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Abstract

Geographic variations in summer (July–August) precipitation data for the northern Qinghai-Xizang (Tibetan) Plateau, collected during the IOP (Intense Observation Period) of GAME-Tibet, were examined. Results indicated that, basically, the daily precipitation amount consistently varies temporally at all sites. An increase in precipitation amount is evident from north to south. The distribution of summer monsoon precipitation is affected by latitude, altitude, and other factors (i.e. atmosphere circulation, water vapor transportation). The latitude effect of precipitation in July and August was significant. August precipitation varied with both latitude and altitude. The site with higher elevation received more precipitation. Topoclimatic controls operating over precipitation on slopes include elevation. The distribution of the precipitation during July–August mainly showed the effects of latitude, but this was modified by the altitude effect. Redistribution processes caused by topography induce increased precipitation with altitude at some sites. Owing to the complexity of surface conditions on the Qinghai-Xizang (Tibetan) Plateau, precipitation is controlled by many factors simultaneously. Without benefit of an expanded observation network, it is difficult to separate the effects of the many factors influencing the distribution of precipitation in the region.

Introduction

Precipitation in mountainous regions is one of the most important factors of mountain climates, and is also a key climate resource. Examining the formation of precipitation in mountains and its distribution is of importance for development and utilization of climate resources. In mountainous regions, elevation and terrain are the decisive factors affecting the distribution of precipitation.

Owing to its size, complexity, and elevation, as well as its unique climate, the Qinghai-Xizang (Tibetan) Plateau is Earth's so-called "third pole." The energy and water cycles on the plateau play an important role in the Asian monsoon system (Krishnamurti and Ramanathan, 1982; Li, 1995; Wu and Ni, 1999; Barnnet et al., 1989; Yasunari et al., 1991; Vernekar et al., 1995; Wu and Zhang, 1998, 1999; Zhang and Wu, 1998, 1999).

Several existing studies of precipitation processes on the Qinghai-Xizang (Tibetan) Plateau (Ye and Gao, 1979; Cheng, 1984; Zhang et al, 1988; Kang et al., 2000; Ueno et al., 1994; Ueno, 1998) concluded that the distribution of annual precipitation decreases gradually from the southeast toward the northwest. Precipitation on the Tibetan Plateau occurs mainly during the summer monsoon period (Yang et al., 2003). The difference between the dry and rainy seasons is well defined. Most of the precipitation occurs during May to September, although the rainy season begins later in the north. The distribution of annual precipitation generally has a one-peak pattern, usually in July or August (Dai, 1990; Qiao and Zhang, 1994).

Studies based on data from meteorological stations have shown that the main characteristic of precipitation on the plateau is the negative correlation between the northern and southern parts (Cai, 1998; Feng, 1999). Between the 1960s and 1980s, precipitation increased in the northern part of the plateau, but decreased in the southern part. Tang et al. (1998) demonstrated that during the mid-1980s precipitation began to decrease in the northern part but increase in the southern part. Corresponding to the plateau's complex topography and physiography, precipitation distribution is also very complex. Based on the annual precipitation data from 81 meteorological stations, Zhu et al. (2004) used the empirical orthogonal function (EOF) and rotated empirical orthogonal function (REOF) to analyze the temporal and spatial distributions of precipitation over the past 30 years on the plateau, but they did not consider the altitude of the meteorological stations. The network of meteorological stations on the Tibetan

