HYDROLOGICAL PROCESSES
Hydrol. Process. **18**, 2991–3005 (2004)

Bias correction of daily precipitation measurements for Mongolia

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Abstract:

Bias correction procedures derived from the World Meteorological Organization's solid precipitation measurement intercomparison dataset for the Tretyakov rain gauge were applied to 20 years of data from 31 meteorological stations in Mongolia. Daily corrections of precipitation biases from wind-induced undercatch, wetting loss, and evaporation loss were made. The bias (systematic error) from wind loss dominates at stations located in prairies and forests. Evaporation loss (caused by the evaporation of precipitation in the gauge before precipitation is measured) and wetting loss of precipitation both cause significant error in regions of low precipitation. Bias corrections suggest that gauge-measured annual precipitation was significantly underreported by 15·2 to 80·6 mm over the 20 years studied. Annual precipitation in Mongolia should be 17 to 42% higher than previously reported, particularly in forests and prairies. The correction factor (CF, corrected/gauge-measured precipitation) varies seasonally and is greater in winter and smaller in summer, primarily because of undercatch of snowfall due to winds. There is clear seasonal variation in the absolute value of the bias correction and in each individual component of the correction. The spatial variation in the absolute correction matches the spatial distribution of gauge-measured precipitation. The value of CF decreases as gauge-measured annual precipitation increases, because precipitation changes occurred mostly in summer. These results will be useful for hydrologic and climatic studies of mid-latitudes and arid/semi-arid regions. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS precipitation; bias (systemic error); Tretyakov gauge; Mongolia

INTRODUCTION

Fluctuations in precipitation profoundly impact water cycles and water resources at both regional and global scales. Accurate ground measurements of precipitation are absolutely critical for regional and global climatic and hydrologic simulations. However, measured precipitation from standard national gauge networks has long been known to underestimate true precipitation amounts. In addition, measured amounts can be incompatible across national boundaries (UNESCO, 1978; Sevruk, 1989; Karl *et al.*, 1993; Legates, 1995). Systematic errors (i.e. biases) in precipitation measurement are caused by wind-induced undercatch, wetting, evaporation loss, and uncounted trace events; such errors affect all types of precipitation gauge (Goodison *et al.*, 1981; Sevruk, 1982). As knowledge of the error magnitude and its variation among gauges has increased, the need to correct the biases has been more widely acknowledged. Such bias correction will ameliorate the deleterious effects of these biases on regional, national, and global climatic and hydrologic studies (Groisman *et al.*, 1991; Groisman and Easterling, 1994; Desbois and Desalmand, 1995; Goodison and Yang, 1995).

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Received 30 June 2003
Accepted 21 June 2004

The World Meteorological Organization (WMO) began the solid precipitation measurement intercomparison project in 1985 (Goodison *et al.*, 1989) to assess various national methods of observing solid precipitation. The intercomparison reference recommended by the WMO is the octagonal vertical double fence (DFIR) surrounding a shielded Tretyakov gauge. Bias correction techniques were developed for other precipitation gauges commonly used worldwide. These correction procedures are recommended in those countries where national meteorological or hydrological station networks use the biased gauges to measure precipitation (Goodison *et al.*, 1998). The bias correction has yielded significantly higher estimates of precipitation in some countries (Metcalfe *et al.*, 1994; Yang *et al.*, 1998).

DFIR attenuates wind effects at the receiving surface of the rain gauge and transforms horizontal eddies into vertical eddies. The shield includes two concentric octagonal fences. The outer octagonal fence, with sides 4·6 min length, is inscribed into a circle 12 m in diameter. The fence is 3·5 m high above the ground and the space between the lower edge of the laths and the ground in 2·0 m. The inner fence is also octagonal, but smaller and lower. It is 4·0 m in diameter and 3·0 m above the ground. Goodison *et al.* (1998) have presented a schematic of the DFIR.

The Tretyakov gauge is the standard instrument used to measure both solid and liquid precipitation in Mongolia. The gauge is used in other countries as well, including the former USSR, Finland, Afghanistan, Vietnam, and North Korea (Sevruk and Klemm, 1989). The cross-sectional area of the gauge opening is 200 cm^2. A windshield is on gauges at all meteorological stations in Mongolia; the gauge opening is at 2 m. Manual observations are performed with a special measure-cup with a 0·1 mm resolution. Numerous studies using Tretyakov gauges have been conducted since the 1960s (Bogdanova, 1966; Goodison, 1981; Sevruk and Hamon, 1984, Golubev, 1985, 1989; Groisman *et al.*, 1991). These studies have summarized the bias correction procedures used in the former USSR station network and reported on the magnitudes of biases in regional and national precipitation data archives. These studies concluded that the archived precipitation records are not only inhomogeneous, due to changes in observation methods, but are also biased due to systematic errors in gauge observations. Accounting for the inhomogeneities and correcting the biases in the measured precipitation data are necessary before regional climatic and hydrologic research can be undertaken (Yang and Ohata, 2001). Yang *et al.* (1995) used statistical regression to develop a method of bias correction in which the Tretyakov gauge catch ratio was empirically related to a function of wind speed and air temperature. Yang and Ohata (2001) performed bias corrections on Tretyakov gauge data for Siberia, which is north of Mongolia.

Mongolia has a continental climate influenced predominantly by a Siberian high-pressure cell called the Mongolian or Asiatic high. This high is often centred over northern Mongolia from winter through to late spring (Zhang and Lin, 1992; An and Thompson, 1998; Samel *et al.*, 1999). In addition, the midlatitude westerly jet converges with southwesterly monsoon airflow over Mongolia (Yatagai and Yasunari, 1995). Forests and rangeland cover 8·1% and over 80% of the total area of the country respectively (Myagmarjav and Davaa, 1999). Permafrost is present over about 63% of Mongolia, which is on the southern fringe of Siberian permafrost (Batjargal *et al.*, 2000). Meteorological instrumentation began in the 1940s, and a network of 31 meteorological stations and 13 hydrological stations operates throughout the country (Dagvadorj and Mijiddorj, 1996). However, few studies on hydrological processes or precipitation climatology have been undertaken or reported.

To improve the accuracy of gauge-measured precipitation in Mongolia, the bias-correction methodology developed by the WMO solid precipitation measurement intercomparison project was applied to 31 meteorological stations in Mongolia for 20 years (1980–99). The magnitudes of the biases, and their seasonal and spatial variability, were computed. Interannual changes in the bias correction were investigated by coupling changes to measured annual precipitation. Bias correction performed in this study should significantly improve the accuracy of observed precipitation data and will meaningfully impact climate monitoring and hydrological modelling in arid- and mid-latitude regions, such as Mongolia.

