MARS' ANNULAR POLAR VORTICES: CAUSE AND STABILITY

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Introduction:

In common with several other planetary bodies, Mars' atmosphere has strong circumpolar zonal winds, known as polar vortices, during winter. A distinctive feature of the Martian polar vortices is that they consist of an annulus of high potential vorticity (PV) with opposing meridional gradients on the equatorward and poleward sides and a local minimum near the geographic pole. These annuli are in PV fields derived from observations, reanalyses, and free-running general circulation model simulations of Mars, but are not a feature of Earth's polar vortices, where there is a monotonic increase in magnitude of PV from equator to pole. The creation, maintenance, and stability of the annular polar vortices on Mars are not well understood.

Here we use reanalyses and simulations from both an idealized shallow water model and the MarsWRF general circulation model to examine the cause of the Martian annular vortices and their long-term stability.

Polar Vortices in Reanalyses:

The annular structure of the Martian polar vortex can clearly be seen in Martian reanalyses. For example, **Fig. 1** shows the PV structure near northern winter solstice in the Mars Analysis Correction Data Assimilation (MACDA) reanalysis (Montabone et al., 2014). Over a 30-solar day (sol) average (**Fig. 1(a)**), a coherent elliptical annulus of PV is seen, with the zonal wind having a maximum some way equatorward of the maximum gradient in PV. When viewed as an instantaneous snapshot, PV does not appear as a smooth ring, but rather a series of smaller patches surrounding the pole (**Fig. 1(b)**). The annular vortex persists from fall to spring, and similar annular features are seen for the southern hemisphere polar vortex and in other Martian reanalyses (Mitchell et al., 2015, Waugh et al. 2016).

Stability of Annular Vortices:

The persistence of the Martian annular polar vortex is surprising since it is known that a strip of uniform vorticity is barotropically unstable, both for planar (Rayleigh 1887) or spherical (Dritschel and Polvani 1992) flow. One possible reason for this persistence is the existence of an external forcing mechanism that suppresses the instability. We explore this hypothesis using simulations with a shallow water model (Seviour et al. 2016).

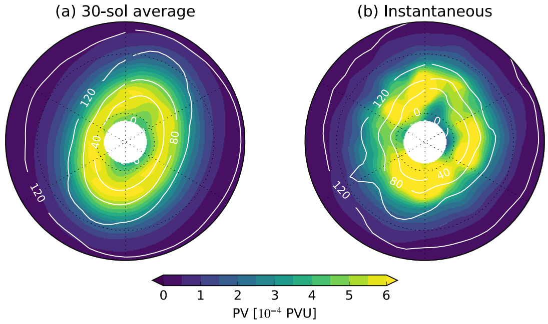

Figure 1: Martian polar vortex in the MACDA reanalysis. Polar stereographic projection (40 ^{o}N to 90 ^{o}N) of PV (colors) and zonal wind [m s $^{-1}$] (contours) on the 350 K potential temperature surface for (a) 30-sol average near solar longitude 270 ^{o} during Martian year 24 and (b) Instantaneous values at solar longitude 270^o.

In unforced, adiabatic simulations annular vortices are unstable, with initially small perturbations growing to large amplitude waves on both the inner and outer edge of the annulus, that lead to the breakdown of the annular structure and formation of a "monopolar" vortex with a monotonic increase in PV from equator to pole (**Fig 2, left**). However, when relaxation towards an annular equilibrium profile (to mimic the effects of radiative relaxation) is introduced the instability can be prevented from growing and a persistent annular vortex with similar characteristics to that observed in the Martian atmosphere is simulated (**Fig 2, right**). The relaxation time scale required to prevent growth of the instability is similar to observed relaxation time on Mars (1-2 sol).

Cause of Annular Vortices:

The shallow water model simulations show that "external" forcing can suppress the instability of an annular vortex. But what is the forcing occurring in the Martian atmosphere?

One possibility is that the forcing is latent heating due to CO_2 condensation in cold polar regions. Temperatures within the winter vortex are sufficiently cold to condense CO_2 to a solid through direct deposition on the surface and by in-situ formation of aerosols and precipitation (snow) from supersaturation. The latent heat associated with this CO_2 condensation leads to destruction of PV and could be the cause of the annular PV structure and suppression of instabilities.

