RADIATIVELY-ACTIVE AEROSOLS WITHIN MARS' ATMOSPHERE: IMPLICATIONS ON THE WEATHER AND CLIMATE AS SIMULATED BY THE NASA ARC MARS GCM.

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Introduction: Large-scale, extratropical weather disturbances (i.e., high- and low-pressure systems or "transient synoptic-period baroclinic/barotropic waves") are critical components of the general circulation of a rapidly rotating, differentially heated, shallow atmosphere such as Mars. Critically, these wave-like disturbances which develop, mature and decay, and travel west to east, act as agents in the transport of heat and momentum between low and high latitudes of the planet, and coincidingly, for the transport of tracers within the atmosphere (e.g., aerosols such as water vapor/ice, and dust for Mars).

We investigate some dynamical and physical aspects of large-scale extratropical weather systems using a new and upgraded version of the NASA Ames Research Center (ARC) Mars general circulation model (GCM) that includes a full cloud microphysics package and a modernized radiative-transfer package. Our recent simulations are designed to explore the influences radiatively-active aerosols have on the present climate, in particular, the radiative effects of water ice clouds. Further, these simulations begin to address complex interactions, couplings and feedbacks between aerosols, clouds and the planet's climate. Just as it is the case for the Earth's climate [e.g., *Hobbs*, 1993; *Randall et al.* 2003], unraveling the complexities of aerosol-cloud-climate interactions and feedbacks remains a grand-challenge problem for Mars. The work presented here is accompanied by two companion papers within this workshop: *Haberle et al.* [2011] focus on Mars' water cycle when clouds are radiatively active; while *Kahre et al.* [2011] consider couplings between the dust and water cycles, in particular feedback ramifications on dust lifting and its seasonality.

Model: Over the past several years, many major improvements have been made to the NASA ARC Mars general circulation model (GCM) to enhance its capabilities and to standardized its infrastructure. Improvements include an updated radiation code based on a generalized two-stream approximation for radiative transfer in vertically inhomogeneous multiple-scattering atmospheres [*Toon et al.*, 1989], together with a correlated-k method for calculating gaseous opacities [*Lacis and Oinas*, 1991]. A sophisticated cloud microphysics package has been included based on the work of *Montmessin et al.* [2004]; *Montmessin et al.* [2007]. Typically, the cloud microphysics module assumes a log-normal particle size distribution whose first two moments are carried as tracers, and which includes the nucleation, growth and sedimentation of ice crystals [*Montmessin et al.*, 2004]. Here, we also limit the radiation code to respond to a prescribed dust distribution based on an opacity climatology derived from MGS Thermal Emission Spectrometer (TES) 9 μm opacity measurements during MY26/MY27. The vertical distribution varies with season and latitude. The cloud microphysics code interacts with a transported dust tracer whose surface source is adjusted to maintain an atmospheric column abundance as observed by TES. Aerosols of dust and water ice, in addition to water vapor, can be separately or collectively either radiatively inert (default case) or radiatively active. Other improvements in the climate model include raising the vertical extent to 85 km; implementing a new planetary boundary layer (PBL) model (i.e., a level-2 Mellor and Yamada approach [*Mellor and Yamada*, 1982]; incorporation of a sub-surface land model; installation of a highly modularized finite difference dynamical core (based on an Arakawa "C"-grid) [*Suarez and Takacs*, 1995] and that incorporates improved tracer transport [*Hourdin and Armengaud*, 1995]. This latest version is state-of-the-art and has been termed *ARC Mars GCM, version 2.1*.

Results: We focus here on two multi-annual water cycle simulations: (i) one where the ice clouds are radiatively inert (the baseline case); and, (ii) one where ice clouds are radiatively active (the RAC case). These two cases are also considered in detail by *Haberle et al.* [2011] to assess different physical attributes in the simulated water cycle, and various comparisons with recent spacecraft observations are also made. Other simulations where both water vapor and/or free dust is (are) radiatively active, or when water vapor latent heating release is included, have been conducted but are not presented here.

