

## An evaluation of the Wyoming gauge system for snowfall measurement

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**Abstract.** The Wyoming snow fence (shield) has been widely used with precipitation gauges for snowfall measurement at more than 25 locations in Alaska since the late 1970s. This gauge's measurements have been taken as the reference for correcting wind-induced gauge undercatch of snowfall in Alaska. Recently, this fence (shield) was tested in the World Meteorological Organization Solid Precipitation Measurement Intercomparison Project at four locations in the United States of America and Canada for six winter seasons. At the Intercomparison sites an octagonal vertical Double Fence with a Russian Tretyakov gauge or a Universal Belfort recording gauge was installed and used as the Intercomparison Reference (DFIR) to provide true snowfall amounts for this intercomparison experiment. The intercomparison data collected were compiled at the four sites that represent a variety of climate, terrain, and exposure. On the basis of these data sets the performance of the Wyoming gauge system for snowfall observations was carefully evaluated against the DFIR and snow cover data. The results show that (1) the mean snow catch efficiency of the Wyoming gauge compared with the DFIR is about 80–90%, (2) there exists a close linear relation between the measurements of the two gauge systems and this relation may serve as a transfer function to adjust the Wyoming gauge records to obtain an estimate of the true snowfall amount, (3) catch efficiency of the Wyoming gauge does not change with wind speed and temperature, and (4) Wyoming gauge measurements are generally compatible to the snowpack water equivalent at selected locations in northern Alaska. These results are important to our effort of determining true snowfall amounts in the high latitudes, and they are also useful for regional hydrologic and climatic analyses.

### 1. Introduction

Biases in gauge-measured precipitation records, notably those caused by wind and those attributable to wetting and evaporation losses [Sevruk, 1989], have been recognized as affecting all types of precipitation gauges. The need to correct the measured precipitation data for these systematic errors, especially for solid precipitation, is now more widely acknowledged since the magnitude of the errors and the variation between various national gauges became known. Their potential impact on regional, national, and global climatological, hydrological, and climate change studies was also recognized [Larson and Peck, 1974; Goodison, 1978, 1981; Goodison and Yang, 1995; Groisman and Easterling, 1994; Groisman et al., 1991; Groisman and Legates, 1994; Karl et al., 1993; Legates and Willmott, 1990; Legates and DeLiberty, 1993; Peck, 1997; Metcalfe et al., 1997; Yang et al., 1998a, 1999a; Yang, 1999].

To assess the national standard methods of solid precipita-

tion observation, the World Meteorological Organization (WMO) initiated the Solid Precipitation Measurement Intercomparison Project in 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 [World Meteorological Organization/WMO/CIMO, 1985; Goodison et al., 1998]. Determination of the reference method for snowfall measurement was critical for this intercomparison project. After reviewing all possible practical methods of measuring true snowfall in a range of climatic conditions, the WMO Organizing Committee for the Intercomparison designated the Russian Double Fence (Figure 1) as the Intercomparison Reference (DFIR) [Golubev, 1985; Goodison et al., 1981; Goodison et al., 1989]. The DFIR has two fences, each having 1.5-m slats at a porosity of 50%, mounted vertically at radii of 2 m and 6 m around a Russian Tretyakov gauge. The orifice of the gauge is set at 3 m, the bottom of the outer fence is set at 2 m, and the inner fence is set at 1.5 m above the ground. This arrangement of fences prevents snowdrift accumulation in the fence vicinity [Goodison et al., 1981; Golubev, 1985]. Since 1985 the DFIR has been operated at 20 stations in 13 countries around the world. Extensive test and assessment of the DFIR performance, conducted in the past 20 years, concluded that the DFIR gives the best estimate of true snow-

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**Figure 1.** (top) Photos of the World Meteorological Organization (WMO) Double Fence Intercomparison Reference (DFIR) and the (bottom) Wyoming shield.

fall amount, although it slightly undercatches snowfall by 5–10% at high wind speeds [Golubev, 1985; Yang *et al.*, 1993a]. A methodology to correct for the undercatch of the DFIR was developed [Yang *et al.*, 1993a] and was recommended by WMO/CIMO [1993] to be applied to the DFIR measurements at the test sites to obtain the true snowfall amount for the intercomparison experiment.

The WMO Solid Precipitation Measurement Intercomparison Project has developed improved bias correction techniques for a number of precipitation gauges commonly used around the world [Goodison *et al.*, 1998], such as the Canadian Nipher snow gauge [Goodison and Metcalfe, 1992], the United States National Weather Service (NWS) 8-inch standard gauge [Yang *et al.*, 1998b], the Russian Tretyakov gauge [Yang *et al.*, 1995], and the Hellmann gauges [Gunther, 1993; Allerup *et al.*, 1997;

Yang *et al.*, 1999b]. Application of the WMO bias correction methods to the national precipitation data has resulted in significantly higher estimates of precipitation particularly in the high-latitude regions [Metcalf *et al.*, 1994; Yang *et al.*, 1998a, 1999a; Yang, 1999]. This increase in precipitation (up to an order of 2.0–2.5) points to a need to review our understanding of both arctic ocean and terrestrial freshwater budgets and the assessment of climate model performance in the high latitudes [Yang, 1999].

To reduce the wind-induced gauge undercatch of precipitation, wind shields of various types were developed and used with precipitation gauges [Sevruck and Klemm, 1989; Larson, 1972; Yang *et al.*, 1999c]. In the United States of America, the Alter shield is the standard wind shield used with national gauges in the NWS observation network. In addition, a double

**Table 1.** Siting and Instrumental Information at Four WMO Intercomparison Sites

Station	Latitude, Longitude, Elevation	DFIR	National Gauges	Wind Shields	Wind Sensors	Observation Method	Observation Period
Reynolds Creek, Idaho, United States of America	43°12'N, 116°45'W, 1193 m	at 3 m	United States 8 inch, Belfort, Tretyakov, Canadian Nipher	Alter, Canadian Nipher, Wyoming fence	at 9.1 m, 3 m, and 2 m	weighing	Nov. 1987 to Feb. 1992
Bismarck, North Dakota, United States of America	46°46'N, 100°45'W, 502 m	at 3 m	Belfort, Tretyakov	Alter, Wyoming fence	at 6.1 m, 3 m, and 1.4 m	weighing	Nov. 1988 to April 1991
Rabbit Ears Pass, Colorado, United States of America	40°23'N, 106°38'W, 2925 m	at 3 m	Belfort, Tretyakov	Alter, larger Nipher, Wyoming fence	at 10 m and 3 m	weighing	Nov. 1989 to April 1993
Regina, Saskatchewan, Canada	50°26'N, 104°40'W, 577 m	at 3 m	Tretyakov, Canadian Nipher	Tretyakov, Nipher, Wyoming fence	at 10 m, 3 m, and 2 m	volumetric	Nov. 1987 to April 1992

fence was also introduced and used at some monitoring and research sites. The Wyoming shield (Figure 1) or “blow” fence was developed by the University of Wyoming [Rechard and Larson, 1971] as an artificial wind barrier to be used in windy, exposed locations. The design of this fence or shield was first empirically determined in a wind tunnel. The shield consisted of two concentric twelve-sided rings of snow fence 3 m and 6 m in diameter, inclined at 45° and 60° angles, respectively, from the horizontal. The outer ring was 1.83 m in height, while the inner ring was 1.52 m high. The shield was constructed of 1.22-m-long wooden, vertical lath fencing with approximately 50% porosity. This type of fencing is commonly used as high-way drifting-snow protection barriers. A gap of 1.5 m was left below the shield to minimize snow buildup around the shield. Initially, the Alter shielded Belfort recording gauges were installed within the Wyoming shield, with the gauge orifice at the same height as the top of the inner ring of the shield. In addition, protective snow fences were installed upwind at some test sites to reduce the amount of snow being transported past the gauges (i.e., to reduce blowing snow).

