MARS DUST: ATMOSPHERIC EFFECTS OF LARGE-SCALE EXTRATROPICAL CYCLOGENESIS AND FRONTAL WAVES. J.L. Hollingsworth¹, M.A. Kahre², R.M. Haberle¹, ¹Space Science and Astrobiology Division, Planetary Systems Branch, NASA Ames Research Center, Moffett Field, CA 94035, (jeffh@humbabe.arc.nasa.gov).

Introduction: Mars reveals similar, yet also vastly different, atmospheric circulation patterns compared to those found on Earth [1]. In both atmospheres, solar differential heating drives global Hadley circulation cells. However during solstice on Mars, its Hadley cells are hemispherically asymmetric: an intense, deep, cross-hemisphere single cell dominates with rising motion in the summer hemisphere and sinking motion in the winter hemisphere. Further, both planets exhibit thermally indirect (i.e., eddy-driven) Ferrel circulation cells in middle and high latitudes. During late autumn through early spring, Mars’ extratropics indicate profound equator-to-pole temperature contrasts (i.e., mean “baroclinicity”). From data collected during the Viking era and recent observations from the Mars Global Surveyor (MGS) mission, the imposition of such strong temperature contrasts supports intense eastward traveling weather systems (i.e., transient synoptic-period waves) [2,3,4] associated with the dynamical process of baroclinic instability. Having more regular lifecycles compared to those on Earth [5], such traveling disturbances and their poleward transports of heat and momentum, profoundly influence the global atmospheric energy budget. In addition, the transient baroclinic waves impact other atmospheric scalars (e.g., temperature, horizontal winds, dust mixing ratio, etc).

Both Earth and Mars also exhibit distinctive large-scale orography and, in a broadly defined context, continentality. For Mars’ northern midlatitudes, Tharsis in the western hemisphere, and Arabia Terra and Elysium in the eastern hemisphere, are the primary large-scale topographic features. In the southern midlatitudes, Tharsis and Argyre in the western hemisphere, and Hellas in the eastern hemisphere are the key topographic features which can influence large-scale circulation patterns. These underlying orographic complexes not only can cause significant latitudinal excursions of the seasonal mean westerly circum-navigating polar vortex but also can significantly modulate the intensity and preferred geographic regions of baroclinic weather systems [6].

Several previous numerical investigations of baroclinic instability in the atmosphere of Mars have adapted relatively coarse horizontal resolution. Spectral global circulation models have typically been truncated at T21 (i.e., approximately 5.6° in longitude-latitude) or lower [5] and grid-point models have had resolutions of 5.0 – 9.0 × 4.0 – 7.5° longitude-latitude [7]. The 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 may develop—are well resolved within such nominal horizontal resolutions. Yet because the models are rather coarse (e.g., the smallest horizontal resolved scale in midlatitudes is O(500–800 km)), energy associated with the synoptic scale O(5000 km) cyclogenesis can not adequately cascade toward smaller and smaller spatial scales. This precludes fully resolving complex circulations such as shear and stretching deformations accompanying intense large-scale cyclonic/anti-cyclonic vortices, and scalar contractions and dilatations accompanying frontal waves on the subsynoptic scale O(1000–2000 km) and less. Quite recently, global circulation models having very high resolution have been implemented to investigate Mars’ baroclinic waves, both in a simplified, mechanistic framework [8] and in a more realistic setting [9].

Our goal is to ascertain the atmospheric environmental conditions under which near-surface and/or upper level fronts (i.e., narrow zones with enhanced mass density, momentum and thermal contrasts within individual transient baroclinic waves) form in Mars’ high latitude baroclinic zone, and whether the dynamical development, intensification and decay of such frontal waves can be assessed using modern diagnostics. That is, we wish to ascertain the atmospheric conditions conducive to frontogenetic (development) and frontolytic (decay) phases of individual frontal waves. In addition, we wish to investigate the interactions of these frontal-wave systems with Mars’ highly-variable surface relief (i.e., on large-scales) and further, the interactions with other atmospheric circulation components (e.g., the diurnally and sub-diurnally varying thermal tidal modes; up-slope and down-slope flows; quasi-stationary circulation components associated with forced Rossby modes; etc).

