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Key Points:

- Gauge undercatch correction is necessary to reduce errors in gauge-based precipitation products in cold months
- More than 50% difference can exist among gauge undercatch correction methods used in the popular GPCC and GPCP products
- GRACE mass change observations provide a unique way to assess gauge undercatch correction methods

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Assessing Gauge Undercatch Correction in Arctic Basins in Light of GRACE Observations

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Abstract Precipitation measurements at gauges are often considered as reference truth for evaluation of satellite precipitation products. However, gauges may contain large errors. A major source of gauge-measurement error is snowfall undercatch in high latitudes. We show that the two popular correction factors (CFs) used in the Global Precipitation Climatology Centre monitoring and the Global Precipitation Climatology Project products are different by more than 50%. The CFs can be as large as 3; thus, the choice of CF introduces large uncertainties. Here, in light of observation of storage change from the Gravity Recovery and Climate Experiment (GRACE) and by using the mass conservation principle, we assess the two popular CFs over six Arctic basins. By investigating monthly time series and multiyear precipitation rates over the studied basins using GRACE-based analysis, the CF based on Fuchs dynamic correction model used in Global Precipitation Climatology Centre monitoring is preferred.

1. Introduction

Despite recent major progress in advancing instruments and methods to improve global precipitation estimation, major challenges remain in high latitudes where precipitation often occurs in the form of light rain and snowfall. Satellites and rain gauges are two major sources of precipitation observation and both are prone to large uncertainties in high latitudes. Satellite-based methods have to deal with several challenges such as limitations in retrieval techniques over frozen surfaces and difficulties with surface emissivity (Ferraro et al., 2013), sensors insensitivities to small droplets and snow particles, poor understanding of the precipitation microphysics, difficulties in distinguishing between light rain and cloud (Berg et al., 2006; Lebsock & L'Ecuyer, 2011), and unreliable or insufficient ground truth data for regional calibration of the estimates. Since summer of 2006, CloudSat Cloud Profiling Radar, with a minimum detectable signal of −28 dBZ, allowed high-quality detection and estimation of snowfall as well as light rainfall and drizzle that are largely undetected by other sensors (Behrangi et al., 2012). However, one has to consider that CloudSat has relatively low temporal sampling, offers only daytime observation (due to battery issue) since 2011 and may miss precipitation occurring in the lowest 1.2 km over land and 1 km over ocean due to near-surface clutter.

Precipitation measurements from gauges may also contain large errors in high latitudes for two main reasons: (1) The precipitation gauge network is often sparse and discontinuous in most regions and (2) precipitation gauges suffer from a variety of limitations in collecting precipitation (e.g., side wetting and wind effect) that can result in underestimation for most gauge configurations. The wind effect (Goodison et al., 1998) is most critical in higher latitude regions where hydrometeors (typically drizzle and snowflakes) fall at lower speed than normal raindrops. Different correction factors (CFs) are available in literature to mitigate these effects. While CFs can be as large as a factor of three for snowfall (Legates & Willmott, 1990), their uncertainty can exceed 100% (Fuchs et al., 2001; Yang et al., 2005).

By limiting the analysis region to frozen grids in northern hemisphere, Behrangi et al. (2018) used mass change observation from the Gravity Recovery and Climate Experiment (GRACE) to estimate monthly and seasonal snow accumulation through water budget equation. The calculated snow accumulations are then used to assess two commonly used gauge undercatch CFs: Legates climatology (CF-L) utilized in Global Precipitation Climatology Project (GPCP; Huffman et al., 2009; Adler et al., 2018), and Fuchs dynamic correction model (CF-F) used in Global Precipitation Climatology Centre (GPCC) monitoring product (Schneider et al., 2017). Their analyses suggested that CF-L and CF-F are effective in improving GPCC estimates, but CF-F is more consistent with the precipitation accumulations calculated using GRACE observations.

The results presented in Behrangi et al. (2018) was limited to frozen grid to eliminate runoff (due to snow melting) from the water budget equation; thus, the application had to be limited to few cold months in winter. Here we will build on the method presented in Behrangi et al. (2018) but use streamflow discharge observations available for several Arctic basins to assess gauge undercatch corrections factors across all months. As CFs have large seasonal variations, the outcome of this study should provide new insights on how CF-F and CF-L perform across different seasons.