The Wyoming gauge system has been widely used in the United States, particularly in Alaska. In 1975 the first Wyoming shields were built on the Canadian north slope and in Alaska, and by 1977 nineteen had been built based on a design described by Rechard [1975] as a “Wyoming blow-fence” snow shield. These shields, referred to as the “Arctic version,” were similar to that described above except that the outer shield was octagonal in shape rather than 12-sided. The fence consisted of PVC-coated, nylon weave, 50% density material instead of the vertical wood slats. The outer and inner snow fence ring diameters were 2.6 m and 1.0 m, respectively. In addition, the heights of the outer and inner rings were 2.6 m and 2.3 m, respectively. The gap at the bottom was about 1.5 m. Various types of precipitation gauges have been mounted within these Wyoming shields including remote recording, propane-heated gauges, storage gauges, Universal weighing gauges, and recording gauges (i.e., pressure transducer and stilling well).

Assessments on performance of the Wyoming shield yielded interesting results. Rechard [1975] reported that the average catch of a gauge equipped with a Wyoming shield was within 10% of that recorded by a standard gauge placed in a small forest opening. Dublin [1979] and Goodison and Metcalfe [1982] reported an average snow catch of the Wyoming shielded (the Arctic version) gauge being about 75% in comparison to the Canadian Nipher snow gauges at several locations in Canada. Benson [1982] used the Wyoming shielded gauge records as reference to correct the NWS standard gauge

snowfall data in northern Alaska and reported the yearly precipitation increased by 200–400%. Sturges [1986] reported the mean snow catch of the Wyoming shielded gauges being as low as 48% compared to the gauges in the forest openings at two test sites in Wyoming and found a relation of decreasing catch efficiency with wind speed. Clagett [1988] stated that the mean catch of the Wyoming shielded gauges was between 80 and 90% with respect to the snow course data at several sites in Alaska, and he believed that the Wyoming shielded gauge provides the best available estimate of snowfall in windy, exposed, and remote locations. Clagett [1988] also suspected that the catch-wind relation described by Sturges [1986] might be due to overcatch of the control (reference) gauge used at the Wyoming test site. Hanson [1989] recently compared the Wyoming shielded gauge data versus the “true” precipitation amounts calculated by the dual-gauge system and concluded that Wyoming shielded gauges, under most of the climatic conditions, can be used to obtain reliable precipitation measurements in an experimental watershed in Idaho. Hanson [1989] also identified a very weak snow catch decrease with increasing wind speed.

During the WMO intercomparison project the Wyoming shielded gauges were tested among other national gauges at four locations in the United States and Canada for the period of 1986 to 1993. The intercomparison data collected at the WMO stations represent a variety of climate, terrain, and exposure. On the basis of these data sets the objective of this work is to evaluate the performance of the Wyoming shield against the WMO reference of the DFIR. It will (1) quantify the mean catch efficiency of the Wyoming gauge system versus the DFIR records; (2) examine the difference of the two gauge systems on a daily timescale and also for precipitation events ranging from hours to days; (3) derive the transfer functions between the two gauge systems; and (4) investigate the effect of meteorological variables, such as wind speed and temperature, on catch efficiency of the Wyoming gauge system. In addition, to further evaluate the Wyoming shield in the high-latitude regions, this study will also compare the Wyoming gauge records with snow course data collected at selected locations in Alaska. The results of this work will be useful for hydrologic and climatic studies in the high-latitude regions.

## 2. Data Sources and Methods of Analysis

Table 1 summarizes the site and instrumental information at four WMO Intercomparison stations where the Wyoming shielded gauges and other national gauges from participating

countries were tested against the DFIR. Installation of the DFIR, Wyoming shielded gauges, national gauges, and other observing equipment and the associated observational procedures followed the experimental guidelines [WMO/CIMO, 1985] and various national standards. At most of the sites, one observation was made each day for five winter seasons from 1987 to 1992. Additional meteorological measurements, such as air temperature, wind speed at selected levels, wind direction, atmospheric pressure, and humidity, were also made at the intercomparison stations. All data collected were quality controlled by the participants before being submitted for archiving in a digital database and used for this study. Additional details on siting, instrumentation, and observation methodology are provided by Goodison *et al.* [1998]. In addition, for analysis of the Alaska stations, daily precipitation records of the Wyoming shielded gauges and snowpack water equivalent (SWE) collected at selected locations were also utilized.

This study emphasizes the comparison of precipitation measurements between the DFIR and the Wyoming shielded gauge at the WMO intercomparison sites and comparison of Wyoming shielded gauge records to snowpack water equivalent at various locations in Alaska. For the gauge intercomparison, wetting loss, evaporation loss, and wind-induced undercatch of precipitation are systematic errors, and they should be corrected in gauge catch analysis [Goodison *et al.*, 1998]. In this study, bias corrections are not conducted; instead, gauge-measured records are used for the analysis, since the main objective is to evaluate the performance of the Wyoming shield against the DFIR. Other factors such as blowing snow, wind reduction from measured height to the gauge orifice level, and data combination and compatibility among the experimental sites are also considered.

In the WMO gauge intercomparison experiment, blowing snow events were recorded by observers at some stations on days of high wind speeds with and without snowfall. These events were identified by a special code in the data archive, and they were eliminated from the analysis of gauge catch versus wind speed, because the DFIR cannot be used to determine the "true" snowfall amount for blowing/falling snow conditions [Goodison *et al.*, 1998]. In the current study, blowing snow events were separated from the nonblowing snow events. This separation allows us to objectively define the performance of gauges/shields for snowfall measurements in nonblowing snow conditions. However, this separation clearly sets up a limit for the application of the WMO results in high-wind conditions. In addition, the blowing snow data sets provide us with a unique opportunity to examine the potential impact of blowing snow to gauge catch in higher-wind conditions.

It has been known that at high wind speeds most precipitation gauges significantly undercatch snowfall and, conversely, they may catch horizontal blowing snow fluxes, reporting false precipitation. On the basis of the available WMO experimental data it is difficult for us to define the effect of blowing snow to gauge catch. Blowing snow certainly is a challenge in assessing the gauge catch of snowfall. Further model and experimental studies are needed to examine the performance of gauges and shields/fences in very windy and cold conditions.

