Comprehensive Pattern of Deep Convective Systems over the Tibetan Plateau–South Asian Monsoon Region Based on TRMM Data

XIUSHU QIE

Key Laboratory for Semi-Arid Climate Change of the Ministry of Education/College of Atmospheric Sciences, Lanzhou University, Lanzhou, and Key Laboratory of Middle Atmosphere and Global Environment Observation (LAGEO), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, and Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China

XUEKE WU AND TIE YUAN

Key Laboratory for Semi-Arid Climate Change of the Ministry of Education/College of Atmospheric Sciences, Lanzhou University, Lanzhou, China

JIANCHUN BIAN AND DAREN LU

Key Laboratory of Middle Atmosphere and Global Environment Observation (LAGEO), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

(Manuscript received 23 January 2014, in final form 11 June 2014)

ABSTRACT

Diurnal and seasonal variation, intensity, and structure of deep convective systems (DCSs; with 20-dBZ echo tops exceeding 14 km) over the Tibetan Plateau–South Asian monsoon region from the Tibetan Plateau (TP) to the ocean are investigated using 14 yr of Tropical Rainfall Measuring Mission (TRMM) data. Four unique regions characterized by different orography are selected for comparison, including the TP, the southern Himalayan front (SHF), the South Asian subcontinent (SAS), and the ocean. DCSs and intense DCSs (IDCSs; with 40-dBZ echo tops exceeding 10 km) occur more frequently over the continent than over the ocean. About 23% of total DCSs develop into IDCSs in the SHF, followed by the TP (21%) and the SAS (15%), with the least over the ocean (2%). The average 20-dBZ echo-top height of IDCSs exceeds 16 km and 9% of them even exceed 18 km. DCSs and IDCSs are the most frequent over the SHF, especially in the westernmost SHF, where the intensity—in terms of strong radar echo-top (viz., 40 dBZ) height, ice-particle content, and lightning flash rate—is the strongest. DCSs over the TP are relatively weak in convective intensity and small in size but occur frequently. Oceanic DCSs possess the tallest cloud top (which mainly reflects small ice particles) and the largest size, but their convective intensity is markedly weaker. DCSs and IDCSs show a similar diurnal variation, mainly occurring in the afternoon with a peak at 1600 local time over land. Although most of both DCSs and IDCSs occur between April and October, DCSs have a peak in August, whereas IDCSs have a peak in May.

1. Introduction

Deep convective systems over the tropics and subtropics are vital in stratosphere–troposphere exchange (Sherwood and Dessler 2000) and play an important role in global energy exchange and the hydrological cycle. The Tibetan Plateau (TP) exerts a crucial impact on the formation and enhancement of deep convection nearby. The southern foothills of the Himalayas are a region known to yield some of the most vigorous deep convection with most active lightning activity on Earth (e.g., Christian et al. 2003; Qie et al. 2003c; Liu and Zipser 2005; Zipser et al. 2006; Liu et al. 2007). Numerical simulations have shown that about 75% of water vapor transported into the global tropical stratosphere in summer may originate from the South Asian monsoon and TP regions.
(Gettelman et al. 2004), and the largest water vapor concentration, at an altitude of about 18 km [unless otherwise stated, all heights in the paper are above mean sea level (MSL)], is located over the South Asian monsoon region (Jackson et al. 1998; Bian et al. 2012). Water vapor, which is transported into the upper troposphere via monsoon convection over the TP and its southern slope, disperses into the large-scale upward motion of the global stratospheric circulation (Fu et al. 2006). It is further suggested that the anticyclone circulation in the Asian monsoon region is an important pathway for water vapor and pollutants to enter the stratosphere (Park et al. 2007; Randel et al. 2010).

As the world’s tallest and largest plateau, the TP is home to a wide range of unusual thermal and dynamic interactions that exert profound impacts upon global climate change and the formation of weather disasters (Wu and Zhang 1998; Xu et al. 2002; Zhou et al. 2008). Qie et al. (2003a) found that the most frequent lightning over the TP takes place in the central plateau region and that lightning activity is more sensitive to the solar heating over the TP than in adjacent areas at the same latitude (Qie et al. 2003b). The South Asian monsoon is one of the most significant monsoons, together with the existence of the Tibetan Plateau, making convection in this region an important scientific topic. Fu et al. (2006) indicated that moist convection over the TP is deeper and transports more water vapor and CO through the tropopause than over the South Asian monsoon region (SAMR). However, Park et al. (2007) found that the most intense convection occurred over the SAS, not the TP or its southern slope. Houze et al. (2007) analyzed the location and the formation of three kinds of extreme precipitation events with deep intense convective echoes, wide intense convective echoes, or broad stratiform echoes by using Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) data during June–September in 2002 and 2003. The results show that deep and wide intense convective echoes over the northwestern Indian subcontinent tend to occur where the low-level moist layer of monsoon air from the Arabian Sea meets dry down slope flow. Following the convection classification of Houze et al. (2007), Romatschke et al. (2010) studied the distribution characteristics and diurnal variations of these three extreme precipitation events. They suggested that convection over the TP is weaker than over the southern slope of the plateau and the southern Asian monsoon region.

