Seasonal migration of cirrus clouds over the Asian Monsoon regions and the Tibetan Plateau measured from MODIS/Terra

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[1] By using a 4-year data set of the Moderate Resolution Imaging Spectroradiometer (MODIS) cirrus cloud reflectance, the seasonal migration of cirrus clouds over the Asian Monsoon regions and the Tibetan Plateau has been studied. There are two distinct regions with large amount of high clouds. One is located between the equator and 20°N, where intensified high clouds show clear northward and southward movements in association with the monsoon. The other is over the Tibetan Plateau, where large amount of cirrus clouds occurs in March to April and shows a more standing feature. Moreover, the significant amount of high clouds over two regions appears to be independent of each other. The one over the Tibetan Plateau is believed to be generated by relatively warm and moist air being slowly lifted over a large area by an approaching cold front and topographic lifting, and the other by the outflow or remains of cirroform anvils of cumulonimbi associated with deep convection in the Inter-tropical Convergence Zone (ITCZ) and monsoon systems.

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1. Introduction

[2] The most common form of high-level clouds is thin and often wispy cirrus cloud. Typically located at heights greater than 6 km (i.e., the upper troposphere and lower stratosphere) cirrus clouds are composed of ice crystals that originate from the freezing of supercooled water droplets. Cirrus clouds can significantly modulate the earth's radiation budget by reflecting the incoming solar radiation, absorbing the thermal emission from the ground and the lower atmosphere, and reemitting infrared radiation into space [e.g., *Liou*, 1986].

[3] Based on an 8-year data set from HIRS (High Resolution Infrared Radiation Sounder) satellite, *Wylie and Menzel* [1999] investigated the global distribution of cirrus clouds. They showed that cirrus clouds often occur in the Inter-tropical Convergence Zone (ITCZ) in the tropics, the mid-latitude storm belts from 30°–50°N, and the mountain region with lower concentrations in subtropical deserts and oceanic subtropical highs. Using water vapor and cirrus clouds data derived from the multichannel imaging data acquired with the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Terra Spacecraft, *Gao et al.* [2003] examined the seasonal variations of water vapor and cirrus clouds over the Tibetan Plateau for 2002, and found that the mean of high-cloud reflectance over the Plateau reaches its maximum in April and minimum in November.

[4] In the tropics, many of the cirrus clouds are generated as the outflow or remains of the cirroform anvils of cumulonimbi associated with deep convection [*Houze*, 1993]. On the other hand, in the middle latitudes cirrus clouds usually form in a location where warm air is being slowly lifted over a large area by an approaching cold front or where topographic lifting takes place. The Asian summer monsoon affects a large portion of Asia, parts of Africa and Australia. Along with the onset of monsoon, the abundant rainfall, in association with strong convective activity, occurs over the Indian subcontinent and China, and the subtropical westerly jet stream advances northward to the northern periphery of the Tibetan Plateau [e.g., *Flohn*, 1957]. Conceivably, strong convective activity within the monsoon system and the highest mountains in the world surrounding the Tibetan Plateau, such as the Himalayas, Pamir, Kunlun Shan and others, make the Asian monsoon regions and the Tibetan Plateau favorable to occurrences of cirrus clouds, and thus plentiful cirrus clouds may exist over these regions. It is possible that such abundant cirrus clouds over the Tibetan Plateau could provide a natural laboratory to study their formation and microphysical properties. Moreover, the bulk characteristics of cirrus clouds over the Tibetan Plateau and the Asian monsoon region, such as time mean, seasonal variations, etc., are important for studying cloud-climate feedbacks and their impacts on the climate change and monsoon-climate dynamics.

[5] Detecting thin cirrus clouds was traditionally difficult until new satellite measurements of the MODIS became available. In this study utilizing the newly available 4-year MODIS cirrus cloud reflectance data set, which was derived by using the retrieval method developed by Gao [e.g., *Gao et al.*, 2002], and was proved to be a rather accurate and reliable observation for detecting high clouds [e.g., *Gao et al.*, 2003], we will examine the seasonal variation and migration of cirrus clouds over the Tibetan Plateau and Asian monsoon regions. In the next section, a brief description of the data used will be given. The results will be shown in Section 3. A summary and brief discussion will be presented in Section 4.

