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Decoupling Jupiter's deep and atmospheric flows using the upcoming Juno gravity measurements and a dynamical inverse model

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ABSTRACT

Observations of the flow on Jupiter exists essentially only for the cloud-level, which is dominated by strong east-west jet-streams. These have been suggested to result from dynamics in a superficial thin weather-layer, or alternatively be a manifestation of deep interior cylindrical flows. However, it is possible that the observed wind is indeed superficial, yet there exists a completely decoupled deep flow. To date, all models linking the wind, via the induced density anomalies, to the gravity field, to be measured by Juno, consider only flow that is a projection of the observed cloud-level wind. Here we explore the possibility of complex wind dynamics that include both the shallow weather-layer wind, and a deep flow that is decoupled from the flow above it. The upper flow is based on the observed cloud-level flow and is set to decay with depth. The deep flow is constructed to produce cylindrical structures with variable width and magnitude, thus allowing for a wide range of possible scenarios for the unknown deep flow. The combined flow is then related to the density anomalies and gravitational moments via a dynamical model. An adjoint inverse model is used for optimizing the parameters controlling the setup of the deep and surface-bound flows, so that these flows can be reconstructed given a gravity field. We show that the model can be used for examination of various scenarios, including cases in which the deep flow is dominating over the surface wind, and discuss the uncertainties associated with the model solution. The flexibility of the adjoint method allows for a wide range of dynamical setups, so that when new observations and physical understanding will arise, these constraints could be easily implemented and used to better decipher Jupiter flow dynamics.

1. Introduction

The nature of the flow on Jupiter below the observed cloud-level is still mostly unknown. Analysis of the cloud-level flow, based on tracking of cloud observations (e.g., Porco et al., 2003), shows strong east-west flow of up to 140 m s^{-1}, with some local non-zonal flows such as around the Great Red Spot. Below the cloud-level, the Galileo probe (Atkinson et al., 1996) showed wind of 160 m s^{-1} going down to a depth of at least 24 bars at a specific location (6°N), but it is questionable of whether this represents the general flow (Orton et al., 1998; Showman and Dowling, 2000). Some studies suggested, based on indirect observations, that non-zero wind should exist below the cloud-level (Conrath et al., 1981; Gierasch et al., 1986; Dowling and Ingersoll, 1988, 1989), but their conclusions were limited to a depth of less than 1% of the planet's radius.

Theoretical understanding and numerical modeling during the past decades can be divided into two general mechanistic approaches. The first assumes the flow is confined to a shallow region, close to the cloud-level, similar to atmospheres of terrestrial planets, and becomes organized into zonal jets due to atmospheric turbulence (Rhines, 1975; 1979). The energy source for the flow can then either come from internal heating or solar radiation. The mechanism governing such shallow zonal flows was suggested to be either turbulence forced from the deeper layers (e.g., Williams, 1978, 2003; Showman, 2007; Kaspi and Flierl, 2007), or shallow decaying turbulence (e.g., Cho and Polvani, 1996; Scott and Polvani, 2007). Other studies, using idealized general circulation models solving for the full primitive equations, were even able to simulate cloud-level flow structures that are consistent with those observed in all Solar System giant planets (Lian and Showman, 2010; Liu and Schneider, 2010). The second approach assumes that the observed cloud-level flow is a surface manifestation of convective columns originating from the hot interiors of the planet (Busse, 1976, 1994). Angular momentum conservation in a rapidly rotating planet like Jupiter leads the flow to be aligned with the direction of the spin

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axis, and it has been shown in many studies that strong internal convection can lead to zonally symmetric flows aligned parallel to the axis of rotation (e.g., Aurnou and Olson, 2001; Christensen, 2002; Wicht et al., 2002; Heimpel et al., 2005; Kaspi et al., 2009; Jones and Kuzanyan, 2009; Gastine and Wicht, 2012; Gastine et al., 2013; Chan and Mayr, 2013). In all these studies, however, the width of the equatorial east to west super-rotation is much greater than that observed on Jupiter. Restricting the width of the equatorial jet to the observed one could be achieved by assuming a transition to a dynamo-controlled region at 0.95 of the planet radius (Gastine et al., 2014). These two approaches have been in debate for the last 40 years with no observed data that could resolve the controversy.

A third option, not considered in previous studies, is that both type of flows exist alongside: an internal flow of an unknown character likely forced by convection, and shallow flow related to the observed cloud-level wind. Such a scenario would require additional dynamics existing beneath the cloud-level so that the weather-layer wind would decay with depth (e.g., due to latent heat release, or enhanced stratification at the radiative-convective boundary), while the deep flows will occupy the deep convective region which is unaffected by the solar radiation.

The expected gravity measurements of Jupiter by Juno might give additional information about the character of the flow. Starting in the fall of 2016, the Juno spacecraft will perform high accuracy gravity measurements, with sensitivity expected to allow measurements at least up to gravity harmonic J_{10} (Bolton, 2005; Finocchiaro and Iess, 2010). Several studies have shown that these gravity measurements could be used to decipher the flow on the planet below its cloud-level (Hubbard, 1999; Kaspi et al., 2010). The assumption is that in the dynamical regime expected to govern the flow on the planet, the flow is accompanied by changes in the density field, so that, given the gravity measurements, a static density stratification together with a flow field could be found to best explain the measurements.

