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Quantification of precipitation measurement discontinuity induced by wind shields on national gauges

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Abstract. Various combinations of wind shields and national precipitation gauges commonly used in countries of the northern hemisphere have been studied in this paper, using the combined intercomparison data collected at 14 sites during the World Meteorological Organization's (WMO) Solid Precipitation Measurement Intercomparison Project. The results show that wind shields improve gauge catch of precipitation, particularly for snow. Shielded gauges, on average, measure 20–70% more snow than unshielded gauges. Without a doubt, the use of wind shields on precipitation gauges has introduced a significant discontinuity into precipitation records, particularly in cold and windy regions. This discontinuity is not constant and it varies with wind speed, temperature, and precipitation type. Adjustment for this discontinuity is necessary to obtain homogenous precipitation data for climate change and hydrological studies. The relation of the relative catch ratio (RCR, ratio of measurements of shielded gauge to unshielded gauge) versus wind speed and temperature has been developed for Alter and Tretyakov wind shields. Strong linear relations between measurements of shielded gauge and unshielded gauge have also been found for different precipitation types. The linear relation does not fully take into account the varying effect of wind and temperature on gauge catch. Overadjustment by the linear relation may occur at those sites with lower wind speeds, and underadjustment may occur at those stations with higher wind speeds. The RCR technique is anticipated to be more applicable in a wide range of climate conditions. The RCR technique and the linear relation have been tested at selected WMO intercomparison stations, and reasonable agreement between the adjusted amounts and the shielded gauge measurements was obtained at most of the sites. Test application of the developed methodologies to a regional or national network is therefore recommended to further evaluate their applicability in different climate conditions. Significant increase of precipitation is expected due to the adjustment particularly in high latitudes and other cold regions. This will have a meaningful impact on climate variation and change analyses.

1. Introduction

It has been well documented that wind-induced gauge undercatch of precipitation, among other known systematic errors, is the greatest source of bias in precipitation observation [*Sevruk*, 1989; *Goodison et al*., 1989; *Groisman et al*., 1991; *Groisman and Easterling*, 1994; *Groisman and Legates*, 1994; *Yang et al*., 1995, 1998a, b; *Peck*, 1997]. To reduce the wind-induced undercatch, wind shields of various types were introduced and used with national precipitation gauges [*Sevruk and Klemm*, 1989]. It is acknowledged that changes in instrumentation may introduce a discontinuity into precipitation time series since the gauge measurement is affected by gauge design, including particularly whether the gauge is equipped with a wind shield [*Karl et al*., 1993; *Groisman and Legates*, 1994; *Metcalfe et al*., 1997], as numerous experimental studies clearly show that a shielded gauge can catch up to 50% more precipitation than its unshielded counterpart for the same environmental conditions [*Larkin*, 1947; *Larson and Peck*, 1974; *Goodison et al*., 1981; *Sturges*, 1984; *Hanson*, 1989].

In the United States the use of Alter wind shields was adopted in the late 1940s at some (20–40%) of the gauges at first-order climate stations; however, prior to 1948 wind shields were absent [*Karl et al*., 1993]. Change from unshielded gauge to shielded gauge also occurred in other countries, such as Sweden, Norway, and the former Soviet Union [*Karl et al*., 1993]. In China the national precipitation gauge was equipped with a wind shield during the period of 1954–1960 [*Sevruk and*

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Klemm, 1989]. The effect of the change, that is, magnitude of discontinuity in precipitation records induced by use of wind shields, was roughly estimated to have increased by 5–40% snowfall measurement in these countries [*Karl et al*., 1993]. It is emphasized that a discontinuity of such magnitude will make climate change detection tenuous at many stations within these countries [*Karl et al*., 1993].

It is known as well that discontinuity also exists across national boundaries owing to the different instruments and observation methods used in neighboring countries [*Sanderson*, 1975; *Sevruk and Klemm*, 1989]. For instance, the Tretyakov gauge has been the standard instrument for measuring precipitation in the former Soviet Union climatological and hydrological station network since the late 1940s [*Groisman et al*., 1991]. The Tretyakov gauge was also used in Finland, Romania, Afghanistan, and North Korea. The Tretyakov gauges operated in Russia and Finland are presently equipped with the Tretyakov wind shield. However, in Romania, Afghanistan, and North Korea the Tretyakov gauges are not shielded [*Sevruk and Klemm*, 1989].

It is reported that in some countries wind shields were used with precipitation gauges only in mountain regions or only in the colder seasons for snowfall measurement [*Sevruk and Klemm*, 1989]. In the United States the number of the Alter-shielded gauges in the National Weather Service (NWS) station network has been reduced from about 500 to fewer than 200 since the 1940s [*Karl et al*., 1993]. It has been realized lately that the combination of precipitation records from shielded and unshielded gauges can result in inhomogenous precipitation time series and can lead to incorrect spatial interpretations [*Sevruk*, 1989; *Karl et al*., 1993; *Desbois and Desalmand*, 1995; *Hanssen-Bauer and Forland*, 1994; *Legates and Willmott*, 1990]. Use of such data for climate change and hydrological studies could be misleading. Adjustment of precipitation records for inhomogeneity is certainly necessary.

The magnitude of the discontinuity induced by the varying use of wind shield has not been quantitatively determined for various wind shields and precipitation gauges operated in many countries owing to the lack of necessary experimental data. The current study will quantify the effect of wind shields (Alter, Tretyakov, and Nipher types) commonly used with many national standard precipitation gauges in the northern hemisphere and will also present a methodology to adjust the discontinuity. In this study the extensive data set compiled from the World Meteorological Organization's (WMO) Solid Precipitation Measurement Intercomparison Project [*Goodison et al*., 1989; *WMO/Commission on Instruments and Methods of Observation* (*CIMO*), 1985] was carefully analyzed. The magnitude of the inhomogeneity and its seasonal variability was clearly demonstrated. The dependence of relative gauge catch (ratio of measurements from shielded gauges to those from unshielded gauges) to precipitation type, wind speed, and air temperature was investigated. Linear relation of precipitation measurements by shielded gauge and unshielded gauge was also examined. Transfer functions between unshielded and shielded gauges were developed. The developed adjustment procedures were tested at selected WMO experimental sites and reasonable agreement between the adjusted amounts and the shielded gauge measurements was obtained. To further evaluate the applicability of these relations to a wider range of environmental conditions, we recommend test application of the adjustment methods in regional observation networks.

2. Sites and Data Sources

Table 1 summarizes the site and instrumental information (gauge type, wind shields, anemometer height, method of observation, period of data collection, and recent references) at 14 WMO intercomparison stations that tested shielded and unshielded national gauges among other types of gauges. The national gauges included the Canadian Nipher snow gauge, the U.S. 8-inch nonrecording gauge, the Russian Tretyakov gauge, the Chinese standard gauge, Hellmann gauges of various versions, the Finnish Wild gauge, and the Belfort recording gauge [*Sevruk and Klemm*, 1989]. The wind shields tested were the U.S. Alter shield, the Russian Tretyakov shield, the Canadian Nipher shields (including large Nipher shield), and European Nipher shields [*Sevruk and Klemm*, 1989]. The double fence intercomparison reference (DFIR) was operated at most of the sites to provide the true snowfall value for the WMO intercomparison project. Installation of the national gauges, the DFIR, and other observing equipment and the associated observational procedures followed the experimental guidelines documented by *WMO/CIMO* [1985].

At most of the sites one observation was made each day for five winter seasons from 1987 to 1992. At some the experimental program was continued all year and a large number of rain and mixed precipitation data were also collected. 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 each participant before being submitted 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 the final report to the WMO and in this study. Additional details on sitting, instrument and method of observation were provided in the references listed in Table 1.

According to *WMO/CIMO* [1985], intercomparison data collected at various time intervals, such as 6-hourly, twice-daily, daily, and event data, should be analyzed. For the purpose of easy application of the WMO intercomparison results to the national precipitation data archives, the daily intercomparison data were used for analyses in this study and the relation of relative gauge catch to environmental variables was also investigated on a daily basis.

3. Methods of Data Analysis

Data analysis in this study follows the guidelines established by *WMO/CIMO* [1985, 1993] and focuses on the comparison of the precipitation measurements by a pair of shielded and unshielded gauges of the same type. Wetting and evaporation losses, undercatch of the DFIR at high winds, blowing snow, wind reduction from measured height to the gauge orifice level, and data combination and compatibility were considered [*WMO/CIMO*, 1993]. Wetting losses were corrected for each nonrecording gauge by precipitation type if volumetric methods were used for observation. Evaporation losses were reported to be small for most of the gauges [*Golubev et al*., 1992; *Elomaa*, 1993], and thus they were not corrected in this study. Undercatch of the reference standard instrument, DFIR, was corrected using the procedures developed by *Yang et al*. [1993], and the true snowfall amount was obtained. Blowing snow events were identified and eliminated from the analysis of relation of relative catch ratio (RCR) to environmental factors. Wind speed at the gauge height is required to evaluate the