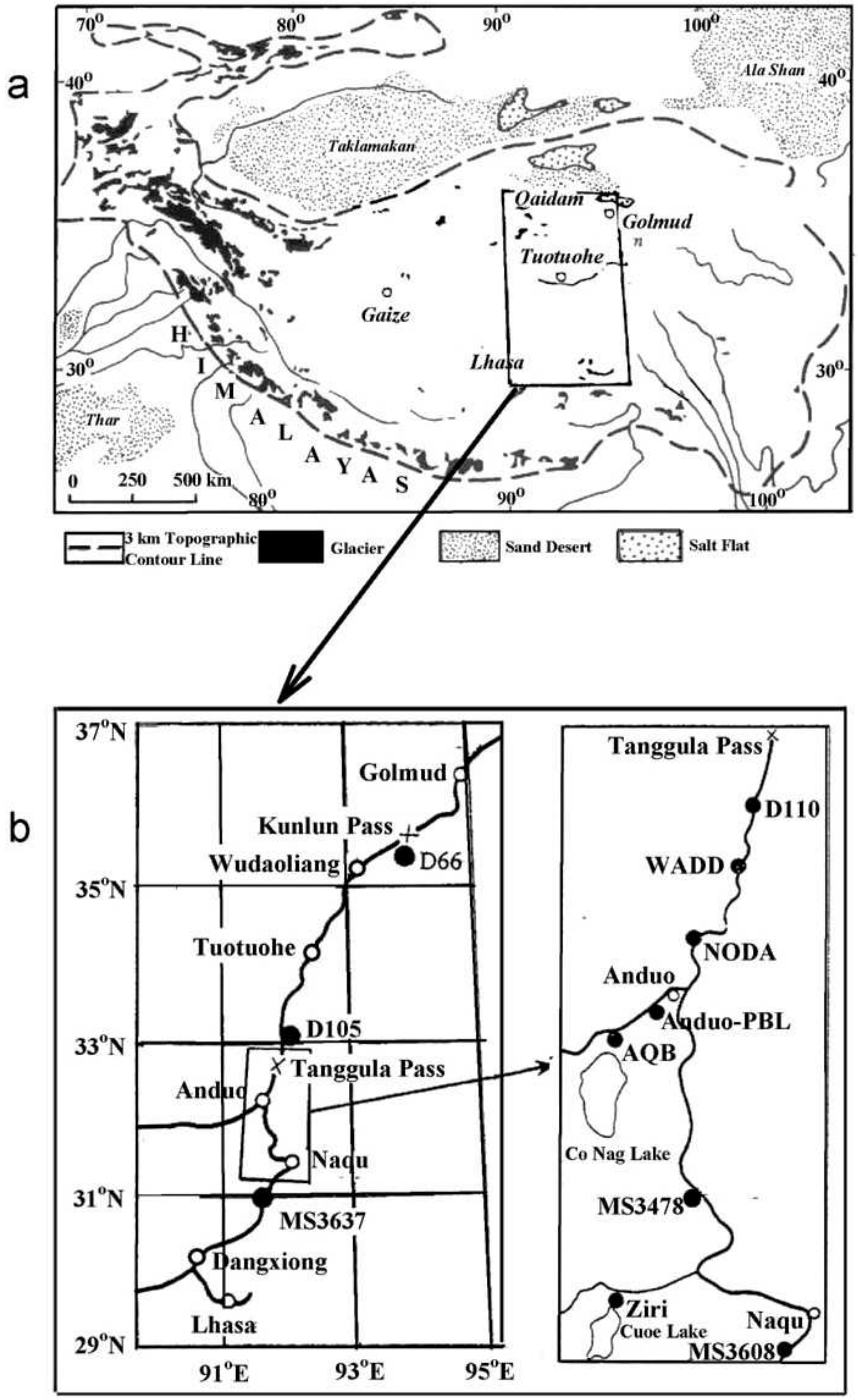

FIGURE 1. Locations of the observation sites. (a) Map of the Qinghai-Xizang (Tibetan) Plateau with 3 km contour shown. The study area is outlined. (b) Enlarged maps of the study area. The right frame corresponds to the small square on the left frame. The solid lines represent roads. The filled circles represent observation sites and the circles represent the meteorological stations. Note some of the meteorological stations are also included in the GAME-Tibet observation network.

Plateau is sparse and its distribution is quite uneven. Most of the stations are located in eastern plateau and probably in river valleys. Data obtained from field expeditions are not abundant. This is especially true in the more remote mountains regions. During the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME)-Tibet IOP (Intensive Observation Period), which operated from May to September 1998, rain gauges were installed at several locations for monitoring the summer monsoon precipitation. This paper reports a preliminary analysis of the monsoon precipitation features in summer 1998 (mainly in July and August) along the Qinghai-Xizang (Tibetan) Plateau highway, based on *in situ* precipitation observation data. The monthly precipitation distribution based on the standard meteorological stations along the highway is also discussed.

Observation Sites and Monitoring Strategy

The Asian monsoon system is one of the most important components of the energy and water cycle in the global climate system. Consequently, the GAME is one of the major projects of the GEWEX. As a part of GAME, the GAME-Tibet project aimed to examine the energy and water cycles on the Qinghai-Xizang (Tibetan) Plateau and their effects on the Asian monsoon (GAME International Panel, 1998).

Mountainous precipitation distribution is very complex, and varies according to different topographic conditions. Kou and Su (1981) highlighted gradients of precipitation over altitudinal sequences in the vicinity of Tuomuer Peak. In discussing changes over altitudinal gradients, it is necessary to distinguish between

TABLE 1

Summary of the rain gauge sites, rain gauge type, and the observation period.

