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A 59-year (1948–2006) global meteorological forcing data set for land surface models. Part II: Global snowfall estimation

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Abstract:

Global terrestrial snowfall was estimated for 59 years from 1948 to 2006 by applying gauge undercatch correction for snowfall and rainfall based on daily meteorological data and gauge type. Following gauge correction, global annual snowfall estimation increased from 9.4 to 12.3×10^3 km^3, while annual terrestrial precipitation increased from 112.8 to 119.6×10^3 km^3. Percentage of snowfall in total precipitation increased from 8.3 to 10.3% with gauge correction. The snowfall distinction method using wet-bulb temperature produced larger values for snowfall than those obtained using a 0°C threshold method and those from reanalysis-based products. In contrast, the increase in total precipitation was half of the increase obtained by using a climatology of correction coefficients from previous studies. The estimated 59-year time series of snowfall amount showed a downward trend after the mid-1980s, suggesting a decrease in snowfall associated with a warmer climate in recent decades.

KEYWORDS global snowfall; gauge correction; LSM

INTRODUCTION

Terrestrial snowfall and its storage are important component of the global water cycle. However, there are not many observations on global snowfall and its variability, even though they are sensitive to climate change as global warming. For example, Trenberth *et al.* (2007) used global data sets to estimate elements in the global water cycle but not snowfall. Oki and Kanae (2006) presented global estimated terrestrial snowfall, but they did not show its annual variations due to the short investigation period.

Two factors can affect snowfall estimation: the method to estimate the percentage of snowfall in total precipitation, and the method to correct gauge undercatch. Common approaches in many hydrological and land surface models to obtain snowfall from total precipitation are 1) to use snowfall or the ratio of snowfall to total precipitation obtained from reanalysis data (e.g., Ngo-Duc *et al.*, 2005) and 2) to estimate snowfall using near-surface climate data (e.g., temperature).

Systematic undercatch of snowfall measurements caused by wind effects is one of the problems of gauge-based precipitation observations. Utsumi *et al.* (2008) found that for simulating river discharge in Japan, correction of wind-induced undercatch of snowfall is more important than correction for orographic effect. Tian *et al.* (2007) showed that the correction of precipitation has large effects on hydrological simulations, especially in cold regions.

Previous studies estimated gridded undercatch correction coefficients by interpolating correction coefficients obtained from available meteorological station data and gauge types. Due to the limitation of available daily meteorological data, monthly climatologies of the undercatch correction coefficients, obtained from monthly means of long-term meteorological data (e.g., Legates and Willmott, 1990) or from daily meteorological data during limited period (e.g., 5 years from 1994 to 1998 by Adam and Lettenmeier, 2003), are commonly used to correct global precipitation data sets. Yang *et al.* (2005) estimated daily precipitation undercatch for a relatively long (1973–2004) period over the northern high latitude, instead of using a climatology of undercatch correction coefficients. For investigating snowfall variability over long time-scales, use of a climatology of monthly means of undercatch correction coefficients, as reported by previous studies (e.g., Hirabayashi *et al.*, 2005), is problematic.

Hanasaki *et al.* (2008) estimated 3-hourly undercatch correction coefficients in 1° grid cells from 1986 to 1995 using the method by Motoya *et al.* (2002) on which much of our methodology is based. Motoya *et al.* (2002) used gauge type data and daily meteorological data to estimate undercatch correction coefficients at each grid.

When gauge-based precipitation observations are used to drive hydrological models, it is essential to obtain the phases of precipitation (rainfall or snowfall) and to correct gauge records for undercatch using the phase information. Previous studies (e.g., Tian *et al.*, 2007) have discussed the effect of gauge correction on hydrological cycle estimation mainly in terms of increased total precipitation; however, it is also important to understand whether the effect is due to the correction

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of the total precipitation or to differences in the phase (rainfall/snowfall) distribution.

Our purpose was to show the range in the amount of global snowfall obtained from different methods for estimating snowfall and rainfall phases, and for correcting undercatch biases. Here, the ratio of snowfall to total precipitation estimated using a distinction equation by Yamazaki (2001) is compared to the value obtained by a simple 0°C temperature threshold method and to two reanalysis products. Then, differences between our snowfall estimation and the results of using climatologies of undercatch correction coefficients are discussed. Finally, the estimated global terrestrial snowfall is compared with that from other data sets.