DATA AND METHODOLOGY

Data

Daily observations of temperature, wind speed, precipitation, and snow depth for the period 1980 to 1999 were used in this study. These data are from 31 meteorological stations, shown in Figure 1, that represent different climatic conditions in Mongolia. Table I contains the mean annual air temperature, gauge-measured precipitation, relative humidity, and wind speed at each site. Air temperature reflects long winters and cool summers. January is the coldest month. The temperature averages between −15 and −35 °C, but it can fall below −50 °C. July is the warmest month. Average temperatures are from 15 to 25 °C, but can reach 44 °C. Precipitation is light and varies spatially and temporally, ranging from 60 mm in the Gobi Desert to 410 mm in the mountain forests. Most of the total precipitation (85–90%) falls during the summer months. The annual mean wind speed varies from 0·9 to 4·7 m s^{-1}. The annual mean relative humidity varies from 45 to 74%.

Methodology for bias correction

A bias-correction method for precipitation measured by the Tretyakov gauge was developed and applied to Siberian data (Yang *et al.*, 1998, Yang and Ohata, 2001). This work follows those studies and uses daily climatic data, including maximum, minimum, and mean air temperatures, measured precipitation, and wind speed. The bias in precipitation measurement was caused by wind, wetting and evaporation losses (Goodison, 1981), and the general precipitation correction formula is (Sevruk, 1989):

$$P_c = KP_g + \Delta P_w + \Delta P_e + \Delta P_t \quad (1)$$

where P_c is the corrected precipitation, K is the wind-induced coefficient (usually $K > 1$) for wind-induced errors and P_g is the gauge-measured precipitation. ΔP_w is wetting loss, which refers to the rain or snow water that is subject to evaporation from the surface of the inner walls of the gauge after a precipitation event, and from the gauge container after it is emptied (WMO/CIMO, 1993). ΔP_e is evaporation loss, which is an undermeasurement caused by water lost to evaporation before measurement. ΔP_t is the trace precipitation, which is a precipitation event of less than the resolution of the Tretyakov gauge, i.e. less than 0·1 mm. Officially, trace precipitation events do not contribute to monthly totals.

The wind-induced coefficient K, a function of the catch ratio CR, is expressed as $K = 100/\text{CR}$. For the WMO intercomparison project, catch ratio was defined as the ratio of the amount of precipitation caught by a gauge to the true precipitation (Goodison *et al.*, 1998). The WMO recommends using DFIR-measured precipitation instead of 'true precipitation' to calculate CR (CR = gauge-measured precipitation/DFIR-measured precipitation). A catch ratio that is a function of wind speed and air temperature was developed for the Tretyakov gauge using WMO intercomparison data (Yang *et al.*, 1995; Goodison *et al.*, 1998). The WMO experiments found that wind speed was the most important factor determining gauge catch; air temperature

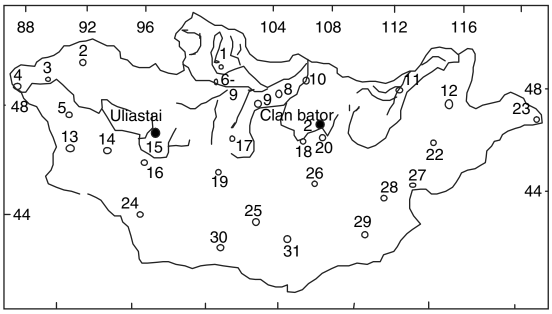

Figure 1. Station location (station numbers are the same as in Table I)

Table I. Mean air temperature, wind speed, and gauge-measured precipitation at 31 meteorological stations in Mongolia, 1980–99

Station	WMO code	Altitude (m a.s.l.)	Ground surface condition	Coordinates		Measured precipitation (mm)	Mean air temperature (°C)	Mean wind speed (m s^{-1})	Mean relative humidity (%)
				Lat. (°N)	Long. (°E)				
1 Khatgal	44 207	1668·0	Forest	50·26	100·09	309·3	−4·3	3·0	65
2 Ulaangom	44 212	939·0	Prairie	48·59	92·05	155·9	−2·8	1·5	65
3 Ulgii	44 214	1715·0	Prairie	48·58	89·58	129·1	0·8	2·7	61
4 Yalalt	44 217	2148·0	Prairie	48·17	89·31	132·6	−3·2	1·3	74
5 Khovd	44 218	1405·0	Prairie	48·01	91·39	129·6	0·6	0·9	64
6 Moron	44 231	1283·0	Forest	49·38	100·10	217·2	−1·0	2·0	61
7 Khutag	44 232	938·0	Forest	49·23	102·42	309·8	−0·4	1·3	71
8 Erdenet	44 236	1300·0	Forest	49·03	104·06	378·7	0·5	1·9	64
9 Bulgan	44 239	1208·0	Forest	48·48	103·33	362·0	−0·9	1·9	69
10 Orkhon	44 242	748·0	Prairie	49·09	105·24	292·0	−0·5	1·3	71
11 Dadal	44 254	987·0	Forest	49·02	111·37	409·5	−0·1	2·0	60
12 Choibalsan	44 259	747·0	Forest	48·06	114·33	264·7	6·8	3·8	67
13 Baitag	44 265	1186·0	Desert	46·07	91·38	68·7	2·8	1·2	62
14 Tonkhil	44 266	2222·0	Prairie	46·19	93·54	117·9	−0·5	3·0	58
15 Uliastai	44 272	1756·0	Forest	47·45	96·51	237·0	−2·0	1·2	58
16 Altai	44 277	2181·0	Prairie	46·24	96·15	188·6	−1·2	3·2	64
17 Tsetserleg	44 282	1691·0	Forest	47·27	101·28	339·5	0·7	2·5	61
18 Khujrt	44 285	1662·0	Prairie	46·54	106·46	296·6	−1·3	1·4	66
19 Bayankhongor	44 287	1859·0	Prairie	46·08	100·41	191·2	0·1	2·9	59
20 Zuunmod	44 290	1529·0	Forest	47·43	106·57	283·9	−1·1	2·4	69
21 Ulaanbaatar	44 292	1300·0	Forest	47·55	106·52	277·2	−0·6	2·6	64
22 Baruun-urt	44 305	981·0	Prairie	46·41	113·17	242·2	1·0	3·6	64
23 Khalkhgol	44 313	688·0	Forest	47·37	118·37	306·5	−0·1	2·8	64
24 Tooroi	44 325	1182·0	Desert	44·56	96·46	58·7	5·7	2·5	55
25 Saikhan	44 339	1301·6	Prairie	44·05	103·33	124·4	5·6	4·1	50
26 Mandalgobi	44 341	1393·1	Desert	45·46	106·17	153·8	1·8	4·5	57
27 Bayandelger	44 352	895·0	Prairie	45·48	112·42	183·7	1·7	4·7	60
28 Sainshand	44 354	938·0	Prairie	44·54	110·07	111·3	2·9	4·3	57
29 Dalanzadgad	44 373	1465·0	Desert	43·35	104·25	131·7	5·2	3·7	46
30 Gurvantes	44 374	1725·8	Desert	43·14	101·02	110·4	5·0	3·8	45
31 Khuvsgul	44 386	995·0	Desert	43·37	109·38	110·5	5·7	2·7	54