Rain Gauge Site	Latitude (°N)	Longitude (°E)	Altitude/ m.a.s.l.	Observation Period Begin	End	Rain Gauge Type	Data Source	Ground Condition
D66	35.52	93.78	4560	22 May	19 Sep	Ogasawara weight	Hourly data	Flat bare land
TTH	35.22	93.08	4533	8 May	19 Sep	Chinese type	NCDC/globalsod	
Wudaoliang	34.22	92.43	4613	8 May	19 Sep	Chinese type	NCDC/globalsod	
D105	33.06	92.16	5020	7 Jun	19 Sep	ETI-NOAH2 weight	Hourly data	Flat bare land
D110	32.69	91.86	5000	19 May	19 Sep	Ogasawara weight	Hourly data	Flat bare land
WADD	32.55	91.80	5080	26 Jun	19 Sep	ETI-NOAH2 weight	Hourly data	Flat bare slope
NODA	32.46	91.80	4980	9 May	10 Sep	ETI-NOAH2 weight	Hourly data	Flat bare land near hill
AQB	32.15	91.43	4578	16 Jun	11 Sep	ETI-NOAH2 weight	Hourly data	Flat bare land near lake
Anduo-PBL	32.24	91.62	4710	12 May	16 Sep	Ogasawara weight	Hourly data	Flat bare land
MS3478	31.93	91.71	5063	9 May	16 Sep	ETI-NOAH2 weight	Hourly data	Flat earth hammock
Ziri	31.55	91.51	4623	8 May	13 Sep	Tipping bucket without heating	Hourly data	10 m sq. flat bare land surrounded by 2 m wall
Naqu	31.42	91.97	4548	22 May	19 Sep	Chinese type	NCDC/globalsod	
MS3608	31.23	91.78	4610	25 May	9 Aug	Ogasawara weight	Hourly data	Flat bare land
MS3637	31.02	91.65	4820	27 May	13 Sep	ETI-NOAH2 weight	Hourly data	Flat bare land

plateau (precipitous elevation change, relatively flat summit) and *alpine* (sloping surfaces with decreasing area/elevation ratio) precipitation patterns, because both environmental conditions and the precipitation itself are very different in these dissimilar types of terrain (Wen and Luo, 1990). The Tibetan Plateau has both a relatively level surface and steep slopes. Therefore, the distribution of precipitation on the plateau should reflect both types of influence.

During the GAME-Tibet IOP, rain gauges were installed at D105, WADD, NODA, AQB, Anduo PBL site, Zuri, Naqu, and MS3637 (N-PAM). Station locations are shown in Figure 1. Related information is listed in Table 1. Total precipitation was also measured at automatic weather stations (AWSs), D66, Tuotuohe, D110 and MS3637. Total precipitation was also measured at the meteorological stations.

Precipitation Variations and Its Relationship with Latitude and Altitude

VARIATIONS IN PRECIPITATION

Figure 2 shows daily precipitation collected by the rain gauges at different sites during the periods of record indicated in Table 1. The maximum daily precipitation during the observation period at Naqu (30.99 mm) and Zuri (28.50 mm) occurred on 6 July. South of Naqu, the maximum daily precipitation during the observation period occurred on 8 July; here, precipitation was 28.57 mm and 18.03 mm at sites MS3608 and MS3637 (N-PAM), respectively. Maximum daily precipitation (14.99 mm) at Wudaoliang during the study period also occurred on 8 July.

At the Anduo, NODA, WADD, and D110 sites, the maximum daily precipitation occurred on 18 August. The values were 30.80, 26.92, 32.50, and 23.94 mm, respectively. However, maximum daily precipitation at site AQB occurred on 28 August (20.83 mm) and the sub-maximum daily precipitation occurred on 18 August (18.29 mm). Even on the northern slope of the Tanggula Mountains (site D105) the daily precipitation was also relatively large (15.40 mm) on 18 August. At the northernmost site (D66) the maximum daily precipitation was 8.94 mm on 23 August. The precipitation increase is evident from Station D66 southward (Fig. 2). The maximum daily precipitation basically decreases northward.

Precipitation records in this study area have different lengths, and those for some stations are very short or discontinuous. These problems are especially acute near the beginning and ending dates of the records (see Table 1). Figure 3a shows daily precipitation variations at all observation sites listed in Table 1. It demonstrates that, as a whole, precipitation began to increase in early June. There was a slight intermission about 20 June and the monsoon precipitation was already very strong on 28 June, indicating onset of the summer monsoon precipitation. Ueno et al. (1999) pointed out that the monsoon began on 14 June 1998 in the Naqu area. They also showed that the active and inactive periods of the summer monsoon precipitation were very evident in the data record, and that these periods appeared alternately. The precipitation decreases dramatically in early September, demonstrating the end of the summer rainy season is from the early to middle September.

