Moisture Sources of Torrential Rainfall Events in the Sichuan Basin of China during Summers of 2009–13

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ABSTRACT

Water vapor sources and transport paths associated with torrential rains are very important to research and forecasts. This study investigates the main moisture sources and transport paths related to torrential rainfall events in the Sichuan basin of China, which is located east of the Tibetan Plateau, using a Lagrangian flexible particle dispersion model (FLEXPART). Based on the analysis of the torrential rainfall distribution during 2009–13, four study areas are selected in the basin. Particles that have a great contribution to the torrential rainfall events within the four study areas are traced back for 10 days, and a quantitative analysis of the contributions from various moisture sources to the torrential rainfall events is also conducted. The results indicate that a large number of target particles start at the Arabian Sea and the Bay of Bengal, land on the Indo-China Peninsula, and finally reach the study areas. This is an important moisture transport path for the torrential rainfall events within the four study areas. Another important path is from the neighborhood of the Sichuan basin. The total moisture supplies from all examined moisture sources within the whole atmospheric layer account for more than 90% of precipitation within the study areas. There are two major moisture sources, the Sichuan basin and the Bay of Bengal, and the South China Sea could be another important moisture source region for the torrential rains in the northeastern Sichuan basin.

1. Introduction

Torrential rains, which can cause floods, landslides, debris flows, and other geological hazards resulting in severe loss of life and property damage, are a great challenge to weather forecasters. Serious floods, landslides, and debris flows often occur in the Sichuan basin of China, which is located east of the Tibetan Plateau, south of the Qinling Heights, and north of the Yunnan–Guizhou Plateau, especially after violent earthquakes, like the Wenchuan earthquake in 2008 (8.0 on the Richter scale) and the Ya'an earthquake in 2013 (7.0 on the Richter scale).

Precipitation occurs throughout the year in the Sichuan basin, mainly as a result of the East Asian monsoon, the Indian monsoon, and the atmospheric circulation system interacting with the Tibetan Plateau. Torrential rainfall in the Sichuan basin usually occurs in the summer season, June–September. Figure 1 shows the topographic height in Sichuan and distribution of total torrential rainfall (24-h accumulated precipitation $\geq$50 mm, based on the precipitation grading standards used at the National Meteorological Center, China) in the Sichuan region from June to September 2009–13. The terrain at the edge of the Sichuan basin is very complex, especially on the western side of the basin, adjacent to the Tibetan Plateau, where the terrain slope is particularly steep (Fig. 1a). Heavy rainfall mainly occurs in the Sichuan basin, especially at the edge of the basin, where terrain is complex and steep

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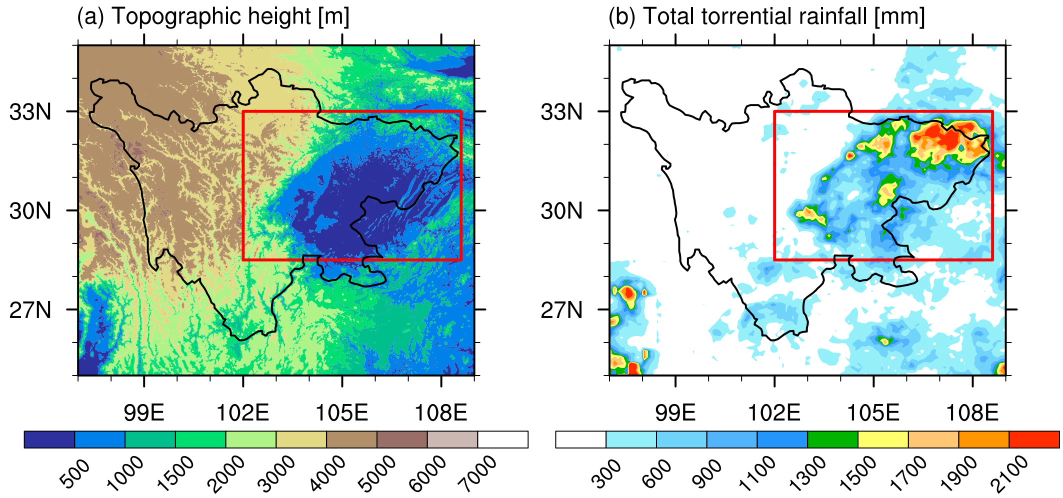

FIG. 1. (a) Topographic height (m) and (b) distribution (mm) of total torrential rainfall (24-h accumulated precipitation ≥50 mm) during June–September 2009–13 in Sichuan. Red rectangles represent the Sichuan basin.

with four strong centers (Fig. 1b), implying complex interactions between circulation and topography. The first center is located in the Ya'an area near steep terrain east of the Tibetan Plateau. The second one is situated in the northeastern corner of the basin, the Daba Shan zone. The third one is in the northwestern part of the basin, and the last one is in the central region of the basin. The terrains of three of these regions—the Ya'an region, the northeastern basin, and the northwestern basin—are very complicated, which may be closely related with the occurrence of heavy rainfall in these regions (Fig. 1b).

For torrential rainfall events to occur, moisture sources (suitable regions of evaporation), transport paths, and uplifting motions are three indispensable conditions (Gustafsson et al. 2010). It is crucial to study moisture source regions and transport paths for heavy rainfall (Newell et al. 1992). In general, local evaporation from the surface of the region, moisture already present in the atmosphere over the region, and water vapor transported into the region by wind have been identified as possible moisture sources for precipitation (Brubaker et al. 1993). Gustafsson et al. (2010) found that atmospheric transport is a prerequisite for extreme rainfall events to occur in southern Sweden, and regional moisture may also play a key role. Drumond et al. (2011a) found that the Arabian Sea and the Bay of Bengal are important moisture sources for the southern and central regions of China by using a Lagrangian approach. As for the Sichuan basin with its very complex terrain, what the most important moisture sources and transport paths are for the torrential rainfall events within the basin is still a big question to be solved, one that is crucial to the research and forecasting of torrential rains, related floods, and geological hazards.

