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Maintenance of equatorial superrotation in the atmospheres of Venus and Titan

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Abstract

This paper extends Leovy's theory on Venus' equatorial superrotation by analytically examining additional terms in the mean zonal momentum equation that stably balances the momentum source of pumping by thermal tides. The general analytical solution is applied to the atmospheres of both Venus and Saturn's moon Titan. The main results are: (i) Venus' equatorial superrotation of 118 m s^{-1} results primarily from a balance between the momentum source of pumping by thermal tides and the momentum sink of meridional advection of wind shear by horizontal branches of the Hadley circulation; (ii) no solution is found for Titan's stratospheric equatorial superrotation centered at the 1-hPa level; (iii) however, if the main solar radiation absorption layer in Titan's stratosphere is lifted from 1 hPa ($\sim$185 km) to 0.1 hPa ($\sim$288 km), an equatorial superrotation of $\sim$110 m s^{-1} centered at 0.1-hPa could be maintained. Titan's equatorial superrotation results mainly from a balance between the momentum source of tidal pumping and the momentum sink of frictional drag.

Keywords: Venus; Titan; Atmosphere superrotation

1. Introduction

A long-standing problem in planetary atmospheric dynamics (including planetary bodies such as Titan) is the maintenance of equatorial superrotation in the atmospheres of slowly rotating planets. Strong equatorial superrotational zonal winds of $\sim$100 m s^{-1} were first observed at Venus' cloud-top level (e.g., Schubert, 1983), which yields an atmospheric angular velocity $\sim$55 times greater than the Venus' solid body rotation. Several mechanisms have been proposed to explain the generation or maintenance of Venus' cloud-top level superrotation (e.g., Schubert and Whitehead, 1969; Fels and Lindzen, 1974; Gierasch, 1975; Rossow and Williams, 1979; Walterscheid et al., 1985; Leovy, 1987; Hou et al., 1990). Most theories have described the possible mechanisms from one (above first four references) or two (above last three references) particular zonal momentum sources or sinks, either qualitatively or quantitatively. Also, most theories have studied equatorial superrotation based on a set of atmospheric parameters specifically adapted to Venus' atmosphere. Two well-known theories that explain the maintenance of the Venus equatorial superrotation are: (i) meridional momentum transport from mid-latitudes by eddy mixing (Gierasch, 1975; Rossow and Williams, 1979); and (ii) momentum pumping by thermal tides (Fels and Lindzen, 1974).

Several atmospheric general circulation models (GCMs) have produced near-global superrotations for Venus or/and Titan's atmosphere without a tidal pumping mechanism (e.g., Hourdin et al., 1995; Del Genio and Zhou, 1996; Yamamoto and Takahashi, 2003) by adopting a zonally averaged solar heating. The maintenance of equatorial superrotation in these models has been explained by horizontal eddy mixing that corresponds to an inverse cascade of energy from small-scale motions to large-scale ones in two-dimensional (2D) turbulence. Such an inverse cascade that transports the angular momentum equatorward by barotropic waves can also be simulated and

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analyzed in a slowly rotating atmosphere by a shallow-water model (e.g., Luz and Hourdin, 2003; Iga and Matsuda, 2005) that carries the a priori assumption of a 2D flow.

The maintenance of stable equatorial superrotational winds requires a balance of two terms in the averaged momentum equation. Leovy (1987) examined the balance between the following two terms at Venus' cloud-top level: (i) wave pumping by semi-diurnal tides proposed by Fels and Lindzen (1974) as a momentum source, versus (ii) vertical advection of wind shear by the upward branch of the Hadley circulation as a momentum sink. The exact physical mechanism that maintains equatorial superrotation on Venus remains a mystery, since the complete mean zonal momentum equation contains at least 10 terms representing the physical processes contributing to the momentum sources and sinks. These terms have never been systematically and self-consistently evaluated in the same dynamical frame. This lack of resolution of the superrotation issue on Venus has led to further confusion and debate concerning equatorial superrotation in Titan's stratosphere (e.g., Hourdin et al., 1995; Tokano et al., 1999). Titan is also a slowly rotating planetary body, which, similar to Venus' cloud layer, has a haze layer that absorbs a significant portion of its incident solar radiation.

