A Bias-Corrected Siberian Regional Precipitation Climatology

DAQING YANG

Water and Environmental Research Center, University of Alaska, Fairbanks, Fairbanks, Alaska

TETSUO OHATA

Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan

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ABSTRACT

A methodology for correcting the Tretyakov gauge-measured daily precipitation for wind-induced undercatch and trace amounts of precipitation is presented and applied at 61 climate stations in Siberian regions for 1986 to 1992. It is found that wind-induced gauge undercatch is the greatest error, and a trace amount of precipitation is also a significant bias, particularly in the low-precipitation regions. Monthly correction factors (corrected divided by measured precipitation) differ by location and by type of precipitation. Considerable interannual variation of the corrections exists in Siberian regions because of the fluctuation of wind speed, air temperature, and frequency of snowfall. More important, annual precipitation has been increased by 30–330 mm because of the bias corrections for the seven years (about 10%–65% of the gauge-measured yearly total). This result suggests that annual precipitation in Siberia is much higher than previously reported, particularly in the northwest sectors of high precipitation; the latitudinal precipitation gradient may also be greater over Siberian regions. An improved regional precipitation ''climatology,'' or description of mean annual precipitation, is derived based on the bias-corrected data and is compared with other existing climatologies. The results of this study will be useful to hydrological and climatic studies in the high-latitude regions.

1. Introduction

Reliable precipitation ''climatologies,'' or descriptions of long-term means and variations, on regional to global scales are critical for climatic and hydrological analyses. Traditionally most existing continental and global precipitation climatologies and maps have been derived from the standard national precipitation gauge records that have long been realized as underestimates of true precipitation amounts and as incompatible across national boundaries (UNESCO 1978; Legates 1995; Sevruk 1989; Karl et al. 1993; Yang et al. 2001). These climatologies have been extensively used for large-scale hydrological and climatic analyses, including evaluation of climate model simulations, input fields in global hydrological models, and validation of satellite precipitation algorithms. Legates (1995) reviewed the existing global precipitation climatologies and found inconsistency in some regions. Walsh et al. (1998) recently reported considerable variation between Arctic precipitation estimates from different sources, and this discrepancy complicates the verification of the model simulations of Arctic hydrological variables.

It has been recognized that uncertainties exist in the estimated precipitation climatologies in the high latitudes due to 1) sparseness of the precipitation observation networks; 2) uneven distribution of measurement sites, that is, sites biased toward coastal and the low-elevation areas; 3) spatial and temporal discontinuities of precipitation measurements associated with changes of observational methods and differences of observational techniques used in different countries; and 4) biases of gauge measurements, such as wind-induced gauge undercatch, wetting and evaporation losses, and underestimation of trace precipitation amounts (UNESCO 1978; Goodison et al. 1998). Of the above factors, systematic errors in gauge measurements are particularly important, because these biases affect all types of precipitation gauges, especially those used in cold environments.

To assess the national methods of solid precipitation observations, the World Meteorological Organization (WMO) initiated the Solid Precipitation Measurement Intercomparison Project in 1985 (Goodison et al. 1989). The octagonal vertical double fence surrounding a shielded Tretyakov gauge was designated as the intercomparison reference (DFIR). Thirteen countries par-

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Corresponding author address: Daqing Yang, Water and Environmental Research Center, Inst. of Northern Engineering, University of Alaska, Fairbanks, Fairbanks, AK 99775-5860.
E-mail: ffdy@uaf.edu

ticipated in this project, and the experiments were conducted at 20 selected sites in these countries from 1986 to 1993 (Goodison et al. 1998). The WMO Solid Precipitation Measurement Intercomparison has developed new bias correction techniques for a number of precipitation gauges commonly used around the world (Goodison et al. 1998), such as the Canadian Nipher snow gauge (Goodison and Metcalfe 1992), the U.S. National Weather Service 8-in. standard gauge (Yang et al. 1998a), the Russian Tretyakov gauge (Yang et al. 1995), and the Hellmann gauges (Gunther 1993; Allerup et al. 1997; Yang et al. 1999a). These correction procedures are recommended for test correction of gauge-measured daily precipitation in those countries where national meteorological or hydrological station networks operate these gauges for precipitation observations (Goodison et al. 1998). Recently it has been reported that applications of the WMO bias correction methods to the archived national precipitation data in some countries have resulted in significantly higher estimates of precipitation, particularly in the high-latitude regions (Metcalfe et al. 1994; Yang et al. 1998b, 1999b; Yang 1999).

Our knowledge of large-scale precipitation patterns is incomplete, and improved climatologies are needed (Legates and Willmott 1990; Xie et al. 1996; Groisman and Legates 1994). This work, as one of the efforts to generate improved precipitation climatologies (Legates and Willmott 1990; Groisman et al. 1996; Xie et al. 1996; Yang 1999), summarizes the methodology of correcting Tretyakov gauge-measured daily precipitation for biases of wind-induced undercatch, wetting loss, and trace amounts of precipitation. The newly developed bias correction methodology was applied at 61 climate stations in Siberia for 7 yr (1986–92), and the magnitude of the biases and their seasonal/spatial variability were quantified. Based on the bias-corrected data, a new regional precipitation climatology has been developed. It is anticipated that bias corrections such as this study will significantly improve the accuracy and homogeneity of precipitation data and will have a meaningful impact on climate monitoring and hydrological modeling (Groisman and Easterling 1994; Desbois and Desalmand 1995; Wang and Cho 1997; Ye et al. 1998; Forland and Hanssen-Bauer 2000). The results of the bias corrections will also be useful for validation of climate model simulation in the high latitudes (Bonan 1998; Walsh et al. 1998; Kattsov et al. 1998).

2. Bias correction methods

The Tretyakov gauge has been the standard instrument for measuring both solid and liquid precipitation in the former Union of Soviet Socialist Republics (hereinafter FUSSR) climatological and hydrological station networks since the late 1940s (Groisman et al. 1991). The Tretyakov gauge operated in the FUSSR is placed at 2 m and is currently equipped with the Tretyakov wind shield (Groisman et al. 1991). This gauge is also widely used in other countries, such as Finland, Mongolia, Afghanistan, Vietnam, and North Korea (Sevruk and Klemm 1989).

Numerous studies on the Tretyakov gauge have been conducted since the 1960s. Bogdanova (1966) compared the Tretyakov gauge with the pit gauge (a gauge installed in a pit with its orifice at the ground level) at about 50 locations in the FUSSR and related the Tretyakov gauge catch of rainfall with storm mean wind speed at the gauge level and with rainfall intensity. During 1972–76, the Tretyakov gauge was tested in the International Rainfall Comparison of National Precipitation Gauges with a reference pit gauge (Sevruk and Hamon 1984). Golubev (1985a, 1989) tested various designs of the double fence with this gauge for snowfall measurement at the Valdai Hydrological Research Station against the so-called Valdai Control System (a shielded Tretyakov gauge located in the sheltered bush site at Valdai) and found that the double fence (gauge) system catches 92%–96% of the true snowfall. Based on the experimental data at the Valdai station, Golubev (1969, 1985b) also developed a relation of the Tretyakov gauge catch of snowfall versus wind speed. Goodison (1977, 1981) investigated the Tretyakov gauge catch of snowfall versus snowboard measurements in a sheltered site in Canada and quantified the catch efficiency as a function of wind speed during snowfall period. Groisman et al. (1991) reviewed the FUSSR experience on precipitation measurements and bias corrections. They summarized the bias correction procedures used in the FUSSR station networks and reported the magnitudes of biases in regional and national precipitation data archives. They concluded that the archived precipitation records are not only inhomogenous because of changes of gauge types and method of observations but also biased owing to the systematic errors in gauge observation. Inhomogeneity adjustments and bias corrections of the gauge-measured precipitation data are necessary for regional climatic and hydrologic analyses.

During the WMO Solid Precipitation Measurement Intercomparison, the Tretyakov gauges were tested against the DFIR reference at 11 stations in seven countries (Golubev et al. 1992, 1995; Goodison et al. 1998). Extensive experiments on the wetting and evaporation losses of the Tretyakov gauge and many other national gauges have been conducted at Jokioinen station in Finland (Aaltonen et al. 1993). In the WMO intercomparison data analysis, the wetting losses for the Tretyakov gauge were corrected for all the experimental sites (Yang et al. 1995), as the volumetric method was used for the Tretyakov gauge readings. The evaporation losses were not corrected, since experiments showed that they were very small for the Tretyakov and U.S. gauges (Aaltonen et al. 1993; Golubev et al. 1992). When wind speed at the gauge height was not measured, it was reduced from a higher height. The DFIR data were corrected for wind-induced losses using the procedure developed by Yang et al. (1993). Blowing snow events

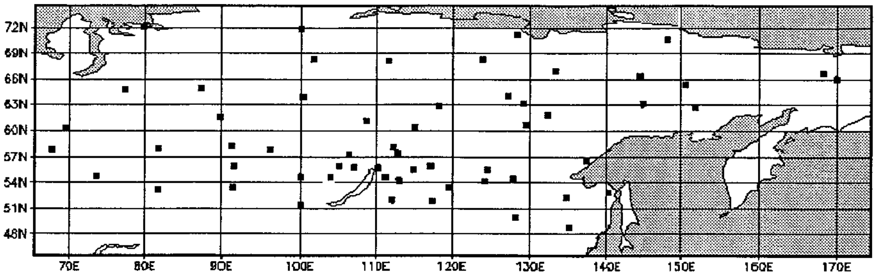


FIG. 1. Selected climate stations in Siberia for this study.

identified by the observers and flagged in the WMO intercomparison datasets were eliminated from the data analysis. The intercomparison data collected at the 11 sites for more than three winter seasons were compiled. They represent a great variety of climate, terrain, and exposure.

