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# The Ubiquitous Zonal Jets in the Atmospheres of Giant Planets and Earth's Oceans

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# The ubiquitous zonal jets in the atmospheres of giant planets and Earth's oceans

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[1] Recent eddy-permitting simulations of the North Pacific Ocean have revealed robust patterns of multiple zonal jets that visually resemble the zonal jets on giant planets. We argue that this resemblance is more than just visual because the energy spectrum of the oceanic jets obeys a power law that fits spectra of zonal flows on the outer planets. Remarkably, even the non-dimensional proportionality coefficient, $C_Z$, determined by data under that spectral law, appears to be constant for all cases and approximately equal to 0.5. These results indicate that the multiple jet sets in the ocean and in the atmospheres of giant planets are governed by the same dynamics characterized by an anisotropic inverse energy cascade, i.e., the flow of energy from isotropic small-scale eddies to anisotropic large-scales structures, as well as the unique anisotropic spectrum. Implications of these results for climate research and future designs of observational missions are discussed. *INDEX TERMS:* 3379 Meteorology and Atmospheric Dynamics: Turbulence; 4528 Oceanography: Physical: Fronts and jets; 3346 Meteorology and Atmospheric Dynamics: Planetary meteorology (5445, 5739); 5707 Planetology: Fluid Planets: Atmospheres—structure and dynamics. **Citation:** Galperin, B., H. Nakano, H.-P. Huang, and S. Sukoriansky (2004), The ubiquitous zonal jets in the atmospheres of giant planets and Earth's oceans, *Geophys. Res. Lett.*, *31*, L13303, doi:10.1029/2004GL019691.

## 1. The Ocean-Jupiter Connection

[2] The pronounced banded structure of Jupiter's disk has long been a subject of fascination and intensive research. The visible bands are formed by clouds moving along a stable set of alternating zonal (east-west) jets [*Kondratyev and Hunt*, 1982; *de Pater and Lissauer*, 2001]. Similar banded structures exist in the atmospheres of Saturn, Uranus and Neptune. Previous studies, while differing in details, agree that the north-south gradient of the planetary vorticity, denoted as $\beta$, is essential for the existence of the multiple jets (here, $\beta = (2\Omega/R) \cos \phi$; $\Omega$, $R$ and $\phi$ are the planetary angular velocity, radius and latitude, respectively) [*Rhines*, 1975; *Williams*, 1978; *Vallis and Maltrud*, 1993; *Chekhlov et al.*, 1996; *Huang and Robinson*, 1998]. More recent research has revealed that their energy spectra follow a universal distribution [*Galperin et al.*, 2001; *Sukoriansky et al.*, 2002]. Numerical simulations using two-dimensional (2D), barotropic models also produce robust multiple jets in a certain range of parameters. The jets' width is proportional to the Rhines scale, $L_R = (2U/\beta)^{1/2}$, $U$ being a typical horizontal velocity. This picture has been modified by taking into account the role of forcing and friction in determining $U$ [*Galperin et al.*, 2001; *Sukoriansky et al.*, 2002]. Given that $U$ in the terrestrial oceans is only of the order of several cm s$^{-1}$, it can be conjectured that the multiple oceanic jets, if they exist, would have a small meridional scale of 1–2 degrees. The ocean-Jupiter connection was first hypothesized by *Williams* [1975]. Here, we shall explore this connection by comparing the energy spectra on giant planets and in the ocean.

## 2. Zonal Jets in the Ocean

[3] Paradoxically, we seem to know more about the zonal flows on giant planets than about the narrow jet systems in the Earth's oceans. Such a state of affairs stems from the fundamental difficulty to conduct basin-wide monitoring of ocean currents with high spatial and temporal resolution. Only recently, computers have become powerful enough to carry out simulations of the global ocean circulation with sufficient vertical and horizontal resolution to discern eddies and structures of the size of 1 degree. The processes on these scales are dominated by the baroclinic instability whose characteristic horizontal extent is measured by the first baroclinic Rossby radius of deformation, $L_d = NH/f$, where $N$ is the buoyancy frequency, $H$ is the characteristic vertical scale, and $f = 2\Omega \sin \phi$ is the Coriolis parameter [*Pedlosky*, 1987]; for the Earth's oceans, $L_d \simeq 50$ km. The combination of the eddy-permitting ocean modeling and cross-sectional measurements provides the most viable means so far to study relatively small-scale features of oceanic circulation and to explore the ocean-Jupiter connection.

