JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. D6, PAGES 6171–6181, MARCH 27, 1999

Bias correction of daily precipitation measurements for Greenland

Daqing Yang
School of Geography and Geology, McMaster University, Hamilton, Ontario, Canada

Shig Ishida and Barry E. Goodison
Climate Research Branch, Atmospheric Environment Service, Downsview, Ontario, Canada

Thilo Gunther
German Weather Service, Berlin, Germany

Abstract. A methodology for correcting the Hellmann gauge-measured daily precipitation for wind-induced undercatch, wetting loss, and trace amount of precipitation was presented and applied at 12 climate stations in Greenland for years 1994–1997. The results show the following: (1) daily corrections of the biases increase the gauge-measured annual precipitation by 35–280 mm for the 4 years (about 25–90% of the gauge-measured yearly total) in Greenland; (2) of the biases, wind-induced undercatch is the source of greatest error; wetting loss and trace amount of precipitation are also significant biases in the northern Greenland regions of low precipitation; (3) monthly correction factors (corrected/measured precipitation) differ by station and, at an individual station, by type of precipitation; (4) considerable intra-annual variation of the yearly corrections has been found in Greenland due to the fluctuation of wind speed, air temperature, and frequency of snowfall. These results suggest that annual precipitation in Greenland is much higher than previously reported, particularly in the southern regions of high precipitation; and the latitudinal precipitation gradient may also be greater over Greenland. These results will have a significant impact to water budget and glacier mass balance studies in Greenland.

1. Introduction

It has long been realized that systematic errors such as wind-induced undercatch, wetting, and evaporation losses in precipitation measurement affect all types of precipitation gauges [*Goodison et al.*, 1981; *Sevruk*, 1982; *Tabler et al.*, 1990]. The need to correct these biases especially for solid precipitation measurement has now been more widely acknowledged, as the magnitude of the errors and their variation among gauges became known and their potential effects on regional, national and global climatological, hydrological, and climate change studies were recognized [*Goodison and Yang*, 1995; *Yang and Goodison*, 1998; *Walsh et al.*, 1998; *Desbois and Desalmand*, 1995; *Legates*, 1995; *Legates and Willmott*, 1990; *Hanssen-Bauer and Forland*, 1994; *Groisman and Easterling*, 1994; *Groisman and Legates*, 1994; *Karl et al.*, 1993; *Groisman et al.*, 1991].

To assess national methods of measuring solid precipitation, including past and current procedures, automatic systems, and new methods of observation, the World Meteorological Organization (WMO) initiated the Solid Precipitation Measurement Intercomparison Project in 1985 [*WMO/CIMO*, 1985; *Goodison et al.*, 1989]. The intercomparison was designed to (1) determine wind-induced errors in national methods of measuring solid precipitation, including wetting and evaporation losses; (2) derive standard methods for correcting solid precipitation measurements; and (3) introduce a reference method of solid precipitation measurement for general use to calibrate any type of precipitation gauge [*Goodison et al.*, 1989].

The reference method for the true snowfall measurement was critical for this intercomparison. After reviewing all possible practical methods (bush shield, double fence shield, forest clearing, snow board, dual gauge system), the WMO Organizing Committee for the intercomparison designated the octagonal vertical double fence, surrounding a shielded Tretyakov gauge, as the intercomparison reference (DFIR) [*Goodison et al.*, 1981; *Golubev*, 1985a, b; *Goodison et al.*, 1989]. The DFIR was operated at 19 stations in 10 countries around the world during the study.

The Hellmann gauge is one of the most widely used precipitation gauges at about 30,080 locations around the world. It is the standard gauge in 30 countries [*Sevruk and Klemm*, 1989]. The Hellmann gauge is a nonrecording gauge for both rain and snow measurements. It is 43 cm high, with an orifice area of 200 cm^2. There are various versions of the Hellmann gauges. The designs of the Hellmann gauges are very similar [*Sevruk and Klemm*, 1989]: they all have the same orifice area. A metal cross is installed in the Danish Hellmann gauge to prevent snow to be blown out of the gauge. In different countries the Hellmann gauges are placed at the height of 0.6–1.5 m above the ground, and in some countries, they are equipped with a wind shield (such as Nipher type shield and Tretyakov shield) [*Sevruk and Klemm*, 1989]. Many experimental studies on the Hellmann gauges have been conducted [*Sevruk*, 1982; *Gunther*,

Paper number 1998JD200110.
0148-0227/99/1998JD200110$09.00

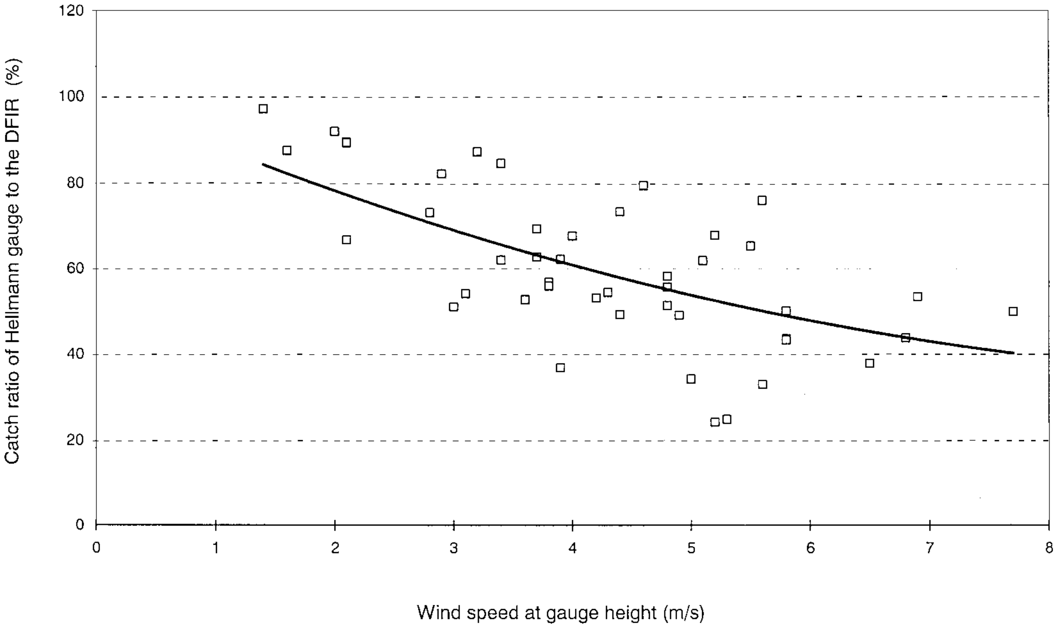

Figure 1. Relation of daily catch ratio of snow for the Hellmann gauge versus daily wind speed at gauge height, Harzgerode, Germany.

1993; *Milkovic*, 1989; *Allerup et al.*, 1997]. The Hellmann gauges were tested in the International Comparison of National Precipitation Gauge with a reference pit gauge [*Sevruk and Hamon*, 1984]. The correction method for wind-induced undercatch of rainfall measurement has been developed [*Sevruk*, 1981; *Sevruk and Hamon*, 1984] and applied to the archived precipitation data in Switzerland [*Sevruk*, 1993].

