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Surface-based precipitation phase determination methods in hydrological models

James Feiccabrino, David Gustafsson and Angela Lundberg

ABSTRACT

We compared solid and liquid precipitation mass output from three categories of common model precipitation phase determination schemes (PPDS) to the recorded precipitation phase in a set of 45 years of 3-hour manual meteorological observations from 19 Swedish meteorological stations. In the first category of rain/snow thresholds, it was found that rain/snow air temperature threshold (ATT) is a better precipitation phase indicator than a rain/snow dew point temperature threshold. When a rain/snow ATT of 0.0 °C (a default value used in some recent models) was replaced by 1.0 °C, misclassified precipitation was reduced by almost one half. A second category of PPDS use two ATTs, one snow and one rain, with a linear decrease in snow fraction between. This category identified precipitation phase better than a rain/snow ATT at 17 stations. Using all observations from all the meteorological stations, a final category using an air-temperature-dependent snow probability curve resulted in slightly lower misclassified precipitation mass at 13 of the 19 stations. However, schemes from the linear decrease in snow fraction category had the lowest misclassified precipitation mass at four meteorological stations.

Key words | hydrological model, precipitation phase, snow, snow fraction, snow model, threshold temperature

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INTRODUCTION

Correct identification of the precipitation phase (rain/snow) is crucial for the function of models that forecast snowmelt floods, water balances for glaciers and polar ices, climate change and avalanche hazards (US Army Corps of Engineers 1956; Braun 1991; Rohrer & Braun 1994; Kongoli & Bland 2000). Precipitation phase influences how large a fraction of the precipitation will be stored as snow, contributing to spring runoff or perhaps even constituting an avalanche hazard. Precipitation phase also affects snow accumulation on glaciers and polar ices and influences how much of the winter precipitation will sublimate in tree crowns (Kokkonen *et al.* 2006). Climate change models also depend on a reliable precipitation phase determination scheme (PPDS) to account for seasonal changes in rain-to-snow ratio due to expected seasonal changes in ambient air temperature (Davis *et al.* 1999).

The importance of PPDSs has long been recognized in snow hydrology (Yuter *et al.* 2006). There is also an ongoing trend to replace meteorological observers with automated systems, and many of these systems do not employ precipitation discriminators. This expanding use of automated meteorological observations increases the need for improvements in model PPDSs for snow processes, estimates of the size of spring runoff and modeling of forest snow processes (Kongoli & Bland 2000). If a model were to misidentify a sleet event (simultaneous rain and snow) as an all-rain event for example, the model output will underestimate snow cover albedo, predict a quicker runoff and underestimate the amount of snow that would need to be melted in the warm season (Davison 2003).

Beyond general runoff considerations, forest processes are important for watershed snow water storage estimates. Maximum canopy storage capacity for rain in a coniferous

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forest is about 2 L m^{-2} while snow canopy storage has been reported as high as 20–25 L m^{-2} (Seppänen 1959; Calder 1990). Snow caught in forest canopies sublimates quicker than snow on the ground because of a greater absorption of shortwave radiation and higher exposure to turbulent-exchange forces (Lundberg *et al.* 2004). Sublimation fractions, as high as 30–50% of total annual snowfall, are reported for dense coniferous forests in both the moist snowy maritime Japanese and the dry cold continental Canadian climates (Nakai 1996; Pomeroy *et al.* 1998; Lundberg *et al.* 2004). Since coniferous canopies can store much more snow than rain, and sublimation of snow in canopies is much more effective than sublimation of snow on the ground, determinations between forested and non-forested landscape and precipitation phase are very important for watershed calculations of snow water equivalent left to melt in the warm season.

The rain/snow determination scheme is one of the three most important parameters for a snow model, according to Kongoli & Bland (2000), and many different types or categories of PPDSs have been used. The most common of these categories is a simple step function where all precipitation colder than the rain/snow threshold temperature (T_{RS}) has an assumed snow fraction (S_{F}) of 100% (snow) and all precipitation equal to and warmer than the T_{RS} is assumed to have a S_{F} of 0% (rain). Other frequently applied PPDS categories use two temperature thresholds: one for snow (T_{S}) and one for rain (T_{R}). All temperatures equal to and colder than T_{S} have a S_{F} of 100%, while all temperatures equal to and warmer than T_{R} have a S_{F} of 0%. These PPDS categories have a mixed precipitation phase zone between T_{S} and T_{R} where $100\% < S_{\mathrm{F}} < 0\%$. One category uses a linear decrease in the S_{F} between T_{S} and T_{R}; another category employs a climatological study to create an S_{F} curve between T_{S} and T_{R}.

The thresholds mentioned above can be based on different types of temperature. Most widespread is the use of average air temperature (i.e. Sælthun 1996) but dew point temperature (i.e. Hirabayashi *et al.* 2008), wet bulb temperature and daily maximum and/or minimum air temperatures (i.e. Schreider *et al.* 1997) are sometimes used. Finally, there are various other methods based on air temperatures at and above the ground surface (i.e. Marshall *et al.* 1994), weather radars and satellite images (i.e. Smirnova *et al.* 2000).

For a location, the overall importance of the PPDS of a model is dependent on the mass of precipitation occurring in near-freezing temperatures.

AIM

The overall aim of this study was to minimize model-misclassified precipitation. First, a review of model PPDSs was conducted. Second, solid (snow) and liquid (rain) precipitation mass outputs from different PPDSs were compared to solid and liquid precipitation mass recorded in a 45-year-long series of manual 3-hour snow/sleet/rain observations. Model PPDSs in the following categories were tested:

- one rain/snow temperature threshold (T_{RS});
- two air temperature thresholds (ATT), T_{S} and T_{R}, with a linear decrease in S_{F} between T_{S} and T_{R}; and
- two ATTs T_{S} and T_{R} with a climatologically based air-temperature-dependent S_{F} curve between T_{S} and T_{R}.

