Precipitation Phase Discrimination in Sweden

JAMES FEICCABRINO[1] AND ANGELA LUNDBERG[1]

ABSTRACT

Estimation of snow storage in hydrological, regional and global climate models depends on correctly identified precipitation phases, proper snow/rain separation is especially crucial for canopy snow models. Precipitation phase is seldom reported from increasingly automated stations, so most models use one or two static air temperatures to separate rain from snow. However, some models use more elaborated algorithms for phase determination. The aim with this study is to verify if the phase accuracy can be improved by using such schemes. Forty-five years of three-hour man-made precipitation phase observations for nineteen Swedish stations were used to compare different phase separation schemes. Upon initial analysis, excluding mixed precipitation, air temperature was found as a better precipitation phase indicator than dew point temperature. If an assumed 0˚C air temperature threshold, a default value in some recent models, is replaced by 1.0˚C the misclassified precipitation is reduced by almost half and can be further reduced with individual station thresholds. Schemes using two temperature thresholds one snow and one rain with a linear increase in percent rain from 0˚C to 2˚C, or from -1˚C to 3˚C performed better than static thresholds at all stations. When the, 16% total, mixed precipitation is included as half rain and half snow a linear increasing scheme from -2˚C to 4˚C performs best. A temperature dependent snow probability curve using all stations produced lower misclassified precipitation errors in all but 5 cases when lower misclassified precipitation errors occurred with linear increasing schemes.

Keywords: air temperature; precipitation phase; hydrological models; rain; snow; threshold temperature

INTRODUCTION

Correct identification of the precipitation phase (rain/snow) is crucial for the functioning of models that forecast snow melt floods, water balances for glaciers and polar ices, climate change and avalanche hazards (US Army Corps of Engineers, 1956; Braun, 1991; Roher, 1994; Kongoli and Bland, 2000). Precipitation phase influences how large a fraction of the precipitation will be stored as snow contributing to spring runoff or maybe constituting an avalanche hazard. The phase also affects the 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 reliable precipitation phase determination to account for precipitation phase changes due to expected seasonal air temperature alterations (Davis et al. 1999).

Snow sublimation due to interception in tree canopies is an important hydrological process in the Boreal evergreen coniferous forests which broadly encircle the northern continents (Harding, et al., 2001). Maximum canopy storage capacity for rain in a coniferous forest is about 2 mm while snow storage has been reported as high as 20-25 mm water equivalent per ground area

[1] Division of Applied Geology, Luleå University of Technology, LTU, Luleå, Sweden.

(Calder, 1990; Seppänen, 1959). Snow caught in forest canopies sublimates quicker, compared to snow on the ground, because of greater absorption of short-wave radiation and by a higher exposure to turbulent-exchange forces (Lundberg, et al., 2004). Sublimation fractions, as high as 30% to 50% of total annual snowfall, are reported for dense coniferous forests in both the snowy maritime Japanese and in the dry cold Canadian climate (Lundberg, et al., 2004; Nakai, 1996; Pomeroy, et al., 1998).

As coniferous canopies can store much snow and sublimation of snow in canopies is much more effective, compared to sublimation of snow on the ground, correct precipitation phase separation become even more important when dealing with canopy snow processes than with snow pack processes. Therefore a lot of effort was put into discussions regarding precipitation phase modeling at project meetings for the SnowMIP2 (2008) project held at IAMAS, Peking, China, August 2005, and at EGU, Perugia, Italy, July 2007. SnowMIP2 is an intercomparison project for snow models focusing on forest snow processes and the project is commissioned by the Commission of Cryospheric Sciences.

The importance of precipitation phase discrimination has long been recognized in snow hydrology (Yuter et al., 2004). The trend to replace weather observers with automated systems increases the need for correct precipitation phase identification for modeling of snow processes, estimates of the size of spring runoff and for modeling of forest snow processes (Kongoli and Bland, 2000). For example, if a model were to misidentify mixed precipitation events as all rain, the model output will underestimate snow cover albedo, predict a quicker runoff, underestimate the amount of snow that will need to be melted (Davison, 2004).

The rain snow temperature scheme is one of the three most important parameters for a snow model according to Kongoli and Bland, (2000), and many different schemes have been used. The most commonly used scheme is a simple step function (threshold temperatures) where all precipitation below the threshold is assumed snow and all precipitation above it is assumed rain. The temperature threshold can be based on different types of temperature. Most widespread is the use of average air temperature but other types of temperature measurements are sometimes used such as; average dew point temperature, average wet bulb temperature and maximum and/or minimum air temperatures. Unless otherwise stated the word temperature in this study refers to air temperature. Another frequently applied scheme is to use two threshold temperatures (one for snow and one for rain) with mixed precipitation between the thresholds. One of these schemes uses a gradual linear change in the snow fraction between the two thresholds, the other schemes uses a temperature dependent snow probability polynomial between the rain and snow thresholds. Finally there are various other methods based on air temperatures at and above the ground surface, weather radars and satellite pictures.

AIM AND SCOPE

The overall aim of this study is to minimize misclassified precipitation phase for improved snow accumulation and forest process modeling. This is made by first reviewing methods used to determine precipitation phase, then comparing a long series of snow/rain/mixed precipitation observations, for stations spread all over Sweden, with modeled precipitation phase using different schemes. The following precipitation phase separation schemes, all based on ground surface temperatures, were tested for all Sweden:

- One single temperature threshold based on average air temperature (ATT).
- Two air temperature thresholds (one for all snow and one for all rain) with linear increase of rain fraction with air temperature between the thresholds.
- An inverted S-shaped increase of rain fraction with air temperature between snow and air temperature thresholds.

The possible improvement by using seasonally or regionally varying surface air temperature thresholds is also investigated.