The WMO Solid Precipitation Measurement Intercomparison provided the opportunity to develop and evaluate the improved correction procedures on a daily or 6 hourly timescale for a number of precipitation gauges commonly used around the world [*Goodison et al.*, 1998; *Goodison and Yang*, 1995; *Yang et al.*, 1995; *Yang et al.*, 1998a]. This paper presents a summary of the methodology of correcting Hellmann gauge-measured daily precipitation for biases of wind-induced undercatch, wetting loss, and trace amount of precipitation. Application of the proposed methodology was made at 12 climate stations in Greenland for four example years (1994–1997). As a result, the magnitude of the biases was quantified and their seasonal and spatial variability was demonstrated. Discussions of the correction methods and results were made by comparison of this work to other studies. It is expected that the bias correction, such as demonstrated by this study, will significantly improve the accuracy and homogeneity of precipitation data and will have an impact on climate monitoring and hydrological modeling. The results of this study will also be useful for validation of the GCM/RCM simulation in the high latitudes [*Walsh et al.*, 1998; *Kattsov et al.*, 1998].

2. Correction Method

During the WMO Solid Precipitation Measurement Intercomparison the Hellmann gauges were tested against the DFIR reference at four stations in Finland, Russia, Germany, and Croatia. Extensive experiments on the wetting and evaporation losses of the Hellmann gauges and many other national gauges have been conducted at the Jokioinen Station in Finland [*Aaltonen et al.*, 1993]. The wetting losses for both the Tretyakov gauge and the Hellmann gauge were corrected when the volumetric method was used for the gauge readings [*Aaltonen et al.*, 1993]. The evaporation losses were not corrected since experiments showed that they were very small [*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 derived by *Yang et al.* [1993]. Blowing snow events in the intercomparison data were carefully identified and eliminated from further analysis. The intercomparison data collected at the four sites for more than three winter seasons were compiled; they represented a great variety of climate, terrain, and exposure. Relation of catch ratio as a function of wind speed and air temperature has been developed for the Hellmann gauges [*Yang et al.*, 1994; *Gunther*, 1993; *Yang et al.*, 1999].

The Hellmann gauges used in Greenland were equipped with a modified Nipher wind shield. This gauge and shield configuration has been tested at Harzgerode in Germany during the WMO intercomparison [*Gunther*, 1993]. Data analysis indicates that wind speed is the only factor with the statistically significant relationship to the gauge catch, and air temperature does not have a statistically significant effect on the gauge catch, when precipitation is classified into snow, rain, and mixed. It is known that an unrealistically large variation of the catch ratio will be introduced by the small absolute differences between gauges for small precipitation events. To minimize this effect, only those intercomparison data when the DFIR measurement was greater than 3.0 mm were used for the statistical analysis.

Figure 1 shows, as an example, the daily catch ratio of snow for the Hellmann gauge versus daily wind speed at the gauge height. A wide range of wind speed and catch ratio (CR) has been sampled over several winter seasons at the experimental site; this may ensure that the derived correction method is more likely to be applicable to a wide range of climate conditions. The scatterplots of the CR wind for rain and mixed precipitation generally have similar patterns as for snow. The scatter of the CR is smaller for mixed precipitation and rain events, and their catch ratios are higher (in comparison to snow events), particularly at high wind speeds, indicating less effect of wind on gauge catch of rain and mixed precipitation. Regression analyses derived the best fit relation of daily catch ratio (CR, %) as a function of the daily wind speed (Ws, m/s) at the gauge height for various precipitation types.

Snow

$$\mathrm{CR} = 100.00 - 11.95\mathrm{Ws} + 0.55\mathrm{Ws}^2, \; (0 \le \mathrm{WS} \le 6.5 \text{ m/s}), \quad (n = 43, \; R^2 = 0.50), \tag{1}$$

Mixed precipitation

$$\mathrm{CR} = 100.00 - 8.16\mathrm{Ws} + 0.45\mathrm{Ws}^2, \; (0 \le \mathrm{WS} \le 6.5 \text{ m/s}), \quad (n = 31, \; R^2 = 0.43), \tag{2}$$

Rain

$$\mathrm{CR} = 100.00 - 4.37\mathrm{Ws} + 0.35\mathrm{Ws}^2, \; (0 \le \mathrm{WS} \le 6.5 \text{ m/s}), \quad (n = 48, \; R^2 = 0.21), \tag{3}$$

Statistical tests show that these relations are significant at 90–95% confidence level. The performance of the correction equations (1)–(3) was further checked independently by using all the intercomparison data (without the DFIR > 3.0 mm limitation) at the Harzgerode WMO intercomparison station. The results demonstrated that the differences between the totals of corrected precipitation and the DFIR measurements were 6% for snow and less than 3% for both rain and mixed precipitation. Therefore these correction equations work generally well at the experimental station and they should be used for test correction of the Hellmann gauge-measured precipitation data in regional station networks.

3. Application of the Method

Twelve climate stations in Greenland were chosen for this study. These stations spread along the coastal lines and represent various climatic conditions (Figure 2). The site and instrumental information (gauge height, shielding information, anemometer height) is given in Table 1. The daily data of temperature, wind speed, precipitation, snowfall, and snow depth on the ground for the period of 1994–1997 were obtained from the U.S. National Climatic Data Center. The mean yearly values of temperature, gauge-measured precipitation, and wind speed at the 12 sites were summarized for the 4 years in Table 2.

Correction of gauge-measured precipitation should be made for trace precipitation, wetting losses, 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 gauge catch, including both the wetting and the evaporation losses, we modified the general model [*Sevruk and Hamon*, 1984] for precipitation correction to

$$P_c = K(P_g + \Delta P_w + \Delta P_e) + \Delta P_t \tag{4}$$

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, and K is the correction coefficient (usually $K > 1$) for wind-induced errors. The method of determining each of the terms in (4) is given below.

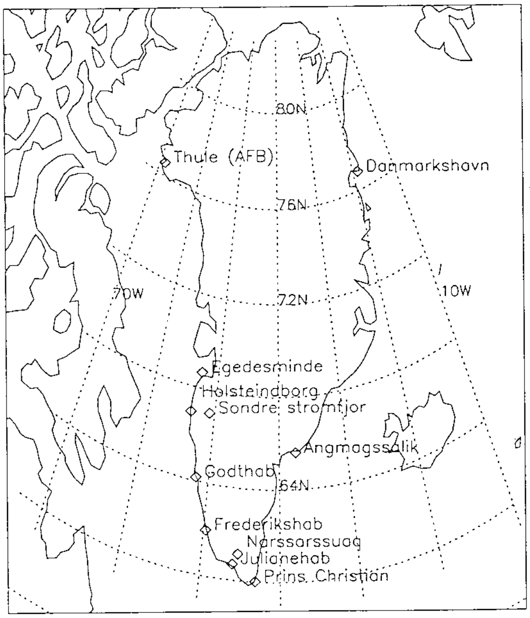

Figure 2. Selected climate stations in Greenland for this study.

3.1. Trace Precipitation

For the Hellmann gauge, a measurement of precipitation of less than 0.10 mm is beyond the resolution of the gauge measurement, and thus it is recorded as a trace precipitation event. Officially, all of the trace precipitation is treated quantitatively as a zero event which contributes nothing to the monthly totals. However, the day during which trace precipitation was recorded is counted as a precipitation day.

Climate data collected during 1994–1997 in Greenland indicate that the annual gauge-measured precipitation varied greatly from 80–200 mm in the northern regions to 350–700 mm in the southern coast. The percentage of snow in annual precipitation decreased from 70–80% in the north to 40–50% in the south coast, 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 120 to 230 at the 12 stations (Table 2). The average numbers of trace precipitation days varied from 60 to 125 for the 4 years. Geographically, more trace precipitation days were recorded in the northern Greenland regions and trace precipitation recordings there can make up 50 to 70% of the annual total of precipitation days. For example, 88 of the 136 precipitation days were trace days at Danmarkshavn and the values were 125 out of 203 at Thule. Seasonally, more trace precipitation days were reported in summer than in winter in northern Greenland, but the percent of trace precipitation days to the total number of days of precipitation is much higher in the relatively dry winter season than in the wet summer season.