The PPDSs were compared by the amount of observed snow classified as rain, the amount of observed rain classified as snow and the sum of misclassified mass. The comparisons were made both excluding and including sleet observations. The possible improvement by using seasonally or regionally varying T_{RS} was also investigated.

REVIEW OF PRECIPITATION PHASE DETERMINATION SCHEMES

One rain/snow temperature threshold

Air temperature thresholds (ATT)

Today, many models and studies use an ATT scheme (Table 1). The majority of these have a fixed ATT while others (e.g. the Cold Regions Hydrological Model or CRHM and (US) National Weather Service or NWS snow accumulation and ablation models) have a default ATT that can be changed either for single events or permanently adjusted (Baun 2005; Pomeroy *et al.* 2007). An early application of the ATT technique was presented in Snow

Table 1 | ATTs applied in models

$S_F = 1$ for $T \le$ ATT and $S_F = 0$ for $T \ge$ ATT	ATT (°C)
SWAP (Gusev & Nasonova 1998), DSPM, SNOW 17 (Reed *et al.* 2008)	Userdef.
BATS (Yang *et al.* 1997)	+2.2
DSPM (Daly *et al.* 2000)	+0.36
Class 2.7 (Bartlett *et al.* 2006), updated SPONSOR (Shmakin 1998), CHRM (Pomeroy *et al.* 2007), FASST (Frankenstein & Koenig 2004) NWS Snow Accumulation, SiB (Sellers *et al.* 1986) ALEX (Kongoli & Bland 2000) Ablation Model (Anderson 1973), colder climate (Motoyama 1990), WaterGAP2 (Döll *et al.* 2003)	±0.0
Warmer climate (Motoyama 1990)	1–3
HBV Norwegian version (Sælthun 1996)	−1 to 4
HBV-ETH Model Version 4, Mountain (Hottelet *et al.* 1994)	−0.6
HBV-ETH Model Version 4, Lower terrain (Hottelet *et al.* 1994)	−0.8 and 1.0

Hydrology (USACE 1956) with the understanding that the ATT varies between locations over the range 1.1–1.7 °C. This study in the Sierra Nevada Mountains also presented and favored the use of a linear decrease in S_F scheme (USACE 1956).

Variations of ATT scheme

Some studies found daily minimum air temperature to act as a better PPDS than the daily average air temperature (Ruddell *et al.* 1990; Schreider *et al.* 1997). Therefore, the Australian Snow Model (Schreider *et al.* 1997) and the Regional Hydrological Simulation Systems Snow Model (RMS) (Coughlan & Running 1997) use a daily maximum and minimum air temperature scheme.

Variation with elevation or season for ATTs

Other studies suggest that ATT may be dependent on elevation or season. Yang *et al.* (1997) suggested a station-specific ATT dependent on elevation while Kienzle (2008) found a seasonal oscillation in ATT at many stations with a maximum ATT in the summer and a minimum in the winter.

Dew point and wet bulb temperature thresholds

Some researchers found dew point temperature thresholds (DTT) to be a better indicator of precipitation phase than ATT (i.e. Hirabayashi *et al.* 2008). D. Marks (pers. comm., 2011) found that the DTT of 0.0 °C performed consistently better than an ATT in mountainous regions. He also stated that ATTs are site specific, change over time and need periodic recalibration while a DTT of 0.0 °C should be more consistent. Feiccabrino & Lundberg (2007) also found the DTT to be 0.0 °C for Sweden; however, the ATT had less misclassified precipitation than DTT in that study. The difference in outcomes could have been due to mountain stations receiving precipitation in a saturated environment (air temperature and dew point temperature are almost equal), while lower elevations often have unsaturated air between the ground and cloud level.

Two rain/snow temperature thresholds

Linear decrease in S_F between T_S and T_R

To account for sleet occurring in air temperatures approaching the T_{RS}, some PPDSs use two threshold temperatures (T_S and T_R) with mixed precipitation between. Examples of studies which applied a linear change in the S_F between T_S and T_R are listed in Table 2.

Table 2 | Models applying a linear decrease in snow fraction (S_F) between a rain (T_R) and snow threshold (T_S)

$S_F = 1$ for $T \le T_S$; $S_F = (T - T_R)/(T_R - T_S)$ for $T_S \le T \le T_R$; $S_F = 0$ for $T \ge T_S$	T_R (°C)	T_S (°C)	ΔT (°C)
Fuchs *et al.* (2001)	+2	0	2
UEB (Tarboton & Luce 1996), GEOTOP (USACE 1956; Zanotti *et al.* 2004)	+3	−1	4
PRISM (Hay & McCabe 2010)	+7.5[a]	−0.007[a]	7.5
This study	+4	−2	6

[a] Monthly average air temperatures.

Air-temperature-dependent S_F curve between T_S and T_R

Other PPDS use an air-temperature-dependent snow probability curve to describe the S_F between T_S and T_R (Table 3). Auer (1974) used 1,000 observations to make an inverted

Table 3 | Air-temperature-dependent S_F curves

Reference	S_F	T_S (°C)	T_R (°C)
CLASS 3.1 (Bartlett *et al.* 2006) WATCLASS 2.7 (Davison 2003)	$0.0202\times T_6–0.366\times T_5+2.0399\times T_4–1.5089\times T_3–15.038\times T_2+4.664\times T+100$	+0.45	+5.97
This study, excluding sleet	$\exp[–0.0817\times(T+1.07)^{3.07}]$	−2	+4.2
This study, including sleet	$\exp[–0.0000858\times(T+7.50)^{4.12}]$	−4	+7

S-shape snow probability polynomial. He noted that it usually does not rain in air temperatures colder than 0.0 °C and that snow was not observed in air temperatures warmer than 6.1 °C. The exponential decay curves used for S_F in this study (Table 3) were modified from fifth-order polynomials from an earlier study (Feiccabrino & Lundberg 2009).

