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Accuracy of Tretyakov Precipitation Gauge
Result of WMO Intercomparison

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ABSTRACT

From 1986 to 1993, the accuracy and performance of the Tretyakov gauge was evaluated during the WMO Solid Precipitation Measurement Intercomparison at 11 stations in Canada, USA, Russia, Germany, Finland, Romania and Croatia. The Intercomparison data for the Tretyakov gauge were compiled from measurements made at these WMO Intercomparison sites. These data represent a variety of climate, terrain and exposure. The effects of environmental factors, such as wind speed, wind direction, type of precipitation and temperature, on gauge catch were investigated. Wind speed was found to be the most important factor determining gauge catch and air temperature had a secondary effect, when precipitation was classified into snow, mixed and rain. The results of the analysis of gauge catch ratio vs. wind speed and temperature on a daily time step are presented for various types of precipitation. Independent checks of the correction equations against the DFIR have been conducted at the 11 Intercomparison stations and a good agreement (difference less than 10%) has been obtained. The use of such adjustment procedures should significantly improve the accuracy and homogeneity of gauge-measured precipitation data over large regions of the former USSR and central Europe.

Key Words: precipitation measurement, systematic errors, DFIR, Tretyakov gauge, correction.

INTRODUCTION

Systematic errors (biases) in precipitation measurement, notably those caused by wind and those attributable to wetting and evaporation loss (for example, see Goodison et al., 1981a) have long been recognized as affecting all types of precipitation gauges. The need to correct these systematic errors and especially those affecting solid precipitation measurement, has now been more widely acknowledged, as the magnitude of the errors and their variation between gauges became known and their potential effects on regional, national and global climatological, hydrological and climate change studies were recognized (Groisman and Easterling, 1994; Groisman et al., 1991).

In 1985, WMO initiated the Solid Precipitation Measurement Intercomparison (WMO/CIMO, 1985). The goal of this project was to assess national methods of measuring solid precipitation against methods whose accuracy and reliability were known, including past and current procedures, automatic systems and new methods of observation (Goodison et al., 1988). The Intercomparison was designed to: (1) determine wind-induced errors in national methods of measuring solid precipitation, including wetting and evaporation losses; (2) derive standard methods for correcting solid precipitation measurements; and (3) introduce a reference method of solid precipitation measurement for general use to calibrate any type of precipitation gauge (Goodison et al., 1994).

The reference method for snowfall measurement was extremely critical in this Intercomparison. After reviewing all possible practical methods (bush shield, double fence shield, forest clearing, snow board, dual gauge system) of measuring "true" snowfall in a range of climatic conditions, the WMO Organizing Committee for the Intercomparison designated the octagonal vertical Double Fence, surrounding a

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shielded Tretyakov gauge, as the Intercomparison Reference (DFIR) (Figure 1) (Goodison et al., 1981a; Goodison et al., 1988). Since 1985, the DFIR has been operated at 19 stations in 10 countries around the world during the study. The Intercomparison focused on countries' current national methods of measurement. The Russian Tretyakov gauge is widely used at 13,620 locations in 7 countries including the former USSR, Finland, Afghanistan, Vietnam, North Korea, Cuinea-Bissau and Mongolia (Sevruk and Klemm, 1989). Hence, it was widely tested, being operated at 11 Intercomparison sites in several European countries, in Canada and in the United States.

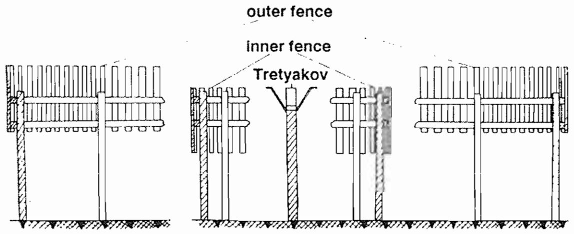

Figure 1. Cross section of WMO Double Fence Intercomparison Reference (DFIR).

The Tretyakov gauge is a manual gauge. It consists of three parts: a receiver of 200 cm^2, a container and a funnel to lead the water to the container. For snow measurement, the funnel is removed and only the receiver and the container are used to collect snowfall. The Tretyakov gauge has been the standard instrument for measuring both solid and liquid precipitation in the former USSR climatological and hydrological station network since the late 1940'S (Groisman et al., 1991). The Tretyakov gauge operated in the hydrological and meterological observing networks of the former USSR and Finland is placed at 2m and 1.5m, respectively, and is presently equipped with the Tretyakov wind shield. In other countries, such as Afghanistan and North Korea, the gauge is not shielded even in the winter season. It has been shown (Goodison et al., 1981a) that, a shielded gauge can catch up to 50% more precipitation than its unshielded counterpart for the same environmental conditions. Thus, it is easy to understand that the combination of precipitation records from different types of gauges, including shielded and unshielded gauges, can result in inhomogeneous precipitation time-series and can lead to incorrect spatial interpretations. Use of such data for climate change and hydrological studies could be misleading.

