EPSC Abstracts
Vol. 8, EPSC2013-286, 2013
European Planetary Science Congress 2013

Jupiter's unearthly jets: a new idealised model

S.I.Thomson, M.E.McIntyre
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, UK (s.i.thomson@damtp.cam.ac.uk)

Abstract

A longstanding mystery about Jupiter has been the straightness of real Jovian jets, quite unlike terrestrial strong jets with their characteristic long-wavelength meandering. The problem is addressed in two steps. The first is to take seriously the classic Ingersoll-Cuong [4], Dowling-Ingersoll [1] and Stamp-Dowling [12] scenarios, with deep zonal jets in the convection layer underlying the weather layer, recognising moreover the relevance of Arnol'd's second shear-stability criterion ('A2 stability') and hence the possibility of stable upper jets even with reversed upper potential-vorticity (PV) gradients (e.g. [12, 2, 3]). The second step is to improve the realism of the small-scale forcing used to represent the effects of Jupiter's moist convection in physical space, albeit within an idealised, $1\frac{1}{2}$-layer setting. The real moist convection is likely to generate cyclonic as well as anticyclonic PV anomalies but with unequal strengths ('PV-biased forcing'), and to occur preferentially where the interface to the deep flow is coldest (e.g. [5]). The resulting model appears to have promise as a way of explaining the jet straightness and of constraining possible values of the Rossby deformation length L_{D} for the real planet, as well as suggesting new guidelines for general circulation model studies.

1. Introduction

Dowling and Ingersoll [1] have argued from cloud-wind data that the large-scale dynamics of Jupiter's weather layer is well described by a $1\frac{1}{2}$-layer, finite-L_{D}, PV-conserving model provided that zonally-symmetric deep jets are present in the convection layer beneath. This conclusion is controversial [8]. Here, however, we explore whether taking Dowling and Ingersoll's conclusion seriously offers a chance of understanding the straightness of the observed jets. Deep jets may well be present in reality, as a result of the dry convection beneath (e.g. [6]). We are interested in the possibility that the deep jets guide the upper jets even if not matching them in strength.

Straight jets are conspicuously absent from typical 1-layer and $1\frac{1}{2}$-layer idealised model studies that have no deep jets. In such models it is easy to generate stable jets with almost any forcing, but Rossby waves on the jets are easy to excite, making meandering behaviour typical, especially at high latitudes where by contrast the real-planet's jets follow latitude circles remarkably closely.

A second issue is that of jet stability. Despite severe observational uncertainties, it is widely believed that the real weather layer has reversed latitudinal PV gradients, i.e. that it *looks* unstable by the standard Rayleigh–Kuo–Charney–Stern criterion. It can nevertheless be stable, by the A2 criterion, for L_{D} values small enough in comparison with L, the jet spacing [2]. Dowling [2] argues that Jupiter is kept A2-marginal through the onset of shear instability whenever A2-marginality is slightly exceeded. However, because such instability takes the form of phase-locked long waves, and because such waves never seem to be observed on the real planet (involving phase-coherent meanders of at least two jets together) we focus instead on the possibility that the real weather layer is A2-submarginal.

A third issue is the nature of the forcing that excites the weather layer (see next section), the PV bias in particular. It is sometimes thought that the forcing details are unimportant. Here we find the opposite. The behaviour can be very sensitive to PV bias.

2. Model experiments

We use the simplest possible model, namely a $1\frac{1}{2}$-layer, doubly-periodic, $2L \times L$ quasigeostrophic model with fixed deep zonally-symmetric jets and finite L_{D}. The zonal period has to be at least $2L$ to allow realistic phase-locked long waves and realistic A2-marginality. The model is 512×256-pseudospectral with very small, quasi-hyperdiffusive dissipation ([10], App. B & refs). We seek cases whose behaviour resembles that of the real planet; thus for instance we use L, L_{D} and jet-strength values that are qualitatively realistic and mostly well within the A2-submarginal regime; in fact we take

$L_D = 1200\,\text{km}$ in most cases.

We follow e.g. [5] in assuming that the most important weather-layer forcing comes from moist convection. The folded filamentary regions and lightning on the real planet suggest that the strongest convection is in the belts, the bases of the belts being isobarically colder than the bases of the zones. By base we mean the interface between the weather layer and the deep-convection layer where dry convection goes over into moist convection. Since the belts are more cyclonic than the zones, a cold belt interface is consistent with the thermal-wind equation provided that the upper jets are stronger than the deep jets.

