The Importance of the Correction of Precipitation Measurements on the Tibetan Plateau

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(Manuscript received 22 August 1995, in revised form 5 February 1996)

Abstract

Precipitation in the monsoon season on the Tibetan Plateau occurs as rain or snow depending on the elevation and temperature conditions. Point measurements of precipitation may not describe the accurate spatial distribution if systematic-error corrections of precipitation measurement are not applied. Precipitation data at 5 points intensively observed in the Tanggula basin (33°N, 92°E) were corrected, and the characteristics of the spatial distribution of precipitation are discussed. The largest correction was required for wind-induced loss of solid precipitation. The average ratio of corrected and measured precipitation was 1.38. An obvious increase of precipitation toward the south and higher elevations was found. Three years of precipitation data at two Chinese weather stations located north and south of the Tanggula basin were also corrected by the same methods. The ratio of corrected versus measured precipitation showed a clear annual variation, nearly constant at around 1.2 times in the monsoon season, but some months showed increase of more than 1.5 times in the non-monsoon season. Recycling of water between the atmosphere and land surface may strongly prevail in the Tibetan Plateau, which means that the corrected higher precipitation amounts directly correspond to a greater evaporation (or sensible heat source).

1. Introduction

The effects of the water cycle on the Tibetan Plateau on the variation of the Asian Monsoon have been discussed by many scientists. The atmospheric heat source over Tibet is mainly modulated by the latent heat release (Chen *et al.*, 1985), in particular, condensation is the primary source of heating over the eastern plateau after the onset of the monsoon (Yanai and Li, 1994). The relation between Eurasian snow cover and the Indian monsoon, studied by Hahn and Shukla (1976) and by Vernekar *et al.* (1995), is well known. The behavior of soil moisture change due to the melting of snow cover over the permafrost areas is now thought to be one of the unique characteristics of the water cycle processes on the plateau. For all these processes, precipitation is the fundamental element determining the absolute amount for water balance. Convective activity accompanied by sharp diurnal variation was observed by radar in 1979 (Zhang *et al.*, 1988), which strongly suggests that a recycling process of water between the surface and atmosphere is dominant over the plateau. The CREQ (Cryosphere Research

on Qingzang Plateau) project was conducted in the Tanggula basin (33°N, 92°E) to clarify the actual behavior of surface water (*e.g.*, runoff, soil moisture, melting of glaciers) in relation to precipitation and evaporation (CREQ, 1992; Ageta *et al.*, 1994). Intensive hydrological and meteorological observations in 1993 clarified the annual and seasonal changes of water and energy balance by budget methods (Ohta *et al.*, 1995; Ohata, 1995). The percentage of annual evapotranspiration to annual precipitation was estimated as 58–77 %, where 75 % of the annual evapotranspiration occurred from May to September (Ohta *et al.*, 1995). Here, fundamental problems arose because the accuracy of point precipitation measurements and the estimation of areal precipitation considerably affect these percentages.

In the Tanggula basin, measured 12 h-precipitation ranged over 2–10 mm, daily precipitation, on average, was 3–5 mm in the monsoon season, and the monthly total was 150 mm with more than 90 % of rainy days in July, 1993 (Ueno *et al.*, 1994). The precipitation events lasted for several hours simultaneously within the basin. The variation of monthly precipitation between stations is up to 1.5 times, but large discrepancies existed in the 12 h-precipitation

Table 1. Comparison between the measured (MP) and corrected (CP) precipitation, and water equivalent of new snow (WS), in the case of night precipitation records of more than 3 mm/12 h from 20:00 to 8:00, 1989.

Day	MP (mm)	CP (mm)	WS (mm)
13.May	3.3	4.3	9.8
26.May	4.8	8.2	15.4
27.May	11.4	13.8	8.5
28.May	19.8	23.9	22.7
5.June	5.9	8.8	4.6
6.June	6.0	11.3	7.4
12.June	4.2	5.6	4.2
Total (mm)	55.4	75.9	72.6
(%)	100	137	131

amount between stations 10–20 km apart. So, it is speculated that intermittent precipitation of several mm per day might be brought on by sporadic convective cells embedded in systematic mesoscale disturbances, and a point value would only be representative if the value was accumulated for a long period, such as for weeks or a month. In other words, errors of point precipitation measurement result in a large loss of the percentage in the total amount. Especially, measurement loss of solid precipitation is one of the most serious problems.