Wind speed at the gauge height is required to evaluate the gauge catch of precipitation. When wind speed was not measured at the gauge height at some stations, it was estimated using the wind profile approach [Golubev *et al.*, 1992]. It is important to emphasize that at all Intercomparison sites, the DFIR was installed and operated according to the same pro-

cedures [WMO/CIMO, 1985]. This produced a common reference standard at all the sites; national gauges were operated according to the country's national methods. The same wind-profile technique is used to estimate wind speed at the gauge height from wind measurement at different heights. Thus the Intercomparison data collected from different sites are compatible in terms of the catch ratio, when wind speed at the gauge height is used in the analysis [Goodison *et al.*, 1998].

### 3. Results

Results of the data analysis are summarized below with emphasis on (1) mean catch ratios of Wyoming shielded gauges to the DFIR measurements, (2) linear relationship of the Wyoming shielded gauges to DFIR observations, (3) catch ratio of Wyoming shielded gauges versus wind speed and temperature, and (4) Wyoming shielded gauge winter total snowfall precipitation versus snowpack water equivalent.

#### 3.1. Mean Catch Ratios of the Wyoming Shielded Gauge

Table 2 compares the total precipitation in millimeters and the mean catch ratio in percent of the Wyoming shielded gauge to the DFIR for various types of precipitation at the four WMO sites. The results and their variation (of the mean catch ratios) among the sites can be explained by wind and snow conditions and gauge installations.

At the Rabbit Ears Pass WMO station the Russian Tretyakov gauge and Universal Belfort recording gauge were tested with the DFIR and Wyoming shield, respectively. All gauges were placed at the same height of 3 m, and the data were collected by individual precipitation events. During the experimental periods, more than 60 snowfall events were observed, with the DFIR total being over 900 mm. The specific gauge and wind shield configuration at this site allows us to compare the same type of gauges installed with the DFIR and Wyoming shield designs. This is the best way to examine the compatibility of the two snow fences, because gauges of the same type would yield compatible records and any significant discrepancy between the data would be attributed to the shield design. The results of comparison show that the Wyoming shielded gauges and the DFIR measured almost the same amount of mixed precipitation and snowfall. The mean snow catch of the Wyoming shield was 97–98% for the Belfort gauge and was 94–95% for the Tretyakov gauge.

At the Reynolds Creek WMO station a Tretyakov gauge was placed at 3 m with the DFIR, and a Belfort recording gauge was installed at 1.3 m inside the Wyoming shield. Observations were made for 82 snowfall days with the DFIR total being 160 mm. Mixed precipitation and (winter) rainfall events, 33 and 38 days, respectively, were also observed. Both gauges gave very similar amounts of snowfall perhaps owing to the low wind speeds on snowfall days. The Wyoming shielded gauge slightly overcatches mixed precipitation and (winter) rainfall with respect to the DFIR (Table 2).

At the Regina WMO site (a cold continental climate regime), 101 snowfall days were sampled, and the DFIR total was over 100 mm. Comparison of the DFIR (with a Tretyakov gauge at 3 m) to the "Arctic version" Wyoming shield (with a Belfort gauge at 2 m) shows the mean catch efficiency of the Wyoming shielded gauge being about 90% for snow and 88% for mixed precipitation (Table 2). Usually the mean catch ratio of a gauge decreases from rain to snow [Yang *et al.*, 1995; Yang and Goodison, 1998; Goodison *et al.*, 1998]. However, here the

**Table 2.** Summary of Comparison of Wyoming Gauge Versus the DFIR at Four WMO Sites

Precipitation Type	Number of events	Mean $T_{max}$ , °C	Mean $T_{min}$ , °C	Mean Wind at 3 m, m/s	DFIR, mm	Wyoming, mm	Wyoming/DFIR, %
<i>Rabbit Ears Pass, Belfort Gauge With DFIR (at 3 m) and Wyoming Fence (at 3 m)</i>							
Snow	71	-3.4	-10.2	3.1	959.6	946.4	98.6
Mixed	10	5.7	0.5	2.1	85.9	83.1	96.7
<i>Rabbit Ears Pass, Tretyakov Gauge With DFIR (at 3 m) and Wyoming Fence (at 3 m)</i>							
Snow	64	-3.9	-10.7	3.2	933.9	879.8	94.2
Mixed	3	1.4	-4.8	2.1	54.1	51.2	94.6
<i>Reynolds Creek, Tretyakov/DFIR (at 3 m) Versus Belfort/Wyoming (at 1.3 m)</i>							
Snow	82	2.6	-6.5	2.4	162.5	166.1	102.2
Mixed	33	7.1	-3.3	3.4	117.7	124.6	105.9
Rain	38	9.5	0.1	2.8	165.6	168.8	101.9
<i>Regina, Tretyakov/DFIR (at 3 m) Versus Belfort/Wyoming (at 2 m)</i>							
Snow	101	-6.2	-16.3	3.4	104.9	93.6	89.2
Blowing snow	46	-7.8	-18.4	5.2	82.9	56.3	67.9
Mixed	31	0.8	-9.3	4.1	47.2	41.5	87.9
<i>Bismarck, Tretyakov/DFIR (at 3 m) Versus Belfort/Wyoming (at 1.4 m)</i>							
Snow	17	-6.2	-12.0	3.5	137.2	119.5	87.1
Blowing snow	9	-2.6	-7.7	4.3	67.1	40.9	61.0

mean catch ratio of the Wyoming shielded gauge is slightly higher for snow than for mixed precipitation, perhaps because of higher wind speeds during mixed precipitation days. Blowing snow events were often observed at Regina, and a separate category for blowing snow was thus summarized in Table 2. In comparison to the DFIR the mean catch of the Wyoming shielded gauge is low during blowing snow events.

At the Bismarck station, two Belfort recording gauges were installed with the DFIR (at 3 m) and the Wyoming shield (at 1.4 m). Comparison of snow event data (17 events with the DFIR total over 130 mm) indicates that the mean catch of the Wyoming shielded gauges is 87% for nonblowing snow events and 61% during blowing snow (Table 2). These mean ratios are almost the same as for Regina, which has similar conditions of wind and temperature and reported many blowing snow events. This similarity of the Wyoming shielded gauge catch between the two sites clearly points out the challenge of dealing with blowing snow events in snowfall observations. Did the DFIR overcatch blowing/falling snow, or did the Wyoming shielded gauge undercatch? Given the data available for this work, it is not possible to determine which condition is more realistic. More effort is needed to define gauge performance under blowing/falling snow conditions.

Overall, in nonblowing snow conditions the Wyoming shielded gauges measured similar amounts of snowfall compared to the DFIR at most of the WMO experimental stations. The difference of mean catch between the two gauges is less than 10% at sheltered locations and about 15% at windy sites. For blowing snow events the catch of the Wyoming shielded gauges is about 60% of the DFIR. The variation of the mean catch ratios among the sites is caused by difference of gauge installation (i.e., gauge type and height), method of observation, and local climate conditions.

