B-5.4 Research on the Interaction Between the Cloud Systems and the Dynamical Processes Related to Climate Change

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Abstract In order to introduce a proper cloud and convective parameterization scheme into the Global Climate Model (GCM), this study is devoted to clarify the interaction processes between cumulus activity and large-scale atmosphere dynamics. Data analysis utilizing meteorological satellite data and numerical studies with GCM are performed.

Primary results of this study are as follows: (1) We identified the theoretical equatorial wave modes in the tropical cloud fields and quantified the characteristic value of the atmospheric waves associated with the cloud activity. (2) We established a method for estimating large-scale distribution of cloud optical properties from satellite data. (3) We conducted numerical experiments and clarified some mechanisms which determine the climatological global precipitation distribution and its relation to the convective parameterization schemes.

Key Words Cumulus convection, Cumulus parameterization, Equatorial waves, Cloud optical properties.

1 Introduction

Cloud process play a significant role in the global climate system through radiation process and the re-distribution of energy as latent heat. However, the actual scale of the cloud is much smaller (up to several kilometers) than the grid size of climate models (usually a few hundred kilometers). Therefore, instead of handling the cloud variables explicitly, we need to find an alternative means to represent the averaged cloud effects in terms of the grid-scale meteorological variables, or 'to parameterize'.

The cumulus parameterization scheme plays a key role in determining the performance of the state-of-the-art climate models. However, general schemes are not truly established yet, because of the lack of knowledge in evaluating of the cloud/precipitation effects and their interaction with atmospheric dynamics. Radiative effects of the cloud are also well understood because we have only limited data on the global distribution of the cloud optical parameters.

The purpose of this study is to clarify the interaction processes between the cloud and the large-scale atmospheric dynamics by means of data analysis, remote sensing and numerical studies. For the meteorological data analysis, we concentrated on large-scale cloud organizations of cloud systems in the tropical region because of their large impact on the global atmosphere and close coupling with the disturbance. For the remote sensing analysis, we concentrated on the estimation of large-scale distribution of the cloud optical properties. As for numerical studies, we concentrated on mechanisms determining global-scale precipitation distribution. We also participated an international field experiment, TOGA-COARE, and started detailed analysis studies concerning the cloud-atmosphere-ocean interactions.

2 Results

(1) Data analysis on tropical cumulus convective activity

The data utilized in the analyses are GMS sattelite infrared equivalent blackbody temperature data , Outgoing longwave radiation data, two global objective analysis data by ECMWF (European Centre for Medium-Range Weather Forecasts) and JMA (Japan Meteorological Agency), Monthly mean sea surface temperature data (by JMA and NOAA), TOGA-COARE sounding data and SSM/I satellite-derived water vapor and cloud data.

Structure of tropical 3-5 day variations: The structures of the 1000km-scale organized convective systems over the tropical Pacific Ocean in the June-August period are obtained utilizing 9-year GMS IR data and ECMWF meteorological data. 3-5 day-period cloud variation dominant in this study was associated with two different types of tropospheric disturbances. Mixed Rossby-gravity wave disturbances are found dominantly over the central Pacific and tropical depression-type disturbances were found in the western Pacific. The dominance of two modes was determined by the global-scale conditions of time-mean vertical wind profile and sea surface temperatures. It was confirmed by comparing the disturbance structure between the El Niño and La Niña years.

Seasonal variation of tropical large-scale cloud systems: Seasonal variation of O(1000km)-scale cloud organizations and their relationship to latitude and sea surface temperature (SST) was analyzed. Especially, it was clarified that the characteristics of the cloud-systems largely differ between the northern summer tropics and the southern summer tropics. In the northern summer, 3-5 day variations which consist of mixed Rossby-gravity waves and tropical depression-type disturbances dominated and had less dependence on the local SST. In the southern summer, on the other hand, shorter-term ($\sim$2 day) variation dominated which showed large correlation with the local SST values.

Case study on tropical disturbances: As for a case study on the behavior of tropical convective activity, the TOGA/COARE data in November 1992 are analyzed. It was found that the mixed Rossby-gravity wave is dominated in this period in the equatorial western pacific. An indication of the formation of tropical cyclones from these mixed Rossby-gravity type disturbances is observed. Moreover, two events of appearance of extremely dry air in the equatorial lower troposphere is observed in radiosonde soundings. It is clarified from trajectory analysis and from satellite water vapor fields that the dry air has intruded from the subtropical region carried by the equatorward flow of the tropical disturbances. This dry air inhibited the cloud activity and modifies the surface radiative flux as much as 150W/m^2.