The functionality of the methods are compared by the amount of total misclassified precipitation, the correlation coefficients between and, the percentage change between predicted and observed snowfall as well as by the bias towards rain or snow overestimation. The comparisons are made both excluding and including mixed precipitation, but no correction for gauge under-catch is made.

REVIEW OF METHODS FOR PRECIPITATION PHASE SEPARATION

Air temperature thresholds ATT

An early application of the air temperature threshold (ATT) technique for separation of rain from snow is presented in *Snow Hydrology* (US Army Corps of Engineers, 1956) with the understanding that the ATT varies between locations in the span 1.1-1.7°C. This study in the Sierra Nevada Mountains also produced a linear decrease in snow probability between a rain and snow threshold (ACOE, US Army Corps of Engineers, 1956). Later, Auer, (1974) found an equal chance of rain or snow at 2.2˚C.

Today most models still use an ATT scheme (Table 1). A majority of these models seem to have a fixed ATT while others like e.g. the *CHRM and NWS snow accumulation and ablation models* have a default threshold that can be changed either for single events or be permanently adjusted (Pomeroy et al., 2007 Braun, 2000). Despite the studies listed above, an ATT of 0.0˚C is commonly used in snow accumulation models developed as late as the late 1990's (Goodison et al., 1998).

Table 1. Set threshold temperature models. Model name, reference and used threshold values.

One single air temperature threshold SF=1 for T<ATT and SF= 0 for T>= ATT	**ATT (°C)**
SWAP (Gusev, 1998), *DSPM, SNOW 17* (Reed et al, 2008)	Userdef.
BATS (Lang et al., 1997)	+2.2
DSPM (Daly et al., 2000)	+0.36
CLASS 2.7 (Bartlett, 2006), updated *SPONSOR* (Shmakin, 1998), *CHRM* (Pomeroy et al. 2007), *FASST* (Frankenstein and Koenig, 2004) *NWS SNOW ACCUMULATION, SiB* (Sellers and Mintz, 1986) ALEX (Kongoli and Bland, 2000) *ABLATION MODEL* (Anderson, 1973), colder climate (Motoyama, 1990),	±0.0
Warmer climate (Motoyama, 1990)	1 to 3
HBV Norvegian version (Sælthun, 1996)	-1 to 4
HBV-ETH Model Version 4, Mountain (Hottelet, 1994)	-0.6
HBV-ETH Model Version 4, lower terrain (Hottelet, 1994)	-0.8 and 1.0

Variations of ATT scheme

The Australian Snow Model (Schreider, 1997) and the *RMS* (Coughlin and Running, 1997) use daily maximum and minimum temperatures in an air temperature based formula for precipitation phase discrimination. It was found that the daily minimum temperature acted as a better precipitation phase indicator than the daily average temperature (Ruddell et al., 1990 and Schreider, 1997).

Variation with elevation or season for ATTs

Other studies suggest that the snow/rain air temperature threshold may be dependent on elevation or season. Lang et al., (1997) suggested a station specific rain/snow threshold while Kienzle (2008) found a seasonal oscillation trend in air threshold temperatures at many stations with a maximum temperature threshold in the summer and a minimum in the winter.

Dew point and wet bulb temperature thresholds

Some researchers have found dew point temperature thesholds (DTT) to be a better indicator of precipitation phase than ATT. Using 8 sites, which routinely sees mixed precipitation, on a mountain in Idaho with 50 m elevation intervals between sites, Marks and Winstral (2007) found that the DTT of 0.0˚C performed consistently better than an ATT. They also state that ATT's are site specific and change over time with climate needing periodic recalibration while a DTT of 0.0˚C should be more consistant. Feiccabrino and Lundberg, (2007) also found the DTT of 0.0˚C for Sweden however, the ATT had less error than DTT in this case. Still other models choose to use surface observation information other than air or dew point temperatures to separate rain from snow such as atmospheric pressure which is used to calculate wet bulb temperature (Yamazaki et al., 2007).

Two threshold schemes

To account for mixed precipitation occurring around the air temperature threshold some models use two thresholds, one for all rain (TR) and one for all snow (TS) with mixed precipitation between (Table 2 and 3). Gradual linear change in the snow fraction between the two thresholds is used in i.e. (US Army Corps of Engineers 1956) (Table 2).

Table 2. Linear transition method with a decline in snow fraction (SF) between a rain (TR) and snow threshold (TS).

Linear snow fration between two temp SF= (T-TR)/(TR-TS) and SF= 0 for T>= TS	TR (°C)	TS (°C)	ΔT (°C)	Scheme I.D.
Fuchs et al (2000)	+2	0	2	D
UEB (Tarboten and Luce, 1996), GEOTOP (Zanotti et al. 2004), (ACOE, 1956)	+3	-1	4	E
This Study	+4	-2	6	F

Table 3. Temperature dependent snow fraction curves determined for Swedish weather stations with and without mixed precipitation.

Mixed precipitation	T (°C)	Snow fraction SF =
Excluded	< 1	$-0.00002*T^6 - 0.0006*T^5 - 0.008*T^4 - 0.048*T^3 - 0.1417*T^2 - 0.1916*T + 0.8903$
	> 1	$0.00005*T^6 - 0.0018*T^5 + 0.0259*T^4 - 0.194*T^3 + 0.7868*T^2 - 1.6555*T + 1.4669$
Included	< 1	$-0.00003*T^5 - 0.0008*T^4 - 0.0088*T^3 - 0.0516*T^2 - 0.1673*T + 0.7047$
	> 1	$-0.000001*T^5 + 0.00003*T^4 - 0.0012*T^3 + 0.0277*T^2 - 0.2393*T + 0.6919$

