
Introduction: One distinctive feature of the Martian atmosphere is that the seasonal polar vortices exhibit annuli of high potential vorticity (PV) around 70–80 degrees latitude and a local minimum near the pole. These annuli can be seen in PV fields derived from observations [1], reanalyses [2,3], and free-running general circulation model (GCM) simulations [3,4] 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 for both the stratospheric and tropospheric polar vortices [5].

The cause of the generation of an annular PV field in the Martian polar vortices is unknown. We present here an analysis of Mars reanalyses and a series of MarsWRF simulations that indicate that the annulus is due to CO₂ condensation in polar regions.

Methods: We examine the evolution and structure of the Martian polar vortices in two recently available reanalysis systems, the Mars Analysis Correction Data Assimilation (MACDA) [6] and the Ensemble Mars Atmosphere Reanalysis System (EMARS) [7], and in a series of MarsWRF [8] simulations. These simulations consist of pairs that differ only in their representation of CO₂ microphysics: in the “standard” simulation there is a simple scheme for condensation and sublimation of CO₂ based on not exceeding saturation, whereas in the “no-CO₂-latent-heating” simulation the CO₂ microphysics is explicitly disabled. The difference between these simulations show the impact of CO₂ condensation on the flow and thermal and polar vortex structure.

Results: The reanalyses show very similar evolution and structure of the polar vortices. During winter, there are very low temperatures in the polar regions with a strong westerly jet in high latitudes that tilts towards the pole with height. There is near-zero PV equatorward of the core of the westerly jet, a large increase in PV just within the jet, and then a decrease in polar regions, resulting in an annulus of high PV just inside the jet (Fig 1a).

The observed evolution and structure of the vortex is reproduced in typical (“standard”) MarsWRF simulations that include the microphysics of CO₂ condensation and sublimation. In particular, in these simulations there is near-zero PV equatorward of the jet core, and strength, extent, and timing of the vortex varies depending on the amount of dust in the atmosphere.

The cause of the generation of an annular PV field in the vortex is unknown, but one possible cause is

Figure 1: North polar stereographic projection maps of monthly(30-sol)-mean potential vorticity (colors) on the θ=300 K isentropic surface at Lₘ=270° (northern winter solstice) for (a) MACDA, and the (b) standard and (c) no-CO₂-latent-heating MarsWRF simulations. The outer latitude is 45°N and 0° longitude is at the bottom of the maps. Black contours also show potential vorticity.
latent heating due to CO₂ condensation in cold polar regions. To test this hypothesis, simulations with no CO₂ microphysics are performed. The vortex structure differs significantly in these “no-CO₂-latent-heating” simulations. While there is still a strong westerly jet with near-zero PV equatorward of the jet, there are lower temperatures, stronger zonal winds, and higher PV in polar regions. Most importantly, there is a monotonic increase in PV from equator to pole with no annular structure (Fig 1c).

Analysis of heating rates shows that in both simulations the high PV is generated by diabatic cooling associated with the downward branch of the Hadley cell, but in the “standard” simulations the latent heat associated with CO₂ condensation compensates partially and leads to destruction of PV in the polar lower atmosphere, inducing the formation of an annular PV structure (Fig. 2). There is close correspondence between the vertical extent of latent heating and the region of the annulus of PV in the standard simulations (Fig. 2a).

Conclusions: Analyses of MarsWRF simulations indicate that the annular structure of PV in Mars’ polar vortices is due to latent heat associated with CO₂ condensation in polar regions. If there is no CO₂ condensation the simulated polar vortex has monotonic PV gradients with maximum PV near the pole, similar to terrestrial polar vortices where there is also no condensation of the most abundant atmospheric species.


Figure 2: Profiles of potential vorticity (colors), zonal wind (m/s, white contours), potential temperature (K, black dashed contours), and latent heating (K/s, solid black contours). Data are 30-sol averages for a period near Ls=270° (northern winter solstice). The thick dotted line is the isentropic surface for Figure 1.