DATA AND METHODS

Methods to distinguish rainfall and snowfall

The global atmospheric data set used (daily precipitation, temperature, shortwave radiation, and humidity) was a global 0.5° daily product described in a companion paper (Hirabayashi *et al.*, 2008; hereafter, H08). We compared two methods for distinguishing snowfall and rainfall phases. The first was a simple method that uses daily mean temperature as a threshold to distinguish rainfall and snowfall phases. Because of limitations in the global availability of atmospheric forcing data, this simple method is still frequently used in global hydrological models. We chose a threshold of 0°C daily surface temperature to determine whether the precipitation was rainfall or snowfall, which is used in some global hydrological models (e.g., WaterGAP2; Döll *et al.*, 2003). When surface air temperature is below 0°C, precipitation on this day is assumed to completely occur as snowfall, while precipitation is assumed to fall as rain only when temperature is larger than 0°C. We selected a 0°C as threshold temperature as according to the method using web-bulb temperature (see below), almost all precipitation falls as snow, if temperature is smaller than 0°C.

The second method uses daily precipitation and wet-bulb temperature as follows (Yamazaki, 2001):

$$s(T_W) = \begin{cases} 1 - 0.5\exp(-2.2(1.1 - T_W)^{1.3}), & T_W < 1.1 \\ 0.5\exp(-2.2(T_W - 1.1)^{1.3}), & T_W \geq 1.1 \end{cases}, \quad (1)$$

where $s(T_W)$ is the proportion of snowfall in total daily precipitation, and T_W is daily wet-bulb temperature (°C). T_W was obtained from daily mean temperature and dew point temperature at each grid cell. Dew point temperature was derived from maximum and minimum temperature and shortwave radiation of H08 by an empirical equation. The method of Yamazaki (2001) using T_W is potentially better for estimating snowfall than the method which uses surface temperature only, since snowfall is observed at temperatures above 0°C especially under dry conditions (Fuchs *et al.*, 2001). Snow depth and temperature in eastern Siberia that were estimated by a one-dimensional land surface model using this method showed good correlation with observations (Yamazaki, 2001), even though Equation (1) was derived from observations at 30 stations in Japan.

To estimate the daily rainfall/snowfall phase, day-to-day variation in the meteorological data is important. Daily precipitation statistics of H08 showed reasonable variation (Hirabayashi *et al.*, 2008). Standard deviations of the daily temperature and shortwave radiation data of H08 are similar to those of observation-based data and better than those of reanalysis-based products (Supplements 1 and 2).

Correction factors for gauge undercatch

To correct the undercatch of precipitation gauges, three different correction coefficients were applied to the daily precipitation data. The first method used the monthly climatology of undercatch correction coefficients obtained from a revised version of the global precipitation product of Legates and Willmott (1990; hereafter LW90; version 2.01; http://climate.geog.udel.edu/~climate/). The global monthly climatology of the gauge correction coefficients was estimated using the monthly climatology of precipitation before and after gauge correction on a 0.5° grid.

The second data set was the monthly climatology of gauge correction coefficients reported by Adam and Lettenmaier (2003; hereafter Ad03). The global 0.5° correction coefficients of Ad03 were obtained by interpolating monthly correction values that were estimated for approximately 8000 daily meteorological station data from 1994 to 1998; the correction incorporated wetting losses and wind-induced precipitation undercatch based on the gauge type provided by the World Meteorological Organization (WMO; Goodison *et al.*, 1998). The data also included an adjustment for orographic effects, as described in Adam *et al.* (2006).

The third type of correction coefficient was obtained using the method of Motoya *et al.* (2002). This correction coefficient, which was used in our product (H08), was based on global gauge-type classification data over 36 countries. Gauge type was determined for 25 countries from Sevruk and Klemm (1989), and for the other 11 countries by information provided by WMO. Goodison *et al.*'s (1998) equations to obtain correction factors for different gauge types were simplified as an exponential function with two parameters (Motoya *et al.*, 2002), and the number of gauge types included in Goodison *et al.* (1998) was reduced to eight by assigning gauges with similar undercatch properties to the same type.

