Accuracy of NWS 8″ Standard Nonrecording Precipitation Gauge: Results and Application of WMO Intercomparison

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(Manuscript received 21 December 1995, in final form 1 August 1996)

ABSTRACT

The standard 8″ nonrecording precipitation gauge has been used historically by the National Weather Service (NWS) as the official precipitation measurement instrument of the U.S. climate station network. From 1986 to 1992, the accuracy and performance of this gauge (unshielded or with an Alter shield) were evaluated during the WMO Solid Precipitation Measurement Intercomparison at three stations in the United States and Russia, representing a variety of climate, terrain, and exposure. The double-fence intercomparison reference (DFIR) was the reference standard used at all the intercomparison stations in the Intercomparison project. The Intercomparison data collected at different sites are compatible with respect to the catch ratio (gauge measured/DFIR) for the same gauges, when compared using wind speed at the height of gauge orifice during the observation period.

The effects of environmental factors, such as wind speed and temperature, on the gauge catch were investigated. Wind speed was found to be the most important factor determining gauge catch when precipitation was classified into snow, mixed, and rain. The regression functions of the catch ratio versus wind speed at the gauge height on a daily time step were derived for various types of precipitation. Independent checks of the equations have been conducted at these intercomparison stations and good agreement was obtained. Application of the correction procedures for wind, wetting loss, and trace amounts was made on a daily basis at Barrow, Alaska, for 1982 and 1983, and, on average, the gauge-measured precipitation was increased by 20% for rain and 90% for snow.

1. Introduction

Systematic errors (biases) in precipitation measurement, notably those caused by wind and those attributable to wetting and evaporation loss (Goodison et al. 1981), have long been recognized as affecting all types of precipitation gauges. The need to correct these systematic errors, especially those affecting 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 (Groisman and Easterling 1994; Groisman et al. 1991).

In 1985, the World Meteorological Organization (WMO) initiated the Solid Precipitation Measurement Intercomparison (WMO/CIMO 1985). The goal of the project was to assess national methods of measuring solid precipitation against methods whose accuracy and reliability were known, including past and current procedures, automatic systems, and new methods of observation (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

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precipitation measurement for general use to calibrate any type of precipitation gauge (Goodison et al. 1994).

The reference method for snowfall measurement was extremely critical in this intercomparison. After reviewing all possible practical methods (bush shield, double-fence shield, forest clearing, snow board, dual gauge system) of measuring ‘‘true’’ snowfall in a range of climatic conditions, the WMO Organizing Committee for the Intercomparison designated the reference to be the octagonal vertical double fence intercomparison reference (DFIR) (Goodison et al. 1981; Goodison et al. 1989), surrounding a shielded Tretyakov gauge. The DFIR was operated at 19 stations in 10 countries around the world during the study.

The U.S. standard 8″ nonrecording gauge has been used throughout the life of the National Weather Service (NWS) as the official precipitation measuring instrument at climatological stations (U.S. Department of Commerce 1963). Today, this gauge is still widely used at 7500 locations in the United States (Golubev et al. 1992) and at about 1340 stations in other countries such as the Bahamas, Bangladesh, Saudi Arabia, Thailand, and the Philippines (Sevruk and Klemm 1989). The NWS 8″ standard gauge consists of three parts: the 8-in. (20.32 cm) receiver or funnel, the 8-in. overflow receptacle, and the measuring tube whose orifice area is one-tenth the area of the receiver, that is, a diameter of 2.53 in. (6.43 cm). Rainfall collected by the receiver funneling into the tube is measured by inserting a graduated dipstick into the storage tube. The receiver and measuring tube are removed in the snow season. Snowfall is collected in the overflow receptacle, melted, poured into the measuring tube, and measured just as if it were rainfall (National Weather Service 1989). Relatively few of the NWS 8″ standard gauges in the U.S. network are currently equipped with (Alter) wind shields, although it has been documented that an Alter shield can increase the catch of solid precipitation by tens of percent and rainfall by several percent (Larkin 1947; Larson and Peck 1974). Since 1940, the number of Alter-shielded gauges at U.S. Weather Bureau stations has been reduced from about 500 to less than 200 now (Karl et al. 1993a,b). The combination of precipitation records from shielded gauges with those from unshielded gauges results in inhomogeneous precipitation time series and leads to incorrect spatial interpretations. Thus, use of such data for climatological and hydrological studies could be misleading.

Many studies on the performance of the NWS 8″ standard gauge have been done since the 1940s (Larkin 1947; Black 1954; Larson and Peck 1974; Golubev et al. 1992; Groisman and Easterling 1994). From 1972 to 1976, the NWS 8″ standard gauge was tested in the International Rainfall Comparison of National Precipitation Gauges with a Reference Pit Gauge (Sevruk and Hamon 1984). Benson (1982) looked at the ability of this gauge to measure snowfall in Alaska, using a Wyoming shielded gauge and snow surveys on arctic slopes as the references. Recently, Golubev et al. (1992) reported some results of intercomparison data collected during the rainfall period of 1966–69 at the Valdai Hydrological Research Station in Russia. Legates and DeLiberty (1993) and Groisman and Easterling (1994) corrected U.S. gauge measurements on a monthly basis by using monthly wind speed and air temperature to estimate correction factors.

This study extends previous studies to other climatic regions. Based on data compiled from three stations where the NWS 8″ standard gauge and the DFIR were operated, this study compares the accuracy of the NWS 8″ standard gauge measurements with those of the designated standard reference (DFIR) for rain, snow, and mixed precipitation.

2. Sites and data sources

Intercomparison data collected at three WMO intercomparison stations have been used in this study.

a. Reynolds Creek experimental watershed

The Reynolds Creek, Idaho, site (43°12′N, 116°45′W; 1193 m ASL) is located on a gently sloping, sagebrush-covered rangeland surrounded by rangeland and irrigated hay fields. In October 1987, the bellowing gauges were installed for the intercomparison: DFIR at 3 m; Tretyakov gauge at 2 m; two Universal recording gauges at 1.30 m with the Wyoming shield and Alter shield, respectively; Canadian Nipher gauge at 2 m; dual gauge system (Larson 1972) at 3.05 m, and one NWS 8″ standard gauge without an Alter shield at 1 m (see photographs in Fig. 1). All the manual gauges and their contents were weighed to eliminate the wetting losses. Temperature, humidity, wind speed at 2 and 9.14 m, and wind direction at the higher level were recorded (Fig. 2a). Daily intercomparison data from November 1987 to March 1993 are analyzed in this study.

b. Valdai Hydrological Research Station in Russia (57°59′N, 33°15′E; 194 m ASL)

It is situated on the flat shore of Valdai Lake. For the WMO Intercomparison project, the Tretyakov gauge, Canadian Nipher snow gauge, and Hellmann gauge (see photographs in Fig. 1) were studied at this site, using the DFIR and the ‘‘bush gauge’’ for comparison (Golubev et al. 1992). Approximately 300 m from the open site is the bush gauge (Tretyakov gauge with a wind shield) placed in 2–4-m-high shrubs in a 3-ha area. Within the 12-m-diameter working area of the bush gauge the shrubs are cut routinely to the gauge orifice height of 2 m. This gauge has been accepted as the working reference for winter precipitation measurement at this station since 1970 because wind-induced errors are reduced to near zero by both the surrounding bush and the Tretyakov wind shield.