Miscellaneous methods incorporating air temperatures and data above the ground surface

Models such as Mesoscale Analysis and Prediction Systems (MAPS; Smirnova *et al.* 2000) and Community Land Model 3.0 (CLM; Vertenstein *et al.* 2004) attempt to identify freezing levels (height of 0.0 °C temperature above the ground) and the temperature characteristics of fronts by using more advanced PPDSs. These schemes require additional data sources, e.g. upper air soundings, weather radars and or satellite imagery.

The Snow 17 model (Table 1) attempts to address the issue of upper air temperatures by allowing a user-defined lapse rate (Reed *et al.* 2008). The Community Climate Model (CCM1) uses a variation of the model PPDS of ATT 0.0 °C (Table 1), stating that if the ground, 30 and 100 m above ground level air temperatures are all warmer than 0.0 °C, then $S_F=0$; otherwise $S_F=1$ (Marshall *et al.* 1994). Fassnacht *et al.* (2001) used weather radar information to predict the amount of precipitation along with the Auer polynomial on surface air temperature observations to determine a model's classification of mixed-phase precipitation in air temperatures just warmer than freezing.

METHODS

Here 45 years of manually reported 3-hourly meteorological observations from 1961 to 2006 at 19 Swedish meteorological stations were used (Figure 1). The observations consisted of the date/time, precipitation phase, total precipitation for the period and average air and dew point temperatures.

Note that freezing rain was considered solid precipitation since it freezes on contact. Ice pellets in air temperatures warmer than 8.0 °C were considered rain since hail from spring and summer thunderstorms would only affect year-round ice sheets. Gauge-reported precipitation was used with no correction for precipitation under catch. All observations with less than 0.1 mm of water equivalent were removed since the precipitation is

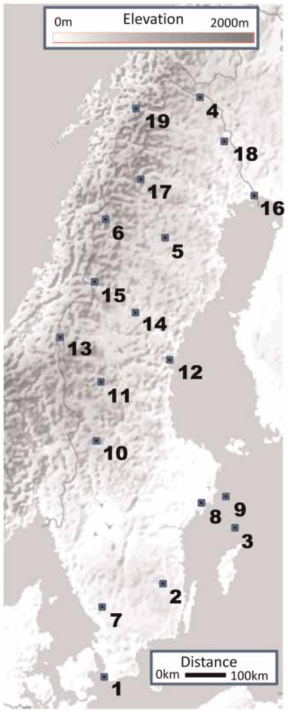

Figure Key

Site Number	Meteorological Station
1	Falsterbo
2	Målilla
3	Gotska Sandön
4	Karesuando
5	Gunnarn
6	Hemavan
7	Torup
8	Stockholm
9	Svenska Högarna
10	Malung
11	Sveg
12	Sundsvalls Flygplats
13	Storlien-Visjövalen
14	Junsele
15	Gäddede
16	Haparanda
17	Kvikkjokk-Årrenjarka
18	Pajala
19	Katterjåkk

Figure 1 | Map of Sweden; meteorological stations highlighted with numbered black squares.

immeasurable and analysis was performed using water equivalents.

Sleet accounted for 16% of total precipitation in Sweden, mostly occurring between the air temperatures of –2.0 and 4.0 °C, with a maximum at 1.0 °C (Feiccabrino & Lundberg 2007). The percentage of sleet to all precipitation mass for a given air temperature had a bell-shaped curve when all stations were taken together (Figure 2), but this was not true for each individual station (Figure 3).

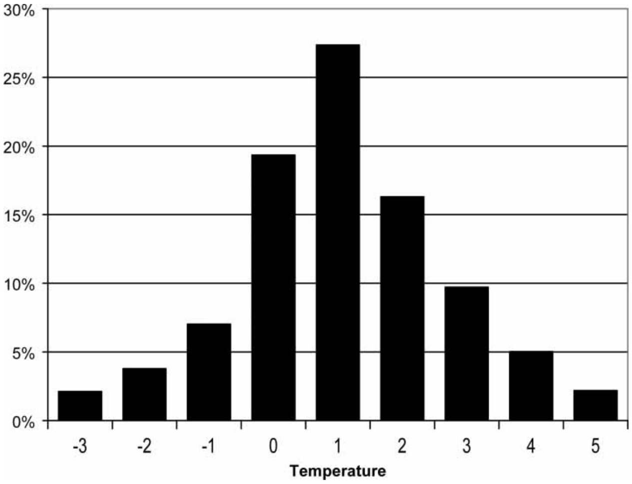

Figure 2 | Air temperature distribution of sleet for all locations together.

Precipitation phase determination schemes

The precipitation outputs from seven schemes in three PPDS categories (Table 4) were compared to observed precipitation phase masses. All three linear transition schemes – D, E and F (Table 4) – had $S_F = 50\%$ at 1 °C (Figure 4(a)). This was the same air temperature as the statistical mean value μ (Figure 2) for sleet and was the ATT found for this dataset (Feiccabrino & Lundberg 2007). The air temperature range between T_S and T_R however varied from 2 to 6 °C. Schemes D and E have been used in other models (Table 2); however, they did not have a large enough range to cover the air temperatures where 98% or more of the observed sleet occurred in Sweden. Scheme F was therefore included in this study to cover this range.

Finally, scheme G applied two air-temperature-dependent S_F curves fit to the results of the climatological study which used 45 years of manual observations to obtain S_F values with a 0.1 °C resolution (Figures 3 and 4(b)), one including and one excluding sleet observations.