Many studies on the Tretyakov gauge have been conducted since the 1960's (Bogdanava, 1966; Golubev, 1969, 1992a; Goodison et al., 1981a; Groisman et al., 1991). From 1972 to 1976, the Tretyakov gauge was tested in the International Rainfall Comparison of National Precipitation Gauges with a Reference Pit Gauge (Sevruk and Hamon, 1984). Golubev (1985a, 1985b) tested various designs of the Double Fence with this gauge for snowfall measurement at the Valdai Hydrological Research Station. Groisman et al. (1991) reviewed the USSR experience on precipitation measurements and the correction of systematic error. Recently, Golubev (1992a, 1995) reported the results of the WMO Intercomparison at the Valdai Hydrological Research Station. Based on the early Russian studies, monthly corrected precipitation measurements in the former USSR, using monthly wind speed and air temperature to estimate correction factors, were published in World Water Balance and Water Resources of the Earth (UNESCO, 1978).

This study extends previous studies, which primarily focused on the Russian Valdai station, to other climatic regions, resulting in the most comprehensive data set ever compiled. Based on data compiled from 11 stations where the Tretyakov gauge and the DFIR were operated, this study compares the accuracy of the Tretyakov gauge measurements with those of the designated standard reference (DFIR) for rain, snow and mixed precipitation.

SITES AND DATA SOURCES

Table 1 summarizes the site and instrument information (gauge height, shielding information, anemometer height, method and time of observation, observation period and recent references) at the Intercomparison stations which operated the DFIR and the Tretyakov gauge. Other national precipitation gauges, such as the Hellmann gauge and Canadian Nipher gauge, were also tested at some of the sites, depending on the national requirements of the participating countries. Installation of the DFIR, the Tretyakov gauge and other observing equipment and the associated observational procedures followed the experiment guidelines documented in WMO/CIMO (1985).

Since the Tretyakov gauge is a nonrecording gauge, the liquid water equivalent of precipitation was determined either by weighing the contents (weighing method) or by pouring the melted contents into a measuring graduate (volumetric method). At most of the Intercomparison stations, one observation was made each day for 5 winter seasons from 1987 to 1992. At some, the experiment program was continued all year and a large number of rainfall and

Table 1. Siting and instrumental information at 11 WMO Intercomparison sites.

Station	*Lat. Lon. Elev.*	*DFIR*	*Tretyakov Gauge*	*Wind Sensors*	*Obs. Method*	*Obs. Period*	*Reference*
Valdai Russia	57°59'N 33°15'E 194m	at 3m	at 2m, shielded/ unshielded	at 3m & 2m	volumetric	Oct.91 to Mar.93	Golubev 1985a, 1985b
Reynolds Creek, Idaho, USA	43°12'N 116°45'W 1193m	at 3m	at 2m, shielded	at 9.14m 3m & 2m	weighing	Nov.87 to Feb.92	Larson 1972
Danville, Vermont, NH, USA	44°29'N 72°10'W 552m	at 3m	at 3m, shielded	at 3m	volumetric	Dec.86 to Apr.92	Bates et al 1987; Larson and Peck, 1974
Jokioinen Finland	60°49'N 23°29'E 104m	at 3m	at 1.5m, shielded/ unshielded	at 3m	volumetric weighing	Oct.88 to Mar.93	Elomaa 1993; Aaltonen et al. 1993
Harzgerode Germany	51°39'N 11°08'E 404m	at 3m	at 2m, shielded	at 3m	volumetric	Dec.86 to Mar.93	Gunther 1993
Bismark ND, USA	46°46'N 100°45'W 502m	at 3m	at 1.4m, shielded	at 6.1m, 3m & 1.4m	weighing	Nov.88 to Apr.91	Emerson 1990
Joseni Romania	45°36'N 14°38'E 750m	at 3m	at 1.5m, shielded	at 10m & 2m	volumetric	Dec.86 to Mar.89	Copaciu 1989
Parg Croatia	45°36N 14°38'E 863m	at 3m	at 2m, shielded	at 11.2m	volumetric	Jan.87 to Apr.89	Milkovic 1988
Peterborough Ont. Canada	44°21'N 78°17W 230m	at 3m	at 2m, shielded	at 10m, 3m & 2m	volumetric	Nov.86 to Mar.91	Goodison and Metcalfe 1989, 1992
Regina Sask. Canada	50°26'N 104°40'W 577m	at 3m	at 2m, shielded	at 10m, 3m & 2m	weighing	Nov. 87 to Apr.92	Goodison and Metcalfe 1989, 1992
Kortright Centre, Ont. Canada	43°51'N 79°36'W 208m	at 3m	at 2m, shielded	at 10m, 3m & 2m	volumetric	Jan.87 to Mar.91	Goodison and Metcalfe 1989, 1992

mixed precipitation data were also collected. In the Intercomparison, the type of precipitation was described as snow only (S), snow with rain (SR), rain with snow (RS), freezing rain (ZR) and rain only (R) (WMO/CIMO, 1985). SR indicates a dominance of snow in the combination, RS a dominance of rain. Additional meterological 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 to the Atmospheric Environment Service, Environment Canada, for archiving in a digital data base in a common format (WMO/CIMO, 1985). The digitized data were reviewed and quality-controlled by the participants before use in this study and in the final report to WMO. Additional details on siting, instrumentation and method of observation were provided in the references listed in Table 1.