Recent studies have shown significant differences among the precipitation and convective features of deep convection over different parts of the Asian monsoon region (Xu 2013; Wu et al. 2013). Although Houze et al. (2007) and Romatschke et al. (2010) studied carefully different kinds of extreme precipitation events over the South Asian monsoon region, they did not discriminate the convective characteristics over different topographic regions. Using data from CloudSat and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), Luo et al. (2011) conducted a comprehensive study on deep convection over different regions of the Tibetan Plateau–Asian monsoon region and worldwide and showed that deep convection over the TP is shallower, less frequent, and embedded in smaller-size convection systems but the cloud tops are more densely packed than the other subregions. CloudSat/CALIPSO observation lacks a full sample of the diurnal cycle (only at approximately 0130 and 1330 local time), and its main task is to detect the vertical structure of clouds and distribution of aerosols and clouds around the world and its ability to detect the internal structure of extreme precipitation events is limited.

This paper attempts to provide a comprehensive description on deep convective systems over the domain of interest ($6°$–$36°$N, $68°$–$103°$E, as shown in Fig. 1), using the Tropical Rainfall Measuring Mission (TRMM) data. Four adjacent subregions in the Tibetan Plateau–South Asian monsoon region (TP-SAMR; the inner rectangular box in Fig. 1) are selected by taking into account the unique topography and related spatial distribution of lightning flash rate (Cecil et al. 2014): as the TP itself (elevation $>3$ km, north of the gray contour line in Fig. 1), the southern Himalayan front (SHF; north of the black curved line, consisting of a short straight line and an arc line, with elevation $\leq3$ km), the South Asian subcontinent (SAS; south of the black curve in Fig. 1), and the ocean farther south. Different from the southern slope of the plateau (SSP) adopted by Fu et al. (2006) and Luo et al. (2011), the SHF in this study is more matching to the topographical features of the Himalayas. The area ratios of the four subregions are approximately...
convective systems (DCSs), no matter how large their 14 km (Liu and Zipser 2005) are further defined as deep convective systems. The Lightning Imaging Sensor (LIS) records the lightning activity of the precipitation system. As an excellent indicator of convective activity, the lightning flash rate provides information on the deep convective intensity (Ávila et al. 2010; Liu et al. 2012). A more detailed description of the TRMM sensor package is given by Kummerow et al. (1998, 2000).

The University of Utah TRMM precipitation feature (PF) database (available at http://trmm.chpc.utah.edu/) was developed based on the framework of PFs defined by Nesbitt et al. (2000) and further improved with features identified from nine years of TRMM observations by Liu et al. (2008). To fully utilize the 3D information from PR reflectivity profiles, the definition of Radar projection precipitation features (RPPFs) is adopted in this study. The detailed process and calculation of parameters is given by Liu et al. (2008). Furthermore, to indicate the impact of the most vertically penetrative convection on stratosphere–troposphere exchange, RPPFs with a 20-dBZ radar echo-top height (Maxht20) exceeding 14 km (Liu and Zipser 2005) are further defined as deep convective systems (DCSs), no matter how large their horizontal scale. It should be noted that, according to this criteria, the database still contains some erroneous DCS cases. For example, the radar echo profile shows an abnormal and discontinuous echo in the vertical; the radar echo contains a thick anvil aloft. Both kinds of radar echo profiles show that their 20-dBZ echo-top height reaches up to 20 km, but obviously they are not DCSs. With the exclusion of such cases, a total of 16 784 DCSs are identified finally, accounting for 2.8% of the total RPPFs. To understand the most intense convective activity in the TP-SAMR, DCSs with 40-dBZ echo-top height ≥10 km—namely the intense DCSs (IDCSs), which may be closely related to extremely strong updrafts—are further investigated. The definition of IDCS is similar to the deep convective cores in Houze et al. (2007) and Romatschke et al. (2010), with convective echo ≥40 dBZ extending 10 km in height. A total of 2433 IDCSs are found over the entire study area, accounting for 14.5% of the total DCSs. In addition, the data collection frequency of the TRMM satellite in different regions from tropic to subtropics depends strongly on their latitude (Negri et al. 2002). That is due to the fact that the satellite spends more time around 34°N in its latitudinal excursion (where its latitudinal speed is slow) than near the equator (where its latitudinal speed is fast), and the sampling frequency has a maximum around 34°N, about 4 times more than that near the equator, and decreasing northward to zero at 36.5°N rapidly. Hence, in this study, by dividing proper coefficients at different latitudes, the sampling biases of the spatial distributions of DCSs and IDCSs are corrected.

Surface (0.995 sigma level) wind and relative humidity are plotted by using 6-hourly products obtained from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) from 1998 to 2010 and the NCEP Climate Forecast System, version 2 (CFSV2), (Saha et al. 2014) for 2011. Because DCSs occur mainly in the afternoon in the studied regions, wind and relative humidity fields at 0600 UTC [about 1200 local time (LT)] are used to represent the atmospheric conditions before the onset of the DCSs.

