Reducing misclassified precipitation phase in conceptual models using cloud base heights and relative humidity to adjust air temperature thresholds

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ABSTRACT

In cold region, conceptual models assigned precipitation phase, liquid (rain) or solid (snow), cause vastly different atmospheric, hydrological, and ecological responses, along with significant differences in evaporation, runoff, and infiltration fates for measured precipitation mass. A set air temperature threshold (ATT) applied to the over 30% annual precipitation events occurring with surface air temperatures between −3 and 5 °C resulted in 11.0 and 9.8% misclassified precipitation in Norway and Sweden, respectively. Surface air temperatures do not account for atmospheric properties causing precipitation phase changes as snow falls toward the ground. However, cloud base height and relative humidity (RH) measured from the surface can adjust ATT for expected hydrometeor-atmosphere interactions. Applying calibrated cloud base height ATTs or a linear RH function for Norway (Sweden) reduced misclassified precipitation by 4.3% (2.8%) and 14.6% (8.9%) misclassified precipitation, respectively. Cloud base height ATTs had lower miss-rates with low cloud bases, 100 m in Norway and 300 m in Sweden. Combining the RH method with cloud base ATT in low cloud conditions resulted in 16.1 and 10.8% reduction in misclassified precipitation in Norway and Sweden, respectively. Therefore, the conceptual model output should improve through the addition of available surface data without coupling to an atmospheric model.

Key words | conceptual models, hydrological model, LSM, precipitation phase, snow

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HIGHLIGHTS

- This paper lays out two new methods to decrease misclassified precipitation in conceptual surface-based models using air temperature thresholds (ATTs) to distinguish between rain and snow, common in hydrological modeling.
- The cloud base height method has not been written about in scientific publications and gives another simple solution to help reduce misclassified precipitation phase in surface-based models.
- The linear relative humidity ATT formula suggested in this paper simplifies earlier attempts to include relative humidity in surface-based precipitation phase determination.
- The information needed for both methods is widely available in surface meteorological reports and improves surface-based models without coupling to an atmospheric model for precipitation phase.

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- In this paper, misclassified precipitation between −3 and 5 °C was reduced by 4.3% (2.8%) using cloud base height ATTs, 14.6% (8.9%) using a linear relative humidity formula, and 16.1% (10.8%) using a combination of both methods in Norway (Sweden), showing great potential for reducing model uncertainties when applying this work.

INTRODUCTION

The fate of precipitation impacting the ground is very different between liquid (rain) and solid (snow) (Jennings *et al.* 2018). This uncertainty makes precipitation phase one of the three most essential parameters in cold region hydrological models (Kongoli & Bland 2000). Areas such as the US Pacific North-West are reliant on mountain snowmelt for drinking water, agriculture, and recreation (Vano *et al.* 2010) to supplement water supplies in the drier summer months. A projected 30% decrease in winter-time snow-dominated areas in the Western United States, coinciding with a 2-month reduction in annual snowfall duration by the mid-21st century will change the timing of, and decrease snowmelt water contributions (Klos *et al.* 2014). Therefore, the accuracy of a precipitation phase determination scheme (PPDS) in a model is essential in both short-term (e.g., rain on snow flood forecasting), and long-term (e.g., magnitude and duration of summer baseflow levels) water resource forecasting (Harpold *et al.* 2017b).

Despite criticism of being too simple (Daly *et al.* 2000; Harpold *et al.* 2017a), a set air temperature threshold (ATT) is often used for the PPDS in hydrological models. These PPDS play a crucial role in water resource management and safety decisions. An advantage of using ATT is that it is a widely available parameter. However, it does not take into account the properties of the atmosphere. These properties drive sensible and latent energy exchanges (microphysics) between hydrometeors and the air they fall through.

In general, depending on air temperature, humidity, and the depth of a warmer than freezing layer, sensible and latent heat exchanges between snow and the atmosphere can cause phase change from dry snow to wet snow to slush to rain (Fassnacht *et al.* 2001; Thériault & Stewart 2010). The equations describing microphysics are calculation intensive. They require detailed information, including initial hydrometeor phase (Harder & Pomeroy 2013), atmospheric properties through which the hydrometeors fall, and hydrometeor shape and size (Harder & Pomeroy 2013). Stewart (1992) had a relatively simple microphysics solution using five equations which approximated: (1) heat exchange resulting from phase change (sublimation 2594 j/G, evaporation 2260 j/G, melting 334 j/G which cool the atmosphere, and condensation 2260 j/G, ice condensation 2594 j/G, and freezing 334 j/G which warm the atmosphere), (2) condensation adding mass to hydrometeors, (3) latent heat flux resulting from condensation, (4) heat exchange due to collision coalescence or accretion of ice and liquid, and (5) latent heat of fusion resulting from melting and freezing when particles contact each other. More complexed microphysical schemes are found in, e.g., Lundquist *et al.* (2008) and Thériault & Stewart (2010). The atmospheric information required for even simple microphysics schemes cannot be recreated from surface data alone. Therefore, attempts to account for microphysics in surface-based hydrological models are seldom attempted.