In the WMO intercomparison, catch ratio has been defined as the ratio of the amount of precipitation caught by a gauge (including the recorded amount and wetting loss) to the true precipitation (Goodison et al. 1998). It is known that small precipitation measurements can create significantly large unrealistic variations in the gauge catch ratios (Goodison et al. 1998). To minimize this effect, only those daily or precipitation events when the DFIR measurement was greater than 3 mm were used in the regression analysis of the WMO intercomparison data (Yang et al. 1995). Relation of catch ratio as a function of wind speed and air temperature has been developed for the Tretyakov gauge using the WMO intercomparison data (Yang et al. 1995; Goodison et al. 1998). It was found in the WMO experiment that wind speed was the most important factor determining gauge catch and air temperature had a secondary effect, when precipitation was classified into snow, mixed, and rain. The results of the analysis of gauge catch ratio (CR = measured/DFIR, %) versus wind speed (Ws, m s^{-1}) at gauge height and temperature (Tmax, Tmin, °C) on a daily time step are presented below for various types of precipitation:

$$\mathrm{CR(snow)} = 103.10 - 8.67\mathrm{Ws} + 0.30\mathrm{Tmax}, \quad (n = 394,\ R^2 = 0.66), \tag{1}$$

$$\mathrm{CR(mixed)} = 96.99 - 4.46\mathrm{Ws} + 0.88\mathrm{Tmax} + 0.22\mathrm{Tmin}, \quad (n = 433,\ R^2 = 0.46), \tag{2}$$

$$\mathrm{CR(rain)} = 100.00 - 4.77\mathrm{Ws}^{0.56}, \quad (n = 569,\ R^2 = 0.47). \tag{3}$$

It is important to note that a wide range of wind speed and catch ratio has been covered by the combined dataset, and, thus, the correction equations developed from the WMO intercomparison dataset are more likely to be used in a great range of environment conditions. The performance of the correction equations was checked independently by using all the intercomparison data (without the DFIR > 3.0 mm limitation) at the 11 WMO experimental stations. The results indicated that at most of the WMO stations the differences between the overall totals of corrected precipitation and the true precipitation amount were within 10% for snow and less than 5% for both rain and mixed precipitation (Yang et al. 1995).

Yang et al. (1995) compared the WMO intercomparison results with other studies of the Tretyakov gauge and found an excellent agreement of catch ratio between the WMO results and Golubev (1985b) for wind speeds up to 8 m s^{-1} on snowfall days. They also noticed that Goodison (1977, 1981) catch ratios were slightly lower, about 3%–5%, than those of Golubev (1985b) and the WMO results for the wind speeds below 4 m s^{-1}, for which there are only a few observations in Goodison (1977, 1981). Given the fact that different methods of determining ''true snowfall'' were used in these studies and that the WMO intercomparison project involved 11 sites in different climatic regions, the results from these studies agree well. Based on the above results and analyses, it probably is reasonable to conclude that the WMO bias correction techniques work well at most of the WMO experimental stations and they generally agree with earlier studies (Goodison et al. 1998). They should therefore be considered for test correction of the Tretyakov gauge-measured precipitation data in regional station networks (Goodison et al. 1998).

3. Implementation of the WMO bias correction methods

Sixty-one climate stations were chosen for this study (Fig. 1) to represent various climatic conditions in Siberia. The daily data of temperature, wind speed, precipitation, and snow depth on the ground for the period of 1986–92 were used for this work. The mean yearly values of temperature, gauge-measured precipitation, and wind speed at the 61 sites are summarized for the 7 yr in Table 1.

Bias correction of gauge-measured precipitation should be made for trace precipitation, wetting loss, evaporation loss, and wind-induced errors caused by the wind field deformation over gauge orifice (Sevruk and Hamon 1984). Since the wind field deformation affects the total

TABLE 1. Mean temperature, wind speed, and gauge-measured precipitation at 61 climate stations in Siberia, 1986–92.

Station no.	Station name	WMO code	Coordinates		Mean temperature (°C)	Mean wind (m s^{-1})	Precipitation days		Snow %	Measured precipitation (mm)
			Lat (N)	Long (E)			Trace	Measurable		
1	Habarovsk	31735	48.31	135.07	2.6	2.7	196	117	10	666.7
2	Blagovescensk	31510	50.15	127.34	1.6	1.6	223	95	8	525.3
3	Im. P. Osipenko	31416	52.25	136.30	−1.9	1.3	241	103	13	483.5
4	Nikolaevsk-Na	31369	53.09	140.42	−1.6	3.1	182	155	29	603.7
5	Bomnak	31253	54.43	128.56	−3.8	1.7	230	112	15	540.7
6	Ajan	31168	56.27	138.09	−2.0	2.5	238	105	18	770.8
7	Mondy	30802	51.41	100.59	−1.7	1.6	245	91	5	353.1
8	Sretensk	30777	52.16	117.42	−2.5	1.3	253	93	8	371.4
9	Cita	30758	52.01	113.20	−1.7	1.8	239	82	6	362.2
10	Mogoca	30673	53.44	119.47	−4.7	1.2	238	98	11	441.6
11	Bagdarin	30554	54.28	113.35	−4.7	1.2	256	78	9	358.0
12	Tassa	30542	54.51	111.09	−4.7	0.5	275	75	11	240.7
13	Zigalovo	30521	54.48	105.10	−3.0	0.9	183	141	19	308.1
14	Tulun	30504	54.36	100.38	−0.2	1.4	185	137	15	361.1
15	Tynda	30499	55.11	124.40	−4.5	1.6	215	121	16	566.3
16	Srdijkalar	30471	55.55	117.32	−8.2	0.6	259	83	8	403.3
17	Kalakan	30469	55.07	116.45	−7.0	0.5	260	90	9	404.6
18	Nizneangarsk	30433	55.47	109.33	−1.9	1.4	195	119	23	337.9
19	Kazachengkoye	30337	56.17	107.34	−2.7	1.1	146	170	21	400.2
20	Orlinga	30328	56.03	105.50	−2.8	0.9	153	174	24	362.4
21	Verhe-Markovo	30229	57.20	107.04	−2.9	1.4	151	178	25	355.0
22	Mama	30157	58.19	112.52	−3.3	1.9	116	210	35	538.1
23	Voroncovka	30151	58.51	112.52	−2.7	1.8	132	198	41	623.0
24	Minusinsk	29866	53.42	91.42	2.0	0.9	225	107	12	349.6
25	Barnaul	29838	53.20	83.42	2.6	1.9	163	146	24	421.1
26	Krasnojarsk	29570	56.02	92.45	1.9	1.8	135	158	18	462.7
27	Bogucany	29282	58.23	97.27	−0.9	1.4	144	152	24	338.1
28	Enisejsk	29263	58.27	92.09	−0.3	1.7	131	191	29	452.0
29	Kolpasev	29231	58.18	82.54	−0.6	1.9	127	177	25	505.5
30	Omsk	28698	54.56	73.24	2.0	2.1	148	151	28	396.2
31	Tobol’sk	28275	58.09	68.15	0.9	2.2	158	161	23	460.9
32	Sejmchan	25703	62.55	152.25	−11.2	1.5	175	132	47	263.2
33	Anadyr	25563	64.47	177.34	−7.4	4.5	164	135	56	381.8
34	Zyrjanka	25400	65.44	150.54	−10.9	1.6	187	128	38	236.8
35	Mys Uelen	25399	66.10	169.50	−7.2	4.5	157	182	41	345.2
36	Ilirnej	25248	67.20	168.14	−13.6	1.2	196	111	37	187.2
37	Mys Schmidta	25173	68.55	179.29	−11.2	3.3	154	147	48	250.9
38	Lensk	24923	60.43	114.53	−4.6	2.2	131	174	34	366.3
39	Pokrjvskaja	24856	61.29	129.09	−9.3	1.8	177	125	27	236.9
40	Erbogachen	24817	61.16	108.01	−5.4	1.5	165	158	37	348.3
41	Curapca	24768	62.02	132.36	−10.4	1.2	221	111	30	209.0
42	Ojmjakon	24688	63.16	143.09	−16.0	0.7	185	125	31	211.2
43	Batamaj	24656	63.31	129.26	−11.0	1.8	200	131	38	257.4
44	Sangary	24652	63.58	127.28	−9.4	2.6	159	142	41	298.9
45	Njurba	24639	63.17	118.20	−8.4	1.5	154	161	33	281.4
46	Tura	24507	64.16	100.14	−7.6	1.4	109	190	34	400.8
47	Ust-Moma	24382	66.27	143.14	−13.5	1.0	218	95	28	180.6
48	Verhojansk	24266	67.33	133.23	−14.5	1.3	208	111	32	170.2
49	Dzardzan	24143	68.44	124.00	−12.0	2.5	172	169	39	315.4
50	Olenek	24125	68.30	112.26	−12.1	2.0	130	164	42	293.7
51	Essej	24105	68.28	102.22	−11.8	1.3	170	139	33	242.0
52	Hanty-Mansijsk	23933	60.58	69.04	−0.9	1.9	118	179	33	509.1
53	Bor	23884	61.36	90.00	−2.8	1.4	106	225	38	647.5
54	Njaksimvol	23724	62.26	60.52	−1.5	1.5	173	167	34	523.0
55	Tarko-Sale	23552	64.55	77.49	−5.7	2.5	116	194	43	513.5
56	Turuhansk	23472	65.47	87.57	−5.9	2.6	84	237	42	669.6
57	Salehard	23330	66.32	66.32	−5.8	2.2	118	170	35	411.6
58	Cokurdah	21946	70.37	147.53	−13.5	2.9	162	143	37	218.0
59	Tiksi	21824	71.35	128.55	−12.7	3.7	112	167	58	335.0
60	Hatanga	20891	71.59	102.28	−13.1	3.2	130	176	49	281.1
61	Ostrov Dikson	20674	73.30	80.24	−12.1	4.5	105	199	58	364.4

gauge catch, including both the wetting and evaporation losses, we modified the general model (Sevruk and Hamon 1984) for precipitation correction to

$$P_c = K(P_g + \Delta P_w + \Delta P_e + \Delta P_t), \qquad (4)$$

where P_c is the corrected precipitation: P_g is the gauge-measured precipitation: ΔP_w and ΔP_e are wetting loss and evaporation loss, respectively; ΔP_t is the trace precipitation, which is generally a small amount and does not need wind corrections; and K is the correction coefficient (usually $K > 1$) for wind-induced errors. The method of determining each of the terms in Eq. (4) has been developed (Yang et al. 1998b) and is briefly summarized below.

a. Wetting loss

Wetting losses are gauge specific and vary by precipitation type and the number of times the gauge is emptied. According to the wetting loss experiments conducted in Russia, the average wetting loss of the Tretyakov gauge was 0.20 mm per observation for rainfall measurement and 0.15 mm per observation for both snow and mixed precipitation (Sevruk 1982; Groisman et al. 1991). Similar values were reported by Elomaa (1993) and Goodison and Metcalfe (1992).

