

Computational Time Steps of Winter Water Balance for Snow Losses at United States Meteorological Stations

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ABSTRACT

When estimating the water balance for a cold region watershed, that is one that receive a substantial portion of its annual precipitation as snow, accumulation and other winter hydrological processes must be considered. For many of these watersheds, all but the most fundamental meteorological data (temperature and precipitation), are either not measured or not measured at a reasonable time step. Of particular importance are wind data, as wind influences underestimates of precipitation due to wind undercatch and losses of snow from the snowpack, specifically, snowpack sublimation, and the occurrence and magnitude of blowing snow. Estimating snow accumulation to yield snowmelt amounts requires summing of gauged precipitation and gauge undercatch, and subtracting minus snowpack sublimation and blowing snow transport. The first two components are computed on a daily time step, while the latter two are computed on an hourly time step. From five National Weather Service meteorological stations, the variations in computed snowpack mass losses minus undercatch using data at different time intervals show that at most sites it is difficult to use monthly time steps for computations derived using hourly or daily data. At the relative dry and cold Leadville, Colorado site the computations were transferable between time steps.

Keywords: solid precipitation, meteorological data, undercatch, sublimation, blowing snow

INTRODUCTION

Snow is disturbed by wind, from snowfall to movement through redistribution to sublimation. Snowfall quantities are underestimated from precipitation gauges due to undercatch from wind, wetting of gauges, and to a lesser degree evaporation (Goodison et al., 1998). Undercatch due to wind is caused by the deformation of the wind field around the gauge orifice. As well, falling snow crystals are more easily blown away from the gauge orifice than rain drops. Snow on the ground can be redistributed based on wind characteristics, upwind and downwind fetch length, and the history of the snowpack surface (Pomeroy et al., 1991). Wind across a snowpack (or across snow held by vegetation) can sublimate snow away from or towards the surface depending upon temperature and humidity profiles (Sverdrup, 1936).

A watershed analysis uses the water balance to partition water storage and movement into different components of the hydrological cycle. At the end of the accumulation period, the remaining snow melts to contribute to runoff. Accumulation, given as snow water equivalent (SWE), is typically estimated as the cumulative precipitation occurring at air temperatures colder than freezing (0 degrees Celsius), without correcting for precipitation underestimation due to gauge undercatch, nor snowpack losses due to sublimation or blowing snow.

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Fassnacht (2004) used equations derived from field measurements to estimate gauge undercatch and compared it to sublimation and blowing snow from six weather stations across the United States (U.S.) in order to adjust monthly and seasonal accumulation. With these considerations, the amount of SWE that accumulates can be computed as

$$SWE = P_g + P_U \mp F_E \mp q_{BS} \quad (1)$$

where P_g is the measured amount of precipitation, P_U is the estimated amount of gauge underestimation (hereinafter assumed to be mainly due to undercatch), F_E is the amount of sublimation (away from or towards the snowpack), and q_{BS} is the amount of blowing snow redistributed (scoured away from or deposited at the snowpack). The precipitation (measured plus undercatch) is an accumulation of snow, as estimated from a gauge, whereas sublimation and blowing snow are losses from the snowpack which has accumulated beside a precipitation gauge. These components can be computed for a point location using meteorological data. Fassnacht (2004) compared these components to see if measured precipitation, without consideration of undercatch or other biases, could be used as an estimate of snowpack accumulation after sublimation and blowing snow had reduced accumulation.

For U.S. National Weather Service (NWS) automated surface observation stations (ASOS), meteorological data are reported over an hourly interval (to be used to compute F_E and q_{BS} in equation 1). The NWS cooperative (COOP) stations data are reported over a daily interval (to be used to compute P_g and P_U in equation 1). These data and monthly summaries are available online via the NWS National Climate Data Center (NCDC, 2006). Data are presented as quantities, with the exception of precipitation events that are less than 0.254 mm (0.01 inches), which are reported as trace events. Fassnacht (2004) assumed that these trace events yielded precipitation at one half of the minimum detection (0.127 mm). Yang *et al.* (1998a) stated that trace events can be significant in drier environments, such as Alaska.