3. Results

a. Climatological characteristics of deep convective systems

The spatial distribution, temporal variation, structural features, and dynamic microphysical properties of convective systems may be significantly different over different regions because of the influence of meteorological
circumstances, cloud condensation nuclei (CCN) concentration, and the unique topography condition of the ground. The climatological characteristics of DCSs over the TP-SAMR are investigated in this section by analyzing their spatial distribution and diurnal and seasonal variations.

1) SPATIAL DISTRIBUTION OF DCSs

In the TP-SAMR, there are 84% of annual total DCSs that appear during May through October. Therefore, based on TRMM PR and NCEP reanalysis data from 1998 to 2011, the geographical distributions of DCSs from May to October are shown in Fig. 2, along with the mean surface wind and relative humidity at 0600 UTC (about 1200 LT) on days with the occurrence of DCS. Their distributions vary significantly in different months and are closely related to the distribution of surface humidity and wind fields (refer to Fig. 2), which provide the necessary moisture and momentum fluxes for the formation of DCSs. DCSs mainly appear over the regions with moderate water vapor content. The numbers of DCSs over the four different subregions are listed in Table 1. Combined with the DCS distribution shown in Fig. 2, it can be found that DCSs mainly distribute over the continental regions while less distribute over the ocean. The number of DCSs over the SAS is the largest, accounting for 45% of the total observed DCSs in the TP-SAMR. Over the ocean, more DCSs are distributed over the Bay of Bengal than over the Arabian Sea, and they locate more densely over the coastal water.

DCSs over the TP occur mainly from June to September, particularly during July and August, when westerly winds weaken gradually from May to August and relative humidity increases westward from the eastern TP. In the boreal summer, strong surface heating over the TP leads to shallow surface depression and deep high at middle and upper troposphere and ultimately forming upward motion over the TP, and this upward motion is stronger over the eastern TP while downward motion forms over the western TP (Wu et al. 2004). Profited also from its high elevation, convection over the TP can strengthen into DCSs easier than elsewhere. As a result, DCSs locate more densely over the central TP in July and move to the eastern TP in August, while quite few DCSs appear over the western TP. After August, the occurrence frequency of DCSs over the TP reduces with a strengthening of westerly winds and a decrease of water vapor content.

DCSs mainly appear near the coast of the Bay of Bengal during the premonsoon season (in May, as shown in Fig. 2) and move northward gradually to the midlatitude region during the monsoon season, particularly in July and August. The burst of the South Asian summer monsoon usually takes place in early June, when the equatorial low pressure zone [the intertropical convergence zone (ITCZ)] moves from the Southern to the Northern Hemisphere. Correspondingly, the south-east trade wind in Southern Hemisphere previously crossed the equator to the Northern Hemisphere and becomes the southwest trade wind affecting the South Asian monsoon region. Then, the southwest monsoon wind dominants gradually over the Indian subcontinent and the interaction of southwest wind and the Himalayan front terrain enhances. As a result, DCSs over the SHF and north SAS occur mainly during the summer monsoon season (June–September) and are located in an arc-shaped belt region along the terrain features of the Himalayas, which is consistent with the distribution of lightning (Kumar and Kamra 2012; Cecil et al. 2014). Meanwhile, with the onset of the South Asian summer monsoon, a low-level moist air mass flows from the Bay of Bengal northward to the TP and is blocked by the steep Himalayas and then turns to the northwest along the foothills of the Himalayas, forming a strong south-east to northwest humidity gradient over the northwest of the Bay of Bengal. Besides, the westerly flow over the Indian subcontinent and the westward airflow along the foothills of the Himalayas form a low-level convergence zone, which is conducive to the occurrence of DCSs over this region. Therefore, DCSs are located mainly to the northwest of the Bay of Bengal in June and September, extend to the northwest and reach the westernmost end of the Himalayas in July and August, and then decrease rapidly with the retreat of the summer monsoon after September.

Houze et al. (2007) and Romatschke et al. (2010) indicated that, during the summer monsoon season, low-level moist flow is capped by dry and cold air from the plateau (the Afghan or the Tibetan Plateau) when it arrives at the foothills of the Himalayas, which inhibits the release of instability and accumulates enough energy for the formation of DCSs. When low-level moist flow impinges on the terrain indentation, it will be orographically lifted to saturation and break through the stable layer to release its instability and trigger formation of the most intense DCSs in the region, where lightning density exceeds 70 flashes per square kilometer per year (Cecil et al. 2014). Meanwhile, the low-level air mass can be further moistened and warmed by the ground surface as it is transported to the western SHF. Our study suggests that water vapor transport along the foothills of the Himalayas from the Bay of Bengal may also play a vital role in the occurrence and formation of DCSs over the westernmost portion of SHF.