There are several methods to identify moisture sources and transport paths for rainfall events, such as isotopic analysis (Weyhenmeyer et al. 2002; Bonne et al. 2014), Eulerian methods (Holman and Vavrus 2012; Sun and Wang 2013), and Lagrangian methods (Gustafsson et al. 2010; Drumond et al. 2011a,b). However, it is impossible for isotopic analysis methods to examine past events for which no rain samples are available (Gustafsson et al. 2010). For the moisture flux, the conventional Eulerian method can only give simple water vapor transport paths and fails to accurately identify the moisture source regions that contribute to torrential rainfall events (Sodemann et al. 2008). Recently, a sophisticated Lagrangian flexible particle dispersion model (FLEXPART) was developed and widely used to study moisture sources and transport paths (e.g., Stohl and James 2004, 2005; Stohl et al. 2008; Sodemann and Stohl 2009; Gimeno et al. 2010a,b, 2013; Chen et al. 2013; Gómez-Hernández et al. 2013).

Huang and Cui (2015) used FLEXPART to study the moisture sources of an extreme precipitation event that occurred in Sichuan in July 2013, causing substantial losses. They found that water vapor originating from the Indian Peninsula–Bay of Bengal–Indo-China Peninsula region had the highest contribution to this extreme event. However, there was only one case analyzed in their study, and a composite analysis of multiple cases in the Sichuan basin of China should be conducted to make their conclusions more statistically significant (Huang and Cui 2015). In this study, by using the same Lagrangian method, the moisture transport paths and main moisture source regions for the multiple torrential rainfall events in the Sichuan basin of China are studied. Meanwhile, we also quantitatively estimate contributions from various moisture sources to the heavy rainfall events.

2. Data, model, and methodology

The precipitation data used in this study are from a 0.1° × 0.1° resolution dataset from 2009 to 2013 generated through hourly precipitation observations by automatic weather stations in China and merged with CPC morphing technique (CMORPH) satellite data (Pan et al. 2012; Shen et al. 2013). The topographic height data shown in Fig. 1a are from the Global Land One-km Base Elevation Project (GLOBE) database (www.ngdc.noaa.gov/mgg/topo/globe.html).

a. Study areas and selection of torrential rainfall events

For the selection of the regions of interest (study areas), probability density function (PDF) and cumulative distribution function (CDF) curves of the heavy rainfall in the Sichuan basin (28.5°–33.0°N, 102.0°–108.6°E; red rectangles in Fig. 1) were plotted and are shown in Fig. 2. From Fig. 2, it is found that inflection points appear around 1300 mm on the curves corresponding to 85% CDF. Based on analysis of this threshold value of the total torrential rainfall in the Sichuan basin, four study areas are selected in the Sichuan basin, as shown in Fig. 3 (middle) and marked by rectangles. Then, the torrential rainfall events occurring in each area and examined in this study are selected by the following two steps. First, we use daily precipitation to identify the torrential rainfall grid points (24-h accumulated precipitation ≥50 mm on each grid). Second, for a torrential rainfall event examined in this study, we require that at least 20% of the grid points in the study area record torrential rainfall. There are 16, 16, 18, and 20 torrential rainfall events selected for the four study areas, respectively (Table 1). Figure 3 (right, left) shows the total rainfall of selected torrential rainfall events for the four study areas. The four total accumulated precipitation centers [Fig. 3 (right, left)] are basically in the center of each selected study area, indicating that the study areas and the torrential rainfall events we selected have certain representativeness.

b. Model setup

To determine the main moisture sources, their contributions to the torrential rainfall, and moisture transport paths of the study areas, FLEXPART, version 9.02, developed by Stohl and James (2004, 2005) is used. FLEXPART is driven by the National Centers for Environmental Prediction Final Analysis (NCEP FNL) Operational Global Analysis data available every 6 h with a 1° × 1° resolution on 26 vertical levels (http://rda.ucar.edu/datasets/ds083.2/) for the region 10°S–60°N, 40°–160°E, and the period from 2009 to 2013, using the domain filling mode, with a total of 1.2 million particles released. The model outputs are recorded every 3 h and include the identity number of particles, the three-dimensional position, temperature, specific humidity, air density, atmospheric boundary layer height at the position of particles, and the mass of each particle. The model settings in this study are the same as those in Huang and Cui (2015) except for the model run time, which was 2009–13 (5 years) in this study.

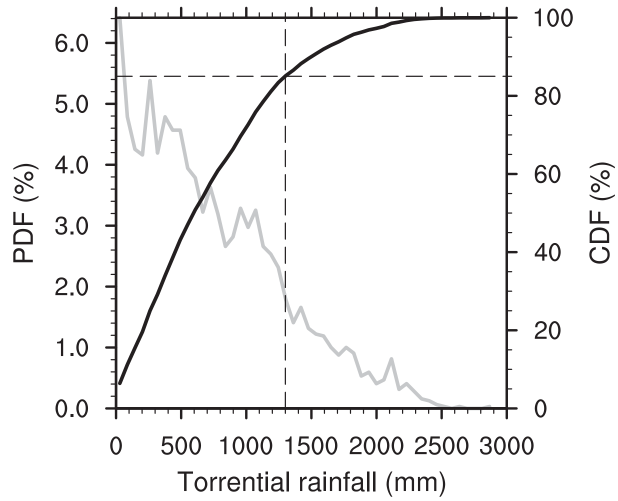

FIG. 2. PDF (%; gray line) and CDF (%; black line) of the total torrential rainfall during June–September 2009–13 in the Sichuan basin (red rectangles in Fig. 1). The horizontal and vertical dashed lines denote 85% CDF and 1300 mm torrential rainfall, respectively.

c. Selection of target particles and determination of contribution from moisture sources

1) SELECTION OF TARGET PARTICLES

Using the Lagrangian method, we can track particles of interest that may have important contributions to torrential rainfall events (named as target particles), identify sites in which target particles' moisture increases, and finally determine moisture source regions of the torrential rainfall. Here, we use a similar method to that applied by Stohl et al. (2008) to determine the target particles. The particles having water vapor release within the study areas in the precipitation period are selected as target particles in this study. Then we obtain the target particles having contributions to the torrential rainfall events, track these target particles, and analyze their contributions to the precipitation. The minimum and maximum number of target particles among the

