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Numerical modeling of orbit-spin coupling accelerations in a Mars general circulation model: Implications for global dust storm activity☆

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ABSTRACT

We employ the MarsWRF general circulation model (GCM) to test the predictions of a new physical hypothesis: a weak coupling of the orbital and rotational angular momenta of extended bodies is predicted to give rise to cycles of intensification and relaxation of circulatory flows within atmospheres. The dynamical core of MarsWRF has been modified to include the orbit-spin coupling accelerations due to solar system dynamics for the years 1920–2030. The modified GCM is subjected to extensive testing and verification. We compare forced and unforced model outcomes for large-scale zonal and meridional flows, and for near-surface wind velocities and surface wind stresses. The predicted cycles of circulatory intensification and relaxation within the modified GCM are observed. Most remarkably, the modified GCM reproduces conditions favorable for the occurrence of perihelion-season global-scale dust storms (GDSs) on Mars in years in which such storms were observed. A strengthening of the meridional overturning circulation during the dust storm season occurs in the GCM in all recorded years with perihelion-season global-scale dust storms. The increased upwelling produced in the southern hemisphere in southern summer may facilitate the transport of dust to high altitudes in the Mars atmosphere during the dust storm season, where radiative heating may further strengthen the circulation. Significantly increased surface winds and surface wind stresses are also obtained. These may locally facilitate dust lifting from the surface. Based on comparison to the historical record, there is a strong likelihood of a perihelion-season GDS in Mars year 33 and/or Mars year 34.

1. Introduction

A recently developed orbit-spin coupling hypothesis (Shirley and Mischna, 2017) suggests the existence of an acceleration field that may modulate large-scale atmospheric circulatory flows through constructive and destructive interference effects, leading to periodic intensification and relaxation of circulatory flows within atmospheres. In this paper, we test the predictions of this physical hypothesis by incorporating the orbit-spin coupling accelerations within a state-of-the-art global circulation model of the Mars atmosphere. The Mars atmosphere is optimal for this purpose, due to the availability of an extended observational record for Mars exhibiting marked interannual variability, its short thermal time constant, and the relative simplicity of its circulation in comparison with those of the Earth and Sun.

According to the physical hypothesis detailed in Shirley (2017), the rate of change of planetary orbital angular momentum (dL/dt, or $\dot{L}$) with respect to the solar system barycenter may be implicated as a forcing function for atmospheric variability. The derived orbit-spin coupling term yields a small horizontal acceleration ($\sim 10^{-5}$ m s^{-2}) within the Mars atmosphere that varies spatially and with time. This acceleration, which we refer to as a "coupling term acceleration" (CTA), while instantaneously small, may cumulatively yield wind velocity changes of several tens of m s^{-1} on seasonal timescales. Under the physical hypothesis investigated here, the global circulation is predicted to follow a periodic cycle that tracks the variability of $\dot{L}$, intensifying during extremes in $\dot{L}$, and relaxing back to the unforced, or 'baseline' state as $\dot{L}$ returns towards zero. Statistical evidence that this is in fact the case for Mars is presented in the companion paper by Shirley and Mischna (2017, and references therein).

Given the temporal and spatial limits to global atmospheric circulation measurements on Mars, testing of this physical hypothesis is ideally suited to numerical simulation through the use of a general circulation model (GCM), which provides the best means of simulating global behavior of the martian atmosphere. With the use of such a tool, we can observe and track the individual components of the wind field across the globe, and assess other changes to the overall atmospheric state.

We explore the influence of the CTA on the martian atmosphere

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with a GCM that has been modified to account for this new acceleration term. We demonstrate that the CTA has an influence on wind speeds and global circulation patterns that tracks the variability of $\dot{L}$. The cyclic variability of the putative forcing function is largely decoupled from the annual cycle of solar insolation that drives the normal seasonal variability on Mars (Shirley, 2015; Shirley and Mischna, 2017). The relative phasing of the two cycles introduces a considerable degree of interannual variability in the martian atmosphere—variability which may lead to the occasional formation of global-scale dust storms (GDS) or other intermittent atmospheric phenomena.

This paper (and the investigation it describes) may be naturally subdivided into two parts. In the first part, we develop and verify the numerical model, and employ this to evaluate specific predictions of the physical hypothesis. In the second part, we employ the modified GCM to investigate the response of the atmosphere in past years that were characterized by the occurrence of global-scale dust storms. We contrast these model results with those obtained for the intervening years lacking observed GDS events.

In Section 2 we describe the GCM employed for this study. Section 3 describes the orbit-spin coupling hypothesis under investigation and provides a detailed explanation of how the accelerations resulting from the coupling are incorporated into the model. “Sanity checking” and initial calibration of our modified GCM is described in Section 4. In Section 5 we continue to explore the properties and behaviors of the modified GCM, by means of an in-depth consideration of model outcomes obtained both with and without the CTA. We focus on the late northern spring (“aphelion”) season for these comparisons, as the Mars atmosphere is relatively dust-free and more quiescent at these times (Shirley et al., 2015). Our attention shifts to the southern spring and summer (“dust storm”) season in Section 6, where we continue to compare forced and unforced GCM simulations in order to determine the consequences for the circulation of the Mars atmosphere from the inclusion of the CTA. We employ a catalog of 21 past Mars years known to have either included global-scale dust storms or to have been free of such storms (Shirley and Mischna, 2017). In Section 7 we perform a statistical evaluation of model-derived global mean daytime surface wind stress values for the years with and without global-scale dust storms. A discussion of the results of Sections 5–7 is provided in Section 8, where we also provide a GCM-based GDS forecast for Mars years 33 and 34. We summarize and conclude in Section 9. This is the third of three companion papers on the topic of Mars GDS. The first paper (Shirley (2017)) introduces the orbit-spin coupling hypothesis, while the second (Shirley and Mischna, 2017) employs historic observations of global-scale dust storms to test the predictions of that hypothesis.

