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On the role of spatially inhomogeneous diabatic effects upon the evolution of Mars' annular polar vortex

Masoud Rostami[a,b], Vladimir Zeitlin[*,a], Luca Montabone[c]

[a] Laboratoire de Météorologie Dynamique (LMD)/IPSL, Sorbonne Universités (Université Pierre et Marie Curie, UPMC) and Ecole Normale Supérieure (ENS), Paris, France
[b] Institute for Geophysics and Meteorology (IGM), University of Cologne, Cologne, Germany
[c] Space Science Institute (SSI), Boulder, CO, USA

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ABSTRACT

The structure of Mars' annular polar vortex is not similar to that of its counterpart on Earth and is characterised by a potential vorticity (PV) low in the vicinity of the winter pole, rather than PV monotonically increasing towards the pole. A number of persistent asymmetric high-PV patches around the central low are also typical for the Martian polar vortex. The simplest vertically averaged model of the Mars atmosphere (a rotating shallow water model on the polar tangent plane) with inclusion of diabatic effects is used to get clues for understanding this surprising behaviour. The standard parameterisation of radiative relaxation is applied, together with a simple parameterisation of latent heat release due to spatially inhomogeneous CO_2 deposition. The parametrisation of inhomogeneous deposition is new in this type of models, and includes dependence on the concentration of condensation nuclei, which are considered as a passive tracer. Linear stability analysis of the zonally and time averaged Mars' winter polar vortex is performed, and thus identified unstable modes are used for initialisation of high-resolution numerical simulations of their nonlinear evolution in four different configurations (adiabatic, diabatic with only radiative relaxation, only deposition, and both radiative relaxation and deposition), in order to identify the role of each process. It is shown that the combined effect of radiative relaxation and inhomogeneous deposition can account for the observed, formally unstable structure of the polar vortex, including the patches of high potential vorticity.

1. Introduction

A surprising property of the Martian atmosphere is the latitudinal distribution of zonally averaged potential vorticity (PV), which has a minimum PV at the North winter pole surrounded by a circumpolar annulus of higher PV. The South pole exhibits similar characteristics of smaller intensity (Mitchell et al., 2015). Such configuration is unstable in the absence of external forcing, and is expected to evolve towards monotonous PV distribution, like e.g. the North polar vortex on Earth. Yet, this does not happen and the annular PV distribution is persistent on Mars. It should be stressed that the Martian polar vortex is annular only on average, as reanalysis datasets (Greybush et al., 2012; Montabone et al., 2014) reveal the existence of patches of high PV (Mitchell et al., 2015; Waugh et al., 2016), with time-scale of the order of a sol (a Martian mean solar day) between about 20 and 50 km altitude around the northern hemisphere (NH) winter solstice ($L_S = 270°$. L_S is the solar longitude, the angular position of Mars in its orbit with respect to the position at NH spring equinox). Fig. 1 shows the evolution of Ertel potential vorticity (EPV) patches during half a sol just before NH winter solstice of Martian year (MY) 24, from the Mars Analysis Correction Data Assimilation (MACDA) v1.0 reanalysis (Montabone et al., 2014). The coherence of such patches throughout local times, and their displacement with the mean flow, are remarkable in this case. Furthermore, maps of 30 *sol* mean PV show a quasi-continuous belt of high PV with an elliptical shape rather than a circular one (Mitchell et al., 2015; Waugh et al., 2016), likely forced by a stationary wavenumber-2 wave aligned with the hemisphere-scale topography, as shown by Barnes et al. (1996); Hollingsworth and Barnes (1996). It should be noted that there are no satellite measurements of winds in the Martian atmosphere so far, and reanalysis datasets have been obtained with the support of Martian general circulation models (MGCM) (see Lewis (2003) for a general review of Mars GCMs).

