論文の内容の要旨

Mechanisms for the distinctive seasonality of the North Pacific transient eddy activity as revealed from comprehensive analysis with the Eulerian statistics and Lagrangian tracking method

（北太平洋に特徴的な移動性擾乱活動の季節進行のメカニズムに関するオイラー的統計とラグランジュ的トラッキング手法による包括的な解析）

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Extratropical transient eddies including migratory cyclones and anticyclones play an important role in our life, as they cause day-to-day weather phenomena. Extratropical cyclones, if intensified, give rise to many natural disasters, which potentially have massive socioeconomic impacts. Over decades, midlatitude stormtracks, where cyclone activity is particularly high, have been intensively investigated. Specifically, Eulerian statistics have enabled us to conduct quantitative diagnosis and analysis especially of eddy/mean-flow interactions, and objective Lagrangian tracking has revealed characteristics of cyclones and anticyclones separately. Although the Eulerian statistics and Lagrangian tracking are by nature intrinsically complementary, they have been applied separately in the previous studies or, at most, conducted just in parallel. Our understandings of extratropical stormtracks are thus still limited. As a typical example, stormtrack activity over the North Pacific exhibits a minimum in midwinter, since the westerly jet speed over the North Pacific clearly maximizes in midwinter. This counterintuitive phenomenon, which is inconsistent with the baroclinic instability theory, has been referred to as “midwinter minimum” and intensively investigated from various viewpoints. However, the mechanisms for the midwinter minimum have still many to be uncovered, and it remains one of the remaining difficult issues on midlatitude atmospheric and climate dynamics.

In the present study, we show the detailed seasonal evolution of climatological-mean Eulerian statistics and energetics of migratory eddies along the North Pacific stormtrack, for comprehensive investigation of the mechanisms for the midwinter minimum. We calculate the efficiency of each of the eddy energy conversion/generation terms, which is independent of eddy amplitude for more straightforward analysis of the midwinter minimum. This study is the first to show that the net efficiency of eddy energy conversion/generation term is suppressed in midwinter mainly due to the baroclinic energy conversion via poleward eddy heat flux under reduced temperature fluctuations.

This study is also the first to develop a practical method to identify regions of cyclonic and anticyclonic vortices based on curvature vorticity, and to reconstruct Eulerian statistics from decomposed contributions from cyclonic and anticyclonic vortices. Westerly acceleration by cyclonic vortices is the strongest in midwinter and concentrated in the lower troposphere, acting to maintain the low-level eddy-driven jet and associated strong cyclonic shear on its northern flank. To the contrary, westerly acceleration by anticyclonic vortices is in deeper structure, acting to draw westerly momentum out of the merged climatological-mean jet in the upper troposphere. We then quantitatively investigate the energetics of migratory eddies along the North Pacific stormtrack from separated contributions from cyclonic and anticyclonic vortices. Total energy associated with anticyclonic vortices show more distinct midwinter suppression than its cyclonic counterpart. Consistently, midwinter suppression of efficiency of baroclinic energy conversion and its net efficiency are much clearer for anticyclonic vortices.

Surface cyclone density increases in midwinter and the region of high cyclone density extends southward in midwinter, while the latitude of maximum anticyclonic density migrates southward and anticyclonic density takes its minimum in midwinter over the North Pacific. The typical amplitude of cyclones is found slightly weaker in midwinter, whereas anticyclones tend to be maximized in midwinter. The cyclones are strongly deformed under the background cyclonic shear. In the upper troposphere, the cyclonic eddies tend to be deformed in the direction of NE-SW to the south of the westerly jet, which is consistent with the southward wave-activity flux. Precipitation is large behind the anticyclonic center and poleward eddy heat flux is large both ahead of and behind the anticyclone center, reflecting the more wave-like structure. Anticyclones tend to tilt northwestward strongly with height.

A method to define the shape of vertically tilted eddy vortices is developed for the first time by combining surface Lagrangian tracking and vortex identification with curvature. High probability of cyclonic domain is in a deep profile to the north of the jet axis and is maximized in midwinter. High probability of anticyclonic domains is in a shallower structure to the south of the jet axis, with a midwinter minimum. Anticyclonic eddies play a more important role in forming the midwinter minimum of total climatological-mean strongly reinforce the lower-tropospheric jet and the associated strong cyclonic shear on its northern flank, while anticyclones act to draw westerly momentum out of the climatological-mean merged jet and to expand the westerly jet poleward in the upper troposphere. Analysis of energetics shows anticyclones show their more distinct midwinter minimum in total energy. The efficiency of the net energy conversion/generation for anticyclonic eddies throughout the winter. “Typical” energy or efficiency is further calculated by dividing energy or efficiency by the probability of cyclones and anticyclones. Seasonal evolution of the total energy for cyclonic eddies shows a weak midwinter minimum, while its anticyclonic counterpart is clearly maximized in midwinter. The efficiency of baroclinic conversion for cyclonic eddies is slightly suppressed in midwinter and thus leads to a midwinter minimum of the efficiency of the net energy conversion/generation (referred to as “net efficiency”). Conversely, the efficiency of baroclinic conversion for anticyclonic eddies clearly exhibits a single peak in early winter, which is reflected in the net efficiency.

Furthermore, long-term modulation of the midwinter minimum of the North Pacific stormtrack activity are investigated. As pointed out by a previous study, the transition between 1985/86 and 1986/87 is striking, after which the midwinter minimum signal has become much less distinct in the Eulerian statistics. The midwinter suppression of the net efficiency is less prominent in the recent period. A relationship between westerly jet speed and Eulerian statistics suggests that the suppression of stormtrack activity under the stronger jet is substantially weaker in the recent period, especially for cyclones. The modulations of midwinter suppression in cyclonic and anticyclonic Eulerian statistics can be interpreted in the framework of energetics. In addition, the modulations of the midwinter minimum in the energetics as the total Eulerian statistics are found to be contributed to by both cyclones and anticyclones.

We have proposed a novel framework for studying stormtrack activity in which eddy-mean flow interaction is investigated by separating contributions from cyclones and anticyclones. It has the potential to renew our basic knowledge about the interaction based on Eulerian statistics widely, because the Eulerian statistics is widely used to investigate atmospheric and climate dynamics. In addition, we have proposed perspicuous clues for solving a difficult problem, namely the midwinter minimum of the North Pacific stormtrack activity.