Inhomogeneity in Winter Precipitation Measurements

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Abstract

Analyses of the long-term (1991–2010) intercomparison data quantify the consistency in winter precipitation observations by six identical Tretyakov gauges at the Valdai research station in Russia. Relative to the standard Tretyakov gauge, the mean catch ratios vary from 97% to 106% for dry snow, 94–104% for wet snow, 87–109% for blowing snow, 96–103% for mixed precipitation, to 98–101% for winter rain. The differences between the highest and lowest mean catches are about 10–11% for snow, 7% for mixed precipitation, and 3% for rain. On average, this difference is about 0.2 mm over the 12-h observation period. The catch difference for blowing

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snow is much higher, up to 22%, or average of 0.6 mm per observation. Comparisons of 12-h observations show a better consistency in gauge performance for the low snowfall events, and a large variation in gauge catch for the high snowfall cases. The differences in 12-h snow catches are mostly less than 2 mm among the 6 gauges. The difference in the 12-h observations is less than 1% for rain and 4% for mixed precipitation. Close linear relationships exist between the 12-h gauge observations for all precipitation types. The maximum differences in gauge snow catches increase very weakly with the wind speed, and higher differences are associated with the warmer temperatures from –5 °C to 0 °C. There is, however, no significant relationship between the max catch difference and mean wind speed or temperature over the 12-h period.

Keywords
Tretyakov gauge · Valdai station · Precipitation · Measurement · Consistency

Background

Systematic and random errors exist in gauge observations of precipitation. Systematic errors include the wind-induced gauge undercatch, evaporation and wetting losses, and trace amount of precipitation (Goodison et al. 1998). Random errors are not easy to define, as they depend on many factors, such as human operation errors and instability of gauge installation and performance. Both random and systematic error affect the accuracy of precipitation measurements; they cause variability and difference in gauge observations and lead to uncertainties in regional precipitation datasets and products, thus affecting climate change analyses, water budget calculations, and calibrations of remote sensing algorithms and land surface models particularly over the cold regions. To quantify the systematic errors in precipitation measurements, intercomparison experiments have been carried out at national and international levels, such as the WMO Solid Precipitation Measurement Intercomparison study during 1986 to 1992 (Goodison et al. 1988, 1998). Many national standard gauges and instruments have been tested during the WMO experiment. The intercomparison data collected during the WMO project are very useful to advance precipitation science and research, such as the evaluation of reference systems for field experiments (Golubev 1989; Yang et al. 1993, 2000; Yang and Simonenko 2013), examination of biases in gauge precipitation measurements (Goodison et al. 1998; Yang et al. 1995, 1998a), development of bias-correction methods for the major national gauges (Goodison et al. 1998; Yang et al. 1995, 1998a, 1999a, b), quantification of wind shield effects on national gauge performance (Yang et al. 1999c), and documentation of incompatibility in national gauge observations (Yang et al. 2001). Applications of the WMO results have produced reliable precipitation data over many countries and large regions (Melcalfe et al. 1993; Yang 1999; Yang et al. 1998b, 1999b, 2005; Yang and Ohata 2001; Zhang et al. 2004; Ye et al. 2004; Adam and Lettenmaier 2003), and these datasets have significantly improved our understanding of cold region climate and hydrology, including regional climate change (Ding et al. 2007), basin water balance (Ye et al. 2012), and large-scale land surface model of the arctic hydrology system (Tian et al. 2007).

It is known that discontinuity exists across the national boundaries owing to the different instruments and observation methods used in the neighboring countries (Sevruk and Klemm 1989; Yang et al. 2001; Sanderson 1975; Nitu and Wong 2011). For instance, the NWS 8-inch gauge is used for precipitation measurements in the US, and the Nipher snow gauge is the standard instrument for snow observations in Canada. Different instruments have also been used at the observational networks within a county. The Type-B rain gauge and Nipher gauge are the standard instruments for rain and snow observations, respectively (Melcalfe and Goodison 1993; Mekis and Vincent 2011); and recently, the Geonor gauges have been installed at the synoptic stations across Canada. Instruments also change over time at most operational networks, resulting in significant breaks in data records. It has been realized that combination of regional precipitation records from different sources may result in inhomogeneous precipitation time series and can lead to incorrect spatial interpretations (Yang et al. 2005). Efforts have been reported to examine the discontinuity across national borders (Sanderson 1975; Yang et al. 2001). However, less is known regarding the inhomogeneity of precipitation records within a country (Groisman et al. 1999). Homogeneous data are essential for studies of climatic fluctuations and changes. At most stations with long-term records, instruments have been altered or relocated, and surrounding buildings and vegetation changed as well. For precipitation measurements, relocation of the gauge is the most frequent reason for inhomogeneities, although instrument changes can introduce abrupt change and discontinuity (break point) in the measurements. Inhomogeneity is an important issue, because most existing national precipitation data and products have been compiled and derived from the combination of various data sources, assuming these data and observations were compatible across the regions and among the observational networks.

Gauge intercomparison experiments mainly compare the various gauges against a reference instrument, so as to quantify the difference between a given gauge and the reference and derive the correction methods to reduce the biases in gauge observations. This chapter examines the repeatability in precipitation observations by the Tretyakov gauge. The Tretyakov gauge is the standard instrument for measuring both solid and liquid precipitation in the former USSR climatological and hydrological networks since the late 1940s (Groisman et al. 1991). The cross-sectional area of the gauge opening is 200 cm^2. At the Russian hydro-meteorological networks, the Tretyakov gauge is placed at 2 m above the ground with a wind shield to improve the catch efficiency (Groisman et al. 1991). Many studies on the Tretyakov gauge have been conducted since the 1960s. Bogdanova (1966) compared the Tretyakov gauge with the pit gauge at about 50 sites in the FUSSR and related the gauge catch of rainfall with storm mean wind speed at the gauge level and rainfall intensity. The Tretyakov gauge was tested during 1972–1976 in the International Rainfall Comparison of National Precipitation Gauges with a reference pit gauge (Sevruk and Hamon 1984). Golubev (1985, 1989) examined various designs of the double fence with this gauge for snowfall measurement at the Valdai Hydrological

Research Station against the so-called Valdai Control System (a shielded Tretyakov gauge located in the sheltered bush site at Valdai), and found that the double fence (gauge) system catches 92–96% of the “true” snowfall (i.e., the Valdai Control System). Based on the experimental data at the Valdai station, Golubev (1985) also developed a relation of the Tretyakov gauge catch of snowfall versus wind speed. Goodison (1981) investigated the Tretyakov gauge catch of snowfall versus snowboard measurements in a sheltered site in Canada and quantified the catch efficiency as a function of wind speed during snowfall period. During the WMO Solid Precipitation Measurement Intercomparison, the Tretyakov gauges were tested against the DFIR reference at 11 stations in seven countries (Goodison et al. 1998; Yang et al. 1995). The catch efficiency of the gauge vs. the DFIR was derived and tested using the WMO intercomparison data (Goodison et al. 1998; Yang et al. 1995). The result has been applied to the historical precipitation records collected by the Tretyakov gauges over large regions, including Siberia (Yang and Ohata 2001), Arctic Ocean (Yang 1999), Mongolia (Zhang et al. 2004), and the Arctic regions as a whole (Yang et al. 2005).

Reducing the known biases in gauge measurements of precipitation is a major challenge particularly for the cold regions. Efforts are ongoing to refine the bias-correction methods for the national standard gauges and to develop new approaches to better observe snowfall with automatic instruments and techniques. The purpose of this chapter is not to address the biases in gauge precipitation measurements (i.e., Yang et al. 1995) or to assess the reference for gauge intercomparison experiment (i.e., Yang and Simonenko 2013); rather it is to investigate the (in)consistency in precipitation observations by the same gauges. This is an important issue for any intercomparison experiments, because it is necessary to determine first how the same gauges will measure precipitation at the test sites. It is assumed that the same gauges will measure similar amounts of precipitation, and that the difference in same gauge observations is usually smaller than that between two different gauges. To test this assumption, determination of the consistency in gauge performance is necessary and useful to accurately evaluate various gauges tested in the intercomparison experiments. In other words, the knowledge of consistency in same gauge observations is critical to decide the acceptable degree of difference (or similarity) in precipitation observations by different gauges.

The objective of this chapter is to quantify and document the difference in winter precipitation observations among the six identical Tretyakov gauges at Valdai in Russia. Specifically, this analysis covers the data period during 1991–2010; it examines the relationship between the six Tretyakov gauges and investigates the major factors contributing to any significant differences among these gauges. It also compares the results with other relevant studies and discusses future needs for similar research and applications. The methods and results of this work will directly contribute to the design and data analysis of gauge intercomparison experiments, including the WMO Solid Precipitation Intercomparison Experiment (SPICE) project for the automatic gauges and instruments (http://www.wmo.int/pages/prog/www/IMOP/intercomparisons/SPICE/SPICE.html). They will also support climate and hydrology research, particularly precipitation changes, snow cover processes, and streamflow modeling over the cold regions.