Table 1. Siting and Instrumental Information at 14 WMO Intercomparison Sites

Station	Latitude, Longitude, Elevation	DFIR	National Gauges	Wind Shields	Wind Sensors	Observation Method	Observation Period	Reference
Valdai, Russia	57°59′N, 33°15′E; 194 m	at 3 m	Tretyakov, U.S. 8-inch, Canadian Nipher	Tretyakov, Alter, Canadian Nipher	at 3 and 2 m	volumetric	Oct. 1991 to March 1993	*Golubev et al.* [1992]
Jokioinen, Finland	60°49′N, 23°29′E; 104 m	at 3 m	Tretyakov, Hellmann, Wild, Canadian Nipher	Tretyakov, Finnish Nipher, Canadian Nipher	at 3 m	volumetric weighing	Oct. 1988 to March 1993	*Elomaa* [1993], *Aaltonen et al.* [1993]
Harzgerode, Germany	51°39′N, 11°08′E; 404 m	at 3 m	Hellmann, Tretyakov	Tretyakov, German Nipher	at 3 m	volumetric	Dec. 1986 to March 1993	*Gunther* [1993]
Danville, Vermont, United States	44°29′N, 72°10′W; 552 m	at 3 m	Belfort	Alter	at 3 m	volumetric	Dec. 1986 to April 1992	*Bates et al.* [1987], *Larson and Peck* [1974]
Reynolds Creek, Idaho, United States	43°12′N, 116°45′W; 1193 m	at 3 m	U.S. 8-inch, Belfort, Tretyakov, Canadian Nipher	Alter, Canadian Nipher, Wyoming fence	at 9.1, 3, and 2 m	weighing	Nov. 1987 to Feb. 1992	*Hanson and Rango* [1992]
Bismarck, North Dakota, United States	46°46′N, 100°45′W; 502 m	at 3 m	Belfort, Tretyakov	Alter	at 6.1, 3, and 1.4 m	weighing	Nov. 1988 to April 1991	*Emerson* [1990]
Rabbit Ears Pass, Colorado, United States	40°23′N, 106°38′W; 2925 m	at 3 m	Belfort, Tretyakov	Alter, larger Nipher	at 10 and 3 m	weighing	Nov. 1989 to April 1993	*Leavesley and Beaver* [1993]
Dease Lake, B. C., Canada	58°05′N, 130°00′W; 816 m	at 3 m	Canadian Nipher, Belfort	Alter, Canadian Nipher, large Nipher	at 10, 3, and 2 m	volumetric	Dec. 1987 to April 1993	*Goodison and Metcalfe* [1989, 1992]
Kortright Centre, Ont., Canada	43°51′N, 79°36′W; 208 m	at 3 m	Canadian Nipher, Belfort	Alter, Canadian Nipher, large Nipher	at 10, 3, and 2 m	volumetric	Jan. 1987 to March 1991	*Goodison and Metcalfe* [1989, 1992]
Parg, Croatia	45°36′N, 14°38′E; 863 m	at 3 m	Hellmann, Tretyakov	Tretyakov	at 11.2 m	volumetric	Jan. 1987 to April 1989	*Milkovic* [1989]
Urumqi Meteorological Station, China	43°54′N, 87°28′E; 940 m	n/a	Chinese standard	Tretyakov	at 10 m	volumetric	Jan. 1986 to Jan. 1989	*Yang et al.* [1989, 1993]
Tianshan Glaciological Station, China	43°13′N, 87°07′E; 2130 m	n/a	Chinese standard	Tretyakov	at 10 m	volumetric	Jan. 1986 to Jan. 1989	*Yang et al.* [1989, 1993]
Leap Forward Bridge Hydrometric Station, China	43°09′N, 87°06′E; 2400 m	n/a	Chinese standard	Tretyakov	at 10 m	volumetric	Jan. 1986 to Jan. 1989	*Yang et al.* [1989, 1993]
Daxigou Meteorological Station, China	43°06′N, 86°50′E; 3540 m	at 2 m	Chinese standard	Tretyakov	at 10 m	volumetric	Jan. 1986 to Jan. 1989	*Yang et al.* [1989, 1993]

DFIR, double fence intercomparison reference.

performance of the wind shields. When wind was not measured at the gauge height at some stations, it was estimated using the wind profile approach [*Golubev et al.*, 1992]. Estimate of the roughness coefficient (Z_0) is important to the wind profile method. 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 values for most sites. These values were used in the study. To expand the coverage of the RCR, wind speed, and temperature, intercomparison data collected for the same gauge type at different sites were combined. It has been reported that these data are compatible in terms of the catch efficiency for the same gauges, when wind speed at the gauge height was used in the analysis [*Goodison et al.*, 1998; *Goodison and Yang*, 1995; *Yang et al.*, 1995].

4. Results

Results of the data analyses were summarized by type of wind shields, with emphasis on (1) mean relative catch ratios (RCR) for various shield and gauge combinations, including intercomparison of wind shields; (2) relations of the RCR versus wind speed and temperature; (3) linear relation of shielded gauge to unshielded gauge measurements; and (4) test of the above relations.

Table 2. Summary of Intercomparison of the Shielded Versus Unshielded Tretyakov Gauges at Three WWO Sites

Precipitation Type	Event Number, Day	Mean T_{max}, °C	Mean T_{min}, °C	Mean Wind at 3 m, m/s	DFIR	Tretyakov Gauge	
						Shielded	Unshielded
				Jokioinen			
Snow	316	−2.1	−5.6	2.6	662.3 mm	494.3 mm	323.9 mm
					204.5%	152.6%	100.0%
Mixed	272	2.1	−0.9	3.0	745.3 mm	657.8 mm	562.1 mm
					132.6%	117.0%	100.0%
Rain	556	10.9	6.8	2.5	1538.0 mm	1475.6 mm	1420.7 mm
					108.3%	103.9%	100.0%
				Valdai			
Snow	136	−1.5	−4.2	4.5	668.9 mm	474.5 mm	323.6 mm
					206.7%	146.6%	100.0%
Mixed	87	1.0	−0.8	4.6	556.2 mm	489.3 mm	420.3 mm
					132.3%	116.4%	100.0%
Rain	122	7.7	5.0	4.0	773.0 mm	759.3 mm	721.5 mm
					107.1%	105.2%	100.0%
				*Rabbit Ears Pass**			
Snow	66	−3.6	−10.4	3.4	1140.5 mm	972.2 mm	671.4 mm
					169.9%	144.8%	100.0%

DFIR, double fence intercomparison reference.
*For event data.

4.1. Mean Relative Catch Ratios

4.1.1. Tretyakov shield. Table 2 gives the summary (total precipitation in millimeters and the mean RCR in percentage) of the comparison of shielded Tretyakov versus unshielded Tretyakov gauges for various types of precipitation at three WMO sites. The DFIR measurements were also included in the table to provide true precipitation amount. It is clear that both shielded and unshielded Tretyakov gauges undercatch precipitation. However, as expected, the shielded Tretyakov gauges caught more precipitation than their unshielded counterparts, particularly for snowfall measurements. The mean RCR of the Tretyakov gauges ranges from 145% to 153% for snow, 116% to 117% for mixed precipitation, and 104% to 105% for rain at these three sites.

Table 3 presents the summary of the comparisons of Tretyakov-shielded and unshielded Chinese standard gauges at four sites in northwest China [*Yang et al.*, 1989]. For mixed precipitation and rain the percentage increase of the relative gauge catch was similar to those for the Tretyakov gauges. However, the mean relative catch of snow of the shielded Chinese gauges, ranging from 114% to 125%, was somewhat lower compared to Tretyakov gauges, owing to the lower wind speeds (generally below 3 m/s) at the Chinese sites (Table 3). In addition, it is important to note that the snow data collected at the Daxigou climate station (located at 4300 m above sea level (asl)) were wet snow events in summer, and the corresponding mean relative catch of the wet snow events was lower compared to that for dry snow.

It is useful to investigate the effect of wind shield on gauge catch on a monthly basis. As an example, the monthly RCRs of the Chinese standard gauges are shown in Figure 1 for the Tianshan Glaciological Station, where the experiment was carried out in all seasons for 1986 and 1987 [*Yang et al.*, 1989]. The seasonal change of the ratio can be summarized as (1) low ratios for summer months and high ratios for winter months and (2) low variation of the ratio in summer season and high variation of the ratio for winter months. The lower variability of the ratios in summer indicates a stable performance of the wind shield and gauge for rainfall measurements. Thus it might be possible to consider the monthly RCR as constant in summer. On the other hand, the higher variability of the ratios in the cold season, which was caused by varying wind speed, air temperature, and percentage (or frequency) of snowfall in these months, indicates the physical complexity of wind shield and gauge for catching snowfall. Therefore it is not appropriate to treat the monthly ratios as constant in the cold season.

4.1.2. Alter shield. The Alter-type wind shield is the standard wind shield in the United States. It has been used with both the NWS 8-inch nonrecording gauge and the Belfort

Table 3. Tretyakov-Shielded Versus Unshielded Chinese Standard Gauges at Four Sites in Urumqi River Basin, China

Precipitation Type	Event Number, Day	Mean T_{mean}, °C	Mean Wind at 3 m, m/s	RCR, %
		Daxigou Station (3549 m asl)		
Snow	54	−0.7	2.5	114.4
Mixed	7	0.9	2.7	107.5
Rain	17	5.8	2.5	103.3
		Leap Forward Bridge (2400 m asl)		
Snow	31	−7.2	2.3	117.9
Mixed	33	0.6	2.1	113.6
Rain	151	9.7	1.9	105.2
		Tianshan Station (2130 m asl)		
Snow	34	−8.9	2.7	125.4
Mixed	25	0.6	1.1	114.9
Rain	110	10.3	1.5	106.6
		Urumqi Station (940 m asl)		
Snow	13	−5.7	1.5	138.6
Mixed	10	2.3	3.0	135.1
Rain	1	7.1	2.6	100.3

RCR, relative catch ratio, equals shielded/unshielded.

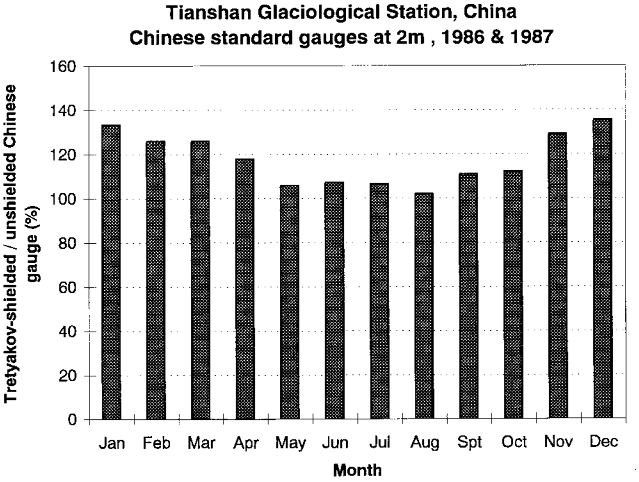


Figure 1. Ratios of monthly precipitation measurements by Tretyakov-shielded and unshielded Chinese gauges at Tianshan Glaciological Station for 1986 and 1987.

recording gauge. The Alter wind shield was also used on the Universal recording gauges at some of the automatic observing stations in Canada [*Goodison et al.*, 1983].

