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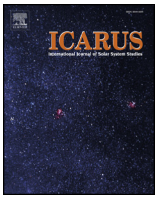

Age of Martian air: Time scales for Martian atmospheric transport

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ABSTRACT

The mean time since air in the Martian atmosphere was in the low-latitude boundary layer is examined using simulations of an idealized “mean age” tracer with the MarsWRF general circulation model. The spatial distribution and seasonality of the mean age in low- and mid-latitudes broadly follow contours of the mean meridional circulation, with the mean age increasing from 0 at the surface to a maximum of 60–100 sols in the upper atmosphere. Substantially older mean ages (exceeding 300 sols) are found in polar regions, with oldest ages in the lower atmosphere (10–100 Pa), above a near-surface layer with very young ages (around 20 sols). The annual maximum ages occur around the equinoxes, and the age in the polar lower atmosphere decreases during the autumn to winter transition. This autumn-winter decrease in age occurs because of mixing of polar and mid-latitude air when the polar vortex exhibits an annulus of high potential vorticity (PV) with a local minimum near the pole. There is no autumn-winter decrease and old ages persist throughout autumn and winter in simulations with CO_2 phase changes disabled, and thus no latent heating, where there is a monopolar vortex (i.e., a monotonic increase in PV from equator to pole) forms. The altitudinal and seasonal variations in the mean age indicates similar variations in the transport of dust into polar regions and the mixing of polar air (with, e.g., low water vapor and high ozone concentrations during winter) into mid-latitudes.

1. Introduction

Transport plays an important role in controlling the atmospheric composition of Mars and other planets. Particularly important for the global climate of Mars are the distributions of dust and ice (H_2O and CO_2) aerosols, and it is important to understand and quantify the transport from, between, and to different source and sink regions and how the transport varies with changes in global and synoptic dynamics (e.g., Clancy et al., 1996; Smith, 2002a,b; Bertaux et al., 2005). Unfortunately, limited quantitative information can be extracted from existing spacecraft observations alone. Constraints on some aspects of the transport have been obtained from observations, e.g., of argon (e.g., Sprague et al., 2007, Lian et al., 2012), ozone (Montmessin and Lefevre, 2013), water vapor (Smith, 2002a,b), and dust (Newman et al., 2002), either from observations alone or in combination with general circulation model simulations.

While simulations of real, observable tracers have the advantage that the results can be compared with observations, it is difficult to extract quantitative transport information as the tracer distributions depend not only on transport but also on (often uncertain) sources and loss processes (e.g., chemical reactions, phase changes, sedimentation). An alternative approach is to use general circulation models to simulate the distribution of idealized tracers which are designed to quantify aspects of the transport. This is common in studies of Earth's atmosphere, and a variety of idealized tracers have been simulated to quantify different aspects of transport (e.g., Plumb and Mahlman, 1987; Hall and Plumb, 1994; Orbe et al., 2013). However, this not a common approach in studies of the Martian atmosphere. One exception is Barnes et al. (1996), who estimated eddy mixing coefficients and “ventilation” timescales in a Mars general circulation model. They found that the eddy mixing and ventilation time scales varied with season and with dust loading, with faster ventilation during dusty solstice conditions.

In this paper we present another such study. Specifically, we use the MarsWRF general circulation model to calculate the mean time since air in the Martian atmosphere was in the low- to mid-latitude boundary layer. Similar calculations of the “mean age” (or age of air) are common in studies of transport in Earth's stratosphere (e.g., Hall and Plumb, 1994; Waugh and Hall, 2002) and, more recently, in Earth's troposphere (Waugh et al., 2013; Orbe et al., 2017; Krol et al 2017). The mean transit time to a location is a fundamental aspect of the transport, and has been used in studies of Earth's atmosphere to quantify the propagation of changes in concentration of constituents (e.g. anthropogenic pollutants) through the atmosphere, and to identify partial barriers to transport (e.g. the edge of stratospheric polar vortices or edges of Hadley Cells). Understanding the variations in the mean age of air in the Martian atmosphere has the potential to help in understanding the distribution of dust, water vapor, and other trace gases on

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Mars.

The model and tracer simulations are described in the next section. The results from the standard simulation are presented in Section 3, while results from additional simulations to test sensitivity of age distribution to CO_2 microphysics, additional dust loading, or source region extent are described in Section 4. Concluding remarks are in the final section.

2. Methods

2.1. Model and simulations

Numerical experiments are performed using the MarsWRF general circulation model (Toigo et al., 2012). The simulations use the same MarsWRF configuration as in Toigo et al. (2017) except for the inclusion of a mean age tracer (see below), and only a brief description is given here. The MarsWRF simulations were conducted at 2° × 2° spatial resolution, with 52 vertical levels, and with a transverse map projection grid that displaces the mathematical pole of the projection to two (antipodal) locations on the equator so as to preserve more accurate representation of the geographic poles. The model includes a parameterization scheme in which condensation and sublimation of CO_2, and subsequent exchange of latent heat, occurs when temperatures fall below or rise above the condensation point (based on local temperature and pressure conditions). When CO_2 condensation occurs in the atmosphere, it is deposited directly on the surface, and the column mass (and hence atmospheric pressure at the surface) is updated and redistributed vertically to account for CO_2 loss or gain in the atmosphere (see Richardson et al. (2007) for details).