Design of the Experiment

The Valdai Hydrological Research Station is situated in the northwestern part of the East European Plain. It is in the middle between Moscow and St. Petersburg. The station (57 59′N, 33 15′E, 194 m above the sea level) is located on the flat shore of Valdai lake in the center of the Valdai Hills. The Valdai Hills are characterized by a hilly moraine landscape where hills alternate with depressions. Predominant elevations are about 200 m above sea level. The area studied in this chapter is in the southern taiga zone mainly with spruce and deciduous forests and pine woods. The forests and bushes occupy 75% and 20% of the region, respectively. The climate near Valdai is mainly continental. Mean annual air temperature is about 3.4 °C, with July mean of 16.4 °C and January average of −9.7 °C. Total annual precipitation is about 800 mm, with annual precipitation days of 207. A stable snow cover is usually observed from late November to mid-April, with the peak accumulation (about 70 cm) in early March. Within the Valdai Hills, the southwestern winds prevail. Mean annual wind velocity is about 4 m/s. The maximum wind speeds (4.0–4.5 m/s) are observed during the winter months.

The Valdai Station has an open/meadow area and a bush site. The meadow site is about 100 × 100 m in area and 25 m from the latticed fence. This site is flat and about 1.5 m above the lake water level during the low-water season. The grass surface during the warm period is regularly mowed. The average vertical angle of obstacles is 1.4°. The instruments on the site are exposed to winds from all directions. The Valdai Station has a long history for testing various meteorological instruments. The site was modified in 1988 for the WMO Solid Precipitation Measurements Intercomparison. Eighteen gauges from six countries were installed during 1988–1995. Some instruments remained during the change in 1988 so as to ensure observation homogeneity and reliability; these instruments included the Valdai control system in the bush, and six Tretyakov gauges located at the corners and in the center of the meadow site (Fig. 1). The gauges in the center of the plot are about 20 m apart, and the four gauges at the corners were 90 m apart. Approximately 300 m northwest of the open site is the bush site, where 2–4 m high shrubs occupy a three-hectare area. There is a fenced area of 70 × 70 m, where the bushes are pruned (in autumn) at height of 2 m above the ground. The mean bush density is about 4 stems/m^2, and the mean diameter of the shrub tops (2 m above the ground) is approximately 25–50 cm. At the center of the site sit the bush gauges (Tretyakov gauge with a wind shield).

Precipitation measurements at the Valdai Station were conducted generally twice daily: at 9:00 and 21:00 of Moscow standard time. The contents of the gauges were both weighed and measured volumetrically with the resolution of 0.1 mm to determine precipitation amount, and over a period of time, an average wetting loss was determined by comparing the difference between the weighed and volumetric measurements. Since 1966, a correction for wetting loss of the Tretyakov gauge (i.e., 0.11 mm/event for rain and 0.06 mm/event for snow) has been added to every volumetric measurement, and therefore no additional correction for this systematic loss is required (Golubev 1989). Wind speed and direction were measured at 2 and

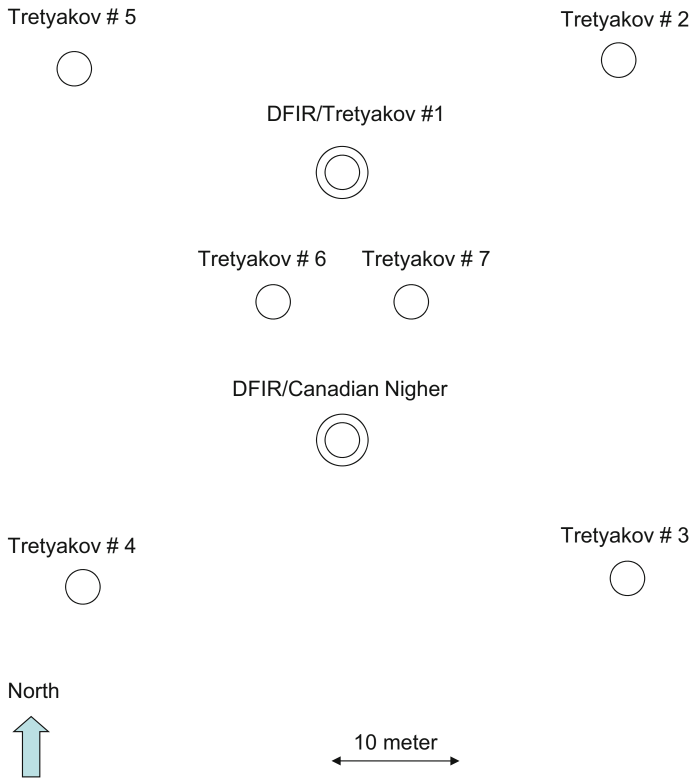

Fig. 1 Valdai meadow site layout and precipitation gauges

3 m heights in the center of the meadow site. Atmospheric pressure, air temperature, and humidity were also measured at the Valdai operational meteorological station located 0.9 km southwestward of the experimental site.

During the data collections, precipitation types were classified by the observers at the times of observations as dry snow, wet snow, mixed precipitation, and rain. Drifting or blowing snow events were also manually identified and reported by the observers. This chapter focuses on the analyses of winter (October to April) season precipitation data, i.e., snow, mixed precipitation, and winter rain. Statistical analyses of long-term 12-h precipitation data measured by the six Tretyakov gauges were carried out. The methods used include calculation of total precipitation amounts during the study period for various precipitation types, determinations of mean wind speed and air temperature on precipitation days, and regression and correlation analyses of precipitation, wind speed, and temperature data. The statistical tools used in this chapter have been recommended and tested in the previous WMO gauge intercomparison. The consistency in methodology is important as it ensures that the results from this work are comparable with those from the last WMO project and other relevant studies. This work also discusses and documents the magnitudes of systematic and random errors in precipitation measurements by other national standard gauges.

Gauge Catch Difference and Wind/Temperature Effect

Based on the data analyses, the results for the mean gauge catch, comparisons of 12-h gauge measurements, and the effects of wind speed and temperature on gauge catch differences are presented and discussed below.

Mean Difference Among the Gauge Measurements

To determine the mean differences among the gauge observations, the total precipitation amounts and mean temperature and wind speed over the long-term period during 1991–2010 were calculated. The gauge observations to the standard Tretyakov gauge (gauge #7 – the working reference at this station) for dry snow, wet snow, blowing snow, mixed precipitation, and rain were compared. The results below were presented by precipitation types (Table 1).

There were 640 events of dry snow reported for the study period. The total snowfall ranged from 992 to 1,019 mm among the six gauges; these values are systematically less than the DFIR and Bush gauge observations due to Tretyakov gauge undercatch of snowfall (Golubev 1988; Goodison et al. 1998; Yang et al. 1995). Mean temperature and wind speed at 2 m during these events were about –6 °C and 3.7 m/s. Relative to the standard gauge (#7), the other Tretyakov gauges recorded 97–106% of the total snowfall. The difference between the highest and lowest total snowfall (measured by gauges #3 and #5, respectively) is about 11%, or 128 mm for the 640 events, and average of 0.2 mm per observation. This difference is quite significant, since the six gauges were identical; they were located 10–50 m apart at an open site and were emptied regularly at the same time in the same way according to the Russian standard observation procedure (Groisman et al. 1991).

There were 506 wet snow events during the study period; the mean temperature and wind speed were –3 °C and 3.7 m/s, respectively. The six gauges recorded total snowfall from 685 to 768 mm. Relative to the gauge # 7, the mean catches of other Tretyakov gauges ranged from 94% to 104%. The difference between the lowest and highest totals (i.e., gauges # 4 and 5, respectively) is 10%, or 79 mm for all the events, average of 0.2 mm per observation. These results are similar to the dry snow data. It is important to note that wind conditions (i.e., long-term mean wind speeds) were similar for both wet and dry snow cases at this site. This may lead to some degree of consistency in gauge catch of snowfall in this region, although the mean temperature for the dry snow is lower than that for the wet snow.

In addition to the dry and wet snow data, there are 79 blowing snow cases reported at Valdai during the study period. The mean temperature and wind speed for these events were –5 °C and 5.2 m/s at 2 m height, respectively. The total accumulation ranged from 179 to 226 mm among the six gauges. Relative to

Table 1 Summary of all 12-h precipitation observations by various gauges at the Valdai experimental station during 1991 to 2010

	No. Event	Tmax (c)	Tmin (c)	Tmn (c)	Wdir (Dgr)	W3m (m/s)	W2m (m/s)	DFIR (mm)	Bush/Tret (mm)	Tret7 (mm) (%)	Tret2 (mm) (%)	Tret3 (mm) (%)	Tret4 (mm) (%)	Tret5 (mm) (%)	Tret6 (mm) (%)
Dry snow															
mean/ total	640	−3.8	−8.1	−5.9	200.8	3.8	3.5	1378.4	1444.5	1019.9	1045.3	992.1	995.3	1080.5	1009.7
RCR										100%	102%	97%	98%	106%	99%
Wet snow															
mean/ total	506	−1.1	−4.9	−3.0	226.9	3.9	3.7	952.3	1012.3	726.0	724.5	684.5	679.7	758.2	706.5
RCR										100%	100%	94%	94%	104%	97%
Mixed P															
mean/ total	323	3.2	−0.8	1.2	218.8	4.4	4.1	1476.0	1554.1	1315.7	1325.5	1276.6	1263.6	1355.3	1290.6
RCR										100%	101%	97%	96%	103%	98%
Blowing snow															
mean/ total	79	−2.6	−7.6	−5.1	216.7	5.7	5.2	338.2	379.6	207.3	205.6	182.4	179.4	225.8	196.0
RCR										100%	99%	88%	87%	109%	95%
Rain															
mean/ total	500	9.1	4.7	7.5	215.3	4.0	3.6	1786.4	1872.7	1729.0	1730.1	1716.7	1694.2	1753.0	1722.4
RCR										100%	100%	99%	98%	101%	100%
Notes:															

W3m wind speed at 3m height; *W2m* wind speed at 2m height; *bush/tret* Tretyakov gauge in bush; *RCR* relative catch ratio to Tret #7 the reference gauge #7, the mean catches of the gauges varied from 87% to 109%. The difference between the highest (gauge# 5) and lowest (gauge # 4) totals is about 47 mm, or 22%, averaging of 0.6 mm per observation. This difference is roughly twice as high as that for both dry and wet snow cases, clearly suggesting potential blowing snow impact to gauge performance at this site.

