EPSC Abstracts
Vol. 12, EPSC2018-834, 2018
European Planetary Science Congress 2018

Forward and inverse kinetic energy cascades in Jupiter's turbulent weather layer

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Abstract

Jupiter's atmosphere has often been compared with a classical quasi-2D, geostrophically turbulent fluid, with kinetic energy transferred upscale, and zonal jets emerging due to the planet's curvature. Using 2D wind fields obtained from Cassini cloud images taken during the December 2000 fly-by, we have measured the direction of Jupiter's kinetic energy cascade throughout the range of observed length scales, using structure functions and spectral fluxes as complementary approaches [5]. These confirm the upscale kinetic energy transfer from eddies on scales $\geq 3000\,\mathrm{km}$ up to the zonal jet scale, with ~90% of the energy transferred into the jets, and downscale transfer of enstrophy from all scales. At scales $\leq 3000\,\mathrm{km}$ or so, however, kinetic energy is transferred downscale, indicating a source at scales 2000–3000 km, comparable with the internal Rossby deformation radius. This suggests an important role for baroclinic instability in energising Jupiter's turbulent atmosphere.

1. Introduction

A distinctive characteristic of a turbulent flow is the nonlinear transfer of energy, vorticity and other flow properties between different scales of motion in processes known as cascades.

In homogeneous, isotropic 3D turbulence, nonlinear exchanges tend to cascade kinetic energy from large to small scales, where it is removed by viscous dissipation, leading to the Kolmogorov -(5/3) law for the kinetic energy spectrum in the inertial range at intermediate scales. In a 2D or quasi-geostrophic system forced at scale L_f, the 'classical' picture suggests kinetic energy will generally cascade towards scales $\geq L_f$ while enstrophy cascades to scales $\leq L_f$, with energy spectra of slopes -(5/3) and -3 respectively.

The prevailing view would anticipate that, given the strong dominance of planetary rotation on large-scale motions on Jupiter, energy is likely to be mostly transferred upscale from the relatively small scales (dominated by convection or baroclinic instabilities) towards the scales of the zonal bands.

2. Cassini observations

Cassini flew by Jupiter in December 2000. We used horizontal winds calculated by two independent cloud tracking analyses of the CB2 near-infrared continuum band Imaging Science Subsystem images at closest approach. Datasets G14g [3] and C11 [2] contain gridded winds for almost four rotations over $\pm 50°$ latitude and $360°$ longitude. Dataset G14s [6] contains scattered wind vectors from the 70 image pairs later stitched together to make dataset G14g.

3. Structure functions

The 3rd order structure function identifies the direction and kinetic energy propagation rate between different scales in a turbulent flow. It is calculated from velocity differences projected along (δu_L) or across (δu_T) a line separating pairs of points as a function of the separation distance r. For homogeneous isotropic turbulence, in 3D $\delta u_L^3 = -(4/5)\epsilon r$ where ϵ is the large-scale energy injection rate. In 2D turbulence, $\delta u_L^3 = +(3/2)Pr$ and $\delta u_L \delta u_T^2 = +(1/2)Pr$, where P is the energy input power due to a small-scale driving force [4]. In both 2D and 3D the 2nd order structure function $\delta u_L^2 \propto \epsilon^{2/3} r^{2/3}$.

Figure 1 shows a linear, positive dependence of the 3rd order structure functions on r for $3500\,\mathrm{km} \leq r \leq 40\,000\,\mathrm{km}$, implying an energy flux from small to large scales with $P \approx 1 \times 10^{-4}\,\mathrm{W\,kg^{-1}}$. Although not proportional to $r^{2/3}$ throughout, the second order structure function is consistent with the measured kinetic energy spectrum. At $r < 3500\,\mathrm{km}$ the third-order structure functions are negative, implying downscale energy flux to small scales, contrasting the tra-

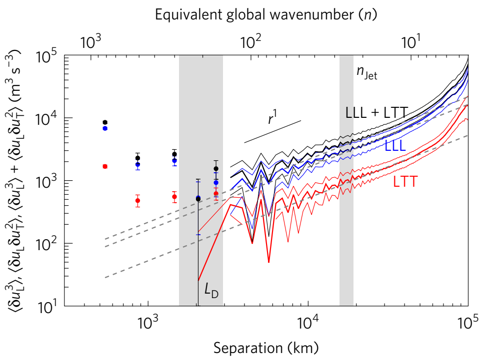

Figure 1: Third order structure functions, using dataset G14s. Grey bands show estimated deformation and jet scales. Dashed lines are linear fits. Dots are negative. Lines show means and 95% confidence intervals [5].

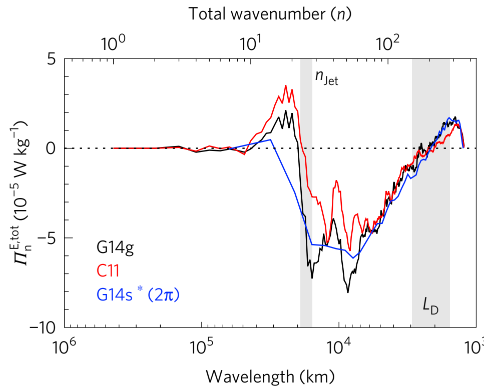

Figure 2: Kinetic energy spectral flux in Jupiter's atmosphere, using all three datasets [5].

ditional picture of Jupiter's atmospheric turbulence. A diverging energy flux implies that the turnaround scale contains a significant kinetic energy source for the flow.

4. Spectral fluxes

Positive spectral flux corresponds to energy transfer from large to small scales, and vice versa [1]. The kinetic energy flux, shown in Fig. 2, is negative and roughly flat between 4,000-15,000 km length scales, suggesting an inertial range with inverse cascade of power $\Pi^{\mathrm{up}}_{\mathrm{E,tot}} \approx (-5 \pm 2) \times 10^{-5}\,\mathrm{W\,kg^{-1}}$ from small scales to the jet scale. At scales $\leq 2000\,\mathrm{km}$, the positive spectral flux corroborates our finding of downscale energy transfer at small scales in the structure functions, with $\Pi^{\mathrm{down}}_{\mathrm{E,tot}} \approx (+1.5{\pm}0.3){\times}10^{-5}\,\mathrm{W\,kg^{-1}}$.

There is a convergence of kinetic energy at the jet scale. This comes from larger scales (up to around 40,000 km) down to the jet scale and from smaller scales (down to around 2,500 km) up to the jet scale. All datasets show that the primary eddy to zonal flow energy conversion occurs at or near the jet scale. There is also remarkable agreement on the length scale at which the switch from upscale to downscale flux occurs. The agreement between this and a typical deformation radius in midlatitudes is striking.

5. Summary and Conclusions

The picture that emerges is a turbulent atmosphere energised by processes that generate kinetic energy around the deformation scale, which then diverges upscale to the jet scale and downscale to small scales. This suggests an important role is played by baroclinic instability. The reversal of the energy cascade around the deformation scale suggests dynamical processes more like those in the Earth's oceans than in its atmosphere. However, the flat part of the kinetic energy spectrum is quite non-terrestrial, and so Jupiter's turbulence may not represent a 'classical' inertial range.

Acknowledgements

Support for RMBY was provided by UK STFC Grant ST/K00106X/1. This work was supported in part by the US National Science Foundation under Grant No. NSF PHY11-25915.

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