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Regolith-atmosphere exchange of water in Mars' recent past

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ABSTRACT

We investigate the exchange of water vapour between the regolith and atmosphere of Mars, and how it varies with different orbital parameters, atmospheric dust contents and surface water ice reservoirs. This is achieved through the coupling of a global circulation model (GCM) and a regolith diffusion model. GCM simulations are performed for hundreds of Mars years, with additional one-dimensional simulations performed for 50 kyr. At obliquities $\varepsilon = 15^\circ$ and 30°, the thermal inertia and albedo of the regolith have more control on the subsurface water distribution than changes to the eccentricity or solar longitude of perihelion. At $\varepsilon = 45^\circ$, atmospheric water vapour abundances become much larger, allowing stable subsurface ice to form in the tropics and mid-latitudes. The circulation of the atmosphere is important in producing the subsurface water distribution, with increased water content in various locations due to vapour transport by topographically-steered flows and stationary waves. As these circulation patterns are due to topographic features, it is likely the same regions will also experience locally large amounts of subsurface water at different epochs. The dustiness of the atmosphere plays an important role in the distribution of subsurface water, with a dusty atmosphere resulting in a wetter water cycle and increased stability of subsurface ice deposits.

1. Introduction

Studies of possible regolith-atmosphere exchange of water on Mars date back many years (e.g. Smoluchowski, 1968; Flasar and Goody, 1976; Fanale and Jakosky, 1982; Fanale et al., 1986; Clifford, 1993; Mellon and Jakosky, 1993; Mellon et al., 1997), but it was not until observations by the Gamma Ray Spectrometer (GRS) suite of instruments aboard Mars Odyssey that the presence of large subsurface reservoirs of water was revealed (Boynton et al., 2002; Feldman et al., 2008; 2007; 2004; Maurice et al., 2011). Since this time, additional observations of water from the surface have been made by the Phoenix lander (Cull et al., 2010; Mellon et al., 2009). The trenches dug by the Phoenix lander exposed ice at a mean depth of 4.6 cm, with the ice found to be mostly pore ice, though thin and relatively pure ice deposits were also observed near the surface (Mellon et al., 2009). Observations using the ChemCam instrument on the Curiosity rover have revealed a hydrogen emission peak in some soils, which may be the result of adsorbed water or hydration of the amorphous component of the soil (Meslin et al., 2013). New impact craters have revealed evidence for relatively pure subsurface ice in the mid-latitudes (Byrne et al., 2009).

In order to understand the regolith-atmosphere exchange of water, and determine the origin of the observed water distribution, numerous laboratory experiments and modelling studies have been undertaken. Laboratory studies have focused on calculating the diffusion coefficient of water vapour in the regolith, and the adsorption of water onto regolith grains (Beck et al., 2010; Bryson et al., 2008; Chevrier et al., 2008; 2007; Hudson and Aharonson, 2008; Hudson et al., 2007; Siegler et al., 2012; Sizemore and Mellon, 2008; Zent and Quinn, 1997). As well as revealing information on likely rates of diffusion and ice stability in different materials at different conditions, these studies also provide useful constraints for models of regolith-atmosphere interaction.

Previous modelling studies have focused on understanding the subsurface water distribution and the stability of subsurface ice in both the past and present epochs. These studies involve either (i) the explicit calculation of water vapour diffusion between the regolith and atmosphere (Böttger et al., 2005; Mellon and Jakosky, 1993; Schorghofer, 2007; Schorghofer and Aharonson, 2005; Schorghofer and Forget, 2012; Tokano, 2003; Williams et al., 2015), or (ii) the determination of the equilibrium ice table depth from subsurface temperatures and near-surface water vapour values (Aharonson and Schorghofer, 2006; Chamberlain and Boynton, 2007; Mellon et al., 2004; Mellon and Jakosky, 1995; Mellon et al., 1997; Zent, 2008).

For present-day conditions, studies find that subsurface ice is mostly stable polewards of ±50°, with the regolith thermal

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inertia and albedo playing a role in the stability of subsurface ice, in agreement with the GRS observations (Aharonson and Schorghofer, 2006; Böttger et al., 2005; Chamberlain and Boynton, 2007; Mellon et al., 2004; Mellon and Jakosky, 1993; Mellon et al., 1997; Schorghofer and Aharonson, 2005; Tokano, 2003). The mid-latitudes are largely ice free, though regions with high surface roughness may contain detectable quantities of ice (Aharonson and Schorghofer, 2006), while shallow subsurface ice is required to account for the distribution of CO_2 ice on pole-facing slopes in the southern mid-latitudes (Vincendon et al., 2010). The formation of ice lenses has been investigated in order to understand the Phoenix observations of shallow, relatively pure water ice that cannot be explained by vapour diffusion alone (Sizemore et al., 2015), and it has been proposed that some subsurface ice in the present day may be the remnants of buried surface ice deposits from a past climate (e.g. Jakosky and Carr, 1985; Mischna et al., 2003; Levrard et al., 2004).