It has been reported that in northern Alaska and the North Pole regions, about 80% of the winter snowfall record consisted of trace [*Yang et al.*, 1998b; *Benson*, 1982; *Colony et al.*,

Table 1. Siting and Instrumental Information at 12 Climate Stations in Greenland

Station	WMO Station Identification	Coordinates		Elevation, m	Wind Sensor Height, m	Gauge Height, m	Wind Shield
		N	W				
Danmarkshavn	43200	76.46	18.46	12	10	3.0	yes
Thule (AFB)	42020	76.31	68.50	59	3	3.0	yes
Scoresbysund	43390	70.29	21.58	66	10	3.0	yes
Egedesminde	42200	68.42	52.45	47	10	3.0	yes
Sondre stromfjord	42310	67.01	50.48	55	10	3.0	yes
Holsteindborg	42300	66.55	53.40	9	8	3.0	yes
Angmagssalik	43600	65.36	37.34	35	8	3.0	yes
Godthab	42500	64.10	51.45	27	10	3.0	yes
Frederikshab	42600	62.00	49.43	16	10	3.0	yes
Narssarssuaq	42700	61.11	45.25	26	9	3.0	yes
Julianehab	42720	60.43	46.03	29	15	3.0	yes
Prins Christian Sund	43900	60.02	43.07	76	8	3.0	yes

1998]. In some winter months, no measurable precipitation was reported in the northern Alaska except trace amounts of snowfall. Similar finding was also reported for Northwest Territories (NWT) and Yukon of Canada [*Metcalfe et al*., 1994]. *Woo and Steer* [1979] designed a method of measuring trace rainfall in the high arctic and determined a mean rate of 0.01 mm/h. 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 Greenland show that a number of events of trace precipitation are reported in a single trace precipitation day, thus it is not unreasonable to assume that a trace precipitation could be a measurable 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 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 6 to 13 mm at the 12 stations, or about 5–11% of the gauge-measured annual precipitation in the northern regions and less than 3% in the southern regions. Unlike Alaska [*Yang et al*., 1998b], the trace correction in Greenland shows very similar values between summer and winter seasons. For instance, the averaged monthly totals varied between 0.8 and 1.3 mm for the 4 years at Thule. On the average, the total corrections at Thule account for 5–25% of the gauge-measured monthly precipitation.

The amount of trace record is inversely proportional to the gauge-measured annual precipitation for the 4 years (Figure 3), as was reported by *Yang et al*. [1998b] and *Benson* [1982] for Alaska. Thus correction for trace precipitation is important especially in the northern Greenland regions of low precipitation. It is important to note that after identifying trace precipitation days, the number of measurable precipitation days exhibits a larger variation across Greenland (Figure 4). Therefore we recommend to separate trace precipitation days from measurable precipitation days when analyzing precipitation climate in the northern Greenland regions.

3.2. Wetting Losses

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, the average wetting loss of the Hellmann gauge was 0.14 mm per observation for rain and 0.10 mm for snow [*Aaltonen et al*., 1993]. In this study, wetting loss was calculated on a daily basis. For each precipitation day, an averaged wetting loss was determined according to the type of precipitation and added to the daily record. This is the minimum correction since generally more than one observation was made in a precipitation day.

For the 4 years, the mean annual totals of the wetting loss correction were between 5 and 15 mm at the 12 stations in Greenland, or 5–6% of the gauge-measured annual precipitation in the northern region and 2–3% for the other regions (Table 3). At each individual climate station, the annual amount of the wetting loss correction is different between the 4 years, and the percentage of the annual correction to the gauge-measured yearly totals is different between years as well.

Table 2. Mean Temperature, Wind Speed, and Gauge Measured Precipitation at 12 Stations in Greenland for 1994–1997

Station	Temperature, C		Wind Speed, m/s	Precipitation Days	Trace Days	Gauge Measured, mm	Percent of Snow
	Min	Max					
Danmarkshavn	−15.1	−8.3	4.2	136	88	80.0	74.3
Thule (AFB)	−14.5	−8.0	4.1	203	125	135.8	80.8
Scoresbysund	−8.4	−2.2	3.7	165	89	193.8	67.6
Egedesminde	−7.5	−2.4	3.4	156	85	195.7	61.4
Sondre stromfjord	−9.6	0.6	3.5	131	88	97.2	52.0
Holsteindborg	−6.7	−1.2	3.2	121	77	154.3	44.9
Angmagssalik	−3.5	1.8	2.1	187	90	489.0	56.0
Godthab	−3.8	1.6	5.1	202	92	405.3	58.8
Frederikshab	−4.0	2.2	3.1	146	60	490.4	47.0
Narssarssuaq	−2.4	4.9	4.1	168	91	345.8	52.0
Julianehab	−2.0	3.9	4.5	171	71	521.3	47.8
Prins Christian Sund	−1.5	2.9	6.8	189	73	720.9	48.1

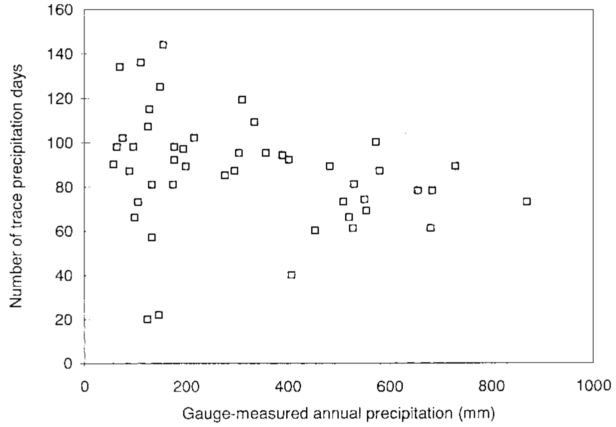

Figure 3. Number of trace precipitation days versus gauge-measured annual precipitation at the 12 climate stations in Greenland for years 1994–1997.

Generally, there is a clear wetting loss increase with increasing gauge-measured annual precipitation in Greenland, since more precipitation generally requires more observations and more observation leads to a higher wetting loss.

3.3. Evaporation Loss

Comprehensive assessment of evaporation losses indicated that average daily losses varied by gauge type and time of the year. For the Danish Hellmann gauge at Jokioinen in Finland, evaporation losses in summer of 0.16–0.27 mm/d and winter of 0.03–0.24 mm/d were measured [*Aaltonen et al.*, 1993]. Ideally, evaporation loss should be corrected. However, because of its strong dependence on weather condition and its daily variation and seasonal change which can be very site dependent, it is not appropriate to estimate the daily evaporation loss at climate stations by using the average evaporation amount obtained from other experimental sites. Therefore evaporation loss was not corrected in this study.

3.4. Wind-Induced Errors

To correct for wind-induced undercatch, wind speed at gauge height is required. When wind speed is not measured at the height of the gauge, it was estimated from measurements at higher heights, using the logarithmic wind profile approach. Roughness length is required by 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 and $Z_0 = 0.03$ m was assigned to the warm period from June to August in Greenland.

It has been well documented that for the same wind speed gauge, undercatch for snow is much higher than for rain [*Goodison et al.*, 1981; *Yang et al.*, 1995, 1998b]. Classifying the type of precipitation is therefore necessary in order to apply the best wind-loss correction. In this study, type of precipitation was classified into snow, mixed and rain. For the snow category, blowing snow events were found reported on some of precipitation days in Greenland.

