論文の内容の要旨

A study on coupling processes between cumulus convection and atmospheric disturbances based on analyses of equatorial Rossby and Kelvin waves

(赤道 Rossby 波と赤道 Kelvin 波の解析に基づく

積雲対流と大気擾乱との結合過程に関する研究）

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Coupling processes between moist cumulus convection and large-scale atmospheric environments are essential to determine large-scale global circulations. However, our understanding is still limited, and climate model simulations do not capture this coupling processes. In this study, we quantitatively investigate the coupling processes based on the convectively coupled equatorial waves (CCEWs), which are major coupled disturbances in the tropics. Previous studies theoretically suggested coupling mechanisms, and they are recently categorized into two groups; the gravity wave mode which focuses on a connection between the gravity wave structure and convective activity and the moisture mode which constructs disturbances of the column water vapor (CWV) including feedback with precipitation. However, it has not been clarified yet how the coupling mechanisms work on the actual processes of the CCEWs. In this study, we investigate the details of convective couplings of equatorial Rossby and Kelvin waves which are considered to have contrasting nature in terms of the coupling processes. Furthermore, we aim to quantitatively investigate how convective activity drives and/or maintains wave disturbances. An accumulation of satellite observations newly enables us to directly quantify 3-dimensional precipitation characteristics, convective heating, and radiative heating. The eddy energy budget analysis can be improved by more realistic estimation of heating profiles. We also aim to make a suggestion on the commonality of the equivalent depths among various

CCEW modes based on statistical analyses.

The theoretical backgrounds and observational contributions from previous studies are summarized in the introduction, Chapter 1. The datasets which are utilized in this study are described in Chapter 2. The analyses methods of wave phase determination, definition of rainfall events, and composite analyses are also described.

We utilize the products of the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) observation. The TRMM observation produces 3-dimensional distribution of precipitation, which directly captures detailed characteristics of rainfall event. Convective heating profiles are retrieved based on the 3-dimensional precipitation data. Furthermore, this provides long-term and consistent observation for 14 years, and thus this dataset is advantageous on statistical analyses. We further utilize CloudSat and CALIPSO satellite data, which provide properties of cloud and radiation. The statistical analyses enable us to estimate combining convective heating from TRMM to radiative heating from CloudSat/CALIPSO.

In Chapter 3, the dynamical and thermodynamical structures of convectively coupled Rossby and Kelvin waves are investigated. The purpose of this Chapter is to quantitatively discuss the existence of theoretically suggested coupling mechanisms in the observed coupled waves. The gravity wave mode can be tested through the phase relationships between vertical motion and temperature, and the moisture mode is discussed based on amplitudes of CWV and their phase relationships to precipitation. Furthermore, convective heating profiles estimated from TRMM are used in order to reliably quantify the eddy energy budget. The satellite-derived heating profiles have not been applied yet to the eddy energy budget analysis.

First, we clarified that the Rossby waves can be assigned to the moisture mode and Kelvin waves correspond to the gravity wave mode. The phase relationship between anomalous vertical motion and temperature is in phase for the Rossby waves and is nearly in quadrature for the Kelvin waves. This strongly suggests the Kelvin waves as the gravity wave mode. Furthermore, it is quantified that the amplitude of CWV is larger in the Rossby wave composite by one-order than in the Kelvin wave composite. Especially, the negative CWV anomaly is nearly zero in the Kelvin waves. The Rossby waves can be amplified and maintained through a feedback process from precipitation anomaly which is in phase with the CWV anomaly. The Rossby waves can be assigned into the moisture mode group in terms of the characteristics of CWV fluctuation. Second, we further quantify the eddy energy budget and found that both waves are driven by top-heavy convective heating, even though they can be assigned to different coupling modes. We also detected that the vertical distributions of the eddy available potential energy (EAPE) generation terms and conversion terms from EAPE to eddy kinetic energy are similar. This may approach the similarity of their equivalent depths.

In Chapter 4, the detailed evolutions of rainfall events utilizing TRMM PR dataset are investigated. The 3-dimensional precipitation radar observation quantitatively clarifies the detailed precipitation characteristics coupled with the Rossby waves or the Kelvin waves, which cannot be directly investigated with objective analyses. We define rainfall events and their 3 indices to express precipitation characteristics utilizing 3-dimensional TRMM PR observation and classify the rainfall events into 5 types: mesoscale convective system (MCS), deep convection, congestus convection, shallow convection, and others. The type of others can be interpreted as stratiform anvil rain in a decaying MCS. We clarify the detailed evolutions of convective activity, which have not been shown in previous studies.

For the Rossby wave composite, the MCS and deep convective events are simultaneously activated, while in the later period of convectively suppressed phase, the shallow and congestus convective events frequently occur. On the other hand, for the Kelvin wave composite, a distinct 5-type evolution from the shallow convective events to the decaying MCS is revealed. We also found that the MCSs dominate in precipitation amount for both waves, and thus the top-heavy heating, which corresponds to the vertical profiles of EAPE shown in Chapter 3, can be induced by these MCS events.

In Chapter 5, the cloud and radiative heating properties are investigated based on CloudSat and CALIPSO observations. These satellites products provide new observational profiles of radiative heating, while radiation and its contribution on diabatic heating has been hardly estimated before. The long-term statistics along the wave phase in this study provides consistent results between precipitation and cloud characteristics. The estimations of diabatic heating associated with the Rossby and the Kelvin waves are achieved for the first time, by combining the convective heating from TRMM and radiative heating from CloudSat and CALIPSO.

We quantified the net effect of radiative heating, which is positive in EAPE generation for both waves. The EAPE generation increases by considering the radiative heating by 30% for the Rossby waves, and by 42% for the Kelvin waves. The upper anvil cloud and the middle-level stratiform cloud deck are almost in phase in the Rossby wave composite. On the other hand, the upper anvil cloud precedes the stratiform cloud deck in the Kelvin wave composite. We found that this difference modulates the role of radiative heating, especially for the longwave radiation. In the Rossby wave composite, shortwave radiation can amplify the EAPE generation, although longwave radiation reduces the EAPE generation. On the other hand, in the Kelvin wave composite, both shortwave and longwave radiation play a role to amplify the EAPE generation.

A general conclusion is presented in Chapter 6. Similarities between the Rossby waves and the Kelvin waves are found as large contributions by MCSs for precipitation amount and a dominance of top-heavy heating on the EAPE generation, and the radiative heating can enhance this EAPE generation in both waves, whereas the coupling processes and the evolutions of precipitation characteristics are different. This similarity may approach the similar values of the equivalent depths among the convectively coupled equatorial wave modes. The slight upward shift of the peak of heating profile due to radiation seen in the Kelvin waves may correspond to a slight difference in the equivalent depth indicated in the zonal-time spectrum. The vertical profiles of diabatic heating may approach the definition process of the equivalent depths.

Analyses in this study are expected to be applied to other equatorial wave modes and the MJO in order to reveal and compare details of various coupling disturbances, and a theoretical approach is required as a future work to shed light on determination processes of equivalent depths of CCEWs based on the diabatic heating.