There were 323 mixed precipitation events, with the mean temperature and wind speed being 1.2 °C and 4.1 m/s at 2 m. Total precipitation for all the events ranged from 1,263 to 1,355 mm among the six gauges. Relative to the standard gauge #7, the mean catch was between 96% (gauge #4) and 103% (gauge# 5). The difference between the highest and lowest totals was 92 mm, or averaging of 0.3 mm per observation. This value is similar to the snow data, indicating some consistency in gauge catch of snow and mixed precipitation at this location.

Winter rainfall data were also collected at this site during October to April. In the winter season, the Tretyakov gauges at Valdai were used without a funnel; this is a standard configuration for snow observations at the Russian networks. In the other seasons, a funnel is installed in the gauge for rainfall collections. There are notes in the Valdai data sheets about the dates of installing/removing the funnel in spring and fall seasons. The wetting loss may be a bit higher for the gauge without a funnel. During the study period, 500 rainfall events were registered by the six gauges in the winter season. These events were between 0.1 and 30 mm for the 12-h period. The mean temperature and wind speed were 7.5 °C and 3.6 m/s, respectively. The total rainfall amounts ranged from 1,694 to 1,753 mm among the six gauges. Relative to the standard gauge (#7), the mean catches varied from 98% to 101%. As expected, the difference in gauge catch (about 3% between the highest and lowest catches) is much smaller than the snow cases, partly due to smaller wind effect and gauge undercatch of liquid precipitation (Goodison et al. 1998; Yang et al. 1995).

To determine the consistency in gauge catch and performance, the six gauges were ranked by total accumulation for various precipitation types, including blowing snow. A clear north-south gradient was found over the site for all precipitation types. This means the two gauges (#2 and #5) on the north site of the plot collected the highest precipitation, and the gauge pair (# 3 and #4) in the south side measured the lowest amount of precipitation. Previous data analysis for this site suggested an even distribution of yearly precipitation over the experiment area, although predominant winds were from the southwest (Golubev et al. 1989). Our results, however, demonstrate a noticeable difference in gauge measurements across the site. Site location and selection are important for instrument intercomparison and test. Strangeways (2009) used the Google Earth to assess several GCOS stations over the UK. Examination of a (May 2009) Google Earth image for the Valdai site and its surroundings reveals a patch of trees on the west side of plot for the most common wind direction. These trees may alter wind flows around the instruments and affect gauge catch of precipitation. The effect of the nearby lake to the site and instruments also needs attention. Future investigation is necessary to consider the influence of micrometeorology, particularly wind distribution and turbulence across this site, on gauge observations.

Comparison of 12-h Observations

Many studies show that wind speed and temperature affect gauge catch of precipitation (Yang et al. 1998a, 1999a; Goodison et al. 1998). Precipitation amount may also play a role in determining gauge performance, particularly for rainfall measurements (Nešpor and Sevruk 1999; Sugiura et al. 2006). To understand the variability in gauge catch, the gauge observations at the 12-h time interval were compared for various precipitation types.

Random errors exist in precipitation gauge observations. To reduce the impact of random errors, the mean precipitation amounts for the six gauges at the 12-h time interval were calculated, so as to identify the lowest and highest snow measurements by the gauges for 12 h. Figure 2 shows the mean, maximum, and minimum snowfall values for the six gauges. The data presented in Fig. 2 are not the time series of observations, but rearranged (or sorted) by the mean precipitation amount, i.e., from the lowest to the highest values for all the snowfall events. It is clear that most dry snow events were less than 2 mm for the 12-h period, and only about 80 cases (about 10%) were greater than 4 mm. The range of measurements by the gauges (i.e., the difference between highest and lowest values) was less than 1 mm for most low snowfall events, and it increased to 2–4 mm for the high snowfall events. This result suggests a better consistency of gauge performance for the low snowfall events, and a large variation in gauge catch for the high snowfall cases. Wet snow data generally demonstrate very similar result, although the difference in gauge catch was smaller relative to the dry snow data.

To reveal the difference in gauge catch, the 12-h data between the gauges were examined. Figure 3 shows the comparisons of dry snow data measured by the six Tretyakov gauges in three pairs. Gauges # 2 and 3 are located about 50 m apart at the east corners of the plot. The 12-h snow data are very similar between these two gauges, with the differences being less than 2 mm for most events, except for a few cases of higher snowfall up to 10 mm. There exists a close linear relationship between the 12-h observations. This relationship can be used as a transfer function between the gauge observations. On average, gauge #3 measures 7% less snow than gauge #2. The gauge pair of #4 and # 5 was located on the west corners of the plots (about 90 m apart); on average, gauge # 5 measured about 8% more snowfall than gauge #4. On the 12-h basis, gauge # 5 systematically collected more snowfall, particularly for the precipitation range from 2 to 8 mm. For a few cases, the differences were about 2–3 mm for the 12-h period. Gauges # 6 and #7 were installed in the center of the plot, about 20 m apart. Both gauges caught similar amount of snowfall. On average, they measure the same amount of snowfall for the 640 cases. But the difference for the individual observations between these two gauges is big, sometimes up to 4 mm for 12 h, which is higher than that for the other gauge pairs. This result is not expected, as these 2 gauges are located very close to each other.

Figure 4 compares the wet snow data collected by the three pairs of the Tretyakov gauges. For the gauge pair of #2 and #3, the 12-h snowfall ranged from trace amount to 14 mm. For most cases, both gauges measured similar amounts of wet snow, with the differences being less than 2 mm. Overall, gauge #3 collected 6% less snow than the gauge #2, although the linear correlation between the two gauges is very high.

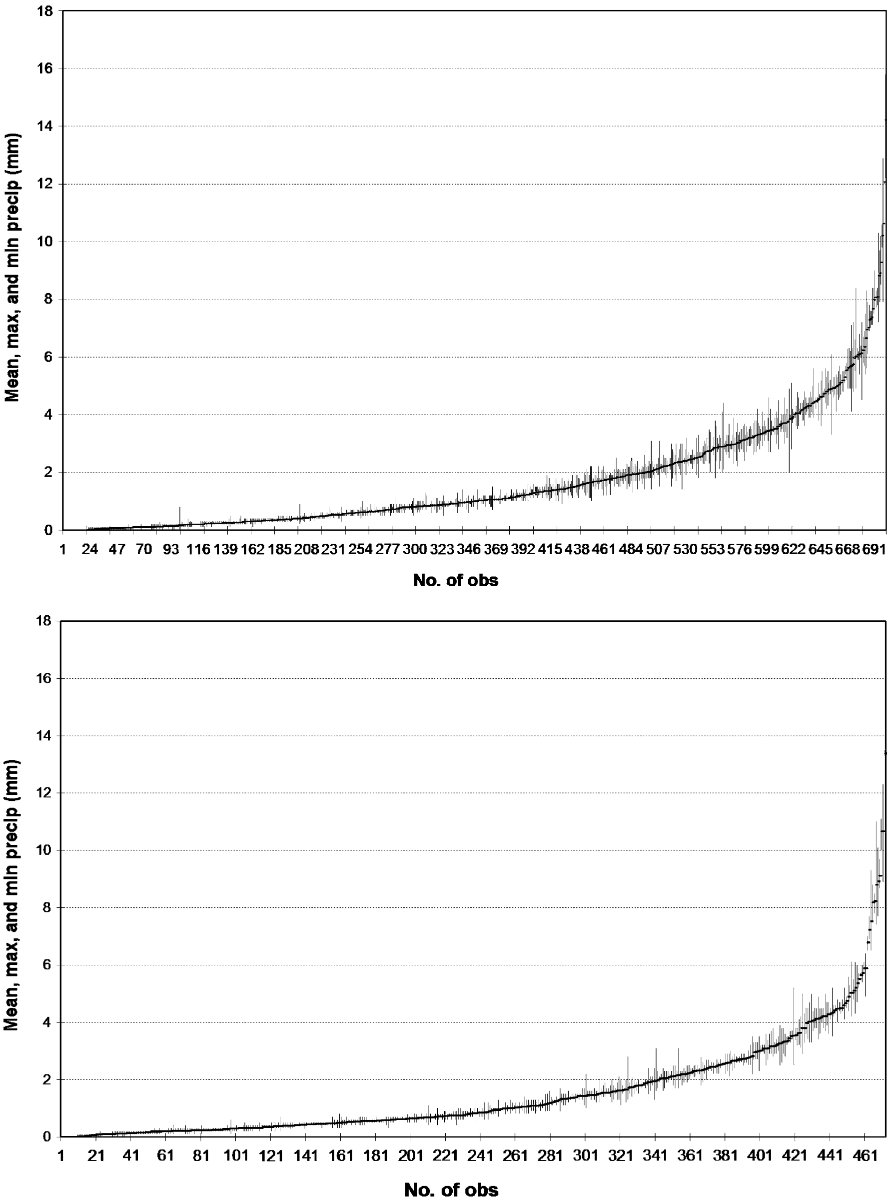

Fig. 2 Mean, maximum, and minimum snowfall measurements by the 6 Tretyakov gauges