Figure 3b was constructed by accumulating precipitation records from all sites. Because the observation period is different at different sites, the number of stations that have observation records is also shown in Figure 3c. Although the period without records was taken as 0 mm precipitation in calculating total precipitation, the key features of the summer precipitation appear in Figure 3b. At least in the study area, the evident active period and inactive period of the summer precipitation exists. Of course, due to the fact that there are not many observation sites at the early GAME-Tibet IOP (the end of May and early June), the above accumulated precipitation does not always reflect the real condition.

RELATIONSHIP BETWEEN LATITUDE AND JULY–AUGUST PRECIPITATION

Observations were made under GAME-Tibet IOP from May to September of 1998. However, owing to varying installation times and instrument problems for May and June, records for these months are incomplete. Observational activity concluded on 19 September. We therefore relied mainly on precipitation occurring in July and August for our analysis. Precipitation from July to August accounts for 75.8% of the summer monsoon precipitation (from June to September) in the northern part of the Tibetan Plateau (Yang et al., 1999). Precipitation data obtained during July to August can therefore represent the whole summer

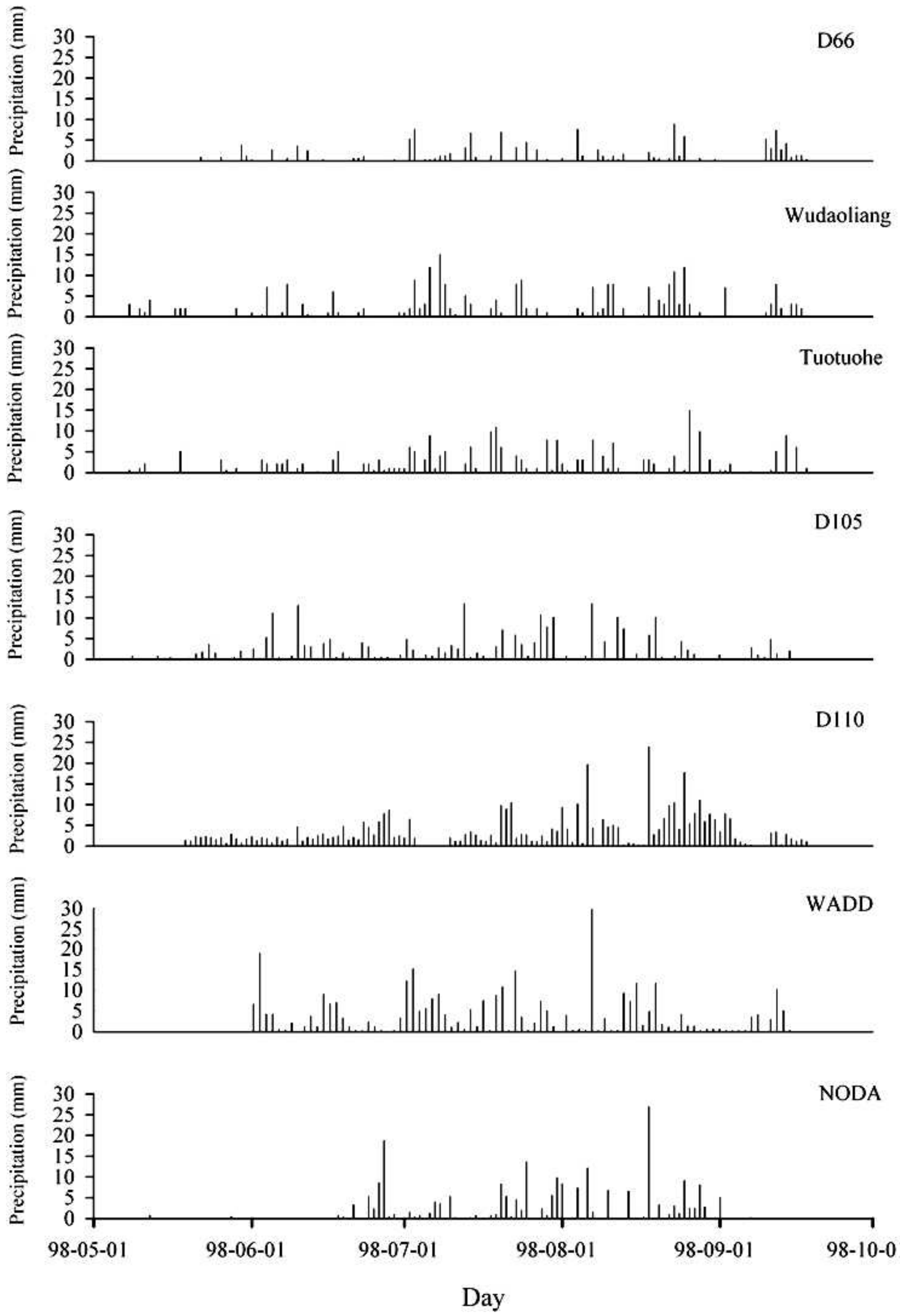

FIGURE 2. The variations of the daily precipitation at different sites.

