Observational Evidence of the Influence of the Qinghai-Xizang (Tibet) Plateau on the Occurrence of Heavy Rain and Severe Convective Storms in China

Abstract

The advance and distribution of the belts of rainfall and of heavy rainfall in China are closely related to sudden seasonal changes in the general circulation over East Asia, but the latter, to a great extent, may be the result of thermal and dynamic forcing by the Qinghai-Xizang (Tibet) Plateau. Observational evidence indicates that many synoptic systems have their origin in the planetary boundary layer over the plateau and its surroundings. They act as producers not only of severe weather events over the plateau itself, but also of very important rain-bearing synoptic systems over eastern, southern, and even northern China that have been steered out of the plateau. The present study is based on excessively heavy rainfalls that have occurred during the past 50 years (1931–80), and which caused serious, damaging floods in much of China. The presence and influence of Tibetan weather systems could be found in most of these heavy rainfall events. The low-level vortices originating in the plateau play a very significant role in producing the heavy rains.

1. Introduction

The Qinghai-Xizang (Tibet) Plateau can exert very important effects on the initiation and development of heavy rainfall and severe storms in China, just as the Rocky Mountains influence the local severe storms in North America. Many rain-bearing synoptic systems have their origin over the plateau, and then move eastward or northeastward to cause excessively heavy rains and outbreaks of severe storms in eastern and northern China. Often, synoptic systems passing over the plateau intensify rapidly on the lee side and eventually give rise to severe weather over a widespread area. The two most notable cases were the devastating flood of the Haihe River in North China in 1963 and the major flood of the Yangzi River in 1954.

China is greatly affected by the monsoon circulation of South Asia. The onset, advance, break, and withdrawal of summer monsoons substantially determine the main characteristics and distribution of precipitation and of excessive rain. Many researchers ascribe the activity of summer monsoons to the thermal and dynamic effects of the plateau. Therefore, if the plateau did not exist, China would be faced with major rainfall regimes very different from the present ones. In the following, we shall briefly outline some observational evidence, mainly obtained by Chinese meteorologists, concerning the influence of the Qinghai-Xizang Plateau on heavy rainfall in China.

2. Sudden changes in the general circulation over East Asia and the distribution of heavy rainfall in China

Every year, in about June, the general circulation in East Asia undergoes a sudden seasonal change, which is basically characterized by the following features (Yin, 1949; Yeh et al., 1958): 1) the subtropical upper westerlies and their associated jet stream systems suddenly jump northward, causing the rapid disappearance of the westerly jet stream over South Asia and the building up of an upper easterly jet stream in low latitudes; 2) at the same time the upper Tibetan high at 200 or 100 mb rapidly moves over the plateau and becomes stable there; and 3) the Indian summer monsoon commences in the lower troposphere and the Mei-yu (plum rains) in the Yangzi River start as the polar front in South China shifts to that region. Based on recent research using upper-air data for a longer period, the above-mentioned popular viewpoint has been confirmed, but a considerable interannual variability was found (Zhu and Song, 1979). The new analyses also revealed that stations closer to the plateau underwent more obvious, more frequent, and earlier sudden changes in the general circulation. These facts reflect the influence of the plateau on such sudden changes in the general circulation over East Asia.

At the same time the subtropical high over the West Pacific also undergoes a similar northward jump (see “a” in Fig. 1) (Shanghai Weather Bureau, 1980). The second northward
Fig. 1. The advances of precipitation belts in China and their relationship to the mean position of the subtropical high and the mean geostrophic westerly component for the region 120°-160°E and for the period 1956-62. Numbers 1, 2, 3, and 4 indicate the stable stages of the subtropical high, of which the latter three stages correspond to the presummer rainy season in South China, the Mei-yii season in the Yangzi valley, and the rainy season in North China, respectively. Letters “a” and “b” denote the sudden jumps of the subtropical high. Wind speeds are given in meters per second.