This result is very similar to the dry snow case. For the gauge pair of #4 and #5, both gauges measured the similar amounts of snowfall in most cases, with the difference being less than 2 mm, except for a few outliers with the differences greater than 3 mm. On average, gauge #5 measured 8% more snow than gauge #4, although a

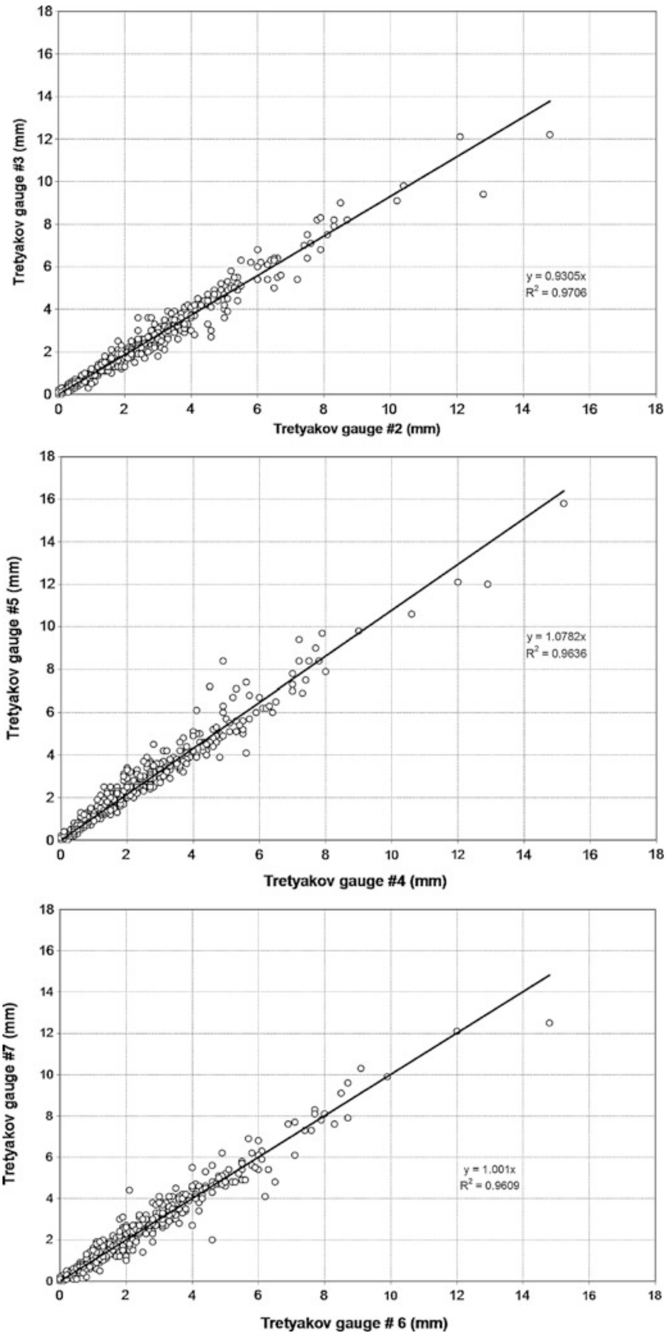

Fig. 3 Comparison of 12-h dry snow data among the 6 Tretyakov gauges

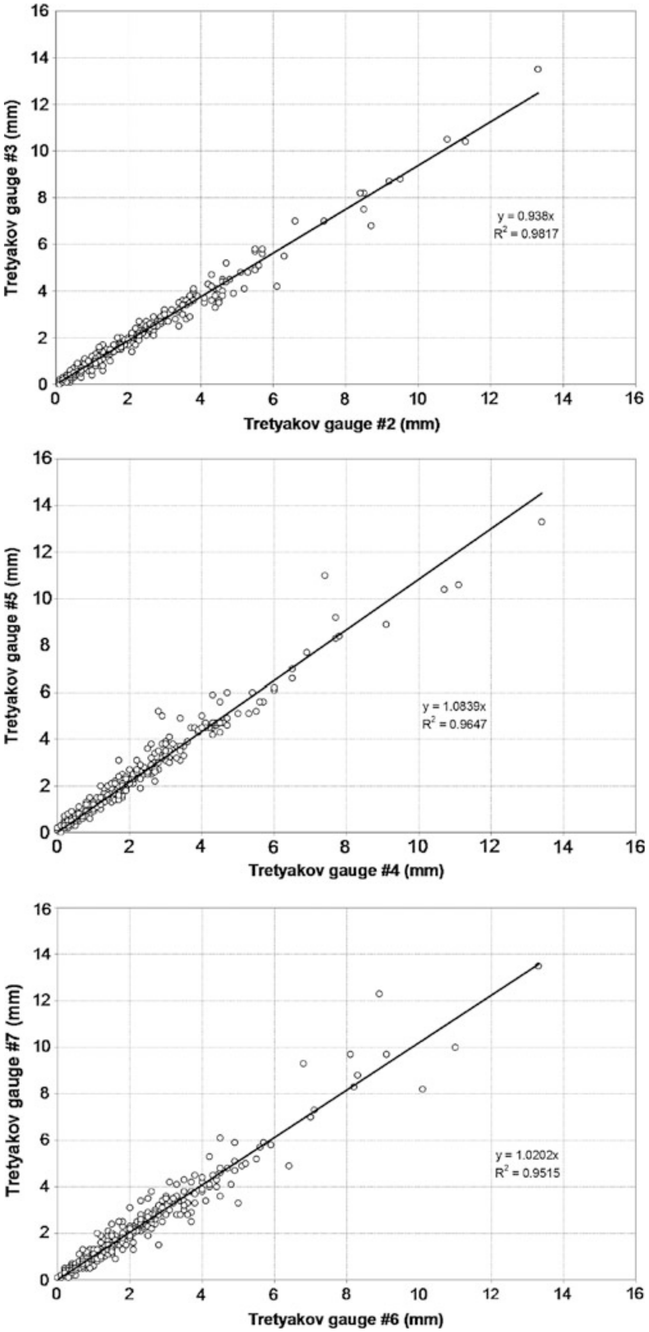

Fig. 4 Comparison of 12-h wet snow data among the 6 Tretyakov gauges

close linear relationship exists. This result is similar to the dry snow data. For the gauge pair #6 and #7, there were many events of less than 6 mm for the 12-h period. Both gauges reported similar amounts of snowfall. For snowfall cases ranging from 6 to 14 mm, the scatter is large with the highest difference of more than 3–4 mm for the 12-h period. Overall, gauge #7 measured 2% more snow than gauge #6. This difference is not very significant, although it is slightly different from that for the dry snow data, when the two gauges, on average, collected same amount of snowfall.

Figure 5 shows the 12-h blowing snow data collected by the six Tretyakov gauges. The data include both dry and wet snow events, but they are hardly distinguishable in terms of both catch difference and its scatter. There are systematic differences among the gauge catch. Gauge #3 measured less snow than gauge #2 for most blowing snow events (including wet and dry snow); on average, it reported 12% less snow than gauge #2. Gauge #5 caught more snow than gauge #4 by 26%, while gauge #7 measured more snow than gauge #6 by about 5% for all blowing snow cases. It is important to point out the consistency in gauge catch between blowing snow and non-blowing snow events. For instance, gauge #2 caught more snow than gauge #3 for both blowing snow and non-blowing snow cases, although the difference in gauge measurements for blowing snow events is much higher, i.e., 12% for the blowing snow vs. 6–7% for dry/wet snow. It is also interesting to note a very small catch difference between the gauges #6 and #7 for snow and blowing snow data, perhaps because these two gauges are situated about 10 m apart in the center of the plot and expose to similar wind and snow conditions.

Figure 6 displays the comparisons of the mixed and rain data during the study period. Mixed precipitation at Valdai ranged from trace amount to 26 mm over the 12-h period. For most measurable events, both gauges #2 and #3 reported similar amount of precipitation, with the differences being less than 1 mm. Overall, gauge #3 collected 4% less than gauge #2, although the correlation between the gauge measurements is very high. This result is very similar to the wet snow data. Rainfall data suggest that Tretyakov gauges #2 and #3 caught very similar amounts of precipitation for the 12-h period. There is a very close linear relationship between the gauge measurements, with the overall difference being less than 1%. The other gauge pairs have similar results to gauges #2 and #3 for both mixed precipitation and rain, respectively.

Maximum Catch Difference vs. Temperature and Wind Speed

The six Tretyakov gauges measure differently for most 12-h individual precipitation events. To understand the gauge performance for all precipitation measurements, the minimum and maximum values for each precipitation observations were identified, so as to calculate the difference between these high and low values and define the maximum catch difference among the six gauges. Examination of the maximum difference vs. temperature and wind speed during the 12-h observation was done. This analysis allows us to identify the factors controlling the variation in gauge observations of snowfall, including blowing snow conditions.