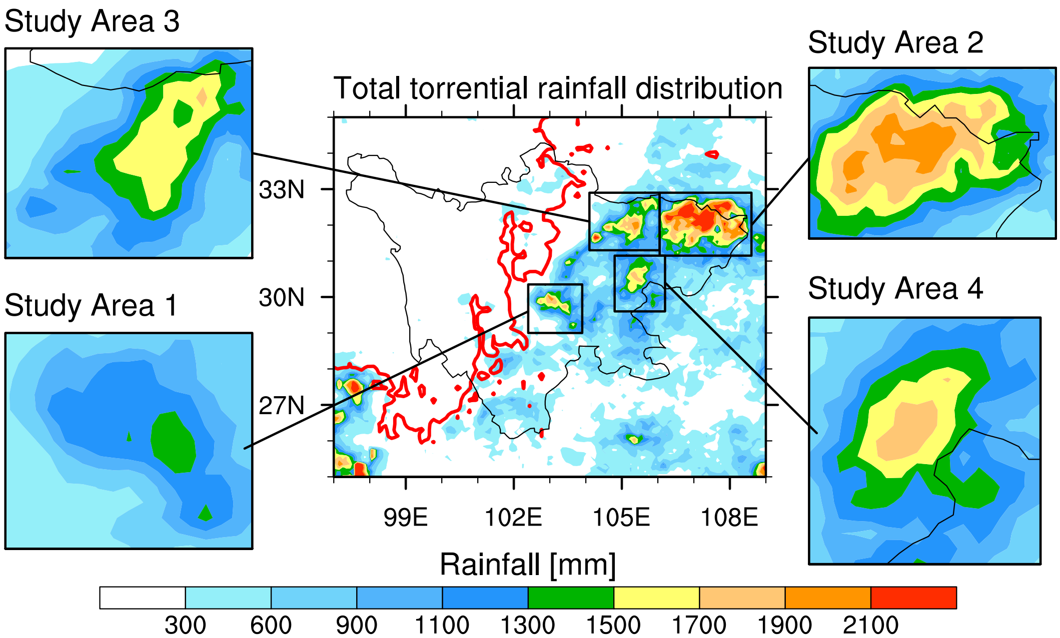

FIG. 3. (middle) Distribution of total torrential rainfall (24-h accumulated precipitation ≥50 mm; as in Fig. 1b) during June–September 2009–13 in Sichuan. (right),(left) Total rainfall (mm) of selected torrential rainfall events for four study areas marked with rectangles in (middle). The red thick solid line indicates 3-km height contours of the Tibetan Plateau.

selected cases and the total number of target particles of all the selected cases in the four study areas are shown in Table 1.

2) DETERMINATION OF CONTRIBUTIONS FROM MOISTURE SOURCES

In the Lagrangian method, for a particle, the mass is m, and rates of moisture increase and decrease along the trajectory are e and p, respectively. Changes of specific humidity q with time t are used to diagnose the water vapor budget of a particle (Stohl and James 2004, 2005):

$$e - p = m\frac{dq}{dt}. \tag{1}$$

Amassing the moisture changes of all N particles residing in the atmospheric column over an area A gives

$$E - P \approx \frac{\sum_{i=1}^{N}(e-p)}{A}, \tag{2}$$

where E and P are the evaporation and precipitation rates per unit area, respectively (Stohl and James 2004). Therefore, $E - P$ represents the surface net freshwater flux. And

TABLE 1. Number of cases selected, min and max number of target particles among the selected cases, total number of target particles of all the selected cases, and number of particles for the climatology in the study areas.

Study area	Area	Number of cases selected	Min number of target particles among the selected cases	Max number of target particles among the selected cases	Total number of target particles of all the selected cases	Number of particles for the climatology
1	29.0°–30.35°N, 102.4°–103.9°E	16	656	1970	16 023	120 114
2	31.15°–32.9°N, 106.05°–108.6°E	16	1371	5047	44 960	255 518
3	31.3°–32.9°N, 104.1°–106.05°E	18	708	2412	24 873	166 649
4	29.6°–31.15°N, 104.8°–106.2°E	20	576	1735	18 968	124 160

dq/dt could be integrated to diagnose $E - P$ by using the Lagrangian model output. The main advantage of the Lagrangian method over the Eulerian method is that the Lagrangian method [Eq. (2)] can track $E - P$ forward or backward in time by evaluating [Eq. (1)] along the trajectories of target particles only (Stohl and James 2004, 2005). When we diagnose torrential rainfall events, a region with $E - P \gg 0$ may be a strong moisture source for the precipitation, and target particles passing over this region may carry water vapor from this region into the target region.

Actually, before precipitation in the study areas occurs, air parcels over the examined moisture source regions may undergo multiple cycles of moisture uptake and release along their way to the target region. Therefore, because of the precipitation during parcel transportation, earlier moisture uptake will contribute less and less to the precipitation within the target region (Sodemann et al. 2008). Hence, continuous changes in particles' moisture along their trajectories to the precipitation in the target regions (the study areas in this paper) should be taken into consideration. To address this issue, Sodemann et al. (2008) introduced a source attribution method, which calculates the contribution of each evaporation region along a parcel's trajectory to the precipitation falling in the target region. This method has been widely applied (Pfahl and Wernli 2008; Sodemann and Stohl 2009; Chen et al. 2011; Martius et al. 2013). In this study, an altered method, the areal source–receptor attribution method introduced by Sun and Wang (2014) based on Sodemann et al. (2008), is used to estimate the contribution of moisture source regions to the precipitation in the target region. For further details on the areal source–receptor attribution method, please refer to Sun and Wang (2014).