To test this hypothesis pairs of simulations of the

MarsWRF general circulation model are performed that differ only in their representation of CO_2 micro-

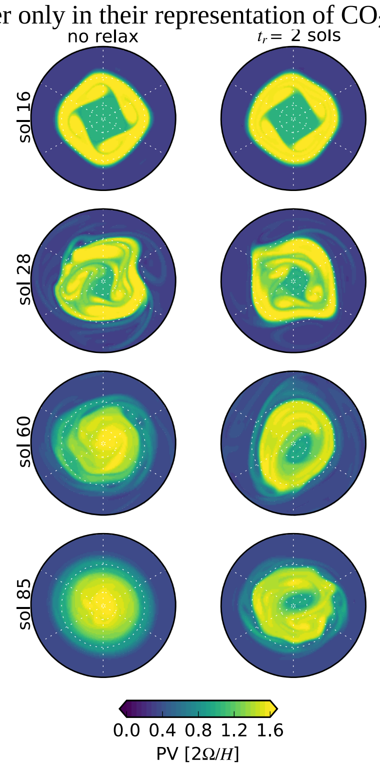

Figure 2: Polar stereographic projection of PV evolution for shallow water model simulation of annular vortex with (left) no relaxation and (right) relaxation with time scale of 2 sol.

physics (Toigo et al. 2016): the "standard" simulations employ a parameterization scheme for condensation and sublimation of CO_2 based on not exceeding saturation, whereas the "no-CO_2-latent-heating" simulation explicitly disables the CO_2 microphysics, and no phase changes or exchange of latent heat occurs.

In the standard simulations there is near-zero PV at low and mid-latitudes and an annulus of high PV at high latitudes (**Fig 3, left**), resembling the PV in Martian reanalyses although with a weaker polar minimum. In the no-CO_2-latent-heating simulation there is still near-zero PV equatorward of the core of the westerly jet and a large increase in PV just within the jet, but there is not a decrease in PV in coldest polar regions (**Fig 3, right**), i.e., there is a "monopolar" vortex if there is no CO_2 condensation. The occurrence of a monopolar rather than annular vortex when there is no CO_2 condensation also occurs in the southern hemisphere, in MarsWRF simulations with increased dust loading in which there is a transient warming of the polar region near winter solstice and temperatures are briefly too high to condense CO_2, and in simulations where CO_2 microphysics is suddenly "turned off" at winter solstice when an annular vortex is already present. These MarsWRF simulations provide compelling evidence that the annular structure of Mars' polar vortices is due to latent heat associated with CO_2 condensation.

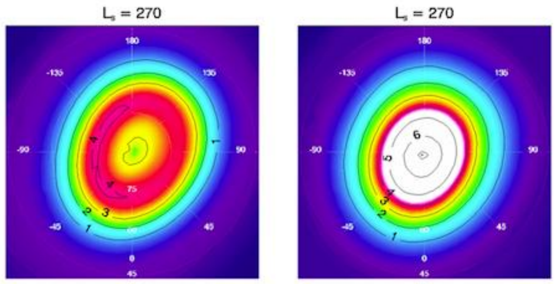

Figure 3: North polar stereographic projection maps of 30-sol average scaled on the θ = 300 K isentropic surface at L_s ~ 270° (northern winter solstice) from a (left) standard and (right) no-CO_2-latent-heating MarsWRF simulations. PV is also shown in black contours. The outer latitude is 45°N and 0° longitude is at the bottom of the maps.

Conclusions:

Our analysis indicates that the existence of annular polar vortices in Mars' atmosphere is related to the condensation of the predominant atmospheric gas species (CO_2) in polar winter regions. The latent heat associated with CO_2 condensation leads to destruction of PV in the polar lower atmosphere, inducing the formation of an annular PV structure. Furthermore, the latent heating and short radiative time scales prevent barotropic instabilities from growing and disrupting the annular structure, and the Martian annular vortices can persist throughout winter.

The existence of an annular polar vortex on Mars has possible implications for the transport of gases and aerosols between high and low latitudes. We are currently exploring the sensitivity of transport and mixing of polar and mid-latitude air on the annular structure of polar vortices.

Acknowledgements:

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