had a secondary effect when precipitation was classified into snow, mixed, or rain. The equations for gauge catch ratio versus wind speed Ws (m s^{-1}) at gauge height, and daily maximum and minimum temperatures ($T_{\max}$, $T_{\min}$) on a daily time step for various precipitation types, are given below. CR is given as a percentage and air temperatures are in centigrade.

$$\mathrm{CR(snow)} = 103{\cdot}10 - 8{\cdot}67\mathrm{Ws} + 0{\cdot}30T_{\max} \tag{2}$$

$$\mathrm{CR(mixed)} = 96{\cdot}99 - 4{\cdot}46\mathrm{Ws} + 0{\cdot}88T_{\max} + 0{\cdot}22T_{\min} \tag{3}$$

$$\mathrm{CR(rain)} = 100{\cdot}00 - 4{\cdot}77\mathrm{Ws}^{0{\cdot}56} \tag{4}$$

Once the daily wind speed and air temperature at gauge height were determined, the daily catch ratio CR for the Tretyakov gauge was calculated using Equations (2)–(4) for snow, mixed precipitation, and rain respectively. The correction equations developed for the WMO intercomparison dataset are used over a great range of environmental conditions. Therefore, it is important that the combined dataset contains a wide range of wind speeds and catch ratios. The performance of the correction equations was checked independently using intercomparison data for 11 WMO experimental stations. At most of the stations, the differences between the overall totals of corrected precipitation and the true precipitation were within 10% for snow, and were less than 5% for both rain and mixed precipitation (Yang *et al.*, 1995, Yang and Ohata, 2001).

The first task in the bias correction is to classify the precipitation type so that a suitable wind-loss correction can be computed for Equations (2)–(4). It has been well documented that the undercatch of snow is greater than that for rain at the same wind speed (Larson and Peck, 1974; Yang *et al.*, 1995, 1998; Goodison *et al.*, 1998). For this study, precipitation type was determined from daily mean air temperature. Snow was assumed for daily temperatures below $-2\,^{\circ}\mathrm{C}$. Rain was assumed for daily temperatures above $2\,^{\circ}\mathrm{C}$. Mixed precipitation was assumed for daily temperatures between -2 and $+2\,^{\circ}\mathrm{C}$. Snow depth records helped confirm the snow classification.

The correction for wind-induced gauge undercatch requires knowledge of the wind speed at gauge height. Wind measurements were made at the standard height (10 m) in Mongolia. Wind speeds at the height of the gauge orifice were estimated from the standard height measurements and a logarithmic wind profile. Roughness lengths of $Z_0 = 0{\cdot}01$ m (September–May, when snow is on the ground) and $Z_0 = 0{\cdot}03$ m (June–August, warm period with no snow) were used. These are appropriate values for snow and short grass respectively, according to Sevruk (1982) and Golubev (1985). Gauge exposure is sometimes considered when reducing wind from the standard height to gauge level (Sevruk, 1982). Gauge exposure depends on the average vertical angle of obstacles around the gauge, and it can be measured directly, or estimated, using a classification system based on metadata archives that include a detailed description of the station (Sevruk, 1982). However, meteorological station metadata were unavailable for this project and, indeed, for most global-scale bias corrections. Thus, gauge exposure was not included in the wind-speed estimates at gauge height. This may introduce a small uncertainty in the estimates of gauge catch efficiency.

Yang and Ohata (2001) reviewed methods to determine each term in Equation (1). Wetting loss of the gauge-measured precipitation varies by gauge type and by precipitation type, and by the number of times the gauge is emptied. Wetting-loss experiments conducted in Russia show that the average wetting loss of a Tretyakov gauge was 0·20 mm per measurement for rainfall and 0·15 mm per measurement for both snow and mixed precipitation (Sevruk, 1982; Groisman *et al.*, 1991). The wetting-loss correction in this study follows these results, which depend on the counts of precipitation events, and are summarized as:

$$\Delta P_{\mathrm{w}}\ (\text{rain}) = 0{\cdot}20\ \text{mm} \tag{5}$$

$$\Delta P_{\mathrm{w}}\ (\text{snow, mixed}) = 0{\cdot}15\ \text{mm} \tag{6}$$

However, the wetting loss may be larger, because precipitation was observed at routine observation times at Mongolian meteorological stations, but not at the ending time of precipitation events.

Evaporation losses are strongly dependent on weather conditions and observation methods, such as the number of daily observations (Sevruk, 1982). A Tretyakov gauge tested at the Jokioinen experimental station in Finland had evaporation losses of 0·30–0·80 mm day^{-1} in summer and 0·10–0·20 mm day^{-1} in winter (Aaltonen *et al.*, 1993). In arid or semi-arid mid-latitude regions like Mongolia, evaporation loss should play a more significant role in the correction than at high latitudes. The annual mean relative humidity ranges from 45 to 74%, and the annual mean vapour pressure, calculated from data in Table I, ranges from 4·1 to 6·3. Such a dry atmosphere will cause a high evaporation rate from the gauge. However, evaporation for this study followed the minimum of both ranges from Aaltonen *et al.* (1993), i.e. 0·10 mm day^{-1} for snowfall and 0·30 mm day^{-1} for others, because the experiments in that study were carried out on non-precipitating days (Yang and Ohata, 2001). In this work, evaporation losses are calculated for every precipitation event:

$$\Delta P_{\mathrm{e}}\ (\text{rain, mixed}) = 0{\cdot}30\ \text{mm} \tag{7}$$

$$\Delta P_{\mathrm{e}}\ (\text{snow}) = 0{\cdot}10\ \text{mm} \tag{8}$$

The correction for trace precipitation is important, especially in low-precipitation regions. The amount of the trace precipitation recorded is inversely proportional to the gauge-measured annual precipitation for Greenland, Alaska, and Siberia (Beson, 1982; Yang *et al.*, 1998; Yang and Ohata, 2001). Unfortunately, such a correction cannot be made here because of data limitations: days with trace precipitation cannot be separated from days with no precipitation.

