B-5.4 Research on the accurate modeling of the feedback process related to climate change

B-5.4.2 Evaluation of feedback process of hydrological circulation in the atmosphere and cloud processes (Final Report)

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[**Abstract**]

In order to clarify the role of cloud feedback in the global climate change, advanced analysis studies utilizing the satellite data were performed. First, 'Semi-random method' for the radiation code was developed to include the effect of finite cloud fraction and implemented to the climate model. Secondly, utilizing the TOGA COARE (Tropical Ocean and Global Atmosphere Coupled Ocean Atmosphere Response Experiment) data, relationship between dynamical atmospheric disturbances and a lifecycle of cloud systems were described in detail. Thirdly, cloud characteristics and its effects were studied by utilizing various satellite data from NOAA/AVHRR (Advanced Very High Resolution Radiometer), ERBE (Earth Radiation Budget Experiment), ISCCP (International Satellite Cloud Climatology Project) and an advanced radiative transfer model. A new algorithm, 'the Normalized Split Window Method, to retrieve the cloud optical properties, was developed and applied to the global data. And cloud radiative forcing for various cloud types was examined utilizing the ISCCP cloud data and advanced radiative transfer model. It was shown that tropical high level clouds play more significant role compared to the mid-high latitude clouds from the viewpoint of the global climate change.

Key Words cloud radiative forcing, cloud optical properties, satellite data, radiative transfer model, organized cumulus convection, normalized split window method

1 Introduction

Clouds play a significant role in the earth climate system through two major processes: One is the radiation process such as the reflection and the scattering of the solar radiative flux and the absorptance and the emittance of the infrared radiative flux. The other is the dynamical process which transports energy accompanying the evaporation and precipitation of water substances. It is shown that only 1% variation of the global cloud fraction corresponds to the change of radiative flux of several W m^{-2} at the top of the atmosphere, which is much more significant than the past 200 years change due to the increase of the greenhouse gases.

For all its importance, the cloud feedback effects to the climate system are quite complicated and still remain as a major uncertainty in the climate modeling. Cess et al.(1990) performed an intercomparison of the climate sensitivity among nineteen different climate models. As a result, global mean sensitivities varied significantly among the models while those for the clear sky were quite similar to each other. They concluded that the sensitivity differences are primarily caused by differences in the treatments of cloud processes. Still, it was not determined what part of the cloud processes attributed the most. Recently, Cess et al.(1996) repeated the intercomparison and showed some reduction of climate sensitivity variation among the models compared to the 1990 study. However, it is emphasized that this does not mean the reduction of the uncertainties in cloud feedback processes (IPCC95).

From the observational point, Ramanathan and Collins(1991) utilized the satellite radiation measurement data of ERBE and estimated the variation of the cloud radiative forcing at the top of the atmosphere associated with El Niño. They concluded that the upper level clouds associated with active cumulus convective activity over the tropical oceans has a negative feedback effect to the sea surface temperature (SST) change and plays as a thermostat for the SST. However, their conclusion was criticized by some following studies for the reason that their analyses merely treated the local relationship between the SST and the clouds over the central Pacific Ocean (Fu et al., 1992). The importance of considering large-scale dynamical effects to the regional effects were emphasized (Wallace 1992, Lau et al. 1994).

Recently, significant efforts have been put to utilize the satellite measurements for the estimate of the global climate studies. ERBE (Earth Radiation Budget Experiment) accomplished the global mapping of short- and long-wave radiative flux observation at the top of the atmosphere. For the purpose of the understanding of global cloud radiative effect, a global dataset of cloud parameters obtained from five geostationary and two orbital meteorological satellites have been constructed by ISCCP (International Satellite Cloud Climatology Project) (Rossow et al. 1985). Various other satellite measurements such as NOAA/AVHRR multi-channel, DMS-P/SSM/I are also useful for the retrievals of the physical variables associated with water substances. Moreover, Japanese GMS-5 newly implemented the infrared split window channels and a water vapor channel. TRMM (Tropical Rainfall Measuring Mission) satellite is scheduled to be launched in 1997. Such progress in satellite measurements should provide good opportunities for a large step in our understanding of the cloud processes.