For the purpose of easy application of the WMO Intercomparison results to the national precipitation archive, the daily precipitation measurements of both the DFIR and the Tretyakov gauge were used in this study and the relation of the gauge catch ratio (gauge measurement / DFIR measurement) to wind speed was investigated on a daily basis as well (e.g. daily catch ratio against daily mean wind speed). A so-called event data set (e.g. total precipitation for each event and mean wind speed and mean air temperature during the period of precipitation) was also created for some of the Canadian and U.S. sites where the timing of precipitation and wind speed were recorded by automatic instruments. This paper focuses on analysis of the daily data.

DATA ANALYSIS

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

Wetting loss refers to the rain or water from melted snow subject to evaporation from the surface of the inner walls of the precipitation gauge after a precipitation event and the water which remains in the gauge container after its emptying (WMO/CIMO, 1993). It is not easy to quantitatively determine the first portion of the error. This study focuses on the second portion, e.g. retention (Goodison, 1977), only. Wetting loss can contribute significantly to the systematic undermeasurement of precipitation, particularly when the volumetric method of measuring gauge contents is used. For instance, retention associated with Canadian Nipher gauge measurements was calculated to be 15-20% of measured winter precipitation at some Canadian synoptic stations (Metcalfe and Goodison, 1993). Wetting losses vary according to the type of gauge, type of precipitation and the number of times the gauge is emptied (Sevruk, 1982; Golubev et al., 1992b; Goodison and Metcalfe, 1992; Elomaa et al., 1993). Based on wetting loss experiments, Sevruk (1982) reported the average wetting loss of the Tretyakov gauge to be 0.20mm per observation for rainfall measurement and 0.15mm per observation for both snow and mixed precipitation. Similar values were reported by Elomaa et al. (1993) and Goodison and Metcalfe (1989, 1992).

Correction of each observation for wetting loss for manual gauges must be applied to the Intercomparison data before further analysis (WMO/CIMO, 1993). In this study, wetting loss was corrected according to the type of precipitation and method of observation. At stations where the volumetric method was used, the correction was done by adding the daily total wetting loss (number of observations per day multiplied by average wetting loss per observation) to the measured daily precipitation. Wetting loss correction was not required for those stations where precipitation measurements were made using the weighing technique.

Evaporation loss is the water lost by evaporation before the observation is made. Unlike weighing recording gauges, no evaporation suppressant, such as light oil, is used in the manual gauge to minimize the evaporation loss. Comprehensive assessment of evaporation losses at the Finnish site indicated that average daily losses varied by gauge type and time of the year. Losses in summer of 0.30-0.80 mm/day and winter of 0.10-0.20 mm/day, respectively, for the Tretyakov gauge were found at Jokioinen in Finland during experiments to measure evaporation losses (Aaltonen et al., 1993).

Ideally, evaporation loss should be corrected before gauge catch analysis. However, because of its strong dependence on weather conditions, timing of precipitation compared to observation time and seasonal change which can be very site dependent, it was not possible at this time to estimate the daily evaporation loss at some Intercomparison stations by using the average amount obtained from the Finnish site. Thus, no correction was made for the potential daily evaporation loss from the Tretyakov gauge.

The DFIR is only considered as a secondary reference standard. At the moment, there is no accepted primary reference for measuring solid precipitation, but a gauge located in bushes which are kept cut to the height of the gauge is one reference method deemed to provide measurement close to "true" (WMO/CIMO, 1985). Yet such sites are not universally available and a secondary reference had to be chosen for the Intercomparison. The need to adjust the DFIR measurement to the "true" value of the bush gauge for the effect of wind was discussed by Golubev (1989), since a comparison of DFIR and the bush gauge data at Valdai, Russia, indicated a systematic difference between the primary and secondary standards. Golubev's proposed adjustment procedure included meteorological measurements of wind speed, atmospheric pressure, air temperature and humidity. Subsequent assessment of Golubev's equation showed that for the same site, pressure and humidity had little effect and the equation could be simplified by using only air temperature and wind speed (Goodison and Metcalfe, 1992). Yang et al. (1993) analyzed the long-term precipitation and meteorological observations from Valdai and found that blowing snow occurred during one-third of the snow events when measured precipitation was greater than 3.0 mm. After eliminating the blowing snow events, the bush gauge still measured more snow than the DFIR. Hence, adjustment of the DFIR measurement was necessary to provide a best estimate of the "true" precipitation. Regression analysis indicated that the most statistically significant factor in the correction of the DFIR was the wind speed during the storms. Correction equations for the DFIR measurements were developed for the different types of precipitation; these were recommended by the WMO Organizing Committee of the Intercomparison (WMO/CIMO, 1993) to be applied to all DFIR data before analyzing the catch of national gauges with respect to the DFIR. All DFIR measurements have been corrected at the 11 WMO sites to derive "true" values for this study.

