5.1 BIAS ADJUSTMENTS TO ARCTIC PRECIPITATION: A COMPARISON OF DAILY VERSUS MONTHLY BIAS ADJUSTMENTS

David R. Legates[1*], Daqing Yang[2], Steven Quiring[1], Kathy Freeman[1], Tianna Bogart[1]
[1] University of Delaware, Newark, Delaware
[2] University of Alaska Fairbanks, Fairbanks, Alaska

1. INTRODUCTION

In the Arctic, gage-based measurements of precipitation contain significant systematic biases. These biases include wind-induced undercatch, wetting losses, and evaporative losses. In addition, trace amounts of precipitation are not routinely counted in daily precipitation totals although they can contribute significantly to precipitation in dry locations in the high latitudes. Thus, gage-based measurements of Arctic precipitation substantially underestimate actual (*true*) precipitation. Accurate precipitation data from the Arctic are required to realistically simulate runoff from Arctic watersheds and model the global water balance (Serreze *et al.* 2003). This study addresses the need for accurate Arctic precipitation data by applying the systematic bias adjustments that have been developed from experimental studies (*e.g.,* Sevruk 1982; Groisman *et al.* 1991; Goodison *et al.* 1998) to gage-measured precipitation. Bias adjustments were applied to 9 years of daily data (1994–2002) from nearly 2800 stations north of 50°N to 1) determine the impact that applying the bias adjustments on a daily versus monthly basis has on monthly and annual precipitation totals, and 2) examine the temporal variability of the bias adjustments.

2. BIAS ADJUSTMENT METHODOLOGY

A precipitation gage generally consists of an upright cylinder with an orifice that is between 0.2 and 2.0 m above the ground. The most common gage orifice sizes are 127, 200, 314, 324, 400 and 500 cm^2. The Hellmann gage (and gages of similar design) is one of the most commonly used gages (~30,000 locations around the world) and it is the standard gage in about 30 countries (Yang *et al.* 1999). The Hellmann gage is a non-recording gage, 43 cm high with an orifice area of 200 cm^2. Hellmann gages are usually sited 0.6–1.5 m above the ground and can be equipped with a wind shield (*e.g.*, Nipher or Tretyakov).

The ability of a gage to accurately measure precipitation varies as a function of the gage characteristics, including the height of the gage, the shape of the gage, the orifice size, the material with which the gage is constructed, the color of the gage, and the presence or absence of a wind shield (Legates 1987). Precipitation measurement errors can be divided into two main categories – systematic and unsystematic (random). Unsystematic errors include human error, such as inaccurate measuring and recording procedures. These errors can result in an increase or decrease in the amount of precipitation measured and they are difficult to correct. Systematic errors include site and location error and how accurately gage-catch approximates actual (true) precipitation. The main sources of systematic precipitation undercatch are due to deformation of the wind field above the gage orifice, wetting losses due to water adhering to the inside of the gage, evaporation and sublimation of precipitation from the gage prior to measurement, precipitation splashing in/out of the gage, and the treatment of trace precipitation as zero. Together, these systematic biases mean that gage-measured precipitation significantly underestimates actual precipitation. Although these biases are usually relatively small for liquid precipitation (4–10%), they are much larger for solid precipitation (Legates and DeLiberty 1993; Yang *et al.* 1998a).

The bias adjustment procedures used in this study are based on those outlined by Legates (1987), Legates and Willmott (1990), and Yang *et al.* (Yang *et al.* 1998a,b; Yang 1999; Yang *et al.* 1999; Yang and Ohata 2001). Gage-measured precipitation is adjusted for systematic biases caused by wind-induced undercatch, wetting loss, evaporative loss, and for trace precipitation. The general equation for adjusting gage-measured precipitation to account for systematic biases has the form

$$P_c = K\left(P_g + \Delta P_w + \Delta P_e\right) + \Delta P_t \qquad (3.1)$$

where P_c is the bias adjusted precipitation estimate (in mm), K is the adjustment coefficient for wind-induced gage undercatch ($K \geq 1$), P_g is the gage-measured precipitation (mm), ΔP_w is the adjustment for wetting loss due to water adhering to the inside of the gage, ΔP_e