This paper follows Leovy's (1987) analytic approach and examines additional terms in the mean zonal momentum equation that could be responsible for the maintenance of a stable equatorial superrotation in a slowly rotating planetary atmosphere. Because of the decoupling nature of a few fields in a slowly rotating fluid together with the sensitivity experiments based on a 2D numerical model (Zhu and Strobel, 2005), all of the possibly important terms can be evaluated analytically. The main advantage of an analytic approach is that the dependence of astronomical and atmospheric parameters can be expressed explicitly. As a result, the model parameters arising from the analytic formulation can also be easily adjusted to be consistent with the available measurements. The extended analytic model is tested by applying the formulations to the atmospheric circulation of both Venus and Titan because both planets slowly rotate and have a cloud or haze layer that strongly absorbs the solar radiation. A preferred theory should be able to consistently explain both the existence and non-existence of a strong and steady equatorial superrotation. Furthermore, since the Earth's atmospheric circulation is best understood and does not have a strong equatorial superrotation in the stratosphere, we also briefly apply the analytic formula to the Earth atmosphere to demonstrate the non-existence of the equatorial superrotation with the extended theory.

In Section 2, we first perform a scale analysis of the primitive mean zonal momentum equation. Section 3 reviews and extends Leovy's analytic theory for Venus' equatorial superrotation. Section 4 derives all the analytic expressions for the zonal momentum budget and applies those expressions to Venus and Titan to solve for the equatorial superrotating winds. Section 5 discusses the physical reasoning for the existence or non-existence of an equatorial superrotation of a rotating planetary atmosphere. Section 6 gives concluding remarks.

2. Mean zonal momentum equation and scale analysis

We start from the following mean zonal momentum equation (Holton, 1975):

$$\begin{aligned}\underset{\text{I}}{\rho\bar{u}_t} = &-\underset{\text{II}}{\frac{1}{a\cos^2\phi}\left(\rho\overline{v'u'}\cos^2\phi\right)_\phi} - \underset{\text{III}}{\left(\rho\overline{w'u'}\right)_z} - \underset{\text{IV}}{\rho\bar{w}\bar{u}_z} - \underset{\text{V}}{2\Omega\cos\phi(\rho\bar{w})} \\ &- \underset{\text{VI}}{\bar{F}_{rx}} + \underset{\text{VII}}{2\Omega\sin\phi(\rho\bar{v})} - \underset{\text{VIII}}{\frac{(\bar{u}\cos\phi)_\phi}{a\cos\phi}\rho\bar{v}} - \underset{\text{IX}}{\frac{\rho\overline{w'u'}}{a}} - \underset{\text{X}}{\frac{\rho\bar{w}\bar{u}}{a}}, \qquad (1)\end{aligned}$$

where $\overline{(\ )}$ and $(\ )'$ represent zonal mean and eddy components. The subscripts t, ϕ, and z denote time, latitude, and altitude derivatives, respectively. Other symbols are defined as follows:

a = planetary radius
Ω = angular velocity of the planet
ρ = background air density
u = eastward velocity (= prograde wind)
v = northward velocity
w = vertical velocity in log-pressure coordinates
F_{rx} = eastward frictional force ($= -\alpha_R\rho\bar{u}$)

The "primitive Eq." (1) for mean zonal momentum contains 10 terms. The common approach of scale analysis is to simplify the equations of motion by eliminating the smaller terms based on a particular set of characteristic scales of the field variables (e.g., Holton, 2004). Frictional force F_{rx} represents the momentum source of the unresolved eddies. Since we will be focusing on an analytic formulation in this paper this term will be parameterized by a Rayleigh friction expression, which implies that eddies will always decelerate the mean flow. Therefore, its effect on the momentum