RESULT OF CORRECTION IMPLEMENTION

Table II lists the annual mean values of the bias correction for daily precipitation at the 31 stations. The bias corrections were computed with Equations (2)–(8). The values in Table II include measured precipitation, snowfall proportion, correction values, corrected precipitation and correction factor CF. The percentage of annual precipitation due to snowfall varies from 4 to 24%. Precipitation totals in the winter are similar all over Mongolia, but large differences occur in the summer. Maximum and minimum CF values are included in Table II to illustrate interannual variability. CF variability is caused by year-to-year fluctuations in wind speed, air temperature, and snowfall frequency. The maximum correction factor was 1·85 in 1984 at Saikhan in response to snowfall, which accounted for 34% of the annual precipitation. The minimum correction factor was 1·13.

For the period 1980 to 1999, annual mean total corrections range from 15·2 mm (station no. 24) to 80·6 mm (station no. 21), which is 17% to 42% of the gauge-measured annual precipitation respectively. Annual mean corrections for the wind-induced undercatch range from 4·4 mm to 48·4 mm which is 5% to 30% respectively of the gauge-measured annual precipitation. The annual corrections for wetting loss vary from 3·7 mm to 18·5 mm, which is 3% to 9% of the gauge-measured annual precipitation, respectively.

The annual mean corrections for evaporation range from 5·1 mm to 24·6 mm, which is 4% to 11% of the gauge-measured annual precipitation respectively. The evaporation-loss bias is slightly higher in this instance than for previous projects undertaken for Siberia (Groisman *et al.*, 1991), estimated at 2 to 8%. This difference should be anticipated, however, when the climate features of Mongolia are taken into consideration. The Siberian climate is cold and moist: the minimum mean annual air temperature among 62 meteorological stations is −16·0 °C (Yang and Ohata, 2001), which is much lower than that in Mongolia, as noted in Table I. Annual evaporation loss in Siberia, therefore, should be small. Indeed, Yang and Ohata (2001) neglected this component in their bias correction in Siberia. For an arid region like Mongolia, evaporation loss is a significant component in the bias of measured precipitation because of large evaporation rates. Myagmarjav and Davaa (1999) have noted that more than 90% of the annual precipitation evaporates in Mongolia.

ANALYSIS

Seasonal variation of bias correction

Great seasonal variability in climate occurs over Mongolia (Batjargal *et al.*, 2000), which leads to a seasonal variation in the bias correction of gauge-measured precipitation. Figure 2 presents the mean monthly correction results and wind speed for selected meteorological stations along the 100 °E meridian for 1988–99. The stations represent desert, prairie, and forest climates in Mongolia. Common features of the bias corrections in the different climate zones include:

1. The sum monthly amounts of bias corrections vary seasonally. Amounts increase in the summer and decrease in the winter in response to the seasonal variation in precipitation.
2. Wetting loss and evaporation loss vary seasonally for all three selected stations. Wind loss shows a seasonal cycle in prairie and forest regions, but not in the desert.

Table II. Summary of bias corrections of daily precipitation data at 31 meteorological stations in Mongolia, 1980–99

Station	Measured precipitation (mm)	Snow proportion (%)	Correction (mm)				Corrected precipitation (mm)	Correction factor (CF)		
			Wind loss	Wetting loss	Evaporation loss	Sum		Mean	Max.	Min.
1 Khatgal	309·3	11	42·5	16·2	21·5	80·2	389·5	1·27	1·38	1·20
2 Ulaangom	155·9	21	15·1	14·0	16·5	45·6	201·5	1·30	1·42	1·20
3 Ulgii	129·1	8	14·6	9·7	13·4	37·6	166·8	1·31	1·45	1·18
4 Yalalt	132·6	12	9·7	10·8	13·7	34·2	166·8	1·27	1·43	1·17
5 Khovd	129·6	9	5·9	10·9	14·6	31·4	160·9	1·23	1·54	1·13
6 Moron	217·2	5	30·9	14·1	16·2	61·2	278·4	1·26	1·39	1·20
7 Khutag	309·8	6	20·3	13·7	18·5	52·4	362·2	1·17	1·23	1·14
8 Erdenet	378·7	9	37·8	13·0	22·4	73·3	452·0	1·21	1·29	1·16
9 Bulgan	362·0	7	33·3	18·5	24·6	76·4	438·4	1·21	1·29	1·15
10 Orkhon	292·0	8	25·1	16·6	22·1	63·9	355·9	1·23	1·30	1·13
11 Dadal	409·5	9	36·7	14·1	18·9	69·7	479·3	1·18	1·24	1·15
12 Choibalsan	264·7	4	43·4	12·3	14·1	69·8	331·6	1·30	1·43	1·22
13 Baitag	68·7	24	4·4	6·1	7·5	18·1	86·8	1·30	1·43	1·15
14 Tonkhil	117·9	6	12·7	8·5	11·4	32·6	150·5	1·29	1·65	1·16
15 Uliastai	237·0	12	22·1	14·9	18·8	55·9	292·8	1·22	1·29	1·16
16 Altai	188·6	15	31·8	10·8	13·5	56·0	242·0	1·31	1·43	1·20
17 Tsetserleg	339·5	11	39·1	17·4	22·8	79·3	418·8	1·24	1·36	1·20
18 Khujrt	296·6	10	31·2	16·5	21·7	69·4	366·1	1·24	1·41	1·15
19 Bayankhongor	191·2	14	22·9	10·4	13·8	47·1	238·4	1·25	1·36	1·18
20 Zuunmod	283·9	13	36·1	14·9	19·2	70·1	354·0	1·28	1·48	1·13
21 Ulaanbaatar	277·2	11	43·3	16·4	20·9	80·6	357·8	1·30	1·38	1·21
22 Baruun-urt	242·2	10	48·4	12·8	17·2	78·4	320·6	1·32	1·50	1·21
23 Khalkhgol	306·5	10	35·6	12·4	15·7	63·7	370·2	1·24	1·41	1·13
24 Tooroi	58·7	7	6·4	3·7	5·1	15·2	73·9	1·29	1·59	1·18
25 Saikhan	124·4	17	22·0	8·3	10·8	41·0	165·4	1·36	1·85	1·21
26 Mandalgobi	153·8	12	45·8	7·9	10·6	64·3	218·1	1·36	1·52	1·20
27 Bayandelger	183·7	14	43·3	11·6	14·9	69·7	253·4	1·40	1·53	1·22
28 Sainshand	111·3	11	23·1	8·0	10·9	42·0	153·3	1·39	1·58	1·28
29 Dalanzadgad	131·7	15	10·4	8·0	8·6	27·0	158·8	1·38	1·46	1·27
30 Gurvantes	110·4	15	19·8	6·8	8·9	35·6	146·0	1·34	1·58	1·21
31 Khuvsgul	110·5	8	14·4	6·8	9·3	30·5	141·0	1·30	1·50	1·18

3. In the prairie and forest, the absolute monthly wind loss was greater than both wetting loss and evaporation loss. In the desert, wind loss was less than wetting loss and evaporation loss.
4. The monthly correction increases significantly from desert to forest in Mongolia.

