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The sensitivity of solsticial pauses to atmospheric ice and dust in the MarsWRF General Circulation Model

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ABSTRACT

Mars exhibits less atmospheric variability at the solstices than it does during periods nearer the equinoxes. Much of this variability in air temperature and dust activity is attributable to a significant decrease in eastward traveling transient wave amplitudes in the lower atmosphere near the solstice. Previous versions of the Mars Weather Research and Forecasting (MarsWRF) model using only dust radiative forcing have reproduced the nature but not the magnitude of this 'solsticial pause' in atmospheric variability. In this paper, we use a version of MarsWRF that includes a fully-interactive dust and water cycle to simulate winter solsticial pauses under a range of dust and water ice conditions. The upgraded model specifically includes a new hybrid binned/two-moment microphysics model that simulates dust, water ice, and cloud condensation nuclei. The scheme tracks mass and number density for the three particle types throughout the atmosphere and allows advection by resolved winds, mixing by unresolved processes, and sedimentation that depends on particle size and density. Ice and dust particles interact with radiation in the atmosphere using a Mie scattering parameterization that allows for variable particle size and composition. Heterogeneous nucleation and condensation use an adaptive bin size scheme to accurately track the particle size during condensation and sublimation processes. All microphysical processes in the model are calculated within the dynamical timesteps using stability-guaranteed implicit calculations with no sub-timestepping. The impact of the addition of water processes to the model was assessed by comparing simulations with only interactive dust (dry simulations) and ones with a fully-interactive dust and water cycle (wet simulations). In dry simulations with dust storms a solsticial pause occurs in the northern winter with a magnitude (or 'depth') that depends on the opacity of the southern summer dust storms. In wet simulations that include water ice and dust particles, deep solsticial pauses are found in both winter hemispheres. In all simulations that reproduce the solsticial pause, energy and instability analysis suggest that a decrease in baroclinic instability and increase in barotropic energy conversion occurs during the solsticial pause. In dry simulations the decrease in baroclinic instability is caused by increased dust opacity leading to increased thermal static stability. In wet simulations, additional opacity from local cap-edge ice clouds reduces the near surface wind shear and further inhibits baroclinic eddy growth. The wet simulations are in better agreement with observations and tend to support results from other models that include ice cloud radiative effects.

1. Introduction

The Martian autumn and winter atmosphere is characterized by a relatively high degree of variability in the periods after the autumnal equinox and before the vernal equinox ($L_s = 180^\circ - 360^\circ$ in the northern hemisphere), but with a distinct transition to much lower variability centered on the winter solstice ($L_s = 270^\circ$ in the northern hemisphere). This transition in the behavior of the polar atmosphere is associated with a dramatic decrease in the number of high latitude dust storms at solstice, as observed by the Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) (Wang et al., 2003, 2005; Wang, 2007; Guzewich et al., 2015), and a shift to both lower transient wave amplitudes and longer wavelengths, as observed by the MGS Thermal Emission Spectrometer (TES) (Banfield et al., 2004; Wang et al., 2005).

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TES observations from just under three Martian years (1999–2006, MY24-27) are available within a gridded 'reanalysis' dataset (the Mars Analysis Correction Data Assimilation (MACDA) reanalysis (Montabone et al., 2014)) that highlights the 'solstitial pause' in particular detail (Lewis et al., 2016; Wang and Toigo, 2016). The reanalysis dataset is especially useful as it provides a uniform estimate of the global state of the atmosphere that is consistent with the more limited observations. As such, it can provide a clearer basis for analysis and yield more robust diagnostics. Using the reanalysis, Lewis et al. (2016) found a solsticial pause in both winter hemispheres with a stronger solsticial pause during northern winter where temperature variability drops by 50% in the near surface atmosphere, and a pause during southern winter with a similar fractional depth but with smaller absolute values. Wang and Toigo (2016) used the same reanalysis dataset to map the relative strengths of the zonal wavenumber 1 to 3 eastward traveling waves as a function of time during the transition into the pause in the northern hemisphere.

General Circulation Models (GCMs) have been used extensively to study transient waves in the northern autumn and winter atmosphere (Barnes et al., 1993; Collins et al., 1996; Wilson et al., 2002; Kuroda et al., 2007; Kavulich et al., 2013; Wang et al., 2013; Wang and Toigo, 2016), and the response of these waves to moderate and large sized dust storms (Basu et al., 2006; Kuroda et al., 2007; Wang and Toigo, 2016), but with only a secondary focus on the pause itself. Most recently, however, Mulholland et al. (2016) used the UK/LMD Mars GCM with both dust and ice radiative forcing to examine the mechanisms of the pause in detail, highlighting the role of both aerosols in modifying the thermal and wind structure at the solstices and in driving the transition of the dominant wavelengths and the amplitudes of transient waves.

