of the two types of tidal modes can produce a standing wave pattern with large tidal amplitudes present in certain longitudinal regions and much smaller amplitudes in others. Viking observations suggest that longitudes in the vicinity of 40 E and 140 W may be regions of enhanced tidal amplitudes - and these are near to the regions in which almost all planet-encircling storms have been observed to originate in the southern hemisphere.

The summer subtropical jet - the existence of which has now been directly detected in MGS radio occultation data - is a very low-level westerly flow located between ~ 10-40 S associated with the rising branch of the cross-equatorial Hadley circulation. It attains a maximum strength near southern summer solstice, and its strength increases with increasing dust loading (as the strength of the Hadley cell increases). Modeling indicates that this jet is most intense in the Noachis Terra region, and in the vicinity of 180 W. It is certainly significant that this jet is much stronger, according to modeling studies, in southern summer than in northern summer - a consequence both of the seasonal asymmetry in the thermal forcing associated with Mars' eccentric orbit and the very different topography in the two hemispheres.

Two additional circulation components may play important roles in the genesis and development of large dust storms: southward winds associated with especially intense (longitudinal) segments of the Hadley cell, and slope winds. The former have been referred to as western boundary currents, and they appear (on the basis of modeling) to be particularly strong in the vicinity of 20-70 W and 40-100 E on east-facing topographic slopes. Again, the western boundary currents are much stronger in southern summer than in northern summer according to the global models. Very strong slope winds (especially night-time drainage winds) are present in the models in the areas of Syria Planum/Sinai Planum/Solis Planum and the Hellas basin.

The further significance for large storms of the southern subtropics, of course, is that there are very strong rising motions in this region associated with the Hadley cell in summer (and these motions are further strengthened by enhanced dustiness). Dust that is raised in this region at this time will tend to be lofted relatively quickly to considerable altitudes - and then transported northward in the poleward branch of the Hadley cell. In the same way that the lower branch of the Hadley cell is strongly longitude-dependent, the rising branch of this cell is also. Model studies (with longitudinally uniform dust loadings) show that longitudes in the vicinity of 0 - 120 W, 30 - 70 E, and 100-180 E are characterized by the strongest rising motions in the southern subtropics during summer. Of course, in reality the regions of strongest rising motion will be strongly influenced by the longitudinal distribution of dustiness in the subtropics.

An additional factor that almost certainly is important for the initiation of large dust storms is the surface supply of dust (which can be injected into the atmosphere) and sand-sized particles. This may be critical in determining the areas in which large dust storm genesis occurs, and in the interannual variability of large dust storms - since this component of the system can have a much longer "memory" than the atmospheric components (however, it does appear possible that just the atmospheric portion of the system could produce sizeable interannual variability, as a result of its strong nonlinearity). It has been speculated on the basis of the historical telescopic observations that the first half of the century was marked by substantially fewer large dust storms than the more recent period. If there are indeed significant variations in the frequency of large dust storms on these kinds of time scales, then processes/factors related to the surface supply of dust would seem to be a prime candidate for producing this variability.

Discussion: Two issues which are central ones in relation to large dust storms warrant further discussion. One of these is the decay of large dust storms, and the other is the interannual variability of large dust storms. The focus here has been on dust storm initiation and growth, but current understanding of the mechanisms underlying the decay of large storms is rather limited. Modeling studies show that atmospheric dustiness constitutes a very strong positive feedback mechanism for most components of the general circulation. One exception is slope winds (and also winds driven by low-level heating gradients), which should decline as surface heating and surface temperature variations diminish due to enhanced dustiness. This effect should begin to be significant at visible optical depths of roughly one. Another exception may be the eastward-propagating tidal components. These tend to be strongly forced by certain longitudinal dust distributions and reduced by other distributions. It thus is possible that conditions can be very favorable for large-amplitude eastward modes in the early stages of a storm, but that as the dust distribution is altered by the growing storm it then can become very unfavorable for the eastward tidal modes. This could constitute a powerful shut-down mechanism for large storms. Another very important negative feedback factor may be the diminished coupling of surface winds with stronger winds aloft resulting from a more stably stratified lower atmosphere produced by increased dustiness. Model simulations, however, have not yet demonstrated that this really provides a strong negative feedback for the circulation. A key factor in the decay of "global" dust storms in current models seems to be simply the progression of season - at dates sufficiently after perihelion and southern summer solstice the circulation weakens sufficiently that wide-spread dust-raising can no longer occur.

In connection with interannual variability, the key question would seem to be why very large, planet-encircling storms occur in some Mars years but not in others. It appears that sizeable regional storms may occur in most Mars years (many years may have several such storms). It appears that there is essentially a continuum of large dust storms on Mars ranging from large regional storms like the Noachis Terra event, to planet-encircling storms that remain mostly confined to the southern hemisphere, to completely global storms like the 1971 event. The mechanisms and processes that determine whether a good-sized local storm grows to regional or planet-encircling size remain uncertain at present. An obvious question, for example, is why did the Noachis Terra storm not grow to even larger scale than it did? Is the seasonal date perhaps the biggest factor in deciding the evolution of a storm? Or is the "precursor" dust loading/distribution perhaps an even more important factor? Atmospheric observations that will be made by MGS, MCO, and future spacecraft should lead to a much better understanding of Martian dust storms. Long-term monitoring of Mars - from orbit, from the Earth, and from the surface - is clearly essential if a good understanding of the interannual variability of large dust storms is to be achieved.

In the context of climatic change, the longer term frequency and magnitude of dust storm activity is very important. It has been hypothesized that the layered terrains in the polar regions are manifestations of variations in dust raising and transport which occur on time scales of 10^4-10^6 years and longer. A basic question of considerable importance is whether global dust storms take place during northern summer, during epochs when perihelion occurs during this season. Modeling studies indicate that large storms might not occur in this season, at least at obliquities similar to the present one, because of the large differences in the topography and atmospheric circulations in the two summer seasons. When the global circulation models are capable of simulating the observed evolution of large storms and the interannual variability on shorter (decadal) time scales, we can have some degree of confidence that they might be capable of also simulating the much longer time scale dust storm variability.