In this study, we utilized various satellite observational data and an advanced radiative transfer model and attacked the various uncertainties in cloud feedback processes. We especially focused on clarifying the relationship among the cloud radiative effects, the organization of cloud systems and the large-scale atmospheric dynamics.

2 Results

2.1 Improvement in the treatment of cloud fraction in climate model using semi-random method

The horizontal distribution of clouds significantly varies depending on the cloud types as cumulus and stratus among others. The distribution has an important role in the reflection of the solar radiation. In order to calculate radiation budget accurately in a climate model, it is thus very important to treat the effect of fractional clouds within a model grid. We have implemented the effect of cloud fraction in the radiation code and compared the results with and without the fractional clouds. The 'random method' is known as a useful method to treat fractional clouds, which is, however, computationally too expensive for the purpose of climate modeling. Thus, we developed the 'semi-random method', which calculates the effect of fractional cloud in a much more efficient way, and incorporated it in the radiation code. To evaluate the performance of semi-random method, the results calculated by semi-random method is compared with those by random method.

We used the cloud cover for each vertical model layer, which is calculated in the large-scale condensation routine of the GCM, as the variable representing fractional clouds. The calculated heating rate including the effect of fractional cloud shows an intermediate values between the clear case and the fully cloudy case. In comparison with random method, semi-random method estimates larger values in heating rate by approximately 0.04[K/day] throughout the atmosphere. The relative error is of the order of 10^{-2}, which is sufficiently small.

In future, we will simulate the climate with the model including the effect of fractional cloud and analyze the results. We will also analyze the observed radiation flux under various conditions of cloud distribution.

2.2 Analysis of quasi two-day cloud systems observed during TOGA COARE

In order to clarify the relationship between the organized cumulus convective clouds and the radiatively effective upper level dense cirrus clouds, a dominant large-scale tropical convective system was studied. Detailed structure of the quasi two-day oscillation observed during the Intensive Observation Period of Tropical Ocean and Global Atmosphere - Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE IOP) was described. We used a variety of observational platforms including high-resolution GMS infrared histogram, rain rate estimate from TOGA and MIT radar measurements, upper-air soundings and boundary layer profiler-winds from the Integrated Sounding System (ISS) and surface data from the IMET buoy.

Figure 1 shows the time variation of the area-mean infrared equivalent blackbody temperature (T_{BB}) for two rectangular regions which corresponds to (151°E -158°E, 1°N-4°S) and (147°E - 166°E, 8°N-11°S). It is clear that quasi 2-day periodicity is dominant for smaller-area (IFACR) mean. Space-time spectral analysis and the structure of the associated atmospheric disturbances revealed this system had the properties of westward traveling $n = 1$ inertio-gravity waves with the zonal scale of 30°and the propagation speed of $\sim 15° \text{ day}^{-1}$.

To obtain the vertical distribution information of the cloud system associated with the quasi 2-day waves, we employ the T_{BB} histogram data which consist of frequency histograms of pixel numbers with the original resolution of about 4 km at nadir for each 0.25°× 0.25° square grid.

Figure 2 shows the composite of the histogram data for the 2° longitude × 3° latitude rectangular area at the IFA center. Four stages in the life cycle of the oscillating cloud-circulation system were identified: (1) the shallow convection stage with a duration time of 12 hours, (2) the initial tower stage (9 hours), (3) the mature stage (12 hours) and (4) the decaying stage (15 hours). Surface and boundary layer observations also showed substantial variation associated with the different stages in the life cycle. Results suggest that the time scale of quasi two-day oscillation is determined by the time required by the lower tropospheric moisture field to recover from the drying caused by deep convection.