Figure 1 shows mean zonal cross section of the zonal wind (color) and temperature (white dashed contours) during northern autumn (L_s = 180°) from the two simulations. In the RAC case (top panel), there is strong baroclinicity within middle and high latitudes of both northern and southern hemispheres, and strong westerly jets are indicated with maximum speeds over 120 m s^{-1}. Differences between these two corresponding fields (bottom panel) from the two annual simulations (i.e., RAC-baseline) show that radiatively-active water ice clouds profoundly affect the seasonal mean climate. There is a bulk warming of the atmosphere in upper layers, a cooling of the atmosphere in the lower and near-surface regions, and, increases in the mean pole-to-equator temperature contrasts (i.e., stronger mean "baroclinicity") resulting in augmented zonal jets. These changes are very profound in the middle and high latitudes. Comparisons with MGS/TES and MRO/MCS measurements indicate better agreement between the model's simulated climate compared to that observed.

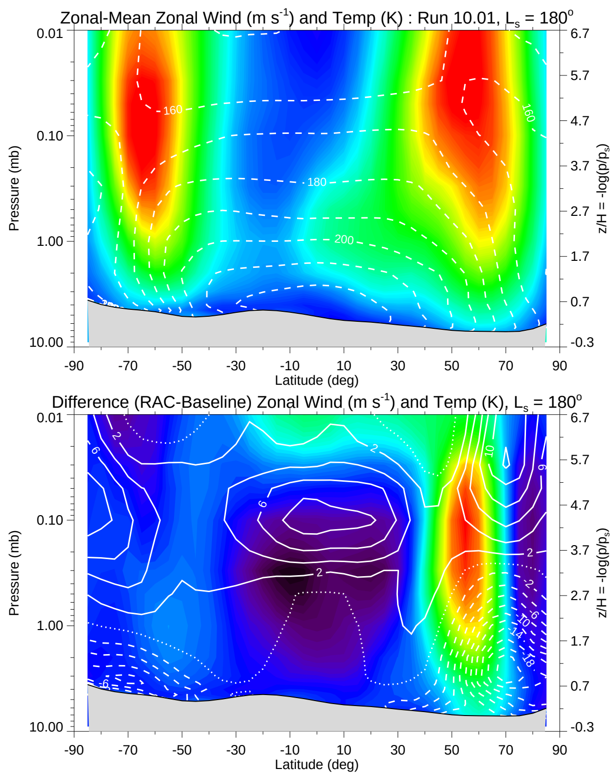

Figure 1: The time and zonally averaged temperature (K) and zonal wind (m s^{-1}) during early northern autumn (L_s = 180°) for the RAC case (a) and the corresponding difference fields (i.e., RAC-baseline) (b) from the water cycle simulations conducted with the ARC Mars GCM. The contour interval is 10 K and 2 K in panels (a) and (b), respectively, and in (b) negative values are dashed. Color shading corresponds to zonal wind.

The increased baroclinicity is robust and significantly affects the intensity and seasonality of synoptic weather systems. Figure 2 shows time series of the daily-averaged surface pressure in the northern hemisphere (NH) Arcadia region, a geographic region previously found to indicate enhanced synoptic-period transient wave activity (i.e., a "storm zone") [*Hollingsworth et al.*, 1996; *Hollingsworth et al.*, 1997]. It can be seen that there is enhanced synoptic period variability (i.e., day-to-day weather) in both amplitude and seasonality in the simulation with radiatively-active water ice clouds (red curve). Similar characteristics are found in the other storm zone regions of the NH. In addition, the SH extratropics also indicate enhanced synoptic-period variability, particularly in the western hemisphere. This result also appears to be insensitive to model (horizontal) resolution. High-resolution (×2) simulations for the RAC and baseline cases indicate very similar transient eddy amplitudes and seasonality.