A summary of the intercomparison of the Alter shield with NWS 8-inch standard gauge and with Belfort recording gauges is given in Tables 4 and 5, respectively. It can be seen that compared to the unshielded NWS 8-inch gauges, Alter-shielded gauges caught 4% more rain, 20% more mixed precipitation, and 69% more snow at Valdai (Table 4). On the other hand, the Alter-shielded Belfort recording gauges measured 12–42% more snow, 9–13% more mixed precipitation, and almost the same amount of rain at five sites in the United States and Canada (except for Dease Lake and Bismarck, where not enough data were collected for mixed and rain events). The snow measurements of the Belfort gauges at Bismarck were too low compared to the DFIR observations; further investigation is needed to explain this discrepancy (Table 5).

It is important to note that the improvement of catch efficiency of snow due to the use of an Alter shield is higher for the NWS 8-inch standard gauge at Valdai than for the Belfort recording gauges at the other sites. The difference in the improved catch efficiency might be mainly due to the higher wind speed on precipitation days at Valdai, as studies show that the effect of wind shields on gauge catch increases with wind speed up to 9 m/s [*Larson and Peck*, 1974].

4.1.3. Canadian Nipher shields. Several different types of Nipher wind shields are currently in use in various countries [*Sevruk and Klemm*, 1989]. The Canadian Nipher shield is a modification of that originally designed by *Nipher* [1878], and it has been used with the Meterological Service of Canada (MSC) Nipher snow gauge (official Canadian instrument for measuring snowfall) since the winter of 1960–1961 [*Goodison et al.*, 1981]. Recently, a large Nipher wind shield was designed and used on the Universal recording gauge in Canada [*Goodison et al.*, 1983; *Goodison and Metcalfe*, 1992].

Intercomparison data collected at Kortright show that on average, the Canadian Nipher shielded snow gauge caught 40% more snow and 9% more (winter) rain than the unshielded counterpart (Table 6). It is important to note that data at this site also show that the RCR values of snow of the large Nipher-shielded Universal recording gauge are very close to those of the MSC Nipher-shielded snow gauge (Table 6). The good agreement of the RCR values of snow between the two gauges confirms that in comparison to the Canadian Nipher shield, the large Nipher shield has the similar effect of improving gauge catch efficiency [*Metcalfe and Goodison*, 1993].

The large Nipher shield and the Alter shield are widely used on Belfort recording gauges in the United States and Canada [*Goodison and Metcalfe*, 1992]. These wind shields were tested with Belfort gauges at three sites during the WMO intercomparison. Data obtained from the WMO project show that the large Nipher shield is more effective than the Alter shield. For instance, at Kortright the relative catches of the large Nipher–shielded Belfort gauge vary from 103% for rain to 139% for snow, compared to those of the Alter-shielded gauge being 99% for rain and 118% for snow (Table 6). Similarly, higher RCR of snow for the large Nipher–shielded gauges (138–145%) and lower RCR for the Alter-shielded gauges (114–119%) were also found at Dease Lake and Rabbit Ears Pass (Table 6). *Larkin* [1947] reported that the NWS 8-inch gauge with modified Nipher shield (Blue Hill and Mount Washington modification) measured 7% more rain than the unshielded gauge, and the Alter-shielded gauge caught 4% more rain than its unshielded counterpart. *Goodison et al.* [1981] reported that the large Nipher shield is more effective than the Alter shield in improving the gauge catch; however, the large Nipher shield could introduce an overcatch of snow due to snow accumulating on the shield during calm conditions and blown into the gauge at gust winds. On the basis of the results of earlier studies and the current work, it seems reasonable to conclude that the large Nipher wind shield is more effective than the Alter shield in improving gauge catch of precipitation.

4.1.4. European Nipher shields. Different types of modified Nipher wind shields were produced and used in European countries, such as Finland and Germany [*Sevruk and Klemm*,

Table 4. Summary of Alter-Shielded Versus Unshielded NWS 8-Inch Gauges at the Valdai WMO Site, Russia

Precipitation Type	Event Number, Day	Mean T_{mean}, °C	Mean Wind at 3 m, m/s	DFIR	NWS 8-Inch Gauge at 1 m	
					Alter-Shielded	Unshielded
Snow	154	−4.1	3.8	327.1 mm 245.0%	225.8 mm 169.1%	133.5 mm 100.0%
Mixed	73	0.7	4.5	429.7 mm 147.0%	350.4 mm 119.8%	292.4 mm 100.0%
Rain	108	10.0	3.6	409.2 mm 110.7%	384.6 mm 104.0%	369.8 mm 100.0%

Table 5. Summary of the Alter-Shielded Versus Unshielded Belfort Gauges at Five WMO Sites

Precipitation Type	Event Number, Day	Mean $T_{\max}$, °C	Mean $T_{\min}$, °C	Mean Wind at 3 m, m/s	DFIR	Belfort Gauge	
						Alter-Shielded	Unshielded
				Danville			
Snow	153	−2.4	−11.6	1.4	894.8 mm	860.4 mm	717.9 mm
					124.6%	119.8%	100.0%
Mixed	49	3.0	−6.5	1.2	827.3 mm	827.8 mm	731.6 mm
					113.1%	113.1%	100.0%
Rain	30	5.2	−1.6	1.0	432.4 mm	481.3 mm	409.2 mm
					105.7%	117.6%	100.0%
				Bismarck			
Snow	18	−2.9	−10.2	3.5	87.1=	15.2 mm	11.7 mm
					744.4%	129.9%	100.0%
Mixed	14	−4.4	−9.8	3.2	58.7 mm	6.9 mm	4.6 mm
					1276.1%	150.0%	100.0%
Rain	3	7.6	1.5	3.3	9.3 mm	n/a	n/a
					···	···	···
				Reynolds Creek			
Snow	65	3.0	−6.0	2.2	141.1 mm	142.7 mm	112.6 mm
					125.3%	126.7%	100.0%
Mixed	32	7.3	−3.1	3.5	117.6 mm	121.0 mm	110.8 mm
					106.1%	109.2%	100.0%
Rain	41	9.3	−0.2	2.7	194.5 mm	187.0 mm	185.0 mm
					105.1%	101.1%	100.0%
				Kortright			
Snow	107	−0.8	−10.6	2.5	249.3 mm	178.8 mm	148.5 mm
					167.9%	120.4%	100.0%
Mixed	42	3.8	−5.3	2.5	213.8 mm	182.6 mm	164.5 mm
					130.0%	111.0%	100.0%
Rain	58	7.8	−0.9	2.4	319.3 mm	221.3 mm	213.1 mm
					149.8%	103.8%	100.0%
				Dease Lake			
Snow	47	−9.6	−12.8	1.7	98.1 mm	94.6 mm	78.6 mm
					124.8%	120.4%	100.0%
Mixed	1	0.0	1.2	1.5	1.3 mm	2.1 mm	1.0 mm
					130.0%	210.0%	100.0%
Rain	1	3.8	1.6	2.9	0.4 mm	1.0 mm	0.5 mm
					80.0%	200.0%	100.0%

Table 6. Summary of Precipitation Measurement Intercomparison at Three WMO Sites

Precipitation Type	Number of Events (Days)	Mean $T_{\max}$, °C	Mean $T_{\min}$, °C	Mean Wind at 3 m, m/s	DFIR	Nipher Gauge at 2 m		Belfort Gauge at 2 m		
						Canadian Nipher	Unshielded	Alter	Large Nipher	Unshielded
					Kortright					
Snow	99	−1.0	−10.4	2.4	224.4	227.3 mm	162.7 mm	154.1 mm	181.4 mm	130.1 mm
						139.7%	100.0%	118.4%	139.4%	100.0%
Mixed	39	4.0	−5.0	2.5	246.2	240.7 mm	198.4 mm	206.4 mm	219.9 mm	188.6 mm
						121.3%	100.0%	109.4%	116.6%	100.0%
Rain	53	8.0	−0.6	2.4	206.6	205.3 mm	187.8 mm	151.0 mm	157.1 mm	152.6 mm
						109.3%	100.0%	99.0%	102.9%	100.0%
					Dease Lake					
Snow	69	−10.4	−13.8	1.8	114.9	···	···	98.0 mm	118.7 mm	86.2 mm
						···	···	113.7%	137.7%	100.0%
					Rabbit Ears Pass					
Snow	44	−2.6	−9.2	3.0	599.7	···	···	521.7 mm	631.4 mm	436.4 mm
						···	···	119.5%	144.7%	100.0%
Mixed	10	5.9	1.3	3.1	108.9	···	···	101.3 mm	112.6 mm	89.9 mm
						···	···	112.7%	125.3%	100.0%

Table 7. Summary of Intercomparison of Nipher-Shielded Versus Unshielded Gauges at Two WMO Sites