In addition, in the upper troposphere, the region to the right of the westerly jet stream during the premonsoon
FIG. 2. Monthly (May–October from top to bottom) geographical distribution of (left) DCSs and (right) surface wind (vectors) and relative humidity (color) during 1998–2011. The spatial resolution of DCSs and relative humidity are 0.5° × 0.5° and the wind field is 2.5° × 2.5°. The DCSs are observed by TRMM PR and the distribution is corrected by using TRMM PR pixels obtained from TRMM product 3A25 and wind and humidity obtained from NCEP CFSR (1998–2010) and CFSV2 (2011).
and the transition zone between westerly and easterly jet streams during the monsoon form an upper divergence outflow (an anticyclone circulation), which is conducive to the maintenance and development of DCSs over this region. Romatschke et al. (2010) and Wu et al. (2013) showed that deep convection over Asia is mainly located south of the Tropic of Cancer during the premonsoon and in midlatitude regions during the monsoon, coincident with the locations of the anticyclone circulation, the southernmost extension of the 200-hPa westerly jet during the premonsoon season, and the transition zone between westerly and easterly jet during the monsoon season.

2) DIURNAL AND SEASONAL VARIATION OF DCSs

The diurnal and seasonal variations of DCSs over four subregions are shown in Fig. 3. It can be seen from Fig. 3a that continental DCSs show significant diurnal variation, appearing mainly in the afternoon with a peak at 1600 LT, which is closely related to the surface heating and the surface gust fronts. DCSs over the TP are more concentrated in the afternoon than the other regions, and there are almost no DCSs between 0000 and 1000 LT. The diurnal variation of DCSs over the SAS is similar to that over the TP, but there are some DCSs at nighttime, which is consistent with that of deep convection by Liu and Zipser (2005) and Romatschke et al. (2010). However, there are more DCS occurring during 0000–0400 LT over the SHF, and the percentage is more than twice as large as over the other continental regions (e.g., the SAS and the TP). The occurrence frequency of oceanic DCS is the least in the afternoon and increases slightly from 0000 LT, with a small peak value at 0400 LT, as shown in Fig. 3a. This shows a kind of inverse relationship between DCSs over land and over water. That is, the oceanic DCSs are slightly enhanced when the continental DCSs quiet, which may be related to the large-scale upwelling and subsidence (Sátori et al. 2009). Compared with the continental convection, the variation of the oceanic convection is generally flat with local time.

The seasonal variations of DCS shown in Fig. 3b manifest a semiannual variation near the equatorial region and an annual variation in the midlatitude region. More precisely, DCSs over the TP are more concentrated in July and August and almost no DCSs occur in winter and autumn. The seasonal variation of DCS activity over the SHF is similar to that over the TP but with more activity than over the TP in May and June and with a peak in August. DCSs over the SAS occur mainly from May to September but occur all the year. Over the ocean, DCSs occur throughout the whole year and show a semiannual variation, with two peaks in May and October, consistent with the semiannual variation of mean number of thunderstorm days and lightning activity in the lower-latitude belts over the Indian subcontinent region (Williams 1994; Manohar et al. 1999). This is caused mainly by the seasonal variation of solar radiation. The sun crosses the tropics twice a year and causes two maxima in surface land temperature over the course of one year, while only one maximum appears over the midlatitude region (north of the Tropic of Cancer, as shown in Fig. 1).

b. Climatological characteristics of the most intense deep convective systems

Statistical results reveal that the average 20-dBZ echo-top height of IDCSs can exceed 16 km. Moreover, more than 31% and 9% of IDCSs can exceed 17 and 18 km, respectively. Usually, the tropopause height increases from higher latitude to the equator and is roughly 16–17 km in the tropical area (Gettelman and Forster 2002). As an outstanding heat source in boreal summer, the TP thermally pushes the tropopause upward by around 2 km compared with the plain area at the same latitude and results in a tropopause height of about 17–18 km over the TP (Feng et al. 2011).
Nonetheless, IDCS with higher echo-top height might be considered to be strong enough to transport water vapor and pollutants directly into the stratosphere. Although IDCSs only account for 15% of total DCSs, they are likely to play a crucial role in transporting water vapor and pollutants (especially short-lived pollutants) into the stratosphere.