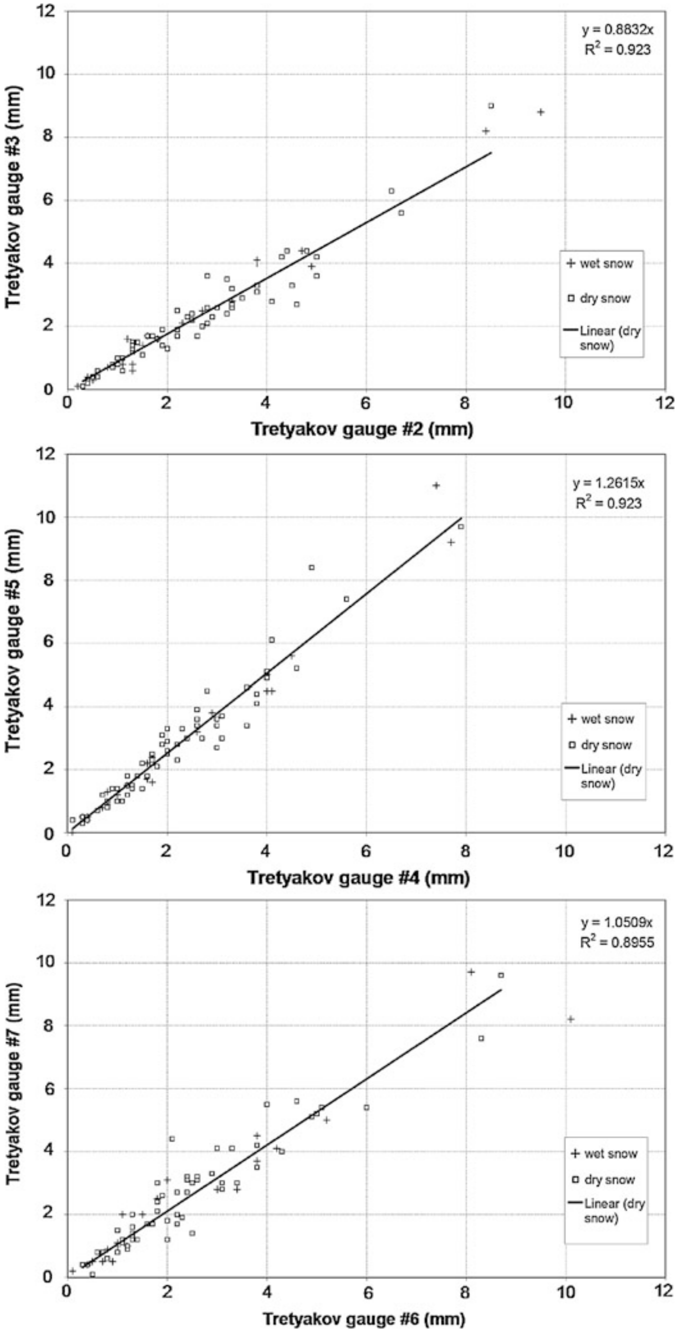

Fig. 5 Comparison of 12-h blowing snow data among the 6 Tretyakov gauges

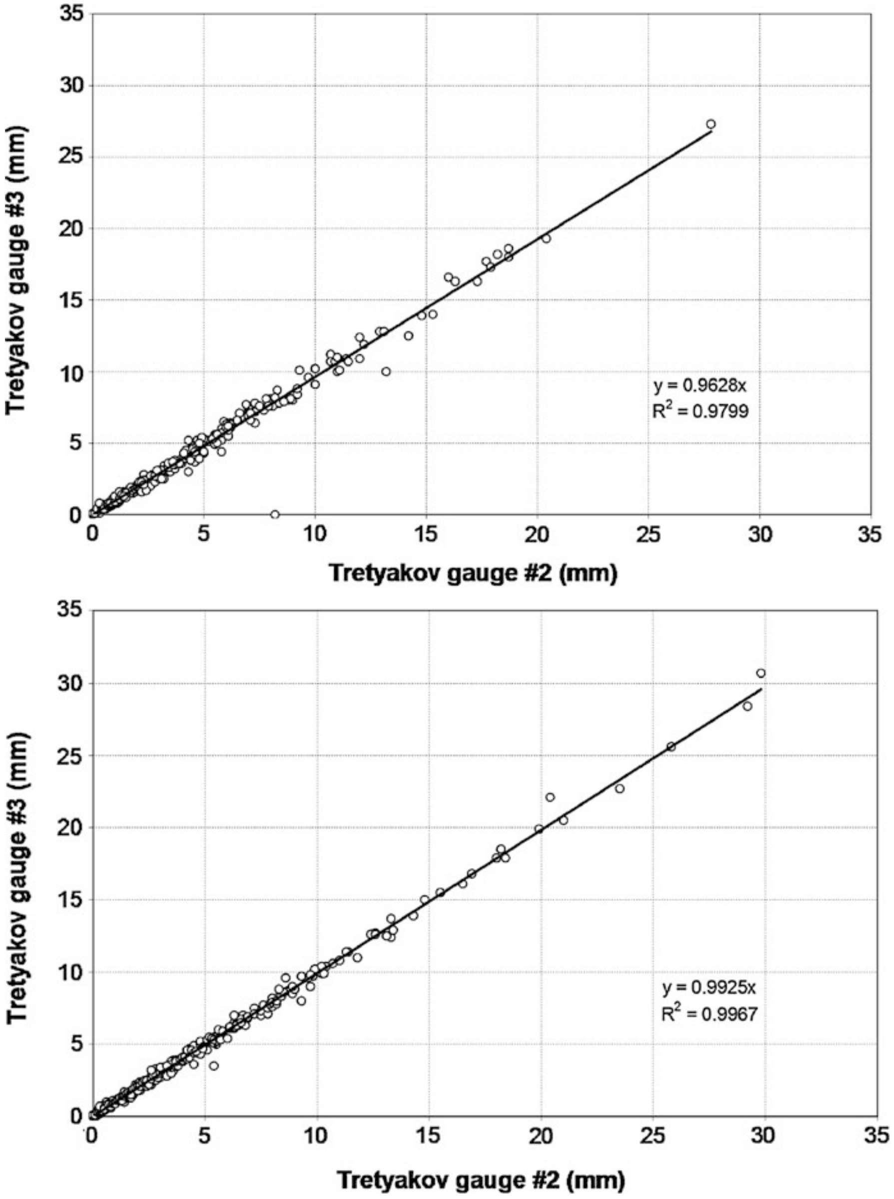

Fig. 6 Comparison of 12-h observations between 2 Tretyakov gauges for mixed precipitation (top) and winter rain (bottom)

Figure 7a shows the scatter plot of the maximum difference in gauge measurements vs. wind speed at 2 m. The range of the max difference varies from less than 1–3 mm for the 12-h period; it seems to rise very weakly with the wind speed. For instance, for higher wind speeds up to 5–8 m/s, there are more data points with higher differences among the six gauges, although the relationship between wind speed and max difference is not significant. This result is reasonable, since many studies show that wind speed is the most important factor to gauge catch efficiency of snowfall (Goodison et al. 1998; Yang et al. 1993, 1998a). The six Tretyakov gauges are installed over an area of 150x150 m; it is possible that they may experience different wind conditions during the snowfall periods. Figure 7b displays temperature vs. the max catch difference among the six gauges. For temperatures range from –20 °C to +5 °C, the max differences vary greatly. As such, there is almost no relationship between these two variables, although bigger differences seem to be associated with warmer temperatures from –5 °C to 0 °C. This association may be related with wet snow and snow sticking on the rimes of the gauges.

Wind speeds during the wet snow events were from 0.5 to 7.5 m/s. Most max differences were less than 1 mm, with some ranging from 1 to 2 mm, and only four cases between 2 and 3 mm (Fig. 8a). There is a weak tendency of larger catch difference associated with the higher wind speeds. This is very similar to the result for the dry snow data. Temperatures fluctuated from –16 °C to 4 °C for the 12-h events (Fig. 8b). The max difference did not change much with temperature, although the difference in gauge catch is higher (up to 3–4 mm) for temperatures between –5 °C and 0 °C. This result is very similar to the dry snow.

For the blowing snow events, wind speeds were from 3 to 8 m/s at the 2 m height and the corresponding max difference in gauge catch was less than 2.5 mm for most events, except one outlier of 2.8 mm with the highest wind speed of 8 m/s (Fig. 9a). It is interesting to note that the wind speed range for the blowing snow events is similar to that for the non-blowing snow cases. There is no clear relationship between the gauge catch difference and wind speed. Temperatures during blowing snow events ranged from –18 °C to 1 °C, the max catch difference varied widely, particularly for temperatures range from –10 °C to 0 °C. Similar to the snow data, there is a weak tendency of higher catch difference associated with the warmer temperatures during the blowing snow (Fig. 9b).

