On a Turbulent Energy Transfer Scale in Ocean Turbulence

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The budget of mechanical energy that goes into ocean circulation at large scales is not well understood. This is due to the contrasting nature of turbulence at large scales–rotating and stably stratified balanced turbulence wherein energy cascades to larger scales–and that at smaller scales–unbalanced turbulence wherein energy cascades to smaller scales. In this research program, we systematically investigate the interaction of turbulence across these asymptotic large-scale and small-scale regimes to better constrain the energy budget. The finding we highlight here is related to the extant phenomenological picture of large-scale turbulence, one aspect of which is that the turbulent cascade of kinetic energy into the gravest vertical mode occurs at a characteristic fixed scale, after which that energy cascades up to larger horizontal scales. In contrast, we find that in oceanographically relevant settings, this turbulent energy transfer scale is variable and scales well with the scale of large-scale energy dissipation.

As much as 90% of the energy that goes into the ocean is dissipated in the top 100 meters. The remaining 10%–that is mainly input on the large scales–drives the interior ocean circulation, a crucial component of the climate system [1]. Consequently, an understanding of the energy budget of the latter component is important from the climate perspective.

In one study of this research program, to better understand the energy budget, we conducted numerical simulations of a prototypical wind-driven ocean circulation problem that spans the oceanographically relevant range of values for a number of parameters (Rossby deformation radius that measures stratification, amplitude of wind-stress, and the coefficient of large-scale dissipation) [2]. A robust feature of all of these simulations is the correspondence in scale between that at which turbulent energy is injected into the gravest vertical mode and that from which energy is removed from this vertical mode by bottom drag. A surprisingly good linear relation, with a slope near unity, is evident (Fig. 1).

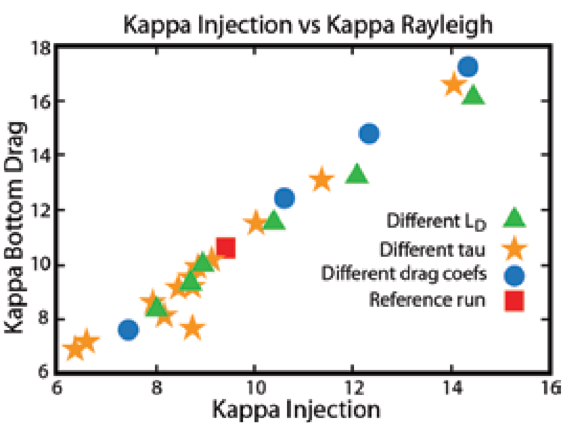

Fig. 1. A plot of the scale at which energy is dissipated at large scales (Kappa Bottom Drag) against the scale at which turbulent energy is injected into the gravest vertical mode (Kappa Injection) in a series of oceanographic, rotating, stably stratified turbulence simulations.

Figure 2 [1] is a schematic of the presently accepted view of large-scale turbulence. According to this picture, energy is injected into the gravest vertical mode at a fixed scale related to the deformation radius (R_d) which then cascades to larger horizontal scales before being dissipated by bottom friction, at a scale commonly referred to as the Rhines scale. However, because the turbulent injection of energy (into the gravest vertical mode) in our study occurs at wavenumbers close to those where bottom drag removes it, a net inverse energy cascade is not needed to balance the energy budget in that mode. Nevertheless, an inverse cascade of energy is seen in these simulations. Then, the inverse cascade should be viewed not as transferring energy from a Rossby radius-like scale to a Rhines-like scale, but rather as part of a new double cascade that we consistently observe (not shown). That is, the inverse cascade is part of a self-organized local recycling of energy in scale space and does not serve the purpose of moving energy from an injection scale to a dissipation scale as proposed by the accepted phenomenology of geostrophic turbulence (Fig. 2).