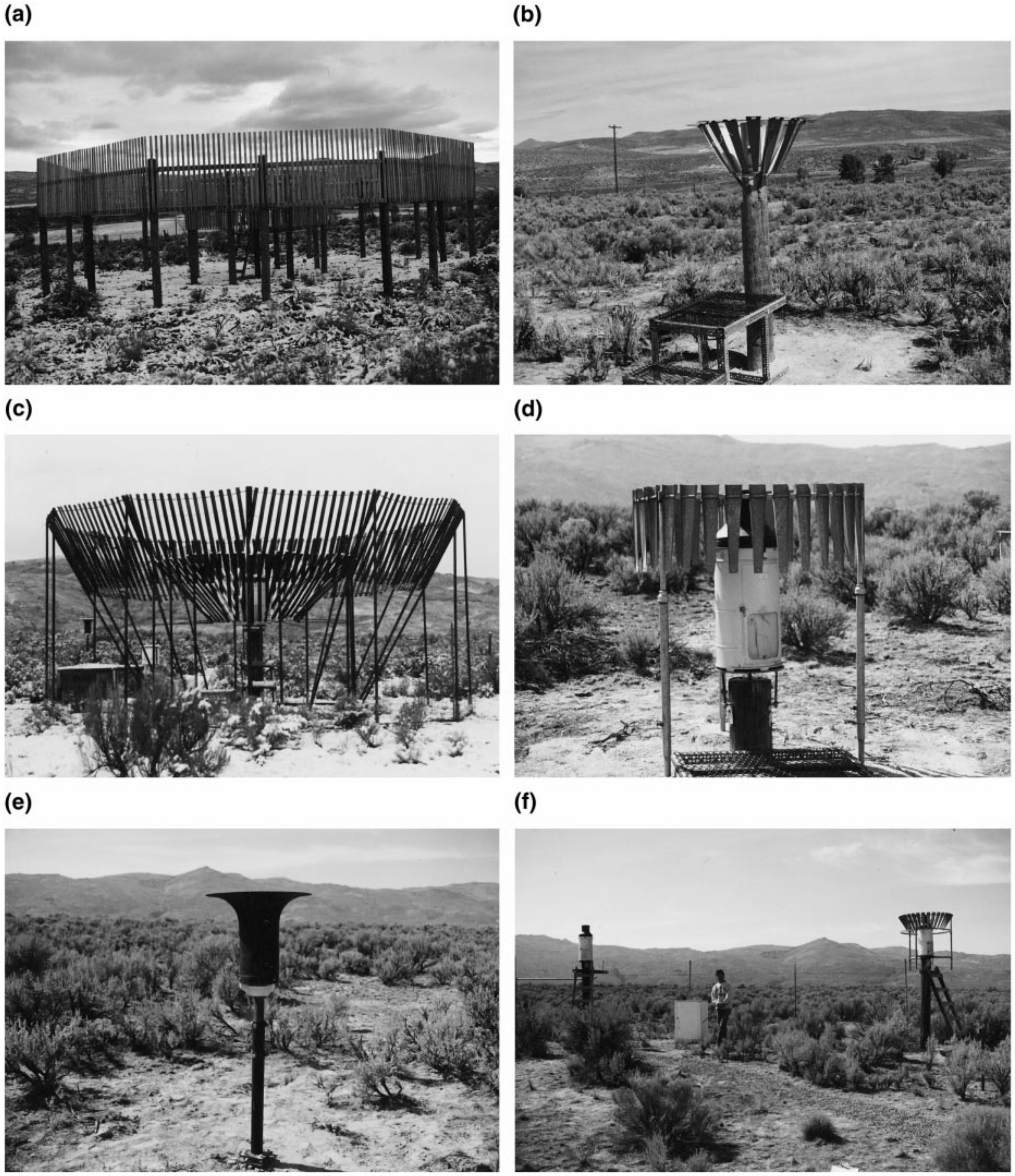

FIG. 1. Photographs of various gauges and wind shields. (a) DFIR; (b) Tretyakov gauge; (c) Wyoming shield with Universal recording gauge; (d) Alter shield with universal recording gauge; (e) Canadian Nipher snow gauge; (f) Dual-gauge measuring system (bridled shield and unshielded universal recording gauges); (g) NWS 8″ nonrecording gauge, with the rainfall collector off as used for snowfall measurement; and (h) Hellmann gauge.

In the fall of 1991, two NWS 8″ standard gauges, one with an Alter shield and the other without, were installed with their orifices 1 m above the ground, which is the standard height for this gauge in the U.S. station network. The gauges both in the open and bush sites at Valdai were measured at 0800 and 2000 LT (local time). The contents of the Tretyakov gauges were both weighed and measured volumetrically to determine the

FIG. 1. (*Continued*)

precipitation amount, and over a period of time an average wetting loss was determined. For the NWS 8″ standard gauge at Valdai, the volumetric method was used for the measurements. Wind speed and direction (at 3-m height), atmospheric pressure, air temperature, and humidity were also recorded (Fig. 2b). The daily intercomparison data from October 1991 to March 1993 are used in this study.

c. Sleepers River research watershed

The townline station (44°29′N, 72°10′W; 552 m ASL) in the watershed north of Danville, Vermont, was established in 1967 as part of a cooperative snow hydrology project (Johnson and Anderson 1968). The site is very flat, slightly sloping to the south. The station was located near the eastern edge of a 6-ha clearing. To the west, forest is about 185 m from the center of the study site with the first 75 m being generally free of vegetation protruding from the winter snowcover and beyond that having scattered clumps of small conifers. It is about 60 m from the center of the site to the forest in both a northeasterly and southeasterly direction. The prevailing winds in winter are from a westerly direction. During the snow seasons of December 1986 to March 1992, a DFIR at 3 m, a Tretyakov gauge at 3 m, Alter-shielded and unshielded Universal recording gauges, respectively, and an Alter-shielded NWS 8″ standard gauge at 1.83 m were operated for the Intercomparison project (Bates et al. 1987). For the manual gauges, the contents were melted and poured into a glass graduate for measurement. The U.S. NWS 8″ standard gauge was measured according to the method outlined above. Temperature, wind speed, and wind direction were measured at 3 m (Fig. 2c). Daily intercomparison data for the period of December 1986 to April 1992 are used in this study.

In the WMO Intercomparison project, the type of precipitation was described as snow only (S), snow with rain (SR), rain with snow (RS), freezing rain (ZR), and rain only (R) (WMO/CIMO 1985). Additional meteorological measurements were also made at the intercomparison stations. All data collected were quality controlled by each participant before being submitted to the Atmospheric Environment Service, Environment Canada, for archiving in a digital database in a common format (WMO/CIMO 1985). The digitized data were reviewed and quality controlled by the participants before use in this study and in the final report to WMO.

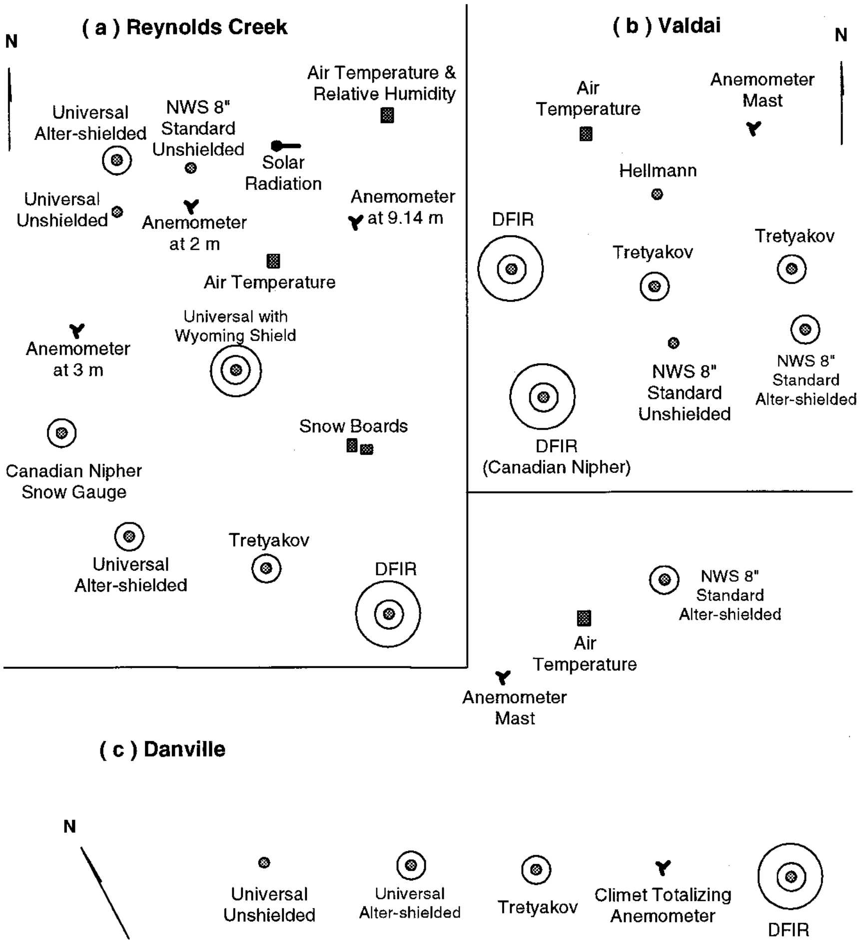

FIG. 2. Layout of precipitation gauges and other instruments at WMO intercomparison sites. (a) Reynolds Creek, (b) Valdai, and (c) Danville.