Other models use a temperature dependent snow probability polynomial to describe the snow and rain fractions between the rain and snow thresholds. Auer's (1974) 1000 observations were used to make an inverted S-shaped snow probability polynomial. He noted that it usually doesn't rain below 0.0˚C and that snow was not observed above 6.1˚C. Two examples of models using a 6th order polynomial based on Auer's (1974) curve with a TS of 0.45˚C and a TR of 5.97˚C to calculate the snow fraction (*SF*) are the *CLASS 3.1* (Bartlett, 2006) and *WATCLASS 2.7* (Davison, 2004),

$$SF(\mathrm{T}) = 0.0202\times \mathrm{T}^6 - 0.366\times \mathrm{T}^5 + 2.0399\times \mathrm{T}^4 - 1.5089\times \mathrm{T}^3 - 15.038\times \mathrm{T}^2 + 4.664\times \mathrm{T} + 100 \quad (1)$$

Miscellaneous methods

The main complication with separating rain and snow using surface observations is that snow forms in the lower atmosphere when cloud temperatures are below freezing. As snow falls through air warmer than 0˚C, a layer of water will form on the outside of the crystal (Fassnacht, 2001). Depending on the temperature and thickness of warm layers snow could change phase to mixed precipitation or rain before reaching the ground (Davison, 2004 and Fassnacht, 2001). Models such as *MAPS* (Smirnova, 2000) and *CLM 3.0* (Vertenstein et al., 2004) attempt to identify freezing levels and the temperature characteristics of fronts by using more advanced schemes incorporating upper air data, weather radars and or satellite pictures for precipitation phase discrimination. The *Snow 17 model* in Table 1 attempts to address the issue of upper air temperatures by allowing a user defined lapse rate (Reed et al, 2008). The *CCM1* is a variation of models using 0.0˚C as a set rain/snow threshold in Table 1, stating that if the ground, 30m and 100m above ground level temperatures are all above 0.0˚C then all precipitation is rain, otherwise all precipitation is snow (Marshal et al., 1994). Fassnacht et al. (2001) used weather radar information to predict the amount of precipitation along with the Auer polynomial on surface temperature observations to correct the classification of mixed precipitation at temperatures just above freezing. They also tested the use of the radars vertical reflectivity profile (VRP) to identify precipitation as mostly snow above a mixed precipitation bright band and as mostly rain below the bright band. While weather radar covers an area rather than a point and weather balloons give valuable information, radars have problems with estimating water equivalent due to scaling problems and false returns while upper air data is normally available only twice a day with large distances between samples.

MATERIALS AND METHODS

This study uses 45 years of three hourly observations from 1961 to 2006 for 19 Swedish weather stations (Figure 1). The observations consisted of; the date/time, total precipitation for the period, average air and dew point temperatures.

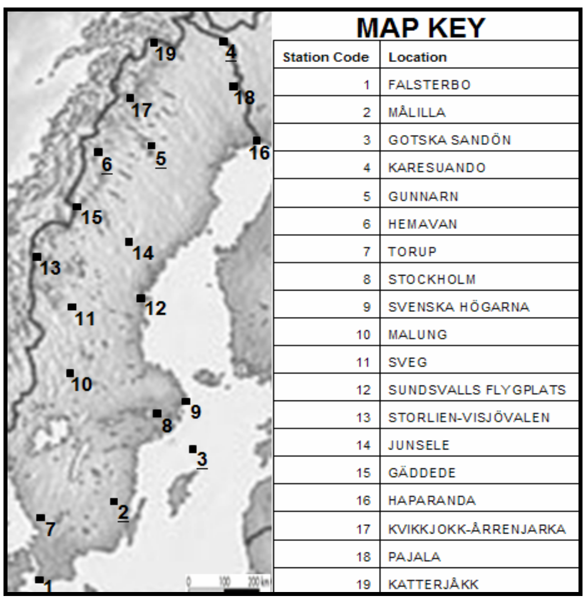

Figure 1. Map of weather stations.

Of note; freezing rain was considered solid precipitation since it freezes on contact, and ice pellets above 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 immeasurable and analysis of error was done for water equivalents.

Kongoli and Bland (2000) suggested testing precipitation phase classifying temperature schemes by the amount of misclassified water equivalent. The error (fraction misclassified

Kongoli and Bland (2000) suggested testing precipitation phase classifying temperature schemes by the amount of misclassified water equivalent. The error (fraction misclassified mass) was calculated as the sum of the snow mass (*S*) above the threshold temperature *TT* and the rain mass (*R*) at and below this threshold divided by the total snow and rain precipitation (excluding mixed precipitation)

$$\text{ERROR} = \frac{S > (TT) + R \leq (TT)}{PREC_{rain+snow}} . \qquad (2)$$

An initial test, neglecting mixed precipitation, to see if air or dew point temperature is better for identifying precipitation phase was done for the same stations as used in this study (Feiccabrino and Lundberg, 2007). All the precipitation observations for the entire country were pooled together, as in Daly et al. (2000) to determine one air temperature threshold (ATT) and one dew point temperature threshold (DTT). This calculation was done for every 0.1°C. Precipitation at the rain/snow threshold was ignored. The optimized thresholds for air temperature and dew point temperatures were found to be 1.0°C and 0.0˚C respectively The optimized air temperature threshold gave less misclassified precipitation (1.8%) than the optimized dew point temperature threshold (2.6%) (Feiccabrino and Lundberg, 2007).

