A CLIMATOLOGY OF THE MARTIAN NORTHERN POLAR VORTEX.

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Understanding the behaviour of Mars' polar vortices, and their modification under different dust loading conditions, is important for understanding its contemporary and ancient climate, including aerosol and chemical cycles. We present an eight martian year climatology of the northern polar vortex, via the assimilation of orbital temperature and dust observations into a global climate model. We show that the general seasonal behaviour and morphology of the vortex is highly interanually repeatable, with the important exception of dust storm effects. Previous work has focused on individual regional or global dust storm effects, specifically solstitial events for the latter; by investigating an eight-year period covering two global and multiple regional dust storms, we are able to investigate the potentially crucial impact of dust storm timing on vortex effects as suggested by previous work [10]. We find that the seasonal timing of atmospheric dust loading does indeed have a crucial role in determining the dynamical effects of a storm on the northern polar vortex. Storms later in the dusty perihelion season, such as solstitial global dust storms and C-type regional dust storms [11], have a significantly greater disruptive effect on both the morphology (including latitudinal extent) and intensity of the vortex than those early in the season, such as equinoctial global dust storms and A-type regional dust storms.

Introduction

Mars' winter atmosphere is characterized by the presence of a region of low temperatures around the winter pole, surrounded by a powerful westerly jet; this region is known as the polar vortex [1, 2]. Mars' polar vortices are important components of the global atmospheric circulation. The cold temperatures enable the condensation of CO_2, dramatically altering the global atmospheric mass budget on a seasonal timescale [3], while the high westerly winds form an effective barrier to intra-polar transport of suspended aerosol and chemical species including water vapour [4] while also controlling the shape of the polar hood cloud belt via planetary wave activity [5]. In addition, understanding the polar vortices may lead to insights into Mars' historical climate, recorded in layers of dust and ice at the permanent polar ice caps [6]. Mars' polar vortices are therefore intimately linked to many of the key concerns of martian atmospheric science, from elemental and tracer cycles through global dynamics to paleoclimate. We present results which show the seasonal trends in behaviour of Mars' contemporary northern polar vortex, and the highly seasonally dependent effects of dust storms on the vortex's intensity and morphology.

Both north and south polar vortices have a distinctive annular shape, differentiating them from Earth's vortices, with this annularity thought to be caused by latent heat release from CO_2 condensation over the seasonal cap [7, 8, 9]. The northern vortex in particular also has an elliptical morphology [1], linked to stationary wave activity forced by the zonal topographic structure of Mars' northern mid-latitudes [2, 8, 10].

Mars' polar vortices appear to have a complicated relationship with atmospheric dust loading, including regional and global-scale dust storms. The northern vortex was found in the MACDA reanalysis to be substantially weakened and shifted off pole by $\sim 10°$ latitude by a late season (C-type [11]) regional dust storm [2]. Atmospheric modelling work using different prescribed dust distributions found that solstitial regional and Global Dust Storms (GDS) could disrupt the northern polar vortex for up to 10s of sols, via the mechanism of shifting the descending Hadley cell branch poleward [12]. An analysis of the OpenMARS reanalysis dataset found that the northern vortex was in general highly sensitive to atmospheric dust loading, with the solstitial MY 28 GDS in particular substantially reducing the intensity of the vortex [13]. On the other hand, work using a reanalysis of the MY 34 equinoctial GDS found that the northern polar vortex, while it was altered in morphology and extent, remained relatively robust despite the extreme atmospheric dust loading [10]. These results suggest that the seasonal timing of large dust events could be crucial in determining their effects on the northern polar vortex.

Large, planet-scale dust events are regular occurrences in Mars' atmosphere. Regional-scale dust storms have been observed to occur every martian year during Mars' dusty (perihelion) season, in a sufficiently repeatable fashion so as to be classifiable into so-called A, B, and C-type regional dust storms [11]. B-storms are confined to the southern polar cap edge and so are unable to have any significant dynamical effect on the northern polar vortex. A and C-storms, however, tend to occur at tropical/mid-latitudes, allowing them to impact the northern vortex dynamically via modification of the meridional overturning circulation. By defini-

tion A-storms occur early in the dusty season, while C-storms occur towards its end. A reanalysis of these events would therefore allow for the investigation of the effects of dust storm seasonal timing on northern polar vortex impacts.