Precipitation Type	Event Number, Day	Mean T_{max}, °C	Mean T_{min}, °C	Mean Wind at 3 m, m/s	DFIR	Gauge Shielded	Gauge Unshielded
Jokioinen, Finnish Nipher Shield With Wild Gauge at 1.5 m							
Snow	448	−2.3	−5.8	2.7	649.0 mm	497.8 mm	351.3 mm
					184.7%	141.7%	100.0%
Mixed	253	2.1	−0.8	3.1	717.8 mm	558.9 mm	520.0 mm
					138.0%	107.5%	100.0%
Rain	333	11.2	7.0	2.5	738.6 mm	678.6 mm	666.4 mm
					110.8%	101.8%	100.0%
Harzgerode, German Nipher Shield With Hellmann Gauge at 1 m							
Snow	107	−1.2	−6.4	3.3	417.1 mm	281.0 mm	258.3 mm
					161.5%	108.8%	100.0%
Mixed	148	3.3	−1.8	4.3	624.7 mm	525.4 mm	489.6 mm
					127.6%	107.3%	100.0%
Rain	172	7.0	1.6	4.2	475.3 mm	410.0 mm	396.8 mm
					119.8%	103.3%	100.0%

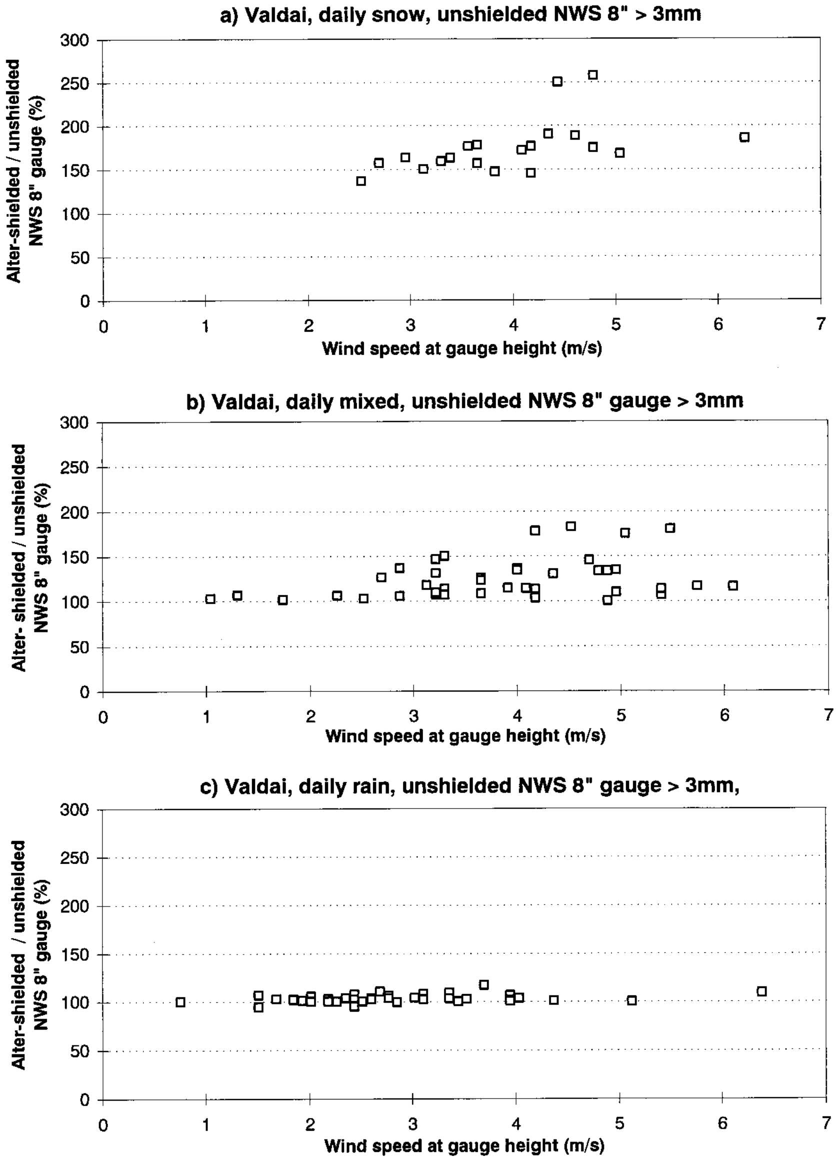
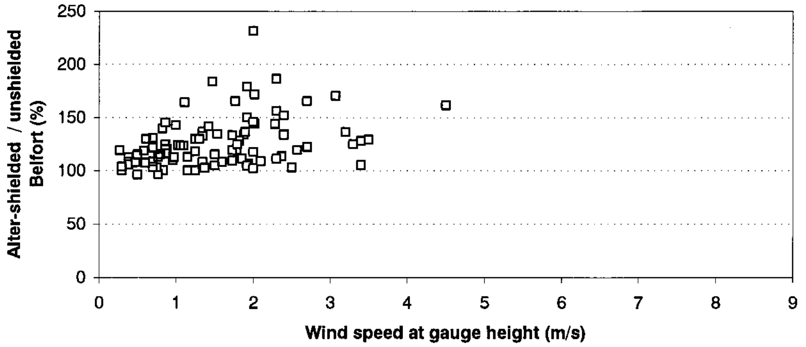
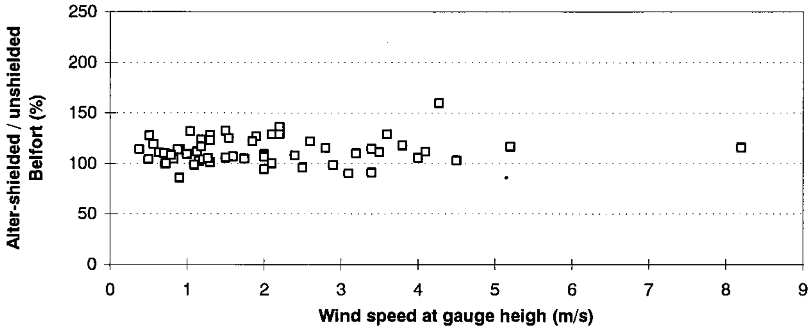


Figure 2. Relative catch ratio (RCR) as a function of wind speed at gauge height, Alter shield with NWS 8-inch standard gauges at the Valdai WMO site: (a) snow, (b) mixed precipitation, and (c) rain.

a) Daily snow, unshielded Belfort gauge >3mm, 5 WMO sites



b) Daily mixed, unshielded Belfort guage >3mm, 5 WMO sites



c) Daily rain, Unshielded Belfort > 3mm, 5 WMO sites

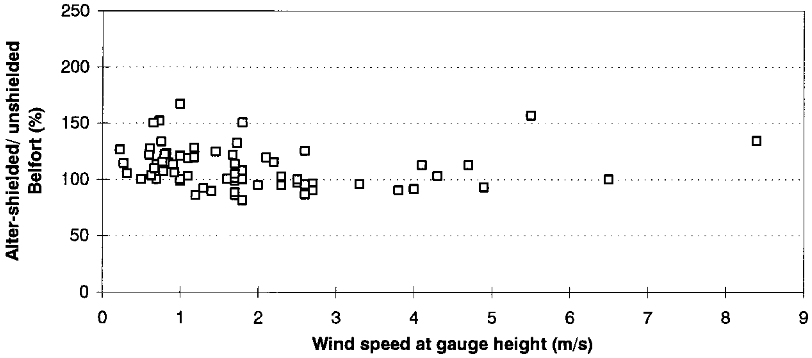


Figure 3. Relative catch ratio (RCR) as a function of wind speed at gauge height, Alter shield with Belfort recording gauges at five WMO sites: (a) snow, (b) mixed precipitation, and (c) rain.

1989]. Intercomparison data collected at Jokioinen in Finland show that the average relative catch of the Finnish Nipher-shielded Wild gauge ranges from 102% for rain to 142% for snow (Table 7). Similar data collection at Harzgrode in Germany indicates that the German Nipher-shielded Hellmann gauge measured 3% more rain and 30% more snow than the unshielded Hellmann gauge (Table 7).

4.2. Relation of the RCR Versus Wind Speed and Temperature

Studies have shown that gauge catch of precipitation depends on both environmental factors and precipitation features and that catch varies in each precipitation event [*Goodison et al.*, 1981; *Goodison and Yang*, 1995; *Yang et al.*, 1995, 1998a]. In order to investigate the relationship of RCR to environmental factors, daily data from several WMO intercomparison stations were compiled. These data represent a wide variety of climate, terrain, and exposure. It is known that small absolute values of gauge measurements can create significantly large unrealistic variations in the ratio of gauge catch [*Goodison et al.*, 1981; *Yang et al.*, 1995]. To minimize this effect, only daily totals when the unshielded gauge measurements were greater than 3 mm were used in the statistical analysis.

Different statistical models were used to describe the relationship of gauge catch to meteorological conditions [*Allerup and Madson*, 1980; *Allerup et al.*, 1997; *Sevruk*, 1982; *Goodison et al.*, 1981; *Yang et al.*, 1995, 1998a; *Gunther*, 1993; *Elomaa*, 1993; *Golubev et al.*, 1992; *Larson and Peck*, 1974]. These models included as input variables many meteorological factors, such as wind speed, temperature, humidity, atmospheric pressure, precipitation amount, intensity, and duration. Of these considered factors, wind speed and temperature have been found to be most important to affect gauge catch. An exponential model similar to that of *Goodison et al.* [1981] was examined in this study; it produced reasonable result when using only wind data as input. To include temperature factors