[4] Figures 1a and 1b compare visual appearances of the planetary disk of Jupiter and of the mid-depth currents obtained in a recent eddy-permitting simulation of the Pacific Ocean by H. Nakano and H. Hasumi (A series of zonal jets embedded in the broad zonal flows in the Pacific obtained in eddy-permitting ocean general circulation models, submitted to Journal of Physical Oceanography, 2004, hereinafter referred to as Nakano and Hasumi, submitted manuscript, 2004) using a state-of-the-art ocean model driven by climatological forcing. The model's resolution is $\frac{1}{6}°$ by $\frac{1}{4}°$ in latitude and longitude, and 54 levels in the vertical. True to the above conjecture, robust multiple zonal jets emerge with about 2 degrees in width, covering the entire ocean basin. The multiple jets in the Pacific Ocean

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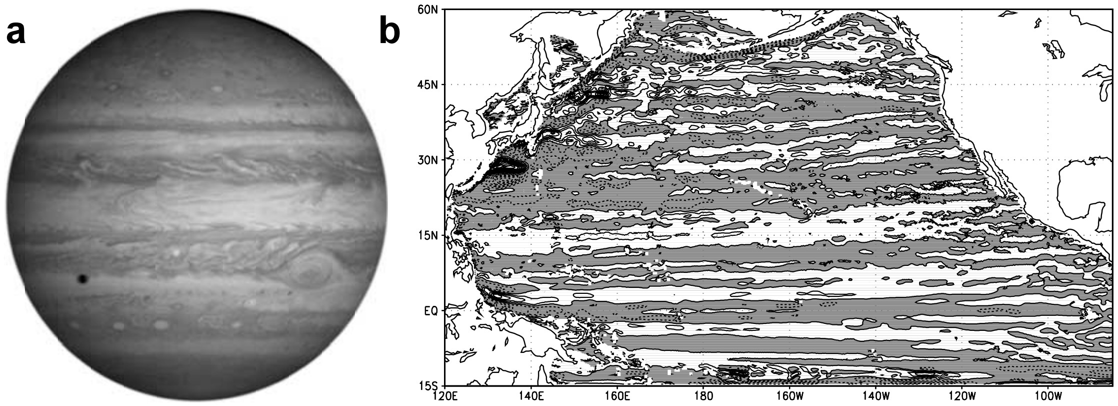

**Figure 1.** (a) Composite view of the banded structure of the disk of Jupiter taken by NASA's Cassini spacecraft on December 7, 2000 (image credit: NASA/JPL/University of Arizona); (b) zonal jets at 1000 m depth in the North Pacific Ocean averaged over the last five years of a 58-year long computer simulation. The initial flow field was reconstructed from the Levitus climatology; the flow evolution was driven by the ECMWF climatological forcing. Shaded and white areas are westward and eastward currents, respectively; the contour interval is 2 cm s$^{-1}$.

simulation extend to a considerable depth while maintaining their alternating pattern in an equivalent barotropic fashion, i.e., eastward currents remain eastward for all depth, but with some change in the amplitude. Similar deep-ocean alternating jets are beginning to be identified in other eddy-permitting simulations [*Treguier et al.*, 2003]. In addition, alternating zonal jets have recently been observed along cross-sections of the North Pacific [*Roden*, 1998, 2000] indicating that the model simulated jets are real.