2. Description of the MODIS Data Used

[6] The MODIS cirrus cloud reflectance data are obtained from a special channel centered at 1.375 μm which was

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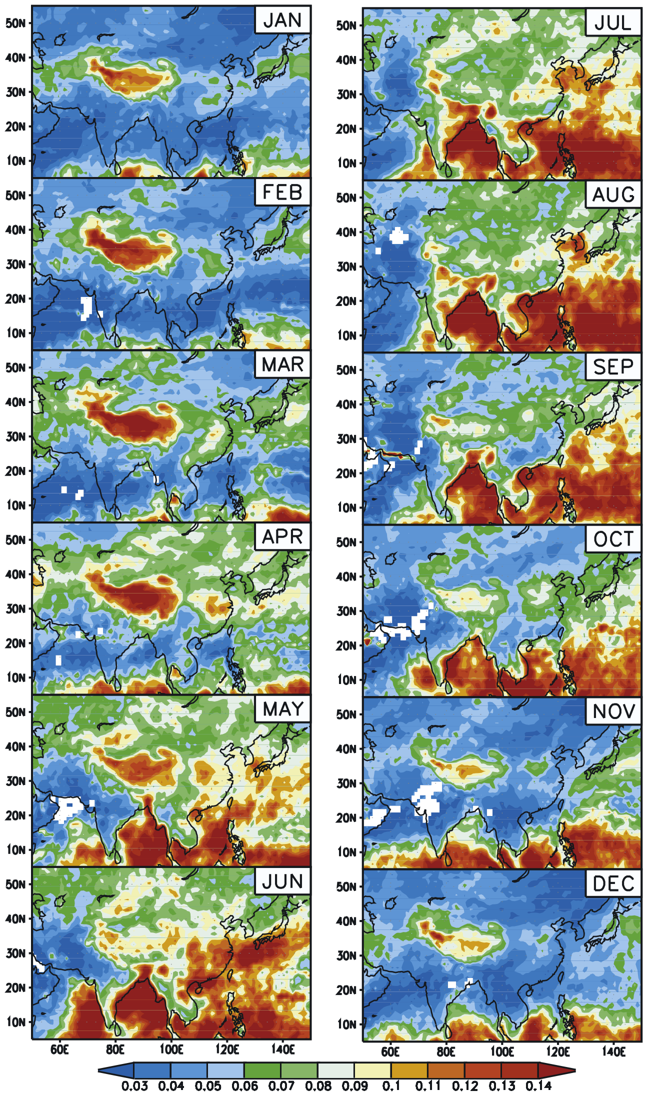

Figure 1. MODIS Level 3 4-year climatology of monthly mean of high cloud reflectance images over the Tibet Plateau and the nearby Asian regions for 12 months.

implemented on the MODIS instruments. The retrieval method is based on the fact that, in the absence of cirrus clouds, little solar radiance scattered by the surface and lower clouds reaches the sensor because of strong water vapor absorption in the lower atmosphere at this spectral band. When the high altitude cirrus clouds are present, the solar radiation scattered by these clouds can be received by the sensor. More details can be found in the work of *Gao et al.* [2002].

[7] The MODIS data are generally processed into different levels from Level 1 (radiances or brightness temperatures that have been geo-located), to Level 2 (derived geophysical data products at the same resolution and location as the Level 1 data), to Level 3 (variables mapped onto uniform space-time grid scale) [e.g., *King et al.*, 2003]. The Level 2 cirrus reflectance products are generated at the 1-km spatial resolution. Through integration of the Level 2 products, the Level 3 daily, 8-day and monthly-mean products are generated globally at an 1° by 1° latitude-longitude grid resolution. Because the MODIS is the first satellite instrument with the capability of the 1.375-micron channel for cirrus detection, the Level 3 MODIS cirrus reflectance data product provides a unique opportunity to study cirrus clouds on regional and global scales and to improve the cirrus climatology.