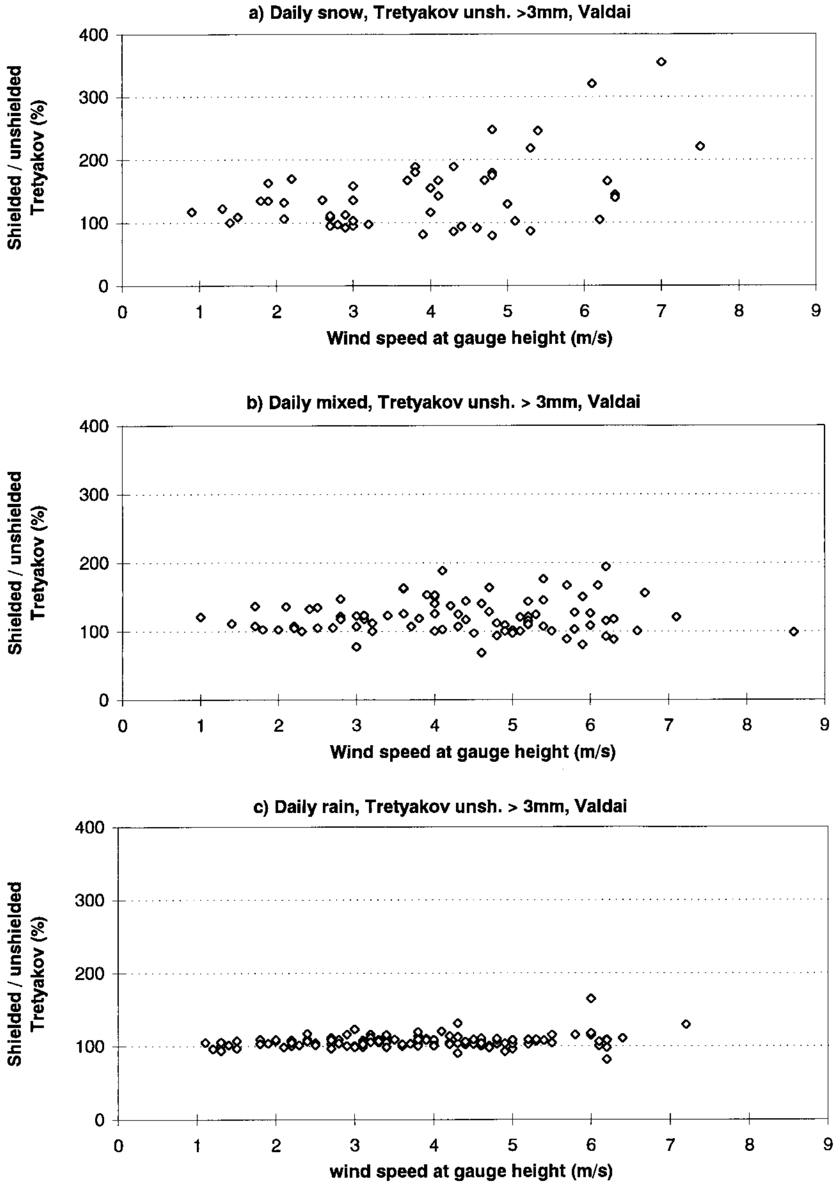


Figure 4. Relative catch ratio (RCR) as a function of wind speed at gauge height, Tretyakov shield with Tretyakov gauges at the Valdai WMO site: (a) snow, (b) mixed precipitation, and (c) rain.

in the analysis, a simple regression model similar to *Elomaa* [1993], that is, RCR = $a + b(\mathrm{Ws}) + c(T_{\max}) + d(T_{\min})$, was adopted and used for this study. In the regression analysis, stepwise regression technique was used to select statistically significant input variables. The regression coefficients were then determined by a least squares approach. Different temperature data were used for the analysis, since at some stations only daily mean temperature data were available. The results of these analyses are summarized by wind shield and gauge type.

4.2.1. Alter shield with NWS 8-inch standard gauge. Figure 2 presents the scatter plot of daily RCR versus daily wind speed at the gauge height for various types of precipitation. It shows that for mixed precipitation and snow, the RCR is close to 100% for the low wind speeds (below 2 m/s), and that for higher wind conditions the RCR increases with wind speed. Statistical analysis shows that wind speed is the most important factor affecting RCR of snow and mixed precipitation, and air temperature has a secondary effect. The RCR of rain was found to be independent to wind speed and temperature. A regression of daily RCR (percent) as a function of daily wind speed (Ws, m/s) at gauge height and air temperature (T_{mean}, °C) yields the best-fit regression equations for snow and mixed precipitation:

$$\mathrm{RCR(snow)} = 102.421 + 12.847 \times \mathrm{Ws} - 6.125 \times T_{\mathrm{mean}}$$
$$N = 20,\ R^2 = 0.320,\ 1.0 \leq \mathrm{Ws} \leq 6.0\ \mathrm{m/s},$$
$$-7.8 \leq T_{\mathrm{mean}} \leq 0.1°\mathrm{C} \qquad (1)$$

$$\mathrm{RCR(mixed)} = 107.730 + 6.013 \times \mathrm{Ws} - 7.802 \times T_{\mathrm{mean}}$$
$$N = 40,\ R^2 = 0.381,\ 1.0 \leq \mathrm{WS} \leq 6.0\ \mathrm{m/s},$$
$$-2.5 \leq T_{\mathrm{mean}} \leq 1.8°\mathrm{C} \qquad (2)$$

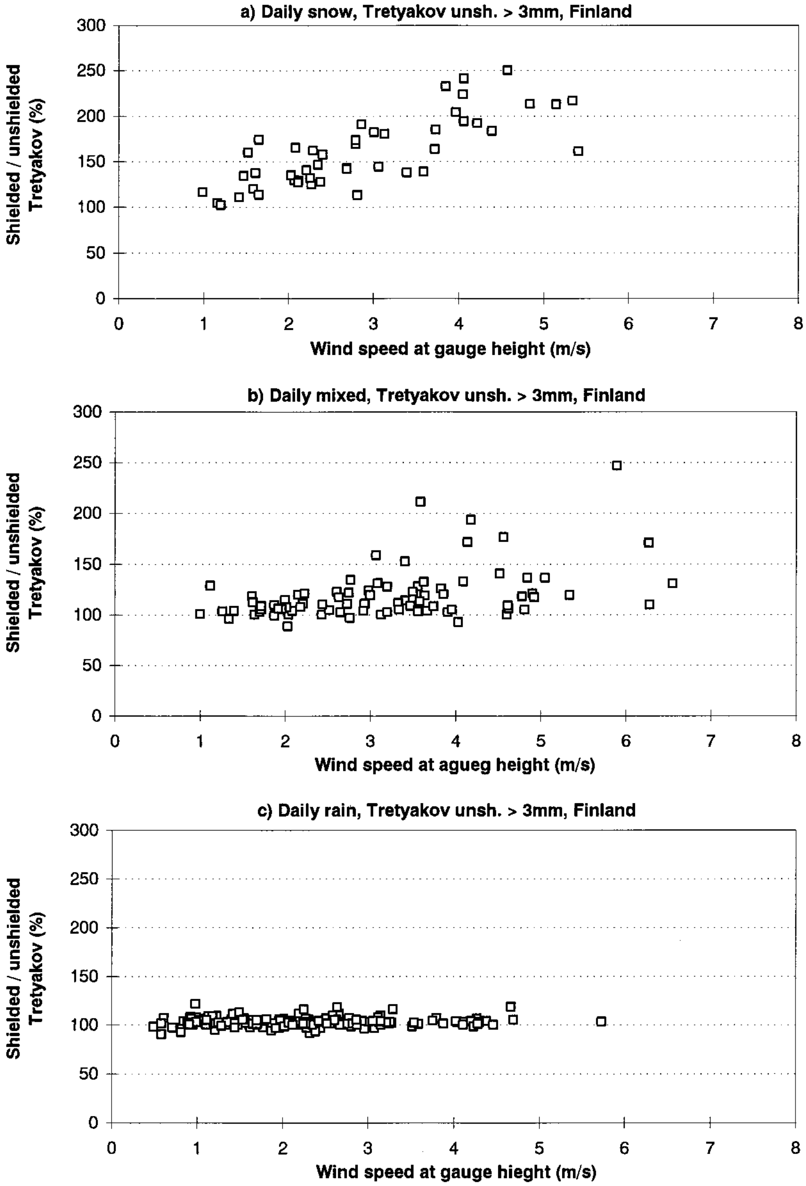


Figure 5. Relative catch ratio (RCR) as a function of wind speed at gauge height, Tretyakov shield with Tretyakov gauges at the Jokioinen WMO site: (a) snow, (b) mixed precipitation, and (c) rain.

4.2.2. Alter shield with Belfort recording gauge. Similar analysis was carried out on the combined daily data for Belfort recording gauges at five WMO intercomparison sites (Figure 3). It is apparent that wind speeds collected at these sites on precipitation days were generally low. It is also noted that compared to the NWS 8-inch standard gauge, a larger scatter of the RCR versus wind speed was observed. Although the plot indicates a weak relation of the RCR of snow versus wind speed at gauge height, regression analysis reveals that this relation was not statistically significant, and the RCR does not relate to air temperature. Observational problems such as wrong timing, wet snow sticking, and wind pumping have been reported [*Goodison et al.*, 1981; *Goodison and Metcalfe*, 1992; *Metcalfe and Goodison*, 1993]. It seems clear that the effect of wind shields on the catch of recording gauges cannot be easily evaluated until some of the identified problems are resolved.