Correction factors were obtained separately for snowfall and rainfall as follows:

$$CR_{snow} = \begin{cases} a\exp(bU) & \text{gauge type known} \\ 50.0\exp(-0.182U) + 50.0\exp(-0.112U) & \text{gauge type unknown} \end{cases}, \quad (2)$$

$$CR_{rain} = 100.0 - 1.51U - 0.21U^2 \quad \text{regardless of gauge types}, \quad (3)$$

where CR_{snow} and CR_{rain} are catch ratios of the precipitation gauge for snowfall and rainfall, respectively; U is wind speed (m s^{-1}) at a height of 2 m; and a and b are parameters that depend on the gauge type. Since the a and b values for the Hellman type gauges by Motoya *et al.* (2002), which were obtained from the Hungarian Hellmann gauge, lead to erroneously high correction amounts under high wind velocity, new a and b values for Hellmann type gauges were obtained from a correction equation of the German Hellmann gauge (Goodison *et al.*, 1998). Supplement 3 summarizes the parameter values a and b. The average compensation equation of Kondo (1994) for snowfall was applied when the gauge type was not specified. Because the difference of rainfall undercatch between different gauges is smaller than that of snowfall undercatch (Sevruk and Hamon, 1984), a single equation (Kondo, 1994) was applied to estimate the undercatch ratio of rainfall (Equation (3)), assuming that rainfall undercatch does not depend on the gauge type. Undercatch correction coefficients for rainfall and snowfall were obtained as $1/CR_{rain}$ and $1/CR_{snow}$. To avoid excessively large correction values, the maximum wind speed to estimate correction coefficients for rainfall and snowfall was subjectively set to 6 m s^{-1} as Goodison *et al.* (1998) ensures the applicability of their equations for wind velocities up to 6 m s^{-1}.

Wind velocity data were obtained from the 40-year reanalysis (ERA40) product of the European Centre for Medium-Range Weather Forecasts (ECMWF; Betts and Beljaars, 2003) from 1957 to 2002 by interpolating the original ERA40 data to a 0.5° grid. Wind data from 1988 to 1996 and from 1983 to 1986 were subjectively selected and used to estimate the correction factors for 1948 to 1956 and 2003 to 2006, respectively. Based on a sensitivity test in which not the wind velocity of the same year was used to correct for undercatch but wind velocity data from other years, we conclude that total correction amount of snowfall on land is underestimated by up to 5% during the periods 1948–1956 and 2003–2006. This is related to the inconsistencies of wet days between the years with wind velocity and precipitation data, as wind velocities on wet days tend to be larger than on dry days.

Because the equations of Motoya *et al.* (2002) assume wind velocities at 2 m height, the 2-m wind velocity used was obtained from the wind velocity of ERA40 at 10 m height, assuming the following logarithmic profile:

$$U_2 = U_{10} \times \ln\left(\frac{2}{z_0}\right) / \ln\left(\frac{10}{z_0}\right), \qquad (4)$$

where U_2 and U_{10} are wind velocity (m s^{-1}) at 2 m and 10 m height, respectively, and z_0 is roughness length (m). Goodison *et al.* (1998) suggested z_0 of 0.01 m for winter and 0.03 m for summer. We set z_0 to 0.03 m, which is close to the roughness of a grass, because wind velocities estimated using equation (4) differed by only 4% between z_0 of 0.01 and 0.03 m and precipitation gauges are usually located on grass. Thus for a global product, a roughness length of grass condition (0.03 m) is more representative than a roughness length of snow condition (0.01 m).

Because our method to estimate undercatch depends on gauge types and wind velocity, we may overestimate correction amounts in the stations where precipitation gauges are located at wind-protected places, as is often the case e.g., in Germany.

RESULTS

We compared mean annual terrestrial precipitation and snowfall from 1986 to 1995 estimated from two different methods for distinguishing snowfall and rainfall phases, three different undercatch correction methods, and from two reanalysis products (Table I). The reanalysis products were NCC, a product of the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) corrected by monthly observations (Ngo-Duc *et al.*, 2005), and ECMWF's ERA40 product. Because the gauge correction coefficient data of Ad03 and the precipitation and snowfall of NCC do not cover Antarctica, all values in Table I represent total values over land excluding Antarctica. We selected the period from 1986 to 1995 because time series of snowfall in ERA40 are problematic before the 1980s, and because the number of observation data to create H08 decreases after the mid 1990s.

Snowfall of H08 estimated using the equations of Yamazaki (2001) was larger than that estimated using the 0°C threshold method. When the 0°C threshold was used to distinguish snowfall from precipitation, the annual snowfall was 9.57 × 10^3 km^3, whereas the H08 value was 11.64 × 10^3 km^3. Differences between the two estimations were large in places with heavy snowfall and gauge types with a large undercatch, including western North America, United Kingdom, the Alps, and the Tibetan Plateau (Figure 1). With the threshold method, computed snowfalls strongly depends on the threshold values. Using a threshold of 2°C (percentage of snowfall in precipitation is approximately 50% at a surface temperature of 2°C), estimated global snowfall increases to 11.70 × 10^3 km^3, which is close to the H08 value.