In this study mixed precipitation events are included (assumed to be 50% rain and 50% snow). Precipitation at the threshold is considered all snow and $PREC_{rain+snow}$ is replaced by $PREC_{total}$ when mixed precipitation is considered in all equations. Three different step functions based on average surface air temperature (ATT) are tested:

scheme A) ATT = 0°C (commonly used in many models)
scheme B) ATT = 1°C (optimized value for all Sweden)
scheme C) ATT = XX-YY °C (optimized value for each location)

In addition four schemes including mixed precipitation were used. These schemes used two thresholds for surface air temperature, one for all snow (TS) and one for all rain (TR). In the schemes D), E) and F) the snow faction decreased linearly with air temperature between the two threshold temperatures and for all these three schemes 50% of the precipitation was assumed to be snow at 1°C (Table 2 and Figure 3a). The temperature range ΔT between the two thresholds however varied from 2C° to 6°C. While schemes D) and E) have been used in other models (Table 2), they did not have a large enough range to cover the temperatures where 2% or more of the total mixed precipitation occurs in Sweden, scheme F) is included in this study to cover this range.

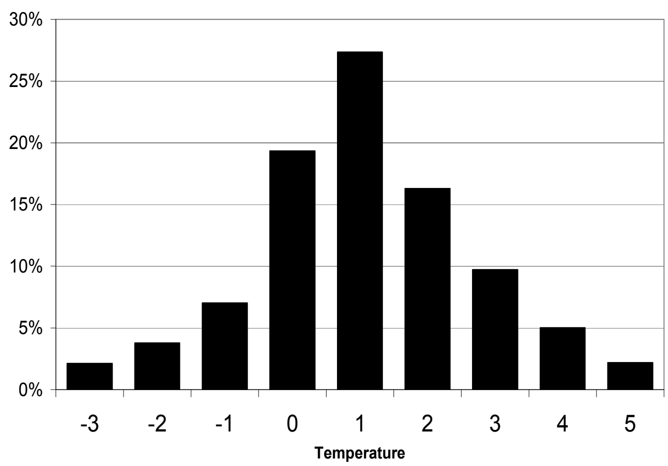

Figure 2. Percent mixed precipitation at transition temperatures for the 19 Swedish weather stations combined.

The mixed precipitation in Sweden accounts for 16% of total precipitation mostly occurring between the temperatures of -2˚C and 4˚C with a maximum at 1˚C (Feiccabrino and Lundberg, 2007). The mixed precipitation has a bell shaped curve when all stations are taken together (Figure 2) but this is not true for individual stations which have their own unique precipitation phase distributions (Figure 4).

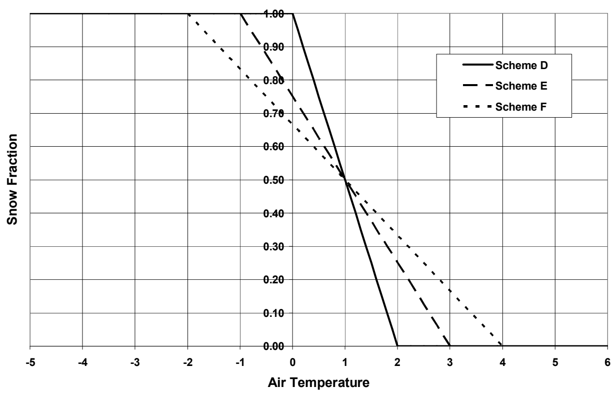

Figure 3a. Linear transition lines D, E and F.

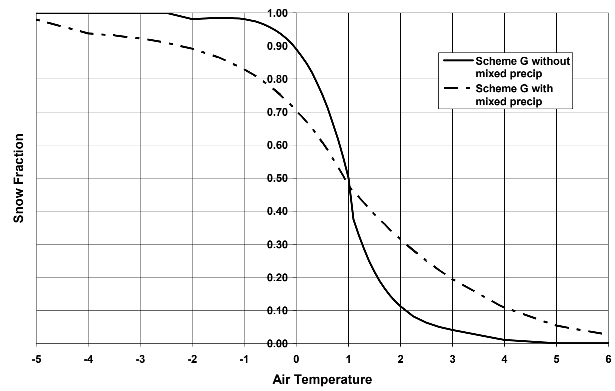

Figure 3b. Temperature dependent snow fraction curves.

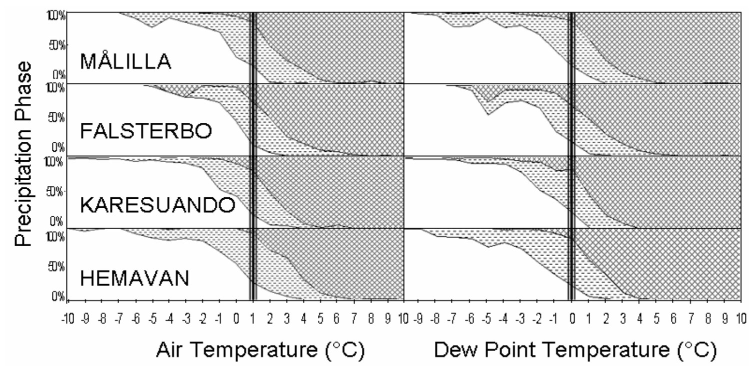

Figure 4. Precipitation phase percentage curves by temperature for four stations white is snow dark grey is rain and between is mixed precipitation.

To describe the inverted S-shaped temperature dependent snow probability curve with and without mixed precipitation for all of Sweden (Figure 3b and 4), the last scheme (scheme G) uses four temperature dependent snow probability polynomials. One polynomial above and one polynomial below the Swedish threshold temperature described the temperature precipitation phase relationship with and without mixed precipitation (Table 3). The TS and TR values were set to temperatures where the curves with and without mixed precipitation have a maximum percentage of snow in negative temperatures and a minimum value for snow in positive temperatures. The TS values were -2.0°C and 4.0°C while TR values of -4.2°C and 7.0°C were used without and with mixed precipitation respectively. If values for SF were above 100% or below 0% they would be replaced with 100% or 0%. Due to the shape of the curves

The possible latitude dependency or improvement of ATT through predictable monthly changes in a single threshold temperature scheme was also tested.