Uncertainties in Gauge Intercomparison

There are uncertainties in data collections and analyses for precipitation gauge intercomparison experiments. These include, for instance, determination of precipitation types, observations, and calculations of mean wind speed and temperature for a given time interval when precipitation was observed. At Valdai, the observers classified precipitation types at the time of the observations (2–4 times a day). Some misclassifications are likely particularly for the mixed precipitation and blowing snow events. Air temperature and humidity are useful to estimate precipitation types (Legates and Bolgart 2009). Yang et al. (1999, 2005) used daily air temperature to determine precipitation types when this information is not available for the northern regions. In this chapter, wind speed and air temperature are the 12-h means; they do not accurately represent the weather condition during the storm. The use of such mean wind speed may lead to uncertainties in gauge comparisons. Data collections

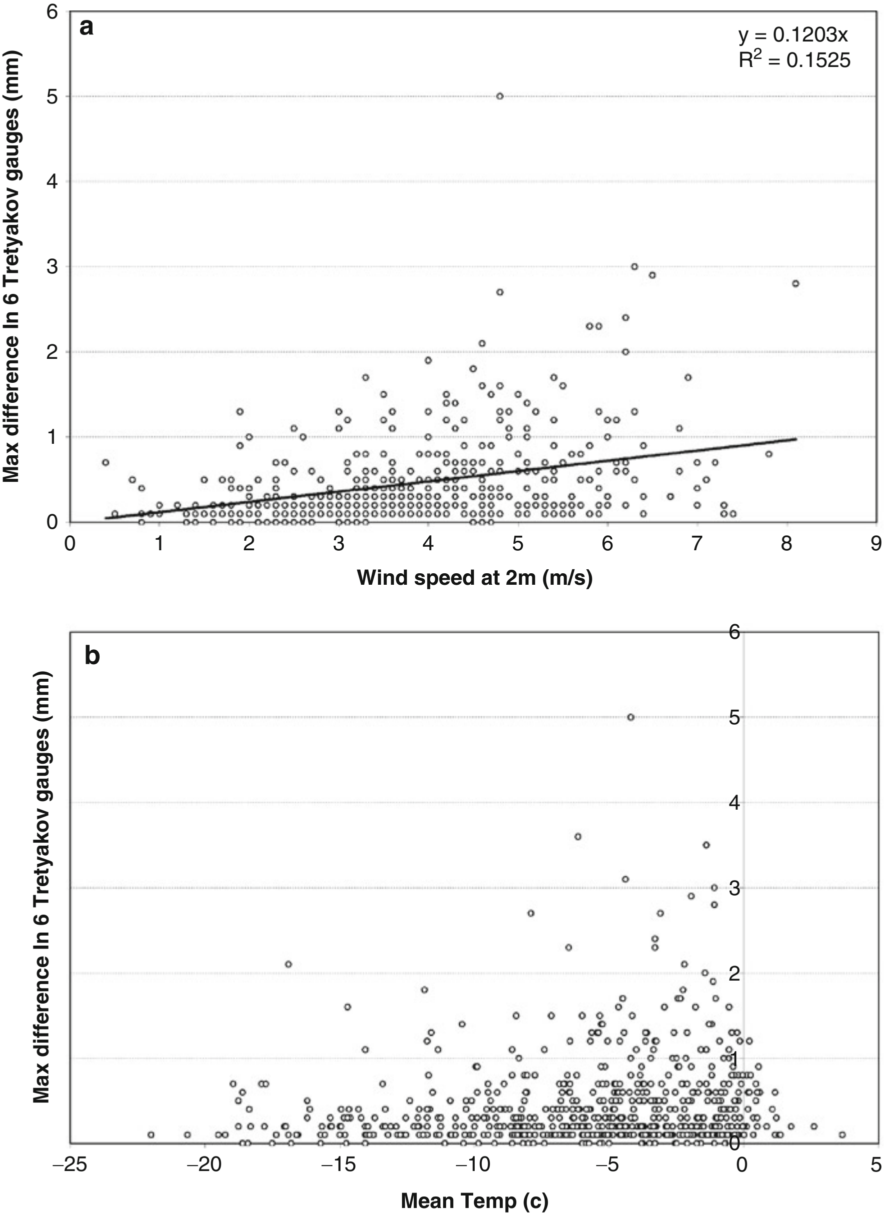

Fig. 7 Scatter plots of maximum catch difference vs. wind speed (**a**) and temperature (**b**) for dry snow

and analyses on shorter timescales, such as hourly or 6-hourly, is expected to produce more reliable results, since wind speeds may vary throughout the day and 12-hourly mean wind speeds may not be representative of wind conditions over the precipitation periods. Automatic sensors will also be important to detect precipitation types at operational and research networks.

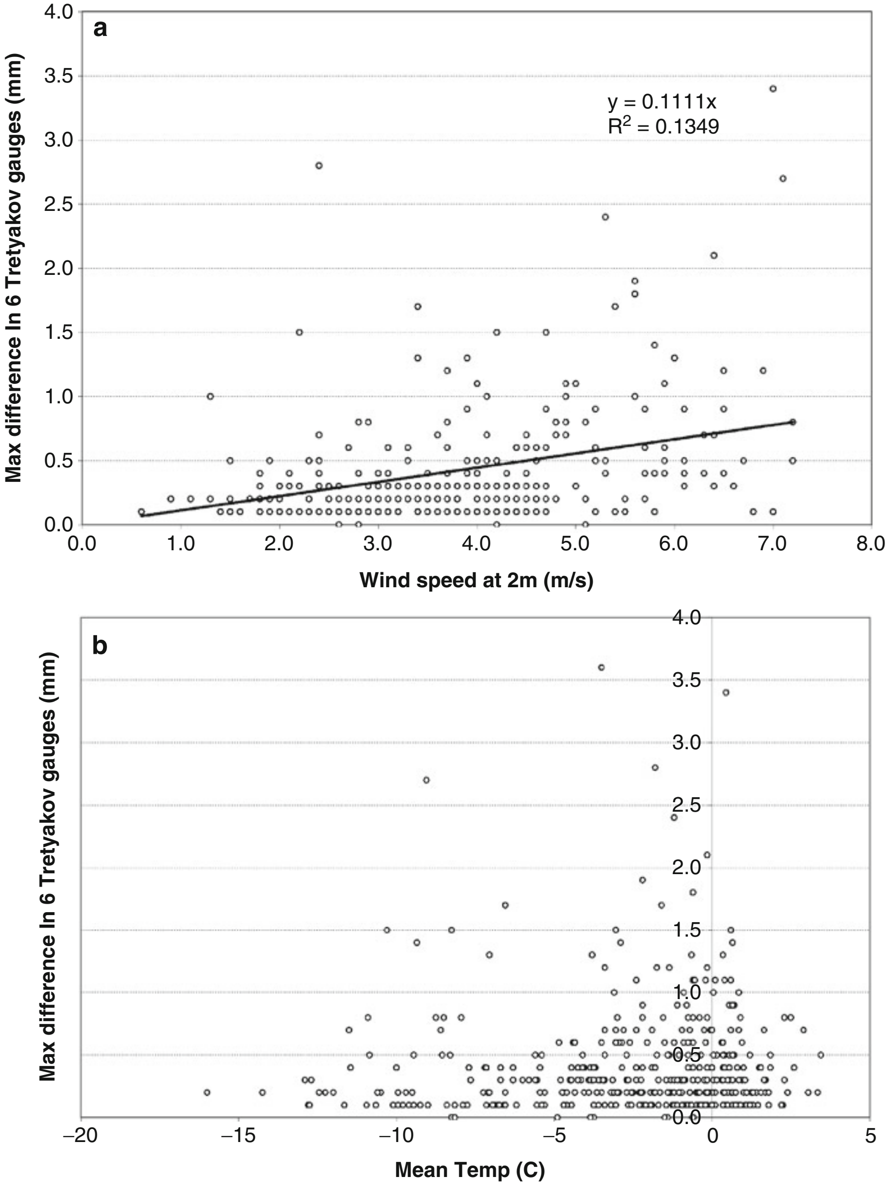

Fig. 8 Scatter plots of maximum catch difference vs. wind speed (**a**) and temperature (**b**) for wet snow

As recommended by the past WMO gauge intercomparison (Goodison et al. 1998), the identification and separation of blowing snow are necessary, because blowing snow conditions are a special case when assessing gauge performance. It is a challenge to quantify the effects of blowing snow on quality of snowfall measurements due to lack of necessary information. Blowing snow fluxes collected by precipitation gauges are called false precipitation (Golubev 1998). The amount of