Cloud base height can be used to adjust ATT for microphysics, even if the required atmospheric measurements to calculate a simple microphysics scheme are not available. In clouds, evaporation and sublimation can be considered non-factors. This is due to the high vapor densities surrounding the hydrometeors (Harder & Pomeroy 2013). Below the cloud level, lower vapor density around hydrometeors will increase evaporation and sublimation (Harder & Pomeroy 2013). This increased latent heat flux will help cool the air and decrease the potential sensible heat flux (or melt energy) and, therefore, explains some theory on why cloud base height values should affect optimal ATTs.

Taking this a step further, lower relative humidity (RH) measured at the surface could indicate a drier environment. Precipitation formation through the Bergeron process can favor ice condensation (snow) over liquid (rain) due to the vapor pressure over ice being less than vapor pressure over water. This leads to more initial snow phase in cold clouds, especially when the air is saturated for ice formation but unsaturated for rain. In a drier environment, latent heat fluxes are more significant than in moist environments allowing evaporation and sublimation heat exchanges to cool the atmosphere. These heat exchanges can offset some melt.

To account for the likelihood of latent heat exchanges, some models use dew point temperature (e.g., Marks *et al.* 2013) or wet-bulb (WB) temperature (e.g., Matsuo *et al.* 1981) in their PPDS. Other models use complexed RH formulas to adjust the ATT assigned for each weather observation (e.g., Matsuo *et al.* 1981; Gjertsen & Ødegaard 2005; Harder & Pomeroy 2013).

Harpold *et al.* (2017a) is one of the latest papers to repeat the call for improved PPDS in hydrological models. Their article called for the improvement of conceptual hydrological models through (1) incorporating new techniques for PPDS, (2) better understanding and quantification of regional variabilities (e.g., ATT adjusted for physiographic classification; Feiccabrino & Grigg 2017), and (3) continued communication to the modeling community addressing the need for accurate PPDS in cold regions. In this paper, one and three above are addressed through (1) developing a new method to improve PPDS when adjusting ATT for reported cloud base height and (2) using measured RH to modify ATT for each weather observation or event.

Here, a linear ATT formula adjusted by RH values, and calibrated ATT values for cloud base height are compared with a set ATT. This comparison was made to determine: (1) Can cloud base height or a linear RH formula improve PPDS? (2) Under what conditions should a linear RH formula or cloud base height ATT be used to strengthen a PPDS? and (3) If RH is not reported, can cloud base height be used as a proxy for RH in precipitation phase determination?

STUDY AREA

84 Norwegian and 85 Swedish meteorological stations were categorized into physiographic groups of ocean, coast, fjord, rolling, hill, and mountain (Table 1). This subclassification of stations within country datasets was to indicate more homogeneous ocean and terrain affects (see Feiccabrino *et al.* 2015) acting on stations within a physiographic group. Further details on station names, GIS classification, station sample sizes for the full 1,002,770 observation dataset, and information about the meteorological data are given in Grigg *et al.* (2020).

Table 1 | Physiographic classification (Feiccabrino & Grigg 2017) using the area within a 15 km radius of each weather station with a total number of stations in each category for Norway and Sweden

1st step % land	2nd step maximum–minimum elevation	Classification	# in Norway	# in Sweden
$X < 10\%$	N/A	Ocean	16	1
$10\% \le X < 60\%$		Coast	12	20
$60\% \le X < 90\%$		Fjord (inlet)	21	7
$90\% \le X$	0–499 m	Rolling	7	36
	500–999 m	Hill	13	4
	1,000–1,500 m	Mountain	14	3

Similar to many studies (e.g., Kane & Stuefer 2015), the number of high elevation stations is limited; however, there are still 14 mountain stations in Norway, and 3 in Sweden. The Swedish sites, dominated by rolling and coastal physiographic groups, have only one ocean station reporting the parameters used in this study. As in previous studies (e.g. Kane & Stuefer 2015), these underrepresented physiographic groups are included in the analysis for the importance of high elevation data despite their low sample size.

METHOD

In this study, only meteorological observations reporting current precipitation were analyzed.