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 Hellmann gauges in

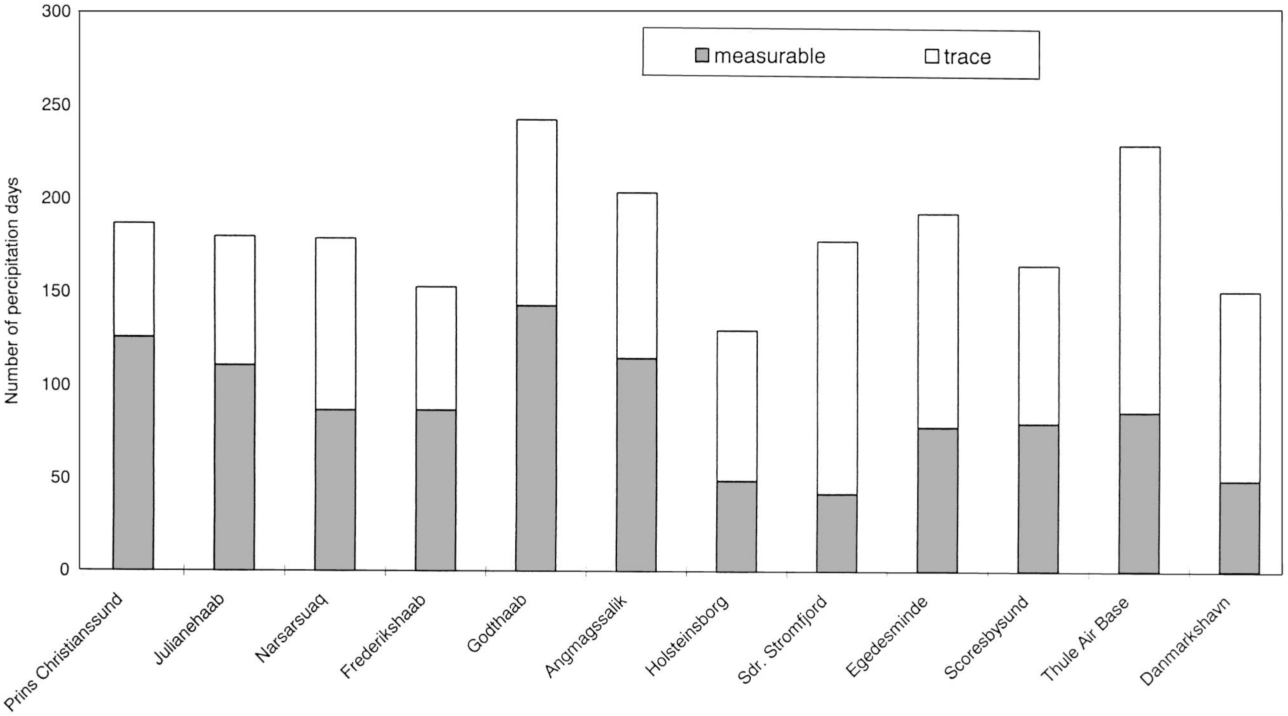

Figure 4. Number of precipitation days in 1996 at the 12 climate stations in Greenland.

Table 3. Corrections of Gauge-Measured Annual Precipitation at 12 Climate Stations in Greenland for 1994–1997

	P_g mm	Corrections, mm				P_c, mm	Correction Factor		
		Wind	Wetting	Trace	Sum		Mean	Min	Max
Danmarkshavn	80.0	60.8	5.1	8.8	74.7	154.7	1.93	1.86	2.04
Thule (AFB)	135.8	90.6	8.3	12.5	111.4	247.2	1.82	1.66	1.99
Scoresbysund	193.8	103.1	8.3	8.9	120.3	314.0	1.62	1.58	1.68
Egedesminde	195.7	77.2	8.2	8.5	96.4	292.1	1.49	1.36	1.76
Sondre stromfjord	97.2	19.3	5.3	8.8	35.9	133.1	1.37	1.31	1.43
Holsteindborg	154.3	61.7	5.2	7.7	74.5	228.8	1.48	1.31	1.52
Angmagssalik	489.0	102.0	11.8	9.0	122.7	611.7	1.25	1.17	1.34
Godthab	409.0	171.8	15.6	10.4	197.7	606.7	1.48	1.24	1.52
Frederikshab	490.4	123.2	10.5	6.0	139.7	630.1	1.28	1.20	1.35
Narssarssuaq	345.8	64.7	9.9	9.1	83.7	429.5	1.24	1.20	1.29
Julianehab	521.3	143.9	12.8	7.1	163.8	685.1	1.31	1.28	1.36
Prins Christian Sund	720.9	262.0	14.7	7.3	284.0	1004.9	1.39	1.35	1.48

Greenland were placed at 3 m above the ground. To avoid the possible overcorrection caused by high wind on precipitation days, an upper value of wind speed has to be determined. Corrections at higher wind speed are estimated by using this threshold wind speed [*WMO/CIMO*, 1993]. This is important since the regression equations that are derived from the 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 wind speed was set up at 6.5 m/s at gauge height for the correction equations in this study, since insufficient wind data greater than this threshold were collected at the WMO sites.

When daily wind speed at the gauge height was available, the daily catch ratio (CR, %) for the Nipher-shielded Hellmann gauges was calculated on a daily basis using the regression equations (1)–(3) for snow, mixed, and rain. The wind-loss correction coefficient (K) was calculated as $K = 100/\mathrm{CR}$.

The average yearly correction for the wind-induced bias at the 12 stations range from 60 to 260 mm for the 4 years (Table 3). Spatial variation of the yearly corrections for wind-induced undercatch in Greenland can be explained by wind speed, percent of snow in annual precipitation, gauge-measured precipitation amount. Generally, the absolute amount of the yearly correction increased with increasing gauge-measured annual precipitation from north to south. However, the percentage of the yearly correction to the gauge-measured annual total decreased from 50–75% in the northern regions to 20–40% in the southern regions, because of the north-south gradient of percentage of snowfall.

3.5. Monthly and Yearly Total Corrections

Monthly variation of the corrections shows the following: (1) in each month the absolute monthly amount of wind-induced error was always greater than wetting loss and trace precipitation; (2) the contribution of trace precipitation and wetting loss to the total correction decreased from north to south, in the most southern region (such as at Prince Christianssund), trace precipitation was almost negligible; (3) monthly precipitation was increased by 30–50% due to the corrections, and it was even doubled for winter months in the northern regions of Greenland (Figure 5, for example).

It is important to note the seasonal variation of the monthly correction factor (CF, ratio of the monthly corrected to gauge-measured precipitation), i.e., the high values for snow data in the cold season from September to May and the low values for rain data in the warm season from June to August, due to the higher wind loss for snow than for rain and due to the smaller amount of absolute precipitation in the cold season than in the warm season. It is even more important to realize the intra-annual variation of the monthly CF values due to the fluctuation of wind speed, frequency (or percentage) of snowfall, number of trace precipitation events, amount of gauge-measured precipitation and air temperature.