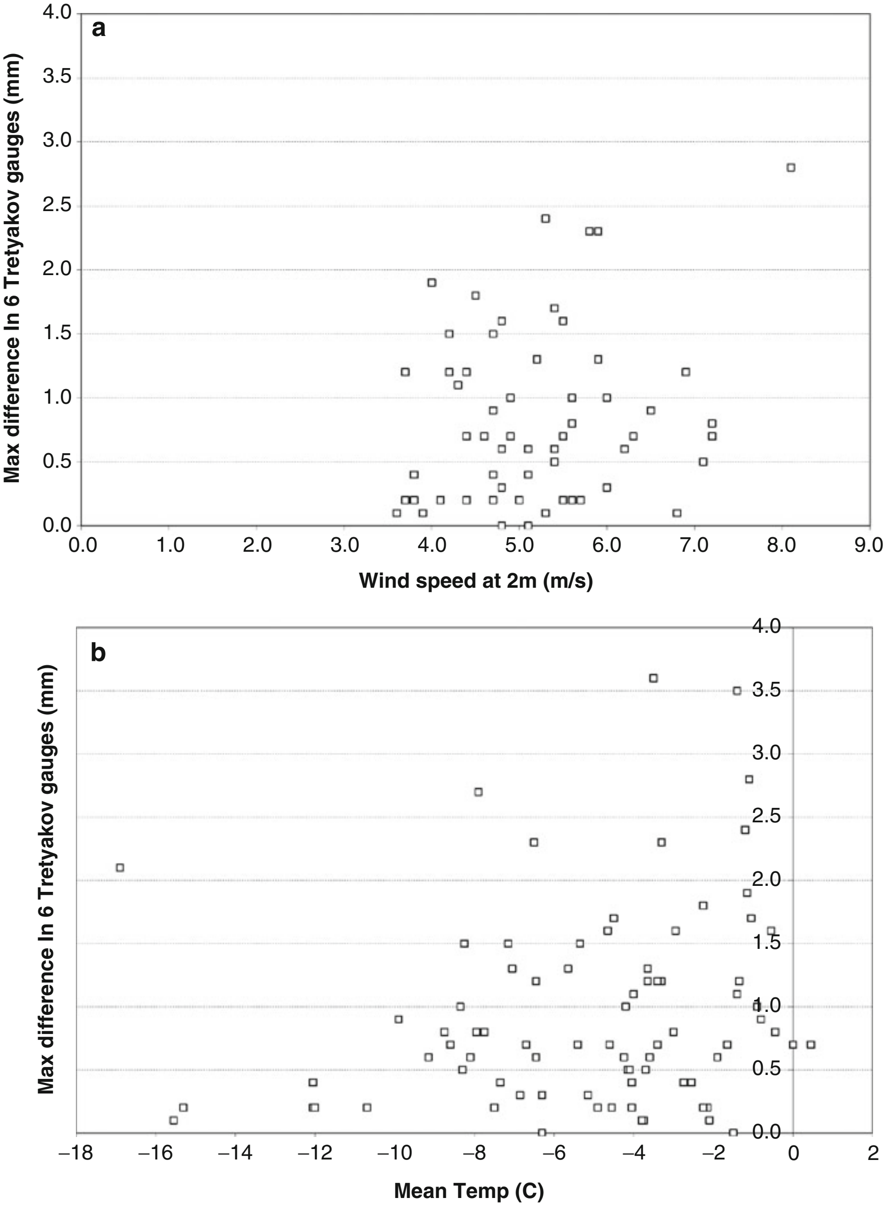

Fig. 9 Scatter plots of maximum catch difference vs. wind speed (**a**) and temperature (**b**) for blowing snow

false precipitation is proportional to the intensity of blowing snow and its duration. Based on field observations at a windy alpine location in the Colorado Front Range, Bardsley and Williams (1997) reported that blowing snow events often occur after the storms at high wind speeds over 20 m/s and may introduce 50% overcatch over a winter season. Yang and Ohata (2001) found an association of higher wind speeds with higher snow measurement by the Tretyakov gauges at the windy and cold Tiksi and Dekson stations in northern Siberia coast perhaps due to blowing snow into the gauges. Many blowing snow events were recorded during the intercomparison experiment at Valdai. The occurrence of blowing snow events was reported for an observation period at Valdai (i.e., 12 h). However, information of blowing snow duration and intensity are critical but mostly unavailable to determine blowing snow flux and its impact to gauge observations in the cold regions (Sugiura et al. 2006, 2009). Blowing snow generally occurs near Valdai station at mean wind speeds of 3–8 m/s at 2 m height (Fig. 5). During blowing snow events, the difference in the six gauge catches is generally higher than that for the non-blowing snow cases. Because of the uncertainty in gauge performance in high wind conditions, it is difficult to assess which Tretyakov gauges at Valdai would have measured snowfall better than the other counterparts. More data collection and analysis of snowfall in higher winds, including blowing snow events, are necessary with automatic instruments at this site and over other northern locations.

Automatic precipitation gauges have been used in the operational networks over many nations. The transformation from the manual to automatic observation systems will have a major impact to climate monitoring, including climate change investigations. It is thus useful to relate and compare the manual approach with automatic technique for precipitation observations (Groisman et al. 1999). For instance, the Belfort precipitation gauges have been widely used in many regions, and they have been tested at five sites during the past WMO gauge intercomparison project (Goodison et al. 1998; Yang et al. 2001). It is possible therefore to analyze the intercomparison data to study the consistency of the Belfort gauge observations of precipitation. Other ongoing efforts in USA, Canada, and through the WMO (Rasmussen et al. 2012) have also tested numerous automatic instruments for snowfall observations in various climate regimes. The data collections and analyses in these projects will improve our capability to better measure snowfall in the cold regions.

It is known that most national standard gauges, including the Russian Tretyakov, Canadian Nipher, and US 8-in. gauges, under measure precipitation especially for snowfall (Goodison 1981; Goodison et al. 1998; Yang et al. 1995, 1998a, 1999a). Compatibility analysis of precipitation measurements by various national gauges suggests little difference (less than 5%) for rainfall observations, but a significant discrepancy (up to 110%) for snowfall measurements (Yang et al. 2001). For instance, many national gauges have been tested at the Valdai station for many years; the experimental data demonstrated that the Canadian Nipher gauge caught, on average, more than 13% snowfall than the Tretyakov gauges (Fig. 10). The U.S. 8-inch gauge at Valdai systematically measured 30–50% less snow and mixed precipitation than the Canadian Nipher gauge (Yang et al. 2001). This difference in national gauge catch has introduced a significant discontinuity in precipitation records between the US and Canada borders particularly in windy and cold regions. It is clear that the catch difference among the national gauges is much higher than that among the six Tretyakov gauges (i.e., 5–10% for snow and 4–8% for mixed precipitation) at Valdai; this result suggests the systematic biases

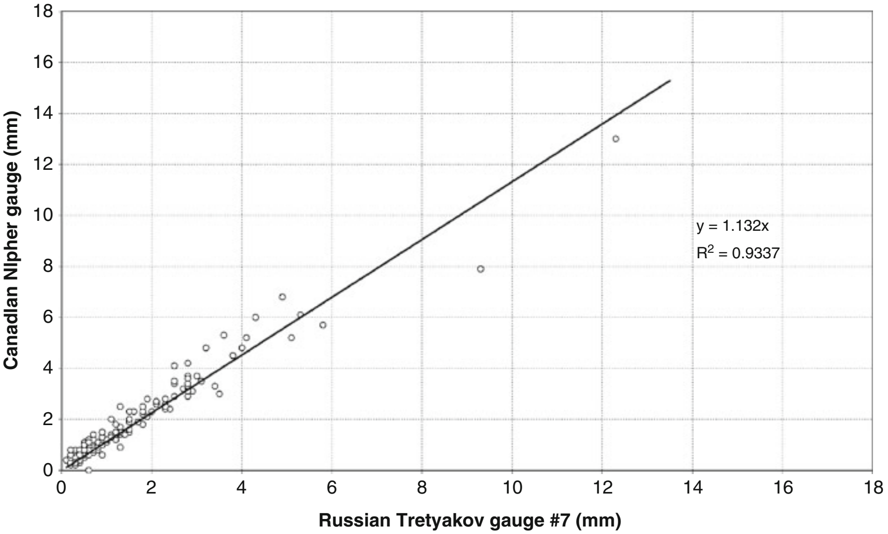

Fig. 10 Comparison of 12-h snow data between the Canadian Nipher gauge and Russian Tretyakov gauge at Valdai

and differences in gauge observations are quite high, and they deserve more research attention. However, documentation and quantification of the catch difference for a given national gauge are important and useful to determine the homogeneity of precipitation data collected by a standard gauge within the national and regional networks.

Summary

Analyses of the long-term intercomparison data define the mean catch of the six Tretyakov gauges for various precipitation types, including blowing snow. Relative to the standard Tretyakov gauge (#7), the mean gauge catch ratios vary from 97–106% for dry snow, 94–104% for wet snow, 87–109% for blowing snow, 96–103% for mixed precipitation, to 98–101% for winter rain. The differences between the highest and lowest mean gauge catches are about 10–11% for snow, 7% for mixed precipitation, and 3% for rain; On average, this difference is about 0.2 mm over the 12-h observation period. The catch difference for blowing snow is, however, much higher, up to 22%, or average of 0.6 mm per observation. It is likely that blowing snow impacts gauge catch and performance at Valdai. Calculations of total accumulation demonstrate a clear south to north gradient for all precipitation types, with the two gauges on the south (north) side of the plot collecting the lowest (highest) amounts of precipitation. Trees and the lake near the site are likely to affect wind regime and gauge catch difference. Our effort continues to examine these factors, mainly via the WMO SPICE experiment at this site, with better wind and snow data collections analyses.

Comparisons of 12-h observations show a better consistency in gauge performance for the low snowfall events and a large variation in gauge catch for the high snowfall cases. There are similarities in gauge catch among the three pairs of gauges and close linear relationships between the 12-h observations. For dry snow, the catch differences are mostly less than 2 mm between the gauges #2 and #3, 2–5 mm for gauges #4 and #5, and 3–4 mm for gauges #6 and #7. The differences in the 12-h observations are much higher for blowing snow (12% between gauges #2 and #3, and 26% for gauges #4 and #5), except for gauges #6 and #7 with 2% (similar to non-blowing snow). The six gauges generally report very similar amounts of 12-h precipitation for both mixed phase and rain, with the difference being less than 1 mm between gauges #2 and #3 for most cases, or less than 1% for rain and 4% for mixed precipitation, respectively. The maximum differences in 12-h gauge snow measurements increase very weakly with the wind speed, and higher differences seem to be associated with warmer temperatures from –5 °C to 0 °C. There is, however, almost no significant relationship between the maximum catch difference and wind speed or temperature over the 12-h period. The effects of wind speed and temperature to gauge catch difference for blowing snow event were weak, and more data analyses are needed to better understand gauge performance in high wind conditions.