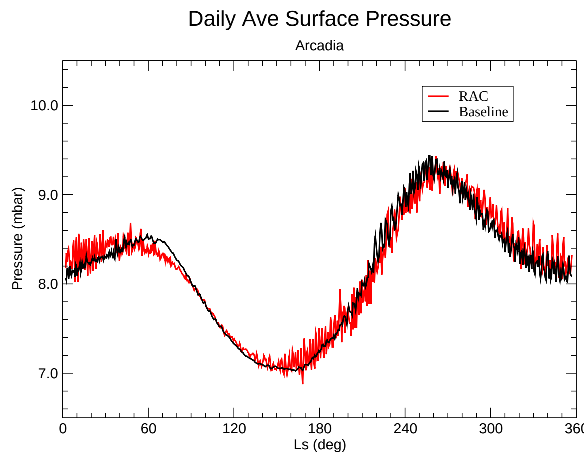

Figure 2: Daily averaged surface pressure in the Arcadia region as a function of L_s for the RAC case (red curve) and the baseline case (black curve).

That the synoptic period variability is significantly enhanced in the RAC case is further demonstrated in Figures 3 and 4. Transient-eddy poleward heat fluxes in the northern extratropics are very much enhanced in the RAC case compared to the baseline case (i.e., by at least a factor five). As such, the baroclinic/barotropic waves are much more efficient in transporting heat, momentum and tracers, within middle latitudes. Figure 4 shows another example of the enhanced synoptic-period wave activity. In terms of surface pressure anomalies, when radiatively-active ice clouds are included in the simulation, the weather systems are very intense (i.e., pressure anomalies are increased by a factors of four to five). In addition, their dominant spatial scales (both zonal and meridional) are increased.

Thoughts on Results: Better bulk (i.e., mean zonal) thermal agreement occurs in the RAC simulation compared to recent observations, particularly when compared to MRO/MCS. [The model simulations do not, however, capture recently discovered upper-level "polar warmings". Such features are likely associated with dynamical activity not simulated in this version of the climate model (e.g., breaking gravity waves and accom-

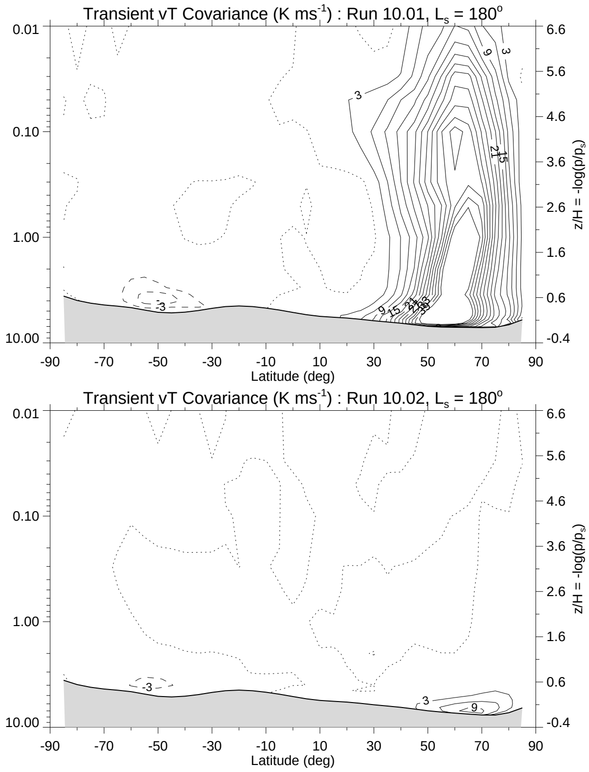

Figure 3: The transient eddy poleward heat flux (K m s^{-1}) for the RAC case (top panel) and the baseline case (bottom panel) during early northern autumn (L_s = 180°). The contour interval in both panels is 3 K m s^{-1}, positive values are solid, negative values are dashed.

