Spectral Analysis on Large-Scale Cloud Disturbances Associated with Equatorial Waves

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1. Introduction

Accurate treatment of cumulus convection is indispensable for climate model simulation. However, at present, it is still under controversy how we should treat the cumulus convection 'accurately' in numerical models. Since the cumulus convection itself is a subgrid-scale phenomena for climate models which have horizontal resolutions as large as several hundreds of kilometers, we need to place some assumptions to represent its effects with grid-scale variables. In order to improve such parameterization schemes, we need precise knowledges of real phenomena related to the large-scale effects of cumulus convection.

In the real global atmosphere, the impact of cumulus convection is large over the tropical oceans. The circulation of tropical atmosphere can be expressed in the summation of the equatorial wave modes (Matsuno, 1966). It is shown that large-scale atomospheric heating by organized cumulus convection forces the equatorial wave responses in the atmosphere (Gill, 1980). On the other hand, precedent works report that large-scale cloud organizations over the tropical oceans indicate the signals of some of equatorial wave modes such as Kelvin waves (Nakazawa, 1988), Rossby waves (Zangvil, 1975) and mixed Rossby-gravity waves (Takayabu and Nitta, 1993).

If equatorial wave modes are dominantly detected in the cloud field, it suggests the existence of interaction between cumulus convection and large-scale atmospheric circulations; the atomospheric equatorial waves which are forced by cumulus convection effects are inversely determining the preferred regions for convection through a certain physical processes. However, there have been no study that examined the equatorial wave mode statistically utilizing the long period of satellite data. Also the characteristic parameters of cloud disturbances are not statistically detemined yet.

The objective of this study is to examine the large-scale (O(1000km)) features of cloud disturbances utilizing 10 year-accumulated satellite data in order to detect their relationship with atomospheric equatorial waves and to obtain the informations about characteristic values of the waves observationally.

2. Data and the Method of Analysis

The principal data used for this study are $1^{\circ}\times 1^{\circ}$grid mean infrared equivalent blackbody temperature (IR/T_{BB}) data observed from the Geostational Meteorological Satellite of Japan. These IR/T_{BB} data provide good indices for cloud top height especially over tropical oceans. All data in the period from January 1980 to December 1989 with the temporal resolution of 3 hours were utilized. The mean wind fields were calculated from the global objective analysis data produced at European Center for Medium-Range Weather Forcasts (ECMWF).

In order to examine the cloud disturbance characteristics from the viewpoint of equatorial wave modes, space-time power spectral analysis (Hayashi, 1977) was performed. Space-time power spectra were calculated for each 92 day-data centered in every month for 1980-1989. For the calculation of spectra, Fast Fourier Transform (FFT) method which provides the standard deviation of power was utilized.

3. Results

Figure 1 shows the latitudinal distribution of the spectra of cloud disturbances. The space-time spectral technique provides us with the information of propagation direction of the wave signals as well as their wavenumber and frequency. In this analysis, since we applied this method to the time series of every longitudinal line of cloud data, we obtained the information about the east-west propagation properties. The right panel shows the eastward-propagating component and the left panel shows the westward-propagating component.

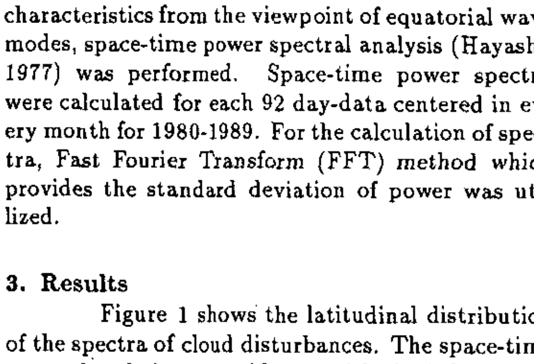

Figure 1: Latitudinal distribution of the T_{BB} space-time spectra for westward- and eastward-moving cloud disturbances integrated in the zonal wavelength region of 120°-40°. Spectral values calculated for all period from December 1981 to November 1989 are averaged. The abscissa is the natural logarithm of frequency labeled in days.

In the eastward-moving component, relatively large power is distributed in 8°N-7°S over the equator with the period around 4-11 days which corresponds to the phase speed of $\sim 10^{\circ}$ day^{-1}. On the other hand, the westward-moving spectra is distinguished between at the equatorial latitudes and at latitudes 5°-10° north and south from the equator. Over the equatorial latitudes of 6°N-6°S, high frequency mode with spectral peak at 1.8-2.3 days are observed. At around ±6°latitude, significant power peak is found around 4 days. Another spectral peak is found in 6°S -10°S with the period of 12 days.