3. Data analysis

Before analyzing the catch of any national precipitation gauge in the WMO project, one must consider wetting loss, evaporation loss, undercatch of the DFIR, the effect of blowing snow on gauge measurement, and adjustment of wind speed to gauge height (if wind was measured at some other height).

Wetting loss refers to the rain or water from melted snow subject to evaporation from the surface of the inner walls of the precipitation gauge after a precipitation event and the water that remains in the gauge container after its emptying (WMO/CIMO 1993). It is not easy to quantitatively determine the first portion of the error, and this study focuses on the second portion, for example, retention (Goodison 1977) only. Wetting losses can contribute significantly to the undermeasurement of precipitation (Metcalfe and Goodison 1993). They are gauge-specific and vary by precipitation type and the number of times the gauge is emptied (Sevruk 1982; Golubev et al. 1992; Elomaa 1993; Goodison and Metcalfe 1992). Based on wetting loss experiments, the average wetting loss of the NWS 8″ standard gauge was determined to be 0.03 mm per observation for rainfall measurement when the gauge is equipped with the funnel and the measuring tube (Golubev et al. 1992). In the snow season when the gauge is operated without the funnel and the measuring tube, the average wetting loss was estimated to be as high as 0.15 mm per observation for snow and mixed precipitation (Sevruk 1982).

Correction for wetting loss must be applied to the intercomparison data before further analysis (WMO/CIMO 1993). In this study, correction for wetting loss was done according to the type of precipitation for both the Tretyakov and NWS 8″ standard gauges at Valdai and Danville, by adding the daily total wetting loss (number of observations per day multiplied by average wetting loss per observation) to the measured daily precipitation. Wetting loss correction was not required for Reynolds Creek data since the gauge content was weighed at this site.

Evaporation loss is the water lost by evaporation before the observation is made. Unlike weighing recording gauges, no evaporation suppressant, such as light oil, is used in the manual gauge to minimize the evaporation loss. As for wetting loss, average daily evaporation loss varied by gauge type and time of the year. Losses in summer of 0.30–0.80 mm day^{-1} and winter of 0.10–0.20 mm day^{-1}, respectively, for the Tretyakov gauge were measured at Jokioinen in Finland (Aaltonen et al. 1993). An evaporation experiment at Valdai with the NWS 8″ standard gauge showed that the loss for rainfall was so small, for example 0.008 mm h^{-1}, that it could be neglected (Golubev et al. 1992).

Ideally, evaporation loss should be corrected before gauge catch analysis. However, because of its strong dependence on weather conditions, timing of precipitation compared to observation time and seasonal change that can be very site dependent, it was not possible to estimate the daily evaporation loss at some intercomparison stations by using the average amount obtained from the Russian and Finnish experimental sites. Therefore, no correction was made for the potential daily evaporation loss from the NWS 8″ standard gauge and the DFIR.

The DFIR is considered as a secondary reference standard. At the moment, there is no accepted primary reference for measuring solid precipitation, but a gauge located in bushes that are kept cut to the height of the gauge orifice is one reference method deemed to provide a measurement close to ‘‘true’’ (WMO/CIMO 1985). Yet sites such as Valdai are not universally available; hence, a secondary reference had to be chosen for the intercomparison. The need to adjust the DFIR measurement to the true value of the bush gauge for the effect of wind was discussed by Golubev (1986, 1989), since a comparison of DFIR and the bush gauge data at Valdai, Russia, indicated a systematic difference between the primary and secondary standards. Further to Golubev’s analysis, Yang et al. (1993) analyzed the long-term precipitation and meteorological observations from Valdai and found that blowing snow occurred during one-third of the snow events when measured precipitation was greater than 3.0 mm. Even after eliminating the blowing snow events, the bush gauge still measured more snow than the DFIR. Hence, adjustment of the DFIR measurement was necessary to provide a best estimate of the ‘‘true point precipitation.’’ Regression analysis of 52 events indicated that the most statistically significant factor for correcting the DFIR was the wind speed (at the gauge height of 3 m) during the storm. Equations for correcting the DFIR measurements to ‘‘bush gauge’’ values were developed for the different types of precipitation; it was recommended by the WMO Organizing Committee of the Intercomparison (WMO/CIMO 1993) that these equations should be applied to all DFIR data before analyzing the catch of national gauges with respect to the DFIR. All DFIR measurements have been corrected at the three WMO sites to derive the best standard reference of precipitation for this study.

Blowing snow conditions are a special case when correcting the DFIR data and when assessing catch relationships between gauges. Although the flux of blowing snow decreases with height, 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 (e.g., the NWS 8″ standard gauge at 1 m), which are efficient in collecting snow passing over their orifice. Blowing snow events in the intercomparison data were carefully identified and eliminated from further analysis, such as catch versus wind speed.

For sites where wind speed was not measured at the height of the precipitation gauge, it was estimated from measurements at higher heights. To estimate daily wind speed from a standard height (e.g., 10 m) to the height of the gauge orifice, for example, the DFIR at 3 m and the NWS 8″ standard gauge at 1 m and 1.83 m, the following logarithmic wind profile was used:

$$U(h) = \frac{[\ln(h/z_0)]}{[\ln(H/z_0)]}U(H), \tag{1}$$

where $U(h)$ is the estimated daily wind speed (m s^{-1}) at the gauge orifice, $U(H)$ is the measured daily wind speed (m s^{-1}), h and H are the heights (m) of the gauge and the anemometer, and z_0 is the roughness parameter (m). 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. The need to estimate wind speed at gauge height when a wind measurement is not available can introduce a small increase in scatter in the derived relationship, but it is more important to use wind values for the height of the gauge rather than wind from some other height. This allows data from different sites with same gauge at different heights to be combined and analyzed as one dataset.

In summary, at all the intercomparison sites, the DFIR was installed and operated according to the same procedures (WMO/CIMO 1985), resulting in a common standard at all the intercomparison sites; national gauges were operated according to the national procedure defined by that country. The DFIR measurements at the intercomparison stations were adjusted to the true precipitation using the same equations. Finally, when it was necessary to estimate daily wind speed at gauge height from wind measurements at different heights at the site, it was done using the same wind-profile technique. Thus, the intercomparison data collected from different sites are compatible in terms of the catch ratio (measured precipitation/true) for the same gauge, when wind speed at the gauge height is used in analysis.

TABLE 1. Summary (total and percentage of the DFIR) of daily observed precipitation for the NWS 8″ standard gauge (with an Alter shield or unshielded) at Valdai, Reynolds Creek, and Danville WMO Intercomparison stations.

Type of precipitation	Number of events (Day)	T_{max} (°C)	T_{min} (°C)	Ws(@ 3 m) m s^{-1}	DFIR	NWS 8″ measured	
						Alter	Unshielded
(a) Valdai WMO site, October 1991 to March 1993							
Snow	154	−4.1	—	3.8	357.4 mm	248.8 mm	156.5 mm
					100.0%	69.6%	43.8%
Mixed	73	0.7	—	4.5	463.9 mm	361.4 mm	303.4 mm
					100.0%	77.9%	65.4%
Rain	108	10.0	—	3.6	434.5 mm	400.8 mm	386.0 mm
					100.0%	92.2%	88.8%
All	335	2.2	—	4.0	1255.8 mm	1011.0 mm	845.9 mm
					100.0%	80.5%	67.4%
(b) Reynolds Creek WMO site, November 1987 to March 1993							
Snow	50	2.6	−6.7	2.5	87.3 mm	—	75.3 mm
					100.0%	—	86.3%
Mixed	27	7.3	−2.8	3.8	100.7 mm	—	86.6 mm
					100.0%	—	86.0%
Rain	36	9.1	−0.3	2.8	183.4 mm	—	170.2 mm
					100.0%	—	92.8%
All	113	6.3	−3.3	3.0	371.4 mm	—	332.1 mm
					100.0%	—	89.4%
(c) Danville WMO site, December 1986 to April 1992							
Snow	158	−2.2	−11.6	1.5	1051.3 mm	1018.4 mm	—
					100.0%	96.9%	—
Mixed	21	2.1	−8.6	1.0	650.8 mm	624.8 mm	—
					100.0%	96.0%	—
Rain	22	6.4	−1.6	1.1	291.1 mm	279.5 mm	—
					100.0%	96.0%	—
All	201	−2.6	−3.0	1.2	1993.2 mm	1922.7 mm	—
					100.0%	96.5%	—

4. Results

The average catch ratio of the NWS 8″ standard gauge to the corrected DFIR value for true precipitation varied by the type of precipitation, wind shield, and mean daily wind speed on days with precipitation.