## 3. Anisotropic Turbulence and Spectra

[5] The visual resemblance of Figures 1a and 1b is striking. But are these ocean jets the same phenomenon as the multiple jets on giant planets? To answer this question, one needs to determine what physical processes govern the large-scale dynamics in both systems. The first important common dynamical characteristic of both systems is their quasi-two-dimensionality stemming from the large disparity between the horizontal and vertical scales of circulation, possible effects of stable vertical stratification and fast rotation, etc. If such systems are excited on relatively small scales, they develop an inverse energy cascade. The second important common characteristic is strong vertically stable stratification for large-scale structures. Combined with the equator-to-pole density differences, it results in baroclinic instability, i.e., energy release in the form of the eddies of the horizontal extent of the order of $L_d$ [*Pedlosky*, 1987]. When the Burger number, $Bu = (L_d/R)^2$, is small, there exists a range of scales between $L_d$ and $R$ on which the behavior of the flow is approximately barotropic, i.e., independent of horizontal density gradients [*Salmon*, 1998; *Rhines*, 1979]. As estimated by *Menou et al.* [2003], $Bu \ll 1$ for all giant planets of the solar system. For terrestrial oceans, $Bu \simeq 6 \times 10^{-5}$. Therefore, one may expect that the dynamics of the large-scale circulation on all these planetary bodies is not only quasi-2D but also is close to barotropic. Indeed, the simulated multiple jets in the Pacific Ocean develop barotropic signature while space observations indicate that the zonal winds on Jupiter contain substantial barotropic component [*Garcýa-Melendo and Sánchez-Lavega*, 2001].

[6] There also exists a similarity between the forcing agents for the planetary and oceanic circulations. In the ocean, the small-scale eddies produced by baroclinic instability can initiate the energy cascade to larger scales. On the giant planets, where the north-south temperature (or density) gradient may be smaller due to a weaker differential solar heating, the small-scale eddies may be produced by a combination of thermal convection [*Gierasch et al.*, 2000; *Ingersoll et al.*, 2000] and other mechanisms, among them baroclinic and barotropic instabilities. Thus, the salient features of the large-scale circulations of the terrestrial oceans and giant planets can be amenable to a simulation by a barotropic model with a random small-scale forcing. Numerical simulations of small-scale forced, barotropic two-dimensional flows on the surface of a rotating sphere were performed by *Nozawa and Yoden* [1997], *Huang et al.* [2001] and *Sukoriansky et al.* [2002] where it was shown that the large-scale flows acquire considerable anisotropy culminating in the formation of a zonal band structure. In addition, the two latter papers demonstrated that these flows develop a unique, anisotropic spectrum. Recall that the energy spectrum in spherical geometry is defined as $E(n) = \frac{n(n+1)}{4R^2} \sum_{m=-n}^{n} \langle |\psi_n^m|^2 \rangle$, where $n$ and $m$ are the total and the zonal wave numbers in the spherical geometry; $\psi_n^m$ is the spectral coefficient of the spherical harmonic $Y_n^m$ for the stream function, and the brackets indicate an ensemble or time average. To reflect the spectral anisotropy, introduce zonal and residual spectra according to $E(n) = E_Z(n) + E_R(n)$, where the former corresponds to the addend with $m = 0$ [*Sukoriansky et al.*, 2002]. The simulations by [*Huang et al.*, 2001] and [*Sukoriansky et al.*, 2002] have revealed that the zonal spectrum develops a steep distribution

$$E_Z(n) = C_Z (\Omega/R)^2 n^{-5}, \tag{1}$$

where $\Omega/R$ represents $\beta$ and $C_Z$ is an $O(1)$ non-dimensional constant. The $-5$ slope in equation (1) extends from some small scales, at which spectral anisotropy commences, to the large scales, $n \sim n_{fr}$, where large-scale damping occurs. At the largest scales, $n < n_{fr}$, the energy spectrum of zonal flow is nearly flat. It has been demonstrated that the spectra of the observed zonal flows on Jupiter, Saturn, Uranus and