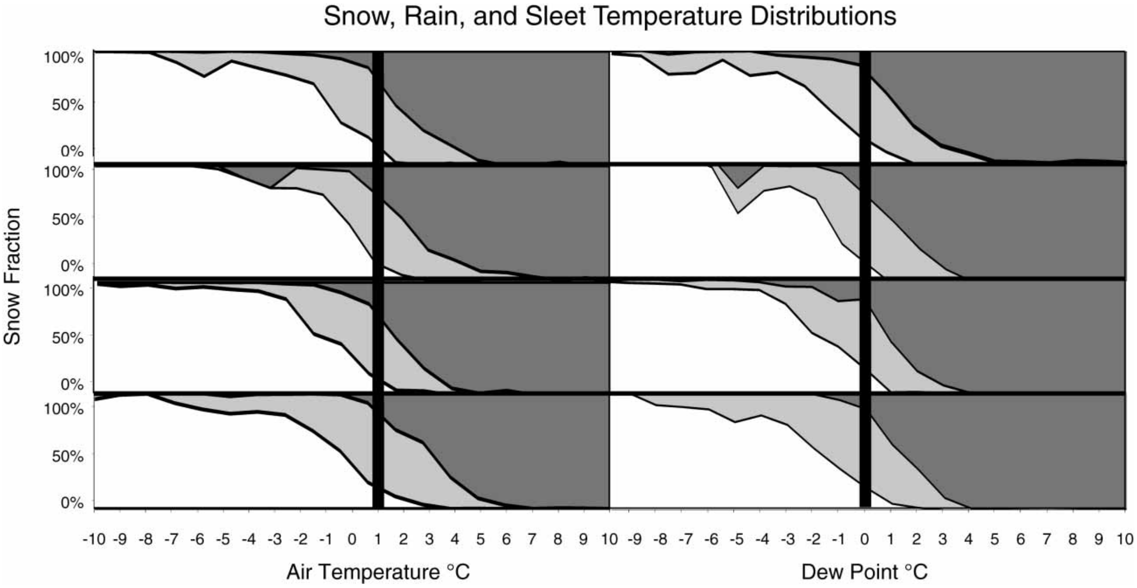

Figure 3 | Observed precipitation phase distribution (snow is white, rain is dark gray, and sleet is light gray) at four meteorological stations 2, 1, 4, and 6 (Figure 1) versus air temperatures (left) and dew point temperatures (right). Thick black line represents the average ATT (left) and DTT (right).

Table 4 | Precipitation phase determination schemes compared in this study

Scheme	T_S T_R or T_{RS} (°C)	Precipitation phase determination category
A	ATT = 0 °C	T_{RS} (commonly used in many models)
B	ATT = 1 °C	T_{RS} (optimized value for all Sweden)
C	ATT = XX–YY °C	T_{RS} (optimized value for each meteorological station)
D	$T_S = 0$ °C, $T_R = 2$ °C	Linear decrease in S_F from T_S to T_R
E	$T_S = -1$ °C, $T_R = 3$ °C	Linear decrease in S_F from T_S to T_R
F	$T_S = -2$ °C, $T_R = 4$ °C	Linear decrease in S_F from T_S to T_R
G w/o[a]	$T_S = -2$ °C, $T_R = 4.2$ °C	Climatologically based S_F curve, T_S to T_R
G w[a]	$T_S = -4$ °C, $T_R = 7$ °C	Climatologically based S_F curve, T_S to T_R

[a]Without (w/o) and with (w) sleet observations.

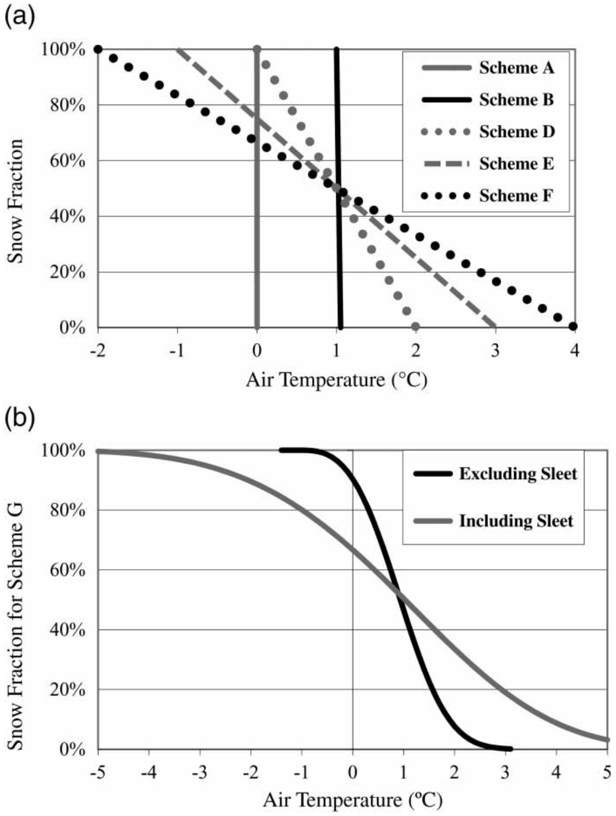

Figure 4 | (a) Rain/snow threshold schemes A and B, with linear decrease in snow fraction schemes D, E and F. (b) Climatologically based S_F, scheme G, excluding and including sleet.

Misclassified precipitation and bias towards rain or snow

Misclassified precipitation excluding sleet was calculated as the total mass of misclassified rain and misclassified snow divided by the total mass of rain and snow (P_{R+S}). First the total mass of observed rain, sleet and snow (S) precipitation phases were calculated for air temperature (T) with a 0.1 °C resolution at all 19 meteorological stations. Snow fractions (S_F) were then calculated for each T step:

$$\mathrm{SF} = \frac{S}{P_{R+S}}(T) \tag{1}$$

The difference between observed snow fraction (S_{FO}) and the modeled snow fraction of a PPDS (S_{FM}) gives the percent misclassified precipitation (ε_{tot}) for each T step. The S_F difference for all the T steps combined gives the misclassified precipitation mass for each scheme:

$$\varepsilon_{tot} = \frac{\sum(|S_{FM}(T) - S_{FO}(T)| \times P_{R+S}(T))}{P_{R+S}} \tag{2}$$

Misclassified precipitation is compared using observations with air temperatures between −1 and 5 °C, the temperature range over which most misclassified precipitation was found to occur. Bias of a PPDS towards misclassified rain (ε_r) or misclassified snow (ε_s) was calculated:

$$\varepsilon_r = \sum(|S_{FM}(T) - S_{FO}(T)| \times P_{R+S}(T)) \text{ for } S_{FO} < S_{FM} \tag{3}$$

$$\varepsilon_s = \sum(|S_{FM}(T) - S_{FO}(T)| \times P_{R+S}(T)) \text{ for } S_{FO} > S_{FM} \tag{4}$$

The difference between modeled snow mass (S_M) of a PPDS and observed snow mass (S_O) was used to determine the change in seasonal snowfall (ΔS) when a scheme is used rather than manual observations:

$$\Delta S = \frac{S_M - S_O}{S_O} \tag{5}$$

Equations (3)–(5) used all observations regardless of air temperature. Sleet observations assumed to be 50% snow and 50% rain can be included in Equations (1)–(5) by adding the sleet mass to P_{R+S} and half sleet mass to S.