It is indicated that in order to represent the cloud role in the climate modelling appropriately, it is important to know how to treat the relationship between the cumulus convection and associated anvil systems coupled through large-scale dynamical processes.

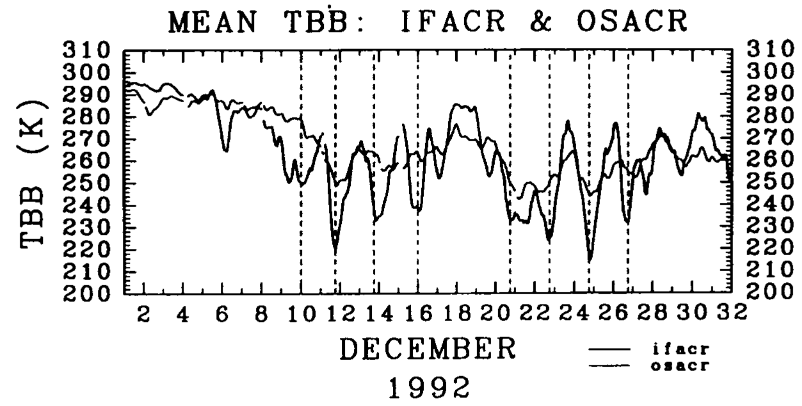

Fig. 1 Time variation of the area-mean T_{BB}. December, 1992.

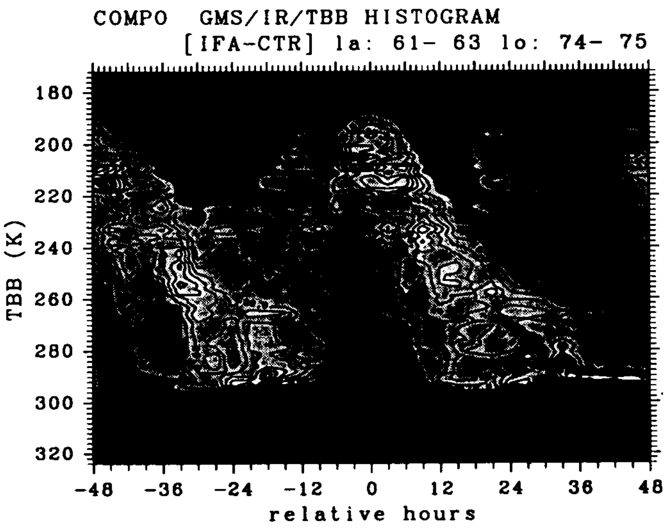

Fig. 2 Composite vertical structure of cloud systems associated with the quasi 2-day wave obtained with T_{BB} histogram data. Abscissa is relative time and the ordinate is the T_{BB} which is a good index of the cloud height.

2.3 Analysis of cloud radiative forcing using ERBE and ISCCP data

It has been revealed in studies using satellite remote sensing data that the cloud radiative forcing varies depending on cloud types and the geographical distribution of clouds. Especially, the radiative heating of cirrus, the widespread thin cloud in upper troposhere, has been controversial. It is first considered to be heating (Stephens et al,.1990), but later it is suggested to be cooling over the El-Nino region (Ramanathan & Collins,.1991). Thus, we investigated the relationship between the cloud radiative forcing and the geographical distribution of clouds.

The data used are ERBE for radiation data at the top of the atmosphere, and ISCCP C2 for cloud data. The analized data are the average over February 1985 – January 1990. The cloud radiative forcing is defined as the difference in radiation flux between that observed and that for clear sky. It is the sum of the cooling effect for shortwave radiation and the warming effect for longwave radiation.