Table 3 summarizes the yearly total corrections for wind-induced error, wetting loss, and trace precipitation. For each station the individual corrections are stated and summed. The sum of the corrections is added to the gauge catch (P_g) to obtain the corrected value (p_c). The overall annual correction factor (CF) is then the ratio P_c/P_g. Although the sum of the

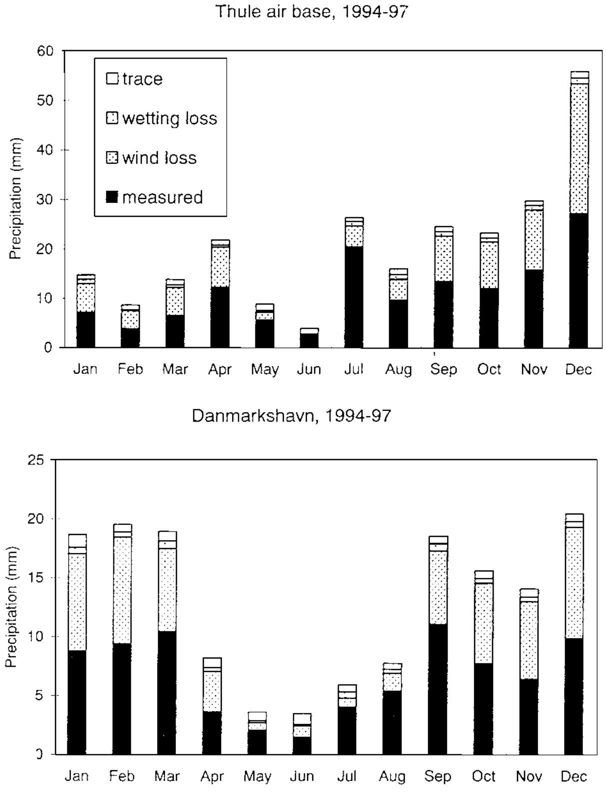

Figure 5. Mean monthly corrections for wind-induced error, wetting loss, and trace amount of precipitation at Thule and Danmarkshavn Stations for 1994–1997.

absolute corrections was highest for Prince Christianssund, the highest annual correction factors were generally in the arctic stations. For the 4 years the maximum CF was at Danmarkshavn and the minimum CF was at Angmagssalik.

Studies of precipitation correction in northern Canada [*Metcalfe and Goodison*, 1993] and Alaska [*Yang et al.*, 1998b] indicated that trace precipitation and wetting loss corrections were important in high latitudes. This study in Greenland showed that due to the higher undercatch of snowfall of the Hellmann gauge, wind-induced error was the largest bias and wetting loss and trace amount of precipitation were significant errors as well. In northern Greenland regions, trace correction is even greater than wetting loss (Table 3).

4. Discussion

Different methods of correcting gauge measurements for systematic errors have been developed and applied for climatological and hydrological studies [*Larsson and Peck*, 1974; *Groisman et al.*, 1991; *Groisman and Legates*, 1993; *Groisman and Easterling*, 1994; *Groisman et al.*, 1996; *Metcalfe and Goodison*, 1993; *Metcalfe et al.*, 1994; *Sevruk et al.*, 1993; *Legates and Deliberty*, 1993; *Goodison and Yang*, 1995; *Yang and Goodison*, 1998; *Yang et al.*, 1998a, b; *UNESCO*, 1974]. The validity of these correction techniques for different climate conditions needs to be evaluated, and the compatibility of the correction results among different geophysical regions also needs to be investigated.

Bias correction was conducted on a daily timescale in this study, using the correction method derived from daily experimental data of the WMO intercomparison. Correction on a shorter timescale, such as hourly or 6 hourly is expected to produce better results since wind speeds may vary throughout the day and daily mean wind speeds may not be representative of wind conditions of precipitation periods. To assess the errors that are incurred in use of daily versus shorter time intervals, hourly or 6 hourly data are required. Hourly or 6 hourly Greenland data are not available to this study. An alternative site at Resolute Bay, NWT, Canada, with similar climate conditions as in Greenland (i.e., windy and cold with snow domination) was thus chosen for the comparative runs of 6 hourly versus daily corrections. It was found that for the Canadian Nipher gauge used at this site, the errors of daily correction in the selected months are small on a daily basis (Figure 6) and the monthly results of daily and 6 hourly corrections compared very well to each other (Table 4). The Hellmann gauge is not used in Canada, and correction factors (CF) were calculated for this gauge, using 6 hourly versus daily wind data at Resolute Station. The results illustrate a visible scatter in the daily CF comparison (Figure 6), but the monthly mean CF values of daily and 6 hourly corrections generally agreed better, with the difference being less than 10% for most of the months (Table 4). Given the uncertainties of estimation of wind speed at gauge height from a standard height and classification of precipitation types by surface air temperature, it seems reasonable to conclude that the errors of daily corrections are essentially random and they tend to cancel out when monthly totals are computed.

It has been lately reported that blowing snow is important to gauge correction in Alaska [*Yang et al.*, 1998b]. Greenland climate data show less blowing snow events due to lower wind speed. It is however important to point out that the threshold wind speed (6.5 m/s) for correcting wind-induced error is not very low for the 12 stations in Greenland. For instance, Prince Christianssund is the windiest site of the 12 stations. The annual mean daily wind was 6.8 m/s at 8 m and 5.6 m/s at gauge height (of 3 m) for the 4 years. At Prince Christianssund there were 41 days out of 190 precipitation days in the 4 years when daily wind speed at gauge height was greater than the threshold wind. Number of days when wind exceeds the threshold was much less at other sites. It is therefore appropriate to set up the threshold wind at 6.5 m/s and to apply the correction procedures with this threshold wind in Greenland.

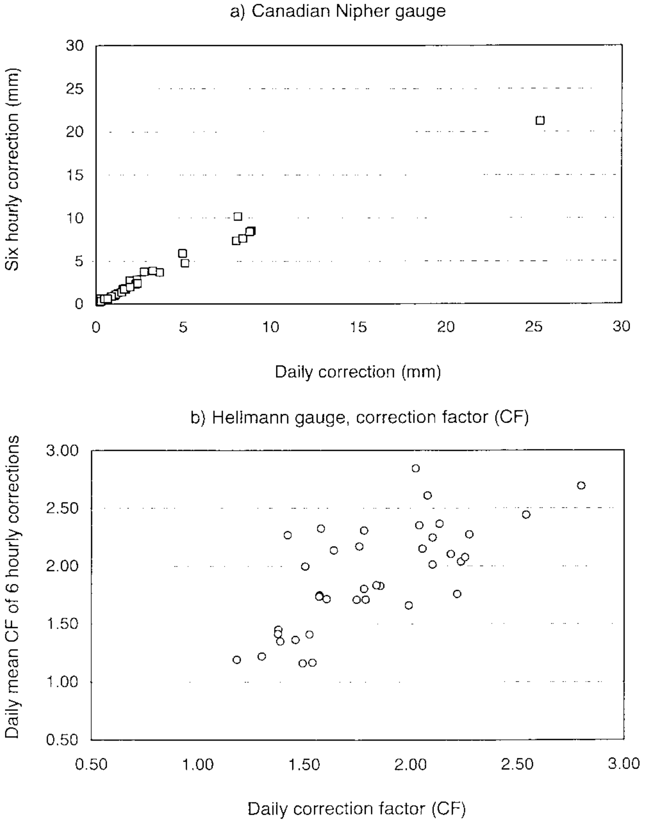

Figure 6. Comparison of daily versus 6 hourly corrections during May to July 1996 at Resolute Bay, NWT, Canada, for (a) corrected daily precipitation of Canadian Nipher gauge (in millimeters) and (b) correction factor of the Hellmann gauge.