Blowing snow conditions are a special case when correcting the DFIR data. Normally the flux of blowing snow will be greater at 1.0m, 1.5m or 2m than at the 3.0m height of the DFIR, and it is possible that under certain conditions, any gauge can catch some blowing snow. Since wind speeds are generally greater during blowing snow events, a larger correction for "undercatch" could be applied to a measured total already augmented by blowing snow. This problem would be most severe for gauges mounted close to the ground which are efficient in collecting snow passing over their orifice. Blowing snow events in the Intercomparison data were carefully identified and eliminated from subsequent analysis of gauge catch versus environmental factors, notably wind speed and temperature.

For those few sites where wind speed was not measured at the height of the precipitation gauge, it was estimated from measurements at higher heights by the following logarithmic wind profile:

$$U(h) = [\ \ln(h/z_0)\ ]\ /\ [\ln(H/z_0)\ ] \times U(H) \qquad (1)$$

where, $U(h)$ is the estimated daily wind speed (m/s) at the gauge orifice, $U(H)$ is the measured daily wind speed (m/s), h and H are the heights (m) of the gauge and of the anemometer respectively, and z_o is the roughness parameter, in metres. According to Sevruk (1982) and Golubev et al. (1992b), z_o = 0.01m for a winter snow surface and z_o = 0.03m for short grass in the summer are appropriate average roughness parameters for most sites. The need to estimate wind speed at gauge height when a wind measurement is not available does introduce a small increase in scatter in the derived relationship, but it is more important to use wind values for the height of the gauge rather than wind from some other height.

It is important to note that: (1) at all Intercomparison sites, the DFIR was installed and operated according to the same procedures (WMO/CIMO, 1985), resulting in a common standard at all the sites; national gauges were operated according to the countries national methods; (2) the DFIR measurements at the Intercomparison stations have been adjusted to the "true" precipitation using the same equations; and (3) when it is necessary to estimate daily mean wind speed at the height of the national gauge from wind measurement at different heights at the Intercomparison site, it is done using the same wind-profile technique. Thus, the Intercomparison data collected from different sites are compatible in terms of the catch ratio (measured precipitation / "true") for the same gauges, when wind speed at the gauge height is used in the analysis.

RESULTS

All data (climatological relationship)

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

Table 2 summarizes the average catch ratio for the shielded Tretyakov gauge as a function of the corrected DFIR for different types of precipitation at the 11 WMO sites. Precipitation was classified as snow only, snow with rain, rain with snow and rain only. Although it was not an objective of this WMO project to study rainfall measurement using this gauge, Intercomparison results at Jokioinen in Finland demonstrated a very good agreement between rainfall measured by the DFIR and the pit gauge (accepted WMO standard for rainfall measurement) in a number of different seasons. Hence, it was reasonable to accept the DFIR as a reference for rainfall measurement in this study, since most of the sites did not have a pit gauge or did not operate it in winter.

At most of the stations, the average catch ratio for the Tretyakov gauge is less for snow than for rain. One may note that there are exceptions, but these are related to differences in the mean daily wind speed, or in sample size (e.g. few precipitation events). Average value of the catch ratio can be very misleading, since all storms are weighted equally, irrespective of wind speed, precipitation amount or other environmental conditions. Valdai and Jokioinen,

Table 2. Summary of the Intercomparison of shielded Tretyakov gauge against the DFIR at 11 WMO sites.

	Snow				*Snow/Rain*				*Rain/Snow*				*Rain*			
Station	*Event (day)*	*Ws (m/s)*	*DFIR (mm)*	*Tret Catch (%)*	*Event (day)*	*Ws (m/s)*	*DFIR (mm)*	*Tret Catch (%)*	*Event (day)*	*Ws (m/s)*	*DFIR (mm)*	*Tret Catch (%)*	*Event (day)*	*Ws (m/s)*	*DFIR (mm)*	*Tret Catch (%)*
Valdai	304	4.1	1181.7	63.1	85	4.6	584.9	71.2	75	4.5	489.7	86.3	230	3.8	1259.2	91.4
Reynolds	50	2.5	105.6	84.4	27	3.8	71.4	88.5	8	4.4	29.3	85.4	40	2.7	206.4	92.0
Danville	157	1.5	1036.2	91.6	21	1.0	999.5	95.0	18	1.4	348.7	94.5	30	1.0	446.3	94.3
Jokioinen	334	2.6	740.9	67.2	149	3.1	405.6	72.5	131	2.9	414.3	84.5	567	2.5	1694.4	86.6
Harzgerode	42	3.0	112.7	72.2	53	3.9	110.2	78.5	127	4.2	538.8	82.4	172	4.2	475.3	81.3
Bismarck	32	3.3	94.6	65.4	16	3.1	53.3	67.8	-	-	-	-	3	3.3	9.3	71.6
Joseni	94	1.1	194.0	85.8	14	1.3	39.8	92.9	11	2.2	53.6	86.9	34	1.2	85.0	90.6
Parg	65	1.0	486.9	91.0	16	1.2	250.1	90.3	31	1.5	550.8	90.7	141	1.6	1573.8	88.2
Peterborough	76	2.0	262.0	81.1	31	2.0	172.3	90.6	20	2.3	219.4	95.0	80	1.9	581.9	95.0
Regina	117	3.5	199.1	59.4	36	4.3	76.9	63.1	-	-	-	-	5	3.9	5.1	97.4
Kortright	107	2.5	274.7	83.1	25	2.7	198.4	85.3	11	4.2	31.9	91.8	64	2.3	342.6	90.0