It is natural to look for an explanation of the existence and longevity of the Mars' annular polar vortex in terms of diabatic effects, and indeed such attempts exist in the literature (Waugh et al., 2016; Seviour et al., 2017; Toigo et al., 2017). For example, Toigo et al. (2017) showed that the latent heat released by CO_2 "condensation" in a MGCM model tends to produce an annular polar vortex. Yet the complexity of general

* Corresponding author at: 24 Rue Lhomond, Paris, 75005, France.
E-mail addresses: mrostami@lmd.ens.fr (M. Rostami), zeitlin@lmd.ens.fr (V. Zeitlin).

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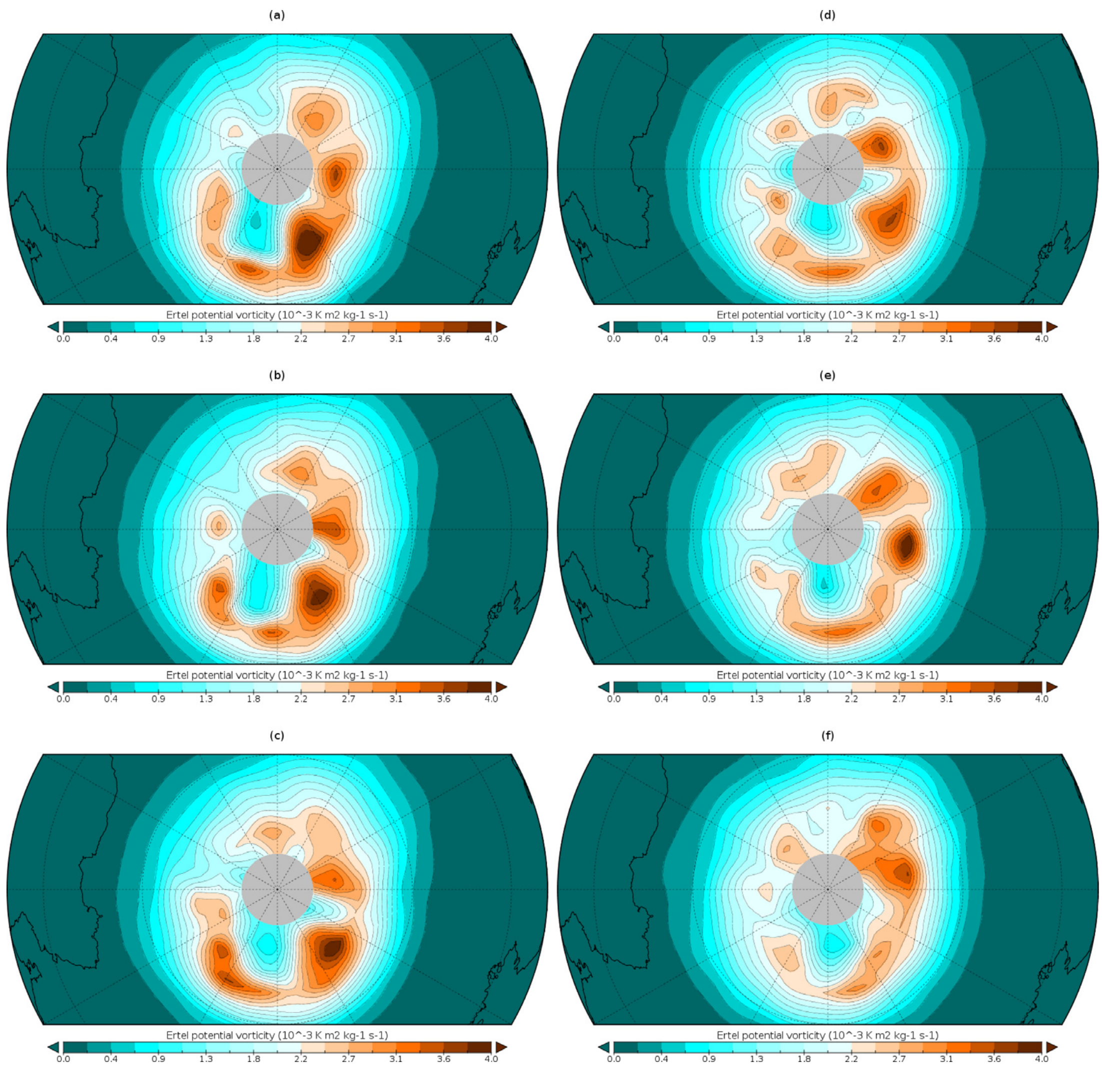