The Tanggula basin is situated in the elevation range from about 4600 m to 6500 m a.s.l. with a width of 70–100 km. The surface air temperature at Base Camp (BC, 5070 m) ranged from 0 to 15°C with large diurnal variation, and the vertical lapse rate was 6.4°C/km in the monsoon season (Ohata *et al.*, 1994). Therefore, the phase of precipitation frequently changed between snow, rain, or hail within the basin. Indeed, frequent snowfall was only observed at BC before the middle of June and after the middle of August, when snow cover lasted not more than 1 day. On the other hand, most of the precipitation fell as snow around Glacier Camp (GC, 5500 m) until the end of July, which caused a continuous increase of the glacier surface level (Seko *et al.*, 1994). Namely, in the Tanggula Basin, precipitation types differ at each observation point depending on the altitude and temperature change, even in the monsoon season; this must induce variation of the wind-induced losses among the stations.

In the cold regions, correction of precipitation is indispensable. The WMO presents guidelines for precipitation correction by intercomparisons of rain gauges (WMO-CIMO, 1992; WMO, 1994). The largest effect is a loss of measured precipitation due to wind field deformation over the rain gauge in the case of solid precipitation. The effect is dependent also on the shape of the gauge orifice (Sevruk *et*

al., 1991; Sevruk, 1993). Recently, the DFIR (Double Fence Intercomparison Reference with a Russian Tretyakov manual gauge) is designated as the WMO reference standard for solid precipitation measurement (Goodison *et al.*, 1988). It is recommended to correct measured precipitation using experimental functions depending on the type of precipitation gauge, type of precipitation, and wind speed. For example, observations in Canada and Alaska showed losses of several tens of percent of precipitation not only due to the wind but also wetting loss (Goodison and Metcalfe, 1992; Yang *et al.*, 1995). The maximum loss of 30–50 % was reported from Finland (Finnish report, 1992). Yang *et al.* (1991) carried out intercomparisons between the Chinese rain gauge and the DFIR in the Urumqi River Basin in China, which also showed 15–20 % wind-induced losses of wet snowfall measurements. They also reported a large discrepancy in the case of dry snowfall, even for low wind speeds.

In the Alps, Sevruk (1983) reported considerable systematic losses in the winter precipitation measurements, using the Swiss storage gauges as compared with the water equivalent of new snow. In Tanggula basin in 1989, also, nocturnal snowfall amount as observed by a storage gauge was compared with the water equivalent of new snow. Seven cases were selected in June and July when a nocturnal snowfall of more than 3 mm/12 h was observed. In Table 1, precipitation amounts from 2000–0800 hours, with and without correction (MP and CP, respectively), were compared with the water equivalent of snow cover (WS). Precipitation was corrected by the formula of Lapin (1989):

$$K = 1.05 + 0.0412U + 0.0307U^2,$$

where K is the conversion coefficient and U is the wind speed (m/s) at 2 m. However, this experimental formula does not necessarily apply to the type of storage gauge used; neither is the type of precipitation considered. A difference between the CP and WS exists of about 5 mm in individual cases. However, the total amount of CP for 7 days shows better agreement with WS than for MP, with an increase of 37 %, indicating that the correction of the measured precipitation may provide more reliable data.

This paper shows the importance of applying corrections to point precipitation measurements on the Tibetan Plateau for the studies of water cycle. The meteorological data used were from the CREQ project in 1993 and empirical formulae developed in Europe were applied. Corrected precipitation was compared at each step to diagnose the effects of different size and shape of the gauge orifice, evaporation, and wind. The appropriateness of the corrections is ascertained by the characteristics of the corrected precipitation distribution.

2. Observation

The Tanggula basin is situated nearly in the center of the Tibetan Plateau (33°N, 92°E) on the north side of the Tanggula mountain range, with a total area of 4538 km² and altitude range of 4600–6500 m a.s.l. The annual temperature range is from –20°C to 10°C at 5060 m (Ohata *et al.*, 1994). The Chinese climatological map by Zhang *et al.* (1988) and Tao *et al.*, 1990) shows annual precipitation totals of 300–400 mm, with 80 % in the monsoon season.