which had extensive observing programs during a long "winter" period and even into the summer, exhibit the "expected" decease in the catch ratio from rain to snow. At some of the WMO sites, such as Danville and Parg, the average catch ratios of the shielded Tretyakov gauge varied little by precipitation type because of the very low average wind speeds on precipitation days. In some cases, mixed precipitation has a lower average catch than snow (e.g. Harzgrode), but the mean wind speed was greater during these events, so this result is not unexpected.

Table 2 shows that the average catch ratio of the shielded Tretyakov gauge varies for the same type of precipitation at the Intercomparison stations. The variation of the average catch-ratios, ranging from 59-92% for snow and 72-97% for rain, changes by type of precipitation. Investigation of the mean catch ratio for all observations at each site versus mean wind speed at gauge height during precipitation days shows that there is a general dependence of the mean catch ratio (R) on mean wind speed (Ws) for snow only (Equ. 2) and snow mixed with rain (Equ. 3).

$$\overline{R} = 101.9 - 10.3 * \overline{Ws}, \quad (n = 11, r^2 = 0.79), \quad (2)$$

$$\overline{R} = 100.4 - 6.7 * \overline{Ws}, \quad (n = 11, r^2 = 0.60), \quad (3)$$

For both cases, the mean gauge catch ratio decreases with increasing mean wind speed for precipitation days. For rain only and rain mixed with snow, there is no significant correlation between mean catch ratio and mean wind speed for precipitation days. It must be noted, however, that in all cases there is considerable scatter at any wind speed. Yet, it is very important to identify the relationship between the average catch ratio and mean wind speed for various types of precipitation, since there has been a tendency recently to use an averaged catch ratio for a gauge, for different types of precipitation, derived at a single site, to correct the archived precipitation data for climatological and hydrological analyses. By not considering the varying effect of mean wind speed on the mean gauge catch, overcorrection of the wind-induced error will occur for those stations with lower wind speed during precipitation than that at the intercomparison site. Undercorrection of the wind-induced error will occur for those stations with higher wind speed during precipitation than that at the intercomparison site. To avoid the overcorrection or undercorrection of the wind-induced errors, a constant catch ratio (e.g. a constant correction factor) is not recommended for any gauge in any season. Instead, the relation of daily or event gauge catch as a function of corresponding daily-mean or event-mean wind speed should be applied to the gauge measured daily or event data, since studies (Goodison, 1977; Goodison et al., 1981a,b) show that gauge catch varies by individual precipitation event.

Shielded vs. unshielded

The beneficial effect of using a wind shield, Tretyakov shield in this case, on gauge catch is clearly shown by the difference between the average catch ratios of the shielded and the unshielded gauges at Valdai and Jokioinen stations (Figure 2). The difference of the mean catch ratio, ranging from 15-23% for snow only, 13-14% for snow with rain, 4-7% for rain with snow and 3% for rain only, clearly indicates the positive benefits of using a wind shield for snow and mixed precipitation measurements. Overall, shielded gauges caught 8-9% more precipitation, when compared to the DFIR, than their unshielded counterparts at Valdai and Jokioinen.

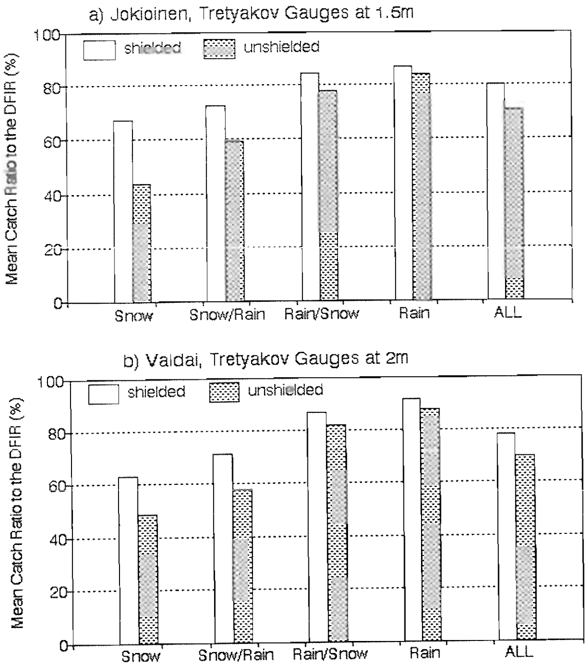

Figure 2. Comparison of the shielded and unshielded Tretyakov gauge catches for different types of precipitation at (a) Jokioinen and (b) Valdai WMO Intercomparison sites.