Figure 2 shows seasonal variations in the absolute value of the bias correction as determined by gauge-measured precipitation. A predominant parameter that affects seasonality of bias correction is precipitation type, i.e. solid, liquid or mixed precipitation. Equations (2)–(4) show that the rate of bias correction that varies with wind speed differs for rain, snow and mixed precipitation. It has been demonstrated that the bias correction for snowfall is greater than that for rainfall (Sevruk, 1982; Groisman *et al*., 1991; Yang *et al*., 1995; Yang and Ohata, 2001). Another important parameter to affect the bias correction is wind speed, which affects the wind loss and evaporation loss. However, the wind speed is low in the study region, with monthly mean wind speeds less than 4 m s^{-1} both at the prairie- and forest-region stations. The strongest wind occurred during late spring, which is not a high precipitation or high snowfall period.

Figure 3 shows an example of how the monthly mean correction factor CF versus wind speed varies for different precipitation types at Bayankhongor. For the same wind speeds, CF for snowfall was much larger

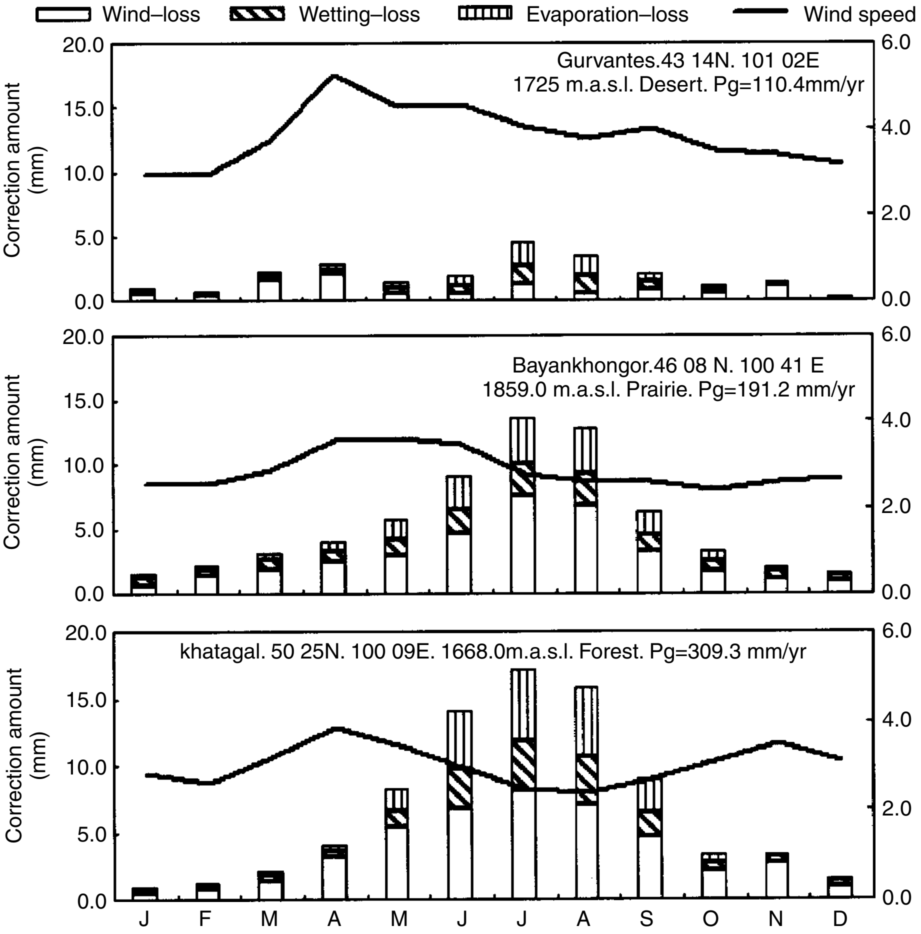

Figure 2. Mean monthly corrections to precipitation amount at selected stations on different ground surfaces (N–S profile along 100°E) for 1988–99

than that for rainfall, by a factor of 2·8 for wind speeds near 5 m s^{-1} for example. Scatter in the plot in Figure 3 results from inclusion of wetting loss and evaporation loss components in CF.

Figure 4 shows the mean seasonal variation in correction factor CF, which is defined as the ratio between corrected precipitation and gauge-measured precipitation, for three representative stations for forest, prairie and desert values. Large CF values occur during snowfall events in the cold season (October to April), and small CF values occur with rain in the warm season (May to September).

Owing to the small seasonality in wind speed of the study region, the precipitation type, which is determined by air temperature, becomes a dominant parameter in altering the seasonal variability of CF. However, it is very difficult to correlate CF statistically to air temperature and wind speed even when including ΔP_w and ΔP_e components in CF. As described in the 'Methodology for bias correction' section, the biases caused by wetting loss and evaporation loss are corrected depending on the precipitation events. Table III compares all of bias-correction components between the cold season (October to April) and warm season (May to September) at three selected stations for 1980–99. The variation coefficients of gauge-measured precipitation were bigger than those of corrected precipitation at all selected stations. The total biases in the warm season (May to September) were more than those in the cold season (October to April) at all selected stations. In contrast, a larger CF was found in the cold season due to a larger bias of wind loss for snowfall.