Modeling Approach: Using very high horizontal resolution global circulation models (based on the meteorological primitive equations) that are driven by highly simplified physical parameterizations (i.e., an SGCM approach), we have been modeling over the last several years [8] cyclogenesis and frontal waves in the atmosphere of Mars in order to mechanistically ascertain dynamical processes associated with baroclinic disturbances. In this investigation, we build upon that mechanistic effort by utilizing a state-of-the-art, full-physics general circulation model (GCM) for Mars [10]. Our approach is motivated by recent MGS imaging from the Mars Orbiter Camera (MOC) which indicate large-scale, spiralling, “comma”-shaped dust cloud structures and scimitar-shaped dust fronts in the northern extratropical and subtropical environment during late autumn and early spring [11,12].

The NASA Ames Mars GCM is formulated using the ARIES/GEOS C-grid “dynamical core”, version 2. The vertical coordinate is a normalized pressure, terrain-hugging one (i.e., σ) which enables the lower boundary with spatially-varying topography to coincide with a coordinate surface. The version used conserves energy...
and mean-square enstrophy, and is fourth-order accurate in terms of vorticity advection by the non-rotational component of the flow [13]. The particular version adapted for this investigation (gcm1.7.3) implements a full radiatively-active dust cycle for a range of dust particle sizes, wherein dust lifting is parameterized in terms of dust-devil and surface-stress schemes which are self-consistent with the atmospheric environmental conditions as simulated by the model [10]. That is, this model version includes the lifting, transport and sedimentation of radiatively-active dust. For the prescribed dust lifting schemes we impose, we assess the importance and relevance at high-resolution of (i) wind stress lifting versus (ii) dust-devil lifting, and their implications on Mars’ dust cycle.

The model configuration we adopt has 24 unequally-spaced σ layers (denoted L24) with a model “top” pressure of $5 \times 10^{-4}$ mbar (roughly 100 km). Vertical spacing between layers increases from $O(10 \text{ m})$ at the surface to $O(5 \text{ km})$ in the upper-most part of the model. In the horizontal, we impose a $2.0^\circ \times 3.0^\circ$, longitude-latitude grid resolution (denoted “G60L24” where the “60” corresponds to half the number of grid points around a latitude circle (also the shortest Nyquist) resolved spatial scale at the equator, $O(180 \text{ km})$). Upper-level momentum drag is specified in terms of a height-dependent drag (Rayleigh friction). This upper-level friction provides an effective “sponge” near the model top so as to inhibit wave reflections caused by the imposed upper-boundary condition (i.e., effectively a rigid lid).

Results: The time and zonally-averaged temperature and zonal wind field from our annual baseline high-resolution (i.e., $2.0^\circ \times 3.0^\circ$ longitude-latitude or G60L24) simulation is shown in Fig. 1. In this experiment, time mean and departure fields have been analyzed for 30 sols during the late northern winter season (i.e., centered at $L_s = 350^\circ$). The mean zonal temperatures appear rather symmetric about the equator. However, upon closer inspection, it can be seen that in the northern extratropics the north-south temperature contrasts at this season, particularly near the surface, are significantly stronger than in the southern hemisphere. This asymmetry in mean zonal fields is also apparent in the mean zonal wind (Fig. 1, bottom) where the northern hemisphere’s westerly polar vortex is roughly twice as strong than in the south, with peak wind speeds of $O(120 \text{ m s}^{-1})$. Inspection of the mean mass stream function (not shown) at this season also shows a nearly equatorial-symmetric Hadley circulation with its rising branch occurring just in the southern subtropics.

That this season can support vigorous synoptic-period transient weather systems in the extratropics and subtropics, can be seen in Fig. 2. This figure shows a variety of near-surface meteorological fields (i.e., within 1 km of the surface) at three different times associated with the large-scale cyclogenesis and subsynoptic-scale frontal waves. (Each panel in Fig. 2 is separated by 6 hrs.) The color-shaded field corresponds to surface pressure anomalies (i.e., instantaneous surface pressure time deviations (the time-mean value has been removed), normalized by a global-mean value of 6.1 mbar). A series of extratropical cyclones and anti-cyclones that develop, intensify and decay can be clearly noted. The surface pressure anomalies are associated with “troughs” and “ridges” that range between $O(\pm 5–10\%)$ from a global reference value. The dominant longitudinal scales of the transient waves (which vary substantially over the 30-sol averaging period) are associated with zonal wavenumbers $s = 1–3$ in the middle and high-latitude baroclinic regions, reflecting an overall preferred selection for large-scale transient wave activity and cyclogenesis, as has been predicted from coarser model simulations. Further, tracking of the anti-cyclone just west of the prime meridian in the top-most panel indicates a east-west (zonal) phase speed, $c^{(z)}$, of $O(20 \text{ m s}^{-1})$. The weather systems are often 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 [6,11,12].

