Land-surface processes and summer-cloud-precipitation characteristics in the Tibetan Plateau and their effects on downstream weather: a review and perspective

Yunfei Fu, Yaoming Ma, Lei Zhong, Yuanjian Yang, Xueliang Guo, Chenghai Wang, Xiaofeng Xu, Kun Yang, Xiangde Xu, Liping Liu, Guangzhou Fan, Yueqing Li, and Donghai Wang

INTRODUCTION

The Tibetan Plateau (TP), located in the eastern part of the subtropical Eurasia, covers an area of about a quarter of China's territory and has an average altitude of >4000 m. It has the highest altitude, largest area and most complex terrain in the world. Since the late 1970s, Chinese scientists have conducted three scientific experiments in the TP: the first Qinghai Xizang Plateau Meteorological Experiment (QXPMEX), the second Tibetan Plateau Atmospheric Experiment (TIPEX-II) and the third Tibetan Plateau Atmospheric Experiment (TIPEX-III). In 2013, the National Natural Science Foundation of China began to implement a major research project called 'Changes in the Land-Atmosphere Coupling System on the Tibetan Plateau and Its Associated Global Climate Effects'.
In the past 40 years, some aspects of atmospheric sciences related to TP have reached consensus in phenomena and mechanisms, such as the mass transport and ozone hole caused by convections [1], an air-heating pump generated by land-surface sensible and latent heat [2,3] and a water tower due to monsoon activities [4]. Studies found that the unique and complicated boundary-layer process was the most fundamental factor producing many phenomena, including the summer prevalence of convective activities in the compressed-air column 5 km above sea level in the TP [5–8]. The thermal-forcing convective cloud in the TP usually moved eastward to downstream eastern China [9,10]. As a result, the TP is considered to be one of the important sources of convective cloud systems, significantly contributing to frequent storm rainfall and floods during summer in eastern China [11]. Chen et al. [12] analyzed the summer convection and precipitation over eastern China and the TP using satellite observations and the apparent heat source (Q1) and moisture sink (Q2). The positive correlation of the deep convection between eastern China and the east TP suggests that the moisture due to the evaporation of cloud water in anvil clouds detrained from the deep convection over the east TP can be transported downstream and benefit the development of convection over eastern China. In addition, the abnormal change in surface sensible heating in the TP generated the anomalous changes not only in the local circulation, but also in Asia and even in the entire northern hemisphere [13].

This article mainly summarizes and reviews recent study progress in land-surface processes and summer cloud precipitation in the TP and their impacts on downstream weather in the mainland of China, and finally gives a new perspective. The review will be organized into the following sections. After the introduction, the first part summarizes achievements in the observation and study of the atmospheric boundary layer, remote sensing of land-surface heat fluxes (LSHFs) and modeling of the precipitation and frozen-thawing process in the TP. The achievements of studies on cloud-precipitation horizontal distribution and vertical structures, cloud microphysical characteristics and precipitation in the TP are introduced in the second and third parts, respectively. Then, the achievements of the effect of the cloud system of the TP on the downstream weather are represented. Finally, the future research direction of atmospheric science on the TP is prospected.

**LAND-SURFACE PROCESSES OVER THE TP**

**Retrieval of key characteristic parameters for land–atmosphere interaction**

Called the roof of the world, the TP has significant impacts on atmospheric circulation and downstream weather conditions through land–atmosphere interactions [2,4]. Besides studies on the mechanical forcing of the TP in early years [14], recent research has mainly focused on the strong surface-heating status of the TP. Some consensuses about the TP heating effects (sensible heat driving an ‘air pump’) have been reached [15] and their links with the establishment and inter-annual variability of the East Asian summer monsoon (EASM) [16]. However, because of the model uncertainties and the lack of land–atmosphere interaction data, especially the shortage of high spatio-temporal land-surface heat-flux data, some debates still exist on how the thermal effects of the TP will influence the South Asian monsoon [17,18]. With the undertaking of several field experiments over the TP since 1979, such as QXPMEX, TIPEx-II, GEWEX (Global Energy and Water Cycle Experiment) Asian Monsoon Experiment on the Tibetan Plateau (GAME/Tibet), CEOP (Coordinated Enhanced Observing Period) Asia-Australia Monsoon Project (CAMP) on the Tibetan Plateau (CAMP/Tibet), Tibetan Observation and Research Platform, China-Japan Meteorological Disaster Reduction Cooperation Research Center Project (JICA/Tibet) and the ongoing project TIPEx-III, a large amount of valuable land–atmosphere interaction data sets have been retrieved and scientific understanding of land–atmosphere interactions has been achieved. However, some wide divergences still exist in the key parameters (bulk-transfer coefficients, aerodynamic roughness length (Z_{0w}), thermodynamic roughness length (Z_{0h}), and excess resistance to heat transfer (kB−1)) [19]. The divergences will cause great uncertainties in estimation of the land-surface heat status and its impacts on the TP. Duan and Wu [20] showed a weakening trend in the TP atmospheric heat source, particularly in the spring surface sensible heat flux since the 1980s. Yang et al. [7] found that the annual mean sensible heat flux had a less weakened trend of 2% per decade based on a newly developed physical method. Chen et al. [21,22] examined the impacts of the large-scale circulation and surface-heat fluxes on the triggering and development of the cloud and precipitation over the TP, and found that the
strong surface-heat flux played an important role in the heavy rainfall events over the TP. According to Wang et al. [19], different calculation methods may be the main reason for the opposite conclusion related to bulk-transfer coefficients. \(Z_{0m}\) and \(Z_{0h}\) are two key variables in weather and climate models. For a long time, they were often thought to be the same value for simplification. Ma et al. [23] found that \(Z_{0m}\) and \(Z_{0h}\) are totally different for different land-surface types, with \(Z_{0m}\) one order of magnitude larger than \(Z_{0h}\) in the TP. The \(kB^{-1}\) exhibited obvious diurnal variation over the TP. Recently, the study of Han et al. [24] showed that, for rugged mountainous areas in the TP, the derived effective aerodynamic roughness length \((Z_{0eff})\) was considerably larger than the small-scale aerodynamic roughness length. This means that the form drag exerted by the topography should be taken into account in the parameterization of land–atmosphere momentum and scalar fluxes.

Remote sensing of LSHFs

The LSHFs from the regional to the global scale can be derived by applying remote-sensing technology. The land-surface variables, such as land-surface temperature, albedo, vegetation index and emissivity, can be derived from satellite measurements. The LSHFs can be estimated indirectly based on the above land-surface parameters. Several approaches have been explored to derive the surface-heat fluxes at multi-spatial and temporal scales that bridge the gap between the point measurements and the regional scale [25,26]. Especially, great improvements have been made in the remote sensing of LSHFs over the TP at different spatio-temporal scales in recent years. Both polar-orbiting and geostationary satellite data have been successfully applied to derive the LSHFs over the TP. Several parameterization methodologies have been developed for different satellite sensors to derive the plateau-scale LSHFs [27]. Recently, by a combined use of geostationary and polar-orbiting satellites, hourly LSHFs for the entire TP were first estimated by Zhong et al. [28]. The spatio-temporal distribution of the LSHFs were consistent with the land-surface heterogeneous status and the general hydro-meteorological conditions of the TP (Fig. 1). The derived results were also found to be superior to the Global Land Data Assimilation System flux products and will help in understanding the diurnal variation of the atmospheric boundary layer [28].