For past epochs, studies have focused on determining the equilibrium icetable depth, and how it varies with orbital parameters (Chamberlain and Boynton, 2007; Mellon and Jakosky, 1995; Zent, 2008), and the time integration of the subsurface ice content in a model initialized with an ice sheet (Schorghofer, 2007; Schorghofer and Forget, 2012). Unlike the present study, these simulations do not consider the feedback between the subsurface water content and the global circulation, and are instead run as one-dimensional models for specific locations on the surface (Chamberlain and Boynton, 2007; Mellon and Jakosky, 1995; Zent, 2008), or consider zonal averages (Schorghofer, 2007; Schorghofer and Forget, 2012). Additionally, the simulations of Mellon and Jakosky (1995), Schorghofer (2007) and Schorghofer and Forget (2012) were run for thousands or millions of years, and as they are interested in the long-term behaviour of subsurface water, large time steps are used. Mellon and Jakosky (1995) use time steps of 5 min for the thermal model and 10 sols for the diffusion model, while Schorghofer (2007) and Schorghofer and Forget (2012) use time steps of 30 min for the thermal model and 100–250 years for changes in subsurface ice content. Because of the one-dimensional nature of the models, various assumptions are made, such as how the atmospheric water content and pressure vary in past epochs, which will affect the diffusion calculation.

In this paper we investigate how the regolith-atmosphere interaction of water vapour via diffusion varies with different orbital parameters, atmospheric dust contents and surface ice reservoirs. We use a global circulation model (GCM) coupled with a regolith diffusion model, and run simulations for hundreds of Mars years. This removes the need to make assumptions about the near-surface atmospheric water content, and allows us to study the spatial distribution of subsurface water over the whole globe, and how it is affected by the atmospheric circulation. One-dimensional studies using the GCM output are also performed over longer time periods (50 kyr) for various locations at different obliquities.

2. Model description

2.1. Global circulation model

The GCM used for this study results from collaboration between the Laboratoire de Météorologie Dynamique (LMD), the University of Oxford and The Open University. The model combines the most recent LMD physical schemes with a spectral dynamical core, an energy and angular-momentum conserving vertical finite-difference scheme and a semi-Lagrangian advection scheme for tracers (for further details see Forget et al., 1999; Lewis et al., 2007). For the surface properties, we use data from the Thermal Emission Spectrometer (TES). Albedos are from Christensen et al. (2001), while thermal inertias are from Mellon et al. (2000), with corrections made to account for the effect of clouds in the initial dataset (Wilson et al., 2007). Small-scale topographic parameters used by the gravity wave drag scheme, along with the resolved topography, are obtained from MOLA data (Smith et al., 1998; Zuber et al., 1992). These data are stored as $1° \times 1°$ global maps, which are smoothed to the required model resolution.

Due to the spectral nature of the model, different resolutions are referenced using the label T*x*, where ‘T’ represents triangular spectral truncation, and *x* represents the horizontal wavenumber the model is truncated at. The results presented in this paper are obtained using two different model resolutions. To enable study of the global regolith-atmosphere interaction over many hundreds of Mars years, the majority of simulations are run at T5 spectral truncation, which corresponds to a grid resolution of 22.5° in latitude and longitude for physical processes. Test simulations using present-day conditions were compared to observations and previous modelling studies (e.g. Smith, 2004; Navarro et al., 2014; Steele et al., 2014b) which showed that the T5 resolution could reproduce the present-day water cycle (see Section 4). Additional simulations are performed at T31 spectral truncation (5° resolution) to gain a better understanding of the spatial distribution and stability of surface and subsurface ice. In the vertical there are 20 levels in sigma coordinates, extending to an altitude of ~85 km.

Dust is not transported in the model because of the difficulty in accounting for surface lifting at low resolutions. Instead, we set the global visible dust optical depth, τ_{vis}, to either 0.3 or 3, in order to account for both clear and dusty conditions (these values are comparable to the optical depths observed in the present day during clear periods and global dust storms respectively). The vertical profile of dust follows a modified Conrath distribution (Lewis et al., 1999), with the altitude of the dust top being dependent on the dustiness of the atmosphere. For the clear simulations ($\tau_{vis} = 0.3$) the dust top is taken to be $z_{top} = 30$ km, while for the dusty simulations ($\tau_{vis} = 3$) we set $z_{top} = 60$ km. These values are in agreement with present-day observations (e.g. Määttänen et al., 2013; Smith et al., 2013).

Water vapour and ice mass mixing ratios are transported as tracers, using the microphysics scheme of Montmessin et al. (2004) to account for the formation and sedimentation of ice particles. Clouds in the model are not radiatively active. While it has been shown that clouds in the present-day climate can influence the temperature structure of the atmosphere and strengthen the overturning circulation (e.g. Wilson et al., 2008; Madeleine et al., 2012; Steele et al., 2014a; Navarro et al., 2014), their inclusion in models has also led to some inconsistencies compared with spacecraft observations. Additionally, as we are not transporting dust we cannot account for the complex coupling between the dust and water cycles (e.g. Kahre et al., 2015). Ice can sediment anywhere on the surface, and if more than 5 pr-μm of water ice is deposited onto the surface, the albedo is changed from that of the regolith (derived from TES data) to that of water ice (0.4). Surface water ice can only sublime if there is no covering layer of CO_2 ice.

2.2. Regolith model

The regolith model is an updated version of that used by Böttger et al. (2004, 2005), which is based on the one-dimensional model of Zent et al. (1993). Diffusion is calculated implicitly on 30 unevenly-spaced levels extending to around 20 m below the surface. (The first four levels are within 1 mm of the surface, with the first level at 0.1 mm.) While the GCMs physical time step is 30 min (used for calculating radiative transfer, tracer transport, turbulence, convection etc.), the regolith model operates on a shorter time step of 1 minute. This reduced time step is needed to avoid numerical instabilities which can occur when large amounts