Daily precipitation

Studies have shown that gauge catch of precipitation, depending on both the environmental factors and the precipitation features, such as rainfall rate (Sevruk, 1982) and falling snow crystal type (Goodison et al., 1981a), can vary in each individual event of precipitation. In order to investigate the dependence of the Tretyakov gauge catch on environmental factors, daily data from the 11 WMO Intercomparison stations, representing a wide variety of climate, terrain and exposure, were compiled. One must be very careful when analyzing ratios and differences between gauges. Small absolute differences between the Tretyakov and DFIR gauges could create significant large variations in the catch ratios (e.g. a 0.2mm difference of Tretyakov vs. DFIR with a DFIR catch of 1mm gives a ratio of 80% versus 96% for a 5mm event). To minimize this effect, the daily totals when the DFIR measurement was greater than 3.0mm were used in the statistical analysis. The results confirm that wind speed is the most important factor for gauge catch when precipitation is classified as snow, snow with rain, rain with snow and rain. Air temperature has a secondary effect on gauge catch. A regression of the daily gauge catch ratio (*R, %*) for the shielded Tretyakov gauge as a function of the daily wind speed (*Ws, m/s*) at gauge height and daily air temperature (*Tmax, Tmin and Tmn, °C*) gave the best-fit regression equations for the different types of precipitation as follows:

Snow:

$$R = 103.10 - 8.67 * (Ws) + 0.30 * (Tmax) \qquad (4)$$
$$(n = 394,\ r^2 = 0.66)$$

Snow and Rain:

$$R = 98.56 - 6.19 * (Ws) + 0.90 * (Tmax) \qquad (5)$$
$$(n = 204,\ r^2 = 0.57)$$

Rain and Snow:

$$R = 98.13 - 3.17 * (Ws) + 0.60 * (Tmn) \qquad (6)$$
$$(n = 228,\ r^2 = 0.42)$$

Rain

$$R = 99.99 - 4.77 * (Ws)^{0.56} \qquad (7)$$
$$(n = 569,\ r^2 = 0.47)$$

Figure 3 shows the daily catch ratio for the shielded Tretyakov gauge versus daily wind speed. A wide range of wind speed has been sampled by the combined Intercomparison data sets in a variety of climatic regions; hence, the correction procedures derived from these data are more likely to be successfully used for a wide range of environmental conditions. The curve in Figure 3 shows the derived daily gauge catch curve versus daily mean wind for a maximum air temperature of -10°C. It is clear from equations 4, 5 and 6 that gauge catch decreases with increasing wind speed on the precipitation day and

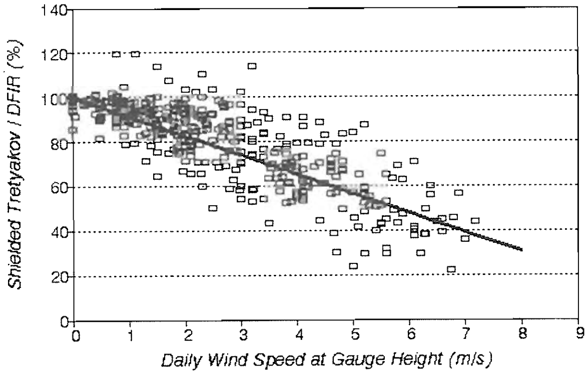

Figure 3. Shielded Tretyakov gauge catch (% of DFIR) of daily snow (DFIR > 3.0mm) versus daily mean wind speed at the gauge orifice height at 11 WMO Intercomparison sites, Tmax = -10°c for the curve.

increases with rising air temperature. However, compared to the wind influence, the effect of air temperature on the gauge catch of snow is small. For instance, an air temperature change of 10°C only results in a 3% change of the gauge catch whereas a wind speed increase of 1 m/s causes a 9% decrease of catch compared to the FDIR (Equ. 4). For mixed precipitation, snow with rain and rain with snow, the effect of air temperature on the gauge catch is more significant and the wind effect becomes weaker. A 10°C change leads to a 9% and 6% catch change whereas a wind change of 1 m/s results in a 6% and 3% catch decrease (Equ. 5 and 6), respectively. For rain measurement, air temperature does not affect gauge catch and wind speed is the only factor.