An initial test to determine if an ATT or a DTT was a better PPDS was conducted. All the precipitation observations from the 19 meteorological stations were pooled together, as in Daly *et al.* (2000), to determine an ATT and a DTT for Sweden.

The performance of each scheme was judged by the

- fraction of total misclassified precipitation (Equation (2));
- change in snowfall mass between S_M and S_O (Equation (5)); and
- bias towards higher rain or snow misclassification (Equations (3)–(4)).

Predictable monthly changes in ATT were also tested for. Finally, individual station ATTs were compared to station elevation and latitude, dew point temperatures and percent of precipitation falling as snow and sleet to see if there was any noticeable relationship due to geographic location.

RESULTS

Air temperature threshold versus dew point temperature threshold

The ATT determined excluding sleet using all observations was found to be 1.0 °C with 2.4% misclassified precipitation. This was 27% less than the DTT of 0.1 °C with 3.0% misclassified precipitation. ATTs were found to have less misclassified precipitation than DTTs at all 19 stations. Therefore, all further analysis was performed using air temperatures.

Misclassified precipitation comparisons

When the T_{RS} schemes were compared, it was noticeable that there was less misclassified precipitation when applying the T_{RS} 1.0 °C than 0.0 °C (Table 5). This was true excluding and including sleet observations at all 19 stations.

Individual station ATTs were compared to the Swedish ATT of 1.0 °C (Equation (2)). There were nine individual station ATTs (scheme C) equal to the Swedish ATT (scheme B). The average misclassified precipitation for all 19 stations decreased slightly when using scheme C rather than scheme B, excluding and including sleet observations from 9.6 to 9.2% and 26.3 to 26.0%, respectively (Figure 5; Table 5). At the 10 stations with ATTs differing from 1.0 °C, there was a 0.93 and 0.57% average percentage point decrease in misclassified precipitation excluding and including sleet observations, respectively. Since scheme C by definition has the least misclassified precipitation of the three T_{RS} schemes, it is compared to schemes D–G.

From −1 to 5 °C with sleet excluded, scheme G had the least amount of misclassified precipitation at all but six stations. At four of those stations, scheme D had slightly less misclassified precipitation mass than scheme G (Figures 5

Table 5 | Percent misclassified precipitation and change in annual snowfall (ΔSnow) excluding (Without mix) and including (With mix) sleet in the precipitation phase determination schemes A–G compared to manual observations. Bold numbers indicate best values

	Misclassified precipitation (%)				**ΔSnow (%)**		**Misclassified as snow (%)**	
Scheme	**Without mix**	**a**	**With mix**	**a**	**Without mix**	**With mix**	**Without mix**	**With mix**
A	17	0	31	0	−13	−24	88	79
B	9.6	0	26	0	1.3	2.6	42	42
C	9.2	2	25	0	0.20	0.90	44	45
D	6.9	4	16	0	**0.00**	−0.38	48	46
E	9.2	0	9.2	2	−0.21	−1.2	52	48
F	14	0	7.2	7	0.70	−0.61	**51**	**48**
G	**6.5**	**13**	**6.9**	**10**	−0.65	**0.04**	53	47

[a] Number of stations with lowest values for each scheme.

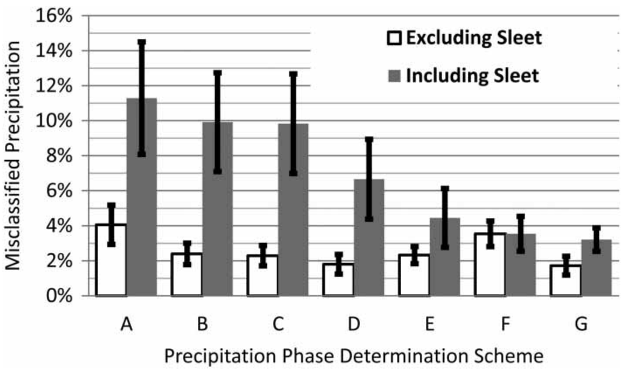

Figure 5 | Misclassified precipitation from −1 to 5 °C with error bars representing the standard deviation from the 19 meteorological stations.

and 6(a); Table 5). Scheme C had the least misclassified precipitation at the other two stations and the most misclassified precipitation at 15 of the 19 stations. Scheme F had the most misclassified precipitation at the other four stations.

When sleet was included, scheme G had the least amount of misclassified precipitation at 10 of the 19 meteorological stations (Figures 5 and 6(b); Table 5). The ATTs had the most misclassified precipitation at all 19 stations, while schemes E and F had the least misclassified precipitation at two and seven stations, respectively. When sleet observations were included as half-rain and half-snow, misclassified precipitation increased (Table 5).