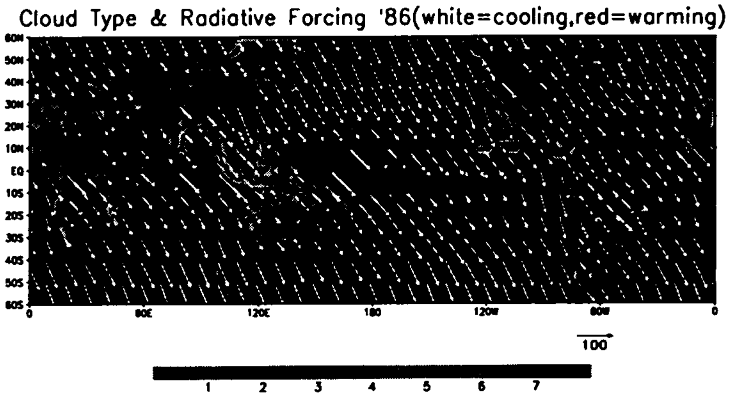

Fig.3 Dominant cloud type and the cloud radiative forcing. (Cloud Type: 1:cumulus, 2:stratus, 3:alto cumulus, 4:nimbo stratus, 5:cirrus, 6:cirro stratus, 7:deep convective, Vectors indicate the LW cloud forcings with x-component and SW with y-component.)

To see the relationship between radiative forcing and the type and location of clouds, the most dominant cloud type in each analyzed grid and the shortwave and longwave components of radiative forcing are shown in Fig.3. The vectors indicate radiative forcing, horizontal component being longwave forcing (positive rightward) and vertical component being shortwave forcing (positive upward). White vectors indicate that the net forcing is negative (cooling), while dark-colored vectors indicate positive forcing (heating). In general, the cloud radiative forcing is negative over most regions. Especially, over the west coasts of continents, it is negative because the ocean currents are cold and the cloud top heights are low, which suppress the greenhouse effect of clouds. Net heating is found over the warm regions in tropics and over the deserts. Over deserts, the magnitude of radiative forcing is generally small (vector length is short). The shortwave cooling effect (albedo effect) of cloud is suppressed over deserts because the surface albedo is relatively high, while the longwave warming effect is enhanced because the surface temperature is high. Regions where the magnitude of radiative forcing is relatively large and the net forcing is positve (heating) are mostly covered with cirrus. Among those regions, however, the relative strength of shortwave and longwave forcing is strongly dependent on locations.

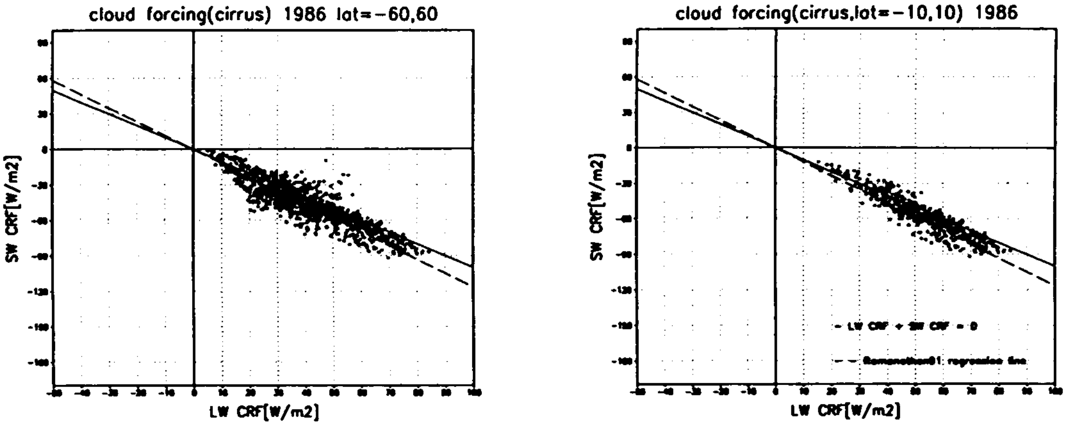

Fig. 4 Cloud forcing over the cirrus region for (a) 60°N-60°S, (b) 10°N-10°S.

