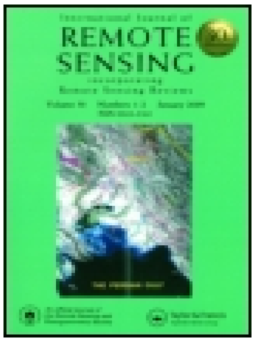

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Seasonal and regional variability of cloud liquid water path in northwestern China derived from MODIS/CERES observations

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This article describes the seasonal and regional variability of cloud liquid water path (LWP) in northwestern China. The regions of interest are: the area influenced by the Asian monsoon, the Tianshan Mountains, the Qilian Mountains and the Taklimakan Desert. The results presented here were derived from the instantaneous observations of cloud LWP from National Aeronautics and Space Administration (NASA) Clouds and the Earth's Radiant Energy System (CERES) Single Scanner Footprint (SSF) Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) Edition 1B data from July 2002 to June 2004, and reflect more detailed subregional features than previous results from International Satellite Cloud Climatology Project (ISCCP) D2 monthly mean data. The seasonal and annual variation in cloud LWP is found to be significant in northwestern China, even within the same climate region.

1. Introduction

Clouds consititute a crucial climate regulator and a sustainable water resource for arid and semi-arid northwestern China, which has a population of about 1000 million and a territory of about 4 290 000 km^2 with various topographies including deserts and mountains. Because of the dearth of observations, inadequately prescribed cloud parameters have been used in climate models and for weather modification research and are thus attributable to problematic cloud properties in this area.

Nowadays, satellite sensor data play an important role in studying cloud properties. Rossow and Lacis (1990) and other scientists (Tselioudis and Rossow 1994, Yi *et al.* 2003, Liu *et al.* 2004, Chen *et al.* 2005) studied cloud properties derived from International Satellite Cloud Climatology Project (ISCCP) data and found that cloud distribution has notable regional features, but the spatial resolution of the ISCCP data is insufficient to probe detailed differences of clouds within small subregions. Although previous research is helpful in understanding the cloud properties over northwestern China by analysing the results from dataset ISCCP D2 (Yi *et al.* 2003, Liu *et al.* 2004, Chen *et al.* 2005), determination of the cloud liquid water path (LWP)

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has not been addressed. Cloud liquid water (Minnis *et al.* 1995) plays an important role in the transport of energy (latent heat) in the Earth–atmosphere system; it varies considerably from cloud to cloud and its determination is important (Huang *et al.* 2006). With features of global coverage, high spatial and spectral resolution, recently available cloud data from the Moderate Resolution Imaging Spectroradiometer (MODIS) show significant spatial and temporal variation in cloud parameters. Therefore, in this work, we used data from the Single Scanner Footprint (SSF) MODIS Edition 1B onboard the Aqua satellite from July 2002 to June 2004, recently released from the National Aeronautics and Space Administration (NASA) Clouds and the Earth's Radiant Energy System (CERES), to advance the understanding of the cloud properties over subregions in northwestern China, and to document the seasonal variability of cloud LWP. The results can only be regarded as an estimate for the seasonal characteristics of the regions described here because the observation period is short.

2. Description of data and methodology

The CERES cloud detection algorithm (Minnis *et al.* 1995) is more advanced than that of previous global cloud datasets (e.g. ISCCP) in that it uses four instead of two wavelengths to decide whether a given pixel is clear or cloudy (Zhang *et al.* 2005). Another advantage is that the broadband shortwave and longwave radiance measurements taken by the CERES scanners are matched to simultaneous retrievals of cloud properties from MODIS. Positioning both imagers on the same satellite platform has provided more accurate data than before for the characterization of the instantaneous state of the atmosphere (Chambers *et al.* 2002). In addition, CERES uses high spectral and spatial resolution cloud imager data to determine cloud and surface properties. The nadir resolution of each CERES footprint on the SSF is 20 km (Minnis *et al.* 2003). Computation of the dataset is performed using 1 km MODIS pixels sampled to a 4 km spatial resolution instead of taking one 4–10 km pixel in each 30 km by 30 km box as in ISCCP. Regional cloud-type frequencies derived for $1^\circ \times 1^\circ$ latitude–longitude equal-area regions are used to determine cloud-type frequencies occurring over the entire 60° S–60° N domain (Zhang *et al.* 2005). Thus the results presented here meet the requirements of characterizing the cloud LWP observations over each typical subregion in northwestern China.