To date, most models linking the wind (via the induced density anomalies) to the gravity field to be measured by Juno, consider only flow that is a projection of the observed cloud-level wind (e.g., Hubbard, 1999; Kaspi et al., 2010; Kaspi, 2013; Zhang et al., 2015; Kaspi et al., 2016). Some assume full cylindrical flow while others allow for the wind to decay with depth. However, none of the models included the possibility of an internal flow that is decoupled from the surface-bound wind. In addition, these models were able to calculate the gravitational moments from a given flow field, but did not offer any methodology for the inverse problem. In another study (Galanti and Kaspi, 2016), an adjoint based inverse method was developed to relate the expected gravity measurements to the flow underneath the cloud-level. It was shown that given an measured gravity field the penetration depth of the observed cloud-level wind could be recovered, even in cases where this depth varies with latitude. The method also allows for measurement uncertainties to be incorporated, and uncertainties in the solution to be calculated.

In this study, we explore the possibility of complex wind dynamics that include both the surface-bound wind, and a deep flow that is completely detached from the flow above it. The methodology developed in this study is a continuation of that presented in Galanti and Kaspi (2016). There, the adjoint method was introduced and simple wind structures were simulated and then shown to be invertible by the adjoint model given the gravity moments. Here, we consider more complex flow cases, and rigorously quantify the uncertainty in the adjoint solution and the inevitability limits. The manuscript is organized as follows: in Section 2 we describe the model and methods used to calculate the complex flow structures, in Section 3 we discuss the various experiments performed, and conclusions are given in Section 4.

2. Methods

2.1. The thermal wind model

The dynamical model relating the flow on Jupiter to the density and gravitational moments, is similar to the one used in Galanti and Kaspi (2016). The model relates the flow field to the density field via the thermal wind equation (Kaspi et al., 2010). It assumes the dynamics to be in the regime of small Rossby numbers, where the flow to leading order is in geostrophic balance, therefore thermal wind balance holds

$$(2\Omega\cdot\nabla)[\tilde{\rho}\mathbf{u}] = \nabla\rho'\times\mathbf{g_0}, \tag{1}$$

where Ω is the planetary rotation rate, $\tilde{\rho}(r)$ is the background density field, $\mathbf{u}(\mathbf{r})$ is the 3D velocity, $\mathbf{g_0}(r)$ is the mean gravity vector and $\rho'(r,\theta)$ is the dynamical density anomaly (Pedlosky, 1987; Kaspi et al., 2009). The calculation takes advantage of a known mean static density $\tilde{\rho}(r)$ and gravity $\mathbf{g_0}(r)$, calculated using the method of Hubbard (1999). In this study we assume the flow is in the zonal direction only and does not vary with longitude, so that $\mathbf{u} = u(r,\theta)\hat{e}_\phi$, where r, θ, ϕ are the radial, latitudinal and longitudinal directions, respectively. The model also assumes sphericity and excludes the effect of gravity anomalies induced by the density anomalies. In a recent study (Galanti et al., 2017), these specific assumptions were shown to be a very good approximation of the full treatment of the equations that includes additional effects such as the self gravitation terms (Zhang et al., 2015) and oblateness effects (Cao and Stevenson, 2015). Moreover, the thermal wind model was also shown to be in good agreement with a more complete potential theory model, which takes into account the full planetary oblateness (Kaspi et al., 2016).

The dynamically induced zonal gravitational moments ΔJ_n are calculated using the density solution ρ' from the thermal wind model, by integrating

$$\Delta J_n = -\frac{2\pi}{Ma^n}\int_0^a r'^{n+2}dr'\int_{-1}^{1}P_n(\mu')\rho'(r',\mu')d\mu', \tag{2}$$

where M is the mass of Jupiter, a is the planet radius, P_n are the Legendre polynomials, and $\mu=\cos\theta$. In the experiments presented here we use the same model to generate both the 'observations', denoted ΔJ_n^o, and the model solutions, denoted ΔJ_n^m. In this study we do not consider tesseral harmonics representing zonal asymmetries in the flow (Parisi et al., 2016).

2.2. Construction of the surface-bound flow and the deep flow

For the upper surface-bound flow (a flow that is manifested in the cloud-level wind), we follow here the methodology of Galanti and Kaspi (2016), in which the observed cloud-level wind are projected along cylinders parallel to the axis of rotation, and set to decay toward the high pressure interior. The zonal wind field has the general form

$$U_{\mathrm{surf}}(r,\theta) = u_0\exp\left(\frac{r-a}{H(\theta)}\right), \tag{3}$$

where $u_0(r,\theta)$ are the observed cloud-level zonal wind extended constantly along the direction of the axis of rotation, a is the planet radius, and $H(\theta)$ is the latitudinal dependent e-folding decay depth of the cloud-level wind. The latitude dependent H is defined as a summation over Legendre polynomials

$$H(\theta) = \sum_{i=1}^{N_H} h_i P_{i-1}(\theta), \tag{4}$$

where $P_i(\theta)$ are the Legendre polynomials, h_i are the coefficients by which the shape of $H(\theta)$ is determined, and N_H is the number of functions to be used. Such formulation allows for a solution to