Identification of equatorial waves: Space-time spectral analysis techniques were applied to the satellite-observed GMS IR data in order to classify the large-scale cloud disturbance in terms of equatorial waves over the tropical ocean. Especially, a significant signal of the westward-propagating inertio-gravity waves was first found in this study. Also, we could quantify a common characteristic value among different modes of equatorial waves which provides important information in understanding large-scale cloud-atmosphere interactions.

Fig. 1 illustrates the large-scale (40°-120°) cloud spectrum in the latitude-frequency diagram. The right panel shows the eastward-propagating component and the left panel shows the westward-propagating component. We found significant differences in distribution between eastward- and westward-propagating systems. The eastward-propagating signals at 4-11 days over the equator correspond with Kelvin waves. Those at 3 days found 5°-8° from the equator in both hemispheres indicate the $n = 0$ eastward-propagating inertio-gravity waves (EIGW). As for the westward-propagation, at 1.5-2.5 days are found $n = 1$ and $n = 2$ westward-propagating inertio-gravity waves (WIGW) around the equator and 4.6-day signals $\pm 7°$ in both hemispheres are indicating the mixed Rossby-gravity waves (MRGW). $\sim$12-day variance seen in the southern hemisphere (6°S-10°S) represents the $n = 1$ Rossby wave mode. Comparing the latitudinal distribution of spectra with the amplitude maxima in the divergence field with the theoretical equatorial waves, the equatorial radius of deformation of $\sim 7°$ can be deduced.

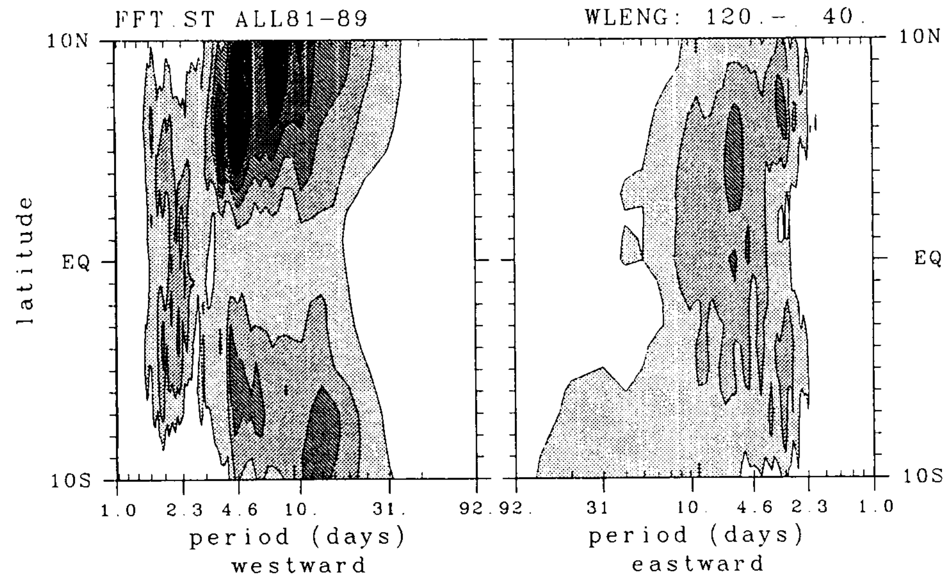

Figure 1: 1981-1989 climatology of the latitude-frequency sections of T_{BB} spectrum integrated for zonal wavelength of 120°-40°. Westward- and eastward-moving cloud disturbances are plotted separately.

The correspondence between large-scale cloud systems and equatorial wave modes are confirmed with the wavenumber-frequency diagram at the equator (Fig.2(a)) and at ~7°N (Fig.2(b)). The dispersion curves of equatorial waves with the equivalent depth of ~17 m and Doppler-shifted with the mean zonal wind at 850 hPa fit well with the spectra. At the equator, Kelvin waves and $n = 1$ WIGW are identified. At 7°N, $n = 1$ Rossby waves, MRGW, $n = 2$ WIGW and slight indication of $n = 0$ EIGW are obtained. The equivalent depth ~17 m is consistent with the above-indicated radius of deformation of ~7° in latitude.