Figure 4(a) shows the relative strength of shortwave and longwave forcing over the regions where cirrus is dominant within 60N–60S. Each component of the radiative forcing of cirrus widely ranges, but the net forcing is almost neutral (solid line). Over some regions, the net forcing is positive as indicated by the dashed line, the regression line determined by Ramanathan & Collins(1991). Figure 4(b) is the same as (a) but for the tropical region within 10N–10S. The radiative forcing in the tropics is fairly close to neutral, in spite of cooling effects of convective clouds under the cirrus.

It is shown that the cloud radiative forcing is strongly related to the geographical feature of the location of clouds.

2.4 Analysis of cloud radiative forcing utilizing ISCCP data and a radiative transfer model

As stated previously, cloud feedback processes are affected by the variation of cloud optical properties and the fractional rate of different cloud types. Therefore, in order for the evaluation of cloud effects in the climate models, it is necessary to know how the clouds are generated and what radiative effects they have in reality. In this study, we developed a method to incorporate the daily cloud information to an advanced radiative transfer model and applied it to the ISCCP D1 data to obtain the cloud radiative forcing for individual type clouds separately.

The cloud optical depth, top temperature and fraction provided by ISCCP D1 data (2.5°×2.5°, 3 hourly) were utilized. Physical depth of the clouds was parameterized following Minnis et al.(1990). Atmospheric profiles were obtained from ECMWF objective analysis data. These values for each 15 cloud types were input to an advanced radiative transfer model 'fstar5b' (Nakajima et al., 1996) for the radiative flux calculation with high accuracy.

'Cloud radiative forcing' is defined as a increase of downward radiative flux at the top of the atmosphere due to the existence of clouds.

Figure 5 shows a time series of the cloud radiative forcing over the warm pool region in the western equatorial Pacific ocean for December 1992. In the latter half of this months, a large scale organized cloud system, called Madden-Julian Oscillation (MJO), propagated over this region. Total cloud forcing (Fig.5(a)) by all types of clouds show the large amplitude variation of long and short wave radiative flux associated with this MJO. By examining the separate cloud type forcing, we can notice that upper thick clouds, such as anvils, have large amplitude in LW and SW but almost canceled each other (Fig.5(b)). While upper thin clouds, cirrus, shares the most part of the total net heating (Fig.5(c)). Mid- and low-level clouds have cooling effects, though their amplitudes here are small. Note, however, that since the satellite visible and infrared measurements used for this data cannot convey the information for lower clouds shielded by the upper clouds, so that the effects of the lower clouds may be underestimated.