In this work, first the data were simply taken as a product at pixel level and then were binned and averaged. The statistics were based on grids with latitude and longitude marked in increments of 1°. Figure 1 shows the regions studied: the area influenced by the Asian monsoon (32 grids), the Tianshan Mountains (15 grids), the Qilian Mountains (14 grids), and the Taklimakan Desert (33 grids). The Qilian Mountains and the area influenced by the Asian monsoon have the advantage of being relatively close to the Indian Ocean and have more moisture, but the Taklimakan Desert and the Tianshan Mountains are farther from the oceans and situated in the westerly wind climatic region, which is generally affected by westerly circulation with limited humidity.

3. Results and discussion

The SSF products include the cloud LWP for two cloud layers defined as the lower and upper layers. Table 1 shows that the lower layer liquid clouds in the monsoon region had the largest LWP value (103.0 g m^{-2}) in autumn. In summer and spring the

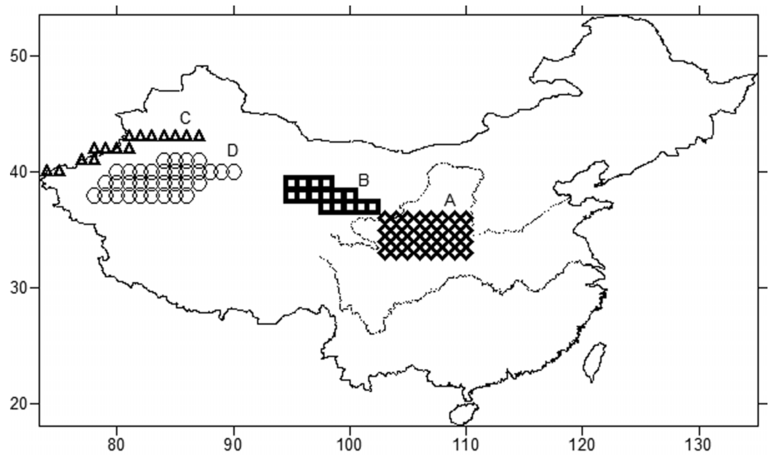

Figure 1. Map of the four regions in northwestern China: A, the area influenced by the Asian monsoon (32 grids); B, the Qilian Mountains (14 grids); C, the Tianshan Mountains (15 grids); and D, the Taklimakan Desert (33 grids).

Table 1. Seasonal and yearly mean values of cloud LWP (in g m^{-2}) in the four regions studied in northwestern China.

		Monsoon	Qilian	Tianshan	Desert
Lower layer cloud	Spring	93.6	50.9	79.6	28.4
	Summer	96.6	52.4	68.4	32.4
	Autumn	103.0	46.9	64.0	24.0
	Winter	66.5	51.3	69.2	35.6
	Yearly	90.4	50.3	70.1	30.1
Upper layer cloud	Spring	88. 5	78.5	57.0	12.4
	Summer	47.0	13.7	42.9	10.7
	Autumn	81.1	39.2	44.9	16.9
	Winter	64.1	26.4	43.9	13.8
	Yearly	80.3	57.9	47.9	24.7

observed values were also large, at 96.6 and 93.6 g m^{-2}, respectively. The mean values of the LWP in this region for the upper layer clouds was largest in spring (88.5 g m^{-2}), and only slightly lower in autumn (81.1 g m^{-2}). In summer, the LWP mean value was the lowest (47.0 g m^{-2}). The magnitudes of seasonal variability of the lower and upper layer clouds were 37.5 and 41.5 g m^{-2}, respectively. The values observed for the seasonal variation feature of LWP tended to be largest in autumn, which is consistent with the main precipitation period in this region (Chen *et al.* 2005). In winter, the observational values of both lower and upper layer clouds are generally small. Figure 2(*a*) shows that the LWP of the lower layer clouds over this region reached a peak in September and fell to its lowest value in January. Figure 2(*b*) shows that the LWP of the upper layer clouds had two peaks in March and from October to December, and its lowest dip came in August.