Fassnacht (2004) scrutinized the validity of undercatch, sublimation and redistribution estimates in trying to determine if and where P_U is approximately equal to F_E plus q_{BS} , so that SWE can be set to P_g for equation 1. Considering that water balance computations are typically made for monthly intervals, this paper compares the components of equation 1 for individual winter months and the entire winter season as computed using different time steps. Specifically the objectives are 1) to compare the transferability of computed snow loss rates (precipitation undercatch, snowpack sublimation and blowing snow transport) over different time scales (hourly, daily, and monthly); 2) for monthly undercatch to determine if there is a difference using monthly average (for temperature and wind speed, with totals for precipitation) of the daily data (hereinafter called average monthly data) versus using monthly data adjusted for the monthly probability of each precipitation type (snow, mixed precipitation, or rain) together with the average wind speed during each precipitation type (hereinafter called monthly phase partitioned data); and 3) to determine if monthly or seasonal gauged precipitation can be used to estimate discrepancies in computations of P_g , P_U , F_E and q_{BS} from different time steps. Since the precipitation undercatch equations were derived from data at daily interval, undercatch was not computed using hourly data.

STUDY SITES

Four of the six meteorological stations across the conterminous U.S. used by Fassnacht (2004) were analysed in this study (Table 1). Pullman WA was substituted for the Stanley ID station, since there were no observed trace events at Stanley during the study period. Pullman WA has a similar climate to Stanley (Table 2 and Fassnacht, 2004), receiving 6 mm more precipitation per winter month, being warmer (−0.6 degrees C average air temperature versus −5.9 degrees C), more humid (a vapour pressure of 4.9 mb versus 3.3 mb), and more windy (4.1 m s^{−1} average wind speed versus 1.3 m s^{−1}), but having the same vapour pressure deficit. The South Lake Tahoe station was not used, as the no suitable undercatch equation has been derived for the heating tipping bucket gauge used to estimate daily precipitation.

Meteorological data for the winter (October–June) of three water years (2000–2002) were retrieved from the NCDC online database (NCDC, 2006). Data were available only for water years 2001 and 2002 for the Rawlins WY station (Table 1).

Snow depths were not recorded, thus, hourly temperature and precipitation data were examined for each year for each station to determine when snow started to accumulate and when its ablation was likely complete. These dates were rounded to the nearest month (Table 1). While the phase of precipitation was not known for the study sites, it was observed that only in the later winter months did precipitation occasionally occur at air temperatures warmer than 0 degrees C. This factor also helped determine the start and end of ablation. The monthly average precipitation, temperature, wind speed and vapour pressure for the winter months are summarized in Table 2, for the winter months given in Table 1.

Table 1. Summary of stations used in analyses, and the periods considered winter for each of the three water years of interest (2000–2002). The precipitation gauge type is denoted as SRN for the NWS standard 8" rain gauge or BUG for the Belfort Universal Recording Rain Gauge.

station	state	elevation (m)	latitude (N)	longitude (W)	winter period			precipitation gauge type
					2000	2001	2002	
Pullman	WA	778	46E45'	117E7'	Dec–Jan	Nov–Feb	Dec–Feb	SRN
Rawlins	WY	2053	41E48'	107E12'	<i>no data</i>	Nov–Mar	Nov–Mar	SRN
Leadville	CO	3029	39E14'	106E19'	Dec–Apr	Nov–Apr	Nov–Apr	SRN
Rhineland	WI	487	45E38'	89E28'	Dec–Feb	Nov–Mar	Dec–Apr	SRN
Syracuse	NY	125	43E7'	76E6'	Jan–Feb	Dec–Mar	Dec–Feb	BUG

Table 2. The average (mean) and coefficient of variation (COV) of the station meteorology for the winter periods listed in Table 1. Note: † precipitation is corrected using daily data.