The performance of each scheme was judged by the

i) percent of total misclassified precipitation (Equation 2),
ii) correlation coefficient between observed snow fraction and snow fraction determined by the scheme for the temperatures where the phase change of precipitation is most prevalent (-3.0°C to 6.0°C)
iii) percent change from the expected percentage of snowfall (Equation 3) and bias towards rain or snow errors which would result in overclassification of one precipitation type (Equations 4 and 5).

Each snow scheme was first analyzed without mixed precipitation, a second analysis was done using the mixed precipitation as half rain and half snow.

Snowfall Change = $\frac{S_{scheme} - S_{obs}}{S_{obs}}$. (3)

Rain Error = $\frac{\sum S_{scheme}(T) - S_{obs}(T) \text{ for } S_{obs} < S_{scheme}}{PREC_{rain+snow}}$. (4)

Snow Error = $\frac{\sum S_{obs}(T) - S_{scheme}(T) \text{ for } S_{obs} > S_{scheme}}{PREC_{rain+snow}}$ (5)

where S_{scheme} is the temperature dependent snow fraction predicted by a given rain snow separation relationship, and S_{obs} is the total amount of snow from the station observations where (T) is in 0.1°C increments.

Finally the threshold temperatures were compared to station elevation and latitude, dew point temperatures and percent of precipitation falling as snow and mixed precipitation to see if there is any noticeable relationship due to geographic location.

RESULTS

ATT vs DTT: The rain/snow ATT determined without and with mixed precipitation is 1.0˚C with 2.4% and 9.8% misclassified precipitation respectively. The DTT without mixed precipitation is 0.1˚C with 3.0% misclassified precipitation. Individual station threshold temperatures compared to the threshold temperature of 1.0˚C using equation 1, yield a maximum decrease in misclassified precipitation of 0.34% and 0.29% at station 2, with no difference at nine stations both without and with mixed precipitation respectively. The overall average error improved when using individual station threshold temperatures rather than a set threshold of 1.0˚C without and with mixed precipitation from 2.4% to 2.3% and 9.9% to 9.8%. There was a 0.19% and 0.17% average error correction without and with mixed precipitation respectively at the ten stations with threshold temperatures different than 1.0˚C.

Precipitation Error Comparisons: When comparing the error from scheme G for observations without mixed precipitation to the errors from scheme C and the lowest error from schemes D,E and F for each station, scheme G performed best at all stations (Figures 5 and 6a)(Table 4). ATT's had the most error at 18 of the 19 stations, outperforming schemes D,E and F at station 19.

Table 4. The percent misclassified precipitation, correlation coefficients, and change in snowfall (Δ Snow) with and without mixed precipitation (MP) for the different phase separation schemes a) to g) compared to weather station raw data. Bold numbers indicate optimum values.

Threshold temperatures (°C)	Misclassified Precipitation (%)				Correlation Coefficient				Δ Snow (%)	
	Without MP	#	With MP	#	Without MP	#	With MP	#	Without MP	With MP
A) ATT = 0	4.1	0	11	0	0.87	0	0.88	0	-13	-24
B) ATT = 1	2.4	0	9.9	0	0.95	0	0.94	0	1.3	2.6
C) ATT = XX-YY 1)	2.3	0	9.8	0	0.95	0	0.94	0	0.20	0.90
D) TS = 0; TR= + 2	1.8	0	6.7	0	0.99	0	0.98	5	**0.00**	**-0.38**
E) TS = - 1; TR= + 3	2.3	0	4.5	2	0.98	1	**0.99**	**10**	-0.21	-1.2
F) TS = - 2; TR= + 4	3.5	0	3.5	3	0.96	1	0.98	0	0.70	-0.61
G) TS = -2.0/-4.0; TR = 4.2/7.0 2)	**1.2**	**19**	**3.2**	**14**	**0.99**	**17**	0.99	4	0.34	1.1

\# Number of stations with optimized values for each scheme. 1) Optimized value for each station. 2) TS and TR without/with mixed precipitation

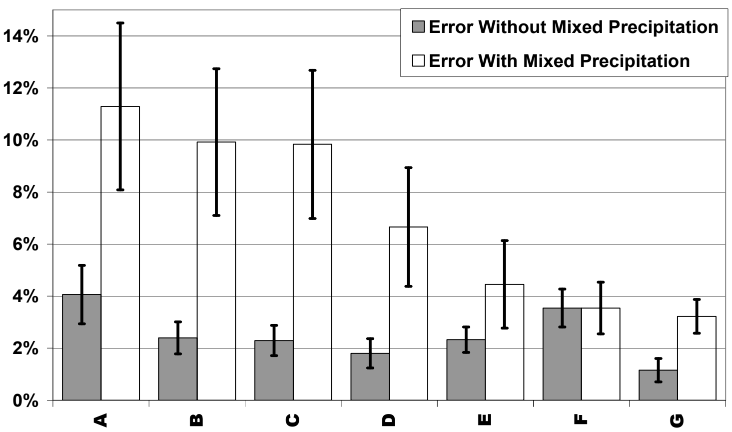

Figure 5. Percent misclassified precipitation for each separation scheme.

When mixed precipitation observations are included scheme G is again compared to scheme C and the best of schemes D,E and F for each station (Figures 5 and 6b)(Table 4). Scheme G outperforms all other schemes at 14 of the 19 weather stations. The single temperature threshold lines have the highest error at all 19 stations, while schemes E and F have the lowest error at 5 stations.