It can be seen in Fig. 2 that the low-level horizontal wind shows a distinct line of convergence in this region which is associated with two (one middle and the other high-latitude) low-pressure anomalies that appear to merge in time (not shown completely in the three time samples depicted). The appearance of this line of flow convergence shows classical signatures associated with frontogenetic processes: that is, shear and stretching deformations, and flow contractions/dilatations which can significantly alter atmospheric scalars (e.g., temperature, dust mixing ratio, etc). Peak low-level horizontal wind speed deviations in this region approach $O(20 \text{ m s}^{-1})$. Such flow patterns resemble terrestrial cold fronts. However, with a smaller planetary radius yet similar Rossby deformation scales, weather systems on Mars appear more hemispherically effective at “stirring” and “mixing” the high-latitude cold air boundary (i.e., the polar front) well into the midlatitudes and sub-tropics.

Also depicted in Fig. 2 are contours of instantaneous surface stress (indicated in white, with regions that exceed the threshold value of $\tau_0 = 22.5 \text{ mPa}$ indicated in red). It can be seen from the figure that a broad region in the Tharsis highlands exists where instantaneous stress values exceed the threshold value (i.e., this marks an active region where surface-stress dust lifting is occurring). These large stresses are often associated with a strong anti-cyclonic circulation (i.e., a near-surface ridge) just upstream (to the west of) the developing frontal wave further to the east. Frequently, the strongest gradient in surface stresses occurs just upstream of the near-surface front. In addition, there is also a region that exceeds the threshold stress value near the center of the tight cyclonic vortex associated with the deep low-pressure anomaly (Fig. 2, bottom panel).

Examination of the details of the frontal wave circulations indicate strong associated secondary cross-frontal (i.e., ageostrophic) circulations at their boundary, with sinking motion behind, rising motion ahead of the sloping frontal surface. In order to maintain thermal and dynamical balance within the environment influenced by the frontal waves, such secondary circulations are requisite. Vertical motions associated with these secondary circulations are capable of lofting dust ahead of the frontal waves. In addition, clear cold-air and warm-air sectors develop associated with the transient surface pressure anomalies, and distinct $\lambda$-like signatures in the low-level thermal field can form. These frontal wave structures are the low-level impressions of traveling, amplifying and decaying baroclinic waves. Orography appears to play a significant role in breaking the hemispheric symmetry of the Martian northern cold polar front, and in so doing, determining the character and meridional scale of the individual baroclinic waves and the accompanying frontal disturbances.

**Summary and Conclusions:** The imposition Mars’ strong baroclinicity supports intense and vigorous eastward traveling weather systems (i.e., transient synoptic-period waves), particularly in northern late winter/early spring that on large scales have accompanying sub-synoptic scale ramifications on the atmospheric environment through cyclonic/anti-cyclonic winds, deformations and contractions/dilatations in temperatures, and sharp perturbations amongst atmospheric tracers (e.g., dust and volatiles such as water and carbon-dioxide ice/frost). Mars’ frontal waves can also exhibit large spatial extents (e.g., reaching from middle and high latitudes in to the sub-tropics), and sometimes longitudinally-extended structures. These systems can effectively distort and “stir” the high-latitude circumpolar cold-air boundary (i.e., the Martian polar front). Compared to models of cyclo-, fronto-genesis on Earth, Mars’ extratropical weather systems appear short-lived. The mid-latitude synoptic-scale cyclones, in addition, tend to develop, travel eastward, and decay preferentially within certain geographic regions (i.e., storm zones).

Our high-resolution simulations utilizing the NASA Ames Mars general circulation model with a consistent, interactive dust cycle indicate that cyclogenetic...
and frontal-wave circulations can significantly alter dust transport and structuring (both horizontally and vertically) within the atmosphere. Modeling the circulation at high spatial resolution is necessary in order to illuminate processes important to local and regional dust activity, and condensate cloud formation, structure, and evolution within regions of the seasonal polar caps. Given similarities between Earth and Mars, characterization of baroclinic waves, frontal cyclones and their evolution, and the nature of storm zones on Mars, may offer insights into fundamental mechanisms active in the terrestrial case.


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