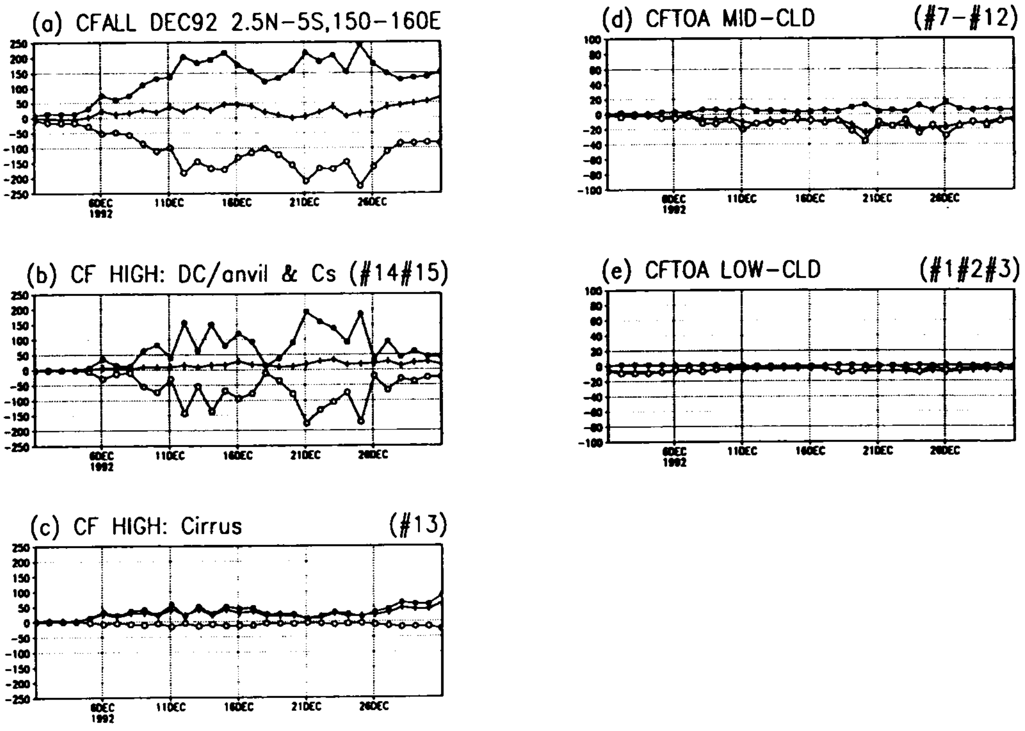

Fig.5 Time series of the cloud radiative forcing at the top of the atmosphere over the western Pacific ocean for different cloud classes: (a) total, (b)thick high-level (2) thin high-level (d) mid-level and (e) low-level clouds. Closed circles: LW forcing, Open circles: SW forcing, Crosses: Net forcing. Units are in W m^{-2}.

For the future work, it is important in order to evaluate the relationship between the cloud radiative effects and the large-scale conditions with the global and longer-term estimates of the cloud radiative forcing for the individual cloud classes.

2.5 Retrievals of ice cloud optical properties using AVHRR infrared channels.

Cloud radiative effect is affected by various elements in a complicated manner. It varies with cloud optical properties and cloud top height. And these properties vary with cloud microphysics as well as large-scale environmental conditions such as the sea surface tempaerature. Thus it is still under controversy in which direction clouds work as the feedback to climate change.

Therefore, in order for an accurate parameterization of the clouds, it is necessary to know the global distribution of the cloud microphysical properties. Although various remote sensing data from satellite have become available in these days, few information has been derived yet for the ice clouds which has especially complicated effects on the radiative budget.

In this study, we first developed a new method to retrieve ice cloud optical properties as optical thickness and effective particle radius. A numerical simulation using an advanced radiative transfer model 'rstar5b' (Nakajima et al. 1996) was performed for the three infrared channel radiance temperatures (T10.8μm, T12.0μmand T3.7μm). to search for an adequate method for the retrieval. The method is named as 'Normalized Split Window 'Method (NSW)'.

As a result, it was shown that T10.8-T12.0 arch (Fig. 6) is suited for the determination of the effective particle radius, since it keeps similarity in shape under various conditions and easy to be normalized. On the other hand, T3.7-T10.8 arch (Fig. 7) is very sensitive to cloud top temperature and works well to determine it. Cloud optical depth is determined from T10.8 itself.

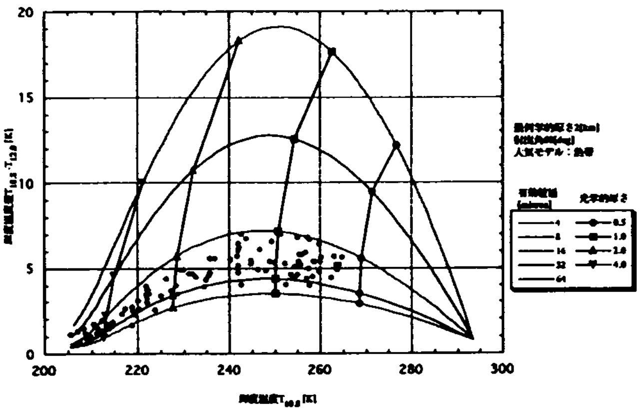

Fig. 6 Arches of for T10.8 and T12.0 for various effective radius. A set of sample data for one grid is overlaid.