**3.2. Relationship Between Wyoming and DFIR Systems**

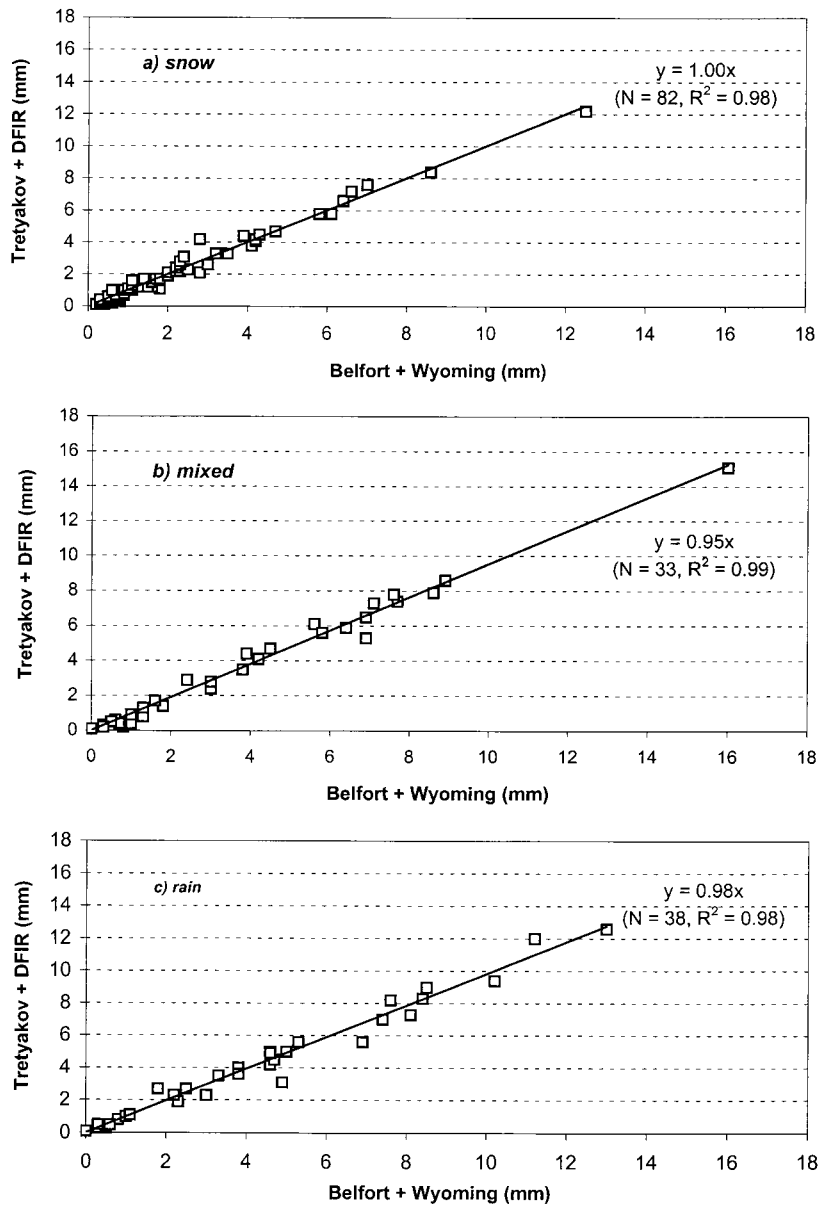
Gauge catch of precipitation depends on both the environmental factors and the precipitation features and can vary for each precipitation event [Goodison et al., 1998; Yang et al., 1995, 1998b, 1999b]. It is therefore desirable, if not essential, to

examine the compatibility of Wyoming shielded gauge and DFIR records on a shorter timescale. In this study, daily observations and precipitation event data are compared between the two gauge systems for different precipitation types. A strong linear relation was found to exist between the Wyoming shielded gauge and the DFIR measurements for all precipitation types and, particularly, for rainfall data (Figures 2–5). The linear relations are derived by a regression approach for various gauge types used with the Wyoming shield and the DFIR (Figures 2–5). These linear relations may serve as a transfer function to adjust the Wyoming shielded gauge measurements to produce a best estimate of true precipitation. It is important, however, to point out that the linear relations have limited applications. They are generally site specific and only valid statistically for the wind speed, temperature, and measured precipitation intervals for which they are developed. They should not be used for extrapolation outside these ranges.

**3.3. Ratio of Gauge Measurements Versus Wind Speed and Temperature**

Similar to the analysis of catch ratio versus wind speed for the national gauges tested in the WMO intercomparison project [Goodison et al., 1998; Yang et al., 1995, 1998b, 1999b], the effect of wind speed and temperature on catch of the Wyoming gauge system was investigated at the four WMO sites. Small absolute values of gauge measurements can create large unrealistic variations in the catch ratios [Goodison et al., 1998; Yang et al., 1995]. To minimize this effect, only those daily (or event) data when the DFIR measurements were greater than 3 mm are used in the analysis.

Intercomparison data from the Reynolds Creek site seem to suggest a weak relationship of decreasing catch ratio (CR) of the Wyoming shielded gauge with wind speed (Figure 6). However, the wind speeds sampled at the Reynolds Creek were generally very low (below 3.5 m/s). A wide range of wind speed and snowfall was collected at the other WMO stations, and these data do not show a decrease of catch ratio with increasing wind speed (Figure 6). It was also found that air temperature has no significant effect on Wyoming gauge catch effi-



**Figure 2.** Comparison of daily precipitation measured by Wyoming gauge and the DFIR at the Reynolds Creek WMO site: (a) snow, (b) mixed, and (c) rain.

ciency. The lack of a decreasing CR-wind relation, as seen for most gauges, would suggest that both the DFIR and Wyoming shields reduce wind speed at gauge orifice in a similar manner. There is no systematic difference between the DFIR and Wyoming shield as a function of wind speed, but the DFIR does generally measure more precipitation as shown above.

