Extratropical Cyclones, Frontal Waves and Mars Dust: Modeling and Considerations

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A Mars GCM is utilized to investigate dust lifting and organization associated with extratropical cyclogenesis and frontal waves. The model is applied at high resolution in simulations related to Mars’ dust cycle. A single extratropical synoptic weather event is examined to ascertain lifting, transport and convergence/divergence of dust by large-scale cyclonic/anticyclonic weather systems, and the sub-synoptic frontal waves that ensue. Low- and high-pressure cores develop, travel eastward and remain mostly confined within the seasonal CO₂ polar cap. The bulk of dust lifting occurs in the northern-hemisphere western highlands associated with nocturnal down-slope drainage flows, and lifting infrequently occurs near the frontal convergence zone. Dust becomes organized and transported within circulations associated with the synoptic/sub-synoptic circulations accompanying the frontal waves. Dynamical considerations are invoked regarding frontogenesis revealing correlations with regards to dust lifting, organization and transport. Implications of large-scale extratropical weather systems on the martian dust cycle are discussed.
1. Introduction

During late autumn through early spring, extratropical regions on Mars exhibit profound equator-to-pole thermal contrasts (i.e., “baroclinicity”). From data collected during the Viking era and observations obtained from the Mars Global Surveyor (MGS) mission, the imposition of this strong temperature contrast supports intense eastward-traveling weather systems (i.e., transient synoptic-period waves) associated with the dynamical process of baroclinic instability [Barnes, 1980; Barnes, 1981; Banfield et al., 2004; Hinson and Wilson, 2002; Hinson, 2006;]. The weather disturbances indicate large-scale, spiralling, “comma”-shaped dust cloud structures and dust fronts in the northern extratropical and subtropical environment [Wang et al., 2003; Wang et al., 2005; Wang, 2007; Wang and Fisher, 2009; Hinson and Wang, 2010]. Such traveling disturbances and their poleward transports of heat and momentum directly influence the global atmospheric energy budget.

Most numerical investigations of baroclinic instability in Mars’ atmosphere have implemented rather coarse horizontal resolution. With such resolutions, large-scale dynamical processes intrinsic to the development and decay of the traveling mid- and high-latitude transient baroclinic waves—the synoptic-scale cyclogenesis from which frontal structures can develop—are adequately resolved. Because the models have been coarse, energy associated with the synoptic scale cyclogenesis is limited in its cascade toward smaller spatial scales. This precludes fully resolving complex circulations such as shear and stretching deformations accompanying intense cyclonic and anticyclonic vortices, and scalar contractions and dilatations accompanying frontal waves on the sub-synoptic scale.
Our goal is to ascertain the atmospheric environmental conditions under which near-surface and/or upper-level fronts form within Mars’ baroclinic zone. We investigate dynamical influences such frontal waves have on the lifting, organization and transport of atmospheric dust in the extratropics and its interaction with other circulation components (e.g., up-slope/down-slope flows; thermal tidal modes; quasi-stationary components; etc). We wish to ascertain the roles such disturbances have on the transport of atmospheric dust, with the goal of assessing the influences such systems have on the dust cycle of Mars.

2. Climate Model

In this investigation, we build upon previous mechanistic studies that utilized high-resolution, simple-physics global circulation models [Hollingsworth, 2003] by applying a state-of-the-art, full-physics general circulation model (GCM) for Mars [Haberle et al., 1999; Kahre et al., 2006; Kahre et al., 2008; Kahre and Haberle, 2010].

The NASA Ames Mars GCM is formulated using the ARIES/GEOS C-grid “dynamical core”, version 2 [Suarez and Takacs, 1995]. Atmospheric transport has been implemented using finite-volume techniques following the work of Hourdin and Armengaud [1995]. The model configuration has 24 unequally-spaced $\sigma$ (i.e., normalized pressure) layers with a model “top” pressure of $5 \times 10^{-4}$ mbar. A $2.0^\circ \times 3.0^\circ$ longitude-latitude grid resolution is imposed in the horizontal.

The version adapted for this investigation includes lifting, transport and sedimentation of radiatively-active dust. The reader is referred to Kahre et al. [2006] and Kahre and Haberle [2010] for complete descriptions of the dust implementations that are only summarized here. Dust particles (with a radius of 1.5 $\mu$m) are injected into the model atmosphere.
through a parameterized wind-stress dust lifting scheme. Dust is advected horizontally and vertically by model-resolved winds, and gravitational sedimentation is governed by the Stokes-Cunningham relationship. The radiative effects of the evolving atmospheric dust are accounted for at visible and infrared wavelengths, with a wavelength-integrated single-scattering albedo and asymmetry parameter of 0.86 and 0.79, respectively \cite{Pollack1990}. The visible to infrared ratio is assumed to be 2.