Wetting loss correction was not conducted in this study, as it has been corrected in the precipitation archives of the FUSSR prior to distributing and archiving the precipitation data (Groisman et al. 1991). It is important to note that different methods were applied in the FUSSR for the record periods before and after 1966; this may have created inhomogeneity in the FUSSR precipitation data (Groisman et al. 1991). The methods of wetting loss correction used in the FUSSR since 1967 are summarized by Groisman et al. (1991) as the following: When there is no moisture in the gauge, no correction applies for the wetting loss. If the gauge measurements are less than one-half of the resolution of the gauge (i.e., 0.1 mm), add 0.1 mm to rain and mixed precipitation events, but not to snowfall data. When the gauge measurements are greater than 0.1 mm, add 0.2 mm for rain and mixed precipitation events and 0.1 mm for snow events.

Studies in the high-latitude regions show that the mean annual totals of the wetting loss correction in the Northwest Territories, Alaska, and Greenland were 5%–10% of the gauge-measured annual precipitation (Metcalfe et al. 1994; Yang et al. 1998b, 1999b). At an individual climate station, the annual amount of the wetting loss correction is different among years and the percentage of the annual correction to the gauge-measured yearly totals varies as well. Generally, there is a clear wetting loss increase with increasing gauge-measured annual precipitation, since more precipitation generally requires more observations and more observations lead to a higher wetting loss (Metcalfe et al. 1994; Yang et al. 1998b, 1999b). The annual correction for the wetting loss in the FUSSR was reported to be between 5% and 15% of the gauge-measured precipitation; for regions of low precipitation it composes up to 40% (Groisman et al. 1991). The mean wetting losses of the Tretyakov gauge determined by the experiments in Russia, Finland, and Canada suggest that the wetting losses were slightly underestimated by the standard procedures used in the FUSSR. More efforts are needed to better quantify the wetting losses and to examine the impact of wetting loss correction on climate change analysis.

b. Trace precipitation

According to the procedures of wetting loss correction (Groisman et al. 1991), a precipitation event of less than 0.10 mm is beyond the resolution of the Tretyakov gauge measurement. For such precipitation events, a wetting loss correction should be applied to rain and mixed precipitation data but not for snow events; this criterion implies that in the archived precipitation records there should be no zero precipitation records for rain and mixed precipitation, except for snow. However, the data used for this work include many zero precipitation events of both liquid and solid forms; this clearly indicates that trace precipitation events do exit in the precipitation archive and they have not been accounted for in the wetting loss corrections.

Climate data collected during 1986–92 in Siberia indicate that the annual gauge-measured precipitation varied greatly from 400–700 mm in the western regions to 200–700 mm in central and eastern regions. The percentage of snow in annual precipitation decreased from 45%–55% in the north to 5%–25% in the south areas, with the temperature increasing from north to south. The total number of precipitation days (e.g., the sum of the days with trace precipitation and measurable precipitation) ranged from 275 to 350 at these stations (Table 1). The average number of trace precipitation days varied from 80 to 275 for the 7 yr. Geographically, more trace precipitation days were recorded in the southern regions and trace precipitation recordings there can make up 50%–80% of the annual total of precipitation days. More trace precipitation days were reported in the summer season than in winter, but the percentage of trace precipitation days to the total number of days of precipitation is much higher in the relatively dry winter season.

It has been reported that in northern Alaska, Greenland, and the North Pole regions about 80% of the winter snowfall records consisted of trace precipitation events (Benson 1982; Yang et al. 1998b, 1999b; Colony et al. 1998; Yang 1999). For instance, in some winter months, no measurable precipitation was reported in northern Alaska except trace amounts of snowfall. Similar findings were also reported for the Northwest Territories and Yukon of Canada (Metcalfe et al. 1994). Woo and Steer (1979) designed a method of measuring trace rainfall in the Canadian high Arctic and determined a mean

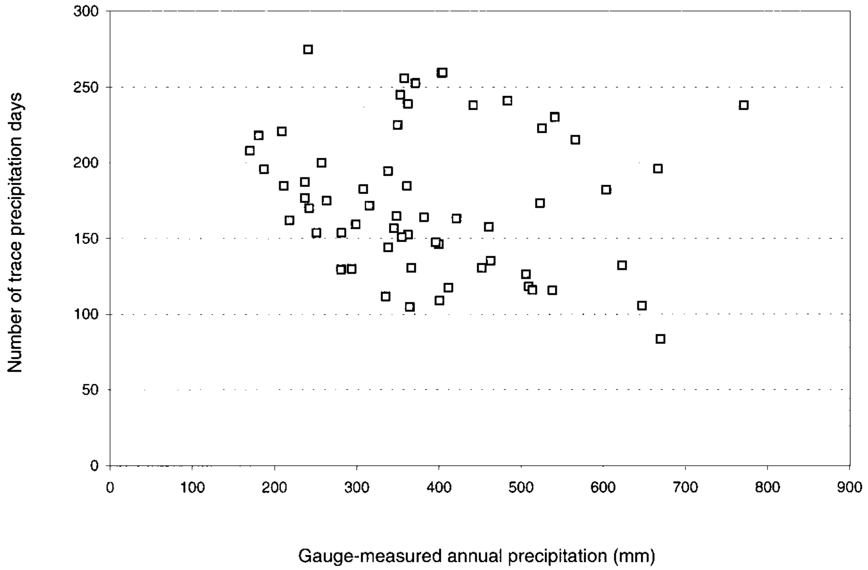


FIG. 2. Number of trace precipitation days vs gauge-measured annual precipitation at 61 climate stations in Siberia for 1986–92.

rate of 0.01 mm h⁻¹. Unfortunately, there were no data available for the period of trace precipitation in the climate archive, since trace precipitation is not measurable by an ordinary precipitation gauge. Precipitation observations in Siberia show that a number of trace precipitation events are reported in a single trace-precipitation day, thus it is not unreasonable to assume that a trace event could be a small precipitation amount of 0.05–0.15 mm. To be conservative, trace precipitation was corrected on a daily basis in this study; for example, for any given trace day, regardless of the number of the trace observations reported, a value of 0.10 mm was assigned and added to the monthly total.

The averaged yearly correction for trace precipitation varied from 8 to 28 mm at the 61 stations, or about 1%–12% of the gauge-measured annual precipitation over Siberia. The amount of trace record is inversely proportional to the gauge-measured annual precipitation for the 7 yr (Fig. 2), as was reported by Yang et al. (1998b, 1999b) and Benson (1982) for Greenland and Alaska. Correction for trace precipitation is thus important, especially in the central and northeast regions of low precipitation. It is important to note that, after identification of trace precipitation days, the number of measurable precipitation days exhibits a larger variation across Siberia (Fig. 3). Therefore, it is necessary to separate trace

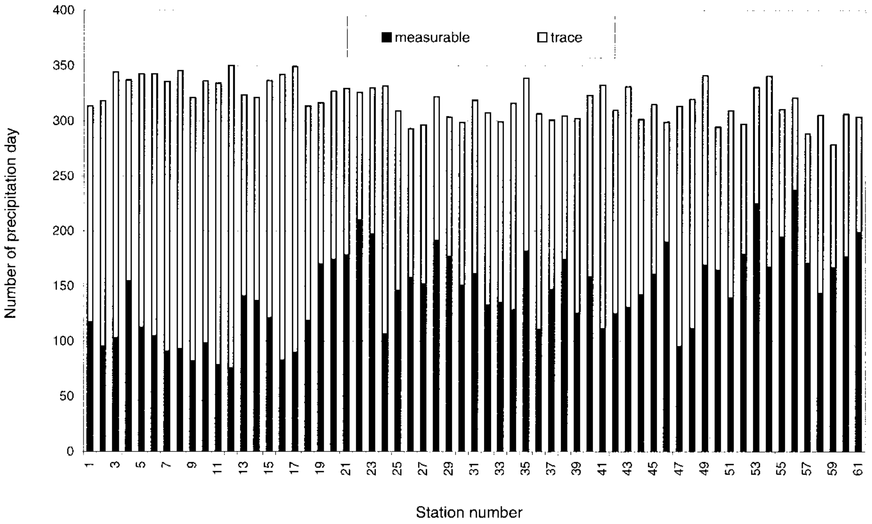


FIG. 3. Mean yearly total number of precipitation days for 1986–92 at the 61 climate stations in Siberia.

precipitation days from measurable precipitation days when analyzing precipitation climate in the high-latitude regions.

c. Evaporation loss

Comprehensive assessment of evaporation losses of many national gauges was conducted during the WMO intercomparison project, and the results indicated that average daily losses varied by gauge type and time of the year (Aaltonen et al. 1993; Goodison et al. 1998). For the Tretyakov gauge tested at the Jokioinen experimental station in Finland, evaporation losses in summer of 0.30–0.80 mm day^{-1} and winter of 0.10–0.20 mm day^{-1}, respectively, were reported (Aaltonen et al. 1993). These evaporation rates are close to the maximum, given that the experiments were carried out on nonprecipitation days. Evaporation losses are strongly dependent on weather condition and methods of observations, such as the number of times of daily observations (Sevruk 1982). Its daily variation and seasonal change are great and can be very site dependent. It is, therefore, difficult to estimate with any confidence the daily evaporation losses at climate station network by using the average evaporation amount obtained from other experimental sites. For the above reasons, evaporation loss in Siberia was not corrected in this study.

In a previous study, the mean July evaporation loss was estimated by Russian scientists to be 2%–8% of the monthly total precipitation over Siberia for the period 1953–65, when precipitation measurements were made two times per day by the Tretyakov gauges (Groisman et al. 1991). For other periods, evaporation loss is much less than that in July. The annual evaporation loss in Siberia regions is expected to be small because of low temperature and relatively small amounts of precipitation, particularly in the northern Siberia regions. Neglecting correction for this loss in this study will therefore not significantly affect the results of the bias corrections.

d. Wind-induced gauge undercatch

To correct for wind-induced gauge undercatch, wind speed at gauge height is required. Wind measurements were made at the standard height of 10 m in the observational network of the FUSSR, and these data for Siberian regions were available for this study. Wind speeds at the height of the gauge orifice were estimated from measurements at the standard height, using the logarithmic wind profile approach. Roughness length is required in the wind profile technique. According to Sevruk (1982) and Golubev et al. (1992), $Z_0 = 0.01$ m for a winter snow surface and $Z_0 = 0.03$ m for short grass in the summer are appropriate average roughness parameters for most sites. In this study, $Z_0 = 0.01$ m was used for the cold period from September to May when snow cover exists most of the time in Siberia. A value of $Z_0 = 0.03$ m was assigned to the warm period from June to August. It has been suggested that exposure of gauge should be considered when reducing wind from the standard height to the gauge level (Sevruk 1982). Gauge exposure depends on the average vertical angle of obstacles around the gauge; it can be directly measured or estimated by a classification system based on metadata archives (Sevruk 1982). Siberian station metadata are not available for this work or most global-scale bias corrections. Site exposure was not accounted for in wind speed estimates at the gauge height. This fact may introduce some uncertainty in estimation of gauge catch efficiency.

