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ANISOTROPIC LARGE-SCALE TURBULENCE ON GIANT PLANETS AND IN THE OCEAN

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Summary Barotropic two-dimensional turbulence with Rossby waves is distinguished by strong anisotropy and energetic zonal jets in alternating directions. Flows on the β-plane and in thin shells on the surface of a rotating sphere develop strongly anisotropic spectrum with steep, n^{-5}, slope for the zonal flows and Kolmogorov-Kraichnan, $n^{-5/3}$, slope for the residuals. The n^{-5} zonal spectrum was found on all four giant planets of our solar system, both with regard to its slope and the amplitude. This spectrum can be used to analyze some basic characteristics of large-scale circulations on giant planets and for interplanetary comparisons. Recently, it was found that the mid-depth ocean currents in the North Pacific ocean also develop a system of alternating zonal jets and build up the same n^{-5} and $n^{-5/3}$ zonal and residual spectral distributions. The main characteristic of the planetary and oceanic flows under consideration is the smallness of their Burger number, $Bu = (L_d/R)^2$, where L_d is the first baroclinic Rossby radius of deformation and R is the planetary radius. Exploring the planetary-ocean analogy, we conclude that the fine-scale oceanic zonal jets are driven by strongly nonlinear, anisotropic dynamics of quasi-2D turbulence with Rossby waves and argue that the latitudinal scaling of these jets is determined by the large-scale friction processes.

ANISOTROPIC TURBULENCE ON GIANT PLANETS

Our previous simulations of barotropic two-dimensional (2D) turbulence on β-plane [1] and on the surface of a rotating sphere [2] have indicated that such flows give rise to strongly anisotropic spectra. In spherical geometry, with R being the radius of the sphere, Ω being its angular velocity, and n and m being the total and the meridional wave numbers, respectively, the following zonal ($E_Z(n)$) and residual ($E_R(n)$ spectral distributions are established:

$$\begin{aligned} E_Z(n) &= C_Z(\Omega/R)^2 n^{-5}, \quad m=0, \;\; n/n_\beta < 1, && (1)\\ E_R(n) &= C_K \epsilon^{2/3} n^{-5/3}, \quad \forall m \neq 0, && (2)\end{aligned}$$

where $C_K \approx 6$ is the Kolmogorov-Kraichnan constant, $C_Z \simeq 0.5$, ϵ is the rate of the small-scale energy input, and $n_\beta = [(\Omega/R)^3/\epsilon]^{1/5}$ is the transitional wave number associated with the crossover between the spectra (1) and (2). The same spectral distributions were observed in steady-state simulations with a linear large-scale drag [3]. The latter paper also provides a detailed analysis of various interrelationships between the zonal and residual spectra.

The development of the flow regime with the spectra (1) and (2) is stipulated by fulfilling the requirement $n_{fr}/n_\beta \ll 1$, where n_{fr} is the wave number associated with the large-scale friction. This requirement is difficult to satisfy in the laboratory conditions and in the Earth atmosphere where friction with the underlying surface is high. However, the atmospheres of the giant planets may provide natural laboratories that can sustain such flows. Since the gas giants don't have solid boundaries, their friction and, therefore, n_{fr} are low. The requirement of the quasi-two-dimensionality is naturally fulfilled for the giant planets' atmospheres as the vertical thickness of the weather layers is much smaller than their horizontal extent. Another crucial requirement pertains to the value of the Burger number, $Bu = (L_d/R)^2$, where L_d is the first baroclinic Rossby deformation radius. It is well known that flows with $Bu \ll 1$ exhibit tendency to barotropization [4] and are, thus, likely to develop the spectral regime (1) and (2) if the criterion $n_{fr}/n_\beta \ll 1$ is also fulfilled. The existing data indicate that indeed, $Bu \ll 1$ for all four solar giant planets [5].

Using zonal velocity profiles obtained from the space stations Voyager 1 and 2 as well as from the Hubble Space Telescope, we have calculated the zonal spectra for all four solar giant planets in spherical representation; they are shown in Fig. 1. One can see a good agreement between the theoretical, Eq. (1), and observed zonal spectra for all four giant planets both with respect to the spectral slope and the amplitude (note that the data for Uranus is insufficient to establish the spectral slope but can be used to test the agreement in the amplitude).