In the context of global warming, the rapid warming and moistening signals were identified over the TP by Zhong et al. [29] in recent years. Studies have found that the thermal effects of the TP had been weakening by a combination of effects of enhanced cooling through radiation loss and a decrease in the land-surface sensible heat flux [7,20]. Further analysis revealed that the decrease in the sensible heat flux over the TP will weaken monsoon circulation and postpone the seasonal reversal of the land–sea thermal contrast in East Asia [30]. A long time series of surface-energy balance components were estimated for the whole TP area from 2001 to 2012 based on satellite observations [31]. It was found that the sensible heat flux decreased overall, especially in the central and northern TP. The decreases in sensible heat flux can be explained by the decrease in wind speeds as well as differences in ground-air temperatures. The latent heat flux increased over the majority of the TP, which is attributed to increases in precipitation and vegetation greening (Fig. 2).

Modeling of precipitation and the frozen–thawing process over the TP

The TP is one of regions with the largest precipitation bias in current climate models. It had been believed that this bias was mainly due to the fact that coarse-resolution climate modeling could not reflect the complex terrain around the plateau. Complex terrain can generate orographic drags at different scales: gravity wave drag, drag owing to low-level flow blocking and turbulence-scale drag. Theoretically, the large-scale orographic drags can be resolved by increasing the model resolution. Rahimi et al. [32] found that increasing the horizontal model resolution significantly decreases the modeled precipitation wet biases over the TP, by comparing the Community Earth System Model (CESM) global model at two resolutions and the regional Weather Research and Forecasting Model (WRF) simulation. However, there were still obvious precipitation errors in regional climate simulations with a resolution of 10 km [33]. The reason could be that the terrain of the Himalayan mountains is extremely complex and the turbulent drag on the air flow induced by orographic variance plays a significant role. This drag is called turbulent orographic form drag (TOFD).

Based on the observations, it is found that precipitable water vapor in current reanalysis data sets is too high and its diurnal variation is too early and too strong over the southern TP (Fig. 3a) [34]. This can be related to the coarse resolutions in the reanalysis models that are not able to resolve the complex terrain. To clarify this point, the WRF simulations with different resolutions were conducted by Lin et al. [35] and the simulated wind speed and water-vapor flux are shown in Fig. 3b. The
Figure 1. Seasonal variations in sensible heat flux (a) and latent heat flux (b) in 2008 over the TP (modified from Zhong et al. [28]). The spatial distribution of sensible heat flux is a little complex, while a clear spatial distribution characteristic can be identified for latent heat flux.
simulation with a coarse resolution (30 km) yields stronger wind speed and thus brings more water vapor into the TP than the one with a fine resolution (2 km). The latter clearly shows that water vapor moves mainly through valleys but is greatly blocked by high mountains. Accordingly, the coarse-resolution simulation produces much more precipitation over the north side of the Himalayas, confirming the importance of orographic drag in this region.

However, it is not easy to parameterize this effect in climate models. Han et al. [24] clearly show that $Z_{\text{eff}}$ could be in the order of 10 m, which implies that the surface layer in the atmospheric boundary layer (or the first level of the atmospheric model) must be several hundred meters if the roughness is used. However, the surface layer in the atmospheric boundary layer is usually assumed to be $<100$ m in current models. Alternatively, a scheme developed by Beljaars et al. [36] was implemented in the WRF model by Zhou et al. [37] to reflect the TOFD. The new scheme exerts the orographic drag on different atmospheric levels rather than changing the roughness length. Simulations with the revised WRF model show that the accuracy of the simulated wind speed and precipitation in the TP can be much improved [37]. The revised WRF was also used to simulate precipitation in the high altitudes of the central Himalayas, where current models have very severe wet biases. Based on the observations along the Yadong Valley, we can see the wet bias is reduced greatly when the grid size varies from 10 to 3 km. Adding the TOFD scheme further reduces the precipitation bias by 50% or so at almost all stations (Fig. 4). Therefore, synergy of the TOFD scheme and high resolution can enhance the orographic drag, slow water-vapor transport and thus weaken wet biases in the terrain-complex region [38]. Yet, it is worth mentioning that the wet biases are still larger. Representation of other processes such as energy and water exchange on the complex terrain should be explored in future.

A most distinct feature over the TP is the land surface occupied by frozen ground; the land-surface processes over the TP must be affected by soil frozen–thawing (FT) that significantly affects the soil water and energy budget, and further influences the land–atmosphere interaction over and around the TP (e.g. Wang et al. [39]). A recent study suggested that the FT process had a water-storage effect [40]. No soil FT process could result in the drier surface (about 10% loss of soil moisture) in the after-thaw period (spring), which is caused by enhanced evaporation. The land-surface processes (i.e.

---

**Figure 2.** Linear trends and significance test maps of sensible heat flux $H$((a) and (c)) and latent heat flux $\lambda E$((b) and (d)) from 2001 to 2012. The trends were classified into four categories ((c) and (d)) according to statistical linear-trend analysis: a significant increase ($P < 0.05$), a significant decrease ($P < 0.05$), an insignificant increase ($P > 0.05$) and an insignificant decrease ($P > 0.05$) (modified from Han et al. [31]).
Figure 3. (a) Seasonal march of precipitable water between GPS-observation and four reanalyses, after elevation correction and average at nine stations during 2007–13 (after Wang et al.[21]); (b) spatial pattern of column water vapor flux (vector) and its meridional component (color) in simulations with 30-km-resolution (WRF30) and 2-km-resolution simulation (WRF2), with the domain average of the meridional component provided in the bottom-left corner. Gray curves represent elevation of 4000 m (modified from Lin et al.[35]).

Figure 4. (a) Comparison of precipitation between in situ observation and WRF 10-km simulations w/o TOFD scheme (WRF10km, WRF10km+TOFD); (b) similar to (a) but the resolution is 3 km. The RG01–09 stations are located along the Yadong Valley of the upper South Himalayas and the RG10–14 stations are at the north side (modified from Wang et al.[38]).

land–atmosphere energy transfer) in cases of frozen soil and unfrozen soil are totally different. Variations in soil temperature and soil moisture further influence the surface diabatic heating status. Model simulation [40] shows that, without the FT process, the surface latent heat flux decreased by \(-1.07 \text{ W m}^{-2}\), while the surface sensible heat flux increased by 4.72 \text{ W m}^{-2}\), as the average over the whole TP.

Parameterization enhancements of soil heat and water transport in the land-surface model (LSM) have made great improvement in the simulation of
terrestrial water cycles and surface-energy balances in cold regions. However, some big bias still exists in LSM simulations, especially at regions with high latitudes and complex topography [41]. To improve the simulation of the soil FT process, some improvements in the FT parameterizations in Community Land Model version 4.5 (CLM4.5) were proposed [41]. Compared to the original parameterizations in CLM, these improvements can not only reproduce the characteristics of soil moisture daily and diurnal changes, especially during the soil-thawing period, but also make the FT-process simulation much closer to the in situ measurements. A recent study suggests that the soil-moisture anomalies caused by the FT process can persist into the summer. These anomalies will enhance the TP’s thermal forcing to the subtropical westerlies and affect stationary Rossby wave train propagation in the middle latitudes [42].