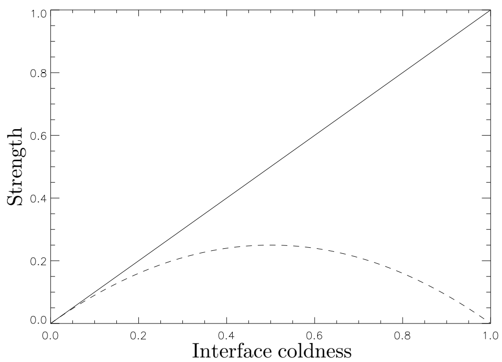

Figure 1: Bias algorithm (see text).

We therefore seek an idealised forcing such that both forcing and PV bias are strongest wherever the interface is coldest and moist convection most vigorous. We presume that in a moist convection event the weather layer receives both heat and mass from below, but relatively more mass when the convection is relatively more vigorous, hence a relatively stronger *anticyclonic* PV bias. An extreme case is the fully-biased, pure anticyclonic forcing used in [7] and [9].

By contrast with the unbiased white-noise and fully-biased forcings used in previous studies, we mimic a single moist-convection event by injecting one small cyclone and one small anticyclone, with relative strengths following an algorithm like that summarised in figure 1. The curves show in arbitrary units the strengths of injected cyclones (dashed) and anticyclones (solid) as a function of interface coldness (increasing to the right). We also use a 'semi-unbiased' variant with zero PV bias in the left half.

Model runs starting from the beta-free A2-marginal states defined in [12], with upper jets stronger than deep jets, show three key features: (1) a competition between PV mixing and the direct effects of PV bias and vortex migration [5]; (2) a strong tendency for bias to bring upper jet strengths closer to deep-jet strengths; and (3) a surprising weakness of the much-studied Kelvin passive-shearing mechanism ([11] & refs). Reintroducing the beta-effect reduces the sensitivity to bias, strengthening the upper jets.

Acknowledgements

S.I.T is funded through an STFC studentship. Andrew Thompson and Emma Boland kindly helped with the model code.

References

[1] Dowling, T.E., Ingersoll, A.P.: Jupiter's Great Red Spot as a Shallow Water System. J. Atmos. Sci., 46, 3256–3278, 1989.

[2] Dowling, T.E.: A Relationship between Potential Vorticity and Zonal Wind on Jupiter. J. Atmos. Sci., 50, 14–22, 1993.

[3] Dowling, T.E.: Estimate of Jupiter's Deep Zonal-Wind Profile from Shoemaker-Levy 9 Data and Arnol'd's Second Stability Criterion. Icarus, 117, 439–442, 1995.

[4] Ingersoll, A., Cuong, P.: Numerical model of long-lived Jovian vortices. J. Atmos. Sci., 38, 2067–2076, 1981.

[5] Ingersoll, A.P. et al.: Moist convection as an energy source for the large-scale motions in Jupiter's atmosphere. Nature, 403, 630–632, 2000.

[6] Jones, C.A., Kuzanyan, K.M.: Compressible convection in the deep atmospheres of giant planets. Icarus, 204, 227–238, 2009.

[7] Li, L., Ingersoll, A.P., Huang, X.: Interaction of moist convection with zonal jets on Jupiter and Saturn. Icarus, 180, 113–123, 2006.

[8] Marcus, P.S., Lee, C.: Jupiter's Great Red Spot and zonal winds as a self-consistent, one-layer, quasi-geostrophic flow. Chaos, 4, 269–286, 1994.

[9] Showman, A.: Numerical simulations of forced shallow-water turbulence: Effects of moist convection on the large-scale circulation of Jupiter and Saturn. J. Atmos. Sci., 64, 3132–3157, 2007.

[10] Smith, K.S. et al.: Turbulent diffusion in the geostrophic inverse cascade. J. Fluid Mech., 469, 13–48, 2002.

[11] Srinivasan, K., Young, W.R.: Zonostrophic Instability. J. Atmos. Sci., 69, 1633–1656, 2011.

[12] Stamp, A., Dowling, T.E.: Jupiter's winds and Arnol'd's second stability theorem: slowly moving waves and neutral stability. J. Geophys. Res., 98, 847–855, 1993.