論文の内容の要旨

Spatial heterogeneity of eddy-mean flow interactions in the Antarctic Circumpolar Current

（南極周極流における渦・平均流相互作用の空間非一様性）

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The Antarctic Circumpolar Current (ACC) region is believed to play a central role in the global ocean circulation that affects the Earth's climate and material circulations. For better understanding of these circulations in the ACC region, detailed knowledges on the ACC dynamics are imperative. Several observational studies have shown that the isopycnal slope associated with the ACC, hence the magnitude of the ACC, is insensitive to the changes in the winds over the region. This interesting aspect, known as the eddy compensation and eddy saturation, has been suggested to be associated with eddy-mean flow interactions in the ACC region. The eddy compensation and the eddy saturation have been studied mainly by idealized models with zonally uniform assumptions. However, satellite observations show that there is significant inhomogeneity in surface eddy kinetic energy (EKE) in the ACC region, with large EKE in regions called as "the hotspots". However, spatial heterogeneity of the eddy-mean flow interactions that generate the EKE distribution has not been investigated quantitatively in realistic conditions. Although idealized channel models suggest the unrealistic downstream development of the hotspots, this problem has been overlooked in previous studies and mechanisms generating the realistic zonal extent of the hotspots are still in a veil. Therefore, we investigate detailed characteristics of spatial heterogeneity of the eddy-mean flow interactions with the regional Lorenz energy cycle concept. Then, initiation and termination mechanisms of the hotspots are explored from energetic viewpoint. In this study, we utilize results from an eddy-resolving Ocean General Circulation Model (OGCM), named OGCM for the Earth Simulator (OFES), in which many characteristics of the ACC, including a length scale of the hotspots, are well reproduced.

First, the eddy-mean flow interactions are estimated quantitatively based on the Lorenz energy cycle concept. It is confirmed that the classical Lorenz energy cycle includes non-negligible errors in the ACC region due to the large density fluctuation from the global reference state, which results in the underestimation of the baroclinic energy conversion rate. It turns out that the modified Lorenz energy cycle that takes into account the finite density fluctuation is more appropriate in the ACC region. An analysis based on this modified Lorenz energy cycle shows that five major hotspots are responsible for more than 70% of the EKE generation and dissipation over the ACC region. The energy conversion is dominated by the baroclinic pathway in the four hotspots, while the mixed barotropic and baroclinic instability is important in the region near the Campbell Plateau. We also calculate the work done by the Ekman transport and the horizontal pressure work as a proxy of the available potential energy gain from the westerlies. The advantage of this quantity against the vertical mean density flux is that it is independent from the reference states defined arbitrarily. It is shown that the westerlies can supply sufficient energy locally to initiate the baroclinic instability in the Indian and Pacific sectors of the ACC, whereas the non-local process is important in the Atlantic sector. These results indicate that the mechanisms responsible for the eddy-mean flow interactions are different among five hotspots. We thus need to consider each hotspot one by one to reveal the mechanisms of eddy-mean flow interactions in more detail and their responses to the external forcing, instead of integrating values over the whole ACC as in the previous studies.

In order to investigate the mechanisms for determining the horizonal scale of the hotspots, we conduct the heat budget and EKE budget analyses. The heat budget for the hotspots demonstrates that the heat flux caused by the transient eddies counterbalances to the heat flux due to the standing meanders. The heat flux due to the standing meanders converges in the northern part of the ACC but diverges in the southern part, resulting in the enhancement of the meridional density gradient. This forms a favorable condition for the baroclinic instability. The zonal distribution of the EKE is related to that of the standing heat flux well, suggesting that the meridional temperature gradient associated with this standing heat flux directly controls the initiation and termination of the hotspots. To reveal the mechanisms responsible for the initiation and termination of the hotspots, each component of the EKE equation for each hotspot is evaluated. The OFES results demonstrate that a large part of the EKE, generated through the baroclinic energy conversion, is balanced by the diabatic dissipation at their generation sites. The remaining part of the EKE is radiated by the advection and pressure fluxes from the upstream side in the hotspots to the downstream side, where it converges. Although the pressure flux convergence plays a secondary role in the horizontal transport of the EKE, it plays a central role in the local EKE sink. It is shown that the vertical pressure flux transports the EKE downward from the depth of eddy energy production above the main thermocline towards the ocean bottom. The EKE converged near the bottom is dissipated due to the diabatic process, indicating that the vertical redistribution of the EKE is the key process for a rather limited zonal extent, i.e. the “downstream decay”, of the hotspots. These results show large contrast to the previous studies based on idealized channel models for the ACC, which suggest that the EKE radiation through the horizontal pressure flux sustains the relatively large EKE even in further downstream of the eddy growth region. Therefore, it is concluded that the baroclinicity associated with the major standing meanders in the ACC region directly controls the initiation and termination of the hotspots through the vertical redistribution of the eddy energy. This process also determines the zonal width of the hotspots as well as the magnitude of eddy-mean flow interactions within the hotspots, hence governing most of the eddy-mean flow interactions within the whole ACC region.