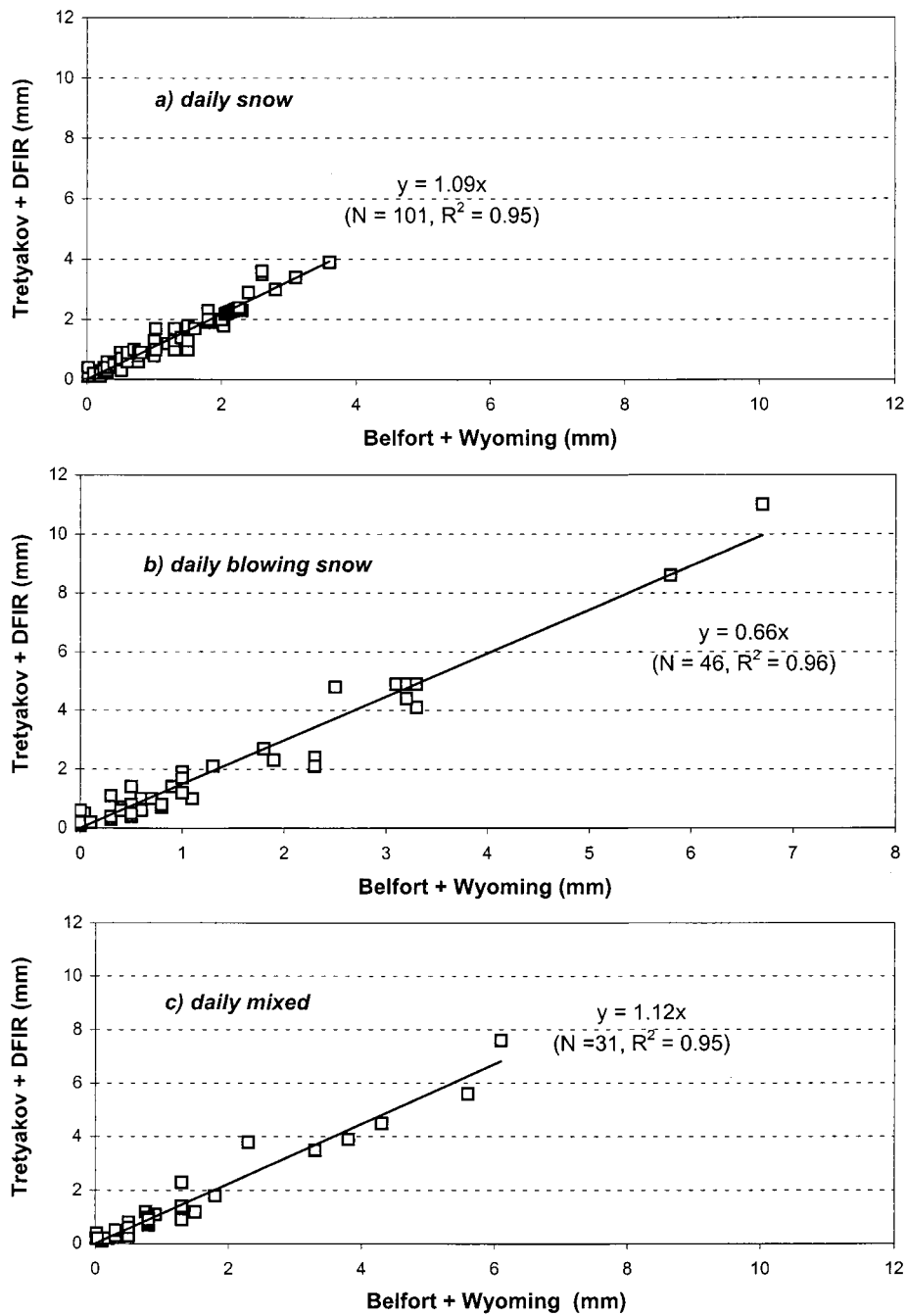
### 3.4. Wyoming Shielded Gauge Winter Snowfall Versus Snowpack Water Equivalent

The WMO intercomparison was conducted in the midlatitude regions. The results of this experiment are expected to be appropriate for the midlatitudes [Goodison *et al.*, 1998]. There is the question of whether the WMO results are applicable in the higher-latitude regions and for arctic conditions in particular. To investigate the applicability of the WMO methods and results to the high-latitude regions, alternative data sets and methods need to be considered.

Comparison of gauge measured snowfall with snow cover

accumulation is a useful method of assessing the accuracy and compatibility of snow data [Goodison, 1981; Woo *et al.*, 1983; Yang *et al.*, 1993b; Sevruk, 1983]. Table 3 compares the Wyoming shielded gauge winter total snowfall versus basin-mean SWE obtained by an intensive basin-wide snow survey at the peak accumulation in the Innvait Creek watershed in northern Alaska. In this arctic tundra basin the Wyoming shielded gauge measurement was  $\pm 10$ – $20$  mm of the snow survey for most of years. The ratio of the Wyoming shielded gauge/basin SWE varies from 80% to 120% mainly owing to the intra-annual fluctuation of snowfall, snow cover, and wind regimes. The mean ratio of the Wyoming shielded gauge/basin SWE is very close to 100% for the five winter seasons.

The basin mean SWE used in this comparison is an integrated determination of basin-wide snow water equivalent. This amount (determined here by field observations) is a function of total winter snowfall, sublimation loss of snow cover,

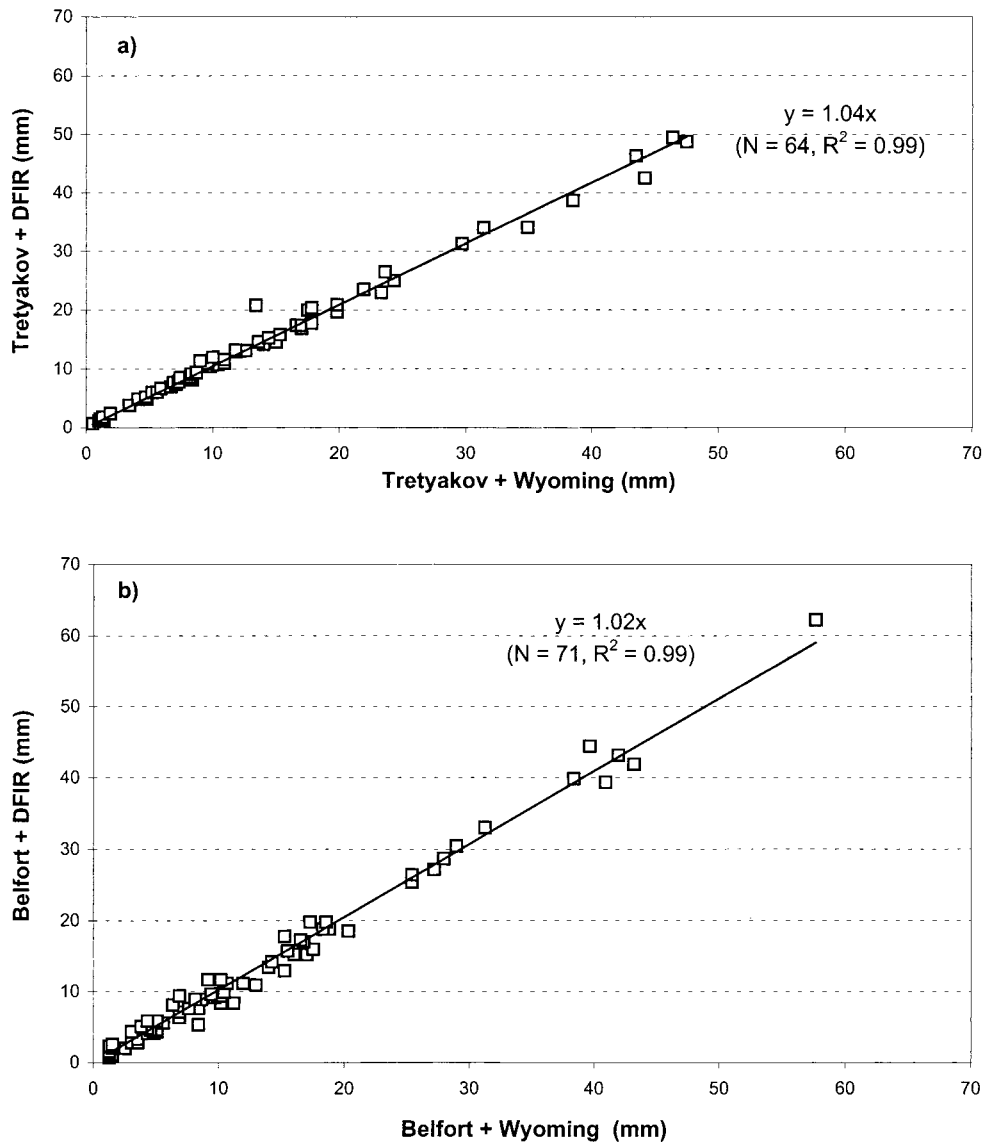


**Figure 3.** Comparison of daily precipitation measured by Wyoming gauge and the DFIR at Regina WMO site: (a) snow, (b) blowing snow, and (c) mixed precipitation.