The air temperature range between T_S and T_R was important for the percentage of misclassified precipitation found using a linear decrease in S_F schemes. When sleet was included, the transition range from $S_F = 100\%$ to $S_F = 0\%$ was larger. When comparing the linear decrease in S_F schemes from Table 4, scheme D had the lowest misclassified precipitation when sleet was excluded (Figures 4(a) and 5), while scheme F had the least amount of misclassified

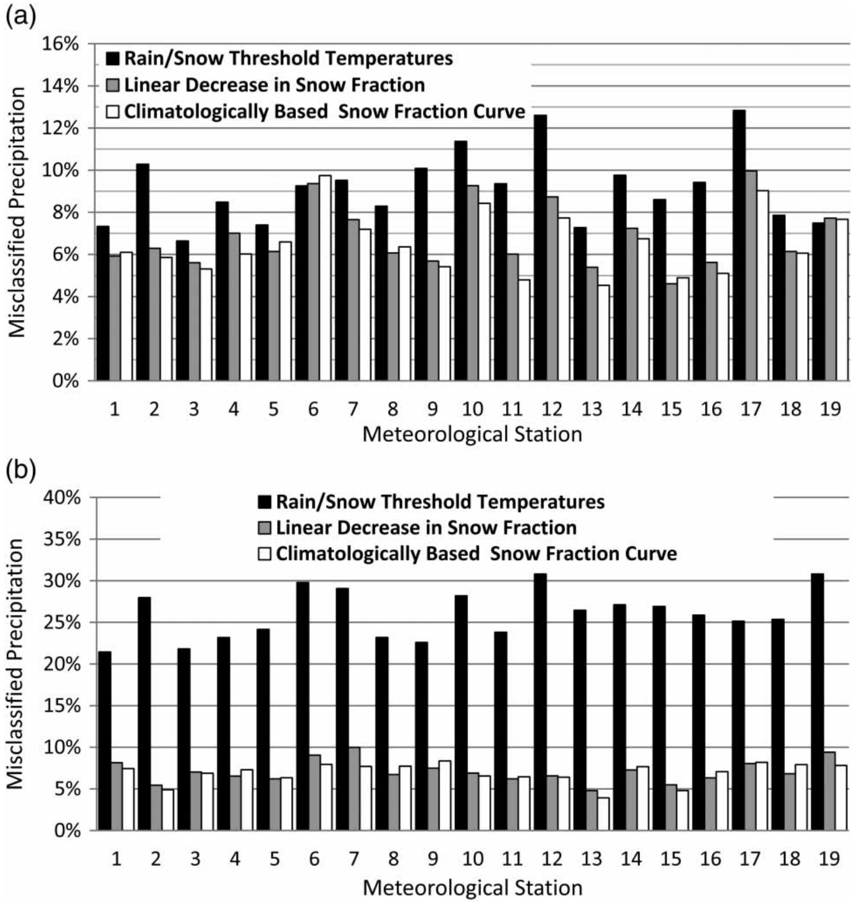

Figure 6 | Misclassified precipitation from −1 to 5 °C (a) excluding sleet observations and (b) including sleet observations for each meteorological station in Figure 1.

precipitation when sleet was included (Figures 4(a) and 5). Of the linear decrease in S_F schemes excluding sleet observations, scheme F had the most misclassified precipitation. Scheme D had the most misclassified precipitation when sleet was included at all stations.

Difference in annual snowfall percentage

Comparing the change in seasonal snowfall amounts between all manual observations and PPDS schemes A–G (Table 5), it was clear that no single scheme performed best at all locations as the standard deviations for all schemes overlap (Figure 7). S_M was always underestimated for scheme A while, for all other schemes, the change from S_O to S_M was either positive or negative. Excluding sleet, 0.0 °C had the largest difference in annual snowfall estimates with a maximum change of –30% from observed annual snowfall percentage at station 1 (Figure 1).

Misclassified rain or snow bias

Using the set of all observations, schemes B–G had 42–53% of the total misclassified precipitation in the solid phase (Table 5; Figure 8). Therefore, there was not a large long-term difference between misclassified rain and misclassified snow masses. Again, most of the standard deviation error bars overlap for these PPDSs. However, 88% of the total misclassified precipitation for ATT 0.0 °C was snow misclassified as rain in warmer than freezing temperatures.

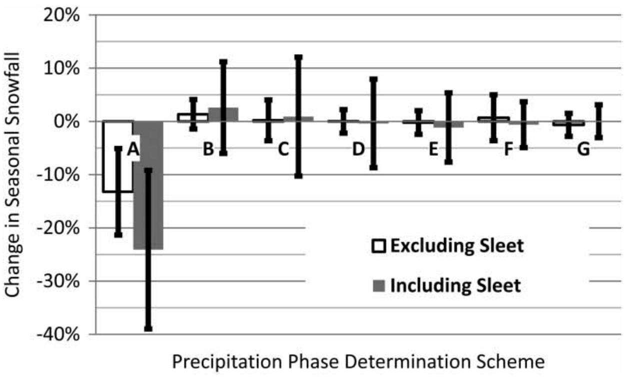

Figure 7 | Change in snowfall as a percent of total precipitation with error bars representing the standard deviation from the 19 meteorological stations.

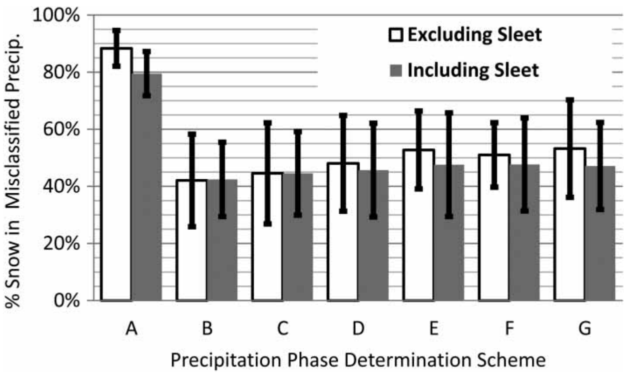

Figure 8 | Percent of misclassified snow in total misclassified precipitation with error bars representing the standard deviation from the 19 meteorological stations.

ATT with geography

There does not appear to be a relationship between ATT and: precipitation percentage of snow; latitude; or elevation, with R^2 values of 0.25, 0.12 and 0.05 respectively. The R^2 values were lower for DTT than ATT. There was also no pattern found for percentage of sleet mass with elevation or latitude.