It has been well documented that, for the same wind speed, gauge undercatch of snow is much higher than for rain (Larson and Peck 1974; Goodison et al. 1981, 1998; Yang et al. 1995, 1998a). Classifying the type of precipitation is therefore necessary to apply the best wind loss correction. In this work, type of precipitation was classified by daily air temperature. The temperature criterions are set at $-2°$ and $+2°\mathrm{C}$, that is, snow and rain for daily temperature below $-2°$ and above $+2°\mathrm{C}$, respectively, and mixed precipitation when daily temperature is in between $-2°$ and $+2°\mathrm{C}$. Snow depth records were also used for confirmation of snow classification.

For the snow category, blowing snow events were found reported on some precipitation days in Siberia. Blowing snow conditions on precipitation days are a special case when correcting the gauge-measured precipitation data. It is possible that, under certain conditions, any gauge can catch some blowing snow. Since wind speeds are generally greater during blowing snow events, a larger correction for undercatch could be applied to a measured total already augmented by blowing snow. This problem would be most severe for gauges mounted close to the ground. The Tretyakov gauges in Siberia were placed 2 m above the ground, and the potential impact of blowing snow on winter precipitation measurements and bias corrections in the Russian Arctic has been recognized by Russian scientists (UNESCO 1978; Struzer 1971). To avoid the possible overcorrection caused by high wind on snowfall days, an upper value of wind speed has to be determined (Goodison et al. 1998). Corrections at higher wind speed are estimated by using this threshold wind speed (WMO/CIMO 1993). This threshold is important because the regression equations that are derived from the WMO intercomparison data are only valid statistically for the interval for which they are developed and should not be used for extrapolation outside of this range. The threshold mean daily wind speed was set up at 6.5 m s^{-1} at gauge height for the correction equations in this study. Blowing snow events were often observed and reported when mean daily wind speeds at 2 m were higher than 6.5–7.0 m s^{-1} at the WMO experimental sites, indicating that wind of 6.5 m s^{-1} (at 2-m height) might be a reasonable value for the initiation of blowing snow.

Once daily wind speed at the gauge height was determined, the daily catch ratio (CR, %) for the Tretyakov gauge was calculated using the regression Eqs. (1) to (3) for snow, mixed, and rain. The wind loss correction coefficient K was calculated as $K = 100/\mathrm{CR}$. The results of the calculations show that average yearly corrections for the wind-induced undercatch range from 6 to 316 mm over Siberia (Table 2). Spatial variation of the yearly corrections for wind-induced undercatch are induced by variability of wind speed, air temperature, percentage of snow in annual precipitation, and amount of gauge-measured precipitation. Generally the corrections are higher in windy and cold regions.

e. Discussion of correction methods and results

Several necessary adjustments were made in the implementation of the WMO bias correction methods to Siberian regions, and consequently the general bias correction equation has not been applied exactly in this study. First, correction for wetting loss was not necessary for this analysis, because it has been added to the gauge measurements (Groisman et al. 1991). Second, correction for evaporation loss was neglected because of insufficient information of regional evaporation rates from the Tretyakov gauges. Third, trace-precipitation events were corrected on a daily basis, not for each observation reported in a day, and no wind correction was applied to the trace-precipitation events. These adjustments made quantification of the biases relatively easier, once wind speed, gauge-measured precipitation, and temperature data are available. The results of bias correction should be regarded as conservative for a majority of the Siberian regions except those areas of very high winds and frequent blowing snow. More important, it has been reported that the WMO intercomparison reference gauge (DFIR) does not overcatch snowfall (Golubev 1985a, 1985b; Yang et al. 1995). The correction for wind-induced gauge undercatch of snowfall in Siberia is therefore not overestimated by the WMO method.

It has been realized that uncertainties exist in the applications of bias corrections because of the techniques used for estimation of wind speed at the gauge level from a standard height and classification of precipitation type by air temperature (Yang et al. 1999b). Random errors in the input data and regression equations will also affect the results of bias corrections and need to be assessed.

4. Bias-corrected precipitation climatology

Monthly bias corrections vary greatly over Siberian regions because of different climate characteristics, particularly snow and wind conditions. To demonstrate the seasonal cycle of the bias corrections and the associated changes in precipitation amount due to the corrections, Fig. 4 presents monthly correction results at selected Siberian climate stations along the 80°E longitude. The common features of the bias corrections across this north–south profile can be summarized as follows. 1) In each month, the absolute monthly amount of wind-induced error was always greater than trace precipitation. 2) A clear seasonal variation of the monthly correction factor (CF, ratio of the monthly corrected to gauge-measured precipitation including wetting loss) exists: high CF values for snow in the cold season and low CF values for rain in the warm season, because of the higher wind loss for snow than for rain and due to the smaller amount of absolute precipitation in the cold season.

Table 2 summarizes the yearly total corrections for wind-induced error and trace amount of precipitation. For each station the individual corrections are stated and summed. The sum of the corrections is added to the gauge catch ($P_g + \Delta P_w$) to obtain the corrected value p_c. The overall annual CF is then the ratio $P_c/(P_g + \Delta P_w)$. The maximum and minimum CF values are also provided in the table to illustrate the interannual variation. This CF variation is induced by year-to-year fluctuation of wind speed, air temperature, and frequency of snowfall. This is particularly accentuated in southern Siberian winter months, for which a small variation in air temperature greatly influences the proportion of snowfall precipitation.

Based on the data in Table 2, yearly precipitation and yearly correction-factor maps were generated and are presented in Fig. 5. The spatial distribution pattern of gauge-measured annual precipitation is quantitatively consistent with other maps based on the longer data records such as Wang and Cho (1997). The bias-corrected yearly precipitation map, however, shows much higher values, particularly in the northwest regions, although precipitation distribution pattern has not been changed much by the bias corrections. A general poleward increase of the percentage of the annual correction, ranging from 1.20 in the southern regions up to 1.75 in the Arctic sectors, is clearly seen (Fig. 5), and it is mainly due to the lower temperature, higher snowfall proportion, and higher winds on precipitation days in the northern regions (Fig. 6). Similar features of the CF distributions were found for the continental United States, Greenland, and northern Canada (Legates and Deliberty 1993; Yang et al. 1998b, 1999b; Metcalfe et al. 1994). In addition, precipitation bias corrections in northern Canada (Metcalfe and Goodison 1993) and Alaska (Yang et al. 1998b) indicated that trace-precipitation and wetting-loss corrections were important in the high latitudes. This study showed that, because of the higher snowfall undercatch of the Tretyakov gauge than the Canadian Nipher snow gauge (Goodison et al. 1998; Yang et al. 1999a), wind-induced error was the largest bias and trace amount of precipitation was also significant, particularly in the central and northeastern Siberian regions.

TABLE 2. Yearly summary of bias corrections of daily precipitation data at 61 climate stations in Siberia, 1986–92.