SUMMERTIME CLOUD OBSERVED FROM GROUND STATIONS AND SATELLITE INSTRUMENTS

Cloud amount, cloud types and their vertical structures are the main parameters for describing the macroscopic properties of clouds, while cloud diurnal variation reflects the local cloud climatology. Since the 1980s, the observations at ground stations and by satellite instruments have revealed the characteristics of the horizontal distribution and diurnal variation of cloud systems in the TP. It was found that the summer convective clouds were very small and exuberant in the TP and presented significant diurnal variation characteristics [43–45]. However, data sets from the observations at weather stations and cloud retrievals of the International Satellite Cloud Climatology Project exposed that dense cirrus, stratus, cumulus and cumulonimbus were typical types in the TP during the four seasons [46]. Convective clouds and precipitation in Nagqu usually occurred at 1100 (local standard time, hereafter the same); the development, merging and growth of local thermal-forcing convection mainly occurred at 1700–1800, and then reached the strongest intensity; since the early night, the precipitation began to weaken and continue until 0600, then convection gradually dissipated in the morning [47]. Recently, by using an hourly cloud-cover data set derived from observations of the Himawari-8 satellites, it was found that the minimum and maximum cloud fractions mainly occurred at 1000 and 1800 in the TP, respectively [48]. It will be necessary to investigate the details of the diurnal-variation amplitudes of the clouds and their regional differences in the TP, which is very important for understanding the land–atmosphere interaction process over there.

Based on the CloudSat/CALPSO data set, it was found that the frequency of clouds in the TP was 69% while the low-level cloud and middle-level cloud were 21% and 14%, respectively, mainly distributed at an altitude of 5–6 and 7–8 km. The high cloud had the smallest frequency and was distributed at an altitude of 11–12 km. There were two higher centers of cloud frequency horizontally distributed in the southeast and northwest of the TP [49,50]. Similar analysis was conducted in the east part of the TP [51]. Studies also revealed that the relative contribution rate of the single-layer cloud in the TP was higher than that in the other Asian monsoon regions [52], and large topography had a significant compression effect on cloud thickness and number of layers, resulting in the thinnest thickness of the cloud layer in the TP [53,54]. This compression effect has been found previously in precipitation profiles in the TP as viewed by the Tropical Rainfall Measuring (TRMM) precipitation radar (PR) [55]. However, observations in Nagqu ground station indicated that the frequency of low-level cloud and middle-level clouds in the TP was 48.3% and 21.9%, respectively [56]. So, the cloud frequency derived from satellite instruments needs to be further validated, and the differences in cloud frequency generated by observations from satellite instruments and ground stations need to be compared with each other. It is worth noting that the measuring manner of the CloudSat/CALPSO operated at the nadir point along the swath, which leads to a very low sampling rate. Therefore, the local cloud frequency derived by the CloudSat/CALPSO data set was not very reliable, but the cloud vertical structure given by the data set had good reliability.

Climate change of clouds in the TP was also a concern. Based on observations at 71 weather stations from the central to eastern TP in the period of 1961–2003, it was indicated that the low cloud amount exhibited a significant decreasing trend during the daytime and an increasing trend during the night-time [57]. The climate characteristics of summer convection over the TP as revealed by a geostationary satellite indicated that the convective activities advance from the southeast of the TP to the northwest with the movement of the South Asian monsoon to the TP [58]. Summer convective systems (CSs), with an average life cycle of about 36 h, contribute >60% of the total precipitation in the central-eastern TP [59].

Cloud microphysical parameters are directly related to cloud radiative forcing estimation and are key to improving cloud physical processes in weather models. During the TIPEX-III, the
diurnal variations in cloud macro-parameters (cloud top, base, thickness and layer) were first obtained using integrated ground-air–space observations and the inversion algorithms on both cloud micro-parameters (cloud water/ice content) and dynamic parameters (air-ascending velocity) inside clouds were established [53,60–62]. The distributions and variations in cloud microphysical parameters inside clouds, such as the microphysical processes of supercooled water and ice-crystal growth together with phase changes, were also obtained [60–62]. It was found that deep convective clouds were mainly ice-phase and rich in small ice particles (fewer large ice crystals) in the cloud at 10 km above (below). The microphysical processes of both strong and weak deep convective clouds mainly included mixed-phase and ice-phase processes inside clouds, which provided a validation basis for the model to simulate the deep convective clouds in the TP [61]. Some cloud microphysical parameters, i.e. cloud optical thickness (COD) and cloud water path, derived from satellite retrievals showed that their variations in spatial distribution were closely associated with the increase in water-vapor transport flux divergence [63,64]. Compared with the regions around the TP, studies also showed that the range of raindrop size was broader, which led to an easy generation of precipitation by the convective cloud system in the TP [61]. The characteristics of cloud microphysical parameters in the TP still need to be further revealed. Therefore, an effective way to solve this issue is that the space–ground integrated observation method should be adopted combined with the simulation method using the high-resolution cloud model.

SUMMER PRECIPITATION OBSERVED FROM GROUND STATIONS AND SATELLITE INSTRUMENTS

Climatological changes in precipitation obtained from rain gauges

It is very difficult to obtain the spatial and temporal distribution of precipitation over the broad TP region because of the few weather stations over there. But Chinese scientists have made full use of the precipitation observations in long time series at limited ground stations to analyze the climate-change characteristics of regional precipitation [65]. Studies found that the opposite change trends existed between annual precipitation amounts and precipitation days from 1980 to 2013. The annual precipitation amounts increased with time while the precipitation days decreased [66]. The summer extreme precipitation in the middle and east of the plateau declined from southeast to northwest during 1961–2014 [67]. It was also found that the precipitation amount and frequency exhibited a bimodal pattern diurnally, occurring in the morning and evening, while the precipitation intensity had no such pattern [68]. Scientists also noted linkages between precipitation in the TP and local or non-local factors, e.g. the daily precipitation at 13 weather stations in the TP was closely linked to the strong and weak monsoon activities [69], and the spatial distribution of summer precipitation was related to the moisture transport controlled by weather systems around the TP [70].

The factors related to the precipitation intensity and its spatial and temporal distribution in the TP need to be focused on, which requires setting up more ground automatic observation systems. The method of synthetic analysis on weather processes in the TP is very important because different weather processes have their own characteristics in generating precipitations. In this regard, a study pointed out that the low-eddy-precipitation data were obtained by matching the daily low-eddy data with precipitation data at each station from 1979 to 2015 in the TP in order to explore the trend of low-eddy precipitation in the TP [71]. It will be the effective way in future study to merge multisource data for revealing the precipitation and its thermodynamic characteristics generated from activities of the different weather systems in the TP.

Microphysical characteristics of precipitation measured by ground-based radar

It was pioneering that two digital x-band 711 radars were operated in Nagqu and Lhasa, respectively, in the first QXPME, which exposed the structures of convective precipitating clouds [72]. In the TIPEX-II in 1998, observations by a Doppler radar in Nagqu showed that very active convective clouds, multiple showers, thunderstorms and hail frequently occurred there. The strongest convective cloud had an echo signal of 40 dBz at a height of 14 km, and the lifetime of most convective cells was about 1 h. There was a lot of weak precipitation with prominent diurnal variation, and the maximum precipitation and atmospheric instability were in synchronous [73–76].