After the gauge correction was applied to the precipitation data, precipitation and snowfall of H08 in-

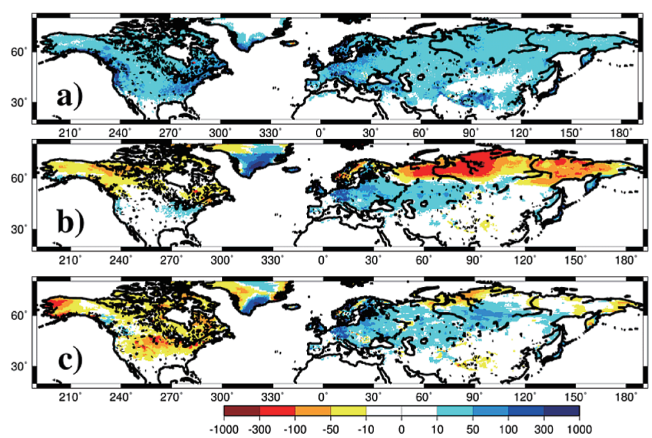

Figure 1. Difference between 1986–1995 mean annual snowfall (mm/year) as computed with a) 0°C threshold method, b) LW90 and c) Ad03, and H08 snowfall.

Table I. Global terrestrial total precipitation and snowfall from 1986 to 1995 (excluding Antarctica). Units are 10^3 km^3/year. Small islands in NCC, where data are missing, are supplemented using H08.

Data	Undercatch correction	Phase detection	Precipitation (correction amount %)	Snowfall (% of total precip.)
H08	No correction	H08 (Yamazaki, 2001)	102.3	8.92 (8.7%)
	H08	H08 (Yamazaki, 2001)	108.3 (+5.9%)	11.64 (10.7%)
	H08	0°C threshold	108.0 (+5.5%)	9.57 (8.9%)
	LW90	H08 (Yamazaki, 2001)	114.9 (+12.3%)	11.59 (10.1%)
	Ad03	H08 (Yamazaki, 2001)	112.5 (+9.9%)	11.36 (10.1%)
ERA40	Reanalysis	Reanalysis	110.8	7.67 (6.9%)
NCC	Reanalysis	Reanalysis	102.0	6.48 (6.4%)

creased by 5.9% (6.0×10^3 km^3) and 30% (2.7×10^3 km^3), respectively. The percentage of snowfall in precipitation reported by H08 increased from 8.7 to 10.7% after wind correction was applied because the correction coefficient for snowfall was larger than that for precipitation. Precipitation correction in H08 (+5.9%) was smaller than in LW90 (+12.3%) and Ad03 (+9.9%). The differences in the total corrected precipitation values resulted in correction amount of rainfall.

Snowfall amounts differed regionally (Figure 1), even though total global snowfall amount was close for all three precipitation corrections. Corrected snowfall of H08 was larger than that of Ad03 and LW90 in the United Kingdom and Germany where Hellman-type gauges, which have the largest correction coefficients of all gauge types, were used to estimate the correction amount of H08.

Snowfall correction in LW90 was higher in the northern part of Eurasia compared to estimates by H08 and Ad03. The difference between LW90 and H08 (and Ad03) arose from the catch ratio used by LW90. Adam and Lettenmaier (2003) explained that the undercatch bias of snowfall used by Legates (1987), which was the same method used by LW90, was larger at higher wind speeds than WMO's regression for Tretyakov-type gauges; this led to higher correction amounts especially over Russia.

The gauge correction coefficients of Ad03 were obtained by the interpolation of monthly climatologies (1994–1998) of correction coefficients from daily meteorological gauging station observations, with additional gauge information in Canada, whereas the correction amount of H08 was estimated based on gauge types and daily meteorological data at each grid. Ad03 includes a correction for topographic effects (Adam *et al.*, 2006) that uses a simple topographic regression method and leads to excessive precipitation on the lee sides of mountainous regions (K. Yoshimura, personal communication, 2008), e.g. east of the Sierra Mountains in North America. These methodological differences led to differences in the correction amount between H08 and Ad03, even though both use the equations of Goodison *et al.* (1998).

Because Ad03 only corrected snowfall in countries in which at least half of the land area experiences snow during the coldest month, the correction amounts of H08 were larger than those of Ad03 in many regions; the difference was especially large in the United Kingdom and Germany, where Ad03 did not correct snowfall and H08 included gauge types with a large snowfall undercatch correction. For Canada, Ad03 developed their own correction ratio instead of using Goodison *et al.*'s equations (1998), resulting in estimation differences between H08 and Ad03 for this area.