Table 1 gives the total measured precipitation and the average catch ratio (measured/corrected DFIR) for the shielded and unshielded NWS 8″ standard gauges for different types of precipitation at the 3 WMO sites. Precipitation was classified as snow, mixed, and rain. Intercomparison results at Jokioinen, Finland, produced a very good agreement for rainfall measured by the DFIR and the pit gauge (accepted WMO standard for rainfall measurement) in a number of different seasons. Hence, the DFIR was accepted as a reference for rainfall measurement in this study since most of the WMO sites either did not have a pit gauge or did not operate it in winter.

At Valdai and Reynolds Creek, the average catch ratio for the NWS 8″ standard gauge is less for snow than for rain. The average value of the catch ratio can be very misleading, however, since all storms are weighted equally, irrespective of wind speed, precipitation amount, or other environmental conditions. Valdai, which had extensive observing programs during a long ‘‘winter’’ period and even into the summer, exhibited the ‘‘expected’’ decrease in the catch ratio from rain to snow. At some of the WMO sites, such as Danville, the average catch ratios of the Alter-shielded NWS 8″ standard gauge varied little by precipitation type because of the very low average wind speeds on precipitation days. In some cases, mixed precipitation has a lower average catch than snow (e.g., Reynolds), but the mean wind speed was greater during these events, so this result is not unexpected.

The beneficial effect of using a wind shield, the Alter shield in this case, on gauge catch is clearly shown by the difference between the average catch ratios of the shielded and the unshielded gauges at Valdai. The difference between catch ratios, ranging from 26% for snowfall to 3% for rainfall, clearly indicates the positive benefits of using a wind shield for snow and mixed precipitation measurements. Overall, the shielded NWS 8″ standard gauge caught 13% more precipitation, when compared to the DFIR, than its unshielded counterpart at Valdai.

Studies have shown that gauge catch of precipitation, depending on both the environmental factors and the precipitation features, such as rainfall rate (Sevruk 1982) and falling snow crystal type (Goodison et al.

1981), can vary with each individual precipitation event. To investigate the dependence of the NWS 8″ standard gauge catch on environmental factors, daily data from the three WMO intercomparison stations were analyzed. One must be very careful when analyzing ratios and differences between gauges. Small absolute differences of measurement between the NWS 8″ standard gauge and DFIR could create significant large variations in the catch ratios (e.g., a 0.2-mm difference of NWS 8″ standard gauge versus DFIR with a DFIR catch of 1 mm gives a ratio of 80% versus 96% for a 5-mm precipitation event). To minimize this effect, the daily totals, when the DFIR measurement was greater than 3.0 mm, were used in the statistical analysis. The results confirm that wind speed is the only important factor for the gauge catch when precipitation is classified as snow, mixed, and rain. A regression of the daily gauge catch ratio (R, %) for the shielded and unshielded NWS 8″ standard gauge as a function of the daily wind speed (Ws, m s^{-1}) at gauge height gave the best-fit regression equations for the different types of precipitation as follows.

- Snow

$$R_{\text{Alter shield}} = \exp(4.606 - 0.036 \times \text{Ws}^{1.75}), \quad (n = 108,\ r^2 = 0.72). \tag{2}$$

$$R_{\text{Unshielded}} = \exp(4.606 - 0.157 \times \text{Ws}^{1.28}), \quad (n = 55,\ r^2 = 0.77). \tag{3}$$

- Mixed precipitation

$$R_{\text{Alter shield}} = 101.04 - 5.62 \times \text{Ws}, \quad (n = 75,\ r^2 = 0.59). \tag{4}$$

$$R_{\text{Unshielded}} = 100.77 - 8.34 \times \text{Ws}, \quad (n = 59,\ r^2 = 0.37). \tag{5}$$

- Rain

$$R_{\text{Alter shield}} = \exp(4.606 - 0.041 \times \text{Ws}^{0.69}), \quad (n = 64,\ r^2 = 0.18). \tag{6}$$

$$R_{\text{Unshielded}} = \exp(4.605 - 0.062 \times \text{Ws}^{0.58}), \quad (n = 64,\ r^2 = 0.27). \tag{7}$$

Figure 3 shows the daily catch ratio for the NWS 8″ standard gauge versus daily wind speed at gauge height. A wide range of both wind speed and catch ratio has been sampled using the combined intercomparison dataset in a variety of climatic regions; hence, the correction procedures derived from these data are more likely to be successfully used for a wide range of environmental conditions. In Fig. 3a, a number of high catch ratios close to 120% appeared at lower wind speeds at Danville. Investigation indicated that these were wet snow events occurring at temperatures near the freezing point. It was quite possible the Tretyakov gauge orifice capped during large wet snow events since its orifice area was smaller than that of the NWS 8″ standard gauge and an internal rim in the gauge allowed snow, particularly wet snow, to build up and cap the gauge.

It is clear from Fig. 3 that 1) the NWS 8″ gauge catch decreased with increasing wind speed for all types of precipitation, and especially for snowfall; 2) for the same wind speed the undercatch of the gauge was always greater for snow than for rain or mixed precipitation; and 3) the difference in the catch ratios between the Alter-shielded and unshielded gauges for rainfall measurement was only about 2%–3%, while for snowfall measurement the shielded gauge caught considerably more than the unshielded gauge (e.g., at wind speed of 5 m s^{-1}, the shielded and unshielded gauges recorded 55% and 29%, respectively, of the true snowfall).

One method to check the performance of the correction equations (2)–(7) for the NWS 8″ standard gauge was to correct all of the intercomparison data (without the DFIR greater than 3.0-mm limitation) at Valdai, Danville, and Reynolds Creek. The catch ratio R was converted to the correction factor K by

$$K = 1/R,$$

hence

$$P_t = KP_m, \tag{8}$$

where P_m is gauge-measured precipitation including the wetting loss, and P_t is the calculated true precipitation estimate. The improvement in the NWS 8″ standard gauge measurements after correcting for wetting and wind-induced errors is shown in Table 2. For snow data, the differences between the corrected precipitation of the Alter-shielded NWS 8″ standard gauge and the true value of the adjusted DFIR is within 3%–6%, for both rain and mixed precipitation, the difference is less than 2%. For the unshielded NWS 8″ standard gauge, the deviations are slightly larger, ranging from 5% to 10% for snow, 3% to 6% for the mixed, and 0% to 2% for rain.

The t test was used on the snow data at Valdai to check the improvement of the correction on the gauge-measured amounts. The results indicate a statistically significant ($\alpha < 0.05$) difference between the gauge-measured and the corrected snow data, and the results also show a statistically significant ($\alpha < 0.05$) agreement of the corrected gauge measurements to the estimated true snow of the DFIR. It is clear that applying a correction for wind-induced error and wetting loss to gauge measurement of snowfall is necessary to obtain the true snowfall. Given the statistically significant difference between the measured and corrected precipitation, particularly for solid and mixed precipitation at all of the WMO sites, the authors feel that these correction equations work well at the intercomparison stations and that they should be used for correcting the daily mea-