the amount of snow blown into and out of the basin, and wind redistribution of snow within the basin. Kane *et al.* [1989] state that the amount of snow that blows into the watershed is close to the amount that blows out the basin, and thus the basin-wide integrated snow is representative of the winter total snowfall except for sublimation losses. Studies show that sublimation of snow is important, and it can reduce the snow cover mass by a significant fraction under certain conditions [Goodison, 1981; Benson and Sturm, 1993; Pomeroy *et al.*, 1993, 1997]. Liston and Sturm [1998], using a physically based numerical snow-transport model, estimated the sublimation losses of 10–40 mm (or 9–22% of the winter total precipitation) in the Im-

navait Creek basin for 4 years (1987–1990) (Table 3). The estimated sublimation loss was added to the measured SWE in the Imnavait Creek basin to obtain an adjusted snow cover mass for each individual year. Catch ratio of the Wyoming shielded gauge was then evaluated against the adjusted snow mass. The results show that Wyoming shielded gauge catch ratios vary from 70% to 83% among the years, and the mean ratio is now 76% (Table 3), about 25% lower than the mean ratio obtained previously without considering the sublimation losses of snow cover.

Table 4 compares the Wyoming shielded gauge data to other measurements in the forest of the Rhoades Creek near Delta

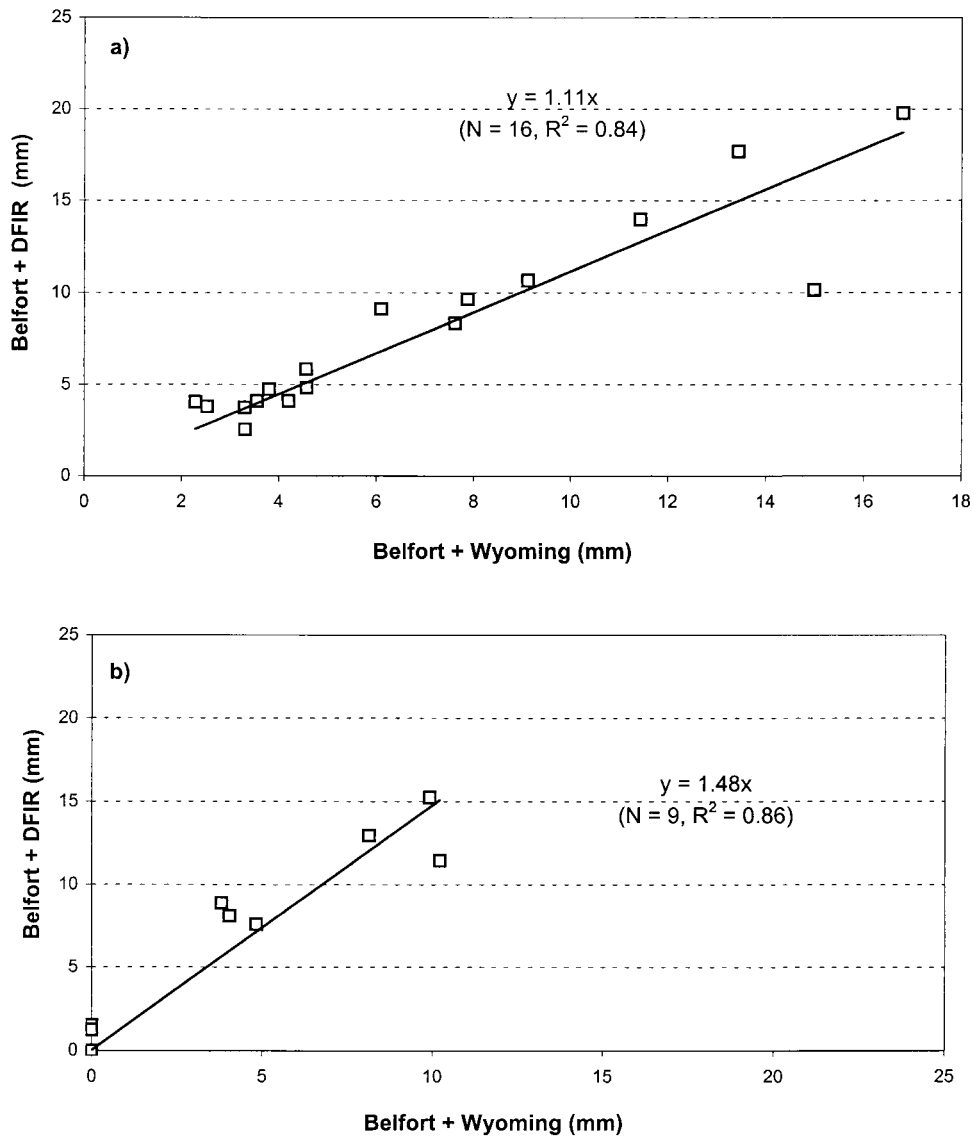


**Figure 4.** Comparison of snowfall event data measured by Wyoming gauge and the DFIR at the Rabbit Ears Pass WMO site: (a) Tretyakov gauge and (b) Belfort gauge.

Junction in Alaska [Clagett, 1988]. This comparison includes (1) a Wyoming shielded gauge in an openly exposed site, (2) a standard gauge in a forest-protected site (the diameter of the opening in the forest surrounding the gauge averaged 2.8 times the height of spruce trees), and (3) snow cover measurements made at a standard, protected snow course. For most of the years the Wyoming shielded gauge undercaught snow by less than 10% in comparison to the standard gauge located in the forest. The catch of the Wyoming shielded gauge compared to the snow survey varies from 75% to 103% for the 4 years, with the mean ratio of 94%. Wind transport of snow was expected to be small in this forest environment. There was no sublimation observation at this site. Sublimation losses were estimated to be between 10 and 20 mm for the 4 years, using the mean ratio of snow sublimation/winter precipitation, reported by Liston and Sturm [1998] for the Innavait Creek basin. Catch ratios of the Wyoming shielded gauge versus the sum of measured SWE and estimated sublimation were then calculated and presented in the last column of Table 4. They range from

66% to 89% in the four winter seasons, and the mean ratio is 78%, indicating the possible undercatch of the Wyoming shielded gauge to be about 25% in this test environment.