Testing of daily precipitation correction equations

Independent checks on the performance of the correction equations 4-7 for the shielded Tretyakov gauge have been conducted using all of the Intercomparison data (without the DFIR > 3.0 mm limitation) at the 11 WMO sites. Catch ratio (*R*) was converted to the wind-loss correction coefficient (*K*) by the following equation:

$$K = 1 / R, \quad \text{hence} \quad P_t = K * P_m \qquad (8)$$

where, P_m is gauge-measured precipitation including the wetting loss and P_t is the calculated true precipitation estimate.

The improvement in the shielded Tretyakov gauge estimate of precipitation after correcting for wetting and wind induced errors is significant. For snow only data, conducting the correction can bring the catch ratio of the shielded gauge from 59-92% up to 83-100%. Overcorrection occurred at only the Kortright station. Overall, the correction raises the gauge catch of snow from 77% to 97% of the DFIR. For snow mixed with rain, applying the correction can increase the gauge catch from 63-90% to 84-100% compared to the DFIR. A small overcorrection occurred at Reynolds Creek (6%), Peterborough (4%) and Danville (2%). On average, the gauge catch for snow with rain was raised from 84% to 100% for the 11 Intercomparison stations. For the correction of rain mixed with snow, the gauge catch was improved from a range of 83-95% to 96-100% of the DFIR. Overcorrection of less than 2-4% occurred at 6 WMO sites. The overall average catch ratio of the gauge for rain mixed with snow was increased from 88% to 101%. Finally, rainfall data were corrected at the WMO sites by using daily mean wind data only. The correction results are very close to the DFIR, with a difference of less than 3% at most of the sites, except for Bismarck and Regina where a very small amount of rain (total less than 10mm for 5 precipitation events) was collected. Overall, the correction brings the gauge catch of rain from 89% to 100% of the estimated "true" precipitation.

The t-test was conducted to the snow data at Jokioinen in order to check the improvement of the correction on the gauge-measured amounts. The results indicate a statistically significant ($\alpha < 0.05$) difference between the gauge-measured and the corrected snow data and the results also show a statistically significant ($\alpha < 0.05$) agreement of the corrected gauge measurements to the estimated "true" snow of the DFIR. Therefore, it is clear that applying the correction procedure to the gauge-measured snow data is necessary in order to obtain the "true" snowfall. Given the statistically significant difference between the measured and corrected precipitation, particularly for solid and mixed precipitation at all the WMO sites, it is the opinion of the authors that these correction equations work well at the Intercomparison stations and that they should be used for correcting the daily measured precipitation at stations where the Tretyakov gauge is used.

For the unshielded Tretyakov gauge, the variation of daily catch ratio of snow as a function of daily mean wind speed at the gauge orifice height of 1.5m has been derived from the Intercomparison data collected at the Jokioinen experimental station in Finland (Elomaa, 1994). The unshielded gauge has a catch ratio of 10-20% lower at Jokioinen compared to that for a shielded gauge at the same wind speed (Figure 4). At high winds, the catch ratio of the unshielded gauge can be 30% less than the shielded one. The large difference of the gauge catch of snow during high winds between shielded and unshielded Tretyakov gauges indicates, once again, that use of a

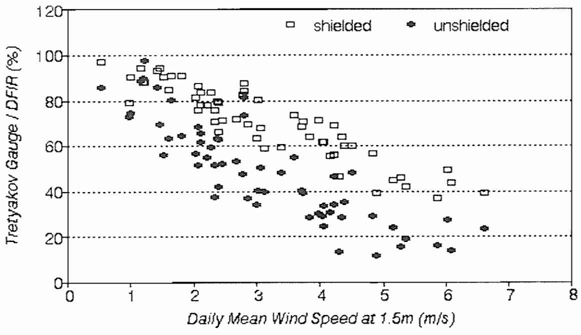

Figure 4. Shielded and Unshielded Tretyakov gauge catch (% of DFIR) of daily snow (DFIR > 3.0mm) versus daily mean wind speed at 1.5 metres at Jokioinen WMO Intercomparison site.

wind shield is critical to achieve significant improvements on the accuracy of solid precipitation measurement in windy and cold environments.

COMPARISON TO OTHER STUDIES

To have confidence in the applications of the WMO Intercomparison results, it is important to compare our results to the earlier studies on the same gauge. As noted previously, Gunther (1993) also reported that both wind speed and air temperature are statistically significant for the Tretyakov gauge catch of snow and mixed precipitation, based on analysis of the Harzgrode data for the Intercomparison. He found that even the duration of the precipitation can affect gauge catch. Duration of storms was not considered in this study since precipitation event data were generally not available at most of the Intercomparison sites which relied on daily or twice-daily observations. Comparison of Gunther's result for snow to the current study indicates that, for the same air temperature (-10°C), Gunther's equation of the gauge catch of snow as a function of wind speed gives a lower catch ratio. At high wind speeds, above 5m/s, his curve is 5-10% lower of the catch ratio to DFIR (Figure 5). The difference could be caused by different methods of analysis, since (1) Intercomparison data with a DFIR measurement greater than 3.0mm were used in current study while Gunther used a value of 2mm; (2) this study uses wind speed at the height of the Tretyakov gauge and Gunther used wind at the height of 10m in his analysis; and (3) the precipitation condition (crystal type, siting, etc.) could be different at any single site compared to averaged conditions for all sites. The difference in height of the wind speed measurements itself would account for much of the difference in the mean curves.