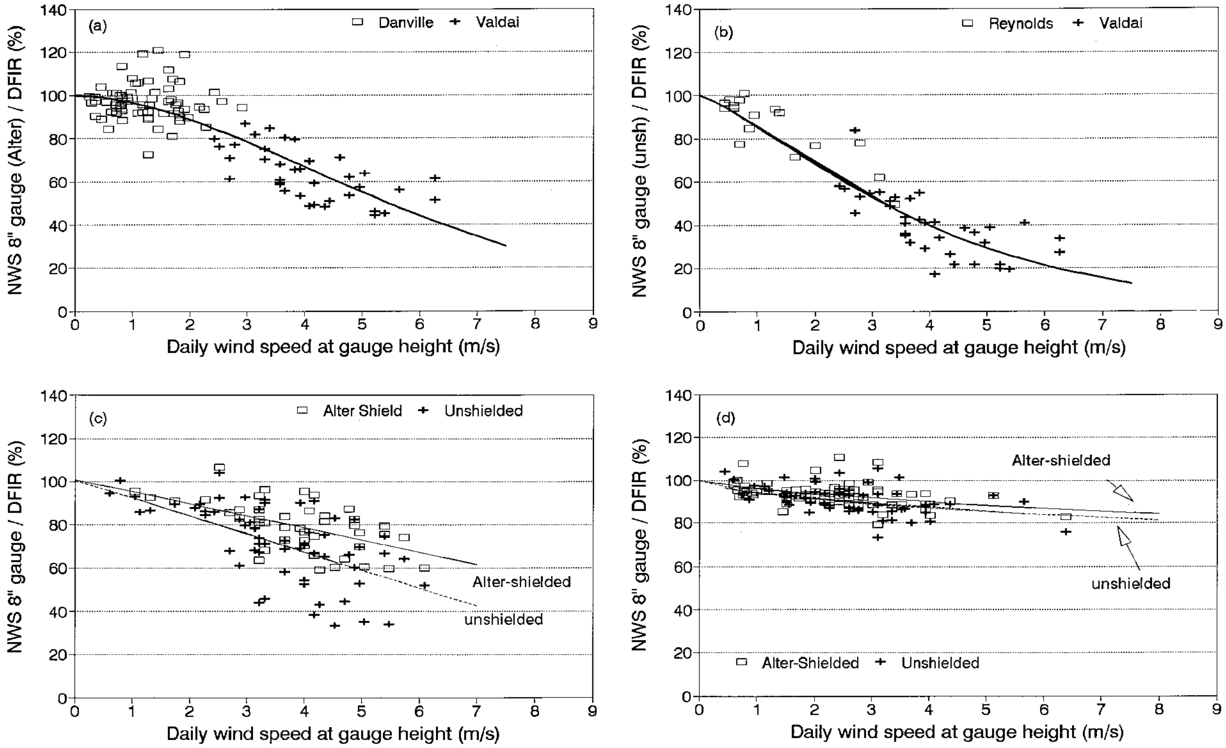

FIG. 3. Daily catch ratio (%) of the NWS 8″ nonrecording gauge to the DFIR as a function of daily wind speed (m s^{-1}) at the gauge height for (a) Alter shielded, snow; (b) unshielded, snow; (c) Alter shielded and unshielded, mixed precipitation; and (d) Alter shielded and unshielded, rain.

sured precipitation at stations where the NWS 8″ standard gauge is used.

5. Application of results to Barrow, Alaska

A better test of the applicability of the corrections proposed is to correct station data and assess the corrected values against other measurements and studies. Barrow (71°18′N, 156°47′W; 9.5 m ASL) is the most northerly first-order station operated by the National Weather Service since 1901. The climate normals of temperature, precipitation, snowfall for the past 30 years, and the mean wind speed for 1982 and 1983 are given in Table 3.

According to the Local Climatological Data (monthly summary) for Alaska, an Alter-shielded NWS 8″ standard gauge was used at Barrow station in 1982 and 1983. To conduct the corrections, the daily data of temperature, wind speed, precipitation, snowfall, snow depth on the ground, and the weather code at Barrow for 1982 and 1983 were obtained from the U.S. National Climatic Data Center.

Classifying the type of precipitation is necessary in order to apply the best correction for wetting loss and wind-induced errors. At Barrow, type of precipitation was classified into snow, mixed, and rain by checking both the weather code (which provided the information on type of precipitation) and the records of new snow on the ground.

Corrections on the gauge-measured precipitation P_g have been made for trace precipitation ΔP_t, wetting losses ΔP_w, and wind-induced errors. Since the wind-induced error caused by the wind field deformation over gauge orifice affects the total gauge catch including the wetting loss, we modified the general model (Sevruk and Hamon 1984) for gauge-measured precipitation correction to

$$P_c = K(P_g + \Delta P_w) + \Delta P_t, \quad (9)$$

where P_c is the corrected precipitation and K is the wind-loss correction coefficient (usually $K \geq 1$). The method of determining each of the terms in Eq. (9) is given below (Table 4).

a. Trace precipitation

For the NWS 8″ standard gauge, a measurement of precipitation of less than 0.005 in. (0.127 mm) is less than half the distance from the end of the measuring stick to the first etched line. It is recorded as a trace of precipitation by entering the letter "T" (NWS 1989). Officially, all of the trace precipitation is treated quantitatively as a zero precipitation event that contributes nothing to the monthly totals. However, the day during which trace precipitation was recorded is counted as a precipitation day.

A large number of trace precipitation days of both snow

TABLE 2. Summary (total and percentage of the DFIR) of daily corrected precipitation for the NWS 8″ standard gauge (with an Alter shield or unshielded) at Valdai, Reynolds Creek, and Danville WMO Intercomparison project stations.

Type of precipitation	Events (Days) All	Events (Days) DFIR > 3.0 mm	DFIR	NWS 8″ measured Alter	NWS 8″ measured Unshielded	NWS 8″ corrected Alter	NWS 8″ corrected Unshielded
(a) Valdai WMO site, October 1991 to March 1993							
Snow	154	37	357.4 mm	248.8 mm	156.5 mm	334.7 mm	374.0 mm
			100.0%	69.6%	43.8%	93.6%	104.6%
Mixed	73	45	463.9 mm	361.4 mm	303.4 mm	457.8 mm	448.5 mm
			100.0%	77.9%	65.4%	98.7%	96.7%
Rain	108	47	434.5 mm	400.8 mm	386.0 mm	435.1 mm	431.6 mm
			100.0%	92.2%	88.8%	100.1%	99.3%
All	335	129	1255.8 mm	1011.0 mm	845.9 mm	1227.6 mm	1254.1 mm
			100.0%	80.5%	67.4%	97.8%	99.9%
(b) Reynolds Creek WMO site, November 1987 to March 1993							
Snow	50	18	87.3 mm	—	75.3 mm	—	95.6 mm
			100.0%	—	86.3%	—	109.6%
Mixed	27	15	100.7 mm	—	86.6 mm	—	94.7 mm
			100.0%	—	86.0%	—	94.1%
Rain	36	20	183.4 mm	—	170.2 mm	—	187.7 mm
			100.0%	—	92.8%	—	102.3%
All	113	53	371.4 mm	—	332.1 mm	—	378.0 mm
			100.0%	—	89.4%	—	101.8%
(c) Danville WMO site, December 1986 to April 1992							
Snow	158	72	1051.3 mm	1018.4 mm	—	1022.8 mm	—
			100.0%	96.9%	—	97.3%	—
Mixed	21	35	650.8 mm	624.8 mm	—	663.7 mm	—
			100.0%	96.0%	—	102.0%	—
Rain	22	18	291.1 mm	279.5 mm	—	290.4 mm	—
			100.0%	96.0%	—	99.7%	—
All	201	125	1993.2 mm	1922.7 mm	—	1976.9 mm	—
			100.0%	96.5%	—	99.2%	—

and rain occurred at Barrow. From 1972 to 1978, the average number of days when precipitation and trace were recorded was 254 and 158, respectively (Benson 1982). For calender years 1982 and 1983, there were 98 and 93 trace precipitation days reported of the total number of precipitation days of 192 and 189, respectively. On average, trace recordings make up 45%–50% of the annual total of precipitation days, with the monthly number of days reporting trace accounting for 15%–80% of the monthly total number of precipitation days.

TABLE 3. Climate normals of temperature (°C), precipitation (mm), and snowfall (cm) for 1963–92 and wind speed (m s^{-1}) for 1982 and 1983, Barrow, Alaska.

Month	Temperature (°C)	Precipitation (mm)	Snowfall (cm)	Wind speed (m s^{-1})
Jan	−25.9	4.3	5.3	4.8
Feb	−27.8	4.1	5.3	5.3
Mar	−26.2	3.3	4.6	5.0
Apr	−18.3	3.8	5.3	5.4
May	−7.2	3.3	4.6	5.3
Jun	1.1	7.9	1.5	5.6
Jul	4.1	22.4	1.3	5.1
Aug	3.4	23.1	1.8	5.5
Sep	−0.9	14.7	8.9	5.9
Oct	−9.3	12.7	17.0	5.5
Nov	−18.3	6.4	8.6	5.4
Dec	−24.1	4.6	6.4	5.7
Annual	−12.4	110.6	70.6	5.4

The 6-hourly observations at Barrow show that a number of traces of precipitation are reported in a single trace precipitation day. In 1982 and 1983, the total number of 6-hourly trace observations were 329 and 322 in the corresponding number of days with trace of 98 and 93. On average, there were 3.5 trace observations for each reported trace day. The number of trace observations varies from 10 to 30 during November to April and from 30 to 60 during May to October.