* *Corresponding author address:* David R. Legates, Center for Climatic Research, Univ. of Delaware, Newark, DE, 19716; e-mail: legates@udel.edu

is the adjustment for evaporation from the gage, and ΔP_t is the adjustment for trace precipitation. Estimates of K, ΔP_w, ΔP_e, and ΔP_t are based on gage-specific equations and in situ meteorological information (temperature, wind speed, and relative humidity).

2.1 Wind Loss

Wind speed is the dominant meteorological factor that affects gage catch. Correcting for wind-induced undercatch can increase annual precipitation by 10 to 140% (Yang *et al.* 1998a). Accounting for wind-induced precipitation bias requires information on the gage type, orifice height, and the presence or absence of a wind shield. Information about the national standard precipitation gage for each country was determined from the published literature (Legates 1987; Sevruk and Klemm 1989; Adam and Lettenmaier 2003). Since detailed metadata are not available for each station, it was assumed that all of the precipitation gages in each country conform to the published national standard (in regards to gage type, gage height, and presence/absence of a wind shield). These assumptions have a significant impact on the magnitude of the bias adjustments (especially the presence/absence of a wind shield, the gage type, and the height of the gage and the anemometer). Therefore, the precipitation bias adjustments for individual stations may be significant over- or under-estimates of *true precipitation* if the station does not conform to the assumed national gage standards.

Since at a given wind speed, gage undercatch of snow is much greater than that of rain, it is necessary to determine whether the precipitation was in solid, liquid, or mixed form in order to calculate the adjustment coefficient. This information can be derived from the daily weather codes that are provided with the Global Surface Summary of the Day (GSOD) data. However, because these codes are not always present, precipitation type was also determined using daily minimum and maximum temperature thresholds. The method employed by Rubel and Hantel (1999) was used to classify daily precipitation as solid (daily mean temperature <0°C), liquid (daily mean temperature >2°C), or mixed (mean temperature between 0°C and 2°C).

Wind speed at gage height was determined using similarity theory (logarithmic profile),

$$U_{gage} = U\left(\ln\left(\frac{h_2}{z_0}\right) \Big/ \ln\left(\frac{h_1}{z_0}\right) \right) \qquad (3.2)$$

where U_{gage} is the wind speed at the height of the gage (h_2), U is the wind speed at the anemometer height (h_1), and z_0 is the roughness length (z_0 = 0.01 m). It was assumed that the roughness length (z_0) was 0.01 m and that the anemometer was at the universal standard height (10 m). Previous studies have used a roughness length of 0.01 m during the winter and 0.03 m during the summer (Sevruk 1982; Golubev *et al.* 1992; Yang *et al.* 1998b; Adam and Lettenmaier 2003).

The gage specific wind speed adjustment equations that are employed in this study were established during the World Meteorological Organization's Solid Precipitation Intercomparison project (Goodison *et al.* 1998). Figure 1 shows the relationship between wind speed at gage height and the solid precipitation adjustment factor for six of the gages used in this study.

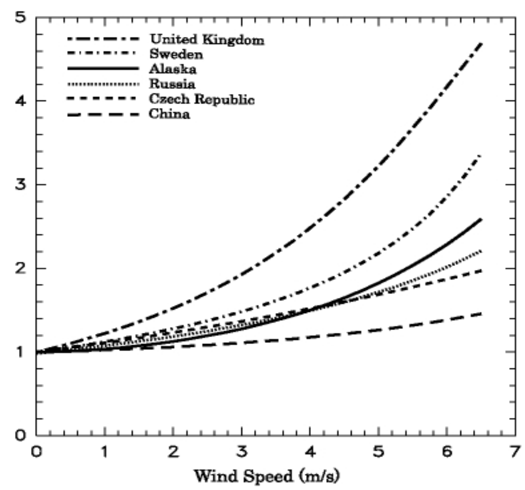

Figure 1. Relationship between the solid precipitation adjustment factor (K) and wind speed at gage height (m/s).