2. Method and Data Sets

Monthly precipitation accumulation is calculated using the mass conservation principle (e.g., Dingman, 2008) applied to several arctic basins with available streamflow observations. If t_1 and t_2 represent accumulation start time and end time for basin B , precipitation accumulation between time t_1 and t_2 can be calculated as follows:

$$\int_{t_1}^{t_2} P(t) dt = \Delta S + \int_{t_1}^{t_2} ET(t) dt + \int_{t_1}^{t_2} \text{Sub}(t) dt + \int_{t_1}^{t_2} Q_{\text{net}}(t) dt \quad (1)$$

where ΔS is the change in storage (i.e., here from GRACE observation) between time t_1 and t_2 and $P(t)$, $ET(t)$, $\text{Sub}(t)$, $Q_{\text{net}}(t)$ are the precipitation, evapotranspiration, sublimation, and net lateral flux (e.g., streamflow) rates for basin B at time t , respectively. The calculated monthly precipitation is then compared with GPCP, GPCC, GPCC-L (GPCC corrected by CF-L), and GPCC-F (GPCC corrected by CF-F), separately for each basin.

Out of several basins identified in arctic regions, six basins were finally selected for analysis: Lena, OB, Yenisei, Mezen, Pechora, and Volga (Figure 1a). The selection was based on considering the location, availability of both quality streamflow observation and GRACE data, basin size, and annual drainage volume. Basins with highly regulated streamflow (e.g., Meckenzie) were not considered. GRACE provides observations of changes in the Earth's gravity field, which are correlated with the movement of water through the Earth's system at monthly temporal resolution and ~ 3 arc degrees spatial resolution. For basin water balance closure, we used basin-averaged time series (Swenson & Wahr, 2002) for river basins with a drainage area greater than 200,000 km² and a drainage volume of greater than 40 km³/year. These criteria help overcome spatial resolution limitations and the associated signal suppressions. The only basin that did not pass these criteria was Mezen, so interpretation of the results for this basin needs caution. Mezen is located in northwest Eurasia where GPCP has shown large overestimation and large discrepancies between CF-F and CF-L has been reported (e.g., Behrangi et al., 2014, 2016, 2018; Schneider et al., 2017).

Below are the data sets used in equation (1). Details on how to access these data sets are provided in the Acknowledgments section.

2.1. Streamflow Observation

Streamflow data for the selected basins are downloaded from Global Runoff Data Center (GRDC). Basin structures are delineated from the Global Hydrologic Archive and Analysis System database. We modified basin boundaries based on the location of streamflow gauges and used the modified basins to perform water budget analysis using equation (1). Because most GRDC data are limited to 2010 for our basins of interest, our analysis covers 2003 (set by GRACE data availability) to 2010 period.

2.2. GRACE Total Water Storage Anomaly

GRACE is a joint mission of the National Aeronautics and Space Administration and the German Aerospace Center that operated from 2002 to 2017. GRACE mission measures range-rate variations between its twin satellites using microwave interferometry. Gravity changes due to mass redistribution within the Earth System perturb the GRACE orbit (e.g., distance between the twin satellites), and these perturbations are used to retrieve mass variations with high accuracy (Tapley et al., 2004). The twin satellites fly at an altitude of about 300 mi (483 km) and are about 137 mi (220 km) apart. Their separation distance is measured within 1 μ m. After processing to account for solid earth, tectonic, and aliased signals, and the reduction of noise, GRACE provides spatially distributed estimates of Terrestrial Water Storage Anomaly. GRACE's primary goal was to track water redistribution on Earth and to improve our understanding of global and regional water cycle. We obtained Terrestrial Water Storage Anomaly data from GRACE Mascon global gridded

Figure 1. Top (a): location of the studied basins and streamflow gauges; bottom (b–m): mean correction factors for all seasons (left column), summer (middle column), and winter (right column). Panels (b)–(d) show CF-L, panels (e)–(g) show CF-F, panels (h)–(j) show a CF difference maps (CF-L – CF-F), and panels (k)–(m) display relative difference by dividing the difference maps by average values of CF-L and CF-F. CF = correction factor.

data product (JPL-RL06M.MSCNv01; Wiese et al., 2018; Watkins et al., 2015). This version uses a priori constraints in time and space to determine global monthly gravity fields. This version also includes improvements in both background geophysical models and orbital parameterization and reduces solutions uncertainty and bias due to leakage effects. GRACE mascon solution is downsampled to 0.5° grid by multiplying it with a scaling factor grid that comes with the data set.