1) SPATIAL DISTRIBUTION OF THE IDCSs

More than 90% of IDCSs occur between April and September over the TP-SAMR continental regions. Therefore, the monthly spatial distribution of IDCSs from April to September is further shown in Fig. 4. The numbers of IDCSs along with their percentage of total DCSs in each of the four subregions are summarized in Table 1. Compared with the distribution of DCSs shown in Fig. 2, it is found that the geographical distribution of IDCSs in Fig. 4 is distinctly different from that of DCSs. IDCSs are more densely distributed over continental regions than DCSs and have conspicuously less occurrence over the ocean. Compared with the DCSs, there are more IDCSs occurring during the premonsoon season (here included as April and May in Fig. 4), accounting for approximately 36% of the total IDCSs. IDCSs are more likely to occur near northwest coast of the Bay of Bengal. During the premonsoon season, because of the South Asian monsoon region begin dominated by the subsidence of the Hadley circulation from the ITCZ upwelling far equatorward, the temperature is increasing and the skies are generally cloud free. At the same time, the atmosphere is significantly conditionally unstable and conducive to the occurrence of the convection with prodigious lightning, which is consistent with the same behavior in Australia found by Williams et al. (1992). Meanwhile, the air mass over the South Asian monsoon region is mainly from midcontinent, with less moisture. As a result, in April, IDCSs occur frequently near the coast of the Bay of Bengal and almost no IDCSs appear over the midlatitude continent and over the west coast of the Indian subcontinent. The occurrence frequency of IDCSs is the largest in May (~22%), when the surface air temperature is at its seasonal maximum and the atmosphere shows the largest conditional instability.
With the onset of the Indian summer monsoon in early June, the monsoon southwesterly flow increases and carries moisture from the Indian Ocean to the Indian subcontinent. Meanwhile, the distribution of IDCSs extends to midlatitude continent from the Indian subcontinent coastal region. IDCSs decrease near the northwest coast of the Bay of Bengal and increase markedly over the SHF. The dense center of IDCSs appears over the westernmost of the SHF, and becomes more prominent during July and August with the strengthening of the summer monsoon. During the same period, except in the northwest of the Indian subcontinent, IDCSs rarely occur over the other regions: for example, the northwest coast of the Bay of Bengal, where IDCSs occur frequently in the premonsoon months. With the end of the summer monsoon, the occurrence frequency of IDCSs decreases in the postmonsoon (October), when they are more uniformly distributed over the continent. Over the TP, IDCSs distribute over the eastern TP in June, then extend westward in July, and widely distribute over the TP in August. In September, the distribution of IDCSs is similar to that in June, mainly over the eastern TP, which is closely related to the seasonal distribution of humidity over the TP.

Comparing the distributions of DCSs and IDCSs (as shown in Figs. 2 and 4), it is found that the distributions of DCSs and IDCSs over the TP are similar from June through September, whereas, over the SHF and the SAS, their distributions are different significantly, especially from July to September. IDCSs are more likely to appear over the concave indentation area in the westernmost SHF, followed by the region to the northwest of the Bay of Bengal. The distribution of IDCSs is more consistent with the distribution of lightning density (Kumar and Kamra 2012; Cecil et al. 2014), because lightning is usually produced by well-developed convection in the vertical. In addition, compared with the distribution of surface wind and relative humidity shown in the right column of Fig. 2, it can be found that the IDCSs are more likely over the region, with relatively large moisture gradients and relative humidity (RH) at moderate levels (40%–60%). The drier circumstance is not suitable for the occurrence of IDCSs. (Air mass is too dry so that it is difficult to attain the lifting condensation level and DCSs obviously cannot form.) Likewise, the regions with high humidity (RH exceeding 60%) are not conducive to the occurrence of IDCSs either: for instance, in the southwestern coast of the Indian subcontinent and the northwestern coast of the Indochinese Peninsula from June to September and in the northeastern portion of the Indian subcontinent in July and August. Williams et al. (2005) pointed out that the “juicy” conditions (in reference to moisture and dewpoint temperature) are not the most favorable conditions for superlative electrification of thunderstorms. Xiong et al. (2006) also found that the higher relative humidity results in lighting activities in dry regions. Additionally, the statistical values listed in Table 1 show that DCSs over the SHF are most likely to strengthen into IDCSs, with about 23% of DCSs developing into IDCSs in this region, followed by 21% over the TP. Although the percentage of DCSs strengthening into IDCS over the SAS is only 15%, the population of IDCS is the largest among the four subregions, which is almost the sum of that over SHF and the TP. On the contrary, the number of IDCSs over the ocean is by far the least and it makes up only 2% of the DCSs, much less than the average percentage over all regions of 15%.

The DCSs develop into IDCSs more easily over continental regions than over ocean, especially over the westernmost indentation of the Himalayas in July and August and the northwest coast of the Bay of Bengal during the premonsoon season (April and May), while oceanic DCSs rarely strengthen to become IDCSs. This is closely related to the differences of atmospheric conditions, such as convective available potential energy (CAPE), humidity, temperature, CCN, and cloud-base height (CBH) over land and ocean. The vertical distribution of CAPE, especially in a lower layer, is important for the development of the convection (Blanchard 1998). Even though CAPE is roughly the same magnitude for continental and oceanic regimes, the shape of CAPE (positive area in the skew T diagram) over land is usually “fat” and the parcel can achieve more buoyancy, but the area between the free convection level and the parcel equilibrium level is thinner. In contrast, the oceanic positive area is “skinny” and can extend to higher altitudes vertically (Lucas et al. 1994). Williams et al. (2005) showed that dry bulb temperature and CBH are important indicators of lightning activity (an indication of intense convection) and by inference the updraft speed in thunderstorms. The CBH plays an important role in regulating the transfer of CAPE to updraft kinetic energy in thunderstorms both in the tropical and midlatitude regions. Thunderstorms with higher total lightning flash rates (larger updrafts) are also found in regions with higher cloud-base heights. Microphysical aerosol effects are closely related to the dynamical effects of aerosols on the cloud intensity and structure (Khain et al. 2005). More CCN in the continental boundary layer resulting from fire or other sources of natural pollution leads to a reduction in droplet size (Williams et al. 2002), with the implication of a large number of small droplets with a low collision rate, resulting in a time delay for raindrop formation and preventing the decrease of vertical velocity caused by the falling raindrops (Khain et al. 2005). When droplets rise
to the freezing level, they release additional latent heat by freezing, which further strengthens the updrafts. So, larger CCN concentration over the continent tends to invigorate convection, which then has larger vertical velocities and attains higher altitudes. In contrast, the oceanic convective clouds form raindrops earlier, which descend through the cloud updrafts and increase the loading at low levels, thereby decreasing cloud updrafts.

