ARTICLE IN PRESS

Icarus xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

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Coupling the Mars dust and water cycles: The importance of radiative-dynamic feedbacks during northern hemisphere summer

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ARTICLE INFO

Article history:
Received 11 April 2014
Revised 11 July 2014
Accepted 15 July 2014
Available online xxxx

Keywords:
Mars
Mars, climate
Atmospheres, dynamics

ABSTRACT

Mars Global Climate Model (MGCM) simulations are carried out with and without cloud radiative forcing to investigate feedbacks between the dust and water cycles that contribute to the middle-atmosphere polar warming during northern hemisphere summer. Compared to the simulation without clouds, the simulation with clouds produces stronger polar warming, which is in better agreement with observations. The enhanced polar warming in the presence of cloud formation is caused by a radiative-dynamic feedback between a strengthened circulation due to cloud radiative effects, vertical dust transport, and further circulation intensification.

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1. Introduction

Temperature observations made by the Mars Climate Sounder (MCS) on board the Mars Reconnaissance Orbiter (MRO) have revealed a strong polar warming in the middle-atmosphere during equinoctial and winter solstitial seasons in both hemispheres (McCleese et al., 2008). Previous Mars Global Climate Models (MGCMs) tended to under predict this polar warming, particularly during the equinoctial seasons over both poles and during northern hemisphere (NH) summer over the south (winter) pole (e.g., Lee et al., 2009). Recent modeling studies that have included fully radiatively active aerosols – dust and water ice – are able to better represent the winter-pole thermal structure at this season due to an enhanced mean overturning circulation (Wilson et al., 2008; Wilson and Guzewich, 2011; Madeleine et al., 2012; Steele et al., 2014). Here we show that a feedback between cloud radiative forcing, the strengthening of the mean overturning circulation and the redistribution of atmospheric dust combine to enhance the polar warming during NH summer.

Radiatively active aerosols – particularly dust and water ice – strongly influence the thermal and dynamical state of the Martian atmosphere. While the critical role of the radiative effects of dust has been known since the Mariner 9 era (Gierasch and Goody, 1972; Haberle et al., 1982; Zurek et al., 1992), recognition of a similar role for water ice clouds is more recent (Hinson and Wilson, 2004; Wilson et al., 2008; Wilson and Guzewich, 2011; Madeleine et al., 2012). Airborne dust efficiently heats the atmosphere because it effectively absorbs energy at visible wavelengths, while the radiative influence of water ice clouds are felt predominantly in the infrared. Tropical clouds produce a net heating of the atmosphere in the vicinity of the aphelion cloud belt. Atmospheric heating by both dust and water ice clouds during NH summer strengthen the mean overturning circulation (Wilson et al., 2008; Wilson and Guzewich, 2011; Madeleine et al., 2012; Steele et al., 2014).

Here we examine the importance of radiative/dynamical feedbacks due to the coupling between the dust and water cycles through cloud formation and show that these interactions are important for producing the observed thermal structure during NH summer. We demonstrate that a radiative-dynamic feedback exists between cloud formation, the vertical distribution of dust, and the strength of the overturning circulation, and that the fully coupled system produces an enhanced polar warming over the south pole that is in good agreement with observations.

2. Numerical methods

The NASA Ames GCM is a 3-dimensional global climate model of the Martian atmosphere that has been used extensively for investigations of Mars' current and past climate, including studies of both the dust and water cycles (Haberle et al., 1999; Kahre et al., 2006; Nelli et al., 2009). The simulations described here were carried out on a latitude/longitude horizontal grid with a resolution of $5° \times 6°$. The model uses a normalized pressure (i.e., σ) coordinate system in the vertical, with resolution decreasing from ~5 m near the surface to ~10 km at the model top (~80 km). Surface properties include MOLA topography and albedo and thermal inertia maps derived from Viking and Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) observations. The model employs a 2-stream radiative transfer scheme that accounts for gaseous absorption and scattering aerosols.

Routines are incorporated into the GCM accounting for the physics of the lifting, transport and sedimentation of radiatively active dust with the goal of allowing for a plausible predicted airborne dust distribution that will evolve self-consistently to changes in the atmospheric circulation initially induced by cloud radiative forcing (see Kahre et al., 2006). Interactive dust lifting is utilized to allow feedbacks to affect the patterns and magnitudes of dust injection. As shown below, such feedbacks on dust lifting are minor, which indicates that the results presented are not sensitive to the choice of dust injection.