2.3. Evapotranspiration and Sublimation

Three different ET products are analyzed to quantify the mean and regional ET uncertainties among the products: (1) Global monthly 0.5° gridded Moderate Resolution Imaging Spectroradiometer ET product from University of Montana (Mu et al., 2011), (2) monthly ET estimates from the Water Gap Hydrological Model (WGHM; Döll et al., 2003), and (3) NASA's Global Land Data Assimilation System (GLDAS; Derber et al., 1991; Rodell, 2001). Moderate Resolution Imaging Spectroradiometer ET showed large gaps over the studied basins; thus, the upper and lower bound of ET estimates are determined from GLDAS and WGHM and used to show uncertainty range in the final estimate. Other ET products (e.g., Javadian et al. 2019) could also be used, but here we use those that are popular for large scale analysis. Most cold-season water budget studies do not consider sublimation, but here it is considered because Behrangi et al. (2018) found that sublimation can account for as much as 7% of the total water budget over some high-latitude regions. Sublimation rate was acquired from the Modern-Era Retrospective Analysis 2 (Rienecker et al., 2011; Gelaro et al. 2017) sublimation variable (“EVPSBLN”) at monthly $(1/2)^\circ \times (2/3)^\circ$ resolution.

Figure 2. Monthly mean correction factors for the (a–f) studied basins.

2.4. GPCC

GPCC integrates station data from different networks in its database (Becker et al., 2013; Schneider et al., 2014, 2017). In high latitudes, and other regions with sparse gauges, GPCC has to rely on interpolation of sparse point measurements. Two widely used GPCC products are assessed in this study: (1) the full data monthly (V7) that is available from 1901 through 2013 and incorporates all stations with tight quality control, but it does not correct for gauge under-catch problem, and (2) the monthly monitoring product (V6) that uses records from fewer gauging stations and is available from 1982 through to present. The monitoring product provides additional information, including CF based on Fuchs et al. (2001). In brief, this method uses a dynamic correction model (Forland et al., 1996; Rubel & Hantel, 1999) and employs various synoptic observations such as air temperature, relative humidity, precipitation intensity, and wind speed. Daily bias correction of synoptic observations are performed after determining precipitation phase using air and dew point temperatures.

2.5. GPCP

GPCP is a widely used community-based analysis of global precipitation estimate at monthly and shorter time scales for climate analysis using a various satellite and ground-based data sets (Adler et al., 2003). GPCP uses CF based on Legates and Willmott (1990) method (CF-L) to correct for gauge undercatch in GPCC. CF-L is a monthly spatially varying climatology factors that are calculated using the best guess of gauge types around the world as of the early 1980s. Gauge measurements are averaged with satellite estimates using inverse estimated error variance as the weights (Huffman et al., 1997). Since its initial release (Adler et al., 2003; Huffman et al., 1997; Huffman et al., 2009) various upgrades have been made to the GPCP. In this study we use the latest release of GPCP (V2.3; Adler et al., 2017) at monthly $2.5^\circ \times 2.5^\circ$ resolution.

3. Results

3.1. Spatiotemporal Comparison of CFs

Figures 1b–1j (bottom panels) show mean CFs for all seasons (left column), summer (middle column), and winter (right column) for the basins shown in Figure 1a. Panels (b)–(d) show CF-L, panels (e)–(g) show CF-F, and panels (h)–(j) show a CF difference maps (CF-L – CF-F).

Figure 3. Mean precipitation rate for all seasons (left column), summer (middle column), and winter (right column). Panels (a)–(c) display GPCP V2.3, panels (d)–(f) are for GPCC full data monthly (V7), panels (g)–(i) show GPCC V7 multiplied by CF-L (GPCC-L), and panels (j)–(l) display GPCC V7 multiplied by CF-F (GPCC-F). CF = correction factor; GPCC = Global Precipitation Climatology Centre; GPCP = Global Precipitation Climatology Project.

It can be seen that annual CF-L is higher than CF-F over western Siberia and part of Eurasia (i.e., over Yenisei, Mezen, Pechora, and Volga basins), but lower in the eastern Siberia (i.e., over Lena and part of Ob basins). The differences are negligible in summer (when it mainly rains) but are large in winter when snowfall is the dominant precipitation type. For example, Figures 1j and 1m show that CF-L exceeds CF-F by more than 0.5 (or 50% relative difference) in several grids in Yenisei, Mezen, Pechora, and Volga basins, while CF-F exceeds CF-L over most of the Lena reaching up to 50% difference in few grids.