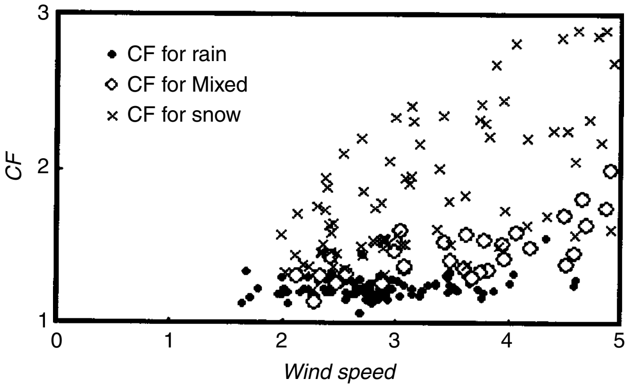

Figure 3. Variation in monthly mean correction factor CF versus wind speed for different precipitation types at Bayankhongor station

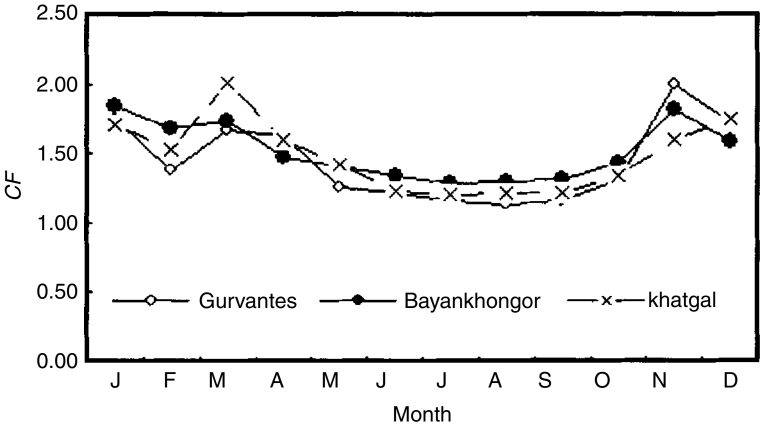

Figure 4. Seasonal variation in monthly mean correction factor CF at selected stations for 1980–99

Many studies have demonstrated that a low catch ratio in rain gauge to snowfall causes the CF to increase in winter (UNESCO, 1978; Goodison *et al.*, 1981; Sevruk, 1982, 1989; Groisman *et al.*, 1991; Karl *et al.*, 1993; Groisman and Easterling, 1994; Desbois and Desalmand, 1995; Goodison and Yang, 1995; Legates, 1995). The solid precipitation measurement intercomparison project initiated by WMO in 1985 also focused on a procedure to assess various national methods of observing solid precipitation (Goodison *et al.*, 1989). There have been many efforts made to improve the gauge by the addition of a wind shield (e.g. Nipher, Alter, Tretyakov) and by designing a new shape of gauge (RT4). DRIR has been evaluated to be the best one and recommended to be the standard for bias correction for gauge-measured precipitation. Yang *et al.* (2000) demonstrated that a snow survey is a helpful technique to improve bias correction of precipitation in high-altitude regions. Moreover, bias correction must be done depending on the classification of precipitation as described in the 'Methodology for bias correction' section, but there have still been no efforts to make a special definition for the bias of snow measurement.

Composition of bias correction

Local climate conditions determine the bias correction for a rain gauge. The dominant bias-correction factor is wind speed. Wind speed alters the CR of the gauge and influences the evaporation rate of water in the gauge before it is measured. Air temperature influences the bias correction by controlling the precipitation

Table III. Comparison of bias-correction components between cold season (October to April) and warm season (May to September) at three selected stations for 1980–99

Ground surface condition		Gurvantes Desert	Bayankhongor Prairie	Khatgal Forest
Mean gauge-measured precipitation (mm)	May to Sep.	92·5	159·1	279·7
	Oct. to Apr.	17·9	32·1	29·6
Wind loss (mm)	May to Sep.	9·7	17·2	31·3
	Oct. to Apr.	10·2	5·7	11·1
Wetting loss (mm)	May to Sep.	5·9	7	13·4
	Oct. to Apr.	0·9	3·4	2·4
Evaporation loss (mm)	May to Sep.	8·3	11·1	19·8
	Oct. to Apr.	0·6	2·6	1·8
Total of bias (mm)	May to Sep.	23·9	35·3	64·5
	Oct. to Apr.	11·7	11·7	15·3
Mean corrected precipitation (mm)	May to Sep.	116·4	194·6	344·6
	Oct. to Apr.	29·6	43·8	44·9
Correction factor (CF)	May to Sep.	1·26	1·22	1·23
	Oct. to Apr.	1·65	1·36	1·52

state (solid, liquid, or mixed). Contributions of each individual component of bias correction to the total differ for different climates. Understanding the composition of the bias-correction value for gauge-measured precipitation is vital to the improving methodologies for precipitation observation and for understanding the causes of undercatch at rain gauges.

Figure 5 shows partitions of the total bias correction at each station for 1980–99. The wind loss ranges from 19 to 71% of the total bias correction; wetting loss varies from 12 to 35% of the total; and the evaporation loss varies from 16 to 47%. The highest proportional wind loss, and smallest proportional wetting loss and evaporation loss, was at Mandalgobi (no. 26), a desert site with strong winds (annual mean speed 4·5 m s^{-1}). The lowest proportional wind loss, but highest proportional wetting loss and evaporation loss, was at Khovd (no. 5), a prairie site with an annual mean wind speed of 0·9 m s^{-1}. Strong winds increase wind loss for gauge-measured precipitation, but not necessarily evaporation loss. The annual means at Mandalgobi (no. 26) and Khovd (no. 5) are 45·8 mm and 5·9 mm respectively. A significant difference in wind speed did not yield a great difference in evaporation loss, however (10·6 mm and 14·6 mm respectively, as shown in Table II).

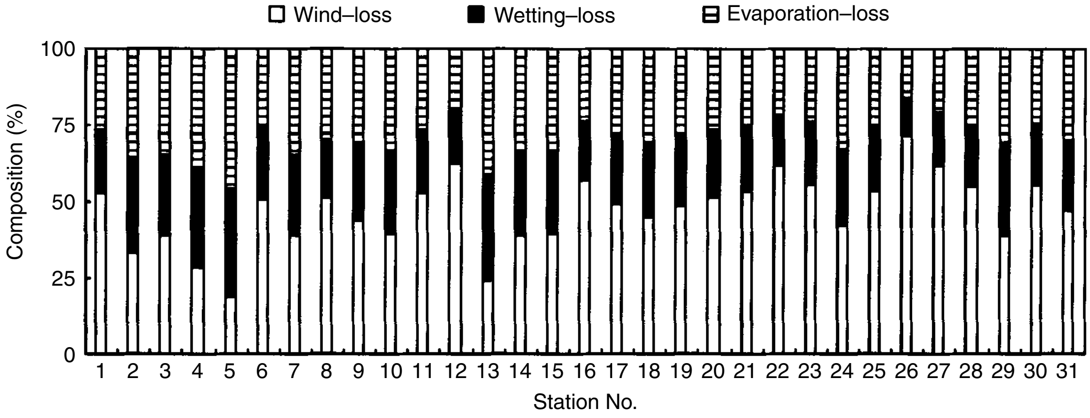

Figure 5. Annual mean values of bias-correction composition at meteorological stations in Mongolia for 1980–99 (station number key is in Table I)

Wind speed at 10 m may not be a good index to elucidate evaporation loss of precipitated water stored at the bottom of the rain gauge before being measured.