In the TIPEX-III in 2014, based on ground-based instruments including microwave radar, results exposed that primary cumulus and stratus often appeared at a 3-km height above the ground in Nagqu, and this height often occurred in obvious updrafts. The height of the deep convection system reached 16.5 km and there were both updraft and downdraft
Inside the cloud, in which there might be supercold water [77,78]. It was shown that the rising strong airflow inside the cloud carried wet snow under a 0°C layer back to the layer above again. Then, through the physical processes of sublimation, riming and clinging, this wet snow quickly grew into hail in just 10 minutes [79]. These observation data and preliminary results provide a basis for further studies on the mechanism investigation of cloud and precipitation, the improvement of the parameterization scheme for cloud and precipitation physical processes, and the retrieval algorithm development of satellite remote sensing.

Ground-based radar observation is very effective for obtaining cloud precipitation within a limited range, but it is insufficient for understanding cloud precipitation over the whole TP. With the improvement in transport, power and other facilities in the TP, it has become possible to set up a number of PRs and cloud radars there, especially in the central and western parts. In addition, ground-based radar-detection results also need to be integrated with other meteorological data, so as to reveal the corresponding thermodynamic characteristics of cloud-precipitation structures.

Precipitation distribution in the whole TP measured by TRMM PR

The distribution of precipitation in the larger area in the TP was obtained by the measurement of the PR on board the TRMM satellite. The PR measurements exposed most TP precipitation with isolated and massive structure and stronger diurnal variation in the TP than surrounding regions [4,55,80,81], which was in line with the convective-precipitation characteristics observed by the ground stations in the past [73–78].

Due to the situation that the TRMM PR algorithm issued data with a large amount of stratiform precipitation in the TP, the stratiform-precipitation proportion reaching up to 80% above in most TP regions, study pointed out that the PR misjudged the strong signal reflected from the ground as one from the bright band of the stratiform so that the weak precipitation was wrongly identified as stratiform precipitation [82]. It was found that there was a relationship between the structure of the temperature/humidity profile and the depth of the precipitating cloud so that new precipitation types were defined in the TP as follows: the strong deep convective precipitation (SDCP), weak deep convective precipitation (WDCP) and shallow precipitation (SP) [83,84]. The WDCP was the dominant precipitation form (67.8%) in the TP followed by the SP (26.4%) and the SDCP (5.8%) forms, respectively. Studies also showed the time differences in frequency peak and intensity peak of both diurnal cycles for SDCP and WDCP [83,84]. Statistics indicated that the intensity and frequency of precipitation increased from the western TP towards the eastern and southeastern TP, while the contrary occurred for the storm top altitudes, as shown in Fig. 5 [83].

Comparative analysis showed that there were different vertical profiles between the TP and its surrounding regions. The vertical structure of the precipitation in mean profiles indicated three layers—ice or supercooled water, mixed ice and water, and droplet coalescence—for the SDCP and WDCP, as shown in Fig. 6 in which the curves represent the precipitation profiles corresponding to different ground-precipitation intensities [55], whereas, in non-plateau regions, such as East Asia or the tropical ocean, convective precipitation usually has a four-layer structure, i.e. beside the three layers, there is a layer of evaporation, in the vertical direction [85].

The differences in the precipitation profiles between the TP and the non-plateau indicated that the structure of the SDCP and WDCP in the TP was moved 6 km upwards, forced by the terrain (Fig. 7). On the other hand, the tropopause height of the TP in the summer was almost the same as that of the non-plateau area in Mid-East China (MEC) [8]. So, the thickness of the precipitation cloud was actually compressed by the terrain. The mean thicknesses of the SDCP and WDCP in the TP were about 7 and 5 km, respectively, while the mean thicknesses of the convective precipitation were up to 9 and 8 km in the MEC and in the South China Sea (SCS), respectively, while it was 7 km in both the East China Sea (ECS) and the tropical ocean (TO). Therefore, the large topography of the TP compressed the air column over it [55].

The next step of the study on the detection of precipitation in the TP should focus on two aspects: one is the comparison of the measurements of the satellite-borne PR (e.g. the Global Precipitation Measurement mission Dual-frequency Precipitation Radar) and ground-based rain radar, especially the identification of precipitation types. Due to the difference in the atmospheric environment between the TP and non-plateau areas, the precipitation structure of the TP is unique and the definition of the precipitation type in non-plateau areas is not suitable for the TP. Therefore, the characteristics of the precipitation structure of the TP should be carefully studied to give a reasonable definition of the precipitation type. The second is the evolution rule of the convective precipitation on the TP,
REVIEW
Fu et al. [87] found that the rain frequency was the highest on the steep southern slope of the Himalayas (SSSH), while the rain intensity was highest on the foothills of the Himalayas (FHH). It was believed that the heaviest precipitation did not occur in the SSSH because most of the water vapor on the FHH has been converted into precipitation, and the residual water vapor climbed along the SSSH, so the precipitation intensity on the SSSH was small but the frequency was the highest. The result also indicated that the effects of elevation and relief have linear relationships with precipitation over the south sub-region of the SSSH, which suggested the important role of both elevation and relief on precipitation over complex plateau topography [87].

The cloud and precipitation on the SSSH need to be studied in more detail because they relate to latent heating release; for example, how do strong or weak monsoons affect the cloud and precipitation on the SSSH, and how does the advancing warm and moist monsoon affect the characteristics of the vertical structure of cloud and precipitation on the SSSH? The impact of the vertical structure of latent heat over the SSSH on atmospheric circulation is also a key factor in understanding the feedback effect of cloud precipitation.

THE EFFECT OF THE CLOUD SYSTEM OF THE TP ON THE DOWNSTREAM WEATHER
During the boreal summer, rainstorms over the Yangtze River Basin (YRB) frequently result in flood disaster, causing substantial ramifications [91–93]. As the upstream water source of the YRB, the TP played an indispensable role in rainstorms over this region [94,95]. Xu et al. [96] and Wang et al. [94] suggested that the eastward movement of clustered convective clouds over the central part of the TP was a major cause of the rainstorms during June–July of 1998 in the YRB and found that the increased transport of atmospheric water vapor over the TP favored rainstorm formation in the middle–lower reaches of the YRB.

In phenomena, many investigations found that the eastward-moving short-wave trough and low-pressure vortex associated with the eastward-moving clouds in the TP were important factors generating the heavy rain in the eastern side of the plateau [97] and the YRB [9,98]. For example, the eastward movement of the southwest vortex along with strong convective clouds from the TP usually triggered heavy rain in the YRB [99]. Xu and Zipser [100] found that, within a range of
about 1000 km eastward from the eastern part of the TP, the diurnal variation in precipitation had an obvious phase eastward-transmission phenomenon. The strong deep convection could move out of the east side of the TP (about 100°E) at 1600 local time and reached 100°E at about 2000 local time [83]. It was found that the Tibetan CS contributed to a lot of precipitation in the YRB [101]. In the TIPEX-III, observations by a C-FMCW radar site at Nagqu in the central TP showed that the vigorous convective activities were mainly distributed in this region and they frequently moved eastward [47,95]. These phenomena suggested the eastward propagation of CSs were related to the rainstorms within the YRB.