It is interesting to note that the catch of the Wyoming shielded gauges is consistent between the open tundra and forest-protected sites in Alaska, although the climate conditions are slightly different, with the northern location being windier and colder in winter. In addition, these Alaska results also compare favorably with those reported by Goodison and Metcalfe [1992] for the Canadian Arctic. This general agreement may suggest certain consistency of the performance of the Wyoming gauge systems in Alaska and northern Canada. It is, however, important to point out that there are challenges and uncertainties in quantitatively determining the compatibility of snow data in the high-latitude regions. First, it is difficult to measure or calculate snowpack sublimation loss for a basin. Liston and Sturm [1998], while emphasizing the impact of sublimation to end-of-winter snow distribution in the Arctic regions, pointed out that the estimations of sublimation losses



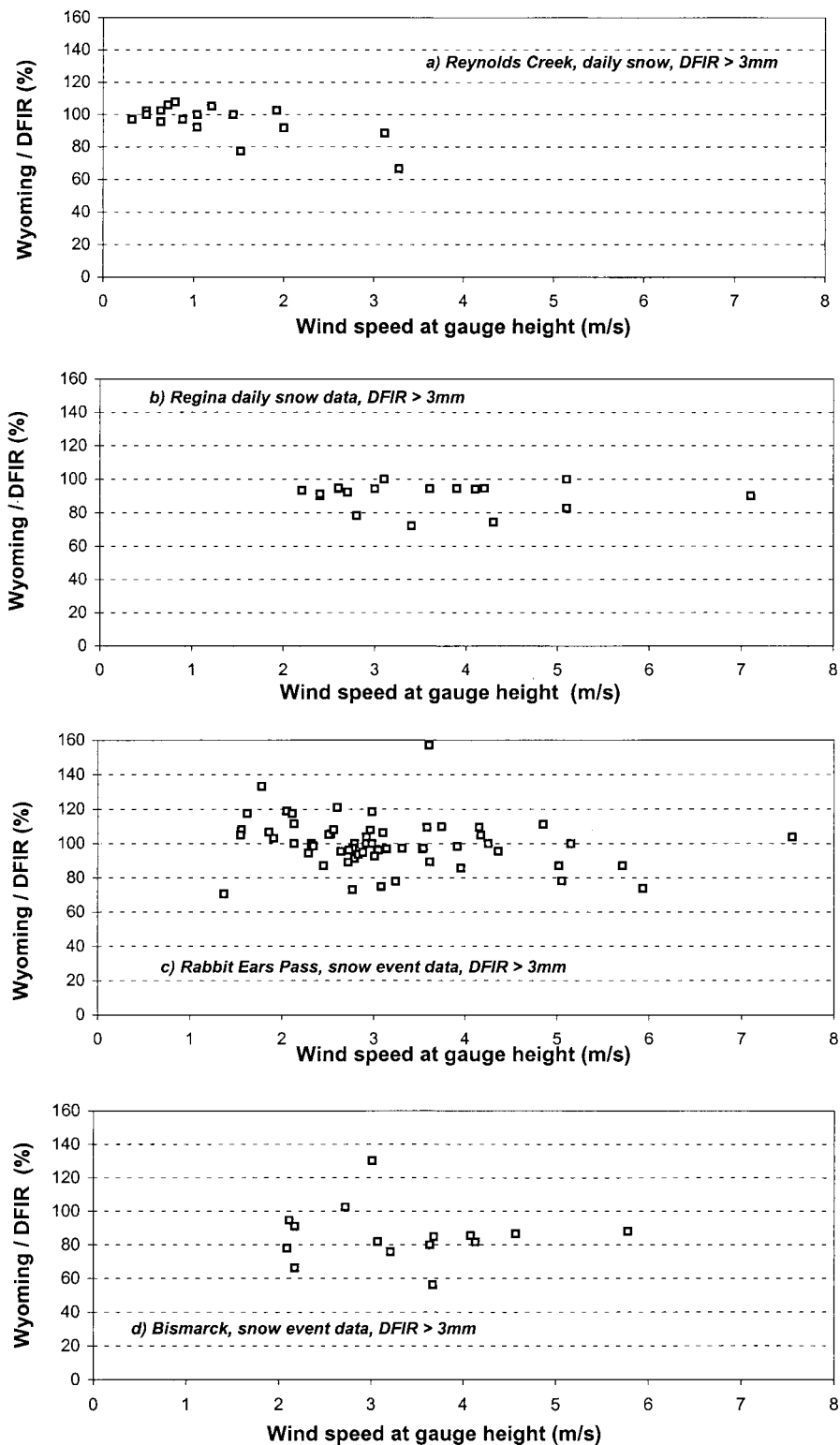
**Figure 5.** Comparison of precipitation event data measured by Wyoming gauge and the DFIR at Bismarck WMO site: (a) snow event data and (b) blowing snow events.

for the Imnavait Creek watershed might be in error because of model limitations and the magnitude and direction of the potential errors were unknown. Second, it is even more difficult because of data limitations to quantitatively determine how much snow was transported by wind into and out the basin during a winter season. Furthermore, because of the strong control of topography and vegetation on snow distribution, snow course data are not always representative of snow condition in a basin, particularly for regions with complex terrain and vegetation [Peck, 1997; Yang and Woo, 1999; Woo and Marsh, 1978; Liston and Sturm, 1998]. To better understand the compatibility of various snow measurements in the high-latitude regions, comprehensive analysis of gauge and snow cover data is necessary for a wider range of climate and terrain conditions.

#### 4. Discussion

Bias analysis of gauge snowfall data for windy and cold climates is a challenge, because gauges significantly undercatch

snowfall at high winds and blowing snow can potentially introduce huge errors. In this study, blowing snow events were separated from the nonblowing snow events, and the mean catch of the Wyoming gauge systems for the blowing snow cases was found to be between 61 and 68% compared to the DFIR. On the basis of the WMO experimental data it is difficult to assess the effect of blowing snow on both the DFIR and the Wyoming gauge catch. Goodison and Metcalfe [1982] reported that the Wyoming shielded Belfort gauges measured higher winter snowfall than the Canadian Nipher gauge at several test sites in Canada because they accumulated trace amounts of snowfall and blowing snow. D. Yang and T. Ohata (A bias corrected Siberian regional precipitation climatology, submitted to *Journal of Hydrometeorology*, 2000) recently analyzed the wind data on snowfall days in Siberian regions and found that gauge-measured snowfall increased with wind speed, particularly for the higher winds (over 15 m/s) with possible blowing snow conditions in the northern Siberia coastal regions. Their finding suggests that precipitation



**Figure 6.** Catch ratio of the Wyoming gauge versus wind speed at the gauge height at the four WMO Intercomparison sites: (a) Reynolds Creek, (b) Regina, (c) Rabbit Ears Pass, and (d) Bismarck.

gauges catch horizontal blowing snow fluxes and overestimate snowfall amount in the Siberian regions. It is clear that blowing snow will be a problem in quantifying the gauge catch of snowfall. Further model and experimental efforts are needed to better examine and define the performance of gauges and

shields (such as the DFIR and the Wyoming gauge systems) in high-wind conditions of the arctic regions.

