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Atmospheric superrotation in an idealized GCM: Parameter dependence of the eddy response

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ABSTRACT

Idealized Earth-like general circulation models (GCMs) have been extensively used to study superrotation on so-called "slowly rotating" bodies like Venus and Titan, however they tend to have difficulty producing superrotation if only the rotation rate is reduced to Titan- or Venus-like values. The Rossby number, $R_O = U/2\Omega L$, which characterizes the influence of rotation on the circulation, is small for Earth but large for both Venus and Titan. However, the differences in other nondimensional control parameters are often ignored in idealized planetary circulation studies. In this study we use a simplified Earth-like GCM to demonstrate the importance of the other nondimensional parameters in obtaining a superrotating flow, and identify the wave-modes responsible for generating and maintaining superrotation. We show that superrotation only emerges on a planet of slow rotation rate if the atmospheric thermal inertia is simultaneously increased; alternatively, superrotation is obtained if the only planetary radius is reduced. When only the rotation rate is reduced, a nearly axisymmetric circulation with intense Hadley cells is produced that prevents strong and persistent winds over the equator. The mechanism for generating and maintaining superrotation in the model involves a coupling between equatorial and high-latitude waves. However, the generation involves equatorial Kelvin-like waves and maintenance involves equatorial Rossby-like waves.

1. Introduction

Nondimensional variables involving typical values of velocities, length, diffusivity, density, viscosity and rotation rate, play a key role in characterizing many dynamical aspects of a flow. Among them, the Rossby number (R_O) is one of the most important parameters in geophysical fluid mechanics to characterize dynamical properties of the atmosphere. Defined as

$$R_O = U/2\Omega L \quad (1)$$

where U, Ω and L are typical magnitudes of zonal wind, planetary rotation and flow length scales, it relates the ratio of advection to Coriolis force for a given flow of a rotating fluid or a large scale atmospheric motion (Holton, 2004; Vallis, 2006). The geostrophic approximation holds for small values of R_O, as is the case for Earth's mid and high latitudes.

The terrestrial bodies in the Solar System with substantial atmospheres, Earth, Mars Venus and Saturn's moon Titan, present two distinct regimes of atmospheric circulation. Fig. 1 shows that at global scales, $R_O \ll 1$ for Earth and Mars while $R_O > 1$ for Venus and Titan. The mean zonal structures of these atmospheres roughly exhibit two different regimes, which we define as the classic and superrotating, and describe in more detail below.

Earth and Mars are fast rotating and large terrestrial bodies, which gives them rather small global values of $R_O \sim 0.01$. In this regime, there are substantial differences between the circulation in low and high latitudes. At low latitudes, the meridional circulation is characterized by upward motion of relatively warm air at the equator and sinking of cold air at subtropical latitudes along the latitudinal plane, which develops prograde zonal flow, on the poleward edge of each tropical overturning circulation, or Hadley cell (Fig. 1). At higher latitudes, on the other hand, the flow is dominated by large scale eddies which arise from baroclinic instability (Holton, 2004; Vallis, 2006). Seasonal cycles complicate this picture somewhat, and we will not consider their effects here.

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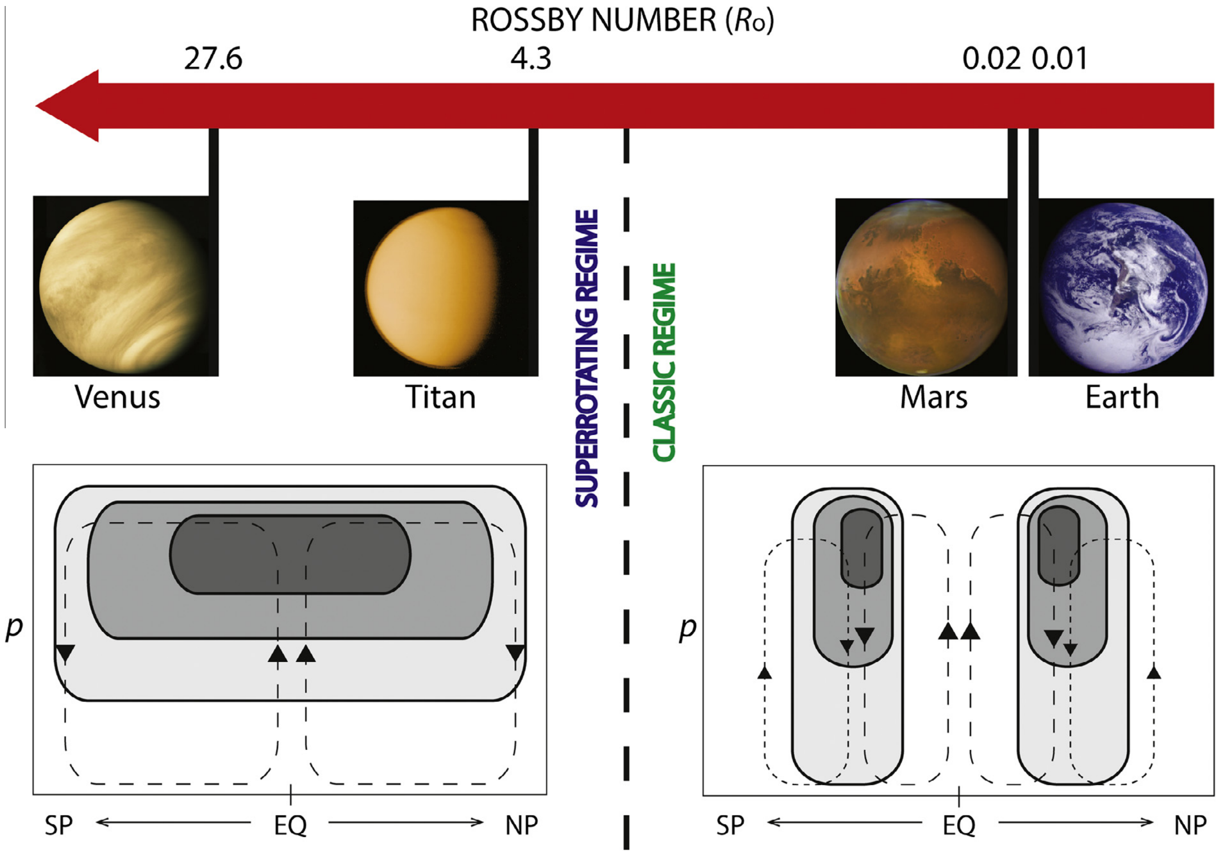