station	precipitation (mm)†		temperature (EC)		humidity (mb)		vapour pressure deficit (mb)		wind (m/s)	
	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV
	Pullman, WA	37.3	0.37	-0.63	-1.57	4.94	0.06	1.04	0.301	4.1
Rawlins, WY	19.2	0.552	-4.71	-0.62	3.12	0.218	1.36	0.294	5.6	0.170
Leadville, CO	27	0.552	-5.24	-0.74	2.44	0.250	1.76	0.449	3.6	0.111
Rhineland, WI	26.7	0.749	-6.64	-0.51	3.19	0.251	0.97	0.278	3.4	0.097
Syracuse, NY	89.9	0.473	-1.66	-1.69	4.32	0.183	1.48	0.250	4.3	0.086

METHODOLOGY

To address the objectives of this paper, precipitation gauge undercatch was estimated using daily and monthly data. The monthly mean of daily data produced the average monthly data. Precipitation was summed for each month. To generate undercatch estimates from the monthly phase partitioned data, daily data were used to identify the form of the precipitation, and yielded a fraction of the monthly precipitation. The average wind speed during each precipitation type was used together with the fraction of the monthly precipitation type. Snowpack sublimation and blowing snow transport were estimated from data at hourly, daily, and average monthly, as detailed in Fassnacht (2004).

The amount of gauge undercatch due to wind was computed as a function of measured precipitation and wind speed (U_z) (Yang *et al.*, 1998b):

$$P_U = f(P_g, U_z). \quad (2)$$

The height of the anemometer at each station was assumed to be at 6m, and the height of the gauge orifice was assumed to be at 2m. The wind speed was converted from a 6m height to a 2 m height, as per Goodison *et al.* (1998) using the snowpack aerodynamic roughness of 0.005 m (Fassnacht *et al.*, 1999).

For solid precipitation, wetting losses were assumed to be small as compared to wind induced losses, and for monthly computations were assumed to be minimal. Similarly, evaporation losses were assumed to be negligible (Goodison *et al.*, 1998). Undercatch equations were derived from daily data for snowfall when the daily air temperature (T_a) was colder than freezing and for mixed precipitation when T_a was between 0 and 3 degrees C (Goodison *et al.*, 1998). The specific equations derived by Yang *et al.* (1998b) for the unshielded 8" NWS Standard precipitation gauge with respect to the Double Fence Intercomparison Reference gauge (DFIR) were used for all sites except Syracuse (Table 1). This station used a Belfort Universal gauge. As per Groisman *et al.* (1999), the Yang *et al.* (1998b) equation was used for snowfall undercatch of the Belfort Universal gauge. Mixed precipitation undercatch was increased by 7% for the Belfort Universal gauge used at Syracuse (Groisman *et al.*, 1999). As per Fassnacht (2004) and Bogart *et al.* (2006), a maximum wind speed of 6.5 m/s was used in the undercatch equations due to the increased uncertainty at the higher wind speeds.

Sublimation and the occurrence of blowing snow are episodic and were thus computed using hourly data. Sublimation was estimated using the bulk transfer approach for the latent heat flux as a function of humidity (RH), air temperature, wind speed, and station pressure (PR):

$$F_E = f(RH, T_a, U_z, PR), \quad (3)$$

as initially formulated by Sverdrup (1936). The occurrence of blowing snow (BSY/N) was initially estimated as a function of wind speed and different temperature considerations, as per Li and Pomeroy (1997):

$$BS_{Y/N} = f(U_z, T_a). \quad (4)$$

Once blowing snow was determined to have initiated, the quantity of blowing snow was computed as a function of wind speed:

$$q_{BS} = f(U_z), \quad (5)$$

using the equation derived by Pomeroy *et al.* (1991). Sublimation and blowing snow quantities were summed to yield net snowpack loss estimates.

The NWS denotes trace events (P_T) as precipitation amounts less than 0.01 inches or 0.254 mm per hour or day (NWS, 2005), while Legates *et al.* (2005) called all measurements less than half the measurable precipitation depth (0.005 inches or 0.127 mm) as a trace event. In this paper, daily trace events will be assigned a value of 0.127 mm.

RESULTS

Hourly, daily and monthly meteorological data were used to compute P_U (Figure 1) and snowpack losses (F_E plus q_{BS}) (Figure 2). The estimated difference between losses and undercatch using the time step specific to the derived equations versus using a monthly time step is presented in Figure 3 for monthly totals, and Figure 4 for seasonal totals. For the difference comparison, the same net result would appear along the 1:1 line, while data at the origin would indicate that measured precipitation could be used as an estimate of snow on the ground. Below the x-axis or to the left of the y-axis, more snow is actually accumulating than estimated from the measured precipitation alone. The difference between the two time step estimates and gauge precipitation for individual months is illustrated in Figure 5, and for each season is illustrated in Figure 6.