Fig. 1. This figure shows the evolution of the Ertel potential vorticity on the 275 K isentropic level (about 25*km* altitude in the NW winter polar region) from the MACDA v1.0 dataset (Montabone et al., 2014) in MY 24 at $L_S \approx 268^{\circ}$ (sol-of-year = 512). Each panel is separated by two hours, for a total evolution time of half a sol. The order of the sequence is from panel (a) to (f), with panel (a) corresponding to 02:00 a.m. at 0° longitude. The longitude-latitude grid (dotted lines) is 30° × 30°. The projection is orthographic, centred on the North pole. The prime meridian is pointing downward. The grey area around the North pole is where the calculation of the latitudinal derivative of the zonal wind is not carried out (we use a conservative approach to avoid possible artifacts in the calculation of EPV from MACDA v1.0 dataset at very high latitudes). Note that we use c_p = 820 J $Kg^{-1}K^{-1}$ to define the isentropic levels, consistently with the study by Mitchell et al. (2015). If one uses c_p = 745 $JKg^{-1}K^{-1}$ as in other studies, these figures correspond to an isentropic level of 287 K.

circulation models, including a plethora of various physical phenomena and their parameterisations, makes it difficult to isolate the particular dynamical role played by each of them. This is why simplified shallow-water models are often used for this purpose. Thus, recently Seviour et al. (2017) obtained an annular PV structure in a shallow-water model by adding thermal relaxation towards an equilibrium state. In all aforementioned studies the CO_2 deposition process is considered homogeneous, without incorporating the effects of aerosols, which may serve as "condensation" nuclei, and thus affect the spatial pattern of deposition (Although the term "condensation" is frequently used in the literature, we use the formally correct "deposition" term to avoid confusion with gas - liquid phase transition).

In this work, we use the simplest column-averaged model of the Martian atmosphere in order to understand the role of two major diabatic effects in the winter season: the radiative relaxation, and the spatially inhomogeneous CO_2 deposition through the vapour-solid phase transition. The model is the rotating shallow water (RSW) model, which is not introduced in an *ad hoc* manner, but is obtained by vertical averaging of the primitive equations in pressure coordinates (Zeitlin, 2007). By the same procedure, the model allows to incorporate the profile of Mars' polar vortex as obtained from the MACDA v1.0 dataset. Using the zonally averaged profile of the polar vortex from the reanalysis, we are able to study its stability and identify the unstable modes that shape the vortex at the nonlinear stage of evolution. A major new feature and improvement of the model is that, while radiative relaxation is incorporated in the standard way, we use recipes similar to those applied for the construction of so-called moist-convective RSW models (Bouchut et al., 2009) in order to include convective fluxes produced by the latent heat release due to CO_2 deposition. Moreover, we extend this approach to allow for spatially inhomogeneous deposition with aerosols serving as deposition nuclei, as it is known that homogeneous ice nucleation is negligible in Mars' atmosphere (Wood, 1999; Colaprete and Toon, 2003; Määttänen et al., 2005). Aerosol nuclei could be any particles, such as mineral dust, water ice crystals, or micrometeorites, which have potential for triggering CO_2 ice nucleation. They are considered to be advected by the flow. We identify the dynamical role of both radiative cooling/heating and CO_2 ice deposition, and show that, even in this simple model, their combined influence allows to explain how the evolution of the most unstable mode of the zonally and time-averaged profile of Mars' polar vortex produces a