Fig. 1. Schematic view of the different Rossby numbers (R_O) and circulation regimes found on the terrestrial bodies of the Solar System with substantial atmospheres. R_O was computed based on typical scales of zonal winds (around 100 m s^{-1} for Venus and Titan and 10 m s^{-1} for Earth and Mars), rotation rate, and planetary radius. The lower panels depicts a hypothetical vertical cross section of zonal mean zonal wind (shaded, arbitrary scale) and mean overturning circulation (dashed lines, arbitrary scales) characteristic of each body's atmospheres. See text for more details (photo credits: NASA/JPL).

Since the rotation rates of Venus and Titan are slower compared to Earth and Mars' (the rotation period is about 16 days for Titan and around 240 days for Venus), numerical studies often focus on Earth-like atmospheres under slow rotation (Williams, 1988a, 1988b, 2003; Navarra and Bocalletti, 2002; Walker and Schneider, 2006; Del Genio and Suozzo, 1987; Del Genio et al., 1993). In parallel, simulations using numerical models set for either simplified or fully parameterized physical process (as for example, turbulent dissipation at the boundary layer, radiative transfer, chemical reactions and aerosols) of Venus (Yamamoto and Takahashi, 2003; Lee et al., 2005, 2007; Hollingsworth et al., 2007; Lebonnois et al., 2010; Parish et al., 2011) and Titan (Hourdin et al., 1995; Tokano et al., 1999; Tokano, 2007; Richardson et al., 2007; Friedson et al., 2009; Newman et al., 2011; Mitchell et al., 2011; Mitchell, 2012) have been performed in order to gain a more complete and accurate view of the general circulation patterns (and their time dependence) for each body. A common feature of all these studies is that the Hadley cell is larger in meridional extent (Fig. 1) and poleward heat fluxes efficiently act to reduce the latitudinal contrast of the temperature. Since the Rossby deformation radius is proportional to Ω^{-1} (Eady, 1949; Vallis, 2006), baroclinic instability weakens in this regime of higher Rossby numbers due to the fact that the typical unstable wavelength no longer fits on of the planet (Williams, 1988a, 1988b; Navarra and Bocalletti, 2002). Due to the large obliquity of Titan (around 26.7° to the ecliptic) the Hadley cell is also expected to have strong seasonal variation changing from a situation depicted in Fig. 1, with a symmetric pair of overturning circulation at the equator during the equinox, to a single inter-hemispheric Hadley cell. Structural changes regarding to the mean overturning circulation from an Earth to a higher R_O regime are common to the modeling studies.

However, few models today are able to reproduce the full strength of the zonal wind distribution on Venus and Titan. Both in situ and indirect observation from each body (for example Bougher et al., 1997; Kostiuk et al., 2001; Bird et al., 2005; Widermann et al., 2008) have shown strong zonal flow with magnitude of 100 m s^{-1} being the dominant component of the atmospheric circulation even at the equator. Such strong zonal winds at the upper level of Venus and Titan's equatorial atmospheres are in, so-called, superrotation. Some models produce only weak superrotation with zonal winds of 2–40 m s^{-1} at the equator (e.g., Tokano et al., 1999; Lee et al., 2007; Richardson et al., 2007; Friedson et al., 2009; Lebonnois et al., 2010) while others produce stronger equatorial winds (Hourdin et al., 1995; Yamamoto and Takahashi, 2003; Newman et al., 2011) more in-line with observations (Widermann et al., 2008; Kostiuk et al., 2001, for example). This discrepancy among similar models has yet to be understood, making the study of superrotating flow a challenging subject in geophysical fluid dynamics.

Through Eq. (1), a larger R_O (for the same wind typical scale U) could be achieved by either slowing the rotation rate of the planet down or decreasing the typical horizontal length scale on which the winds occur. When Earth-like models are run at slower rotation rates, they tend to produce strong jets at higher latitudes but also tend to fail in reproducing superrotating flow over the equator (see for example in Williams, 1988a; Navarra and Bocalletti, 2002). Mitchell and Vallis (2010) changed the Rossby number by decreasing the planetary radius in an idealized Earth-like model, and showed that in the cases with $R_O > 1$, the dynamics