It should be emphasized that the simulations presented in this work fundamentally differ from those presented in \cite{Wang2003}. Our simulations impose a self-consistent dust lifting scheme based on a threshold value of the surface stress as detailed in \cite{Kahre2006}. The simulation results presented in \cite{Wang2003} utilized an arbitrary passive tracer injection scheme and were performed “off-line” using a Lagrangian particle transport model.

3. Results

We focus on the character of one extratropical synoptic weather event and its associated frontal wave in our annual, high-resolution simulation during late northern winter. To construct a “seasonal mean” state (at $L_s \sim 324^\circ$), 40 days of model output have been analyzed centered about this season. Instantaneous time departures, both temporally unfiltered components (e.g., those associated with diurnally-varying modes) and band-pass filtered components (i.e., those associated with only synoptic-period modes), have been examined. The mean zonal temperatures are far colder in the northern hemisphere and there is enhanced low-level baroclinicity near the edge of the retreating seasonal $\text{CO}_2$
polar ice cap. This mean thermal contrast supports a vigorous westerly polar vortex with wind speeds in excess of $\mathcal{O}(160 \text{ m s}^{-1})$ at altitude.

Evidence of intense synoptic-period transient weather systems can be seen in the multi-panels of Fig. 1 (each panel row is separated by 6 hrs)—additional analyses of meteorological fields are provided as on-line electronic supplemental material (doi:10.1029/2010GL044262). A series of extratropical cyclones and anticyclones develop, intensify, travel eastward and decay (Fig. 1a). Surface pressure anomalies are associated with “troughs” and “ridges” that range between $\mathcal{O}(\pm 5–10\%)$ from a global reference value. The dominant longitudinal scales of these transient waves (which vary over the 40-day averaging period) are associated with zonal wavenumbers $s = 1–3$, a range indicating a preferred selection for cyclogenesis near the Rossby deformation scale as predicted from coarser model simulations [Barnes et al., 1993; Collins et al., 1996]. Zonal phase speeds, $c(x)$, of $\mathcal{O}(10–30 \text{ m s}^{-1})$ are indicated. The weather systems are most intense just in the lee of the Tharsis highlands in the Acidalia/Chryse regions. This region has been recognized to be an active storm zone within the western hemisphere [Hollingsworth, 1996; Hollingsworth et al., 1997; Wang et al., 2003; Wang et al., 2005].

The low-level horizontal wind indicates distinct lines of convergence (i.e., frontal zones) in the low-relief regions (Fig. 1a). In the early stages, the frontal zone has a “wishbone”-like structure that rapidly coalesces by 12 hr into a single zone of convergence which then progresses eastward. In the high-relief regions to the west, surface stresses exceed the threshold value. Peak low-level horizontal wind speed deviations in this region are $\mathcal{O}(20 \text{ m s}^{-1})$. These fields show classical signatures associated with frontogenetic pro-
cesses: shear and stretching deformations, and flow contractions/dilatations that can significantly alter atmospheric scalars (e.g., temperature, dust mixing ratio, etc). Such flow patterns resemble terrestrial cold fronts. With a smaller planetary radius and similar Rossby deformation scales, weather systems on Mars appear more hemispherically effective at “stirring” and “mixing” the high-latitude cold polar front well into the midlatitudes and subtropics.

Connected to the surface-pressure variability are variations in surface stresses (Fig. 1a). Stresses generally maximize in the western hemisphere (i.e., along the Tharsis volcanoes, Olympus Mons, Alba Mons) and they maximize somewhat weaker in the eastern hemisphere (associated with the Arabia highlands and Elysium further to the east). The maximum stresses in the western hemisphere are a result of strong nocturnal down-slope drainage flows off the high relief regions. These regions frequently exceed the stress dust-lifting threshold value of $\sigma_0 = 22.5$ mPa. The instantaneous surface stress is also organized within the frontal convergence zone and they are enhanced on the eastward side of the parenting cyclone. Rarely do the stresses accompanying the front exceed the threshold lifting stress. They also are significantly weaker than those found upstream in the high-relief regions associated with nocturnal down-slope flows.

Low-level time deviations of atmospheric dust mixing ratio, $q'$, are organized by the near-surface flow (Fig. 1b). Maximum dust content occurs in the western hemisphere and also within the synoptic weather system and frontal wave. The maximum dust-lifting rate occurs primarily over the high-relief regions to the west. Due to high stresses over Tharsis and the fact that the surface stresses are not increased enough along the convergence line
to exceed the lifting threshold, the peak lifting rate does not consistently occur along the frontal convergence zone. This is in contrast to observational evidence suggestive of dust being lifted within the frontal region [Wang et al., 2005; Wang and Fisher, 2009]. Significant cross-frontal gradients in dust mixing ratio are evident, with maxima occurring near the frontal boundary and minima behind and well ahead of the frontal wave. These patterns indicate “focusing” and organization of dust associated with the frontal wave circulations.