More generally, reanalyses using observations from the Mars Climate Sounder (MCS) now have access to nearly eight full martian years' worth of MCS retrievals, covering a period containing two GDS and many regional dust storms. This provides an opportunity for study of the climatological, yearly behaviour of Mars' northern polar vortex; specifically, both its seasonally repeatable behaviour as well as interannual variability associated with dust storms. Understanding both the morphology (including latitudinal extent) and intensity of the vortex under different dust loading conditions could have significant implications for the transport of atmospheric tracers into the polar regions.

Model, assimilation scheme, and retrievals used

We use the Open University's Mars Global Climate Model (MGCM), which is the result of a collaboration between the Laboratoire de Météorologie Dynamique, The Open University, the University of Oxford, and the Instituto de Astrofísica de Andalucía [14]. The MGCM solves the equations of fluid dynamics, together with parametrized radiative and other physics, to calculate the state of Mars' atmosphere. The MGCM contains a spectral dynamical core and a semi-Lagrangian tracer transport scheme [15]. For this study, the MGCM was run at a spectral resolution of T42, with 50 vertical levels.

The assimilation scheme used is a modified version of the UK Met Office developed Analysis Correction scheme [16], adapted for the martian atmosphere [17]. This method is computationally inexpensive, allowing it to be be run at a similar cadence to the MGCM dynamical core. The scheme's use of the repeated insertion method also helps to counteract a common issue with assimilation schemes for Mars, that of the low thermal inertia of the atmosphere causing rapid relaxation of the assimilated atmospheric state. Dust is assimilated as column dust optical depth (CDOD) from MCS CDOD products, with MGCM dust tracers being scaled to match the assimilated CDOD [18]. The vertical distribution of dust is allowed to evolve freely. Temperature is assimilated in the form of MCS temperature profiles, following previous work with the same MGCM and assimilation scheme [19].

The retrievals assimilated into the MGCM were from MCS [20, 21] aboard the Mars Reconnaissance Orbiter (MRO) , which has now amassed close to eight martian years worth of atmospheric observations. For this study, the assimilated MCS outputs were temperature profiles and derived CDOD products, covering the pe-

riod from when MCS began observing in MY 28 until the end of MY 35.

Potential vorticity diagnostic

Ertel potential vorticity (PV) is a valuable diagnostic for studies of the polar vortex. PV is a measure of air circulation based on the relative vorticity and stratification of the atmosphere; it is also conserved under adiabatic processes, making it especially useful for diagnosing polar dynamics. The polar vortices themselves can be defined as regions of high PV around the poles. For this work, PV is defined on isentropic surfaces (surfaces of constant potential temperature), as the PV of air masses on isentropic surfaces is conserved and cannot be created or destroyed [22]. Analysing isentropic PV enables investigation of the morphology of Mars' polar vortex, its intensity, and how it is affected by factors such as dust storms.

Results and discussion

We present the results of a reanalysis of close to eight full martian years of MCS temperature profiles and derived CDOD products into the MGCM, focussing specifically on the behaviour of the northern polar vortex. We show the interannually repeatable structure of the northern polar vortex, from its inception to decay, and how its morphology (including annularity and latitudinal extent) varies seasonally. We relate this behaviour to the general circulation of the martian atmosphere and the growth and decay of the northern seasonal CO_2 cap.

We then demonstrate how the northern polar vortex is affected by tropical and mid-latitude dust storm activity, specifically A and C-type regional dust storms and the GDS of MY 28 and 34. We examine both the zonally averaged PV impacts as well as the longitudinal distribution of PV over the north polar region. A and C-type regional dust storms in particular provide a natural experiment regarding the effects of seasonal timing on PV disruption, given roughly similar latitudinal distributions and CDOD of the storms themselves.