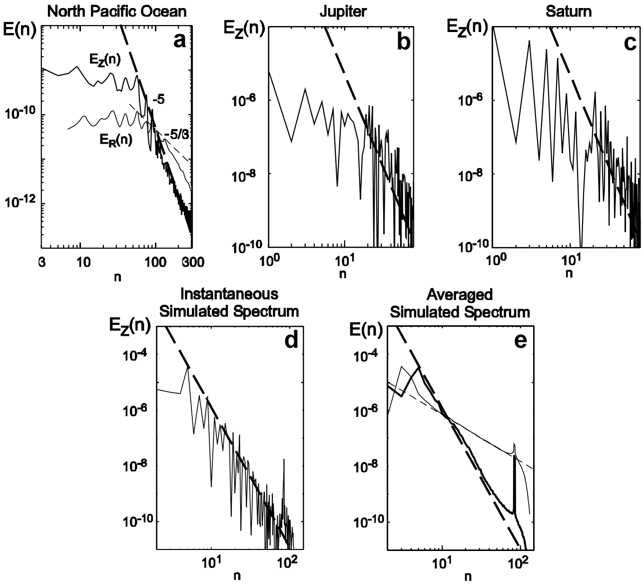

**Figure 2.** Averaged and instantaneous zonal (thick solid lines) and non-zonal (thin solid lines) energy spectra on rotating planets with small *Bu* (top row) and in barotropic 2D simulations on a rotating sphere [*Sukoriansky et al.*, 2002] (bottom row); the high wave number spikes on the latter correspond to the small-scale forcing. All spectra are non-dimensionalized such that $E_Z(1) = C_Z$. Idealized $-5$ (thick dashed lines) and $-5/3$ (thin dashed lines) slopes are superimposed, based upon equations (1) and (2).

Neptune follow a spectral law (equation (1)) with $C_Z \simeq 0.5$ [*Galperin et al.*, 2001; *Sukoriansky et al.*, 2002].

[7] The simulated residual spectrum develops a $-5/3$ slope similar to the classical energy spectrum in non-rotating 2D turbulence,

$$E_R(n) = C_K \epsilon^{2/3} n^{-5/3}, \qquad (2)$$

where $\epsilon$ is the small-scale energy injection rate and $C_K \simeq 6$. The question whether or not $C_K$ preserves its value in quasi-2D flows in three-dimensional (3D) geometries is still open. The steeper spectral slope for the zonal jets is consistent with the notion that the zonal flow is stabilized by $\beta$ [*Huang et al.*, 2001]. The contrasting $-5$ and $-5/3$ slopes point to strong anisotropy favoring the zonal direction; the large-scale zonal flow gains its energy from smaller-scale turbulent modes via anisotropic upscale energy transfer, as verified in numerical and theoretical studies [*Chekhlov et al.*, 1996].

[8] With this background, in order to answer the question of whether or not the ocean jets are the same phenomenon as the multiple jets on giant planets, one needs to find out whether or not the ocean currents follow the spectral distributions (1) and (2). If the answer is yes, the values of $C_Z$ and $C_K$ can be used as a measure of the universality of the spectral regimes.

## 4. Anisotropic Spectra in the North Pacific

[9] To perform the spectral analysis, we used numerical data from an eddy-permitting ocean simulation by (Nakano and Hasumi, submitted manuscript, 2004). A 60-degree wide longitudinal sector of the Pacific basin in the Northern Hemisphere was carved out of the computational domain and repeated 12 fold (6 fold in the Northern Hemisphere, mirror image in the Southern Hemisphere) to form a global field. The velocities at the latitudes higher than 60°N or S were exponentially tapered to zero. The calculated spectrum was averaged over the last 5 years of a 58-year long integration starting from the Levitus climatology. The imposed symmetry with respect to the equator renders meaningful only the modes with odd *n*; only those modes are shown in the calculated zonal spectrum $E_Z(n)$. Also, as the simulated jets exhibit an equivalent barotropic structure, the analysis is based on the vertical average from the surface to 500 m depth. The averaged zonal and non-zonal oceanic spectra are presented in Figure 2a. A $-5$ slope is immediately evident for the zonal flows. Similarly to the case of giant planets (Figures 2b and 2c), this slope extends upward to the dominant scale of the zonal jets yet for smaller *n* the spectrum becomes flat. The universality of $E_Z(n)$ is supported not only by the $-5$ slope, but also by the constancy of $C_Z \simeq 0.5$ for all cases. The energy spectrum for the non-zonal components, $E_R(n)$, exhibits a slope close to $-5/3$ over the range $n = 60 - 120$. The departure of $E_R(n)$ from the $-5/3$ slope for $n > 120$ could be attributed to various factors, such as the interaction between barotropic and baroclinic modes, the effect of direct forcing, damping by the bottom topography, etc. Currently, the resolution of the data and the surface coverage are insufficient to determine $E_R(n)$ for the flows on outer planets. Let us emphasize that both zonal and residual spectra of the horizontal currents have been obtained here from fully 3D, realistic simulations of the circulation in the north Pacific rather than from idealized barotropic 2D simulations used so far in theoretical studies.