To expose the mechanism of the above phenomena, studies pointed out a good relationship between heavy rain in the YRB in 1998 and the wind field in the planetary boundary layer at the eastern edge of the TP [102]. Yasunari and Miwa [9] confirmed that the movement of convective cloud in the TP triggered a cyclonic vortex by plateau-edge cyclogenesis, and this vortex then developed into a cloud system over the downstream YRB associated with the water-vapor flow. By analyzing monthly precipitation data issued by the Global Precipitation Climatology Project and daily precipitation data observed in 438 stations in eastern China, Ge et al. [103] obtained that the extreme precipitation tends in the summer to be more (less) over the YRB when the TP heating is stronger (weaker) than normal. This result suggests that there is a link between the summer extreme precipitation in eastern China and the TP heating. The effects of the upper-level South Asian High (SAH) have emphasized that positive and negative vorticity anomalies in the lower and upper troposphere accompanied by an ascending motion anomaly occurred over the TP regions, respectively. The stronger heating in the TP resulted in the strengthening and eastward extension of the SAH, which led to intensity-strengthening and position-stretching westward of the western Pacific subtropical high. Therefore, there existed more extreme precipitation over the YRB due to the increase in southwestern moisture transport and moisture convergence.

The methods of the correlation analysis, WRF model simulation and Lagrangian backward tracking also confirmed the mechanism of the eastward propagation of CSs in the TP being related to the rainstorms within the YRB, such as a convective zone in the Nagqu region stimulating rainstorms in the YRB and the good relationship of the convective zone in the TP to clouds in the YRB [104,105]. The simulation also showed that the link between the deep convection in the central TP and the rainstorms downstream in the YRB was a 3D WVFV (water-vapor flux vortex) coupled structure with low-level convergence and high-level divergence. The convection would be enhanced by the eastward propagation of the WVFV structure and subsequently developed rainstorms downstream in the YRB.

In general, the above phenomena and mechanism indicate that the hourly trajectories of the simulated integral column WVFV, simulated cumulative precipitation and zonal column cloud mass are
coincidentally coupled with one another, which uncovers the eastward propagation of the 3D WVFV structure originating from convection over the Nagqu region impacting on rainstorms in the downstream YRB. Studies also showed that, due to the thermodynamical forcing in the summer derived from the elevated TP topography, the frequent convective activities together with variation of cloud structures in the central TP provided significant predictive 'strong signals' for the occurrence and development of rainstorms over the YRB [105]. It must be pointed out that the underlying surface in the central and western parts of the TP is mostly sand and gravel, with a small heat capacity. Therefore, there exists a large temperature difference between day and night due to solar radiation. As a result, the half-day thermal forcing on convective activities and their eastward propagation should be investigated in the next step.

**SUMMARY AND FUTURE WORK**

With 49 years of effort, we have been building ground observation systems to carry out experiments in the TP and analyze phenomena measured by various instruments carried by satellites. The surface sensible heat, latent heat, ground-radiation budget and so on are investigated from the local scale to the entire TP. The spatial and temporal distribution characteristics and vertical structure of cloud and precipitation in the TP are understood to a certain extent. There is also a preliminary understanding of how the plateau weather system affects the weather in the downstream regions. Because the weather systems are complicated, however, controlled by various factors, and there exists complex feedback between these systems and factors, there are still many gaps in our knowledge of atmospheric activities in the TP and their impact on the weather and climate around the TP. Studies on the land-surface and atmosphere parameters in the TP will not stop in the current study plan. It is believed that, through the unremitting efforts of several generations, we will eventually gain systematic understanding of the unique role of the TP in the global atmosphere.

So far, limitations to our recognition of the weather systems, including the land process, radiative process and cloud precipitation in the TP, mainly involve how to obtain parameters of the land surface and atmosphere, which depends on the placement of moderately dense ground instruments and the persistence of long-term observation. With abundant observation results, we can obtain detailed information on the overall atmospheric movement in the TP, and understand the thermodynamic effects on atmospheric circulation and weather processes. Although study with limited measuring stations is important, more ground observations with high temporal resolution should be put in place. Especially, some stations during the TIPEx-III only measured the atmospheric temperature, moisture and wind fields twice a day. This is certainly not sufficient for simulating the convection, cloud and precipitation processes, the diurnal variations with high-resolution models and comparisons with reanalysis data.

Satellite remote-sensing technology can make up for the shortage of ground observation to a certain extent. In order to enhance the acquisition of ground and atmospheric information in the TP, one or two geostationary meteorological satellites need to be launched to the equator facing the central part of the TP. In the meantime, multiple polar-orbiting satellites need to be launched to increase their observations with higher temporal resolution at about two hours. Polar satellites should not only carry the current passive instruments, but also carry our own PR, cloud radar and lidar to realize the 3D observations in the TP.

The authors suggest that future research will focus on the following aspects. First, the weather systems in the TP, such as the shear line, low vortex and local severe convection caused by thermodynamic circulation, should be rigorously followed, to study the variations in sensible heat, latent heat and radiation budget, including moisture, temperature and atmospheric stability, and so on, especially before and after the precipitation. That is helpful for us to understand details of the energy and water balance in the TP. The second is how to use cloud models and weather models to correctly simulate the physical processes of cloud and precipitation, for example, how cloud particles change inside the clouds and how these changes differ from those in non-plateau clouds. The third is how to get an accurate latent heat profile of cloud precipitation in the TP from the observed data in order to evaluate the latent heat structure of the model. The fourth is to understand changes in the cloud thermodynamic structure during the eastward migration of cloud clusters in the TP, and how such changes can stimulate the severe convective weather downstream. The fifth is related to investigating the climate effects of absorbing aerosols over the TP. The TP is located close to regions in South and East Asia, where the largest sources of absorbing aerosols (black carbon and dust, BCD in short) are located. The climate effects of BCD on the TP-climate system are manifold. The atmospheric BCD directly heats the atmosphere, reducing surface-incident solar radiation. On the other hand, BCD in snow on the TP could reduce the visible snow albedo by changing the surface optical properties (snow-darkening effects), which
enhance the surface sensible and latent heat flux \[106\]. The snow-darkening effects accelerate the snowmelt, which leads to a significant positive radiative forcing and remarkably alters the regional hydrological cycle: the eastern Asian climate system \[107,108\]. The comprehensive effects of atmospheric BCD and deposited BCD on local radiation balance, sensible heat flux and latent heat flux is still an open scientific research issue. Furthermore, how BCD will alter the TP’s hydrological cycle through BCD–cloud-precipitation interaction needs further investigation as well.

In short, the land-surface processes of the TP and the cloud precipitation generated by these processes have very rich scientific implications, and the research results will improve our understanding of the land–atmosphere interaction over the TP and its effect on the weather downstream and even global atmospheric circulation.

**FUNDING**

This work was jointly supported by the National Natural Science Foundation of China (91837310, 91837208, 91937302 and 41875031), the National Key R&D Program of China (2018YFC1507200), the Strategic Priority Research Program of Chinese Academy of Sciences (XDA20060101), the Key Research and Development Projects of Anhui Province (201904a07020099) and the CLIMATE-TPE (ID 32070) in the framework of the ESA-MOST Dragon 4 Program.