A recent WMO survey indicates a large variety of automatic gauges currently used worldwide, including in the same country, for routine precipitation measurements at the national networks (Nitu and Wong 2010). These gauges differ in the measuring system, orifice area, capacity, sensitivity, and configuration. The variety in automatic gauges is much greater relative to the manual standard gauges (Severuk and Kemm 1989; Goodison et al. 1998). The extensive use of different instruments and configurations significantly impacts the accuracy and consistency of regional and global precipitation time series. It is very clear from this analysis and many other studies that field experiments are critical to address the issues of precipitation data accuracy and consistency; they are essential to evaluate national standard and automatic gauges, including quantifications of random and systematic errors in precipitation observations and their possible relationship with meteorological factors. This chapter is only possible thanks to the long-term data collection at the Valdai station. It is necessary to expand this work to other national standard gauges, such as the US NWS 8-in. gauge widely used in many nations and regions. It will be also useful to examine the automatic gauge data and their consistency at the shorter time periods, i.e., hourly or sub-hourly, as the dynamic and climatology of precipitation may differ at shorter time scales. The WMO SPICE project, currently collecting and analyzing gauge intercomparison data at many test sites around the globe, provide much needed new opportunities to improve snowfall precipitation observation and analysis techniques (Kochendorfer et al. 2017).

References

J. Adam, D.P. Lettenmaier, Adjustment of global gridded precipitation for systematic bias. J. Geophys. Res. **108**(D9), 4257 (2003). https://doi.org/10.1029/2002JD002499

T. Bardsley, M.W. Williams, Overcollection of sold precipitation by a standard precipitation gauge, Niwot Ridge, Colorado. in *Proceedings of Western Snow Conference,* Canada, Western Snow Conference 1997, pp. 354–362

E.G. Bogdanova, Investigation of precipitation measurement loss due to wind. Trans. Main. Geophys. Obs. **195**, 40–62 (1966)

Y. Ding, D. Yang, B. Ye, N. Wang, Effects of bias correction on precipitation trend over China. J. Geophys. Res. **112**(D13), D13116 (2007). https://doi.org/10.1029/2006JD007938

V.S. Golubev, On the problem of actual precipitation measurements at the observations site, in *Proceeding of the International Workshop on the Correction of Precipitation measurements* W MO/TD 104, 1985, pp. 61–64

V.S. Golubev, Assessment of accuracy characteristics of the reference precipitation gauge with a double-fence shelter. in *Final Report of the Fourth Session of the International Organizing Committee for the WMO Solid Precipitation Measurement Intercomparison* (St.Moritz, WMO, 1989), pp. 34–41

B.E. Goodison, Compatibility of Canadian snowfall and snowcover data. Water Resour. Res. **17**, 893–900 (1981)

B.E. Goodison, S. Klemm, B. Sevruk, in *WMO Solid Precipitation Measurement Intercomparison*. TECO-1988 WMO/TD-No. 222, Leipzig, 1988, pp. 255–262

B. Goodison, P.Y.T. Louie, D. Yang, WMO solid precipitation measurement intercomparison. Final Report, WMO/TD-No. 872, 1998, 212 pp

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

P.Y. Groisman, E.L. Peck, R.G. Quayle, Intercomparison of recording and standard nonrecording U. S. gauges. J. Atmos. Ocean. Technol. **165**, 602–609 (1999)

J. Kochendorfer, R. Nitu, M. Wolff, E. Mekis, R. Rasmussen, B. Baker, M.E. Earle, A. Reverdin, K. Wong, C.D. Smith, D. Yang, Y.-A. Roulet, S. Buisan, T. Laine, G. Lee, J.L.C. Aceituno, J. Alastrué, K. Isaksen, T. Meyers, R. Brækkan, S. Landolt, A. Jachcik, A. Poikonen, Analysis of single-Alter-shielded and unshielded measurements of mixed and solid precipitation from WMO-SPICE. Hydrol. Earth Syst. Sci. **21**, 3525–3542 (2017). https://doi.org/10.5194/hess-21-3525-2017

D.R. Legates, T.A. Bogart, Estimating the proportion of monthly precipitation that falls in solid form. J. Hydrometeorol., 1209–1306 (2009). https://doi.org/10.1175/2009JH1086.1

É. Mekis, L.A. Vincent, An overview of the second generation adjusted daily precipitation dataset for trend analysis in Canada. Atmosphere-Ocean **49**(2), 163–177 (2011)

J.R. Metcalfe, B.E. Goodison, Correction Canadian winter precipitation data. in *Eighth Symposium on Meteorological Observations and Instrumentation*, Anaheim, 17–22 January 1993, AMS Boston, pp. 338–343

V. Nešpor, B. Sevruk, Estimation of wind-induced error of rainfall gauge measurements using a numerical simulation. J. Atmos. Ocean. Technol. **16**, 450–464 (1999)

R. Nitu, K. Wong, CIMO survey on national summaries of methods and instruments for solid precipitation measurement at automatic weather stations, WMO/TD-No. 1544, CIOM No. 102 2010, 57pp

R. Rasmussen, Coauthors, How well are we measuring snow: the NOAA/FAA/NCAR winter precipitation test bed. Bull. Amer. Meteor. Soc. **93**, 811–829. (2012). https://doi.org/10.1175/BAMS-D-11-00052.1

M. Sanderson, A comparison of Canadian and United States standard methods of measuring precipitation. J. Appl. Meteorol. **14**(10), 1197–1199 (1975)

B. Sevruk, W.R. Hamon, International comparison of national precipitation gauges with a reference pit gauge. WMO Instrument and Observing Methods Report 17, 1984, 111 pp

B. Sevruk, S. Klemm, Types of standard precipitation gauges, in *Proceedings of International Workshop on Precipitation Measurement*, (St.Moritz, WMO/IAHS/ETH, 1989), pp. 227–236

I. Strangeways, Using Google Earth to evaluate GCOS weather station sites. Weather **64**(1) (2009). 8pp

K. Sugiura, T. Ohata, D. Yang, Catch characteristics of precipitation in high-latitude regions with high winds. J. Hydrometeorol. **7**, 984–994 (2006)

K. Sugiura, T. Ohata, D. Yang, Application of a snow particle counter to solid precipitation measurements under the Arctic condition. Cold Reg. Sci. Technol. **58**(2009), 77–83 (2009)

X. Tian, A. Dai, D. Yang, Z. Xie, Effects of precipitation-bias corrections on surface hydrology over northern Latitudes. J. Geophys. Res. **112**(D14), D14101 (2007). https://doi.org/10.1029/2007JD008420

D. Yang, An improved precipitation climatology for the Arctic Ocean. Geophys. Res. Lett. **26**(11), 1625–1628 (1999)

D. Yang, T. Ohata, A bias-corrected Siberian regional precipitation climatology. J. Hydrometeorol. **2**, 122–139 (2001)

D. Yang, A. Simonenko, Comparison of winter precipitation measurements by Six Tretyakov gauges at the Valdai experimental site. Atmosphere-Ocean (2013). https://doi.org/10.1080/07055900.2013.865156

D. Yang, J.R. Metcalfe, B.E. Goodison, E. Mekis, An evaluation of double fence intercomparison reference (DFIR) gauge. in *Proceedings of Eastern Snow Conference*, 50th Meeting, Quebec City, 1993, pp. 105–111

D. Yang, B.E. Goodison, J.R. Metcalfe, V.S. Golubev, E. Elomaa, T. Gunther, R. Bates, T. Pangburn, C. Hanson, D. Emerson, V. Copaciu, J. Milkovic, Accuracy of Tretyakov precipitation gauge: result of WMO intercomparison. Hydrol. Process. **9**(8), 877–895 (1995)

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

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

D. Yang, E. Elomaa, T. Gunther, V. Golubev, B.E. Goodison, B. Sevruk, H. Madsen, J. Milkovic, Wind-induced precipitation undercatch of the Hellmann gauges. Nord. Hydrol. **30**, 57–80 (1999a)

D. Yang, S. Ishida, B.E. Goodison, T. Gunther, Bias correction of precipitation data for Greenland. J. Geophys. Res.-Atmos. **105**(D6), 6171–6182 (1999b)

D. Yang, B.E. Goodison, J.R. Metcalfe, P. Louie, G. Leavesley, D. Emerson, V. Golubev, E. Elomaa, T. Gunther, C.L. Hanson, T. Pangburn, E. Kang, J. Milkovic, Quantification of precipitation measurement discontinuity induced by wind shields on national gauge. Water Resour. Res. **35**(2), 491–508 (1999c)

D. Yang, D.L. Kane, L.D. Hinzman, B.E. Goodison, J.R. Metcalfe, P.Y.T. Louie, G.H. Leavesley, D. G. Emerson, C.L. Hanson, An evaluation of the Wyoming gauge system for snowfall measurement. Water Resour. Res. **36**(9), 2665–2677 (2000)

D. Yang, B.E. Goodison, J.R. Metcalfe, P.Y.T. Louie, E. Elomaa, C.L. Hanson, V.S. Golubev, T. Gunther, J. Milkovic, M. Lapin, Compatibility evaluation of national precipitation gauge measurements. J. Geophys. Res.-Atmos. **16**(D2), 1481–1491 (2001)

D. Yang, D. Kane, Z. Zhang, D. Legates, B. Goodison, Bias corrections of long-term (1973–2004) daily precipitation data over the northern regions. Geophys. Res. Lett. **32**(19), L19501 (2005)

B. Ye, D. Yang, Y. Ding, T. Han, T. Koike, A bias-corrected precipitation climatology for China. J. Hydrometeorol. **5**(6), 1147–1160 (2004)

B. Ye, D. Yang, L. Ma, Effect of precipitation bias-correction on water budget calculation in Upper Yellow River, China. Environ. Res. Lett. (2012). https://doi.org/10.1088/1748-9326/7/2/025201

Y. Zhang, T. Ohata, D. Yang, G. Davaa, Bias correction of daily precipitation measurements for Mongolia. Hydrol. Process. **18**, 2991–3005 (2004)