Initial processing of datasets consisted of first removing all observations containing a WMO weather code that did not identify precipitation presently occurring. Next, all observations, with air temperatures cooler than −3 °C and warmer than 5 °C, were removed from the datasets. This was due to 0.12 and 0.30% precipitation classified as rain, mixed, or frozen occurring at temperatures cooler than −3 °C, while 0.20 and 0.36% snow, mixed, or frozen precipitation occurred in air temperatures warmer than 5 °C in Norway and Sweden, respectively.

Mixed precipitation observations were then removed from the −3 to 5 °C datasets. This is due to (1) a lack of information on the proportion of rain to snow in mixed observations (e.g. Jennings *et al.* 2018), (2) a previous study in Sweden (Feiccabrino *et al.* 2013) found a Gaussian distribution of mixed precipitation centered on the ATT, and (3) discarding mixed precipitation observations is a common practice in precipitation phase threshold studies (Bartlett *et al.* 2006). The removed, mixed precipitation accounted for 3,022 (1.6%) and 4,374 (2.7%) of the Norwegian and Swedish observations, respectively.

Freezing rain observations were then removed from the datasets. This is due to both (1) freezing rain classification being dependent on the intended use of a model as it can be characterized as liquid if required for energy balance, or solid if trying to calculate immediate runoff, and (2) there were limited occurrences of freezing rain, 246 (0.1%) and 1,435 (0.9%) in Norway and Sweden, respectively.

In the next step, 14 Swedish stations were removed entirely from the analysis for not reporting cloud base height. For the remaining 84 Norwegian and 71 Swedish stations (Figure 1), observations not reporting a cloud base height, 21,951 (11.8%) and 77,422 (47.5%) Norwegian and Swedish observations, respectively, were separated from the primary datasets.

Next, all observations, with cloud base height above 1,000 m reporting category, were separated from the primary datasets. This was for two reasons: (1) precipitation falling through an unsaturated layer over 1,500 m thick is relatively uncommon, 1,854 (1.0%) and 6,105 (3.7%) of Norwegian and Swedish observations, respectively, and (2) a prior study (Feiccabrino 2016) along with these datasets indicate that cloud base heights above 1.5 km do not have a strong influence on optimal ATT values.

The final step in preparing the primary datasets was separating all observations not reporting RH, 7,703 (4.2%) and 2,578 (1.6%) for Norway and Sweden, respectively. Finally, datasets of 150,528 (81.2%) and 71,117 (43.6%) Norwegian and Swedish precipitation observations between −3 and 5 °C were used to directly compare the calibrated cloud base height ATTs to RH adjusted ATTs. The country datasets were kept intact (a common practice in similar studies, e.g., Dai 2008; Klos *et al.* 2014; Jennings *et al.* 2018), allowing a 16-year calibration period with a sufficient sample size (n) to further separate into cloud height, RH, and physiographic bins. A longer dataset with a greater n should increase the robustness of the results by including as much climate variability as possible. However, keeping one long dataset comes at the expense of separating independent validation dataset/s to verify results.

Final datasets for direct comparison were then separated by the reported cloud base height categories of 0 m (0–49 m), 50 m (50–99 m), 100 m (100–199 m), 200 m (200–299 m), 300 m (300–599 m), 600 m (600–999 m), and 1,000 m (1,000–1,499 m). Sweden did not report a 0 m cloud base level, while both Norway and Sweden had their maximum number of observations occur with a cloud base height of 300 m.

For each dataset in Norway and Sweden, air temperatures between −3 and 5 °C at a 0.1 °C interval were tested to determine an ATT. Here, ATTs are the temperature resulting in the lowest misclassified precipitation event percentage for a station or lowest average misclassified precipitation for a group of stations being tested. In this study, a misclassified precipitation event is an observation that has either: (1) snow predicted in air temperatures cooler or equal to the ATT when the observation reported rain or (2) rain predicted in air temperatures warmer than the ATT when the observation reported snow.

Next, cloud base height ATTs were tested as an indicator of RH or if they perform better than a linear RH based ATT formula (T_{RH}). T_{RH} (Equation (1)) from Feiccabrino *et al.* (2015) and Harpold *et al.* (2017a) was calculated for each observation. This T_{RH} equation is based on studies by Matsuo *et al.* (1981), Gjertsen & Ødegaard (2005), and Harder & Pomeroy (2013).

$$T_{RH} = 0.75 + 0.085 * (100 - RH) \quad (1)$$

The sum of misclassified precipitation for a PPDS using cloud base height ATTs, or T_{RH}, is compared with the sum of misclassified precipitation from a PPDS using country thresholds 1.2 and 0.9 °C for Norway and Sweden, respectively.