Precipitation observations were conducted at five stations of different elevations: D100 (4800 m), D105 (5040 m), BC (5060 m), TS (5206 m), which are located from north to south along the highway crossing the basin, and GC (5500 m), located 10 km east-northeast of BC in the vicinity of the Xiao Dongkemadi Glacier. In 1993, the precipitation records showed an intensive monsoon season from June 16 to August 24. At BC, 12 h-precipitation was observed at 0800 and 2000 Beijing time and compared among three different types of precipitation gauge; the Tretyakov (TRET), a tipping bucket type of 0.5 mm resolution (TIP), and a Chinese storage type (ST). At D100, D105 and TS, 10-minute precipitation was automatically recorded by a TIP with a data-logging memory, and accumulated for 12 hours. The TIP does not measure accurate precipitation in the case of snow or when the bucket is frozen, but such cases can be detected by comparing the time sequences of original TIP data between the stations. The data sequences showed several interruptions at the station TS during the night and early morning, accompanied by an abrupt increase of precipitation in the morning, in early June and late August. This is clearly due to the snowfall accumulating in the gauge during the night and melting after sunrise. Except for such cases, we assumed that most of the snowfall measured using the TIP did not induce a serious deficit for the 12-hour accumulated precipitation records. At GC, manual observation were carried out by an ST rain gauge. The precipitation observation at GC was conducted with a glacier experiment period which occupied only 25 % of that at BC, so the missing data were estimated by empirical relations of precipitation between GC and BC, as explained in the next section.

Temperature and wind speed were automatically observed at 2 m at D100, D105 and TS, and at 0.8 m at BC near the rain gauge. At GC, meteorological observations were conducted on the glacier (5600 m). Preliminary results of the meteorological observations have been reported by Ueno *et al.* (1994) and Ohata *et al.* (1994).

3. Methods of correction of precipitation

Systematic errors in the measurement of precipitation are caused by 1) wind-induced loss, 2) evap-

oration loss, 3) wetting loss, and 4) difference of the orifice area of the gauge (Sevruk, 1985; WMO, 1994). 1) is due to the wind field deformation above the orifice (Sevruk, 1993) mainly determined by the design of the gauge, wind shield, size of orifice rim, precipitation type and wind speed. 2) is evident during warm weather and strong radiation conditions, and 3) is induced by wetting of the inner walls of container, and frequent volumetric measurements particularly for “can” type gauge. 4) contributes to the effects 1)–3), especially the percentage of errors are enhanced if the absolute amount of precipitation decreases as the orifice area become smaller. Mechanical differences in the gauges, such as between storage, tipping bucket, siphon, or weighing type, cause random errors, but this paper does not deal with them. The percentage errors due to 2) and 3) are expected to be less than 10 %, especially for the TIP, because the bucket is installed inside the gauge and protected from the outside weather. But, 1) will induce several tens of percent error, particularly for solid precipitation. In this study, the effect of 3) was not taken into account, because precipitation was measured only twice a day using a TRET at BC, and other stations used the TIP. All in all, the following three steps were considered further to correct the systematic errors 1), 2), and 4).

Step 1: Measurement of standard 12 h-precipitation amount (TRET_X) and intercomparison of precipitation gauges at BC.

Evaporation from an exposed ST with a certain amount of water was measured for 3-hour intervals for several cases of fair and cloudy weather in the daytime; the average losses were 0.15 mm/h for fair weather and 0.09 mm/h for cloudy weather, respectively. These losses were larger than found by Lapin and Samaj (1989) in Slovakia, who show hourly evaporation less than 0.05 mm/h on average. However, the total evaporation loss was only 1.6 % of the total monsoonal precipitation, because frequent rainy or cloudy weather prevailed in the Tanggula basin in 1993 and nighttime evaporation was assumed to be zero. The loss was added to the precipitation observed by the TRET according to the weather records at BC, to evaluate effect 2). The measured precipitation by the TRET with correction for the evaporation loss was named TRET_X.