The average proportional wind, wetting, and evaporation losses for the 31 stations were 47%, 23%, and 30% respectively. Evaporation loss cannot be neglected for arid/semi-arid regions like Mongolia.

Spatial variation of bias-correction amount

The catch ratio of a rain gauge is determined by wind speed and precipitation state. The latter is controlled by air temperature. Significant differences exist in bias-correction amount, seasonal variation, and CF among forest, prairie and desert regimes. Large differences in climatic conditions, including precipitation, air temperature and wind speeds, are in the climatic conditions shown in Table I. Previous work has demonstrated that precipitation is the most variable of climatic factors over Mongolia. Annual mean gauge-measured precipitation has been recorded as 300–400 mm in the northern forests region, 50–250 mm in the steppe, 100–150 mm in the steppe–desert, and 50–100 mm in the Gobi Desert (Batjargal *et al.*, 2000). Therefore, the spatial variation of bias correction for gauge-measured precipitation could be investigated by relating it to the distribution of precipitation.

The annual mean of the components of the bias correction and their sum are plotted in Figure 6 against the annual mean gauge-measured precipitation. Wind, wetting, and evaporation losses all increase with annual gauge-measured precipitation. Vegetation distribution patterns are described in the *Mongolian People's Republic National Atlas* (Anon., 1990). The bias corrections for gauge-measured precipitation over Mongolia from this project, and related to the atlas, are 60–80 mm year^{-1}, 20–80 mm year^{-1}, 25–45 mm year^{-1}, and 15–45 mm year^{-1} for forest regions, steppe, steppe–desert, and Gobi Desert respectively.

Interannual changes of correction factor

Changes in climate variables, which include air temperature, wind speed, and precipitation, affect interannual changes in CF. Changes in CF also reflect variations in catch ratios and changes in the relative proportion of snow to the total precipitation. A better understanding of the interannual changes in CF, coupled to changes in precipitation, will improve the bias correction of gauge-measured precipitation and its application. Figure 7 shows the interannual changes of the annual mean correction factor, the proportion of snow to total precipitation, and the deviation P_{dev} of annual gauge-measured precipitation at selected stations in different climatic zones of Mongolia, for 1980–99. The deviation P_{dev} is a normalized index that evaluates effective changes in precipitation and is calculated as

$$P_{\mathrm{dev}} = (P_g - P)/P \tag{5}$$

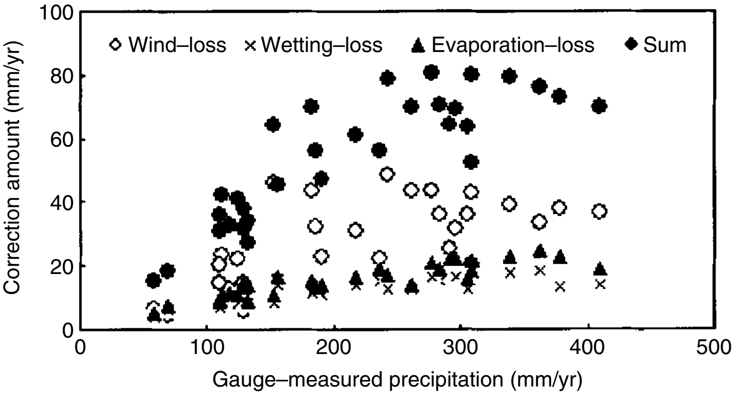

Figure 6. Annual bias correction for wind, wetting, and evaporation losses versus gauge-measured annual precipitation at 31 stations in Mongolia for 1980–99

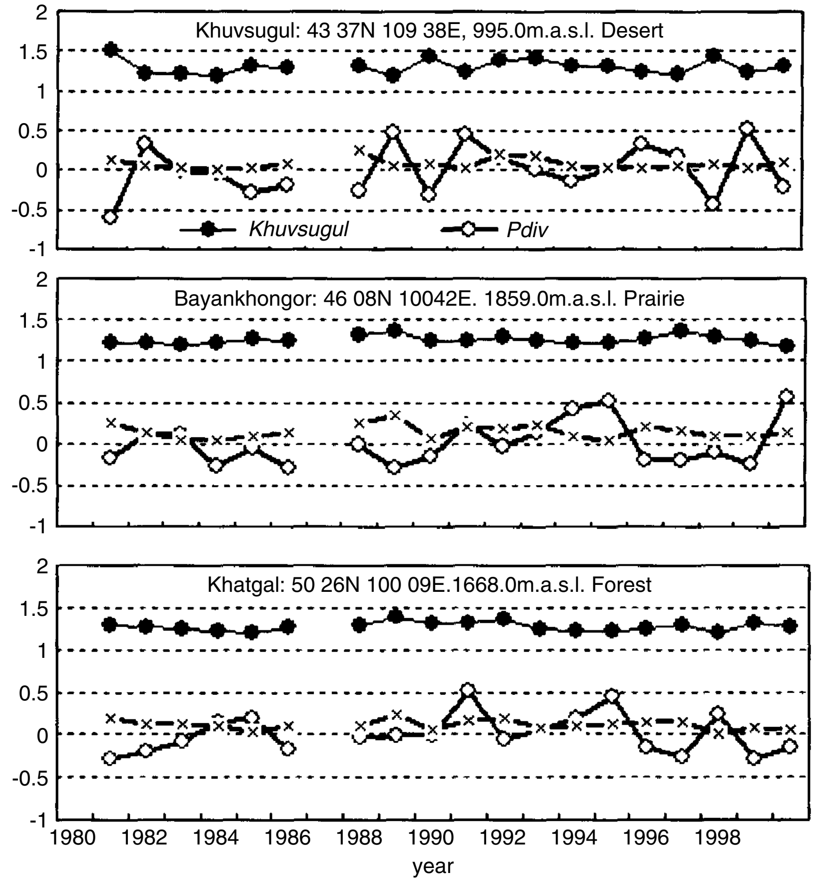

Figure 7. Interannual changes in CF, snow proportion of total precipitation and annual precipitation for three stations in different climatic zones in Mongolia

where P_g is the annual gauge-measured precipitation and P is the average of P_g for the period. Average values of CF are 1·30, 1·25 and 1·27 for Khuvsugul (desert), Bayankhongor (prairie) and Khtagal (forest) respectively. The biggest deviation in the annual precipitation was found at Khuvsugul station (no. 31), which is located in a desert with a mean annual precipitation of 141·1 mm; the annual mean CF varied from 1·17 to 1·50 in response to a P_{dev} ranging from −61 to 52%. The amplitude of CF varied at the other two stations in a similar fashion, ranging from 1·18 to 1·36 at Bayankhongor (prairie), and from 1·18 to 1·38 at Khtagal (forest). The annual precipitation was averaged to be 238·4 at the former and 376·4 at the latter station.