3. Results

a. Moisture transport paths

In this study, we trace the target particles backward from each study area for all of the selected torrential rainfall events within a 10-day transport time, which is the average residence time of moisture in the atmosphere (Numaguti 1999; Trenberth 1999). The trajectory cluster analysis method proposed by Dorling et al. (1992) is used in this study, and cluster mean trajectories representing all the real trajectories are used to analyze water vapor transport from source regions to target regions. Figure 4 shows the cluster mean trajectories of the target particles reaching each study area. As for

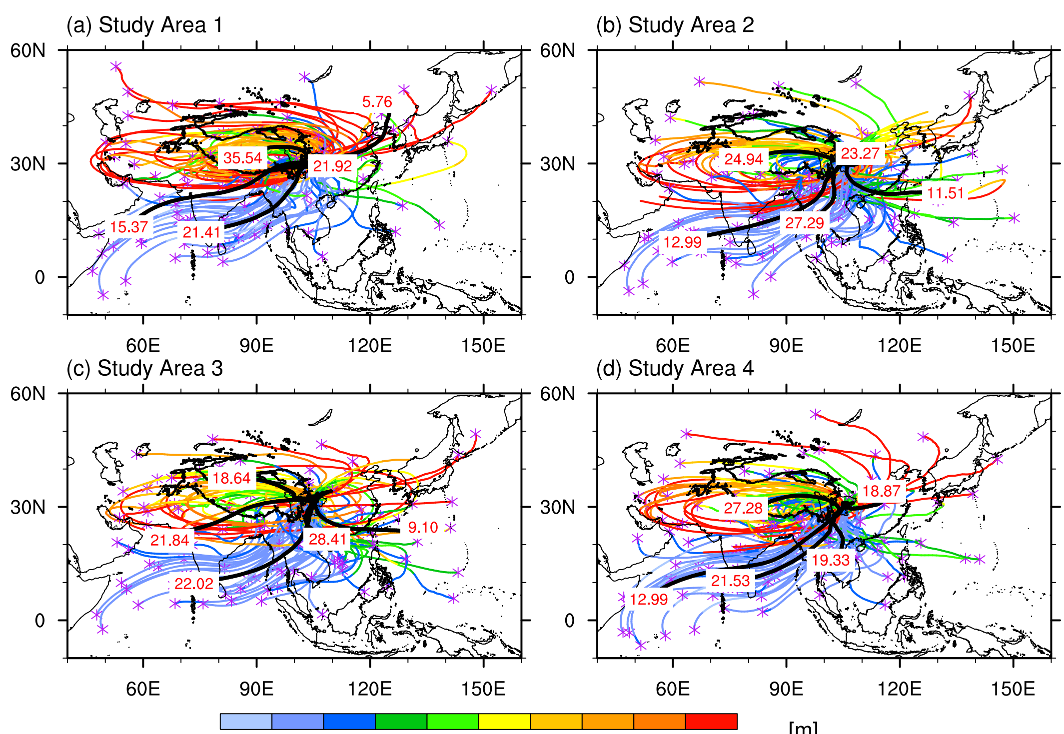

FIG. 4. Cluster mean trajectories (cluster number 100: color trajectories; cluster number 5: thick black solid trajectories) with the percentage of trajectories of each cluster relative to the total trajectories of the target particles reaching each study area provided in red. Trajectory segments are color coded according to the associated altitudes (m AGL). Purple asterisks indicate the beginning of the trajectories. The thin black solid contours indicate 3-km height contours of the Tibetan Plateau.

torrential rains within the four study areas, the most obvious common feature is that a large number of particles start from the Arabian Sea and the Bay of Bengal (Fig. 4). These particles travel through the Indian Peninsula, then join the particles coming from the Bay of Bengal, land on the Indo-China Peninsula, and finally reach the target regions. Moreover, the vast majority of these particles come from relatively low atmospheric layers [below 4000 m above ground level (AGL)]. This should be an important moisture transport path for the torrential rainfall within the four study areas. It should be noted that another important water vapor path is from the neighborhood of the Sichuan basin (purple asterisks in Fig. 4). As in study area 2 (northeastern corner of the Sichuan basin; Fig. 4b) and study area 3 (northwestern basin; Fig. 4c), a few particles come from the East China Sea and the South China Sea. Additionally, another part of the target particles comes from higher atmospheric layers over the Tibetan Plateau.

However, it is worth noticing that, as already stated, air particles may undergo several moisture uptake and release cycles from the moisture source regions to the target regions; thus, the contribution of the source region's moisture to the torrential rainfall within the target region will become increasingly smaller. Quantitative contributions of water vapor sources require further analysis and calculations.

b. *Moisture sources and their contributions to the torrential rainfall*

To identify the moisture source regions of the torrential rainfall events within the four study areas, $E - P$ is diagnosed by using the FLEXPART output data. Figure 5 shows values of $E - P$ diagnosed from trajectories of the target particles 1–10 days before reaching the four study areas. The red areas ($E - P > 0$) in Fig. 5 indicate net uptakes of moisture, representing moisture sources. The blue areas ($E - P < 0$) indicate net releases of moisture, representing moisture sinks. From Fig. 5, for each study area, target particles have abundant water vapor uptakes through the Arabian Sea, the Bay of Bengal, and the Sichuan basin region. For study area 2 (Fig. 5b), the northeastern Sichuan basin, the target particles also get plentiful moisture from the South