**REFERENCES**

1. Zhou XJ, Luo C and Li WL et al. Changes of the total ozone in China and the low ozone center in Tibetan Plateau (in Chinese). Chin Sci Bull 1995; 15: 1396–8.
2. Wu GX, Liu YM and Wang TM et al. The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate. J Hydrometeor 2007; 8: 770–89.
3. Wu GX, He B and Duan A et al. Formation and variation of the atmospheric heat source over the Tibetan Plateau and its climate effects. Adv Atmos Sci 2017; 34: 1169–84.
4. Xu XD, Lu CG and Shi XH et al. World water tower: an atmospheric perspective. Geophys Res Lett 2008; 35: L20815.
5. Fu YF, Liu GS and Wu GX et al. Tower mast of precipitation over the central Tibetan Plateau summer. Geophys Res Lett 2006; 33: L06802.
6. Ma Y, Menenti M and Feddes R et al. Analysis of the land surface heterogeneity and its impact on atmospheric variables and the aerodynamic and thermodynamic roughness lengths. J Geophys Res Atmos 2008; 113: D08113.
7. Yang K, Guo X and Wu B. Recent trends in surface sensible heat flux on the Tibetan Plateau. Sci China Earth Sci 2011; 54: 19–28.
8. Feng S, Fu YF and Xiao QN. Is the tropopause higher over the Tibetan Plateau? Observational evidence from Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) data. J Geophys Res 2011; 116: D21121.
9. Yasunari T and Miwa T. Convective cloud systems over the Tibetan Plateau and their impact on meso-scale disturbances in the Meiyu/Baiu frontal zone. J Meteorol Soc Jpn 2006; 84: 783–803.
10. Xu XD, Zhao TL and Shi XH et al. A study of the role of the Tibetan Plateau’s thermal forcing in modulating rainfall and moisture transport in eastern China (in Chinese). Acta Meteor Sin 2015; 73: 20–35.
11. Tao SY and Ding YH. Observational evidence of the influence of the Qinghai-Xizang (Tibet) Plateau on the occurrence of heavy rain and severe convective storms in China. Bull Amer Meteor Soc 1981; 62: 23–30.
12. Chen J, Wu X and Yin Y et al. Characteristics of heat sources and clouds over eastern China and the Tibetan Plateau in boreal summer. J Clim 2015; 28: 7279–96.
13. Mao JY and Wu GX. Impacts of anomalies of thermal state over the Qinghai-Xizang Plateau and sea surface temperature on interannual variability of the Asian monsoon seasonal transition (in Chinese). Chin J Geophys 2006; 5: 1279–87.
14. Charney JG and Eliassen A. A numerical method for predicting the perturbations of the middle latitude westerlies. Tellus 1949; 1: 38–54.
15. Wu GX, Li WP and Guo H et al. Sensible heat driven air-pump over the Tibetan Plateau and its impacts on the Asian Summer Monsoon. In: Ye D (ed.). Collections on the Memory of Zhao Jiuzhang. Beijing: Science Press, 1997, 116–26.
16. Wu GX, Duan A and Liu Y et al. Tibetan Plateau climate dynamics: recent research progress and outlook. Natl Sci Rev 2015; 2: 100–16.
17. Boos WR and Kuang ZM. Dominant control of the South Asian monsoon by orographic insulation versus plateau heating. Nature 2010; 463: 218–22.
18. Wu GX, Liu YM and He B et al. Thermal controls on the Asian summer monsoon. Sci Rep 2012; 2: 404.
19. Wang YJ, Xu XD and Liu HZ et al. Analysis of land surface parameters and turbulence characteristics over the Tibetan Plateau and surrounding region. J Geophys Res Atmos 2018; 121: 9540–60.
20. Duan A and Wu G. Weakening trend in the atmospheric heat source over the Tibetan Plateau during recent decades. Part i: observations. J Clim 2009; 21: 3149–64.
21. Chen J, Wu X and Yin Y et al. Characteristics of cloud systems over the Tibetan Plateau and surrounding region. J Clim 2017; 30: 3117–37.
22. Chen J, Wu X and Yin Y et al. Thermal effects of the surface heat flux on cloud systems over the Tibetan Plateau in boreal summer. J Clim 2019; 32: 4699–714.
23. Ma Y, Tsukamoto O and Wang J et al. Analysis of aerodynamic and thermodynamic parameters over the grassy marshland surface of Tibetan Plateau. Prog Nat Sci 2002; 12: 36–40.
24. Han C, Ma Y and Su Z et al. Estimates of effective aerodynamic roughness length over mountainous areas of the Tibetan Plateau. Q J R Meteorol Soc 2015; 141: 1457–65.
25. Ma Y, Wang J and Menenti M et al. Estimation of fluxes over the heterogeneous land surface with the aid of satellite remote sensing and ground observation [in Chinese with English abstract]. ACTA Meteor Sin 1999; 57: 180–9.
26. Su Z. The Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes. Hydroch Eart Syst Sci 2002; 6: 85–100.
27. Ma Y, Yao T and Wang J. Experimental study of energy and water cycle in Tibetan Plateau—the progress introduction on the study of GAME/Tibet and CAMP/Tibet [in Chinese with English abstract]. Plateau Meteor 2006; 25: 344–51.
28. Zhong L, Ma Y and Hu Z et al. Estimation of hourly land surface heat fluxes over the Tibetan Plateau by the combined use of geostationary and polar-orbiting satellites. Atmos Phys 2019; 19: 5529–41.
29. Zhong L, Ma Y and Xue Y et al. Climate change trends and impacts on vegetation greening over the Tibetan Plateau. J Geophys Res Atmos 2019; 124: 7540–52.
30. Duan A, Wang M and Lei Y et al. Trends of land surface heat fluxes on the Tibetan Plateau from 2001 to 2012. J Clim 2013; 26: 261–75.
31. Han C, Ma Y and Chen X et al. Trends of land surface heat fluxes on the Tibetan Plateau from 2001 to 2012. Int J Climatol 2017; 37: 4757–67.
32. Rahimi SR, Wu C and Liu X et al. Exploring a variable-resolution approach for simulating regional climate over the Tibetan Plateau using VR-CESM. J Geoph Res Atmos 2019; 124: 4480–513.
33. Ma J, Wang H and Fan K. Dynamic downscaling of summer precipitation prediction over China in 1998 using WRF and CCSM4. Adv Atmos Sci 2015; 32: 577–84.
34. Wang Y, Yang K and Pan Z et al. Evaluation of precipitable water vapor from four satellite products and four reanalysis datasets against GPS measurements on the Southern Tibetan Plateau. J Clim 2017; 30: 5699–713.
35. Lin C, Chen D and Yang K et al. Impact of model resolution on simulating the water vapor transport through the central Himalayas: implication for models’ wet bias over the Tibetan Plateau. Clim Dyn 2018; 51: 3195–207.
36. Beljaars ACM, Brown AR and Wood N. A new parametrization of turbulent orographic form drag. Q J R Meteorol Soc 2004; 130: 1327–47.
37. Zhou X, Yang K and Wang Y. Implementation of a turbulent orographic form drag scheme in WRF and its application to the Tibetan Plateau, Clim Dyn 2018; 50: 2443–55.
38. Wang Y, Yang K and Zhou X et al. Synergy of orographic drag parameterization and high resolution greatly reduces biases of WRF-simulated precipitation in central Himalaya. Clim Dyn 2020; 54: 1729–40.
39. Wang C, Dong W and Wei Z. A study on relationship between freezing-thawing processes of the Qinghai-Xizang Plateau and the atmospheric circulation over East Asia [in Chinese with English abstract]. Chin J Geophys 2003; 46: 438–48.
40. Yang K and Wang C. Water storage effect of soil freeze-thaw process and its impacts on soil hydro-thermal regime variations. Agric For Meteorol 2019; 265: 280–94.
41. Yang K, Wang C and Li S. Improved simulation of frozen-thawing process in land surface model (CLM4.5). J Geophys Res Atmos 2018; 123: 238–58.
42. Yang K and Wang C. Seasonal persistence of soil moisture anomalies related to freeze-thaw over the Tibetan Plateau and prediction signal of summer precipitation in eastern China. Clim Dyn 2019; 53: 2411–24.
43. Jiang JX, Xiang X and Fan MZ. Spatial and temporal distribution of mesoscale strong convective systems over the Tibetan Plateau in summer [in Chinese]. J Appl Meteor Sci 1986; 4: 473–8.
44. Fujinami H and Yasunari T. The seasonal and intraseasonal variability of diurnal cloud activity over the Tibetan Plateau. J Meteorol Soc Jpn 2001; 79: 1207–27.
45. Kurokawa Y and Kimura F. Relationship between topography and daytime cloud activity around Tibetan Plateau. J Meteorol Soc Jpn 2002; 80: 1339–55.
46. Liang P, Chen BD and Tang X. Identification of cloud types over Tibetan Plateau by satellite remote sensing. Plateau Meteor 2010; 29: 268–71.
47. Chang Y and Guo XL. Characteristics of convective cloud and precipitation during summer time at Naqu over Tibetan Plateau [in Chinese]. Chin Sci Bull 2016; 61: 1706–20.
48. Shang HQ, Letu HS and Nakajima TY et al. Diurnal cycle and seasonal variation of cloud cover over the Tibetan Plateau as determined from Himawari-8 new-generation geostationary satellite data. Sci Rep 2018; 8: 1105.
49. Wang H, Luo YL and Zhang RH. Analyzing seasonal variation of clouds over the Asian monsoon regions and the Tibetan Plateau Region using CloudSat/CALIPSO data [in Chinese]. Chin J Atmos Sci 2011; 35: 1117–31.
50. Liu JJ and Chen BD. Cloud occurrence frequency and structure over the Qinghai-Tibetan Plateau from CloudSat observation [in Chinese]. Plateau Meteor 2017; 36: 632–42.
51. Zhang X, Duan Q and Shi PH et al. Cloud vertical profiles from CloudSat data over the eastern Tibetan Plateau during summer [in Chinese]. Chin J Atmos Sci 2015; 39: 1073–90.
52. Liu YM, Yan YF and Lu JH et al. Review of current investigations of cloud, radiation and rainfall over the Tibetan Plateau with the CloudSat/CALIPSO dataset [in Chinese]. Chin J Atmos Sci 2018; 42: 847–58.