Two parameterizations for dust lifting are used simultaneously: wind stress lifting and dust devil lifting. The wind stress scheme lifts dust when the surface wind stress, τ, exceeds a critical value, assumed here to be $\tau = 22.5$ mN m^{-2}. The dust devil scheme is based on the thermodynamic theory of dust devils developed by Renno et al. (1998). In this scheme, the lifted dust flux depends on the magnitude of the sensible heat exchange between the surface and atmosphere, and the depth of the planetary boundary layer. The lifted dust mass is partitioned into a lognormal

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http://dx.doi.org/10.1016/j.icarus.2014.07.017
0019-1035/Published by Elsevier Inc.

distribution with an effective radius of 2.5 μm and an effective variance of 0.5; these parameters have been shown to produce mean atmospheric dust particle sizes that are consistent with observations (see Kahre et al., 2008). Airborne dust interacts with solar and infrared radiation, provides seed nuclei for water ice clouds, and undergoes gravitational sedimentation as free dust and as cores of water ice cloud particles. Both lifting schemes are tuned with multiplicative "efficiency" factors to produce reasonable dust loadings throughout the Martian year (see, for example, Kahre et al. (2006) for a discussion about tuning).

The simulated water cycle includes sublimation from the north residual cap and the microphysical processes of nucleation, growth, and settling of radiatively active water ice clouds (Montmessin et al., 2002, 2004; Nelli et al., 2009; Navarro et al., 2014). A spatially and temporally varying mass and number, and a fixed (constant) effective variance describe the lognormal particle size distributions of dust and cloud. This is a computationally efficient method that allows for the evolution of cloud and dust particle sizes as the result of cloud microphysical processes. As discussed in the next section, the predicted clouds and temperatures using this scheme generally compare well to MGS/TES and MRO/MCS observations during NH summer.

Four simulations are presented. The first (S1) includes an interactive dust cycle that is fully coupled to the water cycle through cloud formation and cloud radiative forcing, and the second (S2) includes an interactive dust cycle but does not include cloud formation or cloud radiative forcing. In both of these simulations, the dust lifting schemes are tuned identically (i.e., they have the same dust lifting efficiency factors). Two additional simulations are executed to isolate the feedbacks present between the dust and water cycles. One simulation (S3) is forced with the temporally varying dust field from S2 and the cloud fields from S1, while the final simulation (S4) is forced with the dust fields from S2 but the clouds are self-consistently predicted. Comparison of S3 and S4 with S1 will reveal the contribution of the feedback-driven dust redistribution on the thermal structure and atmospheric circulation. In these simulations, sequences of 3-dimensional aerosol fields (clouds and/or dust) are sampled and ingested at 1.5-h intervals from S1. We initialize S3 and S4 at $L_s \sim 95°$ from the spun-up state of S1. These simulations are executed for approximately 50 sols before analyses are carried out at $L_s \sim 120°$.

3. Results and discussion

The first two simulations (S1 and S2) have been carried out over multiple annual cycles and have aerosol and temperature distributions that evolve to a quasi-steady state. We focus on NH summer ($L_s = 120°$) in order to investigate how water ice particles in the aphelion cloud belt affect the vertical distribution of dust, the thermal structure of the atmosphere, and atmospheric circulation. Further, the $L_s = 120°$ season is optimal for this study because there is very little interannual variability and dust storm activity is minimal, with smoothly varying atmospheric dust distributions at this time of year (Wilson and Guzewich, 2014).

The fully coupled simulation (S1) produces an afternoon thermal structure that is in general agreement with the observed thermal structure from MRO/MCS at $L_s = 120°$ (Fig. 1; McCleese et al., 2010). In particular, the model reproduces the polar warming observed up to approximately 5 Pa. The fully coupled simulation reproduces the observed temperatures better than any of the other simulations discussed below, which suggests that the feedbacks identified here are important at this season.

The simulated aphelion cloud belt in the fully coupled simulation (S1) forms just after the northern vernal equinox, dissipates just before the northern autumnal equinox, and spans from approximately 30°S to 30°N. At $L_s = 120°$, daytime column 12-μm absorption ice opacities in the aphelion cloud belt of S1 reach approximately 0.13 slightly to the north of the equator (Fig. 2; top panel), which is consistent with MGS/TES observations (Smith, 2004). Although column ice opacity retrievals over the seasonal CO_2 ice caps are not available, comparing the opacities of the edges of the simulated polar hoods to available TES and MCS (not shown) data suggests that the model is over predicting the thickness of the polar hoods.