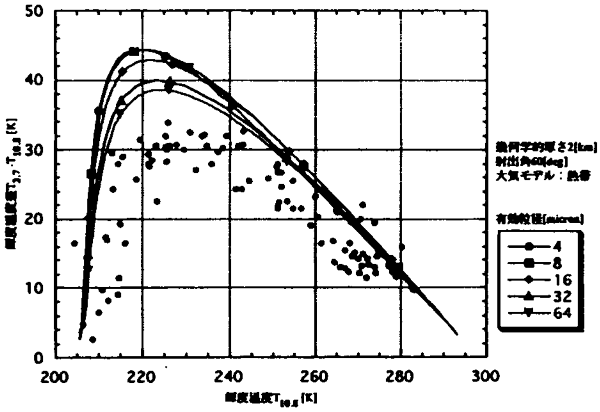

Fig. 7 Same as Fig. 6, but for T3.7 and T10.8.

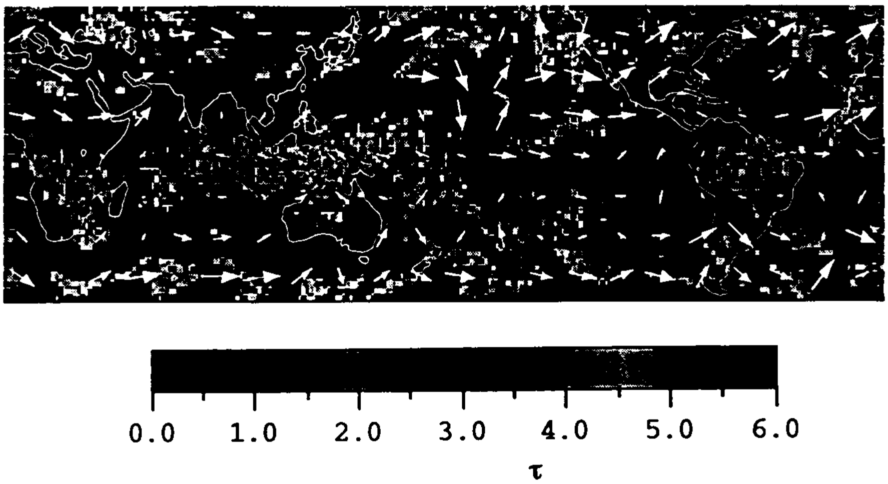

Fig. 8 Global distribution of the cloud optical depth retrieved with NSWM. January 17, 1990. 250 hPa wind vectors are overlaid.

Secondly, we applied NSW to the actual NOAA/AVHRR data to obtain the global distribution of the cloud optical properties. Fig. 8 shows the global distribution of the cloud optical thickness for January 17, 1990. Over the tropical western Pacific Ocean where the cumulus convective activity is abundant, the cloud top height is large and optically thick. And a flow out of optically thin clouds to its surrounding region is observed. At the mid-high latitudes, thick ice clouds are observed associated with the front systems. Over the South American Continent, ice clouds also flow out with the upper level wind. In the tropics, very active generation of the ice clouds were observed in a similar region thoughout the month.

Fig. 9 depicts the latitudinal distribution of the effective particle radius. It is seen that the effective radius distributes mostly in 12-22μm range in the tropics, while in 18-24μm range in mid-high latitudes. Following the cloud feedback parameter dependency on the effective particle radius (Nakajima, 1996), observed 12-22μm size is efficiently small compared to the critical size of 24.5μm and should produce large parameter value. This results suggests that the ice clouds in the tropics have larger impacts to climate sensitivity than mid-high latitude ice clouds.