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^{-1}. In Canada, studies on trace precipitation (Metcalfe and Goodison 1993) found 6-hourly values of 0.03–0.07 mm, with the lower values applying during conditions of ice crystals. As noted, a number of trace observations were reported for each trace 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, a trace precipitation was corrected on a daily basis at Barrow, for example, for any given trace day, regardless of the number of the trace observations reported, a value of 0.10 mm was assigned for that day. In 1982, the monthly estimated total for trace precipitation varied from 0.2 to 1.4 mm

TABLE 4. Correction of the NWS 8″ standard gauge measured precipitation at Barrow, Alaska, for (a) 1982 and (b) 1983.

	Temperature						Corrections						
	Minimum (°C)	Maximum (°C)	Wind speed (m s^{-1})	Percentage of snow	Number of precipitation days	P_g (mm)	Wind (mm)	Wetting (mm)	Trace (mm)	Sum (mm)	P_c (mm)	CF	Potential range of corrected precipitation (mm)
(a) 1982													
Jan	−27.2	−20.7	5.6	100	4	4.30	3.39	0.60	0.20	4.19	8.49	1.97	4.85–9.43
Feb	−25.9	−16.8	5.1	100	8	10.90	8.41	1.20	0.50	10.11	21.01	1.93	12.16–25.89
Mar	−27.7	−21.6	5.0	100	5	6.10	3.27	0.75	0.60	4.62	10.72	1.76	10.05–11.45
Apr	−22.4	−14.2	4.6	100	7	8.63	7.45	1.05	1.20	9.70	18.33	2.12	13.42–22.36
May	−11.0	−6.1	5.0	91	14	8.38	3.42	2.10	1.30	6.82	15.20	1.81	13.16–19.45
Jun	−1.1	3.3	6.0	10	6	5.33	2.16	0.18	1.30	3.64	8.97	1.68	—
Jul	0.8	5.8	5.4	0	8	19.81	2.81	0.24	0.50	3.55	23.36	1.18	—
Aug	−0.4	5.6	5.5	3	10	21.84	3.12	0.30	0.80	4.22	26.06	1.19	—
Sep	−3.0	0.2	6.3	68	15	14.99	8.32	2.25	1.10	11.67	26.66	1.78	22.07–36.57
Oct	−16.3	−11.6	5.8	100	11	14.23	3.44	1.95	1.40	6.79	21.02	1.48	18.40–29.10
Nov	−25.4	−21.4	5.9	100	2	0.51	0.45	0.30	0.60	1.35	1.86	3.65	1.10–2.66
Dec	−25.4	−20.4	6.1	100	4	3.30	2.75	0.60	0.30	3.65	6.95	2.11	3.90–7.46
Annual	−15.4	−9.8	5.5	73	94	118.33	48.98	11.52	9.80	70.30	188.63	1.59	157.50–222.76
Jun–Aug	−0.3	4.9	5.6	4	24	46.99	8.08	0.72	2.60	11.40	58.39	1.24	—
Sep–May	−20.5	−14.7	5.5	95	70	71.34	40.90	10.80	7.20	58.90	130.24	1.83	99.11–164.37
(b) 1983													
Jan	−31.7	−25.2	4.0	100	3	0.76	0.34	0.45	0.20	0.99	1.75	2.30	1.25–1.91
Feb	−28.2	−24.4	5.5	100	5	2.29	1.77	0.75	0.10	2.62	4.91	2.15	3.78–6.08
Mar	−27.7	−22.7	5.0	100	0	0.00	0.40	0.40	0.40	1.20	1.20	—	0.80–1.20
Apr	−19.1	−13.5	6.2	75	8	5.08	3.08	1.20	0.50	4.78	9.86	1.94	8.59–10.26
May	−11.1	−5.7	5.5	100	5	1.78	0.93	0.75	1.70	3.38	5.16	2.90	4.50–5.46
Jun	−1.2	4.1	5.1	55	7	2.79	1.48	1.05	1.20	3.73	6.52	2.33	—
Jul	0.4	6.4	4.8	40	5	2.54	0.76	0.15	0.50	1.41	3.95	1.56	—
Aug	−1.2	3.8	5.5	6	15	26.42	9.13	0.45	1.40	10.98	37.40	1.42	—
Sep	−7.0	−2.1	5.5	55	21	22.61	13.68	3.45	0.70	17.83	40.44	1.79	37.91–42.66
Oct	−16.1	−11.7	5.2	86	15	9.14	5.10	2.25	0.90	8.25	17.39	1.90	15.44–21.51
Nov	−19.6	−14.4	4.8	100	10	6.35	3.94	1.50	0.80	6.24	12.59	1.98	10.88–13.75
Dec	−20.7	−14.2	5.3	100	2	1.27	0.72	0.30	0.90	1.92	3.19	2.51	2.43–4.22
Annual	−15.3	−10.0	5.2	76	96	81.03	41.33	12.70	9.30	63.33	144.36	1.78	133.45–154.43
Jun–Aug	−0.7	4.8	5.1	34	27	31.75	11.37	1.65	3.10	16.12	47.87	1.51	—
Sep–May	−20.1	−14.9	5.2	91	69	49.28	29.96	11.05	6.20	47.21	96.49	1.96	85.58–106.55

and the yearly total correction was 9.8 mm, which is 8% of the measured total precipitation. In 1983, the monthly corrections ranged from 0.1 to 1.7 mm and the yearly total was 9.3 mm, or 12% of the annual gauge-measured precipitation (Table 4).

It is important to note, however, because of the inverse proportion of the percentage of annual trace precipitation to the yearly amount of precipitation, as shown by Benson (1982) at 14 climate stations in Alaska, trace correction is important especially in the regions of low precipitation.

b. *Wetting losses*

At Barrow, wetting loss was estimated on a daily basis, according to the type of precipitation, by adding an average wetting loss to the daily record, using the values given previously. This is the minimum correction since, on average, 1.6–1.7 observations were made every 6 h for each reported precipitation day at Barrow in 1982 and 1983. No correction for wetting loss was applied to trace precipitation. In 1982, the monthly wetting loss correction ranged from 0.30 to 2.25 mm, and the yearly total was 11.5 mm, or 9.7% of the gauge-measured annual total. In 1983, the monthly correction varied from 0.15 to 3.45 mm and the annual total was 12.7 mm, which is equivalent to 15.6% of the gauge-measured yearly total (Table 4).

There was a clear difference in the contribution of wetting losses to the gauge-measured monthly totals between the warm season (June to August) and the cold season (September to May). In the warm season, because of the low mean wetting loss for each observation of rainfall, the total correction was calculated to be 1.5%–5.2% of the measured precipitation, while during the cold period the wetting loss was estimated to be 15%–22% of the measured precipitation due to the much higher mean wetting loss per observation of snowfall. Metcalfe and Goodison (1993) reported wetting loss for the Canadian Nipher snow gauge of 15%–20% of measured winter precipitation at some synoptic stations.

c. *Wind-induced errors*

To correct the gauge measured precipitation data for wind-induced errors, wind speed at the gauge height is

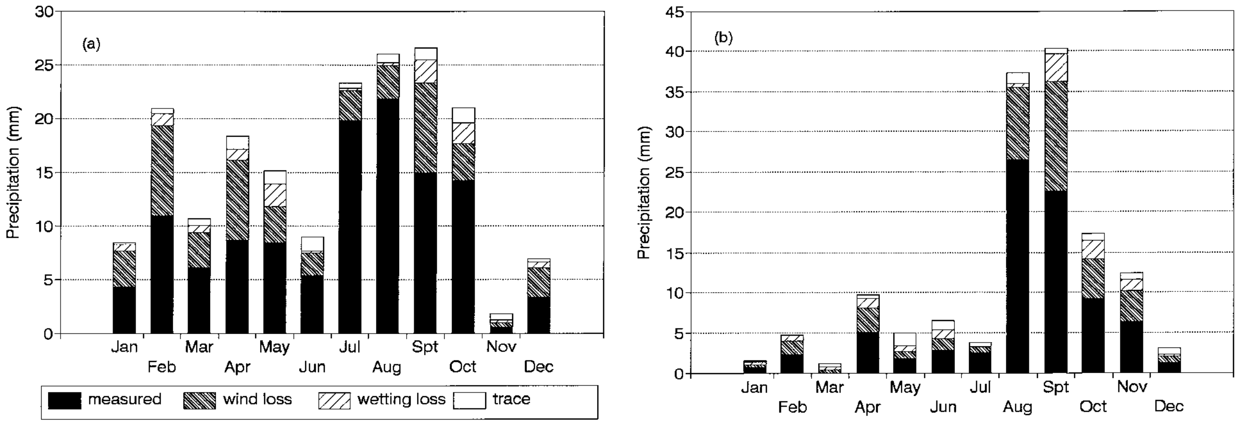

FIG. 4. Corrections of Alter-shielded NWS 8″ standard gauge measurements at Barrow, Alaska, for (a) 1982 and (b) 1983. Note the change of rank made by the corrections.

required. At Barrow, it was estimated, using Eq. (1), from the wind measurements at 9.45 m to the gauge height of 1.83 m. In the equation, $z_0 = 0.01$ m was given for the cold period from September to May and $z_0 = 0.03$ m was assigned to the warm period from June to August.