[8] In this study we used the monthly mean Level 3 MODIS cirrus reflectance, which covers a period from April 2000 to February 2004. In addition, the National Centers for Environmental Prediction (NCEP) reanalysis data are also used to compare with the MODIS data.

3. Results

[9] Figure 1 shows the monthly mean cirrus reflectance for years of 2000 to 2004. From January to March, a significant amount of high clouds is found along a mid-latitude band between 25°N and 40°N with the maximum over the Tibetan Plateau. There is little cirrus seen over the sub-tropical regions such as the Indian subcontinent and Indo-China. In April, the amount of high clouds starts to reduce over the Tibetan Plateau, but increases to the east of Tibet over southern and eastern China as well as around southern Japan. Moreover, the mid-latitude band of high clouds expands towards north and northeast. In May, the most outstanding feature is, being associated with onset of the Asian monsoon, abrupt emergence of great amount of high clouds in the Arabian Sea, the Bay of Bengal, the South China Sea and the Philippine Sea. However, high clouds over the Tibetan Plateau start to reduce. In June, much less cirrus clouds can be found over the Tibetan Plateau. On the other hand circus clouds in the southern Asian region continue to increase and move further northward. Furthermore, co-located with the "Meiyu" front [e.g., *Tao and Chen*, 1987], there is an intensified high cloud band extending from the southeastern edge of the Tibetan Plateau, crossing the southeastern part of China, to the east of Japan around 150°E. From July to September, a great amount of high clouds is still found in the Bay of Bengal, the South China Sea and the Philippine Sea but those in the Arabian Sea decrease and retreat southward. Also, a large amount of high clouds is located around the edges of the Tibetan Plateau, in particular along its southern side. From October to December, cirrus clouds steadily increase over the Tibetan Plateau, and gradually reduce and retreat southward over the Bay of Bengal, the South China Sea and the Philippine Sea.

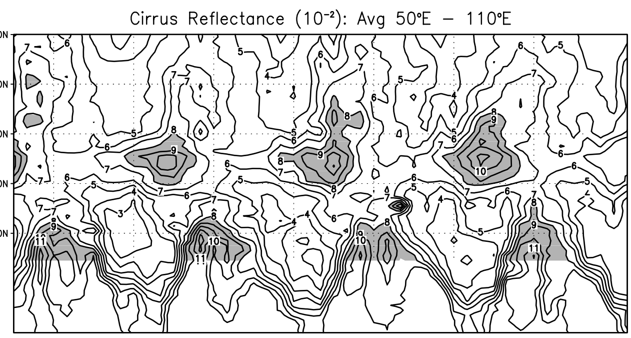

Figure 2. Time-latitude cross section of cirrus reflectance averaged between 50°E–110°E.

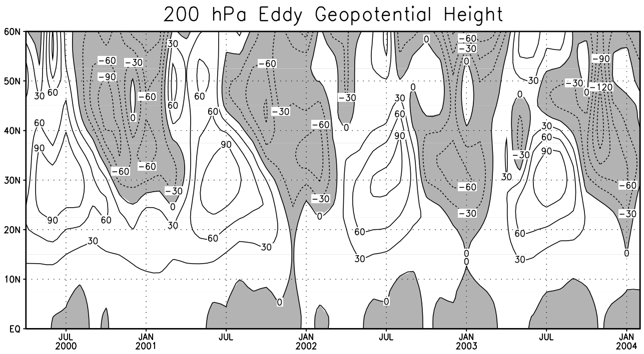

Figure 3. Time-latitude cross section of eddy geopotential height averaged between 50°E–110°E.