monsoon precipitation reasonably well. Figure 4 shows the latitude and the precipitation in July and August 1998 at different sites. From south to north, namely, from site MS3637 located to the south of Naqu about 70 km to site D66 located on the southern slope of Kunlun Mountains, precipitation generally decreased, i.e., precipitation decreases as latitude increases. The correlation coefficient between latitude and precipitation is -0.72 in July and -0.74 in August. The confidence level is above 90% with a sample size of 12. The latitude increases 4.1° from Naqu to D66 and the precipitation decreases 322.5 mm. Some of the sites depart significantly from this general relationship, however. For instance, precipitation in August is high at Sites D110, WADD, and D105, largely due to the higher altitude at these sites (Fig. 4). Figure 4 also demonstrates that precipitation at most sites is larger in August than in July. However, their variations do not coincide. The latitude against total precipitation from July to August plotted in Figure 4 indicates that the latitude effect is more significant than both July and August. The correlation coefficient is -0.87.

RELATIONSHIP BETWEEN ALTITUDE AND PRECIPITATION IN JULY AND AUGUST

The relation between altitude and precipitation in July and August 1998 is also shown in Figure 4. The altitude is basically higher northward. In August, the correlation coefficient is 0.23, indicating more precipitation at higher elevation. Wen and Luo (1990) pointed out that the upward motion, related to the up-valley wind induced by the heating effect of the sloping field, could increase the precipitation along the sloping field on both the