Blowing snow was reported at high wind speeds on some snowfall days at Barrow. In 1982 and 1983, the total number of precipitation days with blowing snow reported was 25 and 15, respectively, and the corresponding gauge measurements of total snowfall for those days were 40 and 8 mm. It is possible that under certain conditions, the NWS 8″ standard gauge at Barrow can catch some blowing snow. To avoid the possible overcorrection caused by high wind on blowing snow days, an upper value of wind speed has to be determined, and corrections at higher wind speed are to be used for the correction of 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^{-1} for the correction equations in this study (Fig. 3).

When daily wind speed at the gauge height was available, the daily gauge catch ratio R was estimated using the regression Eqs. (1), (3), and (5) for snow, mixed, and rain, respectively, and the wind-loss correction coefficient K was calculated as $K = 1/R$. The monthly correction for the wind-induced errors was estimated to be 0.5–8.4 mm for 1982 and 0.4–13.7 mm for 1983, and the yearly totals were about 49 and 41 mm (Table 4), respectively, or about 41% and 51% of the annual gauge-measured precipitation.

The current study also shows the difference in mean wind speed during precipitation days compared to the monthly mean wind speed in the years of 1982 and 1983. Generally, the mean wind speed on precipitation days was higher than the monthly mean, especially in the cold season. Unlike Sevruk (1982), statistical analysis of the Barrow wind data indicated no significant correlation between the monthly mean wind speed and the mean wind speed on precipitation days; this might be due to the low number of precipitation days (less than 10 days) in most of the months. Thus, for the purpose of wind-loss corrections, we strongly recommend use of the wind data on precipitation days when they are available.

d. Monthly–yearly total correction

At Barrow, the absolute total monthly corrections (e.g., sum of the corrections for trace amount, wetting loss, and wind-induced errors) varied from 1.35 to 11.67 mm in 1982 and from 1.00 to 17.83 mm in 1983 (Table 4). The corresponding monthly correction factors (CF) (e.g., ratio of corrected to measured precipitation) varied from 1.18 to 3.65 in 1982 and from 1.42 to 2.90 in 1983. The annual totals of the correction were 70.3 and 63.3 mm, respectively, and the archived yearly precipitation was corrected from 118.3 to 188.6 mm in 1982 and from 81.0 to 144.4 mm in 1983 (Table 4).

It is important to note the seasonal variation of the correction factors, that is, 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, are 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 intraannual variation of the monthly correction factors due to the fluctuation of wind speed, frequency (or percentage) of snowfall, number of trace precipitation, amount of gauge-measured precipitation, and air temperature. In 1982, during the cold period of January to May and September to December, the percent of snowfall in each month was 100%, except in September with 68%, and the average CF was 1.88. In the warm period of June to August, rainfall dominated with snowfall being less than 10% in each month and the mean CF was 1.24. In 1983, the average CF in the cold season was 1.96 and the mean CF in the warm season was as high as 1.51 mainly because of the higher percent of snowfall (55% and 40%) in June and July (Table 4).

A range of the potential corrected monthly precipitation is also given in Table 4. The lower value of the interval was obtained by excluding all of those gauge measurements of daily snowfall from wind-loss corrections when blowing snow was reported on the precipitation day. The upper value was estimated by correcting all of the gauge measurements of daily snowfall (including those when blowing snow was reported) for wind loss, using the measured daily wind data (including those of high values on blowing snow days).

For the cold season in 1982, the absolute difference of the monthly range (upper value minus lower value) varied from 1 to 15 mm. The yearly difference was about 65 mm. In 1983, due to less blowing snow events during the cold season compared to 1982, the absolute difference of the monthly range was smaller, for example, between 0.4 and 6.1 mm, and the yearly difference was 20.9 mm. This shows that blowing snow events can be very important when computing the correction for the effect of wind loss. It is recommended that all blowing snow events on precipitation days should be identified, and wind data during these events should be analyzed when correcting gauge measurements of snowfall for wind loss at cold and windy sites.

It is interesting to compare this work to other studies. Based on an intercomparison of the NWS 8″ standard gauge to the Wyoming-shielded gauge during the winters of 1975–1978, Benson (1982) reported an overall average CF, without considering wetting loss and trace amounts, at Barrow of 3.5 for snow and 1.1 for rain. Our study, correcting wetting loss before dealing with the wind-induced errors, indicated the average CF of 1.2 for rain and 1.9 for snow. Considering that two different instruments of determining the ‘‘true’’ precipitation were used and that different analysis techniques were applied, the results from these two studies were quite compatible for rain but they were different for snow. It is likely that our work applied a minimum correction on the gauge-measured snow data since 1) both trace events and wetting losses were corrected on a daily basis instead of for each observation and 2) a threshold wind speed was set up for those snowfall events when blowing snow was reported at high wind speeds.

Canadian studies on the winter precipitation correction indicated that at some northern stations corrections for trace precipitation, wetting loss, and wind-induced errors were also important (Metcalfe and Goodison 1993). Metcalfe et al. (1994) corrected the Canadian Nipher snow gauge data on a 6-hourly time step for synoptic stations in the NWT of Canada. At Resolute Bay the results indicate that the actual annual precipitation is 50%–100% greater than the gauge-measured yearly total. This study at Barrow shows that due to the higher undercatch of snowfall of the NWS 8″ standard gauge, wind-induced error was the largest systematic error, which was estimated to be about 41%–49% of archived annual precipitation, and the trace amount and wetting losses, accounting for 8%–12% and 10%–16% of the archived annual total, respectively, were not negligible. Further analysis of the corrected precipitation in Alaska and Canada and other circumpolar countries is certainly necessary to confirm the validity of the precipitation correction procedures.

6. Conclusions

In this study, the relation of daily precipitation catch between the NWS 8″ standard gauge (Alter shielded or unshielded) and the DFIR reference measurement of true precipitation as a function of daily mean wind speed at gauge height for the precipitation day was derived for the types of precipitation of snow, mixed, and rain, using the compiled intercomparison data at three WMO sites. It is extremely important to have this relation established since gauge catch ratio R can be calculated using the relation for given daily wind speed for the precipitation day and true precipitation P_t can be estimated by $P_t = P_m/R$ for the gauge-measured amount P_m. The correction procedures outlined in this paper have been applied to Barrow in Alaska for the test years of 1982 and 1983 and gauge-measured precipitation was increased, on average, by 20% for rain and 90% for snow. These correction procedures are recommended for testing correction of NWS 8″ standard gauge measured daily precipitation in those countries where national meteorological or hydrological station networks operate this gauge for precipitation observation. It is felt that application of the proposed correction procedures will improve the accuracy and homogeneity of precipitation data over large regions of the United States and southern Asia.

The WMO Solid Precipitation Measurement Intercomparison project has provided better correction procedures for a number of precipitation gauges commonly used around the world. The current study shows that the correction factors at Barrow differed by type of precipitation and varied by month even for the same type of precipitation since these errors in percentage not only depend on the wind speed but also on the wetting losses, trace amount, and the actual measured precipitation. In addition, there is considerable intraannual variation of the magnitude of the correction due to the fluctuation of the wind speed, air temperature, and the frequency of the snowfall; this was demonstrated in the Barrow example (see also Fig. 4) and also documented by Legates and DeLiberty (1993). It is clear that the monthly correction factors are not constant and, thus, the correction for the errors will have an impact on climate monitoring.

As the results of WMO Solid Precipitation Measurement Intercomparison project show, correction procedures like those demonstrated above have been developed for the Canadian Nipher snow gauge (Goodison et al. 1992), the Russian Tretyakov gauge (Yang et al. 1995), and the Hellmann gauge (Gunther 1993; Yang et al. 1994). It is hoped that through the WMO project and similar efforts, such as establishing regional and national precipitation centers recommended by WMO/CIMO (1993), the correction procedures will be continuously developed and refined for an even larger number of gauges commonly used around the world. It is also hoped that efforts will be made by the national meteorological and hydrological services to apply the appropriate correction procedures to their archived precipitation data in order to produce a consistent unbiased precipitation dataset worldwide.