53. Yan YF and Liu YM. Vertical structures of convective and stratiform clouds in boreal summer over the Tibetan Plateau and its neighboring regions. Adv Atmos Sci 2019; 36: 1098–102.
54. Wang H and Guo XL. Comparative analyses of vertical structure of deep convective clouds retrieved from satellites and ground-based radars at Naqu over the Tibetan Plateau. J Meteorol Res 2019; 33: 446–62.
55. Fu YF, Liu Q and Z Y et al. Summer precipitation and latent heating over the Tibetan Plateau based on TRMM measurements [in Chinese]. Plat Moon Meteor 2008; 28: 8–18.
56. Wu C, Liu LP and Zhai XC. The comparison of cloud base observations with Ka-band solid-state transmitter-based millimeter wave cloud radar and ceilometer in summer over Tibetan Plateau [in Chinese]. Chin J Atmos Sci 2017; 41: 659–72.
57. Duan AM and Wu GX. Change of cloud amount and the climate warming on the Tibetan Plateau. Geophys Res Lett 2006; 33: L22704.
58. Li B, Yang L and Tang SH. The climatic characteristics of summer convection over the Tibetan Plateau revealed by geostationary satellite [in Chinese]. Acta Meteor Sin 2017; 76: 893–95.
59. Li YQ, Wang Y and Song Y et al. Characteristics of summer convective systems initiated over the Tibetan Plateau. Part I: origin, track, development, and precipitation. J Appl Meteor Climatol 2008; 47: 2679–95.
60. Ruan Y, Ruan Z andWei M et al. Research of the vertical structure of summer convective precipitation cloud over the Qinghai-Tibetan Plateau by C-FMCW Radar [in Chinese]. Plateau Meteor 2018; 37: 93–105.
61. Zhao C, Liu L and Wang Q et al. MMCR-based characteristic properties of non-precipitating cloud liquid droplets at Naqu site over Tibetan Plateau in July 2014. Atmos Res 2017; 190: 68–76.
62. Gao W, Liu L and Li J et al. The microphysical properties of convective precipitation over the Tibetan Plateau by a subkilometer resolution cloud-resolving simulation. J Geophys Res Atmos 2018; 123: 3212–27.
63. Li WT, Li XY and Zhang LL et al. Climatic characteristic analysis of cloud water over the Tibetan Plateau (in Chinese). Clim Environ Res 2018; 23: 574–86.
64. Liu J. Analysis on cloud microphysical property over Qinghai-Xiang Plateau using satellite data (in Chinese). Plateau Meteor 2013; 32: 38–45.
65. Tang MC and Peng H. Preliminary analysis of precipitation variability in Qinghai-Tibet Plateau and its surrounding areas (in Chinese). Plateau Meteor 1985; 4: 64–70.
66. Han YZ, Ma WD and Wang BY et al. Climatic characteristics of rainfall change over the Qinghai-Tibetan Plateau from 1980 to 2013 (in Chinese). Plateau Meteor 2017; 36: 1477–86.
67. Cao Y, You QL and Ma QR et al. Probability distribution for the summer extreme precipitation in the Qinghai-Tibetan Plateau (in Chinese). Plateau Meteor 2017; 36: 1176–87.
68. Ji XL, Wu HM and Huang AN et al. Characteristics of the precipitation diurnal variation over Qinghai-Tibetan Plateau in summer (in Chinese). Plateau Meteor 2017; 36: 1188–200.
69. Gong YF, Ji LR and Duan TY. Precipitation character of rainy season of Qinghai-Xiang Plateau and onset over East Asia monsoon (in Chinese). Plateau Meteor 2004; 23: 313–22.
70. Feng L and Wei FY. Regional Characteristics of summer precipitation on Tibetan Plateau and its water vapor feature in neighboring areas (in Chinese). Plateau Meteor 2008; 27: 491–9.
71. Quan SH, Zhu KY and Ren JX et al. Analysis of characteristics of low vortex precipitation in the Tibetan Plateau from 1979 to 2015 (in Chinese). Clim Environ Res 2018; 23: 105–15.
72. Qin HD. Static energy vertical distribution within convective processes in Nagqu, Qinghai-Xizang Plateau (in Chinese). Plateau Meteor 1983; 2: 61–5.
73. Uyeda H, Yamada H and Horikomi J et al. Characteristics of convective clouds observed by a Doppler radar at Naqu on Tibetan Plateau during the GAME-Tibet IOP. J Meteorol Soc Jpn 2001; 79: 463–74.
74. Feng JM, Liu LP and Wang ZJ et al. The statistic characteristics of radar echo and precipitation and some thermodynamic variables in Qinghai-Xizang Plateau (in Chinese). Plateau Meteor 2002; 21: 368–474.
75. Liu LP, Feng JM and Chu RZ et al. The diurnal variation of precipitation in Monsoon season in the Tibetan Plateau. Adv Atmos Sci 2002; 19: 365–78.
76. Zhang HF, Guo SG and Zhang YJ et al. Distribution characteristics of severe convective thunderstorm cloud over Qinghai-Xizang Plateau (in Chinese). Plateau Meteor 2003; 22: 558–64.
77. Liu LP, Zheng JF and Ruan Z et al. The preliminary analyses of the cloud properties over the Tibetan Plateau from the field experiments in clouds precipitation with the various radars (in Chinese). Acta Meteor Sin 2015; 73: 635–47.
78. Liu LP, Zheng JF and Zheng R et al. Comprehensive radar observations of clouds and precipitation over the Tibetan Plateau and preliminary analysis of cloud properties. J Meteorol Res 2015; 29: 546–61.
79. Mei Y, Hu ZQ and Huang XY et al. A study of convective clouds in the Tibetan Plateau based on dual polarimetric radar observations. Acta Meteor Sin 2018; 76: 1014–28.
80. Fujinami H, Nomura S and Yasunari T. Characteristics of diurnal variations in convection and precipitation over the southern Tibetan Plateau during summer. SOLA 2005; 1: 49–52.
81. Hu L, Yang S and Li YD. Diurnal and seasonal climatology of precipitation depth over Tibetan Plateau and its downstream regions (in Chinese). Chin J Atmos Sci 2010; 34: 387–98.
82. Fu YF and Liu GS. Possible misidentification of rain type by TRMM PR over Tibetan Plateau. J Appl Meteor Climatol 2007; 46: 667–72.
83. Pan X and Fu YF. Analysis on climatological characteristics of deep and shallow precipitation cloud in summer over Qinghai-Xizang Plateau (in Chinese). Plateau Meteor 2015; 34: 1191–203.
84. Fu YF, Pan X and Liu GS et al. Characteristics of precipitation based on cloud brightness temperatures and storm tops in summer Tibetan Plateau (in Chinese). Chin J Atmos Sci 2016; 40: 102–20.
85. Fu YF, Pan X and Yang YJ et al. Climatological characteristics of summer precipitation over East Asia measured by TRMM PR. a review. J Meteorol Res 2017; 31: 142–59.
86. Houze Jr RA, Wilton DC and Smull BF. Monsoon convection in the Himalayan region as seen by the TRMM Precipitation Radar. Q J R Meteor Soc 2007; 133: 1389–411.
87. Fu YF, Pan X and Liu GS et al. Precipitation characteristics over the steep slope of the Himalayas in rainy season observed by TRMM PR and VIRS. Clim Dyn 2018; 51: 1971–89.
88. Barros AP, Joshi M and Putkonen J et al. A study of the 1999 monsoon rainfall in a mountainous region in central Nepal using TRMM products and rain gauge observations. Geophys Res Lett 2000; 27: 3683–6.
89. Anders AM, Roe GH and Hallet B et al. Spatial patterns of precipitation and topography in the Himalaya. Geol Soc Am Spec 2006; 398: 39–53.
90. Shrestha D, Singh P and Nakamura K. Spatiotemporal variation of rainfall over the central Himalayan region revealed by TRMM Precipitation Radar. J Geophys Res Atmos 2012; 117: D22106.
91. Tao SY and Ding YH. Observational evidence of the influence of the Qinghai-Xizang (Tibet) Plateau on the occurrence of heavy rain and severe convective storms in China. Bull Amer Meteor Soc 1991; 62: 23–30.
92. Liu X and Yin ZY. Sensitivity of East Asian monsoon climate to the uplift of the Tibetan Plateau. Palaeogeogr Palaeoclimatol Palaeoecol 2002; 183: 223–45.
93. Bett PE, Scaife AA and Li C et al. Seasonal forecasts of the summer 2016 Yangtze River Basin rainfall. Adv Atmos Sci 2018; 35: 918–26.
94. Wang JZ, Yang YQ and Xu XD et al. A monitoring study of the 1999 rainfall along the Yangtze River of China by using TIPEX data. Adv Atmos Sci 2003; 20: 425–36.
95. Zhao Y, Xu XD and Chen B et al. The upstream ‘strong signals’ of the water vapor transport over the Tibetan Plateau during a heavy rainfall event in the Yangtze River Basin. Adv Atmos Sci 2010; 33: 1343–50.
96. Xu XD, Zhou MY and Chen JY et al. A comprehensive physical pattern of land-air dynamic and thermal structure on the Qinghai-Xizang Plateau. Sci China Ser D Earth Sci 2001; 31: 428–40.
97. Gao QY. Analysis on a heavy rain process on the east side of Qinghai-Xizang Plateau (in Chinese). Plateau Meteor 2010; 23: 46–52.
98. Qin DY, Fang ZY and Jiang JX. The cloud systems of heavy rainfall in the typical Meiuyu period and their interactions (in Chinese). Chin J Atmos Sci 2006; 30: 578–86.
99. Fu SM, Sun JH and Zhao SX et al. A study of the impacts of the eastward propagation of convective cloud systems over the Tibetan Plateau on the rainfall of the Yangtze Huai River basin (in Chinese). Acta Meteorol Sin 2011; 69: 581–600.
100. Xu WX and Zipser EJ. Diurnal variations of precipitation, deep convection, and lightning over and east of the eastern Tibetan Plateau. J Clim 2011; 24: 448–65.
101. Hu L, Deng DF and Gao ST et al. The seasonal variation of Tibetan Convective Systems: satellite observation. J Geophys Res Atmos 2016; 121: 5512–25.
102. Li YQ. The PBL wind field at the eastern edge of the Tibetan Plateau and its relationship with heavy rain-flood of the Changjiang River in 1998 (in Chinese). Chin J Atmos Sci 2000; 24: 641–8.
103. Ge J, You QL and Zhang YO. Effect of Tibetan Plateau heating on summer extreme precipitation in eastern China. *Atmos Res* 2019; **218**: 364–71.