It has been widely recognized that vertical velocities in oceanic convection are significantly smaller than in continental convection. The difference is caused by the higher instability of the continental atmosphere. This is usually attributed to a potentially higher surface temperature, a fat-shaped CAPE, a larger concentration of CCN, and a higher CBH. Taken together, these features enable convection over the continent with more intense updraft velocity and hence with greater probability to intensify into IDCS than over ocean. As a result, DCSSs and IDCSs are more frequent over land than over the ocean.

2) DIURNAL AND SEASONAL VARIATION OF IDCSs

The diurnal variation of IDCSs is shown in Fig. 5a. IDCSs over the four subregions show a similar diurnal variation with that of DCSSs, as shown in Fig. 3a. Note that IDCSs over the ocean occur rarely (only 83, accounting for only 2% of the total DCSSs), which results in the diurnal variation with quite a few small peaks. The IDCSs over the TP and the SAS occur mainly in the afternoon with a peak around 1600 LT, while only few IDCSs appear before 1100 LT. The IDCSs over the SHF also occur mainly in the afternoon, but there is a considerable portion of IDCSs appearing during 0000–0600 LT, which is significantly different from the other two continental regions: that is, the TP and the SAS. This may result from the summer monsoon wind and the unique terrain condition: that is, blocking by the steep Himalayas and the strong orographic lifting over the southern slope of the Himalayas.

The seasonal variations of IDCSs over the four subregions are shown in Fig. 5b, and it is distinctly different from that of DCSSs (refer to Fig. 3b). IDCSs over the TP mainly occur in boreal summer (July and August) with a peak in July, whereas, over the subregions of the SHF, the SAS, and the ocean, IDCSs occur mainly during the premonsoon with a peak in May. Combining with the spatial distribution from April to September, it can be found that IDCSs in the SAS during the premonsoon are densely located near the coastal region of the Bay of Bengal. However, IDCSs over the SHF mainly distribute in the eastern SHF during the premonsoon and move to the western SHF during the monsoon season. As a result, the seasonal variation of IDCSs over the SHF shows a main peak in May and a secondary peak in July.

The South Asian summer monsoon circulation exerts a vital impact on the occurrence of DCSSs and IDCSs over the TP–SAMR. During the premonsoon, air masses from the midlatitude continental regions and oceanic regions interact frequently over the coastal region. The atmosphere of the Indian subcontinent shows the largest conditional instability during the premonsoon, especially in May, when the maximum surface temperature can reach about 50°C over India (De et al. 2005) and the oceanic air mass carries abundant moisture from the ocean. IDCSs occur mainly over the coastal region during the premonsoon, with the peak in May, consistent with the seasonal variation of the lightning activity over the Indian subcontinent region (Kandalgaonkar et al. 2003). After the burst of the Indian summer monsoon, the monsoon southwesterly flow becomes dominant and the continental air mass from midcontinent is suppressed. The interaction of summer monsoon circulation and the Himalayan terrain is enhanced and the humidity increases over the Indian subcontinent, with both leading to the frequent occurrence of DCSSs. However, with the onset of the rainy season in the India subcontinent, the cloud area begins to increase and the air temperature drops. The atmospheric environment over the continent becomes moister and cooler than before. The occurrence frequency of IDCSs decreases over the continent. Fewer IDCSs during the monsoon than the premonsoon reveals that convection over the Indian subcontinent is more
intense in the premonsoon season than in the monsoon season. Ranalkar and Chaudhari (2009) also found that the lightning flash counts are larger in the premonsoon season than in the monsoon season. Over the regions north of the Tropic of Cancer, the IDCS population increases after the onset of the summer monsoon. As shown in Fig. 4, IDCSs occur frequently over the westernmost SHF in July and August. DCS and IDCS over the TP occur mainly in July and August, because of the strong surface sensible heating and the increase of humidity over the TP in boreal summer.

c. Convective properties and structures of the DCS

The TRMM PR provides 3D structural features of precipitation systems, and the VIRS provides the cloud-top information on convective clouds, which helps us to investigate the structural features of DCSs easily. The most direct indicator of convection intensity is the vertical velocity of buoyant updrafts, but it is difficult to observe (Zipser et al. 2006). Therefore, parameters such as the height attained by the 40-dBZ radar echo, the minimum brightness temperature at 37 GHz, and the lightning flash rate, all provided by the TRMM satellite, are used to indicate the convective intensity. Accordingly, in this study, six parameters extracted and calculated from the TRMM database are used to characterize convective intensity and structures of DCSs over the four subregions:

- Maxht20 (kilometer MSL), the maximum height of 20-dBZ PR reflectivity within the DCS;
- MinIR (kelvin), the minimum brightness temperature at 10.8-μm wavelength measured by VIRS within the DCS;
- NPixels20, the TRMM PR pixel count for reflectivity exceeding 20 dBZ;
- MaxRht40 [kilometer above ground level (AGL)], maximum height of 40-dBZ radar echo relative to the ground;
- Min37PCT (kelvin), the minimum polarization-corrected temperature at 37 GHz observed by TMI within the DCS; and
- FlRate (flashes per minute), the lightning flash rate within DCS from the LIS.