Days with high wind speeds are often associated with blowing snow and it is possible that some of this blowing snow may be caught by the gage (particularly for gages that are located close to the ground). Therefore, to avoid over-correcting for wind speed (applying a large adjustment to gage-catch that has already been augmented by blowing snow) it is necessary to select an upper threshold for wind speed. Following the literature, a wind speed threshold of 6.5 m/s was used (Yang *et al.* 1998a,b; Yang 1999; Yang *et al.* 1999b; Yang and Ohata 2001; Adam and Lettenmaier 2003). This threshold corresponds to the maximum wind speed observed during the Solid Precipitation Intercomparison study.

Gage specific equations were not available to calculate the adjustment coefficient for wind-induced gage undercatch (K) for all combinations of gage and shield type. Therefore, an equation from the most similar gage (based on orifice size) was used for those gage/shield combinations not studied during the Solid Precipitation Intercomparison project.

2.2 Wetting Loss

Wetting losses occur when precipitation collects on the inside walls of the gage and evaporates (or sublimates) without being recorded. The amount of wetting loss depends on the type of precipitation (liquid, solid, or mixed), the number of times the gage is emptied, the geometry of the gage, and the materials from which the gage is constructed (Legates 1987). For example, the average wetting loss for the NWS 8-inch standard non-recording gage during the summer, when the gage is equipped with the funnel and measuring tube, is 0.03 mm per observation (Golubev *et al.* 1992). During the winter this gage is operated without the funnel and the measuring tube and snow is melted in the larger cylinder and then poured into the measuring tube. The average wetting loss of the NWS 8-inch standard non-recording gage during the winter (for snow and mixed precipitation) is 0.15 mm per observation (Sevruk 1982).

Wetting loss (ΔP_w) was determined for each precipitation day based on gage type and precipitation type. Sevruk (1979) developed an equation for calculating wetting loss

$$\Delta P_w = \bar{a} M \tag{3.3}$$

where $\bar{a}$ is the empirical coefficient of average wetting loss per precipitation event and M is the number of precipitation events. Average values of $\bar{a}$ were compiled for different gages based on the work of Sevruk (Sevruk 1973; Sevruk 1982; Sevruk 1998). The values of $\bar{a}$ for liquid precipitation varied from 0.15 mm to 0.3 mm. Wetting losses for solid and mixed precipitation are calculated by multiplying $\bar{a}$ for liquid precipitation by 0.5 and 0.75, respectively. In this study, M is assumed to be equal to one (there is one precipitation event per day). This is a conservative method of determining wetting loss since precipitation measurements would have been taken more than once per day at most stations.

2.3 Evaporation Loss

Evaporative losses are usually due to a lag between the precipitation event and its measurement (Legates and DeLiberty 1993). Assessments of evaporative losses have shown that the amount of evaporation varies by gage type and time of the year. Legates and DeLiberty (1993) found that evaporative losses are minimal in the United States and only become significant in lower latitudes where temperatures are higher or when long-term storage gages are employed. Results from an experiment carried out in Finland using a Tretyakov gage found that evaporative losses were between 0.3 and 0.8 mm/day in summer, and from 0.1 to 0.2 mm/day in winter (Aaltonen *et al.* 1993). Although evaporative losses are small, especially in the Arctic, they have been accounted for using the method established by Sevruk (Sevruk 1972; Sevruk 1974; Sevruk 1984) where

$$\Delta P_e = i_e \tau_e M \tag{3.4}$$

with i_e representing evaporation intensity (mm/day), τ_e is the duration of evaporation (fractions of a day) and M is the frequency of measurement (as in equation 3.3). It is assumed that precipitation observations are taken once per day and therefore $\tau_e = 0.5$. The magnitude of i_e differs based on gage type and daily weather conditions (vapor pressure deficit) at the site and it can be calculated using equations described by Sevruk (1984) and Legates (1987).