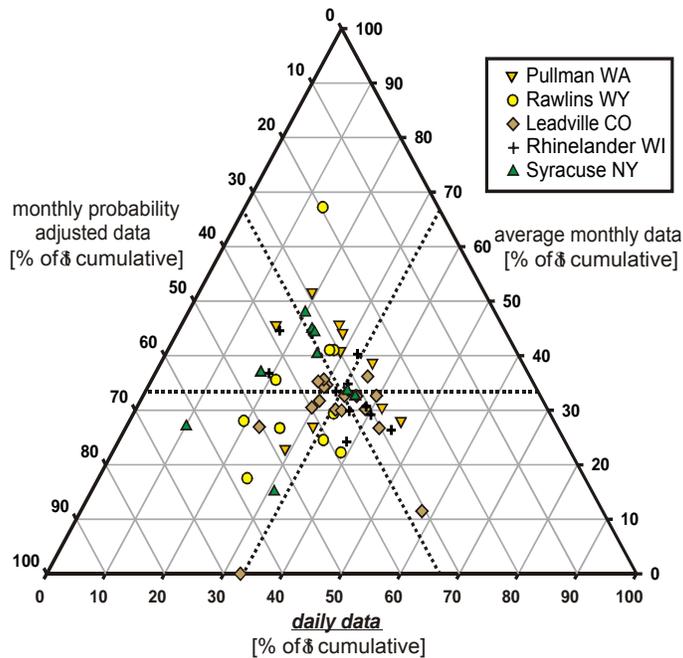


Figure 1. Comparison of monthly precipitation undercatch estimates using daily and monthly data. Each estimate is presented as a percentage of the total of the three different datasets. The values for undercatch have been derived for daily data. The average monthly data were derived from the mean of the daily data, whereas the monthly probability adjusted data were derived using the monthly precipitation distribution (snow, mixed precipitation, or rain) and the average wind speed during each type of precipitation.

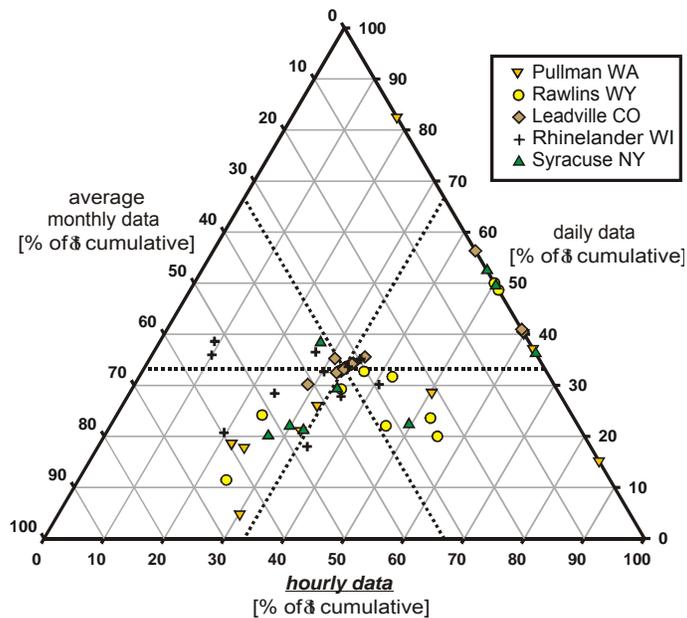


Figure 2. Comparison of relative monthly snowpack loss (sublimation plus blowing snow) estimates using hourly, daily, and monthly data. Each estimate is presented as a percentage of the total of the three different time step estimates. The values have been derived for hourly data.