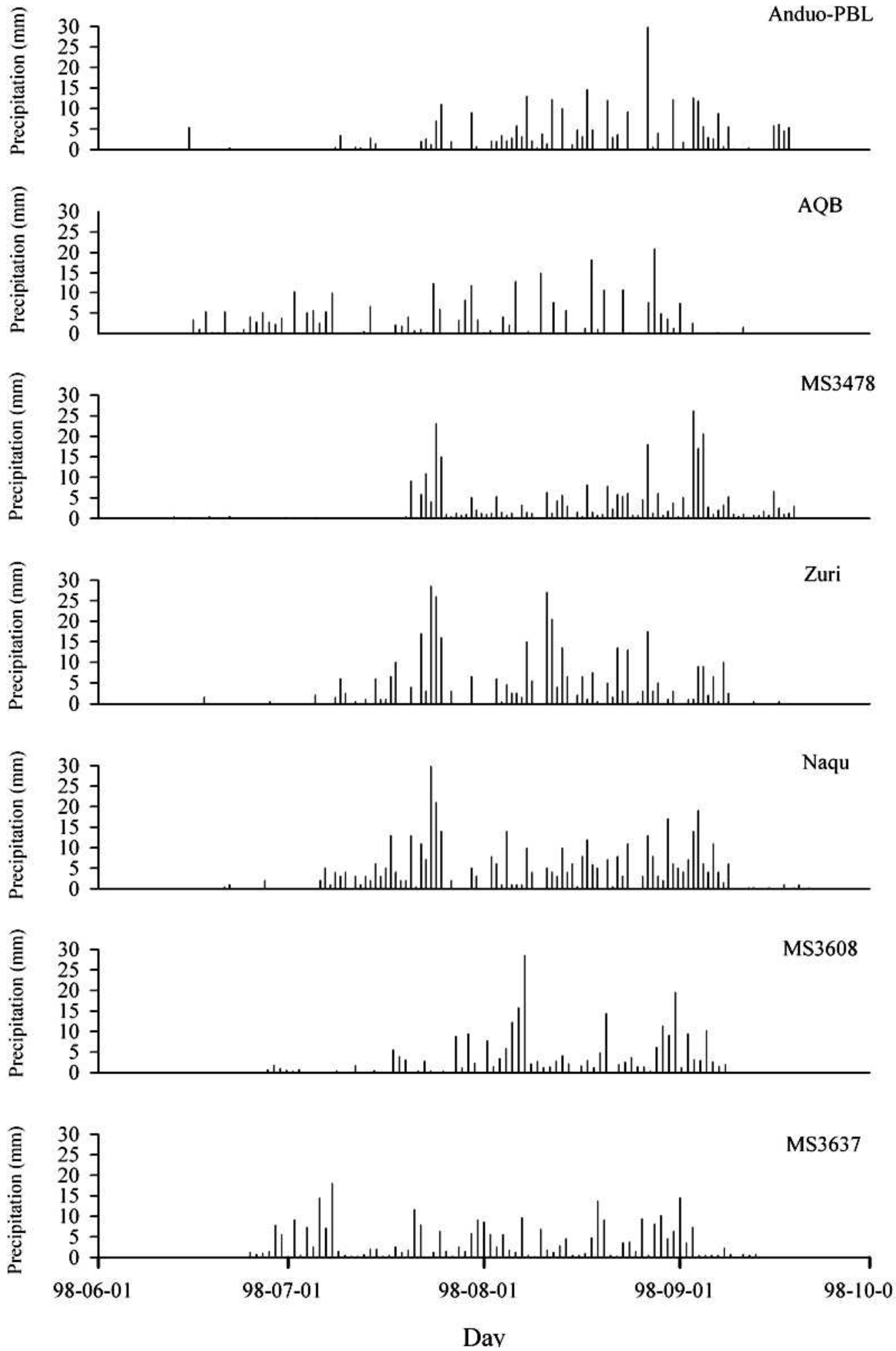

FIGURE 2. Continued.

windward and leeward sides. The total precipitation from July to August in the north of Anduo better displays the altitude effect (Fig. 4) and the correlation coefficient is 0.69. However, it is necessary to note that the number of sites is just seven. This number is insufficient, and more sites and data are needed in the future for convincing conclusions. For the sites south of Anduo, especially at Naqu with relatively low elevation, precipitation was large. In the Naqu area, the low vortex developed frequently (Yu, 2002). The water vapor transportation and the wind direction are basically from south to north. This makes the area north of Naqu get more rainfall at higher elevations. Note that the Nianqing-tanggula Mountains are south of Naqu, and the observation sites were located on the north side of these mountains. The evolution of the plateau low vortex is related to northward movement of large-scale water vapor from the Indian Ocean, Arabia Sea, and Indian subcontinent (Yu, 2002).

Discussion and Concluding Remarks

The GAME-Tibet IOP operated only from May to September in 1998. Although relatively dense precipitation monitoring devices were set up, the observation period is different, and therefore the relationship between altitude and latitude with the