Other Arctic precipitation bias adjustment studies have not corrected for evaporative losses because they were assumed to be insignificant (Yang *et al.* 1998a; Adam and Lettenmaier 2003). Evaporative losses contribute less than 1% to annual precipitation totals over most of the study region.

2.4 Trace Precipitation

Although all trace precipitation events are officially treated as 0 mm of precipitation, they are counted as a precipitation day. With the NWS 8-inch standard non-recording gages, a measurement of less than 0.005 inches (0.127 mm) of precipitation (*i.e.*, less than half the distance from the end of the measuring stick to the first etched line) is recorded as trace. In the Arctic, trace events can account for 50% to 70% of all precipitation days. Therefore, trace events make a small, but important, contribution to precipitation totals. Although there are generally more trace precipitation days in summer, they tend to contribute a higher percentage of precipitation in winter. Most bias adjustment studies assume that trace precipitation is equivalent to 0.05–0.15 mm of precipitation. In this study we adopted the method used by Yang *et al.* (1998a) where each trace precipitation event is treated as 0.1 mm of precipitation. This is likely a conservative estimate since we have no information on the number of trace observations that occurred each day. Weather codes from the GSOD were used to identify trace precipitation days (days were precipitation was observed but none amount was recorded). Yang *et al.* (1998a) found that accounting for trace precipitation added between 3% and 9% to annual precipitation totals in the Arctic.

3. DAILY VERSUS MONTHLY ADJUSTMENTS

3.1 Background

Traditionally, most precipitation bias adjustment studies have been calculated using monthly data because it is more readily available (*e.g.*, Legates 1987; Adam and Lettenmaier 2003). However, using monthly data rather than daily data may introduce a significant amount of error into the bias-adjusted precipitation totals because mean monthly meteorological variables (such as temperature and wind speed) may not be representative of the weather conditions when the precipitation occurred. Two sets of bias adjustments were calculated using the GSOD data. The results from each method will be compared and used to evaluate whether there is a systematic bias introduced from using monthly versus daily data.

Precipitation bias adjustments were calculated for all stations using two different methods. The bias adjustments were first calculated using the daily data (total daily precipitation, mean daily wind speed, maximum and minimum temperature, etc.) from each station. The daily bias-adjusted precipitation totals were aggregated to produce monthly totals. The number of adjustments that were calculated for each month varied based on the number of precipitation events that occurred. The bias adjustments were also calculated from monthly data. The daily meteorological data was aggregated to produce mean monthly temperature, mean monthly wind speed, and total monthly precipitation. Months that had more than 3 days of missing data were excluded from the analysis. One bias adjustment was carried out for each month (although liquid, solid, and mixed precipitation were considered separately). The influence of performing bias adjustments on a daily rather than a monthly basis will be demonstrated using a representative station from countries that lie north of 50°N. Figures 2 and 3 show the mean (1994–2002) monthly uncorrected precipitation data (solid line) and the mean monthly data calculated by applying the bias adjustment procedures on a daily (dotted line) and monthly basis (dashed line) for two representative stations – Nome, Alaska (USA) and Tórshavn, Faeroe Islands (Denmark).

3.2 Results

Figure 2 shows the results for Nome, Alaska (64.51° N, 165.45° W, 4 m). The mean annual (unadjusted) precipitation is approximately 492 mm. The mean annual (daily-adjusted) precipitation is 650 mm. The daily method of bias adjustment adds roughly 32% to the mean annual precipitation (approximately 26% is due to the adjustment for wind-induced gage undercatch, 5% is due to the adjustment for wetting loss, and the adjustments for trace precipitation account for the remaining 1% [there are essentially no evaporative losses]). During the colder months of the year, the daily-adjusted precipitation is usually larger than the monthly-adjusted precipitation. The mean differences between these two methods are 6.7 mm in January and 6.4 mm in February. There is also a great deal of variability in the differences between the two methods during the winter. The observed differences between the two methods (1994–2002) varied from 0.4 to 19 mm in February and from 0 to 0.4 mm in June. During the warmer months, the daily-adjusted precipitation is very similar to the monthly-adjusted precipitation (usually within a 1 mm). The monthly method of bias adjustment calculates the mean annual precipitation to be 623 mm (27 mm more than the daily method).

