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Suppression of the Rhines effect on surface-intensified geostrophic turbulence on a beta-plane by strong horizontal divergence

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Large scale motion in the ocean shows a behavior similar to two-dimensional turbulence due to earth's rotation. However, there are various geophysical factors those may affect on the large scale oceanic motion, e.g. meridional change of the Coriolis parameter and stratification. Especially the meridional change of the Coriolis parameter leads to a wave motion called the Rossby wave. Thus the large scale motion in the ocean may be more complex than ordinary two-dimensional turbulence so that it is called geostrophic turbulence.

Among those geophysical factors, the effect of stratification, or horizontal divergence is investigated numerically, on almost freely decaying geostrophic turbulence on a beta-plane. In the doubly-periodic square domain of the model ocean, the surface layer is assumed to be active above the quiet deep layer to model the surface intensified state observed in the real ocean. Hence the barotropification is prohibited a priori to purify the effect of horizontal divergence. In other words, the Charney-Hasegawa-Mima equation is adopted as the governing equation. To avoid the retarding effect on spectral evolution due to the horizontal divergence, the kinetic energy in the system is kept constant through each experiment.

The effect of horizontal divergence is measured by a non-dimensional number UF/beta, where U is the characteristic velocity of turbulence, F the squared inverse of the deformation radius, and beta the constant meridional gradient of the Coriolis parameter. This non-dimensional number represents the ratio of characteristic velocity to the phase speed of long baroclinic Rossby waves, or a criterion of breaking of long baroclinic Rossby waves. Another interpretation for UF/beta is the squared ratio of the barotropic Rhines scale to the deformation radius.

First, numerical experiment is carried out for small or moderate horizontal divergence as control runs for comparison, i.e. UF/beta is smaller than O(1). As has been reported repeatedly, the beta-effect induces a highly anisotropic field characterized by meridionally alternating bands of zonal currents. This phenomenon is known as the Rhines effect. It is confirmed also that the one-dimensional wavenumber spectrum of kinetic energy has the slope of -5 at high wavenumbers. A moderate value of UF/beta slightly increases the preferred meridional scale of the zonal currents.

Then, horizontal divergence is enlarged enough so that UF/beta is sufficiently larger than 1, for which geostrophic turbulence turns out to behave just as on an f-plane: (1) the field becomes isotropic, and no significant zonal current appears; (2) the inverse cascade of energy is not hindered by the beta-effect though it takes a longer time for turbulence to transfer energy to longer scales than a small divergence case; and (3) the one-dimensional spectrum of kinetic energy (not total energy) has the -3 slope at high wavenumbers. In other words, the Rhines effect or the beta-effect is suppressed by strong horizontal divergence.

An argument based on the physics of long baroclinic Rossby waves is presented to explain why strong horizontal divergence suppresses the beta-effect. Furthermore a transform of variables leads to a modified governing equation, which clearly shows that the beta-effect should disappear for large horizontal divergence. To examine the validity of this argument, additional experiments were carried out based on three different forms of governing equations: (1) the ordinary CHM equation on a beta-plane; (2) the modified CHM equation after the transform of variables mentioned above; and (3) the same as (2) but with beta omitted. When horizontal divergence is strong, the resulting spectra turned out to be the same effectively, indicating the total suppression of the beta-effect by strong horizontal divergence.