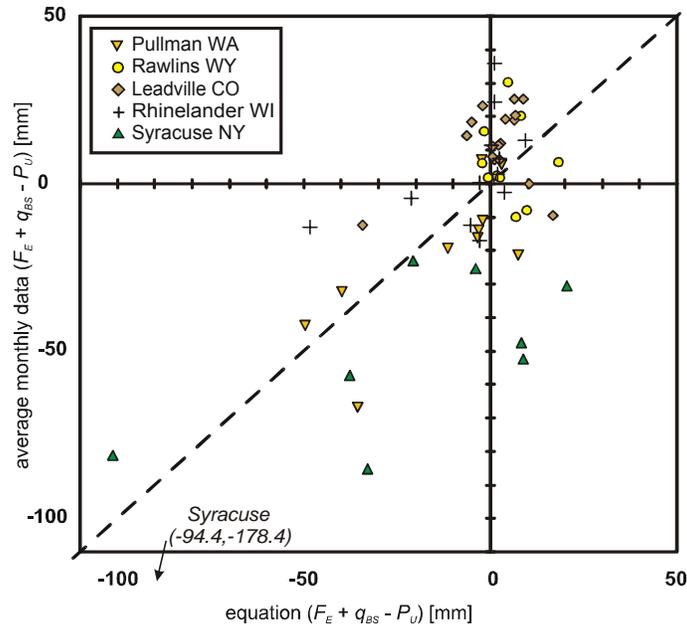


Figure 3. Monthly total comparison of the difference between snowpack losses (sublimation plus blowing snow) and precipitation undercatch estimated using average monthly meteorological data versus the time step for which the values were derived (hourly for losses and daily for undercatch). The dashed line represents the 1:1 relationship.

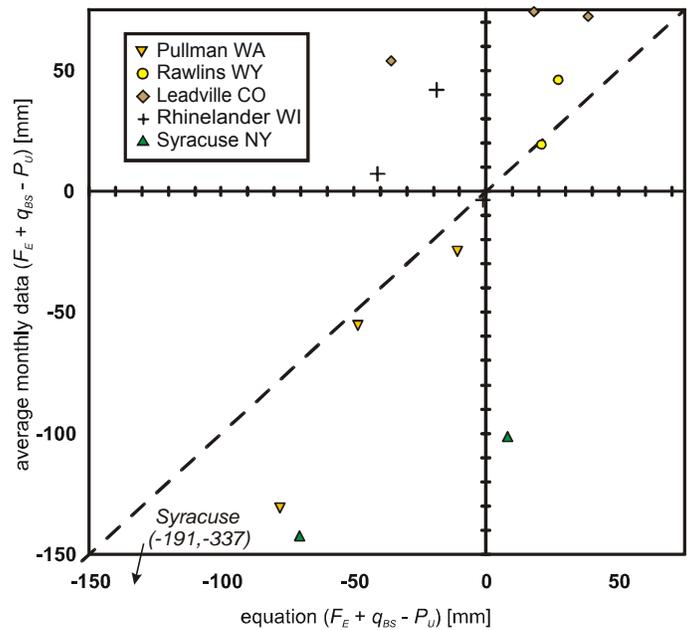


Figure 4. Seasonal total comparison of the difference between snowpack losses (sublimation plus blowing snow) and precipitation undercatch estimated using average monthly meteorological data versus the time step for which the values were derived (hourly for losses and daily for undercatch). The dashed line represents the 1:1 relationship.