It is interesting to compare this work to other studies. In a Greenland arctic drainage basin (76°N) water balance study, *Thomsen* [1991] estimated the annual precipitation correction factors to be 1.25–2.40; this estimation generally agreed well with our correction results (Table 3). Canada has conducted preliminary tests in applying bias correction to its digital archive data in Northwest Territories [*Metcalfe et al.*, 1994]. The results indicated that actual annual precipitation can be 50–100% greater than the gauge-measured amount in Canadian arctic regions. Table 5 gives the results of bias correction at five selected climate stations in the eastern Arctic regions of Canada. These results are compatible to the current Greenland work, since both studies used the same reference instrument (i.e., DFIR) for true snowfall estimation. It is apparent that the relative increase of annual precipitation due to the corrections were lower at the Canadian stations, regardless of the higher percentage of snowfall at these sites; this is mainly because the Hellmann gauge catches much less snow than the Canadian

Table 4. Monthly Summary of Daily Versus 6 Hourly Corrections for Canadian Nipher Gauge and Hellmann Gauge, Resolute Bay, NWT, Canada, 1996

	Mean Temp, °C	Mean Wind at 10 m, m/s	Number of Precip Days	Measured Precip, mm	Nipher Correction		Hellmann Correction Factor	
					Daily, mm	6 Hourly, mm	Daily	6 Hourly
May	−8.9	7.0	7	4.8	6.7	7.3	2.15	2.17
June	−1.0	6.4	16	53.4	74.0	72.2	1.74	1.85
July	3.3	5.6	14	30.4	39.0	39.9	1.76	1.86
Sum/mean	−2.2	6.3	37	88.6	119.7	119.4	1.82	1.91

Nipher gauge at the same wind speeds (Figure 7). This comparison therefore clearly demonstrates that discontinuity of observed precipitation data exist across national boundaries.

Efforts have been reported to produce precipitation climatologies for Greenland. *Bromwich et al.* [1998] have evaluated recent precipitation studies, including results of numerical analyses. *Thomsen* [1991] found large spatial variations of annual precipitation across Greenland: a strong latitudinal gradient, with the annual total being less than 200 mm in the extreme north and more than 1500 mm in the southeastern Greenland; and also a significant longitudinal variation, with higher precipitation at the coast and lower precipitation (200–300 mm) on the ice sheets. *Lenart* [1991] produced a precipitation map for the polar regions (north of 60°N), Greenland precipitation annual totals varied from 800 mm in the south coast to 150 mm in the northern regions. *Ohmura and Reeh* [1991] constructed new precipitation and accumulation maps of Greenland. Their results provided a higher-resolution distribution of precipitation and accumulation. The annual totals of more than 2500 mm on the southeastern tip of Greenland and about 100 mm in northern Greenland were reported; a strong longitudinal gradient in the southern Greenland was also found, with the eastern coast receiving considerably more precipitation than the west coast. The mean annual precipitation for all Greenland was estimated to be 340 mm [*Ohmura and Reeh*, 1991].

The above studies have generally revealed the basic features of precipitation distribution over Greenland, but the climatologies derived are qualitatively very different. This discrepancy may be due to different data sets and analysis methods used for the studies. For instance, *Ohmura and Reeh* [1991] used a combination of snow pits, ice core data, and climatic observations in the coast regions for their analysis, and they estimated annual precipitation on Greenland ice sheets from glacier accumulation. *Thomsen* [1991] considered biases of gauge measurements and used bias-corrected precipitation data in his work.

Ohmura and Reeh [1991] provided the climate normals of annual gauge-measured precipitation for the period of 1950s–1980s at 35 stations operated by the Danish Meteorological Institute in Greenland. In comparison to these long-term annual means, the annual precipitation for 1994 to 1997 was generally lower, perhaps indicating temporal variability of precipitation in Greenland. Given the intra-annual variation of wind, temperature, and precipitation, it is recommended to conduct the bias correction for the entire recording period on a daily timescale [*Yang and Goodison*, 1998]. However, it is also useful to estimate the magnitude of the bias correction by simplified approaches. Table 6 gives an example of such efforts. The maximum and minimum values of yearly CF derived from the daily corrections for 1994–1997 was applied to the long-term means at the selected sites in Greenland. The results indicate that the corrected long-term annual precipitation may vary from 260–280 mm for the northern regions to 3300–3600 mm for the southern coasts. These results suggest that annual precipitation in Greenland is much higher than previously reported, particularly in the southern regions of high precipitation; this may imply a greater latitudinal precipitation gradient across Greenland and also a higher mean precipitation for all Greenland. These bias correction results therefore will have a meaningful impact on water budget and glacier mass balance studies in Greenland.

Legates and Deliberty [1993] reported a general poleward increase of the percent of correction in winter seasons over the continental United States due to the increasing snowfall proportion. This study in Greenland shows the basic feature of increasing percentage of the annual correction from the south coast to the northern arctic regions. To achieve a better understanding of spatial variability of the corrections, more cli-

Table 5. Comparison of Bias Correction Between Eastern Canadian Arctic and Northern Greenland

	Eastern Canadian Arctic, 1947–1992 [*Metcalfe et al.*, 1994]								Northern Greenland, 1994–1997 (This Study)			
	Coordinate											
Station	N	W	Elevation, m	Gauge Measured, mm	Percent of Snow	P_c, mm	Mean CF	Station	Gauge Measured, mm	Percent of Snow	P_c, mm	Mean CF
Alter	82.30	62.20	62	155.5	90.0	207.7	1.37	Danmarkshavn	80.0	74.3	154.7	1.93
Eureka	79.59	85.56	10	68.0	78.5	102.6	1.51	Thule (AFB)	135.8	80.8	247.2	1.82
Resolute	74.43	94.59	67	139.8	73.0	220.2	1.58	Scoresbysund	193.8	67.6	314.0	1.62
Clyde	70.29	68.31	25	225.6	79.0	313.9	1.39	Egedesminde	195.7	61.4	292.1	1.49
Cape Dyer	66.35	61.37	393	633.6	84.0	856.8	1.35	Sondre stromfjord	97.2	52.0	133.1	1.37

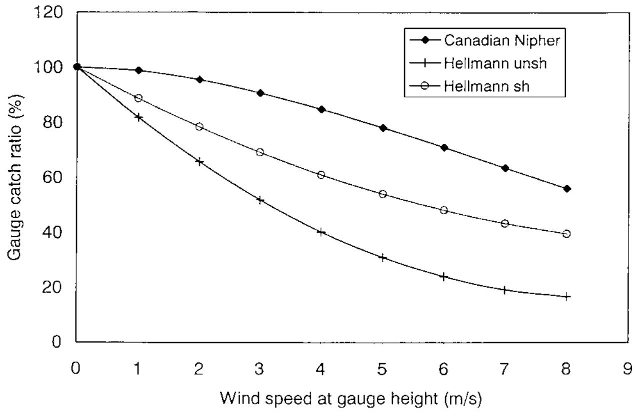

Figure 7. Comparison of the catch ratio of snow as a function of wind speed at gauge height for the Hellmann gauges and the Canadian Nipher snow gauge.

mate stations in Greenland, particularly those research stations located in central Greenland ice cap, should be involved and more years of precipitation data should be corrected. Further analysis of the corrected precipitation in the circumpolar countries is certainly necessary to evaluate the validity of the precipitation correction procedures for the polar regions. Gridded products of the corrected precipitation should also be developed for validation of the climate model simulations [*Walsh et al.*, 1998; *Kattsov et al.*, 1998].

5. Conclusion

The correction procedures derived from the WMO Solid Precipitation Measurement Intercomparison data set for the Hellmann gauge have been applied at 12 climate stations in Greenland for four test years. Biases of wind-induced undercatch, wetting loss and trace amount of precipitation were corrected on a daily basis, and the gauge-measured annual precipitation was increased significantly by 35 to 280 mm (about 25 to 90% of the gauge-measured yearly total) at the 12 stations. Of the biases in precipitation measurement, wind loss is the greatest. Wetting loss and trace amount of precipitation are also significant errors in the northern Greenland regions of low precipitation. Seasonally, the correction is greater in winter and smaller in summer due to the increased effect of wind on gauge undercatch of snowfall.