		Measured precipitation* (mm)	Corrections			Corrected precipitation (mm)	Correction factor (CF)		
Station No.	Station name		Trace (mm)	Wind loss (mm)	Sum (mm)		Mean	Max	Min
1	Habarovsk	666.7	19.6	66.7	86.3	753.0	1.13	1.15	1.10
2	Blagovescensk	525.3	22.3	42.0	64.3	589.5	1.12	1.15	1.10
3	Im. P. Osipenko	483.5	24.1	58.0	82.1	565.6	1.17	1.25	1.12
4	Nikolaevsk-Na	603.7	18.2	163.1	181.3	785.0	1.30	1.41	1.25
5	Bomnak	540.7	23.0	40.8	63.8	604.6	1.12	1.16	1.10
6	Ajan	770.8	23.8	149.9	173.7	944.5	1.23	1.36	1.18
7	Mondy	353.1	24.5	24.2	48.7	401.8	1.14	1.14	1.13
8	Sretensk	371.4	25.3	27.9	53.2	424.6	1.14	1.20	1.12
9	Cita	362.2	23.9	29.8	53.7	415.9	1.15	1.18	1.13
10	Mogoca	441.6	23.8	32.8	56.6	498.2	1.13	1.15	1.11
11	Bagdarin	358.0	25.6	24.6	50.2	408.2	1.14	1.17	1.12
12	Tassa	240.7	27.5	6.5	34.0	274.6	1.14	1.24	1.11
13	Zigalovo	308.1	18.3	17.1	35.4	343.4	1.11	1.14	1.11
14	Tulun	361.1	18.5	26.6	45.1	406.3	1.12	1.16	1.10
15	Tynda	566.3	21.5	40.6	62.1	628.5	1.11	1.14	1.10
16	Srdijkalar	403.3	25.9	16.3	42.2	445.5	1.10	1.15	1.07
17	Kalakan	404.6	26.0	14.4	40.4	445.0	1.10	1.14	1.08
18	Nizneangarsk	337.9	19.5	26.5	46.0	383.8	1.14	1.16	1.11
19	Kazachengkoye	400.2	14.6	26.3	40.9	441.1	1.10	1.12	1.09
20	Orlinga	362.4	15.3	19.8	35.1	397.4	1.10	1.11	1.09
21	Verhe-Markovo	355.0	15.1	31.5	46.6	401.7	1.13	1.15	1.11
22	Mama	538.1	11.6	71.8	83.4	621.5	1.15	1.17	1.13
23	Voroncovka	623.0	13.2	93.2	106.4	729.4	1.17	1.22	1.12
24	Minusinsk	349.6	22.5	19.1	41.6	391.2	1.12	1.12	1.12
25	Barnaul	421.1	16.3	60.2	76.5	497.7	1.18	1.22	1.13
26	Krasnojarsk	462.7	13.5	48.6	62.1	524.8	1.13	1.17	1.12
27	Bogucany	338.1	14.4	28.6	43.0	381.1	1.13	1.16	1.11
28	Enisejsk	452.0	13.1	52.8	65.9	517.8	1.15	1.19	1.12
29	Kolpasev	505.5	12.7	60.9	73.6	579.1	1.15	1.17	1.13
30	Omsk	396.2	14.8	56.6	71.4	467.6	1.18	1.22	1.15
31	Tobol’sk	460.9	15.8	72.2	88.0	548.9	1.19	1.22	1.17
32	Sejmchan	263.2	17.5	33.6	51.1	314.3	1.19	1.24	1.12
33	Anadyr	381.8	16.4	316.2	332.6	714.4	1.87	2.20	1.64
34	Zyrjanka	236.8	18.7	37.7	56.4	293.2	1.24	1.33	1.19
35	Mys Uelen	345.2	15.7	181.6	197.3	542.5	1.57	1.67	1.45
36	Ilirnej	187.2	19.6	21.0	40.6	227.8	1.22	1.25	1.17
37	Mys Schmidta	250.9	15.4	131.4	146.8	397.8	1.59	1.78	1.47
38	Lensk	366.3	13.1	55.6	68.7	434.9	1.19	1.21	1.15
39	Pokrjvskaja	236.9	17.7	24.4	42.1	279.0	1.18	1.23	1.15
40	Erbogachen	348.3	16.5	32.3	48.8	397.1	1.14	1.15	1.10
41	Curapca	209.0	22.1	17.5	39.6	248.6	1.19	1.23	1.14
42	Ojmjakon	211.2	18.5	12.0	30.5	241.7	1.14	1.19	1.12
43	Batamaj	257.4	20.0	32.1	52.1	309.5	1.20	1.26	1.18
44	Sangary	298.9	15.9	79.0	94.9	393.8	1.32	1.36	1.27
45	Njurba	281.4	15.4	31.7	47.1	328.5	1.17	1.20	1.14
46	Tura	400.8	10.9	32.2	43.1	443.8	1.11	1.12	1.10
47	Ust-Moma	180.6	21.8	13.9	35.7	216.2	1.20	1.22	1.17
48	Verhojansk	170.2	20.8	14.6	35.4	205.6	1.21	1.24	1.18
49	Dzardzan	315.4	17.2	82.2	99.4	414.7	1.32	1.40	1.29
50	Olenek	293.7	13.0	52.2	65.2	358.9	1.22	1.29	1.17
51	Essej	242.0	17.0	31.3	48.3	290.3	1.20	1.28	1.14
52	Hanty-Mansijsk	509.1	11.8	68.1	79.9	589.1	1.16	1.19	1.13
53	Bor	647.5	10.6	59.7	70.3	717.8	1.11	1.13	1.09
54	Njaksimvol	523.0	17.3	46.9	64.2	587.2	1.12	1.14	1.11
55	Tarko-Sale	513.5	11.6	126.3	137.9	651.4	1.27	1.36	1.21
56	Turuhansk	669.6	8.4	159.0	167.4	836.9	1.25	1.28	1.22
57	Salehard	411.6	11.8	70.0	81.8	493.3	1.20	1.25	1.16
58	Cokurdah	218.0	16.2	62.7	78.9	296.9	1.36	1.49	1.31
59	Tiksi	335.0	11.2	257.0	268.2	603.2	1.80	1.94	1.54
60	Hatanga	281.1	13.0	121.2	134.2	415.2	1.48	1.73	1.33
61	Ostrov Dikson	364.4	10.5	292.5	303.0	667.4	1.83	1.94	1.65

* Measured precipitation including recorded amount and wetting loss.

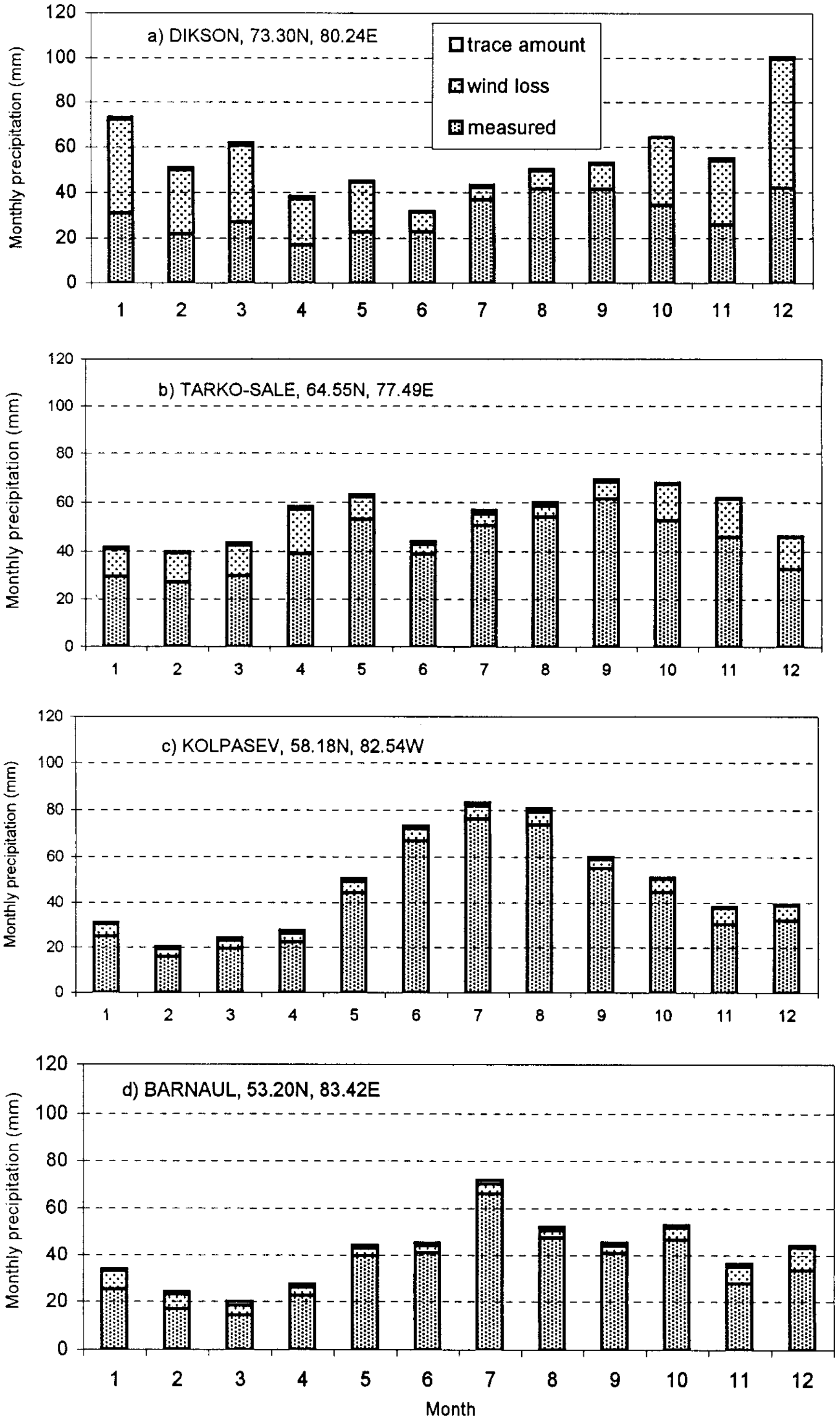
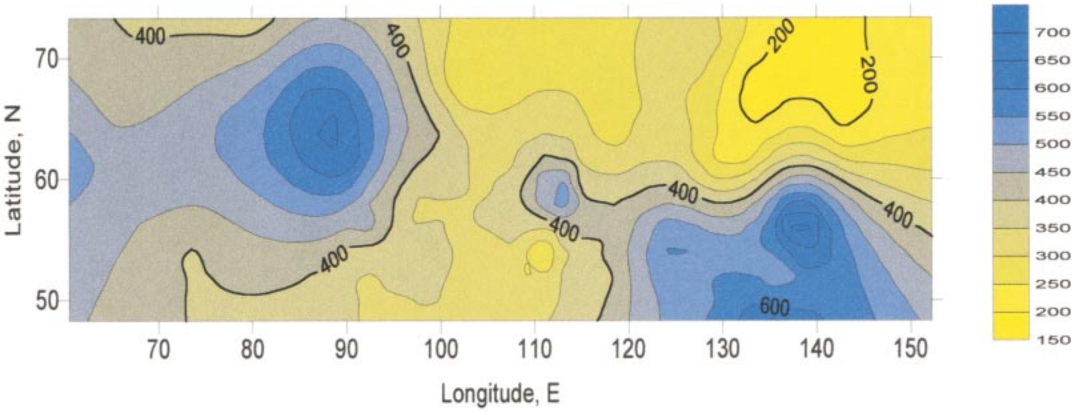
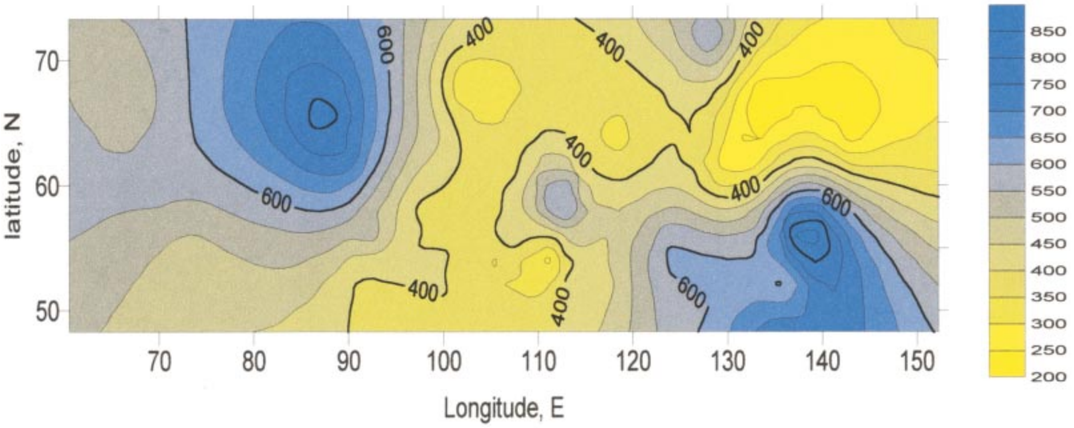


FIG. 4. Mean monthly corrections for wind-induced error and trace amount of precipitation at selected stations (north–south profile along 80°E long) for 1986–92.