The jump of the subtropical high normally takes place in the first half of July, indicating the end of the Mei-yii season in the Yangzi River Valley and the beginning of the rainy season in North China (see “b” in Fig. 1). During this period, the active monsoon may reach the north, northeast, and northwest portions of China, and it is capable of transporting a large amount of moisture, which is the prerequisite for the occurrence of heavy rain and severe storms there. Figure 2 shows the approximate locations of excessively heavy rains in China during the past 50 years, which clearly are concentrated in three bands (South China, Yangzi River, and North China), as indicated already in Fig. 1 (Tao et al., 1980). Note the two gaps in between with a paucity of occurrences of heavy rains. They are not a result of sampling or reporting deficiencies, but are caused by the less frequent occurrence of frontal zones there due to sudden, stepwise northward jumps. More importantly, the described characteristic distribution of heavy rains is closely related to the frequency of synoptic systems originating in, or passing over, the Xizang plateau region. For example, the presummer heavy rains are mainly produced by the disturbances in the southern branch of the westerlies passing to the south of the plateau. The heavy rains in the Yangzi River are mostly caused by low-level vortices and shear lines coming from the plateau and are not the sole consequence of typhoons. When the upper frontal zone shifts northward as the season progresses, the low-level vortices may change their track from an eastward to a northward or northeastward movement, thus leading to the occurrences of heavy rains in North China.

3. Heavy rains and severe storms over the Tibet Plateau

Recent studies show that the plateau is characterized by a unique pattern of precipitation (Yeh et al., 1979). Along the southern periphery of the plateau the world’s highest annual rainfall amounts are observed. In the western and northern parts of the plateau arid and semidesert climates prevail and the rainfall amounts are extremely low. In the interior of the plateau the annual rainfall amounts rapidly decrease from

Fig. 2. The locations of excessively heavy rains with rainfall amounts greater than 200 mm for 24 h. Crosses denote cases with rainfall amounts greater than 200 mm, white circles are for cases greater than 600 mm, black circles for cases greater than 800 mm, and black squares for cases greater than 1000 mm.
600 mm in the eastern part to 50 mm in the western part. There is a pronounced rainy season (April–October) over the plateau, with most of the rain falling in June, July, and August. Each year, about two to three heavy rain cases are observed over the plateau. Xue (1980) analyzed a case of heavy rain that occurred over the middle and lower Yarlung Zangbo River during 22–23 June 1978 and was caused by a low-level shear line. The maximum rainfall amount was recorded at Zamu, with 51 mm for a 24 h period and 91 mm for a 48 h period. The shear line may have been the remnant of the ITCZ that advanced over the plateau from northern India. A very strong low-level jet was located to the south of that line. The region of heavy rain was generated 200–300 km ahead of the jet core, which contained a meridional wind component of 23 m/s (observed scalar wind was 44 m/s) at 400 mb (see Fig. 3). In other years similar cases were observed.

The frequency of occurrences of convective systems or thunderstorms over the plateau is generally higher than in other regions (see paper by Ye, pp. 14–19). They sometimes may be organized into mesoscale severe storms if conditions are favorable. Ding (1975) described the formation of a prefrontal squall line over the plateau, possibly initiated by forced lifting of air ahead of a cold front that intruded into the plateau region from South Xinjiang Province.

The hailfall brought about by severe storms can be a disaster to agriculture on the plateau. Figure 4 indicates the annual mean number of days of occurrences of hailfall (Yeh et al., 1979). The plateau may well have the highest frequency of hailfall in this latitude band of the Northern Hemisphere, perhaps 10 times higher than in other regions. It should be noted that the region with the highest hailfall frequency coincides with the preferred positions of low-level shear lines and vortices in summer.

During the cold season, severe snowstorms visit the plateau, sometimes brought about by an upper trough in the southern branch of the westerlies that is greatly amplified and even dips southward into the tropics. A very strong,
FIG. 5. 200 mb streamline analysis at 0000 GMT, 28 October 1972. The shaded region indicates the cloud band as seen in the satellite picture close to the map time.

nearly south-north oriented, upper jet stream may be observed in advance of this large-amplitude trough, accompanied by a cloud band about 1000–2000 km long, stretching from the tropics northward to the plateau (Ding, 1975).

The presence of such a strong cloud surge accompanying a persistent snowstorm over the plateau had not been known to Chinese meteorologists before the advent of meteorological satellites. Two remarkable cases occurred on 25–31 October 1972 and 22–25 October 1974, respectively. The former case produced an extensive belt of snowfall over the plateau that remained unmelted for almost one month (Fig. 5). When the upper trough meets and merges with tropical storms over the Bay of Bengal, the subsequently produced snowstorms over the plateau may become even more severe. On 12–13 October 1972 a severe snowstorm covered a large area, nearly several hundred thousand square kilometers, of Tibet. It was associated with a severe tropical cyclone in the Bay of Bengal under the influence of the upper trough. The surface station Pali recorded a snowfall of 75 mm for 12 h and 121 mm for 24 h, with a total of 170 mm for three days. Such a widespread precipitation event has rarely been observed there before.