In this paper, we examine the solsticial pause in simulations of the Mars Weather Research and Forecasting (MarsWRF) GCM (Richardson et al., 2007) using a new dust and water ice microphysics scheme. Two groups of simulations are considered. In the first group ('dry'), dust storms are simulated using a two-moment microphysics scheme and are allowed to develop spontaneously in the GCM within a dry atmosphere with no surface or atmospheric water but freely evolving atmospheric dust simulated by the model. In the second group of simulations ('wet'), water vapor and ice are included, and heterogeneous nucleation and condensation processes are allowed to produce a self-consistent dust and water cycle. To examine the strength (or *depth*) of the solstitial pause, we examine three simulations with each of the wet and dry GCMs with different dust and water cycles (driven by different dust lifting and nucleation rates).

The dry simulations in this study are configured with different dust lifting rates to simulate three amounts of atmospheric dust, with the dustiest model regularly exhibiting a type of northern winter dust storm found only infrequently in the observational record. The wet simulations use varying dust lifting rates and nucleation contact parameters to provide three different simulations, with the wettest model exceeding typical observations of the water content of present day Mars. All of the simulations shown use a fully interactive dust and water ice (when present) scheme allowing realistic feedback, and produce stable simulations over decadal timescales.

In Section 2 we review the GCM configuration and describe the new microphysics scheme. In Section 3 we describe the analysis method used to extract the diagnostics of solsticial pause depth, Eady growth rates, and atmospheric energy conversions. In Section 4 the results of the simulations are presented and the diagnostics calculated, and in Section 5 our interpretation of those results are discussed. Finally, in Section 6 the summary of the simulations and our conclusions are provided.

2. Model description

In this study, we use the MarsWRF GCM (Richardson et al., 2007; Toigo et al., 2012), which includes a two-stream correlated-k radiative transfer scheme to treat the interaction of radiation with the atmosphere and surface (Mischna et al., 2012), and the Yonsei University boundary layer scheme that treats vertical mixing of heat, momentum, and tracers (Hong et al., 2006). For this study, we also introduce a modified version of a terrestrial cloud microphysics scheme (Morrison and Gettelman, 2008) that treats microphysical interactions between atmospheric water and dust. In combination with the radiative transfer and boundary layer schemes, the new microphysical scheme in this version of MarsWRF allows for the simulation of self-consistent radiative, dynamical, and microphysical interactions between dust, water, and the thermal and dynamical state of the atmosphere.

2.1. Two–moment dust scheme

Dust is simulated in the model with a fully prognostic two–moment treatment implemented within the framework of the Morrison and Gettelman (2008) microphysics scheme. In the two-moment scheme the dust particle size distribution is tracked using the total mass density Q and the total number density N of the dust at each grid point in the atmosphere. We retain the choice made in Morrison and Gettelman (2008) to use the gamma (Γ) function to describe the family of possible particle size distributions. For the gamma function, the number density, ϕ, is given as a function of particle diameter, D, by

$$\phi(D) = N_0 D^{\mu} \exp^{-\lambda D}, \quad (1)$$

where N_0 is the 'intercept parameter' and λ is the 'slope parameter'. The spectral shape parameter, μ, determines the shape of the distribution within the gamma distribution family, and is prescribed in the model. Negative values of μ have a shape similar to an exponential decay and can be used to simulate a population with large numbers of small particles and fewer large particles. Positive values of μ have a shape similar to normal or log-normal distributions and imply a particle size distribution with a spread of values around a peak value, and the width of the distribution is related to the value of μ (Morrison and Gettelman (2008) use a value of $\mu = 1$ for their Earth microphysics scheme). Using this model we can give expressions for mass density and number density as

$$N = m(0), \quad (2)$$

$$Q = \frac{\pi\rho}{6} m(3) \quad (3)$$

where ρ is the particle density, and $m(p)$ is the pth moment of the gamma distribution calculated as

$$m(p) = \int_0^{\infty} D^p \phi(D) = \frac{N_0}{\lambda^{\mu+p+1}} \Gamma(\mu + p + 1). \quad (4)$$

$\Gamma(n)$ is the integrated gamma function, which obeys the relationship $\Gamma(n+1) = n\Gamma(n)$, and is finite for all real numbers except negative integers n (where the integral diverges). For a fixed value of μ, the values of N, Q, and ρ are sufficient to calculate the values of N_0 and λ as

$$\lambda = \left(\frac{\pi\rho N \Gamma(\mu + 4)}{6Q\Gamma(\mu + 1)} \right)^{\frac{1}{3}}, \quad (5)$$

$$N_0 = N \frac{\lambda}{\Gamma(\mu + 1)} \quad (6)$$