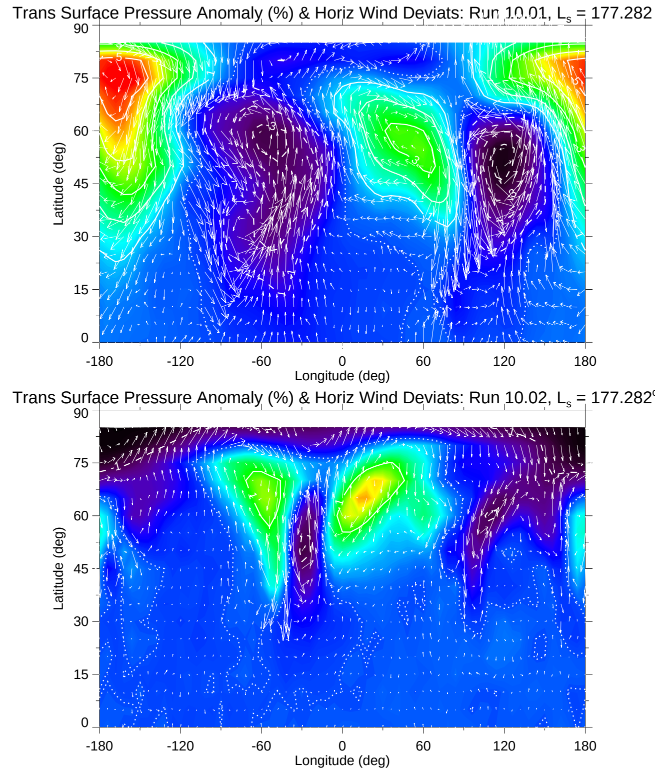

Figure 4: Instantaneous band-pass filtered surface pressure anomalies (i.e., percent departures from a global mean value of 7.0 mbar), and the horizontal wind departures (white vectors) for the RAC case (top panel) and the baseline case (bottom panel) during early northern autumn (L_s = 180°). Red/orange shading are anticyclones and black/purple shading are cyclones.

panying momentum flux deposition).] Increases in the mean baroclinicity in the RAC simulation gives rise to more pronounced synoptic weather systems and an intensification in the NH storm zones.

As discussed in *Haberle et al.* [2011], the low-level cloud activity (i.e., polar hoods) in the baseline and the RAC simulations in high latitudes are anomalously thick compared to observations, especially in the vicinity of the north polar residual cap (NPRC). This is even more the situation in the RAC case. Such enhanced cloudiness reflect sunlight reaching near the surface and cool the high latitudes by 10–20 K in the RAC simulation. As such, mean fields of the net diabatic heating rate are significantly altered between the two cases, particularly in the low-level atmosphere at high latitudes. Such differences drive significantly different large-scale circulation patterns, both the mean overturning circulations and traveling wave disturbances. In particular, the synoptic weather systems' transport capacity is highly amplified. This has implications on the balance and energetics of the atmosphere in the extratropics and high latitudes. Further, this can affect the vigor of dust lifting processes about the edge of the seasonal CO_2 polar ice cap [*Kahre et al.*, 2011] associated with such weather systems.

Summary: Upgrades to the NASA Ames Research Center (ARC) Mars general circulation model (GCM) include a modernized radiative-transfer package which permits radiative effects and interactions of suspended atmospheric aerosols (e.g., water ice clouds, water vapor, dust, and their mutual interactions) to influence the net diabatic heating within the atmosphere. Atmospheric aerosols are critically important in determining the nature of the mean thermal structure and circulation, and hence the overall climate of the planet. Our GCM simulations indicate that radiatively-active water ice clouds profoundly affect the seasonal and annual mean climate in a variety of ways. Preliminary results suggest that the bulk thermal structure and resultant (i.e., balanced) circulation patterns are strongly modified near the surface and aloft. Generally speaking, we find a bulk warming of the atmosphere in upper layers, a cooling of the atmosphere in the lower and near-surface regions, and, increases in the mean pole-to-equator temperature contrasts (i.e., stronger mean "baroclinicity") and augmented zonal jets. Comparisons with MGS/TES and MRO/MCS measurements indicate better agreement between the model's simulated climate compared to that observed. An increased baroclinicity significantly affects the intensity and seasonality of synoptic weather systems.

Using a state-of-the-art Mars GCM, these results highlight important effects radiatively-active aerosols have on physical and dynamical processes active in the current climate of Mars.

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