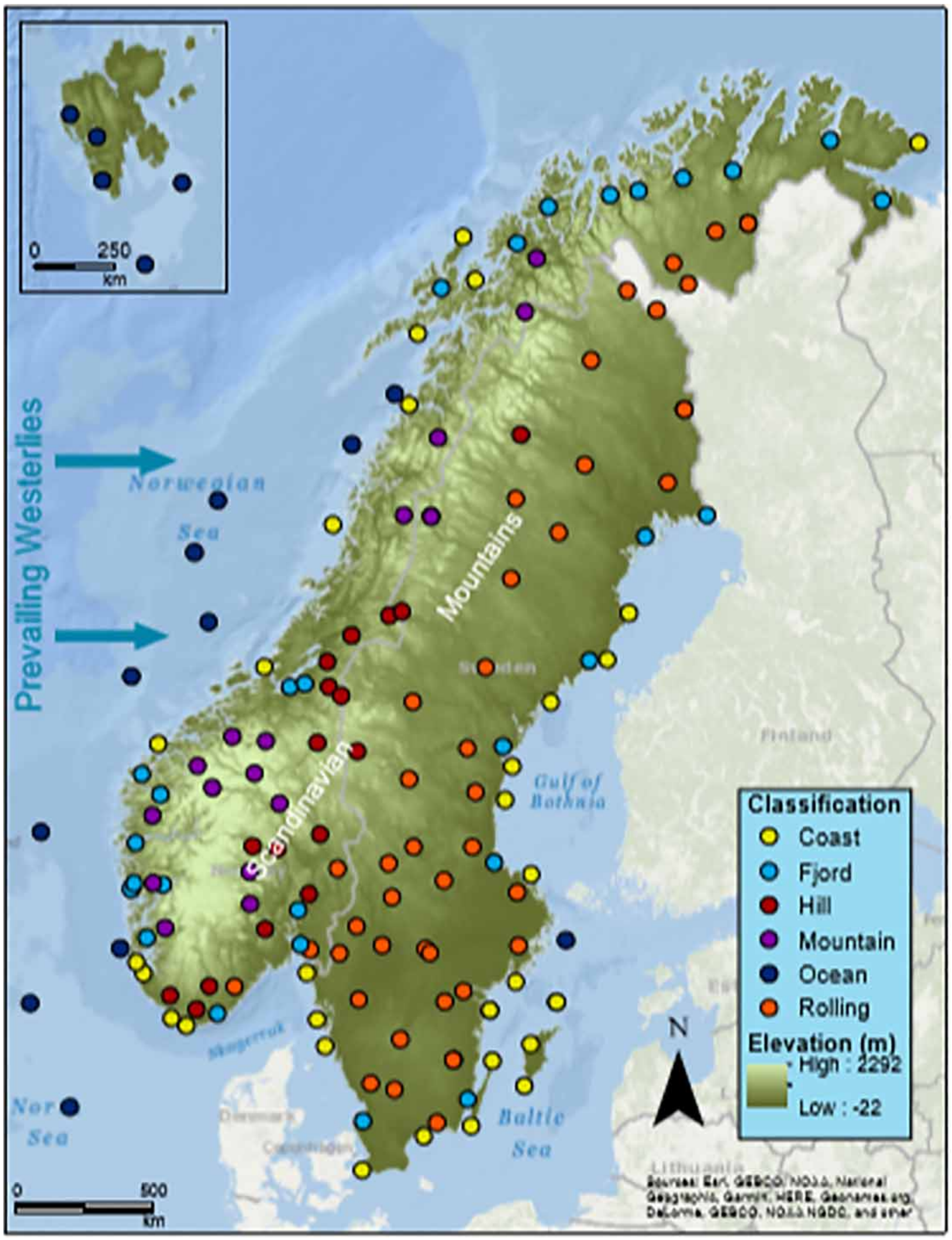

Figure 1 | Map of meteorological stations and their physiographic classification created by Laurie Grigg.

Finally, percent misclassified precipitation and change in percent snow events from the use of cloud base height ATT, T_{RH}, country ATT values, and WB 0.0 °C (Equation (2) from Stull (2011)) will be compared. This air temperature/RH approximation for WB was used due to stations not reporting WB, or some of the parameters, such as saturation vapor pressure, required to calculate WB temperatures.

$$\begin{aligned} TW = {} & TA\,atan[0.151977 * (RH + 8.313659)^{5} \\ & + atan(TA + RH) - atan(RH - 1.676331) \\ & + [0.00391838 * (RH)^{1.5}] * atan(0.023101 * RH) \\ & - 4.686035 \end{aligned} \quad (2)$$

RESULTS

Cloud base height

Cloud base height ATTs for both Norway and Sweden increase as the depth of the unsaturated layer between the cloud base and ground increases (Table 2). The cloud base height ATTs for Sweden are colder than Norway when cloud base heights are low. However, cloud base height ATTs in Sweden have a greater rate of warming with a growing depth of the unsaturated layer than Norway. Both countries have a calibrated cloud base height ATT of 1.4 °C at 1,000 m (Table 2).