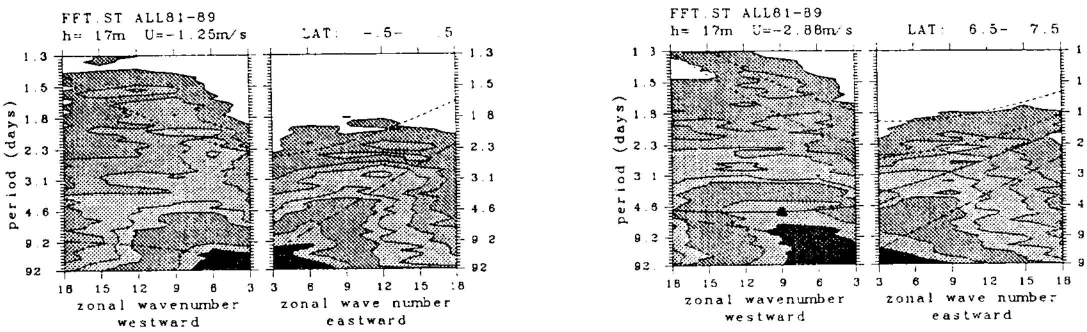

Figure 2: Wavenumber-frequency distribution of space-time power spectral density along the equatorial latitude of 0.5°N-0.5°S (a) and 6.5°N-7.5°N (b). Spectral values are averaged for all period from 1981 to 1989 except for 1984. Doppler- shifted dispersion curves of equatorial waves are overlayed. (Long-dashed line: Kelvin wave, solid line: MRGW and $n = 0$ EIGW, short-dashed line: $n = 1,2$ IGW, dash-dotted line: $n = 1$ Rossby wave.)

(2) Remote sensing study on the large-scale distribution of cloud optical properties

A method for estimating the large-scale distribution of cloud optical parameters is developped and applied it to the subtropical marine stratocumulus in California and tropical cumulus cloud in Amazon basin. The optical thickness and effective radius of cloud droplets are estimated using the data of channel 1,3,4 of AVHRR sensor. The result for Californian marine stratocumulus indicates the influence of the cloud condensation nuclei (CCN) of continental origin to reduce the effective radius of cloud droplets and to enhance the cloud albedo. In the result for the Amazon basin cumulus, however, the reduction of the cloud albedo with the incerase of smoke aresol is observed. In this region, the effect on the droplet size is not so effctive because the background density of CCN is large.

(3) Numerical study on the role of cumulus convection in the global-scale precipitation distribution

Numerical experiments are performed to clarify the role of cumulus convection and large-scale circulation in the formation of time-averaged distribution of precipitation. The experiments are done with with three different parameterization schemes, Kuo, Manabe's adjustment (MAA), and modified Arakawa-Schubert (MAS). Sea surface temperature was fixed globally with broad equatorial peak. The Kuo and MAS experiment resulted in two precipitation zones along ±10°while the MAA resulted in one at the equator. It is interpreted that the different parameterization schemes resulted in differences in atmospheric vertical stratification and the depth of the Hadley Circulation which made the precipitation zone differ drastically in order to accomplish the global-scale energy balance. By the experiments with varying meridional distributions of the sea surface temperature, it was clarified that the location of the strong precipitation zone is highly dependent on the atmospheric boundary layer convergence driven by the SST gradient. This experimental result was conformed by the analyzed relationship between the diagnostically derived boundary layer convergence and the OLR distributions.

3 Concluding Discussions

In this series of studies, we attempt to clarify interactions between cloud and atmospheric dynamics in order to improve the parameterization schemes on clouds. Data analysis studies on the large-scale cloud-atmosphere coupled systems utilizing meteorological satellite data, remote sensing studies on the cloud optical properties and numerical studies with the atmospheric general circulation model were performed.

As a result of numerical experiments, we could understand how the cumulus parameterization scheme can affect the global-scale distribution of precipitation. We also studied the indirect effect of boundary conditions to the precipitation distribution.

From satellite data analysis, we realized that tropical cloud activity is dominantly associated with the theoretical equatorial waves. We identified equatorial wave modes that exists in the real atmosphere and estimated characteristic values that represent their dynamical features. These results provide us with quantitative information in evaluating various parameterization concepts and also the performance of these schemes.

A method for estimating large-scale distribution of cloud optical properties from satellite data is established. This technique should be very useful to get the global distribution of cloud optical parameters, which is crucial information on the cloud-radiation-circulation interaction in the climate scale.

The necessity of further studies on this issue including some new aspects is also suggested. One suggestion is to incorporate effects of convective and stratiform clouds: Convective clouds are important in vertical heat redistribution and stratiform clouds are also important in radiative effects and large-scale cloud systems usually consists of these two elements. Another is the air-sea interaction effects including the boundary layer dynamics. An analysis study utilizing the TOGA-COARE data gave us promise that we should be able to improve our knowledge on cloud-atmosphere-ocean systems with these fine data. This study will be connected to further studies focusing on the connection between the convective effects and radiative effects of the clouds in the global climate systems.

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