Linear regression was performed between the TRET_X and the ST or the TIP, to evaluate effect 4). The amount of TRET_X was almost the same as for the ST, and the relationship between TRET_X and the TIP was formulated as $TRET_X = 0.83 \cdot TIP + 0.56$. An empirical coefficient of 0.56 for the intercept indicates the loss of nearly one tipping bucket amount by the TIP, and 0.83 for the gradient indicates undercatch of precipitation by the TRET due to smaller area of the orifice. 12 h-precipitation

Table 2. Percentage catch of the comparison gauges as a function of wind speed (1 m level) subdivided according to the type of precipitation, as evaluated at the Harzgerode Station in Germany, December–March 1986–1992 (copied from WMO-CIMO, 1992, Appendix I, p. 17).

Mean wind speed (m/sec)	Number of cases	Mean air temp. (°C)	DFIR total (mm)	TRET/DFIR %
Type of precipitation: Snow				
.0–1.0	4	–9.2	2.1	85.7
1.1–2.0	29	–6.3	61.5	81.0
2.1–3.0	28	–3.7	76.3	69.5
3.1–4.0	25	–2.7	85.0	49.5
4.1–5.0	11	–2.0	79.7	48.1
5.1–20.0	2	.6	11.0	27.3
.0–20.0	99	–4.2	315.6	59.6
Type of precipitation: Snow with rain				
.0–1.0	1	–2.0	9.2	68.5
1.1–2.0	16	–1.9	74.1	84.3
2.1–3.0	20	–.8	48.3	70.8
3.1–4.0	11	.5	63.2	62.8
4.1–5.0	14	.6	63.6	53.1
5.1–20.0	7	1.2	41.5	52.0
.0–20.0	69	–.4	299.9	66.1
Type of precipitation: Rain with snow				
.0–1.0	1	–4.0	.1	100.0
1.1–2.0	11	.3	33.9	89.7
2.1–3.0	12	1.3	43.2	85.2
3.1–4.0	35	2.0	149.8	84.2
4.1–5.0	22	2.5	103.7	81.5
5.1–20.0	12	3.5	109.7	78.9
.0–20.0	93	2.0	440.4	82.8
Type of precipitation: Rain				
.0–1.0	3	–1.1	1.6	93.8
1.1–2.0	50	2.0	52.3	88.5
2.1–3.0	50	3.3	83.7	87.2
3.1–4.0	34	5.5	98.8	87.7
4.1–5.0	34	5.1	91.8	80.9
5.1–20.0	25	5.5	143.4	77.3
.0–20.0	196	3.9	471.6	83.2

observed by the ST or the TIP at each station was converted to TRET_X by the experimental relation above.

Step 2: Correction of TRET_X to DFIR.

TRET_X and DFIR were not compared by the CREQ project, nor was any suitable intercomparison made for monsoonal precipitation over such an elevated plateau. To get the correction factors, however, observations at Harzgerode station in Germany (WMO-CIMO, 1992; WMO, 1994) show clear empirical relations between the TRET and DFIR as functions of precipitation type and wind speed (Table 2). These results were used to correct TRET_X in this study. Four types of precipitation, snow, snow with rain, rain with snow, and rain, were classified using the surface air temperature, as an indicator of the probability of the occurrence of solid precipitation. According to Ueno *et al.* (1994), critical tem-

peratures of -0.6°C for 100 % solid precipitation, 2.9°C for 50 %, and 6.5°C for 0 %, were observed at BC, and used to categorize the four types of precipitation conditions. Frequently, precipitation initiated by a strong hail shower was observed in the Tanggula basin. If the hail was considered to be solid precipitation, the probability of solid precipitation for the temperature range above 4°C becomes larger than without the consideration of hail (Ueno *et al.*, 1994). Hail also reduces the amount of precipitation catch due to its bouncing on the orifice of the TIP. However, an estimate of hail contribution is very difficult in the present case, and hail was not considered in this study. The relationships between the wind speed and percentage of TRET/DFIR in Table 2 were formulated as exponential functions. 12 h average temperature and wind speed observed near to the rain gauge were adopted for the calculation. Temperature and wind data were reduced to

Table 3. Total precipitation (mm) at five stations from 23 May to 28 July observed by the TIP and corrected to TRET, DFIR and BUSH. Percentage (%) relative to the BUSH/BC and its distribution between the night (0800 observation) and day (2000 observation) are indicated on the right side. JMA-GCM indicates the estimated precipitation in a grid cell covering the Tanggula basin calculated by the Global Circulation Model of the Meteorological Research Institute in Japan. The last column indicates the mean increase rate at D100, D105, BC and TS, between each correction step.

