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The Vertical Structure of Jupiter's Zonal Wind Using Gravity Waves

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Abstract

The vertical structure of Jupiter's winds is not well known, especially away from the cloud deck. By reanalyzing the data from the Galileo probe, we derive the vertical profile of the zonal wind from Jupiter's upper troposphere (∼340 mbar) to the lower thermosphere (∼65 nbar). This is the first time that a wind profile over such a large altitude range has been obtained. We also identify the altitude of the turbopause. Our profile further supports the presence of a quasi-quadrennial oscillation on Jupiter.

1. Introduction

The meridional structure of Jupiter's zonal wind is well known at the cloud level (∼700 mbar) from studies tracking features in the cloud deck (e.g., [1]). This structure has been extended vertically up to ∼0.5 mbar, away from the equatorial region, using the thermal wind balance [2, 3]. The zonal wind below the cloud deck is known from ∼560 mbar to ∼20 bar at the Galileo probe entry site [4]. In the present work we extend the vertical structure at the entry site up to the lower thermosphere (∼65 nbar).

2. Methodology

Data collected by the Galileo probe provide a vertical temperature profile that stretches from the thermosphere down to the tropospshere [5]. As have been done in the past (e.g., [6]), perturbations in the temperature profile are assumed to be due to presence of gravity waves. The governing equation for the dynamics of such waves is the Taylor–Goldstein equation:

$$\hat{w}'' + k_z^2(z)\,\hat{w} = 0\,. \qquad (1)$$

Here, $\hat{w}(z)$ is related to the perturbations in the vertical velocity, which itself is related to the temperature perturbations through the polarization relation [7]; z is the vertical direction and primes denote derivatives with respect to z; $k_z(z)$ is the index of refraction, which is equivalent to the local vertical wavenumber of the temperature perturbations.

Note that k_z is a complicated function of z through the intrinsic phase speed, $I(z) = [c_x - u_0(z)]$, and other variables that characterize the physical properties of the atmosphere (see Eq. 2). Here, c_x is the horizontal phase speed and u_0 is the background zonal wind. The function is inverted to obtain a nonlinear differential equation for the intrinsic phase speed:

$$II'' + \frac{II'}{H_\rho} + \left[\frac{1 - 2H_\rho'}{4H_\rho^2} + k_x^2 + k_z^2\right] I^2 - N^2 = 0\,, \qquad (2)$$

where H_ρ is the density scale height, k_x is the horizontal wavenumber, and N is the Brunt–Väisälä frequency. This equation is solved numerically using data from the probe to obtain $u_0(z)$.

3. Results

The power spectrum of the probe data shows a broadening of the wavenumber range containing high power at ∼500 nbar level. The broadening is likely due to gravity wave breaking and ensuing turbulence indicative of a turbopause. The spectrum also suggests that the waves have likely originated from a "leaky" ducting layer at, or just below, the cloud deck. The waves then appear to undergo multiple saturation and re-generation as they propagate upward via interaction with existing background zonal wind.

The zonal winds themselves are stronger than the wind at the same latitude-longitude location at the cloud deck level: above the cloud deck, the winds are typically ∼200 $\mathrm{m\,s^{-1}}$. Further, our analysis shows a peak in the flow profile at ∼3 mbar level. A similar peak has been reported in studies analyzing data from 16 years earlier and 5 years later than that in our work [2, 3]. Taken together, these findings support the existence of the quasi-quadrennial oscillation [8].

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