5. Comparison with other climatologies

It has been reported that global precipitation amounts are underestimated by approximately 11% because of gauge measurement biases (Legates and Willmott 1990). These biases generally increase poleward and with elevation because of the increased proportion of snowfall. However, up to now most of the existing global and regional precipitation climatologies have not attempted


a) Measured mean annual precipitation (mm), Siberia, 1986-1992


b) Corrected mean annual precipitation (mm), Siberia, 1986-1992

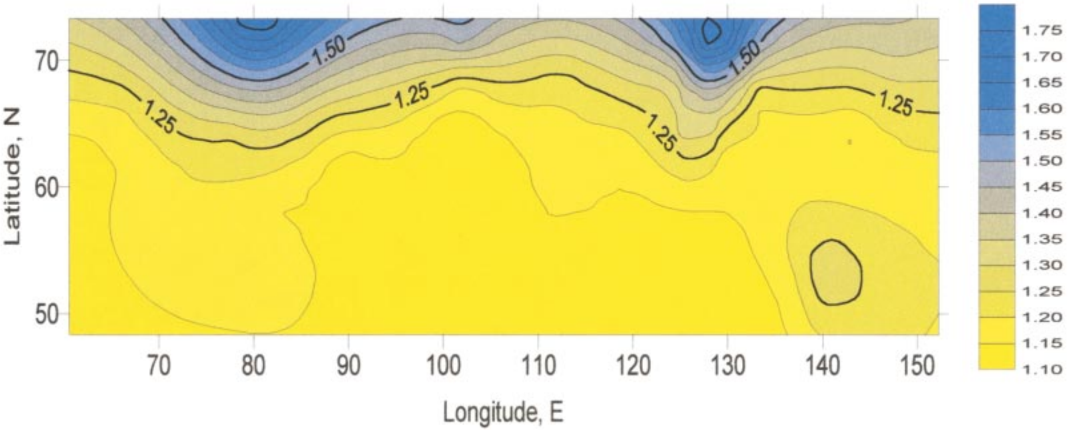
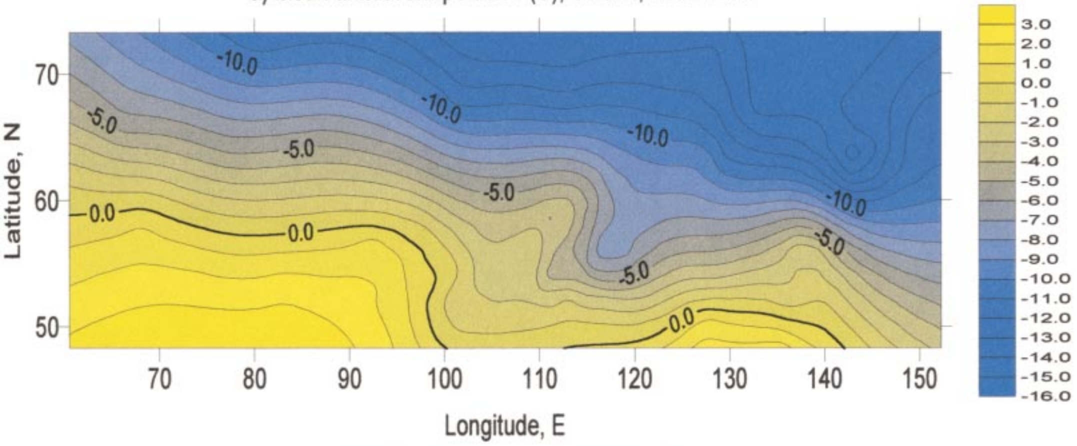

c) Mean annual correction factor, Siberia, 1986-1992

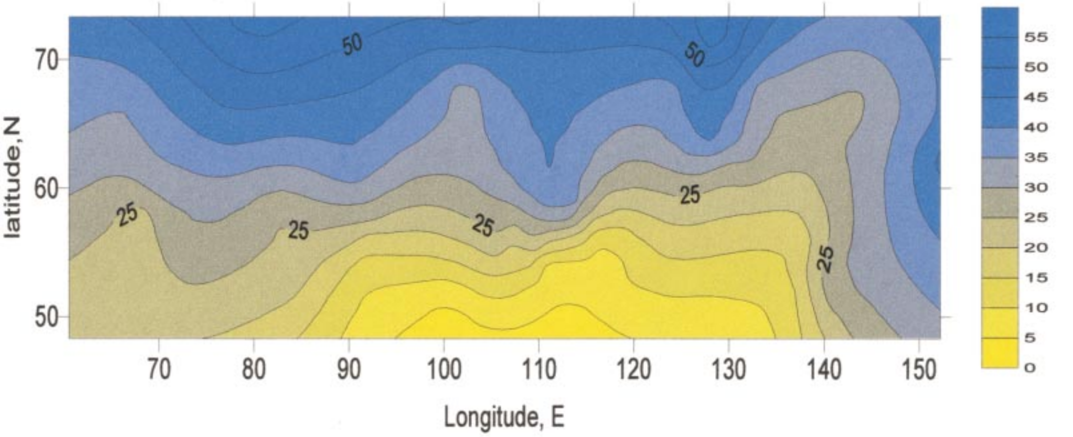
FIG. 5. Contour maps of (a) gauge-measured and (b) bias-corrected annual precipitation, and (c) the correction factor.

to incorporate bias corrections, with only two exceptions. In the late 1970s, Russian scientists, when calculating world water balance, carried out a global-scale bias correction of gauge-measured data on a monthly time step (UNESCO 1978). They produced global maps of bias-corrected precipitation and bias correction factors. For Siberian regions, they reported that bias corrections increased annual precipitation by 50%–70% (UNESCO 1978). Legates and Willmott (1990) conducted bias corrections for the wind-induced gauge un-

a) Mean annual temperature (C), Siberia, 1986-1992



b) Mean snow percent (%), Siberia, 1986-1992



c) Mean daily wind speed (m/s) for precipitation days at gauge height (2m), Siberia, 1986-1992

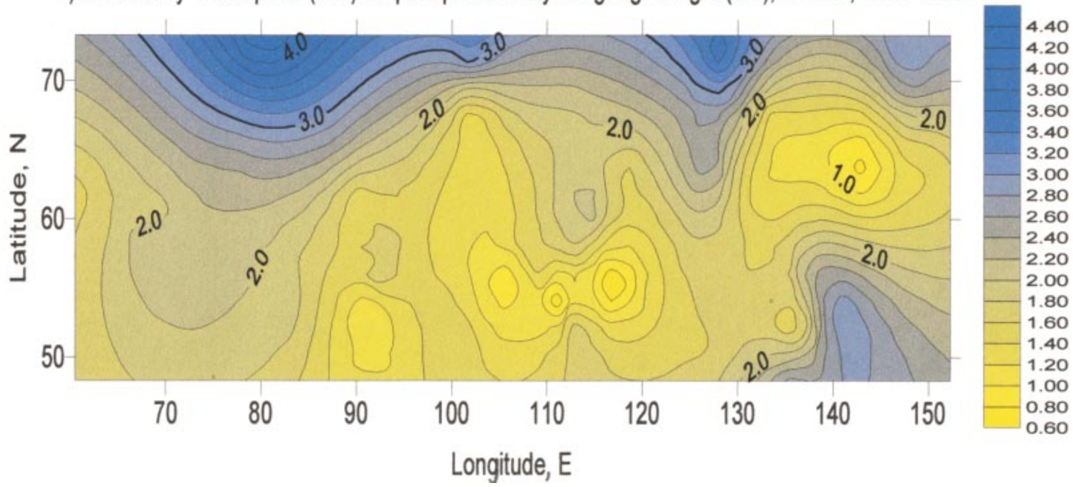


FIG. 6. Maps of (a) mean annual temperature, (b) mean snow percentage, and (c) mean daily wind speed for precipitation days.

dercatch, wetting, and evaporation losses at over 24 000 stations around the world. Their correction procedure, based largely on an extension of methods given by Sevruk (1982, 1989) and Sevruk and Hamon (1984), utilizes mean monthly wind speed and accounts for siting differences between each country, including gauge type, orifice height, and exposure. The bias-corrected results showed a north–south gradient of annual precipitation (200–400 mm) for Siberian regions (Legates and Willmott 1990). A comparative assessment of the existing global precipitation climatologies indicated that the results of Legates and Willmott (1990) compared favorably with the Russian estimates (UNESCO 1978).

Regional precipitation maps and climatologies have also been developed for Siberian regions. Lenart (1991) analyzed gauge-measured data for the polar regions (north of 60°N) and produced a precipitation map. The map indicates that Siberian precipitation annual totals varied from less than 200 mm on the northern coast to over 400 mm in the southern regions. Wang and Cho (1997) examined the spatial and temporal structures of precipitation trend over northern Eurasia. They adjusted the monthly precipitation records for inhomogeneity due to gauge change and systematic error of gauge undercatch, using the methods and information provided by Groisman et al. (1991) and generated long-term annual precipitation maps. Their results show high precipitation of 500–600 mm in western Siberia (Yenisey River basin) and low precipitation of 200–400 mm in the eastern section (Lena River basin). Recently Russian scientists compiled a detailed precipitation map based on the gauge-measured data for the Lena River basin (Zaitzeva 1999). It shows a great spatial variation of annual precipitation over this basin: yearly precipitation varies from 200–250 mm in the northern coastal regions up to 1000 mm in the southern mountain areas, and the central lowlands and river valley are relatively dry, with annual precipitation between 200 and 300 mm.

The above studies have generally revealed the basic features of precipitation distribution over Siberia, but these climatologies are qualitatively different. This discrepancy may be due to different datasets and analysis methods used for the studies. In comparison with those precipitation climatologies mentioned above, the precipitation maps derived from gauge-measured data in this study generally show a similar spatial distribution pattern over Siberia. However, the bias-corrected precipitation maps of this study demonstrated higher annual precipitation over Siberia, particularly in the northwest sectors where bias corrections have raised yearly precipitation from 600 to 750 mm.