Station	TIP (mm)	TRET (mm)	DFIR (mm)	BUSH (mm)	vs BC (%)	0800 (%)	2000 (%)
D100	232.1	238.6	279.8	291.3	96	43	57
D105	177.0	185.5	232.7	245.6	81	38	62
BC	220.0	224.4	297.3	304.4	100	54	46
TS	217.5	233.6	302.9	325.0	107	24	76
GC	—	—	—	447.4	147	49	51
JMA-GCM	—	—	—	115.3	38	—	—
Increase		×1.04	×1.26	×1.05	Total increase =1.38		

the value at 1 m level above the surface by linear and logarithmic interpolation, respectively, to apply the conversion value TRET/DFIR from Table 2.

Step 3: Correction of DFIR to BUSH

Correction of DFIR measurements for wind-caused loss according to a comparison with a bush gauge (BUSH) is required by WMO-CIMO (1992). The following equations by Yang *et al.* (1992), obtained at the Valdai WMO intercomparison site in Russia, are recommended for correcting DFIR:

a) Dry snow

$$\frac{\text{BUSH}}{\text{DFIR}}(\%) = 100 + 1.89 \times U_3 + 6.54E-4 \times U_3^3 + 6.54E-5 \times U_3^5, (N=52, R^2=0.37).$$

b) Rain with snow

$$\frac{\text{BUSH}}{\text{DFIR}}(\%) = 101.67 + 0.254 \times U_3^2, (N=39, R^2=0.38).$$

c) Snow with rain

$$\frac{\text{BUSH}}{\text{DFIR}}(\%) = 98.97 + 2.30 \times U_3, (N=43, R^2=0.34).$$

d) Rain

$$\frac{\text{BUSH}}{\text{DFIR}}(\%) = 100.35 + 1.667 \times U_3 - 2.40E-3 \times U_3^3, (N=120, R^2=0.22).$$

Here, U_3 , N , and R indicate the wind speed at 3 m, sample number, and correlation coefficient, respectively. DFIR data were converted to BUSH equivalent values using these formulae. Methods for the classification of precipitation types and the reduction of wind speed data to the 3 m level are the same as in Step 2.

Step 4: Correction of the data at GC

At GC, 12 h-precipitation was manually observed only for 66 half days using ST on the lateral moraine area. The precipitation data were corrected according to TRET values, as explained in Step 1, using the empirical coefficients observed at BC. The TRET value was converted to DFIR and BUSH values, as shown in Steps 1 and 2, using the temperature and wind speed data observed at the Glacier Station (GS, 5600 m). Wind speed data were reduced to 65 %, and +0.6°C was added to the temperature data to accommodate for different surface conditions and the altitude difference between GS and GC. Significant relationships of the 12 h-precipitation amounts were certified between BC and GC within the 66 half-day samples (Ueno *et al.*, 1994). Therefore, precipitation data missing at GC were interpolated using BC data. Namely, the variation of precipitation at GC is essentially given by the BC values.

4. Results of the correction

Table 3 shows, 1) the accumulated precipitation from May 23 to July 28, when concurrent observations were made without data gaps at all stations, 2) the percentages of daytime and nighttime precipitation for BUSH, and 3) precipitation over the Tanggula area produced with a 2.25° grid interval using the Global Circulation Model (GCM) of the Japan Meteorological Agency (JMA).

Important findings are summarized as follows:

- 1) The final correction of BUSH is 1.38 times larger on average than the original TIP measurements.
- 2) The percentage increase of the measured precipitation due to correction is relatively large at TS and D105, where the highest altitude and windy conditions occur.
- 3) A trend of increase of corrections appears toward the south for all stations except D105.