We examine the transport in the “standard” MarsWRF simulations from Toigo et al. (2017), as well as the “no-CO_2-latent-heating” and “additional dust” simulations also discussed there to test the sensitivity of transport to alternate forcings. The “standard” simulation employs the previously mentioned scheme for CO_2 phase changes and the prescribed dust distribution is based on the “MGS Scenario” as described in Lewis et al. (1999) and Montmessin et al. (2004). The “no-CO_2-latent-heating” simulation uses the same dust distribution but the CO_2 microphysics parameterization is disabled such that there are neither phase changes nor latent heat exchange. The “additional dust” simulation includes the parameterization for condensation and sublimation of CO_2, but a seasonal peak (near perihelion and southern summer solstice) of global-average column-integrated dust opacity twice that of the standard “MGS Scenario” distribution. This simulation also corresponds to the “high dust” simulation of Guzewich et al. (2016). All simulations were run for 3 Mars years with only the third year of results shown. The standard simulation was run for an additional two years to examine the interannual variability.

2.2. Mean age tracer

To quantify the transport from the surface to different regions in the atmosphere an idealized “mean age” tracer that yields the mean time since air was at surface “source” region is included in the simulations. Similar mean age (or age of air) tracers are commonly used in studies of transport in Earth's stratosphere and troposphere (e.g., Waugh and Hall, 2002; Waugh et al., 2013; Orbe et al., 2017). The governing equation for this idealized mean age tracer $\Gamma(\mathbf{x}, t)$ is

$$\frac{\partial \Gamma}{\partial t} + (L) = 1$$

where L is the linear transport operator, including advective and diffusive transport (Haine and Hall, 2002). The boundary condition is $\Gamma(\Omega,t) = 0$ where Ω is the “source” region, and $\Gamma(\mathbf{x},0) = 0$ initially. In other words, the tracer is initially set to a value of zero throughout the atmosphere, is held to be zero over Ω, and subject to a constant aging of 1 sol per sol (where one sol is one Martian “day”) in the rest of the atmosphere. Here Ω is taken as the lowest 10 km of the atmosphere between 45°S to 45°N, to roughly represent the low-to-mid-latitude boundary layer region of the Martian atmosphere, and the idealized mean age tracer yields the mean transport time from this region. (From here on, we will refer to the idealized mean age tracer as the “mean age”, or just “age”, for convenience and simplicity.)

In addition to the two sensitivity simulations mentioned above, two further simulations to test the sensitivity to the size of the source region Ω were also performed. These two simulations use the same set up as the standard simulation, but the tracer source region is altered to have either a lower height (5 km) or a narrower extent (30°S–30°N); these simulations are referred to as the “shallow source” and “narrow source” simulations, respectively.

The evolution of the mean age tracer is simulated using the standard transport scheme in MarsWRF, which is identical to that used in the original terrestrial WRF model (Skamarock et al., 2008; Skamarock and Klemp, 2008). There is no sub-grid-scale convective mixing nor explicit diffusion, so that the model simulates the conservative and passive transport of the mean age tracer only by the explicitly-resolved winds. Furthermore, as the mean age tracer is defined to yield the mean transit time, rather than the mass or number concentration of an atmospheric constituent, there is no rescaling of the concentration of the tracer when mass is added to or removed from the atmosphere through sublimation or deposition in the polar regions.

3. Standard simulation

3.1. Global distribution

We first consider the spatial distribution of the zonal- mean age Γ, and how it varies seasonally. Fig. 1 shows the latitude-pressure variation of the zonal-mean Γ, at each equinox and solstice. As expected, there is a general increase in Γ with distance from the source region, both with increasing height and latitude. At low- and mid-latitudes Γ increases from zero at the surface to 60–90 sols at 1 Pa, and above the surface layer there is a large increase from low- to high-latitudes (e.g., at 50 Pa, Γ increases from less than 20 sols at the equator to values exceeding 200 sols in polar regions).

The general structure of the Γ distribution shown in Fig. 1 can be broadly explained in terms of the mean meridional circulation (red contours) and Hadley cell circulations. The youngest ages are within the Hadley cells, and the regions of youngest age generally follow the seasonal changes of the Hadley cell circulations. At the solstices there is a single nearly pole-to-pole Hadley cell from summer to winter hemisphere, which results in younger air in summer than in winter mid-latitudes in the upper atmosphere (10–1 Pa). In contrast, at the equinoxes there are weak Hadley cells in each hemisphere and these transport air up from the near-surface in equatorial regions and towards each pole at higher altitudes, and as a result in the upper atmosphere there are weak meridional age gradients at all latitudes.

3.2. Polar regions

Unlike at lower latitudes, the oldest air in polar regions is in the lower atmosphere (10–100 Pa) and not the upper atmosphere. The youngest ages at the poles are still near the surface and age increases with height in lower atmosphere, but then decreases from lower-middle atmosphere to the upper atmosphere. Thus, in polar regions Γ does not increase monotonically with altitude. Furthermore, Γ in the polar lower atmosphere (100–10 Pa) is generally much older than that anywhere in the low- and mid-latitudes, i.e., the polar age can exceed 250 sols, greater than what is seen at any altitude in the low- and mid-latitudes.

There is also much larger seasonality of Γ in the polar regions than at lower latitudes, with the annual variation of Γ in some regions over 200 sols (e.g., Γ at 100 Pa varies from around 50 sols to over 250 sols). This seasonality in polar age is shown clearly in Fig. 2, which shows the