[10] Figure 2 illustrates the latitude-time cross section of cirrus reflectance averaged between 50°E and 110°E, which covers the entire Tibetan Plateau. There are two distinct bands of large amount of high clouds, one is located between the equator and 20°N and the other between 30°N and 40°N. Clear seasonal variation can be seen in the both bands. From September in each year, amount of high clouds starts to increase gradually over the Tibetan Plateau, and reaches its maximum around next April. After April, high clouds begin to reduce, reaching the minimum in August. During each spring, it can be seen that there is northward propagation of high clouds starting from the Tibetan Plateau. Moreover, the speed of propagation varies year by year, for example, very rapid northward moving can be found in 2001 but not in 2003. It is obvious that the large amount of high clouds over the Tibetan Plateau is generated locally, and the Tibetan Plateau appears to be a source place for intensive circus clouds. Unlike that over the Tibetan Plateau, the second band comes from the tropics and is closely associated with the northward movement of monsoon rain and the ITCZ. From May of each year to January of the next year, there exist two latitudinal migration processes in the intensified high clouds. One is a rapid northward advance starting at the equator in May and reaching the southern foothills of the Tibetan Plateau in June, and the other is a slow southward retreat from 25°N to the equator during an approximate 6-month period from August to next January. Furthermore, the latitudinal movement of large amount of cirrus clouds appears to vary year by year in terms of speed and intensity etc.

[11] The significant amount of high clouds over the Tibetan Plateau and those over the tropics and sub-tropics appear to be independent of each other. The former is believed to be generated by relatively warm and moist air being slowly lifted over a large area by an approaching cold front or topographic lifting. Geopotential height field is intensively used to identify mid-latitude cold fronts or storms in literature. Figure 3 shows the latitude-time cross section of 200 hPa eddy geopotential height from the NCEP reanalysis, where the eddy geopotential height is defined as the geopotential height with its zonal mean being removed. In comparison with Figure 2, the largest amount of high clouds over the Tibetan Plateau occurs during a transition period from active mid-latitude synoptic systems to the beginning of establishment of the so-called Tibetan High, suggesting a relationship between a large amount of high cloud over the Tibetan Plateau and the mid-latitude storm or front activities. On the other hand, the significant amount of high clouds in the low latitudes is coupled with the latitudinal movements of the ITCZ and onset of the Asian monsoon, in which strong convective activities usually take place. Therefore it is considered that many of cirrus clouds here are formed by the outflow or remains of cirroform anvils of cumulonimbi associated with deep convection in the ITCZ and monsoon system.

4. Summary and Discussion

[12] By using a 4-year MODIS cirrus cloud reflectance data set, the seasonal migration of cirrus clouds over the Asian Monsoon regions and over the Tibetan Plateau has been studied. There are two distinct regions with large amount of high clouds. One is located between the equator and 20°N, where intensified high clouds show clear northward and southward movements in association with the monsoon. The other is over the Tibetan Plateau, where the largest amount of cirrus clouds occurs in March to April and shows a more standing feature. Clear seasonal variation of cirrus clouds can be seen in both regions. Moreover, significant amount of high clouds over two regions appears to be independent of each other. The one over the Tibetan Plateau is believed to be generated by relatively warm and moist air being slowly lifted over a large area by an approaching cold front or topographic lifting, and the other by the outflow or remains of cirroform anvils of cumulonimbi associated with deep convection within the ITCZ and monsoon system.

[13] The findings of the present study are potentially significant for future hydrologic study and for the study of cloud-climate feedbacks as well. For example, the abundant cirrus clouds over the Tibetan Plateau found in this paper could provide a natural laboratory for studying conversion processes between water vapor and water ice clouds in the mid and upper troposphere. In addition, the results also present useful information linking large-scale circulation to diabatic (microphysical and radiative) heating that is crucial for understanding monsoon-climate dynamics.

[14] In this study we have only 4 years data, and simply speculate the mechanism responsible for these observed phenomena. The true mechanism may be different from our speculations. More extended meteorological observation is needed to better understand the formation and variations of high clouds in the Asian monsoon region and in the Tibetan Plateau. Moreover, few climate modelers pay attention to cirrus clouds because of lack of observation and large uncertainty in its parameterization. We expect that our understanding of high clouds in the Asian monsoon region and nearby will be further improved in the future with more atmospheric information being obtained by the observations such as the MODIS, and ultimately will be of benefit to improvements of climate modeling.

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