- 4) An abrupt increase of precipitation is found at GC, the highest station.
- 5) The relatively small amount of precipitation at D105 does not change after the correction.
- 6) The corrected TRET values according to DFIR are the largest.
- 7) No systematic difference between the daytime and nighttime precipitation amounts is found, except at TS.
- 8) The JMA-GCM underestimates precipitation at BC by more than one half.

These characteristics are discussed in the next section.

5. Discussions

5.1 Characteristics of precipitation in Tanggula basin

The following are examples of the amount of measured precipitation increase associated with corrections made in several countries from WMO-CIMO (1992). The increase from TIP to TRET was 1.19 in Canada; that from TRET to DFIR was 1.35 in Canada, 1.33 in Germany, 1.31 in Russia. The increase from TRET to BUSH was 1.09 in Russia. All the increases are larger than that in this study, which means that the total correction of 1.38 in this study is not overestimated by very much. The reason is that the temperature is higher and the wind speed is less in summer over Tibet compared with winter in Europe. (Incidentally, the coefficient of 1.38 is nearly the same as that obtained from the observations made in 1989, Table 1). The total precipitation of TRET at BC from May 23 to July 28 was 55.4 % of that from May 18 to September 21, the CREQ'93 operation period. If the ratio 1.38 is applied through the whole period, the total precipitation from May to September at BC is expected to be 550 mm, and the annual precipitation becomes 688 mm if the monsoonal precipitation comprises 80 % of the annual total. This value is 30–40 % larger than is given in the climatology by the Chinese Academia Sinica (1984), Yang and Woo (1988) and Tao *et al.* (1990) which describe the annual precipitation amount as 300–500 mm around the Tanggula area.

The spatial precipitation distribution, as analyzed by Yang and Woo (1988) or Tao *et al.* (1990), shows increasing amounts from northwest to southeast over the Tanggula area. An analysis of the convective activity by GMS imagery by Ueno *et al.* (1995) also characterizes the frequent development of lower IR- T_{BB} (infrared equivalent black-body temperature) clouds accompanied by a strong diurnal variation to the south of the Tanggula mountain range. Corrections of measured precipitation clearly enhance this characteristic. In other words, the spatial distribution of precipitation at high elevations in the southern area of the basin would

be underestimated if the measured original values were used without corrections. The reasons for the precipitation gradient might be attributed to the moisture gradient provided by plateau-scale monsoonal circulation and topography of the Tanggula mountain range. A difference between the daytime and nighttime precipitation was not evident although some studies noted the large diurnal variations in moisture budget or PBL structure over the Tibetan Plateau (Yanai *et al.*, 1992; Yanai and Li, 1994). The percentage distribution of nighttime precipitation by Zhang *et al.* (1988) shows its maximum along the Brahmaputra River or Yangtze River where strong local circulations dominate, and in the western plateau where sensible heat flux is apparent. We speculate that the diurnal variation is faint in the Tanggula area because of its transitional location between the northern dry and southern wet climates of the plateau, together with orographic effects.

In this study, evaporation loss from storage gauges was not studied in detail together with the temperature or radiation data, but only adjusted by experimental constants defined by weather conditions. Actually, convective showers and strong radiation alternately prevailed within a 12 h time scale in the Tanggula basin, which may provide greater evaporation losses than the results of this study. Better design and materials for the TRET and ST are required to prevent such short-time-scale evaporation losses.

An abrupt increase of precipitation at GC is expected from the basin-scale orographic effect on the precipitation cells, which may provide two types of spatial precipitation distribution between the bottom and ridges of the basin. One is that orographic precipitation prevails only above a certain altitude, and a critical border of altitude exists between frequent precipitation and no-precipitation areas. The other is a continuous increase of precipitation with increasing altitude. We speculate that the smaller amount of precipitation at D105 was induced by the former type. Areal precipitation will change considerably depending on which type prevails. Precipitation-altitude relationships are strongly dependent on the structure of the disturbance and the orography of the windward slopes (*e.g.*, Yoshino, 1975; Barry, 1992). On the Tibetan plateau, most studies, including this one, have not investigated the spatial distribution of precipitation and clouds accurately in relation to basin-scale orographic effects.