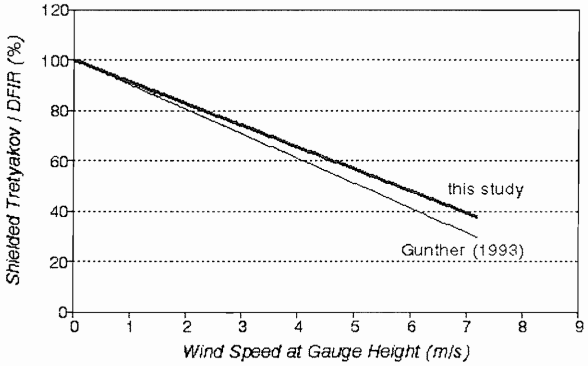

Figure 5. Comparison of catch-wind relations derived from the compiled WMO data (this study) and single-station data (Gunther, 1993), for air temperature at -10°c.

Golubev (1985b) examined the catch of the Tretyakov gauge for snow versus wind speed at the Valdai Hydrological Research Station in the former USSR by using the so-called "bush-gauge" as the reference. Goodison (1977) and Goodison et al. (1981a) reported results on gauge catch including the shielded Tretyakov gauge for snow measurement compared to snowboards in a sheltered site in Canada. Both reported the relation of the gauge catch of snow to wind speed from their experimental data. For easier application of the WMO Intercomparison results to the archived station data, a simplified equation of the daily gauge catch of snow versus daily mean wind speed only was developed from the compiled Intercomparison data set, such that,

$$R = exp\ (\ 4.605 - 0.06 * (Ws)^{1.4}\ ) \qquad (9)$$
$$(\ n = 392,\ \ r^2 = 0.64\ )$$

The comparison of the current study to the others is shown in Table 4. Clearly, there is an excellent agreement in the results from Golubev and the current study and the gauge catches are very similar for wind speeds up to 8 m/s. The agreement may indicate the accurate correction of the DFIR measurements for wind-loss at the WMO Intercomparison sites. Goodison's results are slightly lower, about 3-5 %, than the other two for the wind speeds below 4 m/s where there are only a few observations. Given the fact that different methods of determining "true snowfall" were used and that the current WMO Intercomparison involved 11 sites in different climatic regions, the results from these studies agree well.

For rainfall, Bogdanova (1966) reported that the catch of the Tretyakov gauge changed with storm mean wind speed (m/s) at the level of the gauge orifice and the parameter *N*, which depends on monthly rainfall intensity (mm/h). Sevruk (1981) studied the relation of *N* to the monthly rainfall rate (mm/h) and gave a quite different formula. Unfortunately, rain rate data are not available at most of the WMO Intercomparison sites and, thus, direct comparison of current results to others can not be made at this time. Further study is needed to compare and evaluate the corrections using various procedures at selected climate stations which have both wind and rain-rate data.

CONCLUSION

In this study, the relation of daily precipitation catch between the Tretyakov gauge and the DFIR

Table 3. Shielded Tretyakov gauge catch (%) of snow for selected wind speeds based on Golubev (1985b), Goodison (1977) and current study.

	Wind Speed at Gauge Height (m/s)								
Method	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Golubev (1985b)	100	95	88	77	65	55	47	38	32
Goodison (1977)	-	91	81	70	61	53	45	37	31
This study	99	94	85	75	66	56	48	40	33

reference measurement of "true" precipitation as a function of daily mean wind speed and air temperature for the precipitation day was derived for the types of precipitation of snow only, snow with rain, rain with snow and rain only, using the compiled Intercomparison data at the 11 WMO sites. It is extremely important to have this relationship established, since gauge catch ratio (*R*) can be calculated using the relation for given daily mean wind speed and air temperature for the precipitation day and "true precipitation" (P_t) can be estimated by $P_t = P_m / R$ for the gauge-measured amount (P_m). The correction procedures outlined in this paper are recommended for testing correction of Tretyakov gauge measured daily precipitation in those countries where national meteorological or hydrological station networks operate the Tretyakov gauge for precipitation observation. It is felt that application of the proposed procedures will improve the accuracy and homogeneity of precipitation data over large regions of the former USSR and central Europe. It is hoped that through the WMO project and similar efforts, such as establishing regional and national precipitation centres recommended by WMO/CIMO (1993), correction procedures will be continuously developed and refined for an even larger number of gauges commonly used around the world. It is also hoped that efforts will be made by the national meteorological and hydrological services to apply the appropriate correction procedures to their archived precipitation data in order to produce a consistent unbiased precipitation data set worldwide.

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