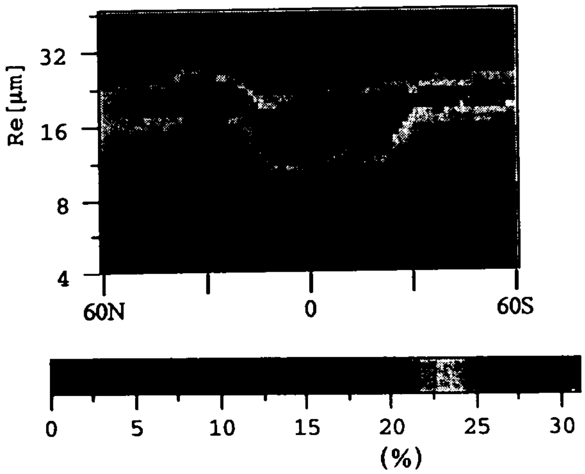

Fig. 9 Latitudinal distribution of the effective particle radius.

3 Summary

Cloud feedback processes play a key role in the climate change prediction. In order to evaluate the cloud effects, we have to know the climate sensitivity of the cloud radiative forcing, which is defined as an increase of the downward radiative flux at the top of the atmosphere due to the existence of clouds. For that, first, it is necessary to know what determines the cloud amount change. Secondly, we have to know the cloud microphysics which determines the cloud optical properties. However, these properties are not clarified yet even for the present climate. In this study, we utilized various satellite observational data and an advanced radiative transfer model and attacked the various uncertainties in cloud feedback processes. Thus we aimed to contribute to the more accurate evaluations of cloud treatments in the climate model and its improvements. Primary results are as follows:

(1) 'Semi-random method' for the radiation code was developed to include the effect of cloud fraction within a model grid, and implemented to the climate model. As a result, more accurate calculation with less computational time was achieved.

(2) The structure of the 1000km-scale cloud systems accompanying the quasi 2-day wave over the tropical ocean was analyzed with various platform data by TOGA COARE (Tropical Ocean and Global Atmosphere Coupled Ocean Atmosphere Response Experiment). Relationship between dynamical atmospheric disturbances and a lifecycle of cloud systems were described in detail.

(3) By utilizing satellite data from ERBE (Earth Radiation Budget Experiment) and ISCCP

(International Satellite Cloud Climatology Project), the cloud radiative forcing was analyzed. It was shown that the cloud radiative effects are intimately related to the geographical location of clouds.

(4) In order to obtain the cloud radiative effects for various cloud classes, we developed a method to calculate the cloud radiative forcing utilizing ISCCP D1 cloud data and an advanced radiative transfer model. The relationship between cloud radiative effects and the dynamical large-scale cloud organizations was studied.

(5) A 'Normalized Split Window Method, was developed to retrieve the ice cloud microphysics, by using satellite multiple infrared channel measurements. NSW method was applied to the infrared data measured by NOAA/AVHRR (Advanced Very High Resolution Radiometer) to obtain the global estimates of cloud optical features. It was indicated that tropical high level clouds play more significant role than the mid-high latitude clouds, from the viewpoint of the global climate change.

4 Concluding Remarks

In order to understand the cloud feedback effects to the climate change, many uncertainties are still remained with the present knowledge. In this study, we utilized various state-of-the-art satellite remote sensing data and an advanced radiative transfer model , developed new methods and performed analyses to reveal the structure of cloud systems and the cloud radiative properties. We also made some improvements in a treatment of clouds in the climate model.

As a result, we developed some new methods to analyze the variation of cloud radiative effects in relation to the large-scale circulation and the geographycal features, global cloud optical properties and time variations of cloud properties associated with the large-scale cloud organizations with more accuracy and detail than previous studies. We also showed the results of quantitative estimates of the global cloud parameters using these methods.

Individual satellite remote measurement, however, may still accompany some inevitable defects. For example, cloud information retrieved from infrared and visible radiance data could not convey information of the cloud overlapping. In order to supplement such individual defects, further efforts should be put to utilize multi-sensor data and intercomparison of retrievals physical quantities by different methods. In future, it is important to consider such points as well as applying those analysis methods to a long-term data to clarify the cloud effects in the climate system and the interaction mechanisms between clouds and large-scale dynamics.

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