The JMA-GCM simulation shows a large deficit in precipitation amount relative to the corrected one. This may be due to an underestimate of latent heat release, the lack of any systematized concentration of water vapor by mesoscale convection, or the lack of orographic effects of the Tanggula mountain

Table 4. Measured and corrected precipitation (MP and CP) and the amount of CP versus MP (CP/MP), averaged for 1990–92 at Tuotuo-he and Amdo station. Results are summarized for monsoonal (May–Sept.) and annual (Year) periods, respectively. The percentage of monsoonal to annual precipitation (%) is shown in the bottom line.

	Tuotuo-he station			Amdo station			
	MP	CP(T)	CP/MP	MP	CP(A)	CP/MP	CP(T)/CP(A)
A(May–Sept.)	210.0	271.5	1.29	435.8	519.8	1.19	0.52
B(Year)	234.0	294.7	1.26	467.8	568.3	1.21	0.52
A/B(%)	90	92	—	93	91	—	—

range in the model scheme. However, several fair days, which interrupted the monsoonal precipitation (Ueno *et al.*, 1994), were more or less reproduced in the JMA-GCM (not shown). We speculate that the intraseasonal variation of monsoonal precipitation in central Tibet is strongly affected by mid-latitude circulation changes which are simulated well by the JMA-GCM.

5.2 Correction of precipitation data at Chinese weather stations.

Weather stations at Tuotuo-he (34.0°N, 92.2°E) and Amdo (32.1°N, 91.8°E) are located respectively in the north and south of the Tanggula basin, where precipitation is observed by a Chinese storage-type gauge. Corrections of the daily precipitation data from 1989 to 1992 are made by using the same experimental methods as shown in Section 3. Daily mean temperature at 1.5 m and wind speed data at 10 m were used, where the wind speed data were reduced to 3 m or 1 m by logarithmic interpolation. Table 4 shows monsoonal (May to September) and annual precipitation before and after the correction, respectively. The percentage of monsoonal precipitation, which accounts for more than 90 % of the annual total, was not changed at either station after the correction. After the correction, the monsoonal precipitation increased 30 % in Tuotuo-he and 20 % at Amdo, corresponding to 271.5 mm and 519.8 mm for the three-year average. The two-fold difference in absolute precipitation amount clearly indicates the dry and wet climates at each station separated by the Tanggula mountain range. If the orographic effects of the Tanggula mountain range are taken into account, the precipitation total of 550 mm from May to September observed at BC is a reasonable amount following correction.

Figure 1 shows the variation of monthly precipitation before and after correction together with the percentage of corrected versus measured precipitation. The percentage clearly shows an annual cycle. From June to September, the percentage is almost constant at around 120 %, but it exceeds 150 % in April and May. Namely, a large discrepancy occurs between the measured and corrected precipitation in the pre-monsoon season, due to snowfall

in cold weather. Especially for Amdo, the correction percentage shows a small peak after the post-monsoon season. If the duration of the monsoon season changes from year to year, correction of the precipitation amount may augment the annual precipitation amount in the southern wet climate areas of the Tibetan Plateau. A maximum rate of more than 200 % was calculated at Tuotuo-he in the winter season, which may result from disturbances in the westerlies accompanied by dry snowfall.

6. Summary and conclusions

Correction of precipitation measurements for systematic errors, particularly in the case of monsoonal snow and rain on the Tibetan plateau, is described. Meteorological observations with an intercomparison of precipitation gauges were conducted in Tanggula basin from May to September 1993. Experimental equations developed for the winter season in Germany and Russia were applied to correct the wind-induced errors. Precipitation data from 1989 to 1992 at two stations near the Tanggula basin were also corrected and compared with observational data. The major results are summarized as follows:

- 1) According to preliminary observations in the pre-monsoon season, the water equivalent of new snow at night showed much better agreement with corrected precipitation than measured precipitation. The result provided strong motivation for the correction of precipitation on the Tibetan Plateau.
- 2) Systematic errors in the measurement of precipitation, such as wind-caused loss, evaporation loss, and difference of the orifice area of the gauges, necessitate corrections. Using an average of four stations, a total increase of 38 % resulted from three correction steps; wind-induced loss as a function of precipitation type and wind speed occupied the largest correction of 26 %.
- 3) After the application of precipitation corrections, a gradient of precipitation increase toward the south was found, because the precipitation in the south of the basin at high elevations could be successfully reconstructed. The gradient can be confirmed from the Chinese climatological map of precipitation and convective activities observed by GMS.