The monthly differences between the CFs is clear in Figure 2, where monthly CFs mean are displayed for each studied basins. The large differences between the two popular CFs during cold months suggest that despite the fact that gauges are often considered as reference truth in comparison studies, measurement uncertainties in gauges can be very large in cold months. CF-L and CF-F are generally very close to each other in summer, but CF-L tends to show larger values than CF-F in colder months. Exceptions are Pechora and Lena basins (Figures 2a and 2e). In Pechora basin in summer, CF-F and CF-L show larger difference than other basins. Pechora basin includes Ural Mountains that receives snowfall in summer. As CF-L tends to be larger than CF-F for snowfall, at least over the Pechora and surrounding regions (Figure 1), the larger value of CF-L than CF-F in summer may not be surprising. The larger values of CF-L than CF-F in summer is also seen in Ungersböck et al. (2001) who compared CF-F and CF-L for Central and Eastern Europe and few other regions. In Lena basin, CF-F is larger than CF-L in cold months. Lena has a very different climatology than other Arctic basins studied in this paper. More specifically, Lena has the coldest air temperature, the coldest dew point temperature, and the lowest wind speed among all other basins. Behrangi et al. (2018) showed that over Siberia CF-L exceeds CF-F at warmer near-surface air temperatures, but at colder temperatures CF-F exceeds CF-L, consistent with this study. However, further analysis is needed to

Figure 4. Time series of monthly mean precipitation rates from GPCC, GPCP, GPCC-L, GPCC-F, and GRACE over the (a–f) studied basins. The shaded area around the GRACE-based precipitation rates represent upper and lower bound of estimates using Water Gap Hydrological Model and Global Land Data Assimilation System ET estimates. GPCC = Global Precipitation Climatology Centre; GPCP = Global Precipitation Climatology Project; GRACE = Gravity Recovery and Climate Experiment.

better understand why the relationship between CF-L and CF-F in Lena basin is not consistent with the other basins.

The impact of CFs on precipitation quantities is shown in Figure 3. It compares winter, summer, and all-season mean precipitation rates from GPCP (Figures 3a–3c) with GPCC full data monthly without correction (Figures 3d–3f) and with correction using CF-L (GPCC-L) and CF-F (GPCC-F) shown in Figures 3g–3i and 3j–3l, respectively. It can be seen that all of the studied basins show a strong seasonal precipitation pattern (i.e., mean precipitation rate is larger in summer and smaller in winter). The overall spatial pattern of these products is similar as they largely depend on GPCC. In high latitudes satellite precipitation products often have large errors; thus, GPCP tends to assign large weights to GPCC-L. This is why GPCP's pattern and values are more similar to GPCC-L than GPCC-F. Figure 3 clearly shows that GPCC-L is larger than GPCC-F over the basins located in the western part of the study region (e.g., Mezen, Pechora, and Volga), but independent data sets are needed to verify, which product is more accurate. In continuation, we show that precipitation estimates from GRACE provide an important alternative for this verification.

3.2. GRACE Perspective on CFs

Figure 4 shows time series of monthly mean precipitation rates from GPCC, GPCP, GPCC-L, GPCC-F, and GRACE over the studied basins. The GRACE-based precipitation rate (hereafter referred to as P_{GRACE}) is back calculated from equation (1) using streamflow observation at each basin and estimated ET and sublimation (section 2.2). The shaded area around the P_{GRACE} is bounded by the two different ET estimates (WGHM and GLDAS) used in this study. For Lena and Yenisei basins (Figures 4a and 4b), P_{GRACE} and other precipitation products agree fairly well in capturing precipitation monthly variation with shifts in phase no more than a month. P_{GRACE} suggests generally higher precipitation rate than other products, especially during

Figure 5. Monthly multiannual mean precipitation rates from GPCC, GPCP, GPCC-L, GPCC-F, and GRACE over the (a–f) studied basins. The shaded area around the GRACE-based precipitation rates represent upper and lower bound of estimates using the two different ET estimates used in the study. GPCC = Global Precipitation Climatology Centre; GPCP = Global Precipitation Climatology Project; GRACE = Gravity Recovery and Climate Experiment.