The correspondence between these spectral signals of cloud field and the equatorial waves is obtained by depicting the wavenumber-frequency distribution of the cloud disturbances and superposing the equatorial wave dispersion curves. Figure 2 shows such distribution along the equatorial latitude of 0.5°N. Here again, the eastward/westward-moving components are contoured in the right/left panels. Superposed lines represent dispersion curves for equatorial waves with a equivalent depth of 17 m. Doppler effect of the mean zonal wind is considered for the dispersion curves. Mean 850 hPa zonal wind speed for the analysis period, −1.25 m, which is calculated from the ECMWF analysis data is used for the advection wind speed.

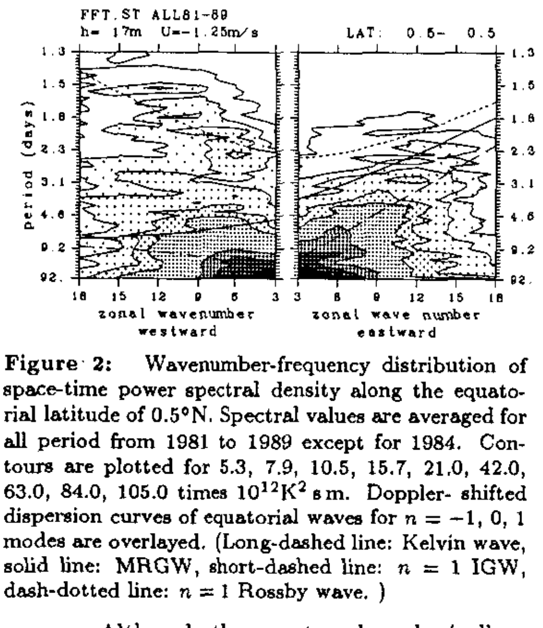

Figure 2: Wavenumber-frequency distribution of space-time power spectral density along the equatorial latitude of 0.5°N. Spectral values are averaged for all period from 1981 to 1989 except for 1984. Contours are plotted for 5.3, 7.9, 10.5, 15.7, 21.0, 42.0, 63.0, 84.0, 105.0 times $10^{12}K^2$ s m. Doppler- shifted dispersion curves of equatorial waves for $n = -1$, 0, 1 modes are overlayed. (Long-dashed line: Kelvin wave, solid line: MRGW, short-dashed line: $n = 1$ IGW, dash-dotted line: $n = 1$ Rossby wave.)

Although the spectra show basically red distribution, significant signals of equatorial waves are noticed. First, the eastward-moving signal shown in Fig. 1 coincide with the Kelvin waves with nondispersive phase speed of ~10 m s^{-1}. As for the westward component, a spectral distribution along the dispersion curve of $n = 1$ westward-propagating inertio-gravity waves (WIGW) is nicely depicted. Note that no evident power is observed for $n = 1$ eastward propagating inertio-gravity waves.

When we depict the similar diagram at higher (*e.g.* 5°N and 5°S) latitudes (not shown), we can identify the signals found along those latitudes in Fig.1. Namely, the westward ~4 day-period signals correspond with the mixed Rossby-gravity waves (MRGW) which are often observed in boreal summer and autumn. Westward ~12 day-period signal in the southern hemisphere corresponds with the Rossby waves.

The latitudinal extent of power distribution for each equatorial mode found in Fig. 1 suggests the equatorial radius of deformation of 5°-6°associated with cloud disturbances. This coincides with the equivalent depth of waves of 15-30 m suggested from the comparison of theoretical waves and spectral power distribution.

4. Conclusions

Spectral features of large-scale cumulus convective systems over the tropical oceanic area are studied and classified from the viewpoint of the atmospheric equatorial waves. Three hourly GMS/IR/T_{BB} data for the period of 1980-1989 are utilized.

As an average property for a long analysis period, robust signals were identified with Kelvin waves, westward-propagating mixed Rossby-gravity waves, Rossby waves and $n = 1$ WIGW. Especially, the signal of $n = 1$ WIGW is newly detected in this study. These results indicate the existence of interaction between the cumulus convection and the large-scale atmospheric circulation.

The equivalent depth of 15~30 m is indicated from the frequency-wavenumber distribution of cloud disturbances except for those associated with tropical depressions. On the other hand, equatorial radius of deformation of 5°~ 6° is deduced independently from the latitudinal distribution of cloud spectra. This value is consistent with the above indicated value of the equivalent depth.

Above results suggest that there exist not only the equatorial wave forcing by convection heating but also the interactive relationship between the large-scale equatorial waves and convective activity over the tropical oceans. Further study is necessary to understand the suggested equivalent depth associated with the vertical heating efficiency of the cloud systems.

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