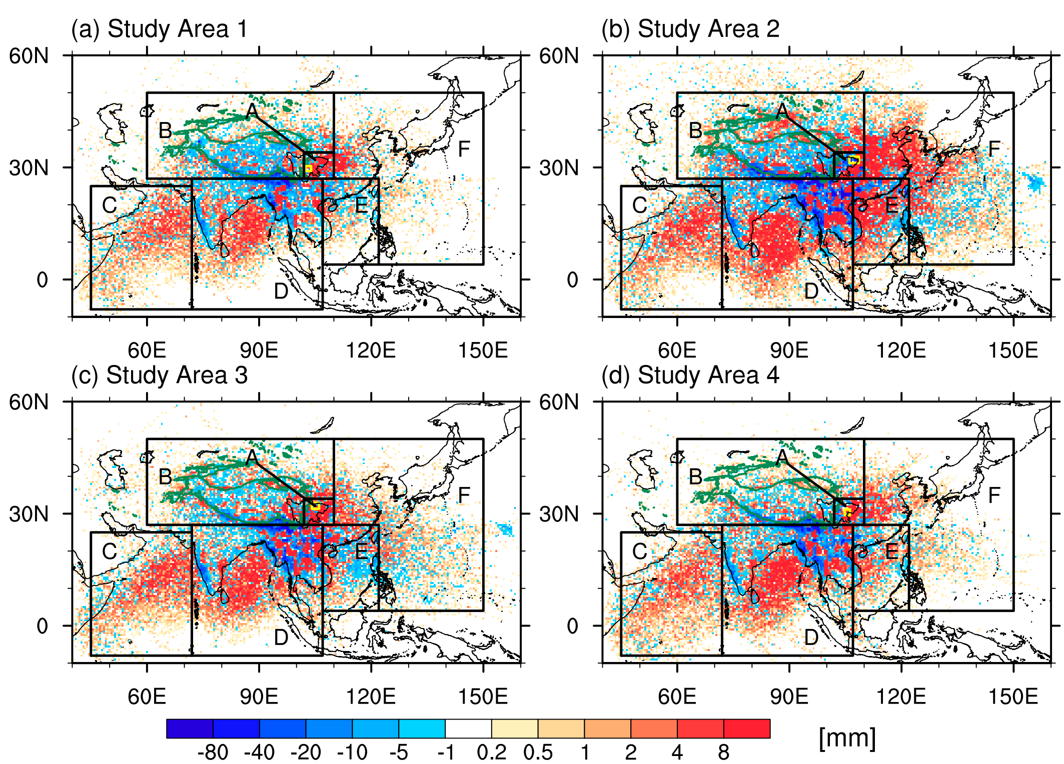

FIG. 5. Values of $E - P$ (mm) diagnosed from trajectories of the target particles 1–10 days before reaching the study area (a) 1, (b) 2, (c) 3, and (d) 4 (yellow rectangles). Black rectangles represent the moisture source regions to be examined in section 3b: the Sichuan basin region (A), the Tibetan Plateau region (B), the Arabian Sea region (C), the Indian Peninsula–Bay of Bengal–Indo-China Peninsula region (D), the South China Sea region (E), and the eastern China–East China Sea region (F). The green solid lines indicate 3-km height contours of the Tibetan Plateau.

China Sea, the East China Sea, and the east-central part of mainland China. It can also be found that, in the process of particles moving from the ocean surface to the land surface, such as on the western coast of the Indian Peninsula and the coast of the Bay of Bengal, the particles have significant net releases of water vapor, indicated by the blue areas ($E - P < 0$) in Fig. 5. Moreover, there are also strong water vapor releases when particles land in the Hengduan Mountains from the Bay of Bengal, which may be closely related to air particles that are uplifted by the terrain and then condense.

To better understand the contributions of various moisture source regions to the torrential rainfall within the study areas, we further divide the model domain into six moisture source regions (black rectangles in Fig. 5) based on an overall consideration of geographical locations, the starting points of the target particles (Fig. 4), and moisture uptake areas (Fig. 5). They are the Sichuan basin region (A), the Tibetan Plateau region (B), the Arabian Sea region (C), the Indian Peninsula–Bay of Bengal–Indo-China Peninsula region (D), the South China Sea region (E), and the eastern China–East China Sea region (F). The net uptakes of moisture in the Indian Peninsula–Bay of Bengal–Indo-China Peninsula region (D), the areas in Fig. 5, are mainly in the Bay of Bengal; thus, hereinafter this region is briefly referred to as the "Bay of Bengal region." To quantitatively understand water vapor uptake and release from the moisture source regions to the study areas, the moisture uptake from each examined source region Uptake was divided into three parts along the target particles' way to the study areas: the part that was lost en route Loss, the part that was released over the study area Released, and the part that reached the study area but was not released Unreleased; this approach is similar to Sun and Wang (2015). Values of Uptake, Loss, and Released for each examined moisture source region were calculated by using the areal source–receptor attribution method (Sun and Wang 2014), and Unreleased was computed by Unreleased = Uptake − Loss − Released (Sun and Wang 2015).

Figures 6 and 7 show the ratios of the moisture uptake from the examined moisture source regions in the whole atmospheric layer $\mathrm{Uptake}_{\mathrm{AL}}$ and the atmospheric boundary layer $\mathrm{Uptake}_{\mathrm{BL}}$ to the total moisture released $\mathrm{Released}_{\mathrm{total}}$ within the study areas, that is, $\mathrm{Uptake}_{\mathrm{AL}}/\mathrm{Released}_{\mathrm{total}} \times 100\%$ and $\mathrm{Uptake}_{\mathrm{BL}}/\mathrm{Released}_{\mathrm{total}} \times 100\%$, respectively, which consist of three parts: the part lost en route, $\mathrm{Loss}/\mathrm{Released}_{\mathrm{total}} \times 100\%$ (orange rectangle); the part that was released over the study area, $\mathrm{Released}/\mathrm{Released}_{\mathrm{total}} \times 100\%$ (green rectangle); and the part that reached the study area but was not released, $\mathrm{Unreleased}/\mathrm{Released}_{\mathrm{total}} \times 100\%$ (blue rectangle). The moisture uptake of local moisture sources within the study areas are also estimated, shown by "T."

The results indicate that, for all study areas, the moisture uptake from the Bay of Bengal region (D) is the largest among all the examined moisture source regions (Fig. 6). The other two regions with the greatest moisture uptake are the Sichuan basin region (A) and the Tibetan Plateau region (B), while as for study area 2, moisture uptake from the South China Sea region (E) and the eastern China–East China Sea region (F) are also important (Fig. 6b). Meanwhile, moisture uptake within the atmospheric boundary layer accounts for approximately half of the moisture uptake in the whole atmospheric layer (Figs. 6, 7), which may have a close relationship with the evaporation in the boundary layer. Moreover, we find that most of the moisture uptake from the examined moisture source regions was released before reaching the study areas (orange rectangles in Figs. 6, 7) and only a small part of the water vapor uptake reached the study areas and was released within the study areas (green rectangles in Figs. 6, 7), especially for moisture uptake from the Bay of Bengal region (D). This may be partially related to the target particles from the Bay of Bengal landing in the Hengduan Mountains and releasing (blue areas in Fig. 5).