We find that the local recycling of energy in scale space referred to above is usually associated with the self-organization of turbulence into coherent structures. In a number of cases, by combining the above results with some of our other studies [3,4], we are able to show that the coherent structures associated with the local recycling of energy in scale space take the form of alternating zonal jets. In Fig. 3 we analyze satellite altimetry over a recent two-year period that makes evident the presence of such alternating jets in the world oceans. That the location of alternating zonal jets is poorly correlated to the hotspots of turbulent kinetic energy (Fig. 4) is consistent with their origin being related to the self-organization of turbulence.

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Funding Acknowledgments
LANL, Laboratory Directed Research and Development Program

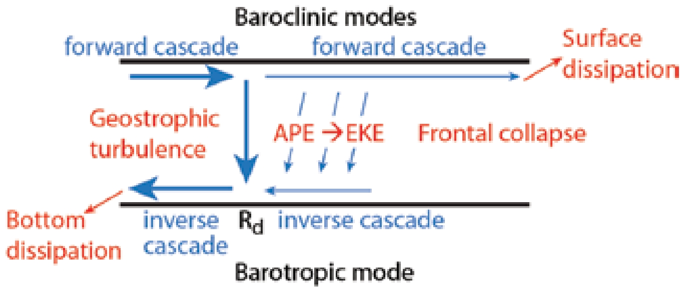

Fig 2. Presently accepted phenomenology of rotating stably stratified turbulence. Barotropic mode refers to the gravest vertical mode; baroclinic modes refer to other vertical modes. According to this picture, turbulent energy is injected into the gravest vertical mode at a fixed scale related to the Rossby deformation radius (R_d), which then cascades to larger horizontal scales before being dissipated by bottom friction [1].

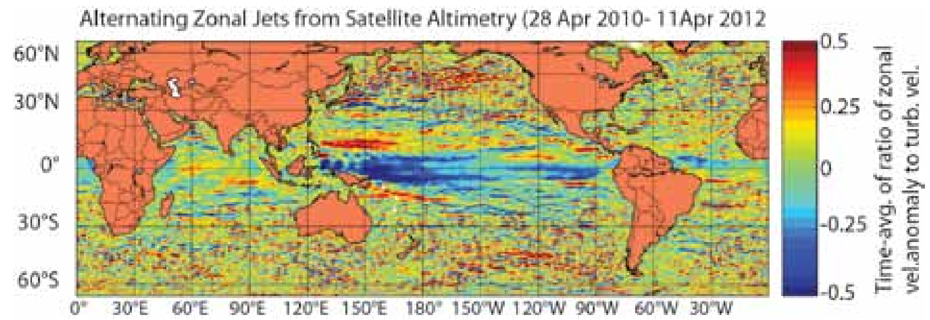

Fig. 3. A two-year average of the ratio of zonal velocity anomaly to turbulent velocity using satellite altimetry (integrated multi-mission ocean altimeter data for climate research and AVISO datasets).

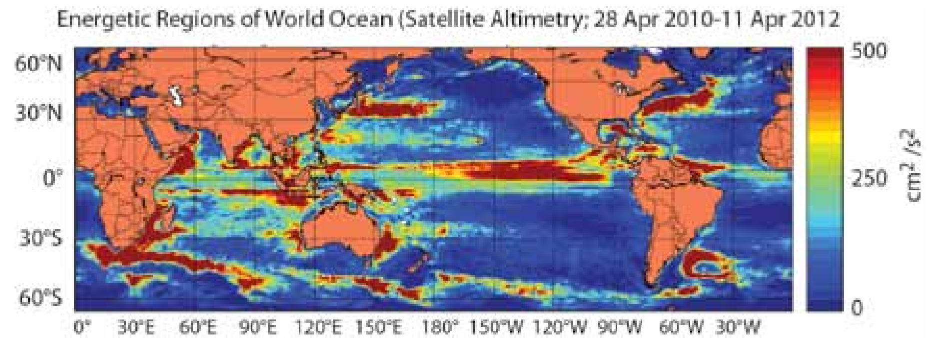

Fig. 4. A spatial map of turbulent kinetic energy for the same period.

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