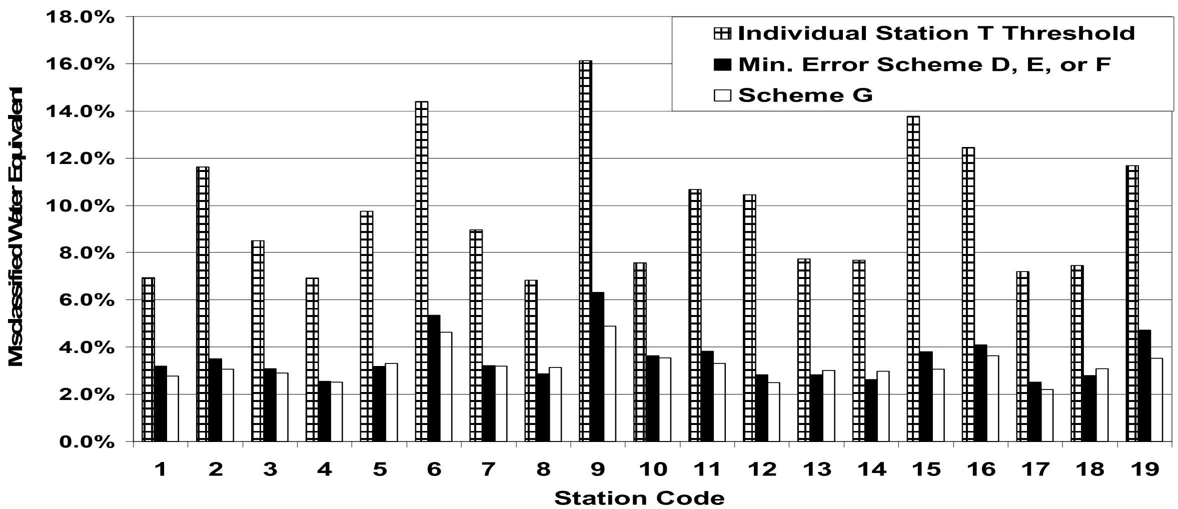

Figure 6a: Percent misclassified water equivalent for each station without mixed precipitation observations.

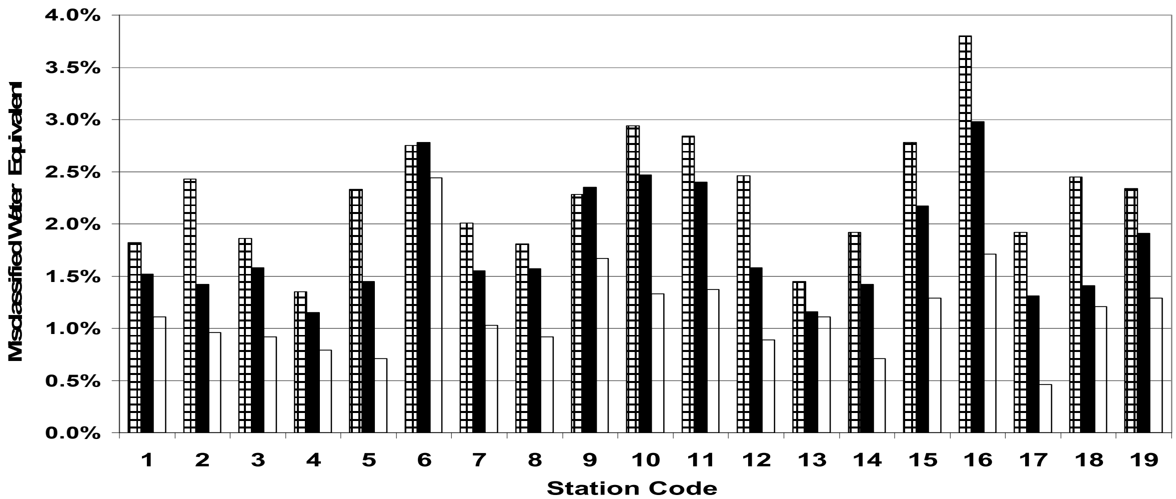

Figure 6b: Percent misclassified water equivalent for each station with mixed precipitation observations.

When the percentages of erroneous precipitation are compared for the 19 Swedish stations using equation 2 for zero degrees, a Swedish threshold of 1.0˚C and individual station thresholds, it is noticeable that for every station there is less error at 1.0˚C than at 0.0˚C with and without mixed precipitation.

The temperature range for the transition from all rain to all snow is important for the percentage error found using lines with two thresholds. When mixed precipitation is included the transition range from all snow to all rain is larger. When comparing the schemes from Table 2, scheme D has the least error when mixed precipitation is ignored (Figures 3a and 5), while scheme F is favored when mixed precipitation is included (Figures 3a and 5). Without mixed precipitation, scheme F has the worst performance, while with mixed precipitation scheme D performed worst at all stations.

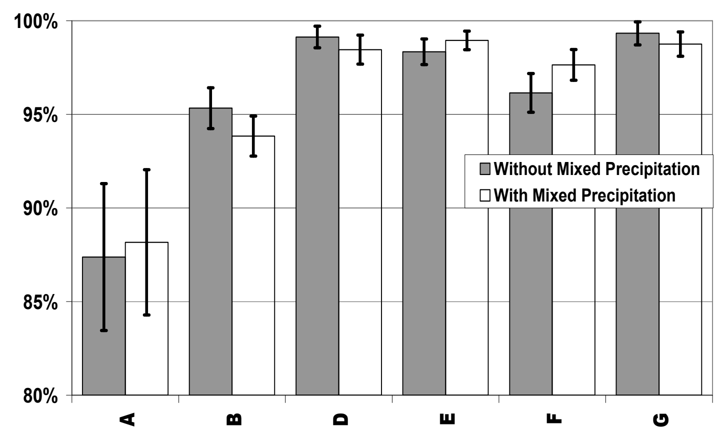

Figure 7. Correlation coefficients and standard deviations for line schemes to reported precipitation at the 19 Swedish weather stations.