These six parameters over the four different topographic subregions are shown in Fig. 6. The parameters in Figs. 6a–c are used to describe the structural feature of DCSs and those in Figs. 6d–f are used mainly to characterize the convective intensity.

The Maxht20 of DCSs over the SHF and SAS are similar, with both higher than those over the TP and the ocean, but the Maxht20 for the top 5% DCSs over the SHF is larger than that over the SAS (Fig. 6a), which means that more DCSs over the SHF develop to higher altitude than over the SAS. The MinIR reflects the cloud-top of the convective cloud, and the lower the MinIR, the higher the cloud top. Figure 6b shows that, apart from the value of 95% over the TP, all the statistical values of MinIR show that the cloud-top height of DCSs increases southward from the TP to the SHF, SAS, and ocean, which is consistent with the results obtained from CloudSat/CALIPSO data (Luo et al. 2011). Also, these findings are consistent with the distribution of average tropopause height, which generally increases from higher latitudes to the tropics. Formally, the tropopause is defined as a level where the environmental lapse rate changes from positive, as it behaves in the troposphere, to the stratospheric negative. Such a stable level is inferred to inhibit deep cumulonimbus growth. From Fig. 6c, it can be easily seen that the size of DCSs over the SHF and the SAS are similar, but it is much larger over the ocean than the other three subregions and it is especially small over the TP.

To reveal the convective intensity of the DCSs and to avoid the influence of the ground elevation over different subregions, the parameter of MaxRht40 is adopted here (Fig. 6d). Combined with the Min37PCT and FlRate (Figs. 6e,f), it can be found that the convective intensity (in terms of 40-dBZ strong echo-top height relative to the ground, large-ice-particle content, and flash rate) of DCS over the TP is weak, even weaker than over the ocean. DCSs over the TP seem to be characterized by a shallower strong radar echo top, a lower large-ice-particle content, and a lower flash rate. However, the convective intensity of DCSs over the SHF is greater than elsewhere, with a deeper strong radar echo, more large-ice-particle content, and a larger lightning flash rate.

To show intuitively the structural features of DCS over the four different terrain subregions, the average 20-, 30-, and 40-dBZ echo structure features of DCSs over the four subregions are schematically shown in Fig. 7. The averaging PR pixel counts above different levels are also listed in Table 2 to quantify and compare the structural features of DCS over different subregions. For the vertical features of DCSs, the 20-dBZ echo top over the SHF is the highest and reaches up to 15.4 km, followed by 15.3 km over the SAS and then the TP and the ocean. The vertical feature of 30-dBZ echo manifests similarly with that of 20 dBZ but about 3 km lower. The tallest 40-dBZ echo core of DCSs exceeds 8.6 km over the TP, followed by 8.3 km over the SHF and less than 8 km over the SAS. DCSs over the ocean have the lowest 40-dBZ echo core of 6.6 km. The horizontal features (according to pixel number of PR) of DCSs are also different over different subregions (Fig. 7). On the
whole, the scale of DCS over the ocean is the largest and the smallest over the TP, while that over the SHF is larger than over the SAS slightly. Table 2 further shows the quantitative PR pixel counts above different altitudes. It can be found that the volume of DCS over the TP is especially small compared with that over the other two continental subregions, the SHF and the SAS. The 20-dBZ echo volume of DCS over the ocean is at least as large as that of the SHF and the SAS, but the difference between the continental region and oceanic region reduces with increasing altitude. The total volume and the volume above a lower altitude (6 km) show that the largest DCSs are found over the ocean, followed by the SHF. However, the volume of DCS in the higher range of altitudes (10 and 14 km) is the largest over the SHF, followed by the SAS. That is, the radar echo volume of DCS over the ocean is the largest but mainly appears in lower altitudes, which reduces more rapidly with the increasing altitude than continental DCS.