4.2.3. Tretyakov shield with Tretyakov gauge. Intercomparison data collected at Valdai in Russia show a large scatter of the RCR versus wind speed for snow and mixed precipitation. For snow data there exist many low RCR values (close to 100%) for the wind range of 3–6 m/s (Figure 4), and statistical analysis shows no significant relation of the RCR to wind speed. However, experimental data obtained at Jokioinen in Finland show that for snow, wind speed and maximum temperature affect the relative gauge catch (Figure 5). For mixed precipitation, minimum temperature is also a controlling factor. For rain the RCR is independent to wind speed and air temperature. The best-fit regressions of the RCR (percent) to wind speed (Ws, m/s) and temperatures ($T_{\max}$ or $T_{\min}$, °C) were derived for snow and mixed precipitation:

$$\mathrm{RCR(snow)} = 76.072 + 27.101 \times \mathrm{Ws} - 3.828 \times T_{\max}$$

$$N = 47,\ R^2 = 0.661,\ 1.0 \le \mathrm{Ws} \le 6.0\ \mathrm{m/s},$$

$$-11.5 \le T_{\max} \le 1.0°\mathrm{C} \qquad (3)$$

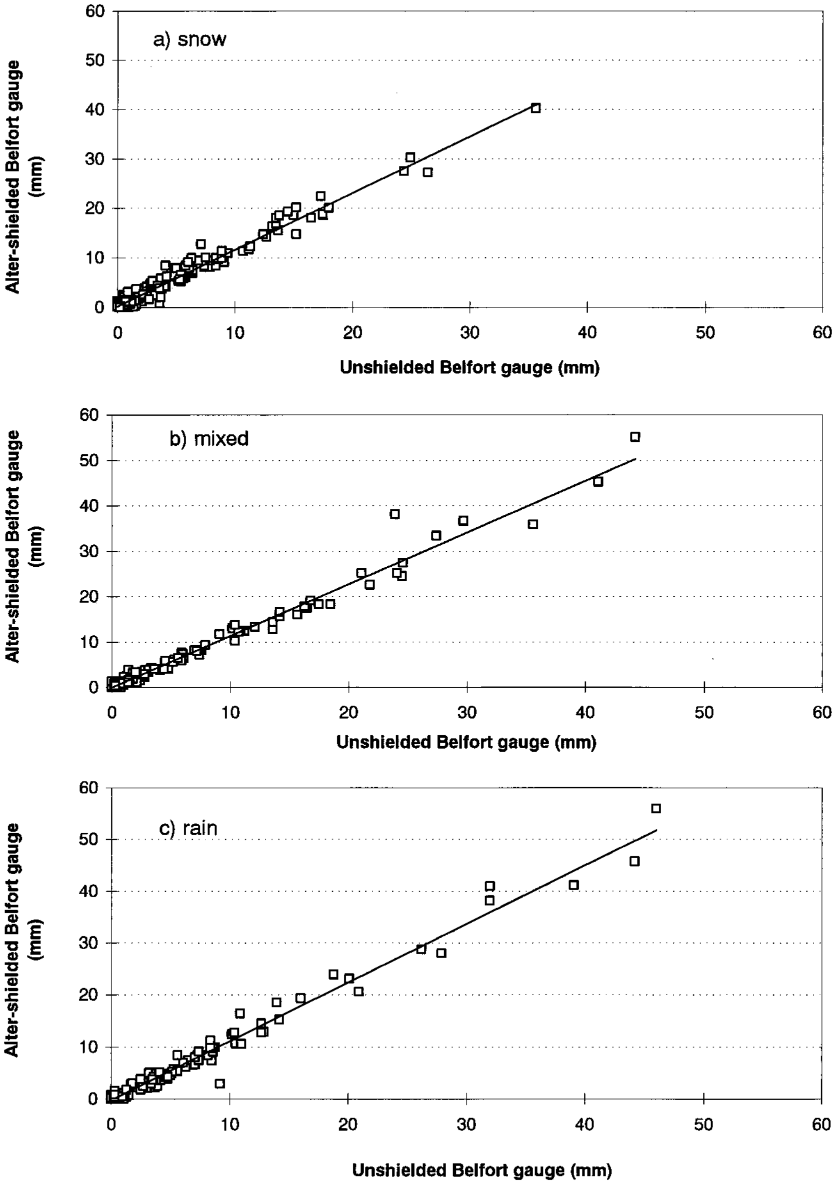


Figure 6. Comparison of daily precipitation measurements by Alter-shielded and unshielded Belfort recording gauges at five WMO intercomparison sites: (a) snow, (b) mixed precipitation, and (c) rain.

$$\mathrm{RCR(mixed)} = 106.87 + 6.983 \times \mathrm{Ws} - 4.536 \times T_{\max} - 5.603 \times T_{\min}$$

$$N = 81,\ R^2 = 0.416,\ 1.0 \le \mathrm{Ws} \le 6.5\ \mathrm{m/s},$$

$$-0.6 \le T_{\max} \le 2.5°\mathrm{C},\ -6.1 \le T_{\min} \le 0.5°\mathrm{C} \quad (4)$$

4.2.4. Other shields. Owing to data limitations particularly wind observations, the relation of the RCR as a function of wind speed and temperature has not been derived for other wind shields and gauge types in this study. Experimental study such as the WMO Intercomparison Project should continue to collect necessary data for further investigations.

4.3. Linear Relation of Shielded Versus Unshielded Gauge Measurements

Catch of shielded and unshielded gauges was directly compared on a daily basis for various precipitation types. A strong linear relation was found to exist for all types of precipitation with a higher correlation for rain than for snow (Figures 6–8). These linear relations were derived by regression approach, and the equations for various wind shield and gauge configurations are summarized in Table 8. It is important to point out that these linear relations and the RCR-wind equations, derived from the WMO intercomparison data, are valid statistically only for the wind speed, temperature, and measured precipitation intervals for which they are developed and they should not be used for extrapolation outside these ranges [*WMO/CIMO*, 1993]. The ranges of wind speed, temperature and gauge-measured daily precipitation amount are given in Table 8 for the linear equations.

4.4. Test of the Relations

The derived relations (i.e., the RCR versus wind and temperature, and the linear relation) provide practical techniques for adjusting the unshielded gauge measurement to obtain an

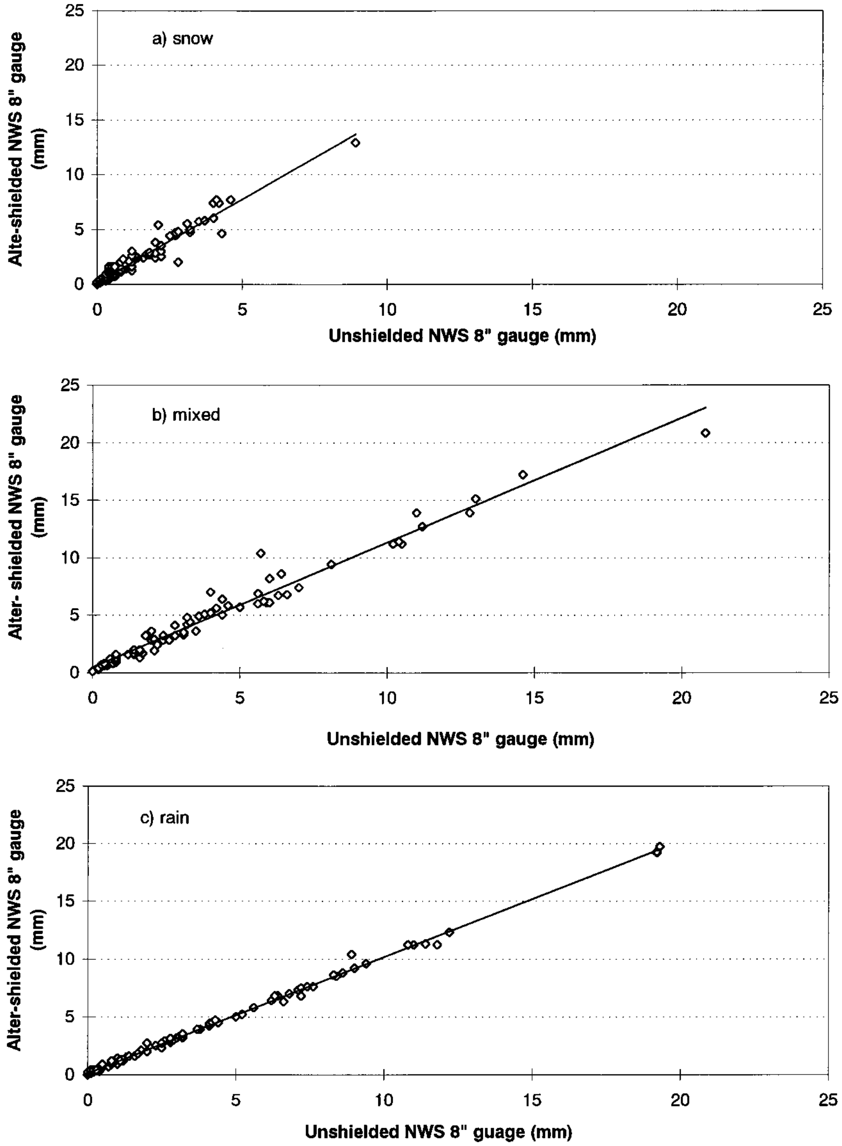


Figure 7. Comparison of daily precipitation measurements by Alter-shielded and unshielded NWS 8-inch standard gauges at the Valdai WMO site: (a) snow, (b) mixed precipitation, and (c) rain.

estimate of the shielded gauge observation. Test of the developed relations is necessary to evaluate their performance. This was done using all the WMO intercomparison data (without the unshielded gauge > 3 mm limitation) at several WMO sites. The inclusion of small precipitation events creates a new database for the test. Statistically, this data set is quite different from the data used to develop the relations. The number of observations in this data set is much larger, as it includes all the intercomparison data collected, and the mean precipitation is smaller and its variation is larger. Wind and temperature conditions are generally similar to the data used for the model development. The relative catch ratio (RCR) was computed on a daily basis using the RCR equations (1) and (2) or (3) and (4) for different precipitation and gauge types. The estimate of shielded gauge measurement (Pa) was then calculated as the product of the RCR and unshielded gauge measurement (Pm), that is, Pa = RCR × Pm. On the other hand, Pa was also determined by the linear relation of shielded gauge versus unshielded gauge.

Summaries of the tests are shown in Tables 9 and 10. For the unshielded Belfort gauges, conducting the adjustment by linear relations generally raises the relative catch of the gauges by 7–11% for rain and 18–28% for snow at the four WMO sites (Table 9). As a result, the adjusted precipitation totals agreed much better to those of the Alter-shielded gauges, although a small overadjustment of snow data (about 6–8%) was observed at Kortright and Dease Lake.