4. Activity of the Qinghai-Xizang (Tibetan) high and its relationship to droughts and floods in eastern China

The Qinghai-Xizang (Tibetan) high is a semipermanent center of action in the upper half of the troposphere during the Northern Hemisphere summer. Many efforts have been made to understand its activity and its relationship to unusual weather events in China and in the Asiatic monsoon regions (Krishnamurti et al., 1973; Kanamitsu and Krishnamurti, 1978; Yeh et al., 1979). For instance, Kanamitsu and Krishnamurti pointed out that the deficient rainfall over central India and western Africa during 1972 may have been related to a weaker-than-normal Tibetan high and its eastward shift. Figure 6 shows two major patterns of the high at 200 and 100 mb. If the center of the high is located east of 90°–100°E (Fig. 6a), regimes of much rainfall in the western and middle part of Sichuan Province and deficient rainfall or drought conditions in the middle and lower Yangzi Valley prevail. On the other hand, when the center of the high shifts to the west of 100°E (see Fig. 6b), the reverse is true. Recently a quasi-periodic oscillation between these two characteristic patterns has been revealed by spectral analysis (Krishnamurti et al., 1973; Shun, 1979). There may be two primary modes in the oscillations of the high with time, one having a period of 10–16 days, another having a period of less than one week. This quasi-periodic time oscillation of the high could be used for medium-range prediction of droughts and floods. Such an attempt has been made in the forecasting of the rainstorms over Sichuan (Wang and Dai, 1978).

5. Low-level shear lines and vortices over and around the plateau—the important rain-producing synoptic systems in China

During spring and summer low-level shear lines and cyclonic vortices are very often observed over the plateau and its surroundings. They develop in the planetary boundary layer (PBL), which may extend to 2 or 3 km vertically. Recently Murakami (1980a,b) arrived at a similar depth of the PBL over the plateau. Two types of low-level shear lines can be identified, one found at 700 mb over the eastern part of the

FIG. 6. Two major patterns of the Tibetan high at (a) 200 mb; and (b) 100 mb.
FIG. 7. The frequency distribution of low-level vortices over the plateau during the period May–September 1969–76.

plateau, another found over the plateau itself below 600 mb. The former usually evolves from the southern portion (tail portion) of an upper trough passing over the plateau when it is retarded and when, at the same time, it is accompanied by the formation of a small high to the north of it under the influence of the topography of the plateau (Yeh et al., 1979; Murakami, 1980a). The mean position of this type of shear line is nearly the same as that of the Yangzi River, about 30°N. It is one of the main rain-producing synoptic systems there. The second type of shear line often causes the rainfall and heavy rain over the plateau, of which a good example was given in Section 3.

The plateau-related, low-level vortices are of subsynoptic scale and have their geographical origin in three areas: the eastern part of the plateau (so-called “southwest” vortices because of their location in the SW part of China); the main body of the plateau; and the northern part of the plateau (so-called “northwest” vortices because of their location in the NW part of China). Figure 7 shows the total number of days of occurrence of low-level vortices over the plateau during May–September for 1969–76 (Yeh et al., 1979). Two frequency maxima can be seen over the middle of the plateau, implying that the vortices were generated in situ over the plateau. Whether or not a vortex over the plateau will move out of this region is a problem of great interest to Chinese forecasters, because some of these vortices have the potential to develop into major extratropical cyclones that can cause extensive and heavy rain and outbreaks of severe storms in

FIG. 8. Percentage of departures from normal rainfall for July 1954.
China and in Japan. The statistics for April–July of 1970–74 indicate that of 112 low-level SW vortices, 51 caused heavy rain along the middle Yangzi, accounting for 65% of the total vortex number (Tao et al., 1980). Also, according to similar statistics for May and June of 1959–66, 55 of 106 SW vortices caused heavy rains or excessively heavy rains (40 cases) in the lower Yangzi River Valley. Ding (1975) gave a good example demonstrating how a low-level vortex over the middle of the plateau moved eastward and eventually developed into a cyclone wave that caused extensively heavy rain in eastern China with maximum rainfall amounts of more than 400 mm/24 h. Huang et al. (1976) and Shi (1978) studied similar cases of the development of wave cyclones in the Yangzi Valley under the influence of difluent upper troughs.