Snowfall amounts from reanalysis products (ERA40 and NCC) were smaller than the H08 estimate (Table I). The percentages of snowfall in the total precipitation of the reanalysis data sets were also lower (6.9 and 6.4%) than those estimated by H08 and the 0°C threshold method, indicating that snowfall in reanalysis products is underestimated compared to observations. Corrected mean annual terrestrial (including Antarctica) precipitation of H08 during the period 1948–2006 was 119.6×10^3 km^3, as compared to 112.8×10^3 km^3 of annual terrestrial precipitation without gauge correction. Annual snowfall increased from 9.4 to 12.3×10^3 km^3 with gauge correction.

H08 snowfall shows a downward trend (Figure 2). This downward trend in snowfall was not the result of a decrease in total precipitation because the amount of snowfall estimated by applying the fixed snowfall ratio (10% of precipitation) did not show a notable trend. The percentage of snowfall in total precipitation has decreased, probably related to the increase in terrestrial temperature in recent decades. The Mann-Kendall trend test (Kendall, 1938) shows a 99% significant trend of snowfall from 1981 to 2006, while there is no statistically significant trend in the precipitation time series. The increase of surface temperature may not only be due to the change of climate change, but also the result of urbanization of regions close to the gauges to create the surface temperature data of H08. The rapid increase in snowfall in ERA40 stems from lower precipitation before the 1970s, which is considered to be an artificial trend caused by a change in the observation data used to create the reanalysis product (Chen and Bosilovich, 2007). Both ERA40 and NCC show downward trends from approximately 1990, although these trends are smaller than the trend of H08.

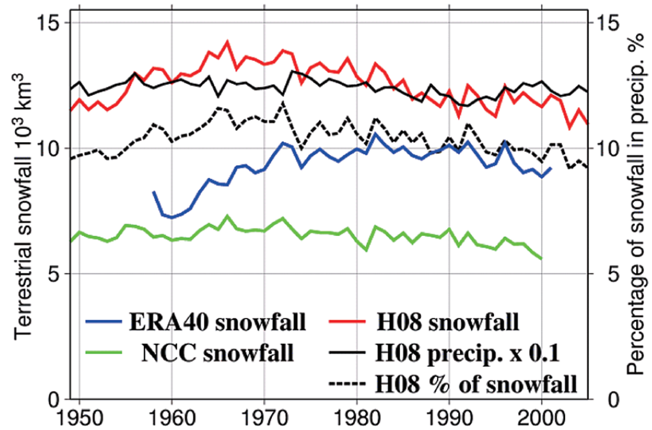

Figure 2. Time series of annual terrestrial snowfall and percentage of snowfall in total precipitation. H08 and ERA40 include Antarctica, and NCC excludes Antarctica.

CONCLUSION

Global terrestrial snowfall was estimated for 59 years from 1948 to 2006. Observed precipitation was corrected for wind-related gauge undercatch of rainfall and snowfall, depending on gauge types. The precipitation phase distribution method of H08 using dew point temperature resulted in larger snowfall than the 0°C threshold method, and is expected to assist more realistic snowfall estimation especially in dry regions. The percentage of snowfall increased after the gauge correction for rainfall and snowfall was applied because the correction coefficient for snowfall was larger than that for precipitation. The correction amount for precipitation of H08 was approximately half of the amounts that we obtained using correction coefficients of previous studies, because of the lower correction amount in rainfall.

Snowfall estimations with the different correction methods differed significantly in some regions. Because we estimated undercatch correction using daily atmospheric data, H08 snowfall allows to determine long-term variations of snowfall more reliably than snowfall estimates that are derived using a climatology of correction factors. The estimated 59-year time series of snowfall amount shows a downward trend after the mid-1980s that may be due to a warmer climate.

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SUPPLEMENTS

Supplement 1. Zonal means of the standard deviation of daily temperature from 1986 to 1995 of the observation-based product of the Global Teleconnection System (GTS) by the National Oceanic and Atmospheric Administration, our product (H08), and the ERA40 and NCC reanalysis products.Units are K.

Supplement 2. Zonal means of the standard deviation of shortwave radiation from 1986 to 1995 of the satellite-based product of the Surface Radiation Budget (SRB) project (Release 2.8, Gupta *et al.*, 2006; http://eosweb.larc.nasa.gov/), our product (H08), and the ERA40 and NCC reanalysis products. Units are W m^{-2}.

Supplement 3. Parameters in exponential functions of snowfall catch ratios (Motoya *et al.*, 2002) for different gauge types.

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