The presence of clouds does not significantly affect the amount of dust throughout the majority of the atmosphere. Column 9 μm absorption dust opacities between 30°S to 60°N range in both simulations (S1 and S2) from zero to just over a tenth, which is in good agreement with MGS/TES-observed dust opacities at this season (Fig. 2; middle panel). The dust devil lifting scheme is responsible for provid-

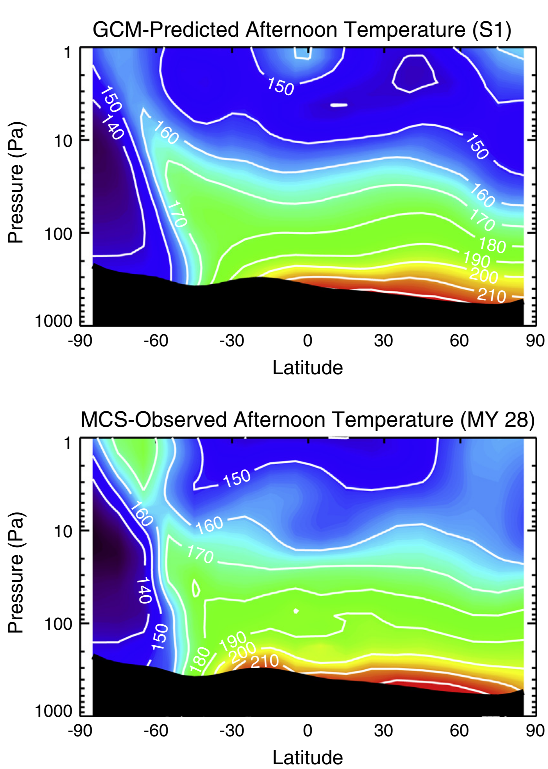

Fig. 1. 10-sol zonal mean GCM-predicted (S1; top) and MCS-observed (bottom) afternoon temperature structure at $L_s = 120°$.

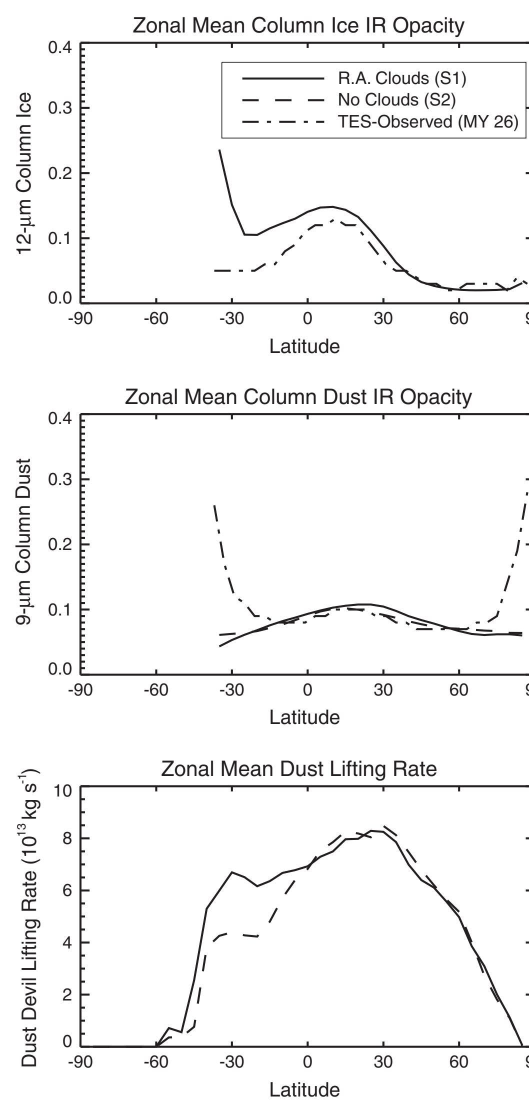

Fig. 2. 10-sol zonal mean TES-observed and GCM-predicted 2 pm column water ice 12 μm opacity (S1; top), TES-observed and GCM-predicted 2 pm column dust 9-μm opacity (S1 and S2; middle), and sol-mean GCM-predicted dust devil lifting rate (S1 and S2; bottom) at $L_s = 120°$. GCM-predicted quantities in the top two panels are only shown where observations are available.

Please cite this article in press as: Kahre, M.A., et al. Coupling the Mars dust and water cycles: The importance of radiative-dynamic feedbacks during northern hemisphere summer. Icarus (2014), http://dx.doi.org/10.1016/j.icarus.2014.07.017