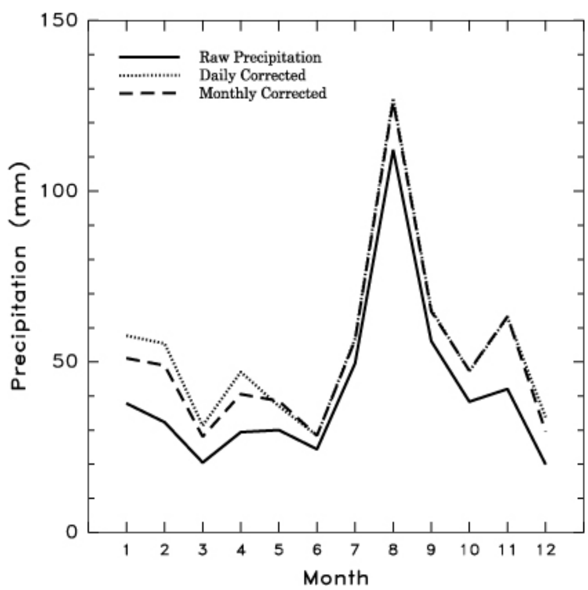

Figure 2. Mean (1994–2002) monthly precipitation (mm) for for Nome, Alaska (64.51° N, 165.45° W, 4 m): uncorrected, bias-adjusted using daily data, bias-adjusted using monthly data.

Figure 3 shows the results for Tórshavn, Faeroe Islands (Denmark) (62.01° N, 6.76° W, 39 m), where considerable differences between the daily and monthly adjustments were observed. The mean annual (unadjusted) precipitation is approximately 1245 mm. The mean annual (daily-adjusted) precipitation is 1718 mm. The daily method of bias adjustment adds roughly 38% to the mean annual precipitation (approximately 31.5% is due to the adjustment for wind-induced gage undercatch, 6% is due to the adjustment for wetting loss, and the adjustments for trace precipitation and evaporative loss account for the remaining 0.5%). During the colder months of the year, the monthly-adjusted precipitation is usually larger than the daily-adjusted precipitation. The mean differences between these two methods are 26, 44, and 41 mm in January through March. There is also a great deal of variability in the differences between the two methods during the winter. The observed differences between the two methods (1994–2002) varied from 0.1 to 87 mm in January and from 0 to 5.0 mm in July. During the warmer months, the daily-adjusted precipitation is about 3 to 4 mm greater than the monthly-adjusted precipitation. The monthly method of bias adjustment calculates the mean annual precipitation to be 1851 mm (133 mm more than the daily method).

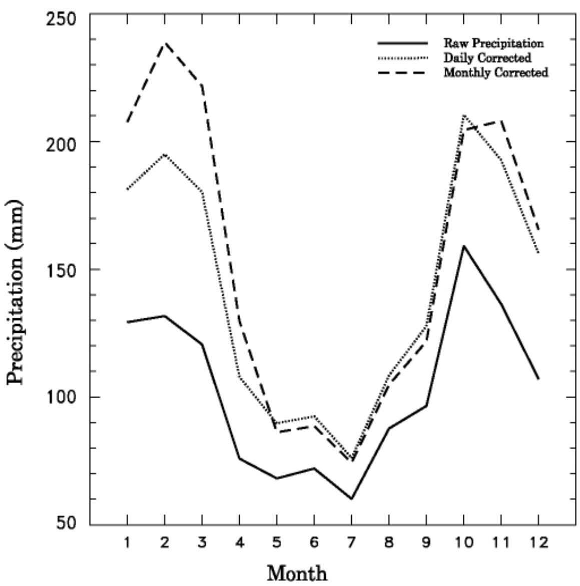

Figure 3. Mean (1994–2002) monthly precipitation (mm) for Tórshavn, Faeroe Islands (Denmark) (62.01° N, 6.76° W, 39 m): uncorrected, bias-adjusted using daily data, bias-adjusted using monthly data.