The monthly correction factors (corrected/measured precipitation) in Greenland differed from station to station. At an individual station the monthly correction factors varied by type of precipitation and by month even for the same type of precipitation, since these biases not only dependent on the wind speed but also on the wetting loss, trace amount of precipitation, and the actual gauge-measured precipitation amount. In addition, there is a considerable intra-annual variation of the magnitude of the correction, 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 further detailed analysis on 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 at gauge height on precipitation days, temperature, precipitation type, and gauge-measured amount of precipitation) for their implementation.

The WMO Solid Precipitation Measurement Intercomparison has provided new 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 (NWS) 8″ standard gauge [*Yang et al.*, 1998b], the Russian Tretyakov gauge [*Yang et al.*, 1995], and the Hellmann gauge [*Gunther*, 1993; *Yang et al.*, 1994; *Yang et al.*, 1999]. These correction procedures are recommended for test correction of the gauge-measured daily precipitation in those countries where national meteorological or hydrological station networks operate these gauges for precipitation observation. It is expected that the correction will provide reliable unbiased estimates of the true amount of precipitation for the national observational networks and the corrections will have an impact on climate monitoring. It is hoped that more effort will be made by the national meteorological services to apply the correction procedures to their archived precipitation data. It is believed that to do so will significantly improve the accuracy and homogeneity of precipitation data over large regions in the Northern Hemisphere.

Table 6. Estimated Correction of Long Term Mean Annual Precipitation at 11 Sites in Greenland

Station	Mean Annual Precipitation, mm	Range of Correction Factor		Range of Corrected Precipitation, mm		Data Period
		Min	Max	Min	Max	
Danmarkshavn	139	1.86	2.04	259	284	1951–80
Thule (AFB)	113	1.66	1.99	188	225	1951–73
Egedesminde	300	1.36	1.76	408	528	1951–80
Sondre stromfjord	151	1.31	1.43	198	216	1941–65
Holsteindborg	358	1.31	1.52	469	544	1961–80
Angmagssalik	961	1.17	1.34	1124	1288	1951–79
Godthab	734	1.24	1.52	910	1116	1951–80
Frederikshab	812	1.20	1.35	974	1096	1951–80
Narssarssuaq	607	1.20	1.29	728	783	1961–80
Julianehab	847	1.28	1.36	1084	1152	1961–80
Prins Christian Sund	2471	1.35	1.48	3336	3657	1951–79

Acknowledgments. This study would not have been possible without the co-operation of the participating countries and the many observers at the stations where the WMO Intercomparison was conducted for a number of years. The authors would also like to thank Dr. Henning Madsen and Mr. Fleming Veijen, Danish Meteorological Institute, for providing Greenland climate station and instrumental information. The authors appreciate constructive comments of two reviewers of the original manuscript.

References

Aaltonen, A., E. Elomaa, A. Tuominen, and P. Valkovuori, Measurement of precipitation, in *Proceedings of the Symposium on Precipitation and Evaporation*, vol. 1, edited by B. Sevruk and M. Lapin, pp. 42–46, Slovak Hydrometeorol. Inst. and Swiss Fed. Inst. of Technol., Bratislava, 1993.

Allerup, P., H. Madsen, and F. Veijen, A comprehensive model for correcting point precipitation, *Nord. Hydrol*., *28*, 1–20, 1997.

Benson, C. S., *Reassessment of Winter Precipitation on Alaska's Arctic Slope and Measurement on the Flux of Wind Blown Snow*, 26 pp., Geophys. Inst., Univ. of Alaska, Fairbanks, 1982.

Bromwich, D., R. Cullather, Q. Chen, and B. Csatho, Evaluation of recent precipitation studies for Greenland ice sheet, *J. Geophys. Res.*, *103*, 26,007–26,024, 1998.

Colony, R., V. Randinov, and F. R. Tanis, Measurements of precipitation and snow pack at Russian north pole drifting stations, *Polar Rec*., *34*(188), 3–14, 1998.

Desbois, M., and F. Desalmand, Past and present precipitations related to climate changes—methodologies and perspectives, *Bull. of Am. Meteorol. Soc*., *76*(7), 1173–1178, 1995.

Golubev, V., On the problem of standard conditions for precipitation gauge installation, in *Proceedings of the International Workshop on the Correction of Precipitation Measurements*, *WMO/TD-104*, pp. 57–59, World Meteorol. Organ., Geneva, 1985a.

Golubev, V. S., On the problem of actual precipitation measurements at the observation site, in *Proceedings of the International Workshop on the Correction of Precipitation Measurements*, *WMO/TD-104*, pp. 61–64, World Meteorol. Organ., Geneva, 1985b.

Golubev, V. S., P. Y. Groisman, and R. G. Quayle, An evaluation of the U.S. 8-inch nonrecording rain gage at the Valday polygon, Russia, *J. Atmos. Oceanic Technol*., *49*(5), 624–629, 1992.

Goodison, B. E., H. L. Ferguson, and G. A. McKay, Comparison of point snowfall measurement techniques, in *Handbook of Snow*, edited by D. M. Gray and M. D. Male, pp. 200–210, Pergamon, Tarrytown, N. Y., 1981.

Goodison, B. E., B. Sevruk, and S. Klemm, WMO solid precipitation measurement intercomparison: Objectives, methodology, analysis, in *Atmospheric Deposition*, *IAHS Publ. 179*, pp. 57–64, Wallingford, England, 1989.

Goodison, B. E., P. Y. T. Louie, and D. Yang, WMO solid precipitation measurement intercomparison, final report, *WMO/TD-No. 872*, 212 pp, World Meteorol. Organ., Geneva, 1998.

Goodison, B. E., and J. R. Metcalfe, The WMO solid precipitation intercomparison: Canadian assessment, in *WMO Technical Conference on Instruments and Method of Observation*, *WMO/TD-462*, pp. 221–225, World Meteorol. Organ., Geneva, 1992.

Goodison, B. E., and D. Yang, In-situ measurement of solid precipitation in high latitudes: The need for correction, in *Proceedings of the ACSYS Solid Precipitation Climatology Project Workshop*, *WMO/TD-739*, pp. 1–12, World Meteorol. Organ., Geneva, 1995.

Groisman, P. Y., and D. R. Easterling, Variability and trends of total precipitation and snowfall over the United States and Canada, *J. Clim*., *7*(1), 184–205, 1994.

Groisman, P. Y., and D. R. Legates, The accuracy of United States precipitation data, *Bull. Am. Meteorol. Soc*., *75*(2), 215–227, 1994.

Groisman, P. Y., V. V. Koknaeva, T. A. Belokrylova, and T. R. Karl, Overcoming biases of precipitation measurement: A history of the USSR experience, *Bull. Am. Meteorol. Soc*., *72*(11), 1725–1732, 1991.

Groisman, P. Y., D. R. Easterling, R. G. Quayle, and V. S. Golubev, Reducing biases in estimates of precipitation over the United States: Phase 3 adjustments, *J. Geophys. Res*., *101*, 7185–7195, 1996.

Gunther, T., German participation in the WMO solid precipitation intercomparison: Final results, in *Proceedings of the Symposium on Precipitation and Evaporation*, vol. 1, edited by B. Sevruk and M. Lapin, pp. 93–102, Slovak Hydrometeorol. Inst. and Swiss Fed. Inst. of Technol., Bratislava, 1993.