ATT seasonal variation

Adjusting an ATT by month was not possible on the country scale for Sweden. Table 6 shows that, in all cases (except June) when including sleet observations, the average change in monthly ATT was smaller than the standard deviation, making the change statistically insignificant. If there were not at least 12 rain and 12 snow events in a month over the 45 years, the data for that month were excluded from Table 6. When a monthly ATT was applied at individual meteorological stations, misclassified precipitation was reduced by 15 and 3.4% excluding and including sleet, respectively.

DISCUSSION

The main complication with separating rain and snow using surface observations is that snow forms in the lower atmosphere when cloud temperatures are colder than freezing, and these temperatures are not uniquely related to the

Table 6 | The average difference between annual (scheme C) and monthly station-specific rain/snow threshold values, with ± standard deviations and the number of stations having 12 rain and 12 snow observations during a given month over the 45-year climatological record

Sleet	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
With	0.38 ± 0.5	0.09 ± 0.6	−0.01 ± 0.5	−0.07 ± 0.4	−0.37 ± 0.6	−0.14 ± 0.5	−0.34 ± 0.6	−0.04 ± 0.3	−0.20 ± 0.2	−0.63 ± 0.4
Without	0.40 ±0.5	0.23 ± 0.6	0.12 ± 0.5	−0.09 ± 0.4	−0.17 ± 0.7	0.06 ± 0.7	−0.17 ± 0.5	0.00 ± 0.4	0.05 ± 0.6	0.14 ± 0.7
#	6	16	19	18	17	14	14	19	13	3

temperature at ground level. As snow falls through air warmer than 0.0 °C, a thin water surface will coat the outside of the crystal (Fassnacht *et al.* 2001). Depending on the air temperature and thickness of warm layers, energy exchanges between snow and the atmosphere could cause a phase change to sleet or rain before the hydrometeor reaches the ground (Fassnacht *et al.* 2001; Davison 2003). The PPDS in the SNOW 17 model (Reed *et al.* 2008) allows a user-defined lapse rate. This is a first step in addressing the lower atmosphere in hydrological model PPDSs. However, using a set lapse rate would fail to take into account changes in the lower atmosphere caused by air mass boundaries (Feiccabrino *et al.* 2012). A long-term solution for PPDS in hydrological models would therefore be to incorporate either upper air data (weather balloon data, weather radar or satellite data) or use output from a meteorological model as the surface rain/snow determination scheme for a hydrological model.

This study did not attempt to add upper air data to current surface-based hydrological model input; instead, it worked with current model constraints. The goal was to find the PPDS that results in the least amount of misclassified precipitation with as little change to a model as possible. Using a T_{RS} resulted in the most misclassified precipitation (Figure 3). This misclassified precipitation occurred mostly in temperatures approaching the ATT. Surprisingly, the linear decrease in S_F schemes performed statistically as well as the climatologically based S_F curve. This is good, as it would be easier to apply a linear decrease in the S_F scheme than to determine different climatologically based S_F curves at different sites. Below is a discussion of the results and important notes about the method.

Air temperature threshold versus dew point temperature threshold

ATT had less misclassified precipitation than DTT, excluding and including sleet observations, at all 19 stations spanning mountain areas to islands from southern (55 °N) to northern (68°N) Sweden (Figure 1). An ATT of 1.0 °C excluding sleet had 45% less misclassified precipitation than the often used ATT = 0.0 °C. An ATT of 1.0 °C is slightly lower than the USACE (1956) suggested range of values; however, it is the same ATT found for Iceland (Aoalgeirsdottir *et al.* 2006).

Misclassified precipitation comparisons

The correct classification of precipitation phase is key to precipitation–runoff modeling (Braun 1991). Single-day precipitation events near the T_{RS} are sometimes modeled differently because of different S_F from each PPDS. The PPDS is therefore most important in regions where a large fraction of winter precipitation falls at near-freezing temperatures. In this study PPDS for southern and island stations 1–3 and 7–9 (Figure 1) had the most influence, up to 30% difference, in seasonal snowfall. The chosen PPDS is less important in cold continental climates (i.e. interior Canada). In this study, the choice of PPDS at stations 17–19 (Figure 1) changed modeled snowfall by under 10%. For northern inland stations (17–19) a quick 1–2-week cooling and warming period at the beginning and end of winter reduced precipitation occurrences in near-freezing temperatures.

Kongoli & Bland (2000) state that the best temperature scheme results from the lowest misclassified water equivalent. With this in mind the overall lowest average misclassified precipitation for water equivalent, excluding or including sleet observations, was obtained by using a climatologically based air-temperature-dependent S_F curve. The second-best schemes were the linear decrease in S_F schemes. The linear decrease in S_F scheme D (smallest air temperature difference between T_S and T_R) had the least misclassified precipitation when sleet was excluded, while scheme F (largest air temperature difference between T_S and T_R) had the least misclassified precipitation when sleet was included. This was due to a larger range of air temperatures involved in the observed phase transition from air temperatures with all snow to all rain when sleet observations were included (Table 5; Figure 5). Of all the PPDSs, T_{RS} had the most misclassified precipitation (Table 5; Figure 5). Daly *et al.* (2000) blamed the simple approach of a set T_{RS} for the weakness in his results. This weakness allowed his model to predict lower than observed snow water equivalent and a systematic increase of misclassified precipitation over time. The greatest amount of misclassified precipitation at all but four stations excluding and all stations including sleet occurred using an ATT of 0.0 °C.

Between −1 and 5 °C, scheme G had the lowest overall misclassified precipitation at 13 meteorological stations when sleet observations were excluded and 10 of 19 stations when sleet was included (Figures 6(a) and (b)). The relationship between air temperature and S_F has an inverted S shape (Figure 3) at all stations in this study. The linear decrease in S_F schemes should therefore have more misclassified precipitation then climatologically based air-temperature-dependent S_F curves, if calculated for individual stations. However, location-specific polynomials are most likely too specialized for most model needs. There was also little found to relate changes in the shape of S_F curves with latitude or elevation, making it more difficult to assign different premade polynomials according to station geography.