[10] For comparison, $E_Z(n)$ and $E_R(n)$ obtained from a model of 2D flow on a rotating sphere [*Sukoriansky et al.*, 2002] are shown in Figure 2e. These spectra are averaged over the equivalent of about 300 years. As could be expected, longer averaging produces smoother spectra. The observed zonal spectra for Jupiter and Saturn (Figures 2b and 2c) are, in fact, instantaneous spectra since the characteristic time for the large-scale variability on these planets, obtained by simple energy balance arguments [*Galperin et al.*, 2001], is larger than the time of observations. Recent long-term observations of the Jupiter jets [*Garcýa-Melendo and Sánchez-Lavega*, 2001] and the new data from the Cassini spacecraft [*Porco et al.*, 2003] confirm low variability of the off-equatorial jets' main features. Note that the equatorial jets on the gas giants may be governed by different mechanisms (e.g., deep rotating convection) [*Busse*, 1983; *Aurnou and Olson*, 2001; *Yano et al.*, 2003] and their variability may be higher [*Sánchez-Lavega et al.*, 2003; *Flasar et al.*, 2004]. Finally, Figure 2d shows a typical instantaneous zonal spectrum from the 2D simulation. Large fluctuations are characteristic of all instantaneous spectra. Instantaneous spectra (not shown here) in the ocean also exhibit fluctuations of a similar magnitude.

[11] The universal energy spectra of the zonal flows in terrestrial ocean and planetary atmospheres suggest that the jets are maintained by the momentum flux from the eddies

of smaller scales. (In physical space, the convergence of eddy momentum flux balances the large-scale damping of the jets.) A rigorous confirmation of the presence of the inverse energy cascade requires consideration of the scale-by-scale budget of zonal kinetic energy [*Huang and Robinson*, 1998] which is beyond the scope of this Letter. A possibility of the anisotropic inverse energy cascade in 3D flows with a topographic $\beta$-effect has recently been demonstrated experimentally [*Read et al.*, 2004]. In the ocean, since the scale of the jets is about 1–2 degrees, the relevant scale for the eddies is even smaller. This explains why robust multiple zonal jets could not be simulated by previous generations of ocean models, as they were unable to resolve the eddies. With the same $R$, the $L_d$ for terrestrial atmosphere is about 1000 km, consistent with the fact that Jupiter-like multiple jets do not form in the Earth's atmosphere.

## 5. Discussion

[12] Being based upon realistic 3D simulations of circulation in the north Pacific, this paper presents the first hard evidence that the theoretical spectral distributions (1) and (2), as well as the underlying flow regime are indeed common in Nature.

[13] The findings here have many implications for climate research and for future planning of observational missions. The ocean models that have been used for simulating Earth's climate under global warming, as reported in the recent Intergovernmental Panels for Climate Change report [e.g., *Houghton et al.*, 2001], did not possess a fine enough resolution to produce the multiple jets. However, we expect oceanic multiple jets to emerge in future climate simulations using eddy-permitting ocean models. Since these jets are the strongest currents in the mid-depth ocean, it will be an immediate challenge to understand the impact of the jets on the transport properties of the ocean that are crucial for determining the climate of the coupled ocean-atmosphere system. To assist in this endeavor, matching observational efforts are required to verify the model simulated multiple jets and their dynamics. While the existing observations of deep ocean currents in North Pacific [*Roden*, 1998, 2000] are consistent with our model results, a comprehensive basin-wide observation program is still lacking. On the planetary front, although observations of large-scale circulations on giant planets have been made over the last several decades using various spacecraft missions and the Hubble Space Telescope, the energy spectra and energy transfer properties pertaining to the zonal jets have not been often emphasized in the data analyses. One of the key quantities that are yet to be determined observationally is the non-zonal spectrum $E_R(n)$ and the corresponding constant $C_K$. It will be extremely useful if they can be determined observationally from future missions to the outer planets and to the deep oceans of the Earth. The forthcoming Cassini observations of the Saturn atmosphere may present the first opportunity to measure a non-zonal spectrum on an outer planet.

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