Fig. 1. Annual variation of measured and corrected monthly precipitation (MP and CP, unit: mm) indicated by black and white columns, respectively, at Tuotuo-he (top) and (bottom) Amdo stations. The solid line indicates the percentage change of corrected precipitation versus measured values; the scale is given on the right axis.

4) Three years of precipitation records at two weather stations located in the south and north of Tanggula were corrected, and compared with our data. Precipitation data showed a clear contrast of dry and wet climate of north and south of the Tanggula mountain range, and the corrected data observed in the Tanggula basin were confirmed to be adequate. The correction percentage showed clear annual variations. A constant value of around 120 % was observed from June to October, while the percentage increased to 150–200 % from March to May due to solid precipitation in the pre-monsoon season.

Ohta *et al.* (1995) estimated annual precipitation

of 724 mm in the large watershed of Tanggula basin, together with our data and winter precipitation reconstructed by Ohata (1995). They clarified the annual water balance using the precipitation and run-off data (Ohta *et al.*, 1994), and showed an annual evaporation of 574 mm. Also, they estimated the evaporation rate in the monsoon season by the short-term water balance method and heat balance method, and both methods showed very similar seasonal variations. Such large values of evaporation in a cold alpine region indicate that unique water recycling functions may prevail over the plateau due to the strong radiation and wet surface con-

ditions. If the monsoonal precipitation is not corrected, the amount of annual evaporation is also underestimated to be around 400 mm, which signifies an underestimate of the latent heat release from the plateau surface. Hence, the correction of the precipitation distribution is quite an important factor in determining the energy and water balance of the Tibetan plateau.

To determine the spatial precipitation distribution accurately over the Tibetan plateau, some important problems remain for the future. One is that we need to develop empirical equations for the wind-caused loss of the monsoonal snowfall by convective clouds on an alpine plateau. Estimation of accurate areal precipitation is another great problem in such a remote area. Sporadic precipitation from the convective cells, enhanced by orographic effects, prevents the estimation of areal precipitation by the point observation method. Currently, the installation of a Doppler radar system on the Tibetan plateau, together with a DFIR precipitation gauge and satellite observation, is being planned by the GEWEX/GAME international project (Koike *et al.*, 1995); this may provide rapid progress in understanding the water cycle of the Tibetan Plateau.

Acknowledgments

The authors wish to express their thanks to Dr. H. Ohno, Japan International Research Center for Agricultural Sciences, who provided us many references and technical comments about the correction of precipitation. They also thank Dr. T. Ohta of Iwate Univ. and Dr. T. Koike of Nagaoka Tech. Sci. Univ., who contributed many ideas concerning this work, and Dr. R. Oki of the Remote Sensing Technology Center of Japan, who archived the JMA-GCM data. This study was supported by grant No.01041043 from the International Science Research Program, Ministry of Education Science, Sports and Culture, Japan.

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チベット高原における降水量補正の重要性について

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モンスーン期のチベット高原では、観測地点の標高及び気温状況に応じて、降雪と降雨が混在してもたらされる。従って、雨雪判別を加味した地点降水量の補正を行わないと、正確な降水量分布が求まらない可能性がある。本研究ではタングラ流域5地点で観測された降水量の補正を行い、いくつかの段階での補正の効果と得られた降水量分布の特性を考察した。その結果、降雪に伴う補足率の補正の影響が最も大きく、最終的に地点平均で1.38倍の降水量増加が見込まれた。南部で標高の高い地点ほど降水量が増加する傾向が認められた。さらに付近の中国気象官署2地点での過去3年分の降水量を同様の方法で補正した結果、補正による増加の割合は年変化をし、モンスーン期中には1.2倍程度とほぼ一定値を示す一方、ブレモンスーン期や冬期には1.5倍以上の値を示す月が存在した。高原上では再循環する水の割合が大きいことが予想されるため、補正による降水量増加分はそのまま蒸発量(潜熱)の増加につながる事が示唆される。