Hanssen-Bauer, I., and E. J. Forland, Homogenizing long Norwegian precipitation series, *J. Clim*., *7*(6), 1001–1013, 1994.

Karl, T. R., R. G. Quayle, and P. Y. Groisman, Detecting climate variations and change: New challenges for observing and data management system, *J. Clim*., *6*(8), 1481–1494, 1993.

Kattsov, V., V. Meleshko, and V. Govorkova, Simulations of snow/ice and ablation over Greenland and Antarctic in atmospheric models, in *Proceedings of a Meeting of Experts on Cryosphere and Climate*, edited by R. G. Barry, pp. B4.1–B4.10, *WMO/TD-867*, *WCRP-102*, World Meteorol. Organ., Geneva, 1998.

Larson, L. W., and E. L. Peck, Accuracy of precipitation measurements for hydrological modelling, *Water Resour. Res*., *10*(4), 857–863, 1974.

Legates, D. R., Precipitation measurement biases and climate change detection, in *Proceedings of the 6th Symposium on Global Change Studies*, pp. 168–173, Am. Meteorol. Soc., Boston, Mass., 1995.

Legates, D. R., and T. L. DeLiberty, Precipitation measurement biases in the United States, *Water Resour. Bull*., *29*(5), 854–861, 1993.

Legates, D. R., and C. J. Willmott, Mean seasonal and spatial variability in gauge-corrected, global precipitation, *Int. J. Climatol*., *10*, 111–127, 1990.

Lenart, W., Structural and measurement problems of arctic atmospheric water balance, in *Arctic Hydrology: Present and Future Tasks*, *Tech. Rep. 23*, pp. 37–46, Norw. Natl. Comm. for Hydrol., Oslo, 1991.

Metcalfe, J. R., and B. E. Goodison, Correction of Canadian winter precipitation data, in *Proceedings of the 8th Symposium on Meteorological Observations and Instrumentation*, pp. 338–343, Am. Meteorol. Soc., Boston, Mass., 1993.

Metcalfe, J. R., S. Ishida, and B. E. Goodison, A corrected precipitation archive for the Northwest Territories, in *Mackenzie Basin Impact Study*, interim report 2, pp. 110–117, *Proceedings of the Sixth Biennial AES/DIAND Meeting on Northern Climate*, Atmos. Environ. Serv., Yellowknife, NWT, Canada, 1994.

Milkovic, J., Preliminary results of the WMO field intercomparison in Yugoslavia, in *Proceedings of the International Workshop on Precipitation Measurement*, Swiss Fed. Inst. of Technol., St. Moritz, 1989.

Ohmura, A., and N. Reeh, New precipitation and accumulation maps for Greenland, *J. of Glaciol*., *37*(125), 140–148, 1991.

Sevruk, B., Method of correction for systematic error in point precipitation measurement for operational use, *WMO-589*, 91 pp, World Meteorol. Organ., Geneva, 1982.

Sevruk, B., Method of correction for systematic error in point precipitation measurement for operational use: Corrections in Switzerland, in *Proceedings of the Symposium on Precipitation and Evaporation*, vol. 1, edited by B. Sevruk and M. Lapin, pp. 155–159, Slovak Hydrometeorol. Inst. and Swiss Fed. Inst. of Technol., Bratislava, 1993.

Sevruk, B., and W. R. Hamon, International comparison of national precipitation gauges with a reference pit gauge, *WMO Instrum. Obs. Meth. Rep. 17*, 111 pp., World Meteorol. Organ., Geneva, 1984.

Sevruk, B., and S. Klemm, Types of standard precipitation gauges, in *Proceedings of the Workshop on Precipitation Measurements*, edited by B. Sevruk, pp. 227–236, World Meteorol. Organ., Geneva, 1989.

Tabler, R. D., N. H. Berg, D. C. Trabant, H. S. Santeford, and P. A. Rechard, Measurement and evaluation of winter precipitation, in *Cold Regions Hydrology and Hydraulics*, edited by W. L. Ryan and R. D. Crissman, pp. 9–38, Am. Soc. of Civ. Eng., Reston, Va., 1990.

Thomsen, T., Arctic hydrology in Greenland-permafrost hydrology and data technology, in *Arctic Hydrology: Present and Future Tasks*, *Tech. Rep. 23*, Norw. Natl. Comm. for Hydrol., 1991.

UNESCO, *World Water Balance and Water Resources of the Earth (WWB)* (in Russian), 638 pp., Gidrometeoizdat, St. Petersburg, Russia, 1974. (Engl. Transl., 1978)

Walsh, J. E., V. Kattsov, D. Portis, V. Meleshko, Arctic precipitation and evaporation: Model results and observational estimates, *J. Clim*., *11*(1), 72–87, 1998.

Woo, M. K., and P. Steer, Measurement of trace rainfall at a high arctic site, *Arctic*, *32*(1), 80–84, 1979.

World Meteorological Organization (WMO)/CIMO, International Organizing Committee for the WMO Solid Precipitation Measurement Intercomparison, final report of the first session, *WMO Rep*., 31 pp., World Meteorol. Organ., Geneva, 1985.

World Meteorological Organization (WMO)/CIMO, International Organizing Committee for the WMO Solid Precipitation Measurement

Intercomparison, final report of the sixth session, *WMO Rep.*, 140 pp., World Meteorol. Organ., 1993.

Yang, D., and B. E. Goodison, Comment on "Reducing biases in estimates of precipitation over the United States: Phase 3 adjustments" by P. Y. Groisman et al., *J. Geophys. Res.*, *103*, 6221–6227, 1998.

Yang, D., J. R. Metcalfe, B. E. Goodison, and E. Mekis, An evaluation of the double fence intercomparison reference gauge, in *Proceedings of the Eastern Snow Conference*, pp. 105–111, Quebec City, Quebec, Canada, 1993.

Yang, D., B. Sevruk, E. Elomaa, V. Golubev, B. Goodison, and T. Gunther, Wind-induced error on snow measurement: WMO Intercomparison Results, paper presented at the International Conference on Alpine Meteorology, Lindau, Germany, pp. 61–64, 1994.

Yang, D., et al., Accuracy of Tretyakov precipitation gauge: Results of WMO Intercomparison, *Hydrol. Process.*, *9*(8), 877–895, 1995.

Yang, D., B. E. Goodison, J. R. Metcalfe, V. S. Golubev, R. Bates, T. Pangburn, and C. L. Hanson, Accuracy of NWS 8-inch standard non-recording precipitation gauge: Result of WMO Intercomparison, *J. Atmos. Oceanic Technol.*, *15*(2), 54–68, 1998a.

Yang, D., B. E. Goodison, C. B. Benson, and S. Ishida, Adjustment of daily precipitation at 10 climate stations in Alaska: Application of WMO Intercomparison results, *Water Resour. Res.*, *34*(2), 241–256, 1998b.

Yang, D., E. Elomaa, B. Goodison, T. Gunther, V. Golubev, B. Sevruk, H. Madsen, and J. Milkovic, Wind-induced precipitation undercatch of the Hellmann gauges, *Nord. Hydrol.*, *30*(1), 23–31, 1999.

S. Ishida and B. Goodison, Climate Research Branch, Atmospheric Environment Service, Downsview, Ontario, M3H 5T4, Canada.

T. Gunther, German Weather Service, Berlin, Germany.

D. Yang (corresponding author), Inst. for Global Change Research, SEAVANS Building North, 7th floor, 1-2-1 Shibaura, Minato-ku, Tokyo 105-6791, Japan. (dyang@frontier.esto.or.jp)

(Received June 26, 1998; revised October 27, 1998;
accepted December 3, 1998.)