cold months when precipitation undercatch in gauges is often the largest. In other words, P_{GRACE} suggests that larger CFs should be used in Lena and Yenisei basins to correct for winter time gauge undercatch. For the other basins (Figures 4c to 4f), P_{GRACE} shows that CF-F is often effective in mitigating the large cold-month precipitation undercatch. However, CF-L (used in GPCC-L and GPCP) results in changes in monthly precipitation pattern, so the corrected products often become out of phase compared to P_{GRACE} and GPCC-F and show shift of precipitation peak to later months of calendar year. Based on P_{GRACE} , the peak of corrected precipitation should not show a large shift. GPCC-F agrees with P_{GRACE} relatively well, with much smaller shift in seasonal precipitation distribution than GPCC-L. Therefore, we conclude that CF-F is the preferred correction scheme based on the basin-scale water budget analysis enabled by GRACE. However, our analysis over Pechora basin (Figure 4e) is less conclusive than the other basins, mainly because precipitation peak of P_{GRACE} occurs around midsummer, consistent with the other arctic basins, but about a month or two earlier than that observed in GPCC. Figure 4e shows that GPCC-F tends to follow GPCC pattern, but GPCC-L and GPCP show a shift to later months, about a month or two in the peak intensity compared to GPCC and larger compared to P_{GRACE} . Furthermore, despite other basins, GPCP and GPCC-L are considerably different in Pechora basin, suggesting that in this region GPCP likely assigns smaller weight to ground observation and larger weight to satellite precipitation estimate.

It should be noted that the larger values of CF-L compared to CF-F over our study region have also been noted in previous studies (e.g., Fuchs et al., 2001; Schneider et al., 2017; Ungersböck et al., 2001). This study confirms and quantifies these differences using a combination of streamflow and gravity observations from GRACE.

Figure 5 shows a multiyear average monthly precipitation rates over the six studies basins. The shaded area around P_{GRACE} represents upper and lower bound of estimates based on the two different ET estimates. The results are consistent with Figure 4, showing generally good consistency in timing of monthly precipitation distribution, except in Mezen and Pechora. GPCC shows the least precipitation amount at all months and GPCP tightly follows GPCC-L, although GPCP tends to fall between GPCC-L and GPCC-F (especially in Mezen, Pechora, and Volga). Large CF-Ls results in GPCC-L exceeding P_{GRACE} in cold months, clearly noticeable in Ob, Mezen, Pechora, and Volga. The independent assessment of CFs using P_{GRACE} suggests

that CF-L is likely overcorrecting snowfall rates over Eurasia, consistent with previous findings (Behrangi et al., 2014, 2016). Note that the CF-Ls are so large in Volga that they modify the seasonal distribution of GPCC-L by introducing a winter time precipitation peak (Figure 5f). Over Mezen and Pechora (Figures 5d and 5e), CF-L shifts the timing of peak precipitation by few months to late fall and early winter. These peaks are not observed in GPCC, GPCC-F, and P_{GRACE} . The observed inconsistency between GPCC-L, GPCC-F, and P_{GRACE} over Pechora suggests that additional efforts may be needed to determine the best CFs over this basin.

4. Conclusions

Accurate quantification of precipitation in high latitudes is not straightforward. While precipitation measured at gauges is often considered as reference truth, it may contain large errors. A major source of gauge-measurement error is snowfall undercatch, a common feature in high latitudes. The CFs used to mitigate the undercatch problem can be as large as 3 but can be different by more than 50% depending on the methods used to determine CFs. The need for such corrections and potential uncertainties that may come with them are not always recognized by users.

We applied mass conservation principle over six Arctic basins (i.e., Lena, OB, Yenisei, Mezen, Pechora, and Volga) and used observation of storage change from GRACE to assess two popular CFs: (1) CF-L that is currently used in GPCP and (2) CF-F which is a dynamic correction model and is used in GPCC monitoring product. Our study period was from 2003 (set by GRACE data availability) to 2010 (set by availability of streamflow observations for the terminal river stations at the time of our analysis).

Our GRACE-based precipitation analysis supports CF-F over CF-L and suggests that CF-L overcorrects snowfall undercatch in cold months. This was concluded based on investigating monthly time series and multiyear precipitation rates over the studied basins and comparison with P_{GRACE} , back calculated from equation (1). The larger values of CF-L compared to CF-F over our study region have also been noted by previous studies, but here for the first time we quantitatively assessed the differences between the two correction methods using independent data from gravity and streamflow observations. By analysis of monthly time series of precipitation estimates, we also found that CF-L can cause considerable shift in monthly precipitation distribution that is mainly due to its large values during cold months. While monthly precipitation rate using GRACE might introduce slight shift in the timing of monthly precipitation rate in few basins, our conclusion is unlikely affected by this shift.

GPCP currently uses CF-L to correct for precipitation undercatch prior to bias adjustment of satellite products. Our results recommend that CF-F might be a better alternative than CF-L to be used in GPCP, at least for the studied regions. With the successful launch of the GRACE Follow-on mission (gracefo.jpl.nasa.gov) in 2018, future extension of the analysis presented in this study to more recent years is possible.

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Acknowledgments

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