For the NWS 8-inch standard gauges at Valdai, both the linear relation and the RCR technique yield almost the same amount of adjustments. The adjustments improved the relative catch of the unshielded gauge by 69% for snow and 4% for rain (Table 9). The adjusted precipitation totals agreed very well to those measured by the Alter-shielded gauge.

For the Tretyakov gauges at three sites the linear adjustment increased the relative catch by 41% for snow and by 4–8% for rain, and the adjusted snowfall totals were 3–11% lower with respect to the shielded Tretyakov gauge measurements at the sites (Table 10). On the other hand, the RCR technique raises

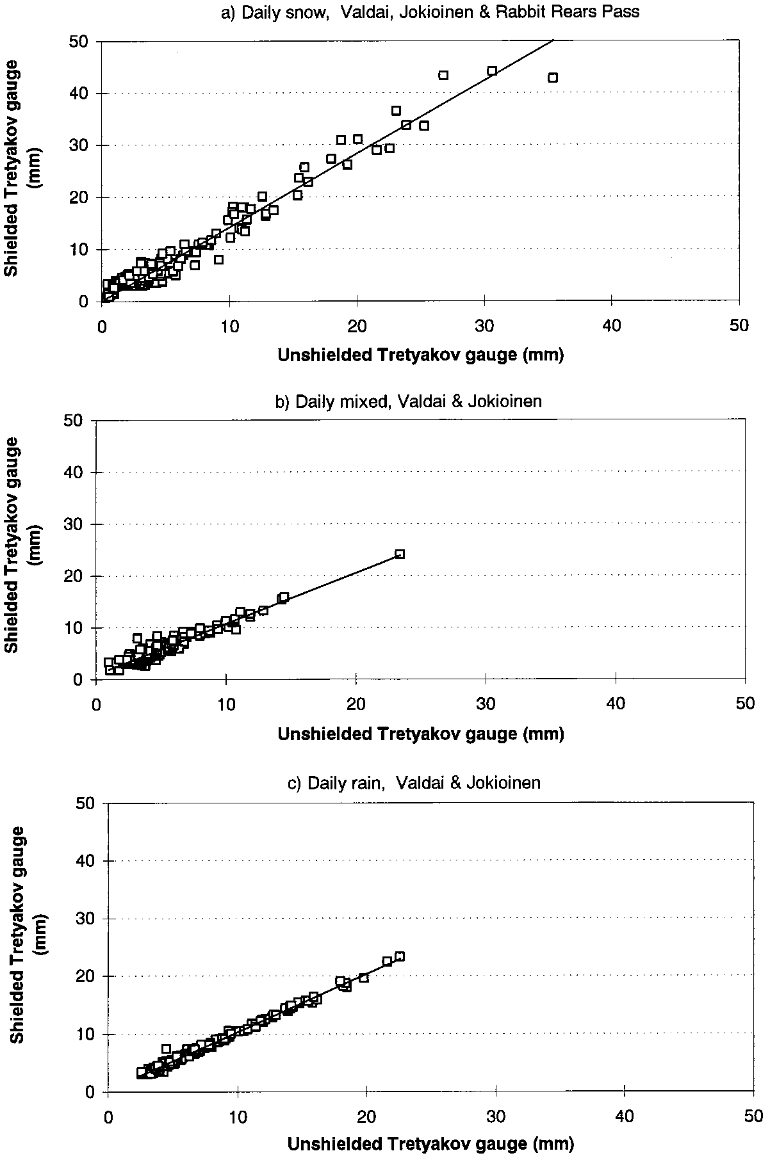


Figure 8. Comparison of daily precipitation measurements by Tretyakov-shielded and unshielded Tretyakov gauges at three WMO sites: (a) snow, (b) mixed precipitation, and (c) rain.

the relative catch of the unshielded gauge by 47–90% for snow and 17% for mixed precipitation. A small underadjustment (about 6%) of snow was obtained at Jokioinen, and a notable overadjustment of snow data was observed at Rabbit Ears Pass (37%) and Valdai (43%).

It is not unexpected to see the overadjustment of snow data at Valdai, since (1) at Valdai the RCR versus wind speed exhibits a large scatter, and statistical analysis shows that the RCR does not change with wind speed, and (2) the scatter plot of the RCR versus wind speed is different between Valdai and Jokioinen (Figures 4 and 5): at a given wind speed the RCR values were generally lower at Valdai in comparison to those at Jokioinen. The tested relation of the RCR versus wind speed and temperature, derived from the Jokioinen data, showed a gentle increase of the RCR with wind speed for a given temperature. When this relation was applied to Valdai, it produced higher RCR (i.e., higher adjustment) than Valdai data suggested, resulting in the overadjustment at this site. Further investigation is needed to explain the discrepancy; factors such as gauge installation, method of observation, and wind and snow conditions should be considered.

The relation of the RCR versus wind speed has not been investigated owing to insufficient wind data at Rabbit Ears Pass. Intercomparison data were collected on the basis of precipitation event at this site, and thus the adjustment was computed for each precipitation event. The overadjustment of snow data might be introduced by the use of mean wind speed and temperature during a precipitation event as input to the daily adjustment functions.

Overall these tests show significant improvement of the unshielded gauge catch due to the adjustment, particularly for snow and mixed precipitation. The adjusted precipitation data generally agree well with the shielded gauge measurements at most of the test sites, although overadjustment and underadjustment were observed at some sites. Given the fact that the adjustment methods were derived from the combined intercomparison data, which represent a general relation between the measurements of shielded gauge and unshielded gauge,

Table 8. Summary of Linear Relations (Daily) of Shielded Gauges to Unshielded Gauges and Associated Meteorological Conditions

					Conditions		
Precipitation Type	a	b	R^2	N	Temperature, °C	Wind, m/s	Pm, mm
Alter Shield With NWS 8-Inch Gauge							
Snow	1.516	0.153	0.87	21	−15.7–2.2	0.2–4.5	0.0–35.0
Mixed	1.085	0.456	0.95	41	−11.4–11.7	0.4–8.2	0.2–44.0
Rain	1.004	0.124	0.99	40	−22.0–16.1	0.2–8.4	0.0–46.0
Alter Shield With Belfort Gauge							
Snow	1.143	0.190	0.97	299	−23.0–3.0	0.2–4.5	0.0–35.0
Mixed	1.137	−0.070	0.98	61	−11.4–11.7	0.4–8.2	0.2–44.0
Rain	1.128	−0.215	0.98	138	−22.0–16.1	0.2–8.4	0.0–46.0
Canadian Nipher Shield With Nipher Gauge							
Snow	1.346	0.926	0.93	99	−21.1–3.1	0.0–5.8	0.1–19.0
Mixed	1.178	0.166	0.95	39	−15.4–11.7	1.0–4.1	0.2–29.0
Rain	1.039	0.191	0.99	53	−9.4–16.1	0.9–4.3	0.3–22.8
German Nipher Shield With Hellmann Gauge							
Snow	1.259	0.167	0.94	127	−17.7–2.3	0.6–7.7	0.1–9.7
Mixed	1.029	0.146	0.99	141	−6.0–6.0	1.0–9.0	0.0–21.0
Rain	1.018	0.035	0.99	172	−4.6–10.3	0.7–7.7	0.1–17.9
Tretyakov Shield With Tretyakov Gauge							
Snow	1.413	0.000	0.96	196	−16.0–2.6	0.9–7.6	0.4–35.0
Mixed	0.984	0.845	0.92	170	−11.2–7.7	1.0–8.6	1.0–23.4
Rain	1.005	0.198	0.99	276	0.0–20.5	0.5–7.2	3.0–23.0
Tretyakov Shield With Hellmann Gauge							
Snow	1.024	0.141	0.99	65	−16.0–1.5	0.5–9.5	0.0–70.0
Mixed	1.012	0.147	0.99	47	−6.0–7.6	0.5–6.5	0.0–43.0
Rain	1.010	0.106	0.99	141	−3.3–14.7	0.5–9.2	0.0–100.0

Pm, unshielded gauge measurement. Shielded $= a \times \text{Pm} + b$.

and a complex dependence of the RCR on wind speed and temperature, it is our opinion that both the linear relation and the RCR-wind technique perform reasonably well at the selected WMO sites. To further evaluate the applicability of these relations to a wider range of environmental conditions, we recommend test application of the adjustment methods in regional observation networks.

5. Conclusions

In this study various combinations of wind shields and national precipitation gauges commonly used in the northern hemisphere have been studied on the basis of the combined intercomparison data collected at 14 stations during the WMO Solid Precipitation Measurement Intercomparison Project. The results of this study confirmed that wind shields of various types improve gauge catch of precipitation and the use of wind shields on precipitation gauges for snowfall measurement is more effective than for rain. On average, shielded gauges measure 20–70% more snow than unshielded gauges (Figure 9). It is therefore certain that use of wind shields on precipitation gauges has introduced a significant discontinuity into precipitation records particularly in cold and windy regions. Because the magnitude of the discontinuity is so large, it will make the detection of climate change tenuous at many stations [*Karl et al.*, 1993], where varying use of wind shield has occurred. This discontinuity must be adjusted for in order to obtain homogenous precipitation data for climate change and hydrological studies, particularly on a national level [*Mekis and Hogg*, 1999].

The relationship of the relative catch ratio (RCR) as a function of wind speed and air temperature has been developed for Alter and Tretyakov wind shields. It is important to have this relation established, since (1) it shows that discontinuity introduced by use of wind shields is not constant, that it varies with wind and temperature, and (2) this relation provides a useful technique to adjust the discontinuity in a variety of climate conditions. Strong linear relations between daily precipitation measurements by shielded gauges and unshielded gauges have also been found and they have been derived by regression approach for various precipitation types and for different wind shield and gauge combinations. These linear relations provide a simple approach to adjust the unshielded gauge–measured data when wind speed and temperature data are not available. However, the linear relation does not fully take into account the varying effect of wind speed and temperature on gauge catch. Overadjustment by the linear relation may occur at those sites with lower wind speeds, and underadjustment may occur at those stations with higher wind speeds. The RCR technique is anticipated to be more applicable in a wide range of climate conditions. The linear relations and the technique of RCR versus wind speed and temperature have been tested at selected WMO intercomparison stations, and good agreements of the adjusted amounts to the shielded gauge measurements were obtained at most of the test sites. This indicates that both the linear relation and the RCR-wind technique perform reasonably well at the selected WMO sites. To further evaluate the applicability of these adjustment methods to a wider range of climate conditions, test application of the adjustment techniques in regional observation networks is recommended.