However, most of the low-level vortices are nondeveloping. They may move successively eastward from the plateau along a northeastward-oriented shear line. For instance, during 14 days between 3 and 16 April 1973, a sequence of 12 vortices successively moved out of the plateau and caused a spell of uninterrupted rain with frequent thunderstorm activity in the middle and southern part of China (Tao et al., 1980). Similar cases were also observed during the Mei-yü season. The most notable example was a long and persistent heavy rain in the Yangzi River valley in June and July 1954, which was one month longer than normal and caused a most serious flood (Tao et al., 1980; Chen, 1957). Figure 8 shows the percentage (%) departure from normal of the rainfall amount for July 1954. Values of departure as high as + 300–600% can be noted in the middle and lower Yangzi Valley. These anomalies had a close relation to the position of westerlies, which were located farther south than normal. Their position allowed a sequence of wave troughs to pass over the plateau and move eastward (Fig. 9). Eight or nine low-pressure disturbances, mostly originating over the plateau and passing over the Yangzi River Valley with steering wave troughs (see Fig. 10), were the primary cause of these uninterrupted rainfalls. As a matter of fact, the unusual circulation and weather events in July 1954 were not confined to East Asia, but were noted in other regions of the world. For example, a rare flood event in India was caused by four upper troughs passing to the south of the plateau. At the same time, a severe drought condition prevailed in the
United States, especially in the Midwest, with extremely high temperatures recorded in many places as a stable subtropical high dominated much of that region. We are not yet certain what the teleconnection between such events might be, but we suspect that the plateau could affect the weather events in distant regions through planetary waves (Reiter and Ding, 1980).

The major flood of early July 1931 in the Yangzi Valley had a great resemblance to that in 1954. Based on surface data available (no upper-air data were taken at that time), this flood was also caused by five to six low-pressure disturbances that had their origin in the eastern part of the plateau. At the beginning of July 1935, another excessively heavy rain took place in the middle Yangzi Valley, with maximum amounts of 1200 mm during five days. The flood-producing synoptic systems were two low-pressure disturbances forming near Lhasa and Sichuan.

Under certain circulation conditions, low-level vortices move northward and may cause heavy rain and severe storms in North China. An unprecedented heavy rain in August 1963 occurred under such circumstances and caused a destructive flood along the Heiho River. A surface station at the eastern slope of the Taihan Mountains recorded a total rainfall amount of 2059 mm during about nine days. The large-scale circulation is shown schematically in Fig. 11. Two stable highs at 500 mb existed on either side of the heavy rain area—one was located over the Qinghai-Xizang Plateau, the other over the sea of Japan. Cold air advection of weak or moderate strength ahead of a long-wave ridge centered over Lake Baikal led the upper flow into a southwest-northeast-oriented low-pressure trough or shear line and stimulated the repeated development of heavy rain over that region. More importantly, three low-level vortices emerged from the plateau region and were the main producers of heavy rains. The most intensive rains appeared as the low-level vortices passed the rain region (Tao et al., 1980; You, 1965). A similar case of excessively heavy rain in Beijing (Peking) on 1–2 July 1972 was caused by a northward-moving SW vortex under the steering influence of a very strong S-N-oriented upper jet. The vortex produced a total rainfall amount of about 200 mm during slightly more than 24 h, which was second to the record established on 26 June 1893 (Tao et al., 1980; Wang, 1974).

Besides the persistent heavy rains, as described previously, excessive rains of short duration also occur frequently in China (Ding et al., 1978). The conditions favorable for such occurrences are in many ways similar to those summarized by Maddox (1978, 1979) and Hales (1978) for heavy rain
in the United States. Such rainfall events can lead to flash floods in relatively localized regions. Not all of these events are related to the synoptic systems over the plateau, however.

It should be pointed out that the occurrences of heavy rains and severe storms are closely related to a low-level jet (LLJ) stream (correlation coefficients of about 0.8). However, the generation and development of the LLJ and the propagation of its wind speed maximum are, to a large extent, controlled by the orographic effects of the plateau on the airflow along the western periphery of the subtropical high and on the amplification of low-level vortices. Figure 12 shows the mean LLJ for July, which is located between the plateau and the subtropical high (Tao et al., 1980). When the subtropical high stretches westward and at the same time a plateau-related vortex is developing, one often observes the presence of a very strong LLJ reaching wind speeds of 20–25 m/s. This situation is very similar to those observed over North America (Wexler, 1961) or over eastern Africa (Findlater, 1969).

Finally, one should mention that tornadoes very seldom occur in China, in spite of the frequent presence of severe storm systems that have a potential to spawn them (Ding et al., 1980; Golden, 1980). We think that the reason for this lack of tornadoes lies, at least in part, in the different effects of the Qinghai-Xizang Plateau and on the circulation patterns as compared to those induced by the Rocky Mountains.

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