To illustrate this more clearly, the contributions of various moisture source regions to the torrential rainfall within the study areas, the contributions of the moisture source regions to the precipitation within the four study areas in both the boundary layer, and the whole atmospheric layer by using the areal source–receptor attribution method (Sun and Wang 2014) are shown in Fig. 8. The contributions of local moisture sources within the study areas and the total moisture contributions from all of the examined moisture source regions are also estimated, shown by "T" and "Total" in Fig. 8, respectively. It is found that the moisture sources with key contributions to the torrential rainfall within the four study areas are the moisture sources in the Sichuan basin region (A) and the Bay of Bengal region (D). However, contributions of these two moisture sources to the four study areas are slightly different. For the torrential rain in the Ya'an region (Fig. 8a), the moisture source of the Sichuan basin has the greatest contribution, and the contribution in the boundary layer (17.72%) is around half of the contribution of the whole atmospheric layer (36.54%), which indirectly implies that surface evaporation of the Sichuan basin may make an important contribution to the torrential rainfall in the summer season in the Ya'an region. The moisture source of the Bay of Bengal region (D) has the greatest contribution to the torrential rainfall in the central region of the Sichuan basin (Fig. 8d). As for torrential rainfall in the northeastern (Fig. 8b) and northwestern (Fig. 8c) Sichuan basin, moisture sources in the Sichuan basin region (A) and the Bay of Bengal region (D) have similar

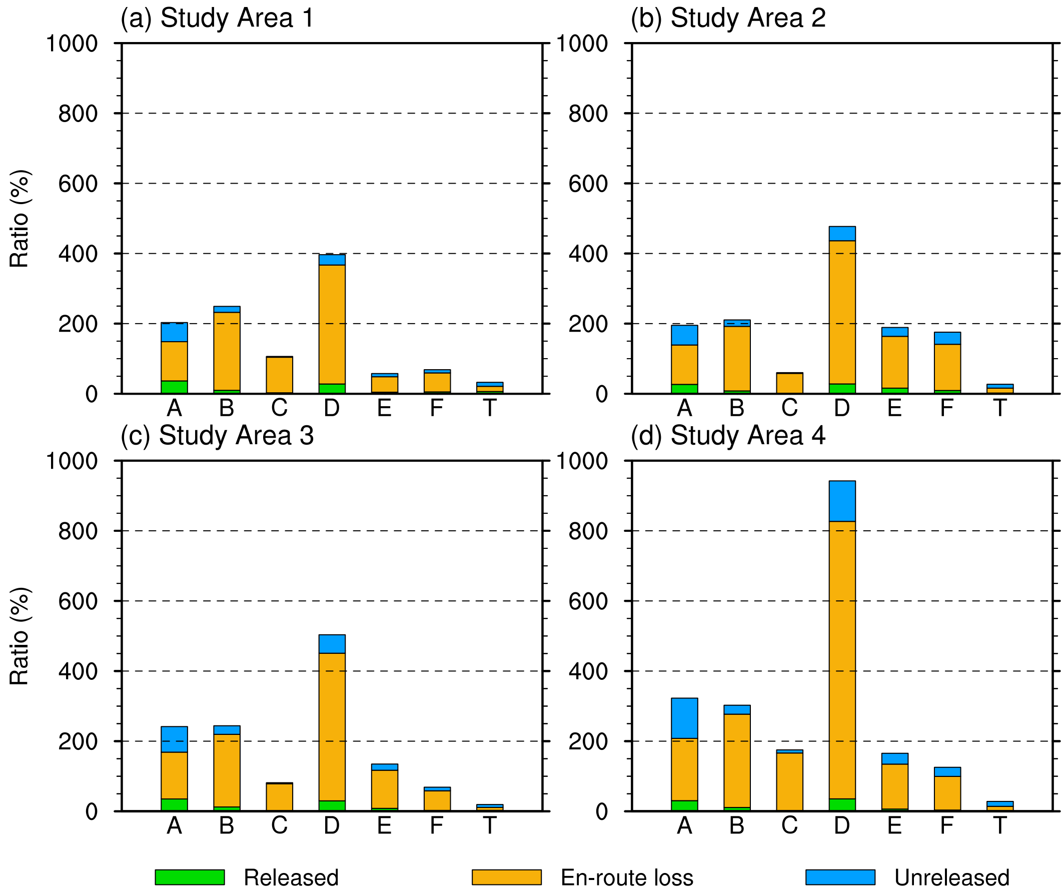

FIG. 6. Ratios (%) of the moisture uptake from the examined moisture source regions in the whole atmospheric layer to the total moisture release within the study area (a) 1, (b) 2, (c) 3, and (d) 4. These consist of three parts: the part lost en route (orange), the part released over the study area (green), and the part that reached the study area but was not released (blue). The moisture source regions A–F are shown in Fig. 5; the T indicates the study area.

contributions. Furthermore, for the torrential rainfall occurring in the northeastern Sichuan basin, there is another important moisture source, the South China Sea (Fig. 8b). Moreover, the total moisture from all examined moisture source regions for the four study areas within the whole atmospheric layer account for 92.59% (study area 1), 90.77% (study area 2), 92.78% (study area 3), and 91.39% (study area 4) of the precipitation in the study areas (Fig. 8), which means that the moisture source regions selected in this study could account for most of the moisture sources of the torrential rainfall in each study area. Moisture sources unable to be identified in this study may be from outside the moisture source regions selected in this study, or the moisture source may have been present in the target particles 10 days before. Overall, the moisture uptakes within the Sichuan basin and the Indian Peninsula–Bay of Bengal–Indo-China Peninsula region make key contributions to the torrential rainfall in the Sichuan basin.

To compare with moisture sources for the torrential rainfall events, a climatology of the moisture sources is also conducted by using a random sampling method. The numbers of particles for the climatology to build in the four study areas are shown in Table 1. Figure 9 shows contributions of each examined moisture source region shown in Fig. 5 to the total moisture released within the four study areas calculated from 10-day trajectories of the air particles during June–September 2009–13. As for climatology, the Sichuan basin region (A) is the moisture source region making the largest contribution to the total moisture released within the four study areas (Fig. 9), and it is the common key moisture source for the four study areas during torrential rainfall events and climatology, whereas the contributions of moisture from the Bay of Bengal region (D) apparently reduce for the four study areas compared with contributions during torrential rainfall events. Meanwhile, contributions of the Tibetan Plateau region (B) increase to some extent