Compatibility of gauge measurements owing to different gauge designs is also an important issue in gauge intercomparison experiment and climate change analysis [Sevruk, 1989;

**Table 3.** Comparison of Wyoming Gauge Winter Snowfall With Basin-Mean Snowpack Water Equivalent (SWE) at the Imnavait Creek Watershed<sup>a</sup>

Winter	Mean Temperature, °C	Mean Wind Speed, m/s	Wyoming Gauge, mm	Basin-Mean SWE, mm	Snow Sublimation, mm	Wyoming/SWE	Wyoming/SWE Plus Sublimation
1985–1986	missing data	missing data	97	109	NA	0.89	NA
1986–1987	–14.3	4.2	104	108	38	0.96	0.71
1987–1988	–13.7	3.9	86	78	25	1.11	0.83
1988–1989	–14.2	4.0	missing data	155	38	NA	NA
1989–1990	–14.3	4.0	89	106	13	0.84	0.75
1990–1991	–15.4	2.6	97	82	NA	1.18	NA
Mean	–14.4	3.7	97	106	29	0.99	0.76

NA, not available.

Groisman et al., 1999; D. Yang et al., Compatibility evaluation of national precipitation gauge measurements, submitted to *Journal of Geophysical Research*, 2000]. The Wyoming shield, like other wind shields or fences, can be and has been used with different gauge types in both operational observation networks and at most experimental sites. For instance, an unshielded storage gauge was installed within the Wyoming shield in Alaska, but in the WMO intercomparison experiment the Alter shielded Belfort recording gauge was used with the Wyoming shield at most of the test sites. The combination of the Wyoming shield with different gauge types results in the design error associated with each gauge type being incorporated into the evaluation of the gauge system (i.e., gauge and shield). More importantly, different methods (such as shielded gauges, snowboards, and snow course/snow survey) have been used to determine the “true” snowfall amount in gauge experimental studies, and these methods do not always produce compatible results. For example, Clagett [1988], when noticing and explaining the substantial discrepancy of the Wyoming shield performance between Alaska and Wyoming test sites, considered the different references used in these studies, that is, snow course data in Alaska versus gauge measurements in Wyoming. Clagett [1988] pointed out that lower catch efficiency and the catch-wind relation reported by Sturges [1986] might be mainly caused by the possible (20%) overcatch of the reference gauge (located in a small forest opening) due to blowing snow from the nearby trees after the storms. The current study shows that the mean catch of the Wyoming gauge system is 80–90% compared to the DFIR and about 75% compared to the adjusted snow course data. The adjusted snow survey data are expected to be representative of the basin total winter snowfall. The DFIR, however, has been known to undercatch snow by about 10% at high wind speeds, and this undercatch has not been adjusted in the current data analysis. If this undercatch of the DFIR were adjusted, the mean catch ratios of the Wy-

oming shielded gauges would drop by 10–15%, resulting in the gauge intercomparison results agreeing better with the Alaska results.

For the Wyoming shielded gauges used in the Alaska coastal regions, riming events are another problem since the supercooled fog coats everything including the inside of the orifice of a precipitation gauge. Most of the Wyoming shielded gauges in Alaska are located in remote locations and are visited at best once or twice a month; rime events, which build up from time to time, can reduce or sometimes completely block the gauge orifice. The error in gauge readings due to riming is magnified either by a net loss of precipitation or a net gain when the rime melts into the gauge [Clagett, 1988]. The magnitude of the errors in the Wyoming shielded gauge measurements is unknown and needs to be quantified through field experiment.

### 5. Conclusion

Intercomparison data collected during the Solid Precipitation Measurement Intercomparison Project show that the mean catch efficiency of the Wyoming shielded gauge versus the DFIR is about 80–90% at most of the WMO sites. Catch efficiency of the Wyoming shielded gauges does not change with wind speed or air temperature compared to the DFIR; this indicates that the Wyoming shield has similar properties to the DFIR and, with corrections for the errors noted above, could serve as a suitable reference for snowfall observation in windy, exposed, and remote locations. A close relation between the Wyoming gauge system and the DFIR observations was found both on a daily timescale and for precipitation events. This linear relation was derived from the WMO data, and it can be used as a transfer function to adjust the Wyoming shielded gauge data to the DFIR. In addition, Wyoming shielded gauge measurements show generally compatible relations to the snowpack water equivalent at selected tundra and

**Table 4.** Comparison of Wyoming Gauge, Forest Protected Gauge, and Standard Snow Survey Measurements at Rhoades Creek<sup>a</sup>

Winter	Wyoming Gauge, mm	Forest Protection, mm	Snow Survey, mm	Snow Sublimation, mm	Wyoming/Forest	Wyoming/Snow Survey	Wyoming/Snow Survey Plus Sublimation
1983–1984	66	69	64	11	0.96	1.03	0.88
1984–1985	99	119	132	17	0.83	0.75	0.66
1985–1986	94	96	91	15	0.98	1.03	0.89
1986–1987	66	71	71	12	0.93	0.93	0.80
Mean	81	89	90	14	0.92	0.94	0.78

<sup>a</sup>After Clagett [1988].

forest locations in Alaska, indicating some consistency to the WMO gauge intercomparison result.

On the basis of the WMO experiment and other relevant studies a summary of the advantages and disadvantages of both the DFIR and the Wyoming gauge systems is possible and useful. Both gauge systems are designed for measuring true snowfall amount, and both shield designs have significantly improved gauge catch of snowfall compared to unshielded and shielded gauges. The DFIR was reported to undercatch snowfall at higher wind speeds [Golubev, 1985; Yang *et al.*, 1993a]. The Wyoming gauge system may undercatch snow as well, since it generally measures less snow than the DFIR at the WMO experimental sites. Deposition of blowing/drifted snow under the leeward side of the DFIR was observed at some WMO test sites [Goodison *et al.*, 1998]. The Wyoming shield, however, was configured to have the advantage of accelerating airflow downward and thus eliminating snow drifts under the fences [Clagett, 1988]. The physical size of the Wyoming shield is smaller than the DFIR, making the Wyoming shield a more practical choice for operational use. Installation of both systems is time-consuming and difficult. The cost of building and operating these shields varies by location, and an annual inspection and maintenance may be required depending on the local environment.

The Wyoming shielded gauges currently existing in Alaska constitute a valuable precipitation observation network in addition to the NWS stations. These gauges provide reliable snowfall data for regional hydrological and climatic studies. However, caution is needed when using the Wyoming shielded gauge data in conjunction with the archived NWS climate records to analyze spatial distribution of precipitation, as the NWS records are obtained by unshielded or shielded standard gauges which undercatch snowfall by 50–100% [Black, 1954; Benson, 1982; Yang *et al.*, 1998a]. Compatible and accurate data sets are critical for hydrologic and climatic analyses at both regional and global scales. In order to generate reliable and less biased regional precipitation data sets and improved precipitation climatologies, more efforts are needed to conduct bias corrections of the archived precipitation records in Alaska and other northern regions.

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