Large spatial and temporal variability of the magnitude of the bias corrections of the gauge-measured data has been re-

Table 9. Summary of Test of the Linear Relation and the RCR Technique at Several WMO Sites for Belfort Recording Gauges and the NWS 8-Inch Standard Gauge

Precipitation Type	Event Number, Day	Mean $T_{\max}$, °C	Mean $T_{\min}$,=°C	Mean Wind, m/s	Gauge Measurement		Adjustment of Unshielded Gauge	
					Alter	Unshielded	Linear Relation	RCR Technique
*Danville**								
Snow	153	−2.4	−11.6	1.4	860.4 mm	717.9 mm	849.6 mm	n/a
					119.8%	100.0%	118.3%	···
Mixed	49	3.0	−6.5	1.2	827.8 mm	731.6 mm	828.4 mm	n/a
					113.1%	100.0%	113.2%	···
Rain	30	5.2	−1.6	1.0	481.3 mm	409.2 mm	455.0 mm	n/a
					117.6%	100.0%	111.2%	···
*Reynolds Creek**								
Snow	65	3.0	−6.0	2.2	142.7 mm	112.6 mm	141.1 mm	n/a
					126.7%	100.0%	125.3%	···
Mixed	32	7.3	−3.1	3.5	121.0 mm	110.8 mm	123.7 mm	n/a
					109.2%	100.0%	111.7%	···
Rain	41	9.3	−0.2	2.7	187.0 mm	185.0 mm	199.7 mm	n/a
					101.1%	100.0%	107.9%	···
*Kortright**								
Snow	107	−0.8	−10.6	2.5	178.8 mm	148.5 mm	190.1 mm	n/a
					120.4%	100.0%	128.0%	···
Mixed	42	3.8	−5.3	2.5	182.6 mm	164.5 mm	184.1 mm	n/a
					111.0%	100.0%	111.9%	···
Rain	58	7.8	−0.9	2.4	221.3 mm	213.1 mm	227.6 mm	n/a
					103.8%	100.0%	106.8%	···
*Dease Lake**								
Snow	47	−9.6	−12.8	1.7	94.6 mm	78.6 mm	98.8 mm	n/a
					120.4%	100.0%	125.7%	
Valdai†								
Snow	154	−4.1‡	3.8	···	225.8 mm	133.5 mm	225.8 mm	225.2 mm
					169.1%	100.0%	169.1%	168.7%
Mixed	73	0.7‡	4.5	···	350.4 mm	292.4 mm	358.1 mm	357.5 mm
					119.8%	100.0%	122.5%	122.3%
Rain	108	10.0‡	3.6	···	384.6 mm	369.8 mm	384.7 mm	380.8 mm
					104.0%	100.0%	104.0%	103.0%

RCR, relative catch ratio.
*Belfort gauge.
†NWS 8-inch gauge.
‡Daily mean temperature at Valdai.

Table 10. Summary of Test of the Linear Relation and the RCR Technique at Three WMO Sites for Tretyakov Gauges

Precipitation Type	Event Number, Day	Mean $T_{\max}$, °C	Mean $T_{\min}$, °C	Mean Wind at 3 m, m/s	Gauge Measurement		Adjustment of Unshielded Gauge	
					Shielded	Unshielded	RCR Technique	Linear Relation
Jokioinen								
Snow	316	−2.1	−5.6	2.6	494.3 mm	323.9 mm	475.0 mm	457.8 mm
					152.6%	100.0%	146.7%	141.3%
Mixed	272	2.1	−0.9	3.0	657.8 mm	562.1 mm	659.4 mm	782.9 mm
					117.0%	100.0%	117.3%	139.3%
Rain	556	10.9	6.8	2.5	1475.6 mm	1420.7 mm	n/a	1537.8 mm
					103.9%	100.0%	···	108.2%
Valdai								
Snow	136	−1.5	−4.2	4.5	474.5 mm	323.6 mm	614.0 mm	457.2 mm
					146.6%	100.0%	189.7%	141.3%
Mixed	87	1.0	−0.8	4.6	489.3 mm	420.3 mm	492.2 mm	487.1 mm
					116.4%	100.0%	117.1%	115.9%
Rain	122	7.7	5.0	4.0	759.3 mm	721.5 mm	n/a	749.3 mm
					105.2%	100.0%	···	103.9%
*Rabbit Ears Pass**								
Snow	66	−3.6	−10.4	3.4	972.2 mm	671.4 mm	1218.4 mm	950.0 mm
					144.8%	100.0%	181.5%	141.5%

*For event data.

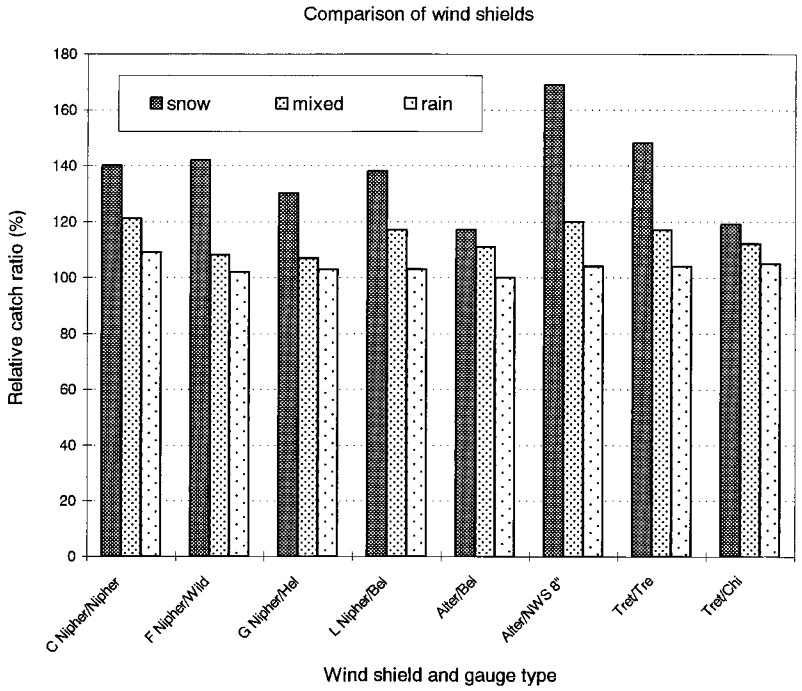


Figure 9. Mean relative catch ratios (RCR) for various shield and gauge combinations. Abbreviations are as follows: C Nipher/Nipher, Canadian Nipher shield with Nipher snow gauge; F Nipher/Wild, Finnish Nipher shield with Wild gauge; G Nipher ?Hel, Herman Nipher shield with Hellmann gauge; L Nipher/Bel, large Nipher shield with Belfort gauge; Tre/Tre, Tretyakov shield with Tretyakov gauge; Alter/NWS 8″, Alter shield with NWS 8-inch nonrecording gauge; Tre/Chi, Tretyakov shield with Chinese standard gauge.

ported particularly in cold climate regions [*Yang et al.*, 1998b; *Legates and DeLiberty*, 1993]. To better quantify wind shield–induced discontinuity and to better evaluate the impact of the proposed adjustments on precipitation change and variation analyses, test implementation of the derived adjustment methodology should be made to those sites where shielded and unshielded gauges have been operated during different observation periods. On the other hand, to eliminate the spatial inhomogeneity of precipitation records collected by shielded and unshielded gauges in an observational network or across national boundaries, data measured by unshielded gauges should be adjusted using the proposed techniques or other adjustment methods to obtain the estimates of the measurements of shielded gauges. Significant increase of precipitation amount is expected owing to the adjustments, particularly in cold regions.

It is important to point out that inhomogeneity adjustment and bias correction of precipitation data can serve different purposes: the former attempts to reduce or eliminate the inconsistency of the precipitation records, and the latter aims to estimate or obtain the true values. In other words, inhomogeneity adjustments such as those proposed in this study will only bring the unshielded gauge measurements closer to the shielded gauge observations, not to the true precipitation amounts. Studies have shown that both shielded and unshielded gauges undermeasure precipitation owing to biases such as wind-induced undercatch, wetting, and evaporation losses [*Yang et al.*, 1995, 1998a; *Goodison et al.*, 1998; *Sevruk*, 1982; *Larson and Peck*, 1974]. Corrections for these biases are therefore necessary for all types of gauge measurements. Bias-correction methods have been recently developed from the WMO Intercomparison Project for many national gauges [*Goodison et al.*, 1998; *Yang et al.*, 1995, 1998a], and they are recommended to be implemented to current and archived national records so as to produce the unbiased (true) precipitation data over large regions [*Goodison et al.*, 1998; *Yang and Goodison*, 1998].

Incompatibility of precipitation data across national boundaries owing to different observational methods and instrumentation used by neighboring countries has also been recognized [*Karl et al.*, 1993; *Sevruk and Klemm*, 1989]. Research efforts to quantify and adjust this incompatibility are needed for large-scale climatic and hydrological studies such as GEWEX [*WMO/WCRP*, 1989] and ACSYS [*WMO/WCRP*, 1994] projects. The WMO Solid Precipitation Measurement Intercomparison Project has tested many national standard gauges; the intercomparison data collected at 23 stations in a wide range of climate conditions of many countries will be useful to address this important issue.

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