The above analysis reveals that DCS over the ocean has higher cloud-top height (refer to MinIR) but lower 20-dBZ echo-top height than over the land. Liu et al. (2007) also showed that categorization of cold cloud features (CCFs), based on the minimum brightness temperature at 10.8 μm (TB11) and 20-dBZ heights, demonstrated that the coldest clouds occur most frequently over the west Pacific (the same as over the Bay of Bengal). There is a large depth of ice clouds undetectable by the PR. The vertical distances between the cloud-top heights determined from TB11 and PR 20-dBZ echo-top heights are smaller over land than over ocean. The largest distances are over the Indian Ocean during northern summer and spring, SPCZ southern summer, and west Pacific northern summer. Using
CALIPSO/CloudSat data, Luo et al. (2011) also found that oceanic convection has higher cloud-top height but lower radar echo-top height. As mentioned earlier, the CAPE positive area over the ocean is narrower but deeper than over land; as a result, the updraft within oceanic DCS is weaker but can reach a higher altitude. In addition, the level of neutral buoyancy (LNB) over the ocean is higher than over land, which permits even weak convection to produce deep cold clouds without 20-dBZ echo-top heights above 10 km (Liu et al. 2007). Over the continental regions, a fat CAPE positive area can produce a stronger updraft, which may penetrate the LNB and cause DCSs with cold cloud-top temperatures and high 20-dBZ echo-top heights.

4. Conclusions and discussion

The climatological characteristics of DCSs and IDCSs over four adjacent geographical regions are analyzed using TRMM data from 1998 to 2011, and the diurnal and seasonal variations of DCSs and IDCSs are compared for the four subregions with different terrain conditions. Finally, the convective properties and structural features of DCSs over different unique subregions are investigated and compared. The main results are summarized as follows:

- The occurrence of DCSs and IDCSs is more frequent over continental regions than over the ocean. The DCSs are located mainly over the SHF, northeastern SAS, and TP. IDCSs account for 15% of total DCSs in the entire region, but they behave obviously different over the four subregions. DCSs over the SHF are most likely to strengthen to become IDCSs (with a proportion of 23% of total DCSs) compared to the other three subregions, followed by the TP (21%), SAS (15%), and ocean (2%).
- DCSs mainly occur between May and October (84%), with a peak in August, while 90% of IDCSs occur between April and September, with a peak in May. Over...
the TP, both of DCSs and IDCs occur mainly in July and August. However, the IDCs over the other three subregions show a maximum in May, corresponding to the strong conditional instability over the Indian subcontinent during the premonsoon. This also means that convection over the Indian subcontinent during the premonsoon is more intense than during the monsoon. Impacted by the different atmospheric conditions before and after the burst of the summer monsoon, in terms of air temperature, moisture transport, and the interaction of wind and terrain of the Himalayas, IDCs more densely located over the coastal region of the Bay of Bengal during the premonsoon and over the westernmost SHF during the monsoon.

The diurnal variation of DCSs and IDCs are similar, showing a kind of inverse relationship between those over land and over water. Both DCSs and IDCs occur mainly in the late afternoon over continental regions with a peak around 1600 LT (IDCs are slightly later), while oceanic DCSs and IDCs have a slight peak at late night and the early morning and a second peak in the afternoon. The occurrence of early morning DCSs over the SHF is more common than in the other continental regions.

The convective properties and structural features of DCSs are significantly different over different terrain regions. The strong radar echo-top height (40 dBZ), ice-particle content, and lightning flash rate all indicate that the convective intensity of DCSs over the SHF is the strongest, followed by the SAS. However, the convective depth (or convective cloud-top height) behaves differently. Cloud-top height (refer to MinIR: mainly reflects smaller ice particles) of DCSs increases southward from the TP to the SHF, the SAS, and then the ocean. The oceanic DCSs have the largest echo size in the horizontal and tallest cloud top in vertical, but their convective intensity is weaker: that is, lower 40-dBZ echo top, fewer large ice particles, lower lightning flash rate, and smaller echo volume at higher levels. The difference of DCSs over continent and ocean reveals that the oceanic DCS has higher cloud-top height but lower TRMM PR echo-top height (e.g., 20, 30, and 40 dBZ).

Houze et al. (2007) hypothesized that the low-level southwestern airflow is moistened over the Arabian Sea, warmed by sensible heat flux over the Thar Desert, and then lifted over the Himalayan foothills, to trigger and warmed by sensible heat flux over the Thar Desert, and southwestern airflow is moistened over the Arabian Sea, to trigger and warmed by sensible heat flux over the Thar Desert, and southwestern airflow is moistened over the Arabian Sea, to trigger and warmed by sensible heat flux over the Thar Desert, and southwestern airflow is moistened over the Arabian Sea, to trigger and warmed by sensible heat flux over the Thar Desert, and southwestern airflow is moistened over the Arabian Sea.

**Acknowledgments.** The authors thank the University of Utah for providing the TRMM database via their website (http://trmm.chpc.utah.edu/), as well as the NOAA/OAR/ESRL PSD for providing the NCEP CFSR and CFSV2 reanalysis data (http://rda.ucar.edu/pub/cfsr.html). This research was completed cooperatively between Institute of Atmospheric Physics and Lanzhou University, and the main results come from part of the Ph.D. dissertation of Xueke Wu in Lanzhou University supervised by Xiushu Qie. This research was supported jointly by the National Key Basic Research and Development (973) Program of China (2010CB428601) and the National Natural Science Foundation of China (40930949 and 40905008). The authors thank Dr. Earle Williams and one anonymous reviewer for their valuable suggestions, which improved substantially the quality of this paper.

**REFERENCES**


Christian, H. J., and Coauthors, 2003: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector.