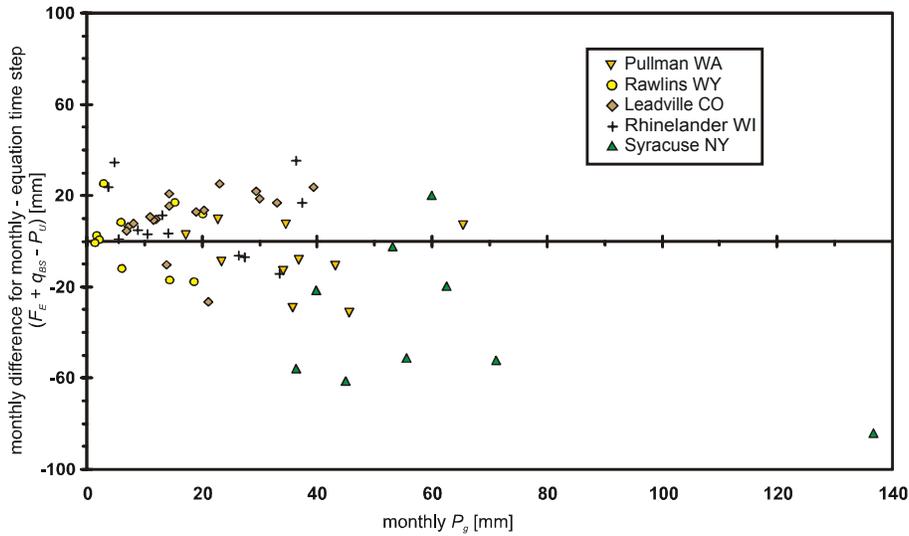


Figure 5. Monthly total difference between monthly derived and equation appropriate time step losses minus undercatch versus monthly gauge precipitation.

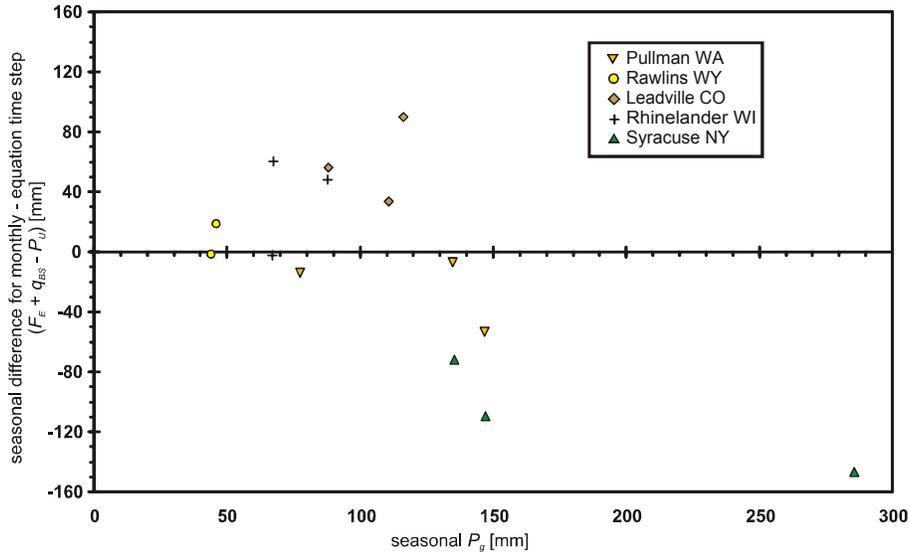


Figure 6. Seasonal total difference between monthly derived and equation appropriate time step losses minus undercatch versus monthly gauge precipitation.

With the exception of January 2002 at Pullman WA, March 2002 at Rawlins WY, and December 2001 at Syracuse NY, undercatch estimates from daily data were at least comparable to those from average monthly and from monthly partitioned data (Figure 1). Undercatch estimated from monthly average data was representative of those estimated from daily data, while the monthly partitioned data was more representative. The results from both monthly dataset were most similar for Leadville CO, Rhinelander WI and Syracuse NY, yet for Pullman WA and Rawlins WY the monthly partitioned data yielded undercatch estimates more similar to using the daily data than using the average monthly data. The mean monthly undercatch estimate for all stations and months using daily data was 29.3 mm (standard deviation, s of 27.4, and a maximum of 127), using average monthly data was 35.8 mm (s of 40.6 and a maximum of 229), and using the monthly partitioned data was 31.5 mm (s of 31.5 and a maximum of 168).

Snowpack loss estimates were more similar for the different time steps (Figure 2), except for the 25% of the months when monthly data yielded no loss estimates. For 13 months, monthly derived

estimates were equal to the sum of hourly and daily derived estimates, primarily due to very small hourly estimates. The average monthly snowpack losses were 22.7 mm (s of 12.3 and a maximum of 54.9), 24.3 mm (s of 13.4 and a maximum of 57.1), and 27.5 mm (s of 22.8 and a maximum of 113) for hourly, daily and monthly time steps.