In this study, the relative increases of annual total precipitation owing to the bias corrections vary from 10%–25% in the southern regions to 40%–80% on the northern coast. The magnitudes of these relative increases are compatible with those reported by Russian scientists (UNESCO 1978) and Legates and Willmott (1990). This result is expected, because the spatial variability of the relative increases of annual precipitation due to the bias corrections is much smaller than that of the corrected precipitation amounts (UNESCO 1978; Yang et al. 1998b, 1999b). The Russian studies and climatologies take into account gauge metadata and local knowledge of snow climate and the recording procedures (UNESCO 1978; Groisman et al. 1991). The results of this work confirm the conclusions of earlier studies (UNESCO 1978; Groisman et al. 1991) that the precipitation amount in Siberia is higher than previously reported, particularly in winter season and in northern locations where snowfall dominates.

It is important to emphasize that the focus of this study is a test application of the WMO bias correction methodology to Siberia to explore the applicability of this procedure to the high-latitude regions. This study has some advantages over other similar analyses. It utilizes a consistent bias correction methodology that has been developed from the WMO experiments and successfully tested in a variety of climate conditions (Goodison et al. 1998). It conducted bias correction of precipitation records in Siberia on a daily basis for 7 yr and quantified the monthly, annual amounts of the biases and their interannual variations. Usually daily bias corrections will produce better results than monthly corrections, because daily wind speeds vary throughout a month and monthly mean wind speeds may not be representative of wind conditions on precipitation days (Yang et al. 1998b). Legates and Willmott (1990) showed that observation-based precipitation climatologies are generally consistent regardless of the time period of record. This work, however, used consistent observation periods, which have fewer inhomogeneity problems in comparison with the long-term data for other studies. Comparisons of our results with other studies have demonstrated a general agreement. As found in this study, test applications of the WMO bias correction methods in other cold regions, such as in northern Canada (Metcalfe and Goodison 1993; Metcalfe et al. 1994), Nordic countries (Forland et al. 1996), Alaska (Yang et al. 1998b), Greenland (Yang et al. 1999b), and the Arctic Ocean (Yang 1999), clearly show that the WMO methods are easier to use and more applicable than the other bias correction procedures derived from local experiments. Systematic implementation of the WMO bias-correction procedure to regional and national precipitation records in the high latitudes will produce unbiased and compatible precipitation datasets and climatologies for the northern regions as a whole.

6. Discussion

Bias correction of snowfall data for windy and cold climates is a great challenge, because gauges significantly undercatch snowfall at high winds and blowing snow can potentially introduce huge errors. The WMO bias correction methods were developed from a midlatitude experiment (Goodison et al. 1998). These meth-

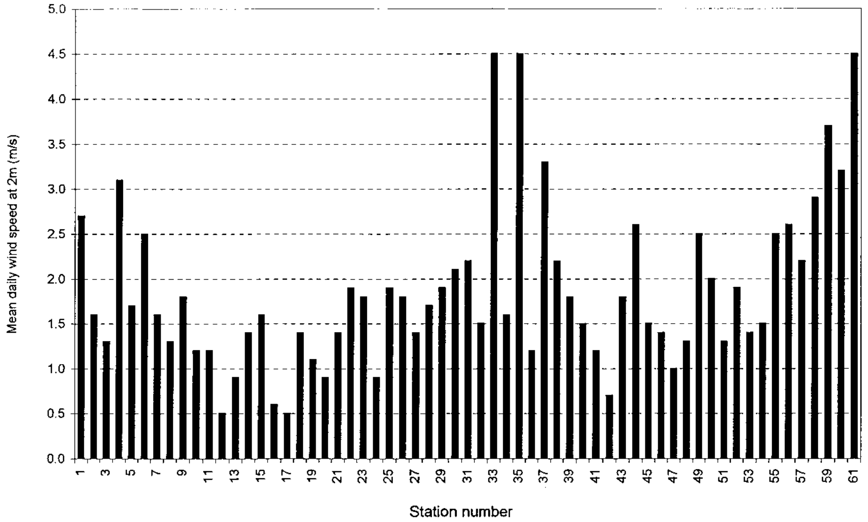


FIG. 7. Mean daily wind speed at 2 m for snowfall days at the 61 sites in Siberia.

ods are expected to be appropriate for daily mean wind speeds below 6.5 m s^{-1} at the gauge height, as blowing snow events at higher wind speeds were eliminated from the method development (Goodison et al. 1998). Recently there have been some concerns about its applicability in the high-latitude regions and for Arctic conditions in particular (WCRP/ACSYS 1997).

To evaluate the applicability of the WMO methods to the high latitudes, wind conditions need to be examined. Figure 7 shows the mean daily wind speeds for snowfall days at the 61 locations in Siberia. It is seen that mean wind speeds were lower than 6.5 m s^{-1} at most stations, except at few windy locations in northern Siberia. Daily wind speeds (at 2-m height) on snowfall days were analyzed in detail at 10 selected stations in Siberia (Fig. 8). It was found that, along the northern Siberian coast, daily gauge-measured snowfall ranged from less than 1 up to 25–30 mm, with the mean value between 10 and 15 mm day^{-1}. Daily wind speeds spanned from calm up to 20 m s^{-1}, and the mean wind speeds for snowfall days were near 3.5–5.9 m s^{-1}. It is important to note that, in the northern coastal regions, daily wind speeds on 50%–60% of snowfall days fell in the wind range of 8–20 m s^{-1}. Under such high wind conditions in cold temperatures, it is likely that blowing snow may occur (Li and Ponmeroy 1997; Struzer 1971; Pomeroy and Gray 1995). In addition, there is a general tendency of high gauge-measured snowfall amount associated with high wind speeds in northern Siberia, such as at Tiksi and Dikson stations. This relationship may suggest that Tretyakov gauges collected blowing snow fluxes. In the Siberian inland regions, mean daily snowfall amount was lower, with the maximum being less than 15 mm day^{-1}. The corresponding daily wind speeds were lower (ranging from calm to 7 m s^{-1} at most of the sites) in comparison with the northern coast. There is no association of high snowfall amounts with high wind speeds in the Siberian inland regions. This analysis indicates that possible blowing snow events may be a problem that will create uncertainties in quantifying gauge catch of snowfall in the northern Siberian regions.

Blowing snow fluxes collected by precipitation gauges are called false precipitation (UNESCO 1978). Based on field observations at a windy alpine location in the Colorado Front Range, Bardsley and Williams (1997) reported that blowing snow events often occur after the storms at high wind speeds over 20 m s^{-1} and may introduce 50% overcatch over a winter season. Pomeroy and Gray (1995) reported that blowing snow fluxes can reach 2 m in height when wind speeds at 10-m height are between 6 and 8 m s^{-1}. Under severe blowing conditions and over terrain where the upstream fetch is several kilometers long, the layers of suspended snow extend to heights of hundreds of meters (Pomeroy and Gray 1995). Struzer (1971) found that the critical (mean daily) wind speed at 2-m height for false snowfall condition was 8.5 m s^{-1} over Antarctic land areas, and Struzer and Bryangin (1971) developed methods of calculating false snowfall amount. Their methods employ station elevation, air temperature, wind speed at the gauge height, and the duration (hours) of blowing snow in a day. Jordan et al. (1999), when calculating heat budget on snow-covered sea ice of the Arctic Ocean, used the methods of Struzer and Bryangin (1971) to estimate false snowfall at high wind conditions. Golubev et al. (1997) summarized the Russian techniques and computed false snowfall amounts at selected locations in the FUSSR. Their results showed the correction factors for snowfall data differed by less than 20% with and without accounting for false precipitation at seven out of eight sites. At Dikson Island in northern Siberia (the eighth site), winter wind speeds were very high and the CF difference was as high as 140% (Golubev et al. 1997).

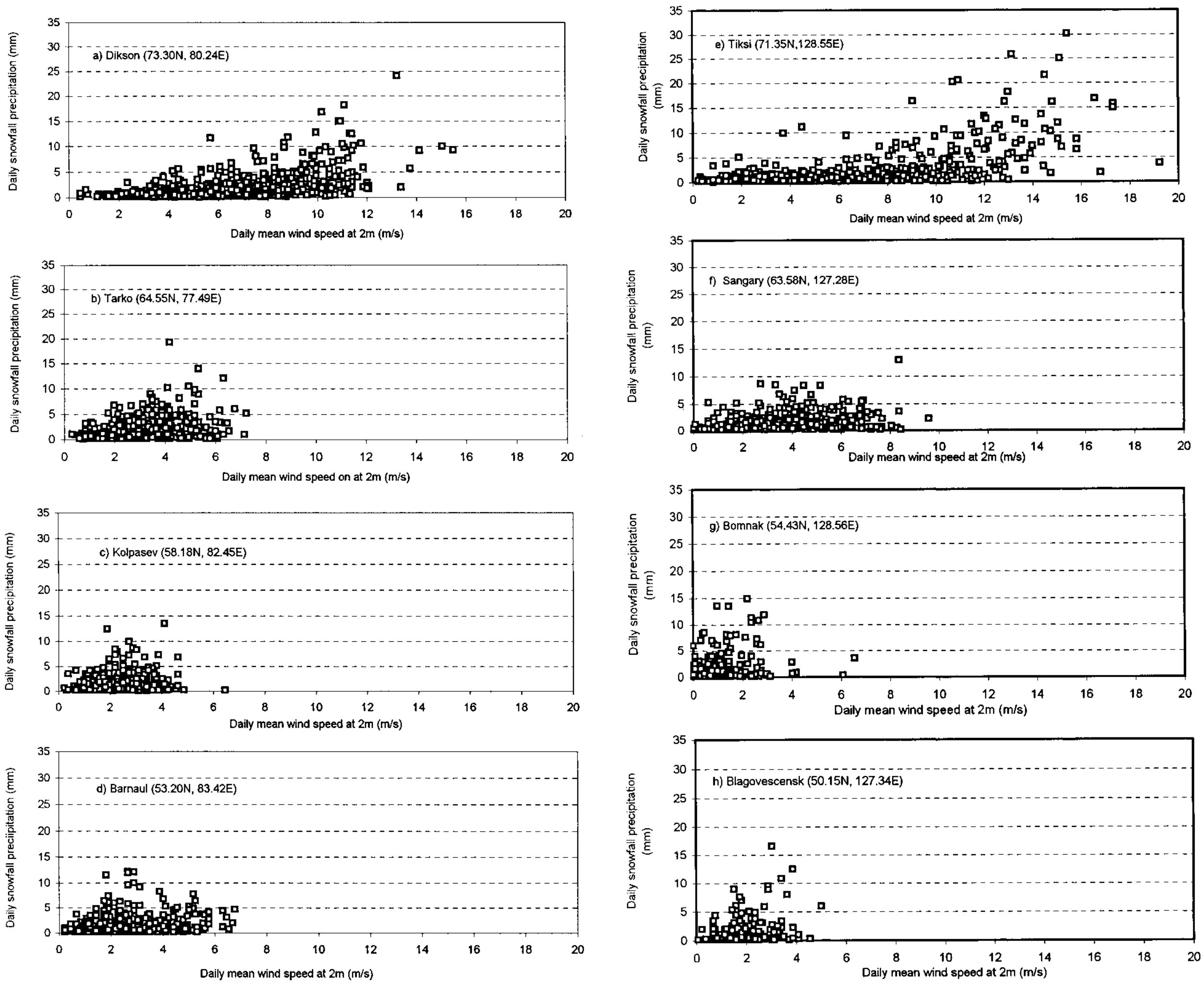


FIG. 8. Daily snowfall amount versus daily wind speed (at 2-m height) at selected stations in Siberia.