Acknowledgments. This study would not have been possible without the cooperation of the participating countries and the many observers at the stations where the WMO Intercomparison project was conducted for a number of years.

REFERENCES

Aaltonen, A., E. Elomaa, A. Tuominen, and P. Valkovuori, 1993: Measurement of precipitation. *Proc. Symp. on Precipitation and Evaporation,* Vol.1, Bratislava, Slovakia, Slovak Hydrometeorlogical Institute and Swiss Federal Institute of Technology, 42–46.

Bates, R. E., T. Pangburn, and H. Greenan, 1987: WMO Solid Precipitation Measurement Intercomparison at Sleepers River Research Watershed. *Proc. Eastern Snow Conf., 44th Meeting,* Fredericton, NB, Canada, Eastern Snow Conference, 1–7.

Benson, C. S., 1982: Reassessment of winter precipitation on Alaska's Arctic slope and measurement on the flux of wind blown snow. Geophysical Institute, University of Alaska, Rep. R-288, 26 pp. [Available from Geophysical Institute, University of Alaska, P.O. Box 757320, Fairbanks, AK 99775-7320.]

Black, R. F., 1954: Precipitation at Barrow, Alaska, greater than recorded. *Trans. Amer. Geophys. Union,* **35,** 203–206.

Elomaa, E. J., 1993: Experiences in correcting point precipitation measurement in Finland. Preprints, *Eighth Symp. on Meteorological Observation and Instrumentation,* Anaheim, CA, Amer. Meteor. Soc., 346–350.

Golubev, V. S., 1986: On the problem of standard condition for precipitation gauge installation. *Proc. Int. Workshop on the Correction of Precipitation Measurements*, WMO/TD 104, Zurich, Switzerland, World Meteor. Org., 57–59.

——, 1989: Assessment of accuracy characteristics of the reference precipitation gauge with a double-fence shelter. *Final Report of the Fourth Session of the International Organizing Committee for the WMO Solid Precipitation Measurement Intercomparison,* St. Moritz, Switzerland, World Meteor. Org., 22–29.

——, P. Ya. Groisman, and R. G. Quayle, 1992: An evaluation of the United States 8-inch nonrecording raingage at the Valdai Polygon, Russia. *J. Atmos. Oceanic Technol.,* **9,** 624–629.

Goodison, B. E., 1977: Snowfall and snow cover in southern Ontario: Principles and techniques of assessment. Ph.D. dissertation, University of Toronto, 403 pp. [Available from University of Toronto, 60 St. George St., Toronto, ON, M5S 1A7 Canada.]

——, and J. R. Metcalfe, 1992: The WMO solid precipitation intercomparison: Canadian assessment. *Proc. WMO Technical Conf. on Instruments and Method of Observation,* Vienna, Austria, World Meteor. Org., 221–225.

——, H. L. Ferguson, and G. A. McKay, 1981: Comparison of point snowfall measurement techniques. *Handbook of Snow,* D. M. Gray and M. D. Male, Eds., Pergamon Press, 200–210.

——, B. Sevruk, and S. Klemm, 1989: WMO Solid Precipitation Measurement Intercomparison: Objectives, methodology, analysis. *Atmospheric Deposition (Proc. Baltimore Symp.)* Baltimore, MD, IAHS, 57–64.

——, E. Elomma, V. Golubev, and B. Sevruk, 1994: WMO Solid Precipitation Measurement Intercomparison: Preliminary results, TECO'94. WMO/TD 588, 15–19. [Available from World Meteor. Org., Publication Sales Unit, Case Postale 2300, CH-1211 Geneva 2, Switzerland.]

Groisman, P. Ya., and D. R. Easterling, 1994: Variability and trends of total precipitation and snowfall over the United States and Canada. *J. Climate,* **7,** 184–205.

——, V. V. Koknaeva, T. A. Belokrylova, and T. R. Karl, 1991: Overcoming biases of precipitation measurement: A history of the USSR experience. *Bull. Amer. Meteor. Soc.,* **72,** 1725–1732.

Gunther, Th., 1993: German participation in the WMO solid Precipitation Intercomparison: Final results. *Proc. Symp. on Precipitation and Evaporation,* Vol.1, Bratislava, Slovakia, Slovak Hydrometeorological Institute and Swiss Federal Institute of Technology, 93–102.

Johnson, M. L., and E. Anderson, 1968: The cooperative snow hydrology project—ESSA Weather Bureau and ARS Sleepers River Watershed. *Proc. Eastern Snow Conf., 25th Meeting,* Boston, MA, Eastern Snow Conference, 13–23.

Karl, T. R., P. Ya. Groisman, R. W. Knight, and R. R. Heim Jr., 1993a: Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *J. Climate,* **6,** 1327–1344.

——, R. G. Quayle, and P. Ya. Groisman, 1993b: Detecting climate variations and change. New challenges for observing and data management system. *J. Climate,* **6,** 1481–1494.

Larkin, H. H., Jr., 1947: A comparison of the Alter and Nipher shields for precipitation gages. *Bull. Amer. Meteor. Soc.,* **28,** 200–201.

Larson, L. W., 1972: Approaches to measuring ''true snowfall.'' *Proc. Eastern Snow Conf., 29th Meeting,* Oswego, NY, Eastern Snow Conference, 65–76.

——, and E. L. Peck, 1974: Accuracy of precipitation measurements for hydrological modelling. *Water Resour. Res.,* **10,** 857–863.

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

Metcalfe, J. R., and B. E. Goodison, 1993: Correction of Canadian winter precipitation data. *Proc. Eighth Symp. on Meteorological Observations and Instrumentation,* Anaheim, CA, Amer. Meteor. Soc., 338–343.

——, S. Ishida, and B. E. Goodison, 1994: A corrected precipitation archive for the Northwest Territories. *Mackenzie Basin Impact Study, Interim Report 2, Proc. Sixth Biennial AES/DIAND Meeting on Northern Climate,* Yellowknife, NWT, Environment Canada, 110–117.

Sevruk, B., 1982: Method of correction for systematic error in point precipitation measurement for operational use. WMO Tech. Note WMO-589, 91 pp. [Available from World Meteor. Org., Case Postale 2300, CH-1211, Geneva, Switzerland.]

——, and W. R. Hamon, 1984: International comparison of national precipitation gauges with a reference pit gauge. WMO Instrument and Observing Methods Rep. 17, 111 pp. [Available from World Meteor. Org., Case Postale 2300, CH-1211, Geneva, Switzerland.]

——, and S. Klemm, 1989: Types of standard precipitation gauges. *Proc. Int. Workshop on Precipitation Measurements*, St. Moritz, Switzerland, WMO/IAHS/ETH, 227–236.

U.S. Department of Commerce, 1963: History of weather bureau precipitation measurements. Washington, DC, 15 pp. [Available from NWS/NOAA, 1325 East-West Highway, Silver Spring, MD 20910.]

U.S. National Weather Service, 1989: Cooperative station observations. NWS Observing Handbook 2, 83 pp. [Available from NWS/NOAA, 1325 East-West Highway, Silver Spring, MD 20910.]

WMO/CIMO, 1985: International organizing committee for the WMO Solid Precipitation Measurement Intercomparison. Final Rep. of the First Session, Norkoping, Sweden, WMO, 31 pp. [Available from World Meteor. Org., Case Postale 2300, CH-1211, Geneva, Switzerland.]

——, 1993: International organizing committee for the WMO Solid Precipitation Measurement Intercomparison. Final Rep. of the Sixth Session, Toronto, ON, Canada, WMO, 140 pp. [Available from World Meteor. Org., Case Postale 2300, CH-1211, Geneva, Switzerland.]

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

Yang, D., J. R. Metcalfe, B. E. Goodison, and E. Mekis, 1993: An evaluation of the double fence intercomparison reference gauge. *Proc. Eastern Snow Conf., 50th Meeting,* Quebec City, PQ, Canada, Eastern Snow Conference, 105–111.

——, B. Sevruk, E. Elomaa, V. Golubev, B. Goodison, and Th. Gunther, 1994: Wind-induced error on snow measurement: WMO intercomparison Results. *Proc. Int. Conf. on Alpine Meteorology,* Lindau, Germany, Selbstverlag des Deutschen Wettwedienstes, 61–64.

——, and Coauthors, 1995: Accuracy of Tretyakov precipitation gauge: Results of WMO intercomparison. *Hydrol. Processes,* **9,** 877–895.