The net difference between losses and undercatch was greater or equal for Rhinelander WI when the monthly time step was used compared to the appropriate time step, whereas they tended to be equal or less for Syracuse NY (Figure 3 for monthly totals and Figure 4 for seasonal totals). As shown by Fassnacht (2004), losses tended to be larger than undercatch, i.e., only 4 months of data are in the third quadrant of Figure 3, and only 1 season in the second quadrant of Figure 4. Data for Leadville CO and to a lesser extent Rawlins WY plotted along or close to the 1:1 line in Figures 3 and 4 (estimates were similar for both time steps). At Rawlins WY, some months had greater differences derived from the appropriate time step in the first quadrant and below the 1:1 line.

The difference between the y-axis (monthly time step) and x-axis (equation appropriate time step) (Figure 3 and 4 for monthly and seasonal totals) is presented as a function of gauged precipitation for monthly and seasonal time steps (Figures 5 and 6, respectively). Points along the x-axis in Figures 5 and 6 correspond with points along the 1:1 line in Figures 3 and 4. For monthly totals (Figure 5), there is no systematic trend, except that the monthly difference may decrease as gauged precipitation increases. The Leadville CO data are clustered around the x-axis more closely than other stations.

DISCUSSION

For some months at some stations estimates of month undercatch and snowpack losses (snowpack sublimation and blowing snow transport) are similar using data at an hourly, a daily, or a monthly time step. The appropriate time step is daily for undercatch and hourly for sublimation and blowing snow. To estimate accumulated SWE from gauge precipitation (equation 1), data at a monthly time step could be used for the Leadville CO station, which is a dry environment (low humidity) with moderate precipitation and wind (Table 2). Computationally this occurs in part since snowpack losses are precipitation limited for some months, i.e., F_E plus q_{BS} are equal to P_g plus P_U for some months. However, using the bulk transfer method has been shown to overestimate sublimation (Hood *et al.*, 1999). In particular, the latent heat flux equation uses the vapour pressure deficit to compute sublimation, which in drier environments can be greater than the available energy flux. As well, blowing snow estimates are likely larger than actual. Information on the snowpack history may assist in improving blowing snow estimates. The occurrence of blowing snow equations from Li and Pomeroy (1997) are based on the initiation of blowing snow on an hourly basis. Finer temporal resolution data (and observations) could improve blowing snow estimates. However, archived meteorological data are usually not available at shorter time intervals than hourly.

Both mean monthly undercatch and snowpack loss estimates increased as the temporal resolution of the data decreased, since there is more variation (s is larger) due to more large values. In particular, there were substantially larger monthly estimates from average monthly data for Syracuse NY, which had a persistent wind and various large precipitation events. Removal of the March 2001 Syracuse NY (six large events) estimate reduced the mean monthly average undercatch of the remaining 69 station-months by 1.6, 3.4, and 2.3 mm using the daily, average monthly and monthly partitioned data. This was also the month with the most gauged precipitation (138 mm), as illustrated in Figure 5. The monthly mean undercatch estimates for the other four stations were 22.9, 24.9, and 24.5 mm.

Undercatch estimates for December 2000 at Syracuse NY were similar for the different time intervals, but it should be noted that snow occurred on 27 days of the month with an average monthly wind speed of 5.3 m s^{-1} . For five days with snow, the daily average wind speed was greater than 7 m s^{-1} . This was the only month where the monthly difference was greater than the equation difference (Figure 5).

The daily wind speed can exceed 6.5 m s^{-1} (achieved at all stations), which would result in an undercatch ratio in the order of 20% (collecting one-fifth of the actual snowfall). The undercatch equation is based on data from a number of stations. To improve this and the estimates of sublimation and blowing snow requires field observations. The precipitation undercatch computed in this paper is for unshielded NWS gauges, except at Syracuse. The NWS unshielded gauge is typical, but results were similar for the Belfort Universal gauge (Groisman *et al.*, 1999). Net precipitation increased by 0.2 to 1% when the Groisman *et al.* (1999) increase to mixed precipitation was considered for the Syracuse site.