3.3 Summary

The preliminary results indicate that performing bias adjustments using monthly rather than daily data can have a significant effect on monthly and annual precipitation totals. The bias adjustments that are carried out using daily data are significantly more accurate than those based on monthly data because the daily meteorological data is more representative of the actual conditions when precipitation occurred. For example, there is often a significant difference between mean monthly wind speed and the wind speed during an individual precipitation event. The difference between the daily- and monthly-adjusted precipitation totals varies by season, gage type, and climate. The magnitude and variability of the differences between the two methods are most pronounced during the cold months of the year for all gages. This can be attributed to the fact that the adjustment factor for wind-induced undercatch for solid precipitation is extremely sensitive to differences in wind speed (Figure 1) and that wind speeds tend to be higher during the winter months. Generally, those locations that receive predominantly liquid precipitation and have lower wind speeds show the closest agreement between the two bias adjustment methods.

Another way to compare the two bias adjustment methods is to produce a scatter plot of the daily method of bias-adjustment versus the monthly method (Figure 4). It is evident that although the two methods show some correspondence, particularly during drier months, there is no systematic pattern. During some months the monthly method of bias adjustment over-predicts monthly precipitation (compared to the daily method), while during other months it under-predicts. This means that it would be difficult to devise a method of calculating bias adjustments from monthly data that is as accurate as using daily data.

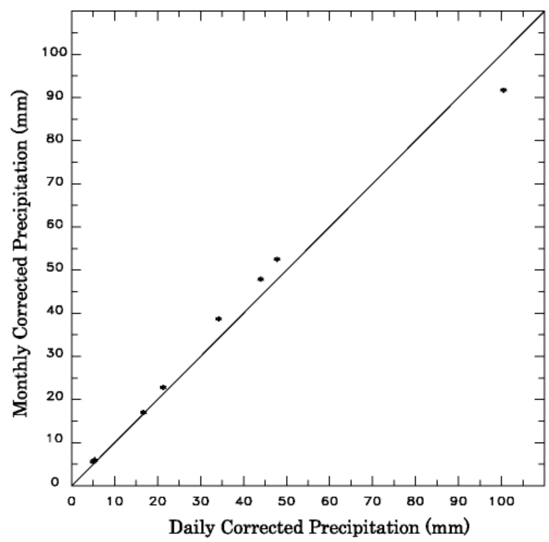

Figure 4. Daily versus monthly bias-adjusted January precipitation (1994–2002) for Anchorage, Alaska

The results shown here likely underestimate the true amount of error that is introduced by calculating the bias adjustments using monthly rather than daily data because most monthly datasets do not provide information on the number of trace events, precipitation type (the amount of snow, rain, and mixed precipitation), or the mean wind speed during precipitation events. Some of the previous studies that have used monthly data have estimated precipitation type using the mean monthly temperature and wind speed during precipitation events is usually estimated from mean monthly wind speed. Further study is needed to determine if the results from the individual stations described here are representative of the conditions at all locations within each country.

4. CONCLUSION

The results demonstrate that applying the bias adjustments on a daily (as opposed to monthly) basis produces more realistic estimates of monthly and annual precipitation. The results also reveal the presence of substantial inter– and intra-monthly variability in the magnitude of the bias adjustments. This variability is primarily driven by variations in the amount of precipitation, the type of precipitation (solid, liquid, or mixed), the number of precipitation events, and the wind speed during the events. Therefore, Arctic precipitation data that has been adjusted on a daily basis will be more accurate than data adjusted on a monthly basis (*e.g.*, Legates 1987; Legates and Willmott 1990), or adjusted using mean monthly correction factors (*e.g.*, Adam and Lettenmaier, 2003).

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