104. Zhao Y, Xu XD and Liu LP et al. Effects of convection over the Tibetan Plateau on rainstorms downstream of the Yangtze River Basin. *Atmos Res* 2019; **219**: 24–35.

105. Zhao Y, Xu XD and Ruan Z et al. Precursory strong-signal characteristics of the convective clouds of the Central Tibetan Plateau detected by radar echoes with respect to the evolutionary processes of an eastward-moving heavy rainstorm belt in the Yangtze River Basin. *Meteorol Atmos Phys* 2019; **131**: 697–712.

106. Lau WKM, Kim MK and Kim KM et al. Enhanced surface warming and accelerated snow melt in the Himalayas and Tibetan Plateau induced by absorbing aerosols. *Environ Res Lett* 2010; **5**: 25204.

107. Qian Y, Flanner MG and Leung LR et al. Sensitivity studies on the impacts of Tibetan Plateau snowpack pollution on the Asian hydrological cycle and monsoon climate. *Atmos Chem Phys* 2011; **11**: 1929–48.

108. Rahimi S, Liu X and Wu C et al. Quantifying snow darkening and atmospheric radiative effects of black carbon and dust on the South Asian monsoon and hydrological cycle: experiments using variable-resolution CESM. *Atmos Chem Phys* 2019; **19**: 12025–49.