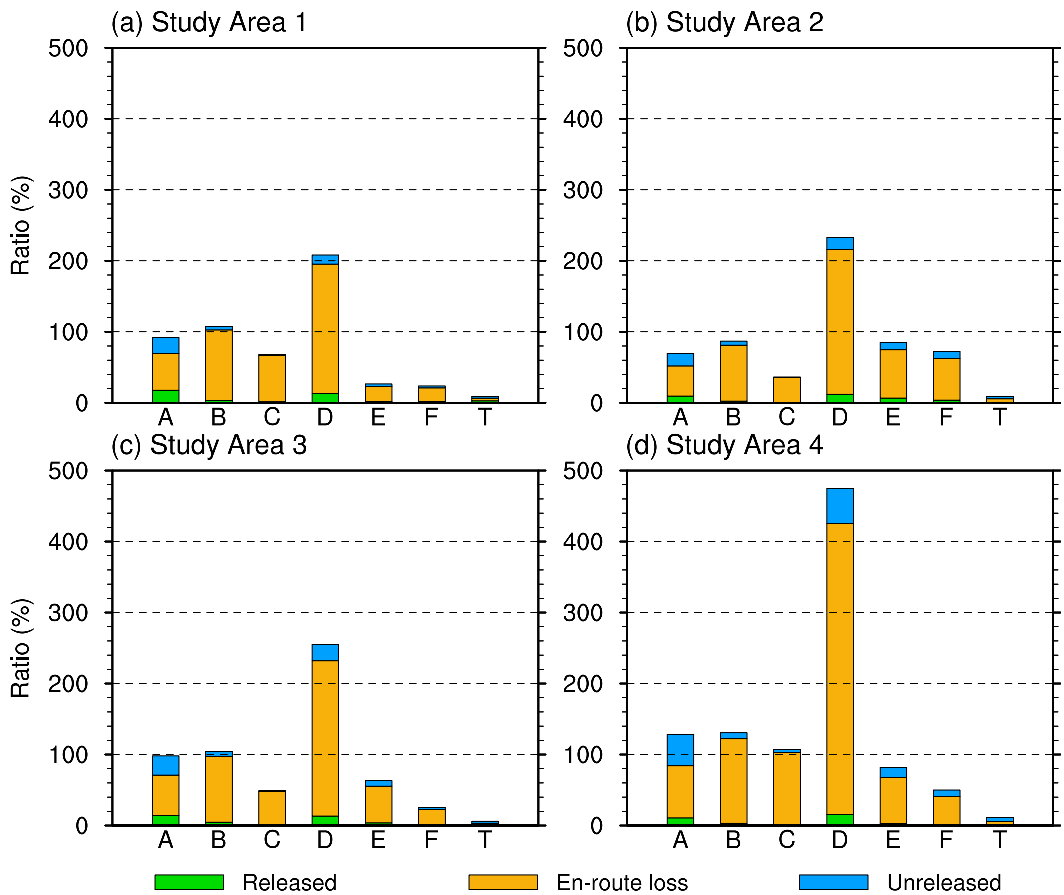

FIG. 7. As in Fig. 6, but for ratios (%) of the moisture uptake from the examined moisture source regions in the atmospheric boundary layer to the total moisture release within the study areas.

(Fig. 9). Therefore, moisture sources over the land have greater contributions to the four study areas than those over the ocean during the warm season (June–September) of 2009–13.

4. Conclusions and discussion

In this study, the Lagrangian flexible particle dispersion model (FLEXPART) is applied to investigate the main moisture sources and transport paths for the torrential rainfall in the Sichuan basin of China with complex topography, where floods, debris flows, landslides, and other secondary geological disasters occur frequently, leading to severe life and economic losses. Based on the torrential rainfall distribution in the Sichuan basin, four study areas are selected at first: the Ya'an region, the northeastern Sichuan basin region, the northwestern Sichuan basin region, and the central region of the Sichuan basin, where torrential rains often occur. Main moisture transport paths and quantitative analysis of contributions from moisture sources to the torrential rainfall within the study areas are performed. Major conclusions are as follows.

1) Trajectory analysis shows that a large number of target particles, which almost all come from relatively low atmospheric layers, start from the Arabian Sea and the Bay of Bengal, land on the Indo-China Peninsula, and finally reach the four study areas. This moisture transport path should be important to the torrential rainfall within the four target regions. Another important moisture transport path is from the neighborhood of the Sichuan basin. As for the northeastern and northwestern Sichuan basins, there are also a number of particles from the East China Sea and the South China Sea. Moreover, there is another part of the target particles coming from higher atmospheric layers over the Tibetan Plateau. However, this part of the particles makes little moisture contribution to the torrential rainfall in the Sichuan basin on analysis (section 3b).