It is interesting to note that increases in CF often coincide with decreases in P_{dev}, which imply decreases in annual precipitation. Such a tendency can also been seen from the correlation of annual mean CF versus gauge-measured annual precipitation (Figure 8). The correlation can be elucidated by features of climatic changes and seasonality of precipitation in Mongolia. Interannual changes in precipitation were dominated by summer precipitation fluctuations. It has been demonstrated that more than 80% of precipitation occurred during summertime, and fluctuation in annual precipitation was predominantly due to summer precipitation (Batjargal *et al.*, 2000). The lower CF values for rainfall lead to an annual mean CF decrease that should also be reflected in a decrease in the ratio of snow to total precipitation. But the positive coupling tendency of CF and the snow proportion cannot be observed in Figure 7 because the snow proportion is too small to show a significant variation.

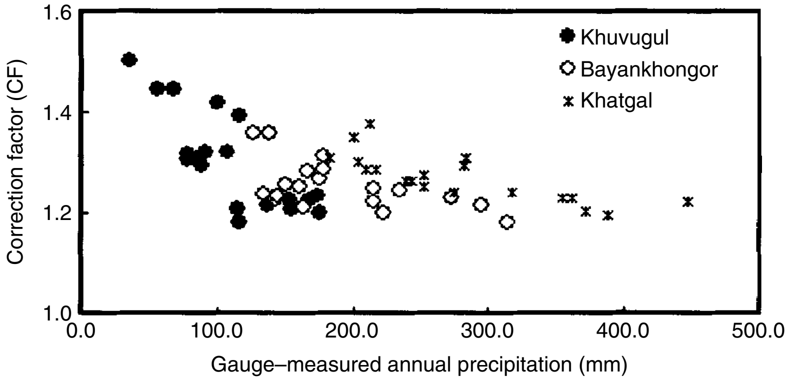

Figure 8. The variation of annual mean correction factor CF versus gauge-measured annual precipitation at three stations in Mongolia for 1980–99

CONCLUDING REMARKS

Bias correction procedures derived from the WMO solid precipitation measurement intercomparison dataset for the Tretyakov gauge were applied to 31 climate stations in Mongolia with 20-year records. Biases from wind-induced undercatch, wetting loss, and evaporation loss were corrected daily. The results show that the gauge-measured annual precipitation increased significantly by 15·2 to 80·6 mm (about 17 to 42% of the gauge-measured annual precipitation). The absolute bias correction is small, compared with the results from other regions like Siberia (Table IV). For an arid region with annual precipitation from 58·7–409·5 mm, however, an increase in corrected precipitation of 17 to 42% of the gauge-measured annual precipitation underscores the necessity of bias correction for improving our understanding of regional water cycles and resources.

Simple corrections to gauge-measured precipitation are difficult to determine because the bias correction varies both temporally and spatially. The spatial variation in bias corrections is related to the spatial distribution in gauge-measured precipitation. The bias correction for gauge-measured precipitation over Mongolia was 60–80 mm year^{-1} for forests, 20–80 mm year^{-1} for steppes, 25–45 mm year^{-1} for steppe–deserts, and 15–45 mm year^{-1} for the Gobi Desert. Extension of these correction procedures to other areas should not be performed without first analysing wind and snow conditions in detail.

At individual stations, a clear seasonal variation exists in the absolute value of the bias correction, as well as in each individual component of the correction. In addition, considerable intra-annual variations in the magnitude of the bias correction are in evidence at study stations; these variations are caused by fluctuations in the snowfall frequency. A negative correlation exists between the interannual change of the correction factor and the fluctuation in annual precipitation. The bias correction decreases as gauge-measured precipitation increases, which is caused by a decrease in the proportion of snow to the total precipitation. The temporal variability of bias in precipitation measurement implies that correction should be performed on a daily basis.

Table IV. Results of annual mean bias corrections of daily precipitation data in Mongolia and Siberia (Siberian results are from Yang and Ohata (2001)

Region	Study period	Measured precipitation (mm year^{-1})	Proportion of snow (%)	Correction (mm year^{-1})					Corrected precipitation (mm)	Correction factor (CF)
				Wind loss	Wetting loss	Evaporation loss	Trace loss	Sum		
Mongolia	1980–99	58.7–409.5	5–24	4.4–48.4	3.7–18.5	5.1–24.6		15.2–80.6	73.9–479.3	1.17–1.40
Siberia	1986–92	170.2–770.8	5–58	6.5–316.2			8.4–27.5	30.5–332.6	216.2–944.5	1.10–1.87

Wind loss was the greatest of the three biases in precipitation measurement at stations located in prairie and forest areas. Evaporation from water deposited in the gauge before the precipitation was observed and wetting loss of precipitation were also significant sources of bias in regions of low precipitation. The correction for trace precipitation cannot be made in this study because of database limitations. Information on the quality of the database, including installation information and additional meteorological data (i.e. wind speed at gauge height, air temperature, precipitation and number of trace precipitation days), is indispensable for the bias correction.

It is important to emphasize that the focus of this study is a test application of the WMO bias correction methodology to Mongolia, located at the periphery of the Eurasian snow cover/frozen ground region, in order to generate reliable and less-biased regional precipitation datasets. As found in this study, systemic implementation of the WMO bias-correction procedure is applicable in the study region, and results of implementation have demonstrated a general agreement comparing similar studio. The significant corrections made to the precipitation data may imply a necessity to recommend the correction procedure to the national meteorological services to apply the correction to their archived precipitation data. Further effort is needed in the future in performing correction in this region, e.g. experimental observation of evaporation loss and wetting loss in gauge-measured precipitation to clarify their uncertain dependence on climatic fluctuation. It is believed that doing so will significantly improve the accuracy of precipitation data.

ACKNOWLEDGEMENTS

We would like to thank the Frontier Observational Research System for Global Change (FORSGC) of Japan. We would also like to express our appreciation for the constructive comments and suggestions of the reviewers.

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