The compact, linear segment of dust that slopes from the southwest to the northeast (Fig. 1b) resembles structures that appear in MOC daily global maps (e.g., Figs. 4 and 8 in Hinson and Wang, [2010]). This particular synoptic cyclone, anti-cyclone pair (i.e., baroclinic traveling wave) at $L_s = 315^\circ$ corresponds to a wavenumber $s = 2$ disturbance with a period of 3 days, a result which is comparable to MGS/RS observations [Hinson, 2006]. The predominant extratropical wave mode varies between wavenumbers $s = 1$ and $s = 2$, however, during this seasonal segment in the simulation.

Within 12 hr, the dust filament “fractures” in mid-section, with the northern part progressing northward and eastward with the parenting cyclone, and the southern part remaining near stationary over higher relief. There is also a tendency for dust to be organized and enhanced in the eastward flank of the cyclonic system associated with strong horizontal flow convergence. This is consistent with observations from MGS/MOC [Wang and Fisher, 2009]. Further, the morphology of dust organization and transport in this simulation is reminiscent of the results presented in Wang et al. [2003].
Distinct cold-air and warm-air sectors associated with the transient surface pressure anomalies develop, and “λ”-like looking signatures in the low-level thermal field can form. Continental-scale orography plays a significant role in breaking the hemispheric symmetry of the martian northern polar front, and in determining the zonal and meridional scales of the individual baroclinic disturbances, the accompanying frontal waves, and the sub-synoptic circulation patterns.

4. Dynamical Considerations

In terms of instantaneous fields of surface pressure, near-surface horizontal flow, temperature and dust mixing ratio, there is necessarily a relationship between spatial and temporal patterns of such scalars as they are all intertwined within an individual frontal wave. This is requisite for dynamical balance within the 3D circulation associated with a developing large-scale cyclone/anticyclone pair, and the concomitant energy cascade toward sub-synoptic scale fronts. Further, spatial/temporal offsets in meteorological scalar fields delimit different stages of development within a given sub-synoptic scale system, and for balance constraints, such offsets are requisite for the transport of heat, momentum and individual tracer species within and out of a developing/decaying frontal wave.

We have explored temporal and spatial evolution of higher-order diagnostic quantities such as time deviations in relative vorticity $\zeta' = v'_x - u'_y$, where $v'$ and $u'$ are deviations in meridional and zonal winds, respectively, and the subscripts $x$ and $y$ denote spherical partial derivatives in the eastward and northward directions. Instantaneous fields of relative vorticity $\zeta'$ show the sharp locations of the parenting cyclone and the associated
frontal convergence zone which acts to organize (via horizontal transport) atmospheric
dust within a given frontal wave (cf. on-line electronic supplemental material).

The circulation within an cyclone/anticyclone disturbance and its accompanying frontal
wave is richly 3D due to the requirement for thermal and dynamical balance within an
individual weather system [Hoskins and Pedder, 1980; Sanders and Hoskins, 1990]. Associated
with the convergent/divergent and stretching/deforming quasi-horizontal circula-
tions in a frontal system, is a secondary, cross-frontal (ageostrophic) circulation [Hoskins
and Pedder, 1980; Sanders and Hoskins, 1990] which results in ascending (descending)
motion ahead (behind) the frontal zone. The occurrence of this secondary circulation can
be assessed in terms of the so-called Q vector where $Q = (Q_x, Q_y, 0)$ is a horizontal vec-
tor whose components are comprised of the products of horizontal shears in the horizontal
wind and directional derivatives in potential temperature, $\theta$ [Kurz, 1992]

$$Q \equiv (u_g \theta_x + v_g \theta_y, u_g \theta_x + v_g \theta_y, 0)$$

where the subscript $g$ indicates the geostrophic components of the wind components.
Further, $Q$ is a good dynamical indicator of frontogenetic/frontolytic processes within a
front, and the cross-frontal (secondary) circulation can be shown to be related to it by
$w \propto -\nabla \cdot Q$ [Sanders and Hoskins, 1990]. Under quasi-geostrophic theory, the quantity
$Q \cdot \nabla \theta$ is proportional to the Langrangian time derivative of the squared temperature
gradient [Hoskins and Pedder, 1980], a quantitative measure of development or decay of
a frontal wave.

Longitude-latitude sections of the instantaneous thermal anomaly, together with $Q$ and
its divergence (Fig. 1c) for the same time steps indicate dynamical correlations with the
low-level circulation field (Fig. 1a). Over this time period, there are rapid and significant changes in the $\mathbf{Q}$ vector. Along the frontal zone, convergence of $\mathbf{Q}$ is depicted (red solid contours) and a resultant upward (induced secondary) motion can be inferred. The thermal anomaly associated with the sub-synoptic weather system exhibits a filament-like structure in the extratropics, similar to the dust mixing ratio (Fig. 1b). Further, the warm anomalies are accompanied by clear ascending motion (Fig. 1c) just ahead of the front.