Correlation Coefficient comparisons (all lines): The average correlation coefficients and standard deviations for the 19 Swedish stations with different temperature precipitation phase relationship schemes are compared in Figure 7. The highest correlation coefficient values for the schemes did not always match the lowest error results (Table 4). The standard deviations for many of the correlation coefficients for the schemes overlap into three groups in which they are statistically indifferent. Without mixed precipitation the three groups in order from highest correlation coefficients are;1. schemes D,E and G, 2. schemes B,C and F, 3. scheme A. With mixed precipitation the groups are similar with the only change being that scheme F moves from the second to the highest correlation coefficient group. At all weather stations the highest correlation coefficient from schemes D,E and F are greater than the highest correlation coefficient from ATT's. Also for all stations with and without mixed precipitation, scheme A had the lowest correlation coefficient of all schemes.

At 17 of 19 stations, scheme G has the highest correlation coefficient without mixed precipitation but, with mixed precipitation scheme G is highest for only four stations. With mixed precipitation, the linear transition lines have the highest correlation coefficient of all lines at 15 stations 5 with scheme D and 10 stations with scheme E. With mixed precipitation, Scheme F was better for 17 of 19 stations when comparing errors between the linear transition lines however, scheme F has the highest correlation coefficient for no stations.

Snow percentage change: When comparing the percentage of change in snow accumulations to the data from each station it is clear that there is no line that performs better at all locations, as the standard deviations for all lines overlap. With scheme A the amount of snow is always underestimated, while for all other lines the change from observed snowfall to predicted snowfall can be positive or negative.

Without mixed precipitation, the ATT at zero degrees has the largest change in relative snow precipitation for all stations with a maximum change of -30% at station 1. The station threshold has the lowest change of all schemes at one station, while 1.0˚C has the lowest change of all schemes at 5 stations. Without mixed precipitation, 11 of 19 stations have there lowest change in snow percentage using the linear transition lines, 3 are with scheme D, one is with scheme E and 7 are with scheme F. 2 stations have their lowest change in snow with scheme G.

With mixed precipitation the largest change for all stations came with ATT's, 3 stations, at the station threshold, while the other 16 were with zero degrees. 14 stations had their lowest change in percentage of snow with linear transition lines. Of these stations, 3 were with scheme D, station 2 was with scheme E, and the other 10 were with scheme F. This left five stations (one tied with scheme F), with the lowest percentage snow change using scheme G.

Rain or snow misidentified: There is little difference with the total percentage of misidentified snow and rain between the different temperature precipitation relation schemes. The only scheme with a large difference is scheme A with an ATT of zero degrees. In this case there is more misidentified snow than rain. Again most of the standard deviation error bars overlap for the different schemes.

Threshold with geography: There does not appear to be a relationship between threshold temperature and any of precipitation percentage of snow, latitude, or elevation with R^2 values of 0.25, 0.12 and 0.05 respectively. There was also a poor relation between elevation and percentage snowfall. The relations between dew point threshold temperature with percent of total precipitation snowfall, latitude and elevation had R^2 values lower than air temperature. There was also no pattern found for percentage of precipitation being mixed with elevation or latitude.

Seasonal variation: Adjusting a single threshold temperature by month rather than a single threshold temperature for the year is not possible on the country scale for Sweden. Table 5 shows that in all cases, except June when including the mixed precipitation, the average change in monthly threshold is smaller than the standard deviation making the change statistically insignificant. There were some stations that experienced snow in July and August, however for the data in Table 5 if there were not at least 12 rain and 12 snow events in a month over the 45 years the locations data for that month was ignored. However if the monthly threshold change is looked at on the individual location scale it results in an average decrease in error of 0.34% and 0.33% with a standard deviation of 0.21% and 0.17% having a maximum correction of 1.0% and 0.83% at station 6 without and with mixed precipitation respectively.

Table 5 Average threshold temperature change by month for with and without mixed precipitation.

Mixed prec.	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

Number of stations

DISCUSSION

ATT vs DTT: In Feiccabrino and Lundberg (2007) the air temperature threshold was found to be 1.0˚C with 1.8% misclassified precipitation, however in this report 2.4% misclassification was found due to the formula in this paper including precipitation at the threshold temperature as all snow where the earlier study ignored precipitation at the threshold. The air temperature threshold (ATT) of 1.0˚C without mixed precipitation was found to have 27% less misclassified precipitation than the dew point threshold (DTT) of 0.1˚C. ATT had less misclassified precipitation than DTT with and without mixed precipitation at all 19 observation stations, spanning from mountain areas to islands, from Southern (55˚N) to Northern (68˚N) Sweden. ATT = 1.0˚C without mixed precipitation had comparatively 45% less misclassified precipitation than the often used ATT = 0.0˚C. An ATT = 1.0˚C is slightly lower than the ACOE (1956) suggested range of values however, it is the same ATT used in Iceland (Aoalgeirsdottir et al. 2006). When mixed precipitation is included as ½ rain and ½ snow all errors increase and the difference between 1.0˚C and individual station threshold temperatures decreases slightly.

Error comparisons: The correct classification of precipitation state is a key to precipitation-runoff modelling (Braun, 1991). Single day precipitation events near the rain/snow threshold are sometimes modelled differently because of different parameterization schemes for snow percentage (Hayhoe et al., 2006) Kongoli and Bland (2000) state that the best temperature scheme results from the lowest misclassified water equivalent. With this in mind the overall lowest average error in precipitation classification for water equivalent with or without mixed precipitation comes with using climatologically based temperature dependent snow probability polynomials. The second best schemes were the linear transition lines. With the linear transition scheme D (thinnest linear transition line) working best when mixed precipitation is ignored, while scheme F (widest linear transition line) has less error when mixed precipitation observations are included. This is due to a larger range of temperatures involved in the phase transition from snow to rain when mixed precipitation is included. Of all the rain/snow classification techniques ATT's performed the worst. Daly et al. (2000) blamed the simple approach of a set threshold temperature for weakness in the results of his study, allowing the model to predict lower than observed SWE and a systematic increase of error over time. The worst overall error performance for all stations with and without mixed precipitation occurred with an ATT of zero degrees.