Apart from the upper layer clouds over the Qilian Mountains, the seasonal variability of LWP in the desert and two mountain regions was smaller than that of the monsoon region. For the lower layer clouds over the two mountain regions, autumn

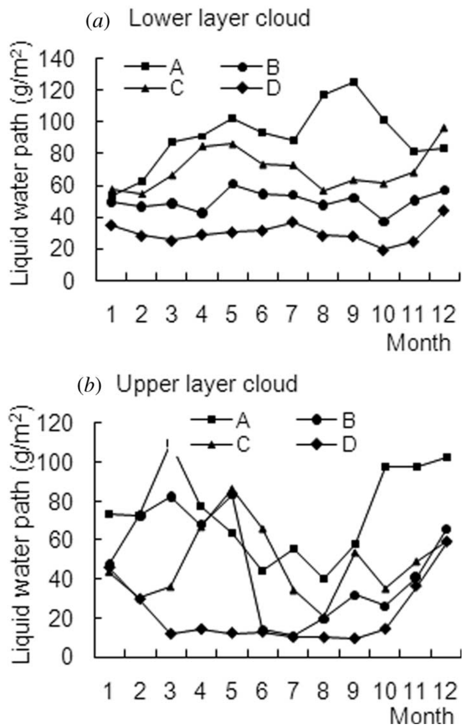

Figure 2. Annual cycle of the LWP over regions A, B, C and D for (*a*) lower layer clouds and (*b*) upper layer clouds, where A is the area influenced by the Asian monsoon, B is the Qilian Mountains, C is the Tianshan Mountains, and D is the Taklimakan Desert.

was the season of the smallest LWP (46.9 g m^{-2} for the Qilian Mountains and 64.0 g m^{-2} for the Tianshan Mountains) and spring and summer were the seasons of the largest LWP, reaching 52.4 g m^{-2} over the Qilian Mountains and 79.6 g m^{-2} over the Tianshan Mountains. For the upper layer clouds, summer was the season of the smallest LWP (13.7 g m^{-2} for the Qilian Mountains and 42.9 g m^{-2} for the Tianshan Mountains) and spring was the season of the largest LWP, reaching 78.5 g m^{-2} over the Qilian Mountains and 57.0 gm^{-2} over the Tianshan Mountains. The magnitudes of seasonal variability of the lower and upper layer clouds for the Tianshan Mountains are 15.6 and 14.1 g m^{-2}, respectively, and for the Qilian Mountains the corresponding values are 5.5 and 64.8 g m^{-2}. Figures 2(*a*) and 2(*b*) show that the monthly variation curves of LWP for the two layer clouds over the Qilian and Tianshan Mountains are different in magnitude.

In the desert region, the lower layer clouds had the largest observational values of LWP in winter (35.6 g m^{-2}) and the smallest in autumn (24.0 g m^{-2}). The observational values for the upper layer clouds were largest (16.9 g m^{-2}) in autumn and smallest (10.7 g m^{-2}) in summer. The magnitudes of the seasonal variability of the lower and upper layer clouds were 11.6 and 6.2 gm^{-2}, respectively. The monthly variation curve for the lower layer clouds was of low amplitude (19.4 gm^{-2}) and the peak value (43.9 g m^{-2}) was in October and December (see figure 2(*a*)). A sequential period of small observational values of LWP for upper layer clouds from March to October was found. One significant large value was observed in December (see figure 2(*b*)).

As expected, of the four regions, the desert region had the smallest yearly means for LWP, mainly because of the lack of moisture. Nevertheless, the observational values for the upper layer clouds in the desert region are very close to those in the mountain regions during the four months from October to January. Table 1 shows that the largest differences in cloud LWP observational values occurred between the monsoon region and the Taklimakan Desert. The differences in LWP yearly mean observational values for the lower and upper layer clouds between the Tianshan Mountains and the Qilian Mountains are significantly large.

Previous data (Chen *et al.* 2005) derived from ISCCP D2 found that the multiyear average regional mean of water path observational values was 77.6 g m^{-2} for the region with monsoon influence, which is significantly smaller than that found in this study; 50.7 g m^{-2} for the plateau climatic region where the Qilian Mountains are located, which is close to the value found in the current in this study; and 44.9 g m^{-2} for the westerly wind climatic region where the Tianshan Mountains and the Taklimakan Desert are located, which is significantly smaller than that found in this study for the Tianshan Mountains and larger than that for the Taklimakan Desert.

In summary, the spatial resolution of ISCCP datasets used by previous researchers was insufficient to probe detailed differences of clouds among the small subregions studied here, but the current study finds that the subregional differences of seasonal cloud LWP observational values are significant, even in the same climatic region in northwestern China. This should be taken into account in climate modelling because in climate model comparisons large differences in simulated net cloud radiative feedback have been found to be directly related to differences in the amount of cloud liquid water produced by the models. As a final note, the results presented here should only be regarded as an estimate of the seasonal characteristics of the regions described above as the observation period is fairly short.

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