The occurrence of global-scale dust storms in some years but not in others is a dominant feature of the interannual variability of the Mars atmosphere. An intensification of surface wind stress seems to be a key requirement in order to initiate dust lifting (Haberle, 1986; Shirley, 2015, and references therein). Such intensification may be particularly significant in certain key areas of the martian surface, due to factors such as the availability of surface dust for lifting, the strength of feedbacks of local or regional storms at these locations, or interaction with other components of the circulation that impact the growth and spread of atmospheric dust (e.g. waves, tides; Wang and Richardson (2015)). Accordingly, for this preliminary investigation, we focus primarily on near-surface winds (in the lowest model layer), on surface wind stresses, and on global circulation. Other key atmospheric indices and phenomena, such as temperature, pressure, and thermal tides, are not examined here, although these will be considered in later work.

2. The MarsWRF GCM

We use the Mars Weather Research and Forecasting (MarsWRF) GCM for this investigation. MarsWRF (Toigo et al., 2012) is a Mars-specific implementation of the PlanetWRF GCM (Richardson et al., 2007), which is a global model derived from the terrestrial mesoscale WRF model (Skamarock and Klemp, 2008). MarsWRF solves the primitive equations using a finite difference methodology on an Arakawa-C grid (Arakawa and Lamb, 1977). The prognostic equations solved by MarsWRF are based on conserved variables, and it has been shown (Richardson et al., 2007) that quantities like angular momentum show no long-term trend on the decadal scales we are considering here. Both the horizontal and vertical resolution of the model are variable and selectable at run time; a 40-layer vertical grid (from 0 to 80 km) is used, following a modified-sigma (terrain-following) coordinate. The lowest model layer, from which we obtain near-surface winds, is ~75–100 m above ground level, depending on location and season. In the present investigation, we have chosen a horizontal resolution of 5°x5°, which corresponds to a grid of 72 points in longitude x 36 points in latitude. The total present-day atmospheric CO_2 budget, as well as the CO_2 ice albedo and emissivity for each hemisphere, are adjusted until the modeled pressure curves best match those observed at the Viking Lander 1 and 2 sites (Guo et al., 2009). Both surface albedo and thermal inertia are matched to MGS-TES observations (Christensen et al., 2001; Putzig and Mellon, 2007), while water ice albedo and emissivity are fixed at 0.45 and 1.0, respectively.

2.1. Dust, water ice, and water vapor

Dust plays a key role in shaping the temporal variability of the Mars atmosphere, similar to that played by water in the terrestrial atmosphere, by absorbing and re-radiating solar radiation, and locally heating the atmosphere, thereby strongly influencing the atmospheric circulation on all scales. Because we wish to isolate, to the greatest extent possible, the effects of the putative orbit-spin coupling mechanism, we have chosen to exclude atmospheric dust from the MarsWRF GCM in most model runs described here, although specifically noted runs will include atmospheric dust.

Although the model also incorporates elements of the surface/atmosphere system such as subsurface vapor diffusion and a full atmospheric water cycle, these components are turned off during this investigation, as they play no substantive role in the short-term evolution of atmospheric winds. Water vapor plays, at most, a minor role in atmospheric dynamics (Lewis, 2003; but also see Kahre et al., 2015). Radiative transfer is applied using the scheme detailed in Mischna et al. (2012).

One important consequence of our choice to exclude dust is shown in Fig. 1. This figure illustrates zonal wind and meridional streamflow (“Hadley cell”) plots for MarsWRF model runs performed both with and without dust. Panels (a) and (b) show the zonal mean zonal wind and zonal mean meridional streamfunction, respectively, for a dust-free simulation averaged around the aphelion season from $L_s = 70°$ to 90°. Panel (c) shows the streamfunction for the same season, but including radiatively active (but not interactive) dust, using a simple distribution from the Laboratoire de Météorologie Dynamique (LMD) Mars GCM (Forget et al., 1999), incorporated into the Mars Climate Database, and chosen to fit most of the thermal profiles observed during the Mars Global Surveyor mission. In panels (b) and (d), positive values of the streamfunction (shaded blue-green) correspond to counterclockwise circulations. Closed contours follow the general trajectory of the meridional overturning (Hadley) circulation. In this season (late northern spring), panels (b) and (d) thus indicate rising air in the north and descending air in the south. By far the largest portion of the atmospheric mass transfer occurs in the lowest two scale heights, below the 50 Pa pressure level (~25 km), due to the increased density of the air in the lower atmosphere. (Note the difference in the vertical scales of panels (a/c) and (b/d).) The overturning circulation in the dust-free scenario is comparatively shallow in comparison with that for the simulation including dust, due to the absence of radiative heating effects of dust in the dust-free model run. The circulations are morphologically similar, particularly near the surface. Similar peak values are obtained for the counterclockwise circulations in both