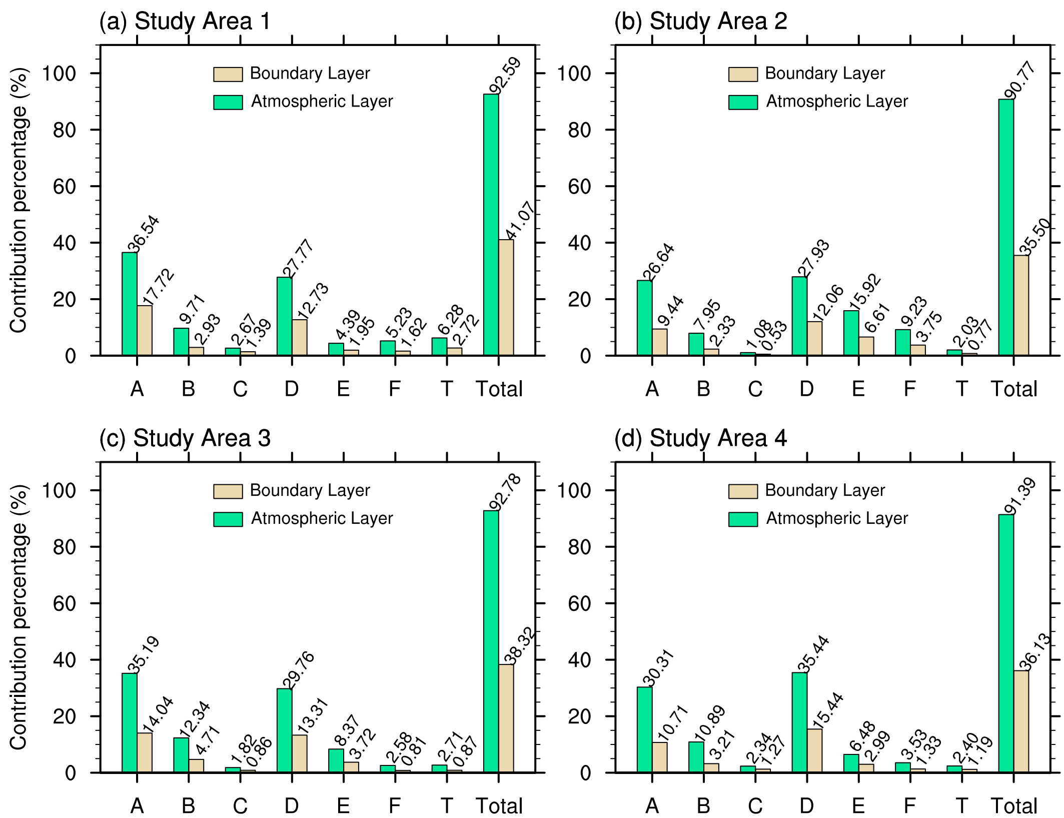

FIG. 8. Contributions (%) of the moisture source regions (A–F in Fig. 5) to the total moisture released within the study area (a) 1, (b) 2, (c) 3, and (d) 4 calculated from 10-day trajectories of the air particles during the selected torrential rainfall events. T indicates the study area and Total represents total moisture contributions from all of the examined moisture source regions.

2) Quantitative analysis of contributions from the moisture sources to the torrential rainfall addressed in this study shows that there are two major moisture source regions, the Sichuan basin and the Bay of Bengal, that make key contributions to the torrential rainfall within the four study areas in the Sichuan basin. The South China Sea could be another important moisture source region for the torrential rain occurring in the northeastern Sichuan basin. The total moisture supplies for the four study areas from all of the examined moisture source regions within the whole atmospheric layer account for more than 90% of rainfall within the target regions, which means that moisture source regions selected in this study have accounted for most of the moisture sources of the torrential rainfall in each study area.

As for climatology, moisture originating from the Sichuan basin makes the highest contribution to the total moisture released within the four study areas, while the contribution of the Bay of Bengal markedly reduces. This means that the plentiful moisture uptake from the Bay of Bengal plays a more important role in the torrential rainfall in the Sichuan basin. The major findings in this study are similar to those in the previous single-case study (Huang and Cui 2015). Hence, this multiple-case study verifies the previous conclusions well, and the conclusions are robust and statistically significant.

Analysis of water vapor sources and transport paths is very important to the research and forecasting of rainfall events, especially torrential rains. For climatology of torrential rains, identification of main moisture sources and transport paths and further analysis of their long-term variations may help us to understand the climatological characteristics of torrential rainfall and related trends of variation. For forecasts of torrential rainfall events in the Sichuan basin of China, this study could also help us to understand and grasp the main foreboding or precursory factors of the torrential rains. While rainfall processes are very complicated, especially near complex terrains where large-scale circulations and their variations, interactions between topography and local circulations, and cloud microphysical processes

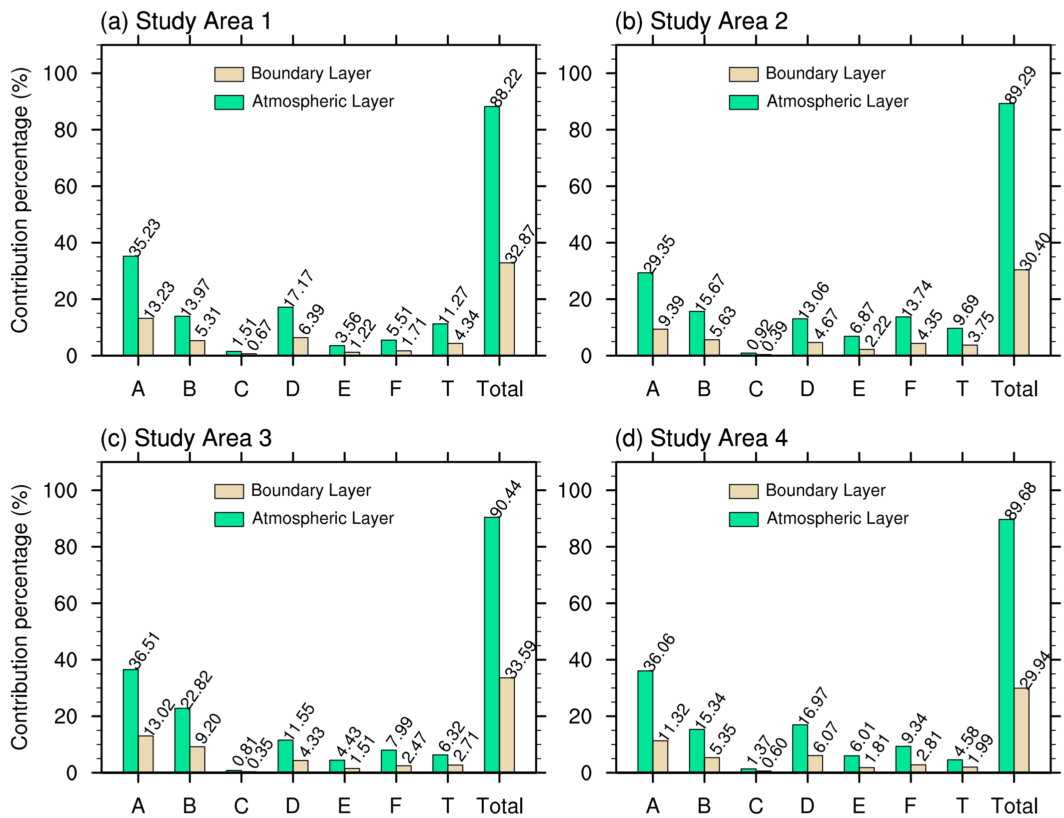

FIG. 9. As in Fig. 8, but for June–September 2009–13.

could all contribute to the torrential rains, related studies, including interactions between terrains and circulations and cloud microphysics, should be carried out based on multiple case studies or typical case studies. Studies on the moisture sources and transport paths of torrential rains in other similar areas of the world are also needed. Moreover, it is also important to investigate which conditions have conducted the moisture anomalies observed during the torrential rainfall events.

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