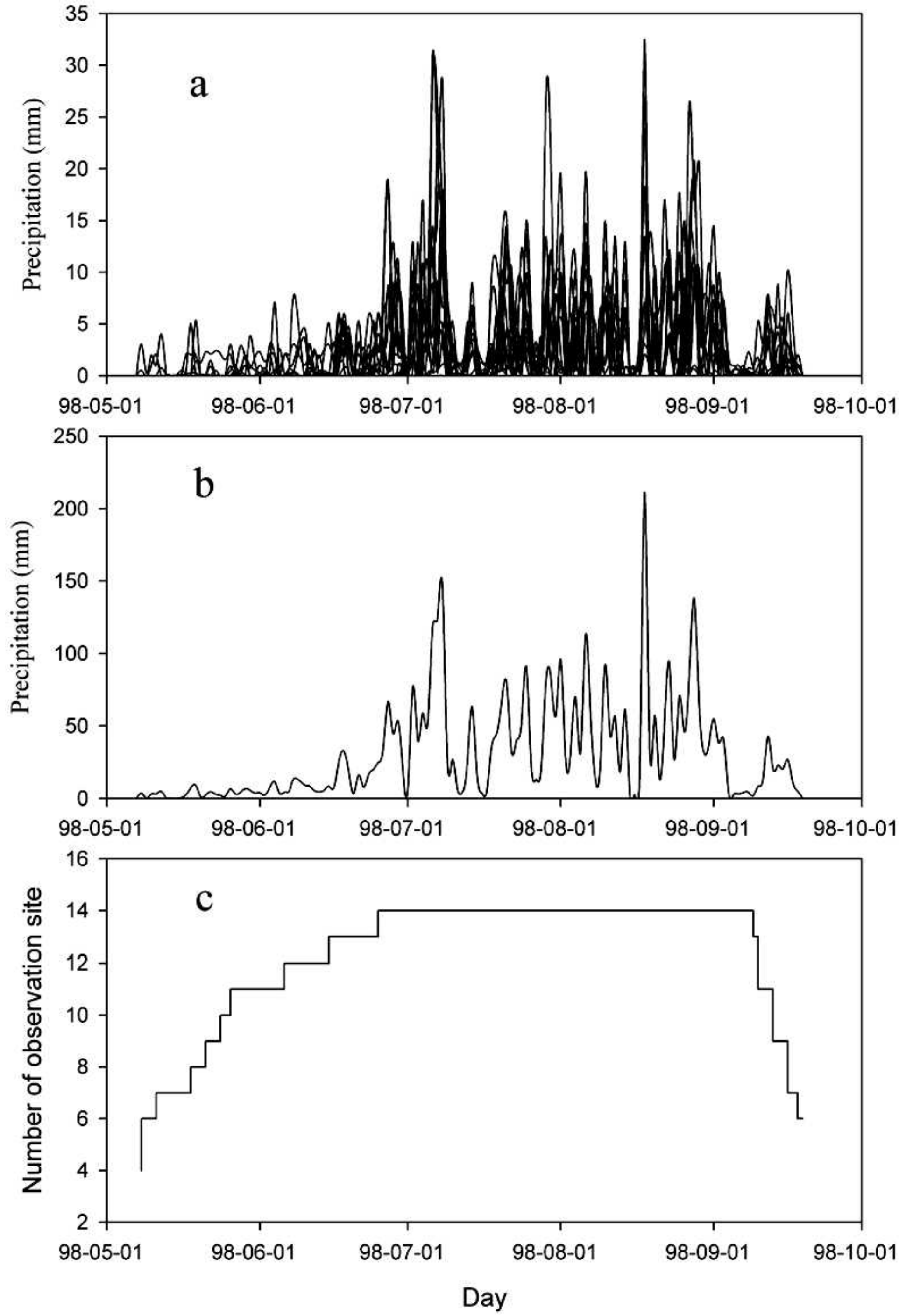

FIGURE 3. The daily precipitation of 14 sites. (a) The daily precipitation at all different sites (Table 1); (b) the total precipitation at all sites; and (c) the number of stations that have the observation records.

precipitation just focused on July and August in above analysis. However, there are several standard meteorological stations (Fig. 1) located along the Qinghai-Xizang (Tibetan) highway and the observations are for more than 30 years. Therefore, the whole year precipitation distribution can be examined further. We have ignored the annual variations and averaged the precipitation from 1971 to 2000. Table 2 shows the monthly distribution of the precipitation in the 7 meteorological stations (from south to north: Lhasa, Dangxioang, Naqu, Anduo, Tuotuohe, Wudaoliang, and Golmud). It shows that the precipitation mainly occurred from June to September. The monthly maximum precipitation occurred in July except for Lhasa, which was in August. The monthly precipitation from November to March is less than 1% of the total precipitation in a whole year (Table 3). The precipitation is about 2% in April and 2%–4% in October. In May, the precipitation is about 6–8% of the whole year.

It is emphasized that the relationship between annual precipitation and the latitude is negative. The correlation coefficient is -0.89 for annual precipitation (Table 4). However, Table 4 shows that the negative correlation is more significant during summer, especially in July and August. The correlation coefficient between annul precipitation and altitude is 0.63. The highest correlation is between altitude and precipitation in February. The correlation between altitude and precipitation in July and August is 0.59 and 0.50, respectively, which is not high compared with other months.