Figure 1 shows northern mid-high latitude PV on the 300 K isentropic surface together with tropical CDOD. The general pattern of the northern polar vortex is seen to show a high degree of interannual repeatability, with the exception of large dust loadings (discussed below). Roughly speaking, the vortex (on this isentropic surface) first appears between L_S=150-180°, and grows in intensity. However, it only gains its characteristic annular PV structure from approximately L_S=210°; this lasts until approximately L_S=330°. In Fig. 1, this is visible as a peak in PV at around 80° N, with a local PV minimum over the north pole itself. The peak in PV intensity occurs between approximately L_S=210-330°.

While these general trends hold for most of the MYs presented here, there is apparent interannual variability, linked to either gaps in the MCS data for assimilation or high tropical atmospheric dust loading. The latter are discussed below.
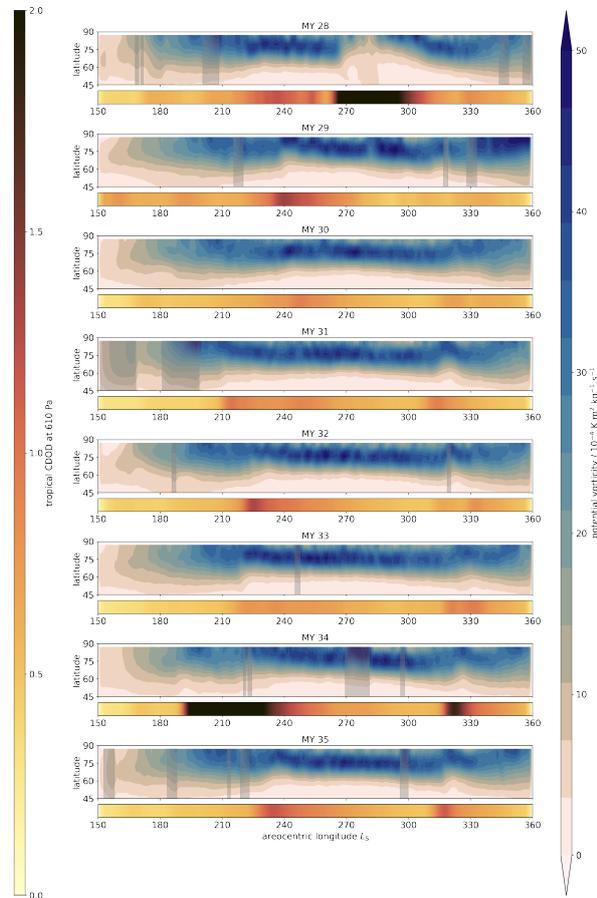
Figure 1: Zonally-averaged Ertel PV on the 300 K isentropic surface (top of each panel) and averaged tropical (30° S-30° N) CDOD at the 610 Pa reference pressure (bottom of each panel) in the assimilated MGCM for MY 28-35, L_S=150-360°. Shaded areas represent time periods when MCS data was unavailable for assimilation, and so the MGCM was allowed to run freely.

Fig. 1 shows an evident correlation between high tropical dust loading and modification of the northern polar vortex, though this relationship is not necessarily a straightforward one. For example, it can be seen that the MY 28 solstitial GDS caused substantial disruption to the northern vortex, while the MY 34 equinoctial GDS had a much more limited effect, as has been reported in previous work [10]. Likewise in the case of regional scale dust storms, there appears to be a dichotomy between the effects of the early season A-storms and the late season C-storms, with the latter

causing greater disruption of the vortex (specifically, compression towards higher latitudes) even when they have similar CDOD magnitudes (for example, compare the A-storm at around L_S=220-250° and the C-storm at around L_S=320-340° of MY 33).

Conclusions

Mars' polar vortices are crucial components of its global atmospheric circulation, and affect the transport of aerosols and chemical species. Understanding their behaviour, and how they are modified by the ubiquitous martian phenomena of dust storms, is therefore of great importance for general studies of the martian atmospheric system. We present results from assimilation of eight martian years' worth of MCS observations into an MGCM to explore the general behaviour and climatology of Mars' northern polar vortex.

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