Using data at a monthly time step produced an average wind speed that was more than the threshold for blowing snow for only one station for one month (January 2002 at Rawlins WY with an average U_z of 7 m s^{-1}). Using daily data, the blowing snow threshold wind speed was only achieved 41% of the time. With hourly data, it was achieved at least twice each month at each station. Snow blowing into the gauge is a consideration for certain gauge and/or shield configuration, such as the Tretyakov (Goodison *et al.*, 1998). However, this has not been observed to be a problem for the NWS Standard Rain gauge nor the Belfort Universal gauge (Yang *et al.*, 1998b).

The appropriate time step versus monthly time step (Figures 3 and 4) yielded similar estimates for most months at Leadville CO and some months Pullman WA, Rawlins WY, and Rhinelander WI. Additional winters of data should be examined at these and other stations with a variety of climates.

At present, monthly or seasonal gauged precipitation cannot be used to estimate discrepancies in computations from different time steps. With more months and stations, it may be possible to identify a systematic trend, at least for seasonal data.

Averaging of data to coarser temporal resolutions does not always produce smaller estimates of undercatch, while sublimation estimates tend to be smaller. This was due in part to difference in wind speed during precipitation events compared to when no precipitation occurs, as well as the nature of averaging, as indicated by comparing undercatch estimated with average monthly data versus monthly partitioned data.

Gauge precipitation is not a useful indicator of the difference between monthly and equation appropriate time steps losses minus undercatch, *i.e.*, it cannot be used to systematically adjust monthly time step estimates of losses minus undercatch for monthly or seasonal totals (Figure 5 and 6). Thus, the appropriate time step should be used for most locations for the computations. At some stations for some months, there is even a substantial difference between monthly totals estimated using hourly versus daily data (Figures 1 and 2).

Trace events have been illustrated to be important for determining monthly and seasonal precipitation amounts (*e.g.*, Yang *et al.*, 1998a). The amount of precipitation assigned to trace events is especially important for drier environments. Undercatch during trace events is a problem, as it may be uncertain how much snow is actually falling, and thus what the actual undercatch ratio is. The frequency of occurrence of measurable versus trace precipitation events could be used as a guide to highlight the importance of trace events.

To quantify the monthly total precipitation, cumulative monthly precipitation should be measured at gauging sites, together with daily (and hourly) measurements. While gauge evaporation was not considered as it tends to be small for snow (Goodison *et al.*, 1998), it can account for some non-wind undercatch. Finer resolution precipitation measurements may need to quantify gauge evaporation and wetting losses. The resolution of the non-recording gauge that is used at thousands of NWS Cooperative sites across the U.S. is 0.254 mm (0.01 inches) thus making the assignment of a value to trace events important. For automated sites, especially those at airport (presented in the paper), finer resolution gauges, such as the Geonor (2006) vibrating wire gauge, should be explored, especially for hourly measurements.

CONCLUSIONS

Precipitation gauge undercatch of snowfall should be estimated using daily data, unless new relationships between undercatch, wind speed, etc., are developed at different temporal resolutions. The inaccuracies of using monthly averaged data are evident from adjusting the average data for the monthly probability of each precipitation type and considering wind speeds during each type. However, these data must be derived from daily data. For snowpack losses (sublimation and blowing snow), it is reasonable to use daily data in lieu of hourly data when computing monthly or seasonal values.

Average monthly data yielded no blowing snow, except for one month at Rawlins WY. No sublimation was estimated 25% of the time using monthly data. For Leadville CO and Rhinelander WI, monthly sublimation plus blowing snow was computed to be very similar using each of the time steps, for most months.

The net accumulation difference, i.e., sublimation plus blowing snow minus undercatch, computed from the time step of data for which the equations were formulated (hourly for sublimation and blowing snow, daily for undercatch) can be estimated from monthly time step data at Leadville CO and for several months at Rhinelander WI. Seasonally, monthly time step data overestimate for 2 of 3 seasons at Rhinelander WI. Underestimates occur at Rawlins WY, for 1 season at Pullman WA, and 2 of 3 seasons at Syracuse NY.

Neither monthly nor seasonal gauged precipitation can be used to estimate discrepancies in computations from different time steps, as no systematic trend is obvious. More stations and years are required, especially focusing on specific climates.

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