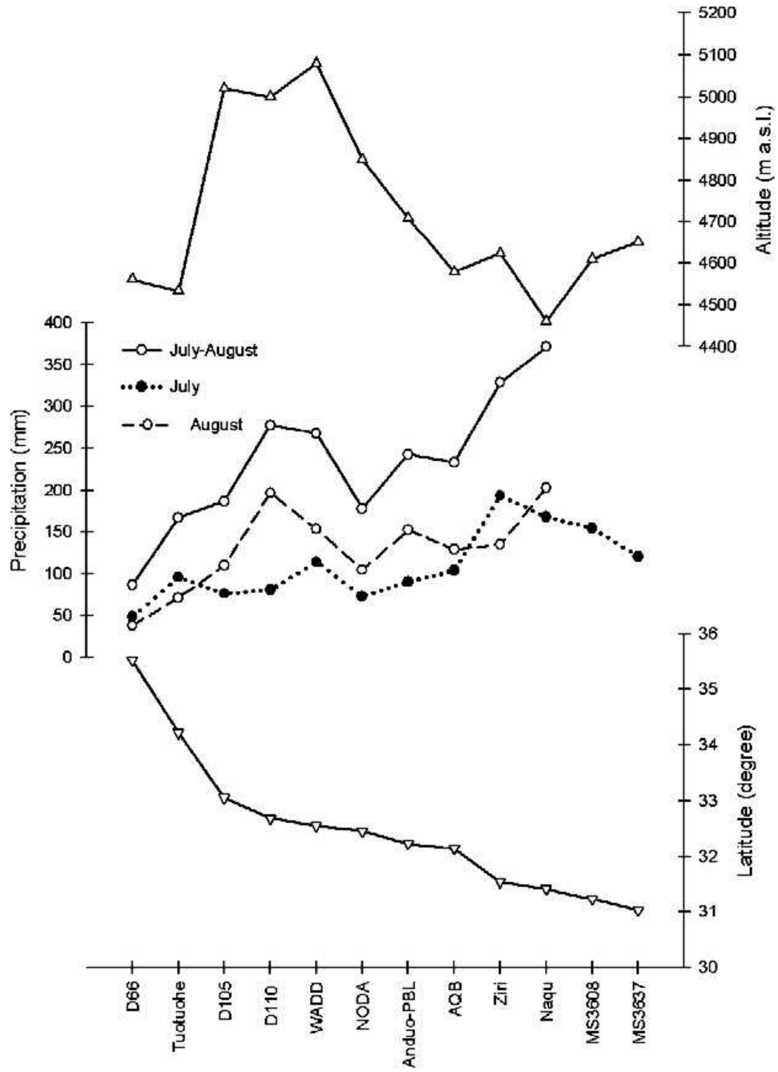

FIGURE 4. The latitude (triangles pointed down), altitude (triangles pointed up), and precipitation (circles) at different sites in northern Tibetan Plateau in July and August 1998.

TABLE 2

The annual and monthly precipitation at the meteorological stations average from 1971 to 2000.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Golmud	0.6	0.4	1.1	0.9	3.7	8.5	13.5	7.8	3.4	0.9	0.7	0.7	42.2
Wudaoliang	1.2	2.0	3.5	7.1	23.7	49.1	69.4	65.4	43.6	7.5	0.9	1.3	274.7
Tuotuohe	1.7	1.8	1.8	5.5	17.6	53.0	77.5	60.8	42.0	11.7	0.9	1.1	275.4
Anduo	2.7	2.8	2.6	8.6	27.6	87.2	109.7	100.5	70.9	18.1	2.7	2.3	435.7
Naqu	3.2	3.3	3.6	11.2	28.5	83.8	103.1	91.5	75.2	20.4	3.8	2.6	430.2
Dangxioang	2.7	2.3	3.7	10.8	29.0	81.3	119.1	109.3	77.8	16.1	3.7	3.9	459.7
Lhasa	0.8	1.2	2.9	6.1	27.7	71.2	116.6	120.6	68.3	8.8	1.3	1.0	426.5

TABLE 3

The percentage (%) of the monthly precipitation on the annual precipitation at the meteorological stations (averaged from 1971 to 2000).

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Golmud	1.42	0.95	2.61	2.13	8.77	20.14	31.99	18.48	8.06	2.13	1.66	1.66	100
Wudaoliang	0.44	0.73	1.27	2.58	8.63	17.87	25.26	23.81	15.87	2.73	0.33	0.47	100
Tuotuohe	0.62	0.65	0.65	2.00	6.39	19.24	28.14	22.08	15.25	4.25	0.33	0.40	100
Anduo	0.62	0.64	0.60	1.97	6.33	20.01	25.18	23.07	16.27	4.15	0.62	0.53	100
Naqu	0.74	0.77	0.84	2.60	6.62	19.48	23.97	21.27	17.48	4.74	0.88	0.60	100
Dangxioang	0.59	0.50	0.80	2.35	6.31	17.69	25.91	23.78	16.92	3.50	0.80	0.85	100
Lhasa	0.19	0.28	0.68	1.43	6.49	16.69	27.34	28.28	16.01	2.06	0.30	0.23	100

TABLE 4

The correlation coefficients between precipitation in each month and annual precipitation and the meteorological station altitude ($r_{altitude}$) and latitude ($r_{latitude}$).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
$r_{altitude}$	0.67	0.85	0.57	0.73	0.70	0.70	0.59	0.50	0.63	0.75	0.41	0.43	0.63
$r_{latitude}$	−0.46	−0.43	−0.62	−0.68	−0.82	−0.83	−0.92	−0.94	−0.89	−0.63	−0.65	−0.57	−0.89

The energy and water cycles on the plateau play an important role in the Asian monsoon system. Corresponding to its complex topography and physiography, the distribution of precipitation over the plateau is also very complex. From south to north, the precipitation decreases as the latitude increases. July falls within the rainy season on the plateau, and July and August have the most precipitation at all the observed sites. However, the altitude effect of the precipitation distribution in July and August is not evident but the latitude effect is relatively significant (Table 4).

The upward motion related to the up-valley wind induced by the heating effect of the sloping field could increase the precipitation in sloping field (no matter whether on the windward or leeward side) (Wen and Luo, 1990). Local evaporation is an important source of precipitation. The precipitation formed by water vapor evaporated locally accounts for 46.86% of the total precipitation, at least during the summer monsoon season (Yang et al., 2006). This will redistribute the precipitation convectively. Topography plays an important role in precipitation processes, and this is best illustrated in July and August, when there is a clear relation between precipitation and elevation. The small number of observation sites available for this study is insufficient for more detailed conclusions, however, and more sites and more data are required to establish firm conclusions.

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