Scheme G has the lowest overall error at all 19 weather stations when mixed precipitation observations are ignored. However, this is only true for 14 of 19 stations when mixed precipitation is included. At the other 5 stations scheme F has less error when mixed precipitation is included. The relationship between temperature and snow fraction is S shaped (Figure 4) at all stations in this study. Therefore, linear transition lines should have more error then climatologically based temperature dependent snow probability polynomials if calculated for individual stations. However, location specific polynomials are most likely too specialized and expensive for most model needs. There was also little found to relate the shape of the polynomial with latitude or elevation making it more difficult to assign different premade polynomials according to station location.

ATT threshold variation: The lack of correlation between individual station thresholds to elevation and latitude came as no surprise, as Daly et al. (2000) also failed to find one. However, the lack of a seasonal dependent change in threshold was unexpected. As other studies i.e.

Kongoli and Bland (2000) claim that the temperature threshold is often climate, location, and season dependent. While Roher and Braun, (1994) claim that the frequency of rain snow and mixed precipitation may depend on the season and type of data used. Even when the ATT for individual stations was changed by month the overall error was still higher than using a linear transition line.

Correlation coefficients, snow %, error rain and snow: Sticking with the idea that the temperature scheme with the lowest error is best, other tests such as correlation coefficient, change in the annual snowfall percentage, and a measure of the balance between rain and snow errors act as secondary tests. For the correlation coefficients, the overall results support the results from the misclassified precipitation, but are a bit more indifferent in which scheme performs best. The results for the change in percent snow do not support or argue against the results from the error tests. Instead they indicate that for the purposes of climate studies needing total snowfall for a station any of the schemes besides the ATT zero degrees can work best depending on the station. Finally in the comparison of percent rain and snow all schemes were closely balanced between rain and snow error, while the ATT of zero degrees was the exception missing more snow than rain. Most of these tests were indifferent between the schemes used at a regional scale giving no reason to question the results from the error tests. However, most of the precipitation missed when using an ATT of zero degrees is in the form of snow above the snow fraction line which would result in delayed runoff (Davison, 2004) and more sublimation in tree canopees (Lundberg et al., 2004).

Assumption that 50% snow 50% rain of mixed Precipitation: Mixed precipitation appears evenly distributed with a maximum volume at 1˚C, the same temperature as the found ATT which could be expected. Unfortunately, this does not excuse the exclusion of mixed precipitation as a source of error in the determination of a rain/snow threshold. A sharp transition from rain to snow oversimplifies the importance of the 16% of mixed precipitation in this study. Also, the approach of considering mixed precipitation as ½ rain and ½ snow is too simple and will add to error in the calculations. In a similar situation where mixed precipitation was prevalent between 0˚C and 1.1˚C radar found a transition from snow to rain dominance in terms of volume fraction at 0.5˚C (Yuter et al., 2004). This indicates that the errors should balance out on both sides of the threshold.

Precipitation phase temporal change: The precipitation phase usually changes over a short time period, this was a source of error pointed out by Kongoli and Bland (2000), 16% mixed precipitation is higher than expected. A higher temporal resolution such as that produced by automated weather stations could reduce the amount of mixed precipitation. However, when a station is first changed from manned to automated, caution should be taken if changes in the precipitation thresholds or amounts occur (Roher and Braun, 1994) i.e. Switzerland had a change in the rain/snow threshold of 1.0˚C (Braun, 1991). This might be avoided by using results of a rain/snow threshold study in the automated programing.

Gauge under catch: No correction for gauge undercatch of precipitation due to wind errors was performed. These errors can range from 2-14% for rain and from 5-80% for snow (Kokkonen et al. 2006). The wind errors for rain and snow are usually similar around the threshold since wet snow approaches the density of rain at these temperatures. Thus, snow missing the gauge will affect the total amount of snow in model output more than it will affect the rain/snow threshold.

Compensating errors in models: Improving the way a model determines the phase of precipitation may actually make a model perform worse, this is because runoff models are normally calibrated solely against runoff. This leaves plenty of room for compensating errors. An erroneous description of the rain/snow separation producing too small snow accumulation can e.g. be compensated by neglecting sublimation due to snowdrift or by neglecting snow sublimation in the tree crowns. It can also be compensating for a poor description of the temperature laps rate within the basin. This might lead to a situation where a model is improved by a better description of the precipitation phase. However, the resulting runoff might deteriorate since other processes are neglected.

CONCLUSION

An ATT of 1.0˚C performs much better than a DTT of 0.1˚C. With only 0.1% difference in misclassified precipitation between an ATT of 1.0˚C and ATTs calculated at individual stations, 1.0˚C performs well as an ATT for Sweden. When using a set ATT you are accepting a certain amount of error that comes with the S shaped temperature snow fraction relationship. The S shaped relationship is why a temperature based snow probability curve has the least error in precipitation identification between the three common model methods using an ATT, a linear transition line and a climatologically based temperature dependent snow probability polynomial. Surprisingly the linear transition lines have similar results, with only slightly more error than polynomials based on climatology. However, the amount of error from the polynomial and linear transition lines are closely tied to the phase transition temperature range for a station and the range covered by the snow fraction line. This indicates some importance in accounting for station specific trends. Still, if the temperature scheme in a model is made more accurate, the model performance will need to be checked to account for compensating errors.

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