ATT seasonal variation

Low R^2 between individual station ATTs and elevation or latitude came as no surprise, as Daly *et al.* (2000) also failed to find a relationship. However, the lack of a seasonal-dependent change in ATT was unexpected. Other studies, e.g. Kongoli & Bland (2000), claim that ATT is often climate-, location- and season-dependent. Rohrer & Braun (1994) claimed that the frequency of rain, snow and sleet observations may depend on the season and type of data used. Even when the ATT for individual stations was changed by month, the yearly total misclassified precipitation was still higher than using a linear decrease in S_F scheme.

Snow %, misclassified rain or snow

Sticking with the idea that the air temperature scheme with the lowest misclassified precipitation is best, other tests such as difference between modeled and observed seasonal snowfall percentage and a measure of the balance between rain and snow misclassified precipitation are reasonable secondary tests. The results for the difference between seasonal modeled and observed snowfall mass indicate that, for the purposes of climate studies which need annual snowfall at a station, any of the schemes (with the exception of the ATT 0.0 °C) work well (Figure 7). Finally, all schemes were closely balanced between mass of misclassified rain and misclassified snow; the ATT 0.0 °C was the exception having more misclassified snow than rain (Figure 8). These extra tests did not vary from one scheme to another, giving no reason to question the misclassified precipitation results. Note that the majority of the misclassified precipitation from an ATT of 0.0 °C was snow that prevailed in air temperatures warmer than freezing. This would result in runoff being observed later (Davison 2003) and more sublimation in tree canopies (Lundberg *et al.* 2004) than model output would suggest.

Assumption that sleet is 50% snow and 50% rain

Instances of sleet appear evenly distributed with a maximum at 1.0 °C (Figure 2), the same air temperature as the Swedish ATT which could be expected. Excluding sleet from the observed dataset would overlook the importance of the 16% precipitation mass. Considering sleet to always be half rain and half snow regardless of air temperature is too simple.

A few studies focus on the ratio of snow to rain in mixed precipitation and the studies that are available (e.g. Yuter *et al.* 2006) are short term, usually analyzing a single storm. In a study by Yuter *et al.* (2006), radar data found sleet to be prevalent between 0.0 and 1.1 °C with a sharp transition from snow to rain dominance in terms of volume fraction at 0.5 °C. This indicates that sleet observations in the colder half of a temperature distribution (Figure 2, air temperature <1.0 °C) should be mostly snow, and the warmer half should be mostly rain.

Feiccabrino *et al.* (2012) conducted a 20-year climatological study comparing S_F temperature relationships for sleet considered all rain, all snow and excluded. Excluding sleet resulted in S_F values: just lower than when sleet was considered all snow for temperatures colder than a T_{RS}; just above those for sleet considered all rain in temperatures warmer than a T_{RS}; and about halfway between all rain and all snow at temperatures near the T_{RS}. This agrees well with the Yuter *et al.* (2006) study and provides a good reason to exclude sleet observations from similar studies.

Precipitation phase temporal change

The precipitation phase usually changes quickly from all snow to all rain or vice versa. Shorter time intervals between observations should therefore reduce the amount of sleet observed, a source of error pointed out by Kongoli & Bland (2000). The 16% sleet found in this study was higher than expected. A higher temporal resolution such as that produced by automated meteorological stations could reduce the amount of sleet observations. However, when a station is first changed from manned to automated, caution should be exercised if changes occur in the precipitation catch (Rohrer & Braun 1994). After a switch from manual to automated observations, the ATT in Braun's (1991) Swiss Alps study changed by 1.0 °C. This might be avoided by using results of a manual rain/snow threshold study in the automated observing program.

Gauge under catch

No correction for gauge under catch of precipitation due to wind errors was performed. These errors can have values over the range 2–14% for rain and 5–80% for snow (Kokkonen *et al.* 2006). The difference in wind error for rain and snow in air temperatures approaching a T_{RS} should be at the lower end of possible differences. This is caused by changes in the shape of the snowflake with temperature (Allerup *et al.* 1997) and the density of wet snow becoming closer to that of rain. Snow missing the gauge will therefore affect the total amount of snow in model output more than it will affect the rain/snow threshold.

Compensating errors in models

Improving the PPDS of a model may have undesirable effects on model output if compensating errors from the replaced PPDS are not also found and adjusted. An erroneous PPDS producing too little snow accumulation can be compensated for by means such as neglecting sublimation due to snowdrift, or neglecting snow sublimation in the tree crowns. It can also be compensated for by a poor description of the air temperature lapse rate within the basin. This might lead to a situation where, for example, a runoff model is upgraded with a better PPDS. However, the modeled runoff might be well off observed measurements if other snowpack processes are not also updated.

CONCLUSION

Of the tested traditional precipitation phase discrimination schemes, scheme G (a snow probability polynomial) provided the least amount of misclassified total precipitation between –1 and 5 °C (6.5%) followed closely by scheme D, a two threshold linear decrease in snow fraction between 0 and 2 °C with (6.9%) misclassified.

A commonly used ATT 0.0 °C resulted in the highest misclassified precipitation between –1 and 5 °C (17%), the largest underestimation of long-term snowfall, and at all stations more snow was misclassified as rain than rain misclassified as snow.

Given the results of this paper and prior studies comparing surface-based precipitation phase discrimination, the use of 0.0 °C as an ATT should be avoided with the possible exception of studies in mountainous terrain (e.g. Motoyama 1990).

The relatively small change in yearly snowfall and the close balance between rain and snow errors suggests that any of the traditional precipitation phase discrimination schemes (with the exception of the ATT 0.0 °C) could be used with confidence in models requiring seasonal or yearly snowfall information.

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