To estimate the amount of false snowfall associated with high winds and possible blowing snow events in northern Siberia, the methods of Struzer and Bryangin (1971) were applied to Tiksi daily data for 1986. The critical (mean daily) wind speed at 2-m height for false snowfall condition was set up at 8.5 m s^{-1} over land (Struzer and Bryangin 1971; Golubev et al. 1997). According to this threshold, the number of days of possible false snowfall at Tiksi ranged from 0 to 6 days in the winter months of 1986, with a yearly total of 15 days. Duration of blowing snow in a day is required to calculate the false snowfall amount; this parameter is not available in the climate data used for this work. A study in Najar-Mar in the FUSSR indicated the daily maximum duration of blowing snow may vary from 6 to 24 h for daily wind speeds over 7 m s^{-1} (Golubev et al. 1997). In our calculation, a duration of 12 h was assigned to all the possible blowing snow days when daily wind speeds were greater than 8.5 m s^{-1}. The results of the calculation show that the false snowfall amount in most winter months was estimated to be 0–20 mm, that is, 50%–100% of the gauge-measured monthly total snowfall, and in March the estimated false snowfall exceeded the gauge-measured amount. The yearly total of the estimated false snowfall is about 60 mm, or 23% of the gauge-measured annual precipitation (Table 3).

To further illustrate the impact of possible false snowfall in gauge catch, monthly $P_c - P_f$ and the ratio of $(P_c - P_f)/P_g$ were computed and presented in Table 3. The value of $P_c - P_f$ should be considered to be the most conservative bias correction, because it excludes false snowfall from the bias-corrected winter precipitation amount. This conservative correction brings up the winter monthly snowfall at a lower rate, that is, about 50%–70% increase (in comparison with 150%–240% increase for P_c). The relative annual increase of the yearly precipitation due to the bias corrections is about 25% versus 50% with and without considering possible false snowfall.

It seems clear that blowing snow events and possible false precipitation can be very important when com-

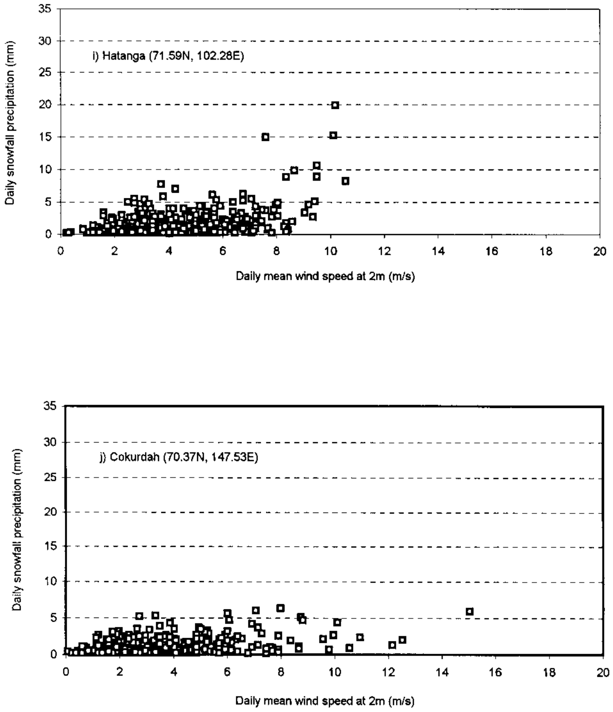


FIG. 8. (*Continued*)

puting gauge catch of snowfall in windy locations. However, it is important to point out that the scope of blowing snow and false snowfall is limited to only the northern Siberian regions. At most Siberian sites, wind speeds on snowfall days are lower than the threshold wind, indicating that the WMO bias correction methods are suitable for the majority of the Siberian regions. Similar work in Alaska and Greenland also showed a general applicability of the WMO bias correction techniques in those regions (Yang et al. 1998b, 1999b). These findings probably justify the implementation of the WMO bias correction procedures with the threshold wind speed (6.5 m s^{-1}) in the high-latitude regions.

Limitations and uncertainties exist in both bias correction and estimation of the false snowfall in Siberian regions. The WMO bias correction method and the procedure of estimating false snowfall (based on studies in the Antarctic) need further testing and validation in the northern high latitudes (Goodison et al. 1998; Golubev 1996). More efforts to refine the bias correction techniques and further gauge intercomparison experiments to investigate gauge performance in the Arctic regions of high winds have been recommended (WCRP/ACSYS 1997).

7. Conclusions

The bias correction procedures derived from the WMO Solid Precipitation Measurement Intercomparison dataset for the Tretyakov gauge have been applied at 61 climate stations in Siberian regions for 7 yr. Biases of wind-induced undercatch and trace amounts of precipitation were corrected on a daily basis, and the gauge-measured annual precipitation was increased significantly by 30–330 mm (about 10%–65% of the gauge-measured yearly total). Of the biases in precipitation measurement, wind loss is the greatest. Trace amount of precipitation is also a significant error in the regions of low precipitation. The correction is greater in the winter season and smaller in summer because of the increased effect of wind on gauge undercatch of snowfall.

The monthly correction factors in Siberia differed from station to station. At an individual station, the monthly correction factors varied by type of precipitation and by month, since these biases depend on wind speed, trace amount of precipitation, and the actual gauge-measured precipitation amount. In addition, there is a considerable interannual variation of the bias cor-

TABLE 3. Estimation of false precipitation amount at Tiksi for 1986. Tmn = monthly mean temperature; U_g = wind speed at gauge height (2 m); P_g = gauge-measured precipitation, including wetting loss; P_f = false precipitation; P_c = corrected precipitation.

	Precipitation days									Correction factors	
Month	All	$U_g > 6.5$ m s^{-1}	$U_g > 8.5$ m s^{-1}	Tmn (°C)	U_g (m s^{-1})	P_g (mm)	P_f (mm)	P_c (mm)	$P_c - P_f$ (mm)	P_c/P_g	$(P_c - P_f)/P_g$
1	13	2	0	−34.2	3.7	8.2	0.0	14.0	14.0	1.71	1.71
2	12	9	6	−25.3	10.8	27.2	20.0	66.3	46.3	2.44	1.70
3	11	5	4	−22.8	9.0	18.2	21.6	39.8	18.2	2.19	1.00
4	6	1	0	−16.3	4.9	6.0	0.0	9.6	9.6	1.60	1.60
5	17	0	0	−6.5	5.6	18.6	0.0	30.6	30.6	1.65	1.65
6	14	0	0	2.8	5.3	25.8	0.0	30.5	30.5	1.18	1.18
7	15	0	0	4.7	4.5	18.3	0.0	20.4	20.4	1.11	1.11
8	15	0	0	5.8	5.0	66.1	0.0	74.2	74.2	1.12	1.12
9	23	0	0	1.5	6.2	41.9	0.0	48.8	48.8	1.16	1.16
10	19	8	3	−6.4	8.5	20.8	10.4	41.2	30.8	1.98	1.48
11	13	4	2	−23.8	6.9	7.1	7.1	11.5	4.4	1.62	0.62
12	10	1	0	−28.2	4.5	5.9	0.0	8.9	8.9	1.51	1.51
Mean/sum	168	30	15	−12.4	6.2	264.1	59.1	395.8	336.7	1.50	1.27

rections, due to the fluctuation of wind speed, air temperature, and frequency of snowfall. It is clear that the monthly correction factors are not constant. Thus correction of the biases should not be conducted on a monthly basis, and the monthly correction factors obtained from one intercomparison station should not be used for other climatic and hydrological stations without detailed analysis of wind and snow climate. Bias corrections should be conducted on a daily basis for the entire recording period for each individual station in an observational network. These corrections require considerable station information (metadata) and additional meteorological information (i.e., wind speed at gauge height on precipitation days, temperature, precipitation type, and gauge-measured amount of precipitation) for their implementation (Yang and Goodison 1998). The bias correction such as demonstrated in this work will have a meaningful impact on climate change and variation analyses of large regions.

Significant increase of precipitation amount due to the bias corrections has been recently reported in the high latitudes (Metcalfe et al. 1994; Goodison and Yang 1995; Yang et al. 1998b, 1999b; Yang 1999). This increase points to a need to review our understanding of both terrestrial and oceanic water budgets in the northern regions. In addition, model validation based on available precipitation estimates has shown that most of the Atmospheric Model Intercomparison Project models appear to oversimulate present-day Arctic precipitation (Bonan 1998; Kattsov et al. 1998; Walsh et al. 1998). Results of the bias corrections of precipitation records in the northern regions (Metcalfe et al. 1994; Goodison and Yang 1995; Yang et al. 1998b, 1999b; Yang 1999) argue that this apparent oversimulation in fact partly results from the observed precipitation being too low because of the observational biases. This result may also imply that the models are performing better in the high-latitude regions than we give them credit. To obtain compatible and unbiased precipitation databases and climatologies at regional to global scales, more efforts are needed to further reduce the observational biases and other uncertainties in precipitation estimates, particularly in the high-latitude regions.

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