5. Summary and Conclusions

The imposition of Mars’ strong baroclinicity supports intense and vigorous eastward traveling weather systems (i.e., transient synoptic-period waves), particularly in northern late winter/early spring. These weather systems have accompanying sub-synoptic scale ramifications on the atmospheric environment through cyclonic/anticyclonic winds, deformations and contractions/dilatations in temperatures, and sharp perturbations amongst atmospheric tracers (e.g., dust). Mars’ frontal waves also exhibit large spatial extents, reaching from middle and high latitudes, and even into the subtropics [Wang et al., 2003; Wang et al., 2005; Hinson and Wang, 2010].

As a result of large-scale cyclogenesis, the associated frontal waves exhibit rich spatial/temporal filamentary structures on sub-synoptic scales for nearly all meteorological fields (e.g., instantaneous temperature anomalies, wind shears, relative vorticity, $\mathbf{Q}$, $-\nabla \cdot \mathbf{Q}$, etc), and the evolution of such dynamical structures demarcate various stages in the development/decay of the weather systems. Our high-resolution GCM simulations utilizing the NASA Ames Mars general circulation model with an interactive dust cycle suggest that in the northern hemisphere, dust is lifted primarily by nocturnal down-slope
flows over the Tharsis volcanoes and Alba Mons of the western hemisphere. Maximum surface stresses typically occur in these regions and just on the leeward side of Alba Mons (e.g., -80°E). Temporal variability is highest in these regions as well, and instantaneous surface stresses often exceed the threshold stress value required for stress-related dust lifting ($\sigma_0 = 22.5$ mPa). Dust that is lifted and lofted into the atmosphere there can become organized and carried downstream associated with synoptic weather systems and frontal-related circulations. Depending on the timing of passage of such weather systems, the nocturnal down-slope flows can be enhanced (particularly in the lee of this region), further increasing the lifting potential of dust.

Observations by MGS/MOC appear to indicate that dust lifting may very well be occurring along frontal convergence zones themselves [Wang et al., 2003; Wang and Fisher, 2009]. However thus far, our GCM simulations indicate that stress-related dust lifting occurs primarily upstream, and that low-level dust can become “focused” within the frontal systems via intense circulations, and deformations and dilatations of this radiatively active tracer. In terms of the simulated total column opacity, our simulations indicate a much broader “well-mixed” region within the subtropics (cf. on-line electronic supplemental material).

This brings to light that stress-related dust lifting parameterizations to date are perhaps insufficient and may be lacking key physical processes required to raise dust within highly gusty and/or turbulent environments likely to be occurring within Mars’ frontal waves. Alternatively, it may be the case that keying dust-lifting off of a higher-order, sub-synoptic scale circulation quantity (e.g., vorticity or attributes of the secondary circulation) may
better capture the dust raising in such frontal systems. Under quasi-geostrophic conditions, the relative vorticity can be shown to be related to an extremum in cross-frontal shear [Parker, 1999], and within a traveling and evolving shear zone accompanying a frontal wave, mechanical forms of dust lifting could become enhanced. We need to continue to look closely at frontal wave dynamics and the secondary circulations with an eye on improving our dust-lifting parameterizations. In addition, further work needs to be done at assessing the thermal tidal “gate” and the interactions of the low-topographic relief “duct” in order to assess the modulations of interhemispheric dust transport initiated via extratropical cyclones and frontal waves.

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References


Figure 1. Longitude-latitude sections at $L_s = 315^\circ$ of a variety of low-level meteorological fields from the GCM simulation. (a) the instantaneous surface pressure anomalies (percent deviations from a global mean value of 6.11 mbar) (color); the instantaneous low-level vector horizontal wind (m s$^{-1}$); and, the instantaneous time deviations of surface stress magnitudes (white contours, mPa). Regions exceeding the threshold value of 22.5 mPa are highlighted in red. (b) the instantaneous dust mixing ratio time deviations, $q'$, corresponding to the kinematic fields shown (a). Solid black contours highlight regions of maximum dust-lifting rate. (c) the instantaneous near surface temperature anomalies (percent deviations from a global mean value of 170 K) (color); the $\mathbf{Q}$ vector; and, $-\nabla \cdot \mathbf{Q}$ (red contours with positive values solid, negative values dashed). In (a) the surface stress contour interval is 10 mPa, and the dark blue contours are topography with a contour interval of 2 km. The rows in the figure correspond to $t = t_0$; $t = t_0 + 6$ hr; and, $t = t_0 + 12$ hr.