One can observe that the slope -5 extends to some wave number which can be associated with n_{fr} and remains approximately level for $n < n_{fr}$. This zonal spectrum distribution allows one to analyze some large-scale characteristics of the atmospheric circulation on giant planets. By integrating Eq. (1) from 0 to ∞, obtain the total kinetic energy of the circulation,

$$E_{\rm tot} = (5C_Z/4)(\Omega/R)^2 n_{fr}^{-4}. \tag{3}$$

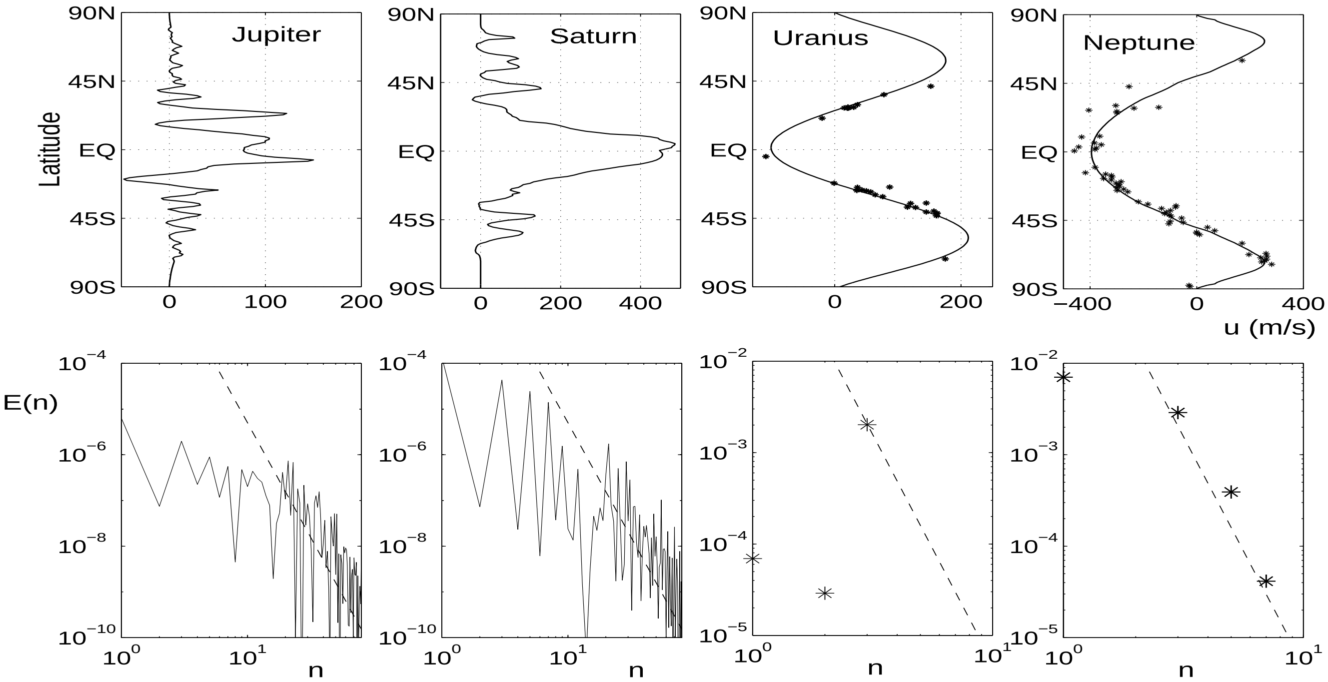

Figure 1. Top row: observed zonal profiles deduced from the motion of the cloud layers [6, 7, 8, 9]; bottom row: observed zonal spectra (solid lines and asterisks) and theoretical zonal spectra Eq. (1) (dashed lines) on the giant planets [all spectra are normalized with their respective values of $(\Omega/R)^2$].

Equation (3) indicates that $E_{\rm tot}$ depends on R, Ω and n_{fr} only and does not depend on the rate of the energy injection ϵ. Being the only flow-dependent parameter in (3), the frictional wave number n_{fr} plays a paramount role in the global energetics.

ANISOTROPIC TURBULENCE IN THE OCEAN

In recent simulations with high resolution, eddy-permitting ocean general circulation model it was found that the mid-depth ocean currents in the north Pacific ocean also develop a system of alternating zonal jets and obey the zonal and residual spectral distributions (1) and (2). Since the Burger number in the ocean is small, one can infer that the planetary and sub-surface terrestrial ocean jets are generated and maintained by the same mechanism pertaining to quasi-2D turbulence with anisotropic inverse energy cascade. The connection between the planetary and terrestrial circulations sheds some new light on the basic properties of stability and variability of the large-scale flows in both systems.

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