Table 2 | Cloud base height ATTs along with a smoothed ATT change between reporting cloud base height categories (ATT pattern) for Norway and Sweden

Cloud base height

		Norway		Sweden	
Subgroups	**Name**	**ATT pattern**	**Calibrated ATT**	**ATT pattern**	**Calibrated ATT**
0–49 m	0 m	0.5	0.4	N/A	N/A
50–99 m	50 m	0.7	0.5	0.2	0.1
100–199 m	100 m	0.9	0.9	0.4	0.6
200–299 m	200 m	1.1	1.0	0.6	0.6
300–599 m	300 m	1.3	1.3	0.9	0.9
600–999 m	600 m	1.4	1.4	1.2	1.2
1,000–1,499 m	1,000 m	1.4	1.4	1.5	1.4

T_{RH} and cloud base height methods in different cloud environments

Using a country ATT value would result in more misclassified precipitation than the T_{RH} and cloud base height PPDS options for all reported cloud base heights up to 1,000 m in Norway (Figure 2). Cloud base height ATTs produce less misclassified precipitation than T_{RH} for cloud base heights up to 100 m in Norway and 300 m in Sweden over which heights T_{RH} results in less misclassification (Figure 2). The percent improvement from the use of a static ATT value (Figure 3) or the decrease in misclassified precipitation phase if using T_{RH} and cloud base height PPDS methods gives scale to Figure 2.

T_{RH} parameterization, with cloud base heights above the categories of 100 m in Norway and 300 m in Sweden, leads to much less misclassified precipitation than either a country ATT or cloud base height ATTs (Figure 3). Importantly, the T_{RH} PPDS would increase misclassified precipitation in Sweden for cloud base heights below 600 m (Figure 3).

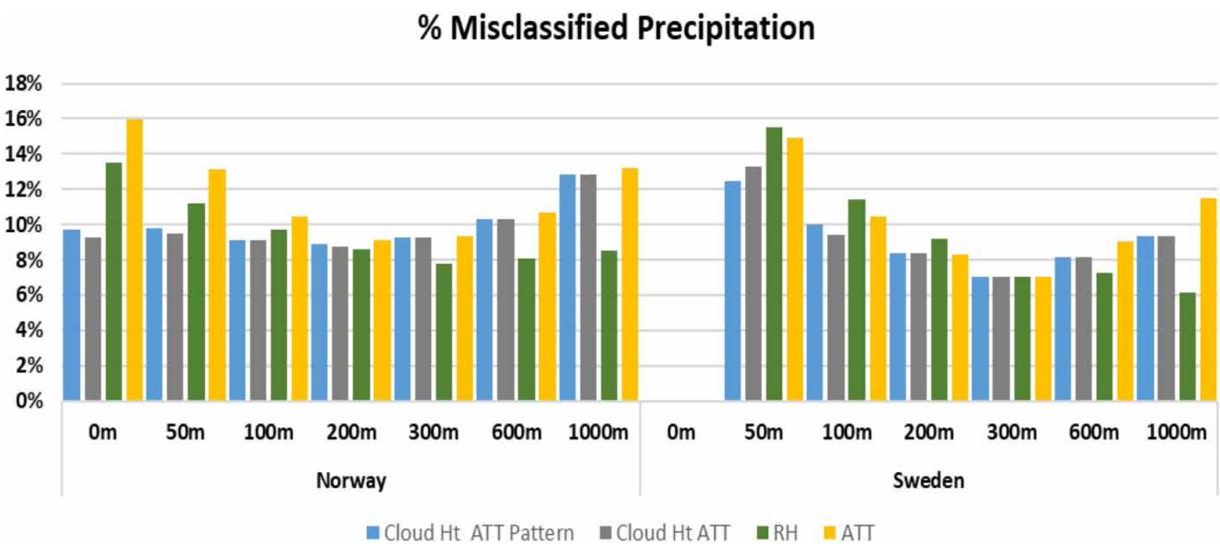

Figure 2 | Percent misclassified precipitation in Norway and Sweden for each precipitation phase parameterization method by cloud base height category.

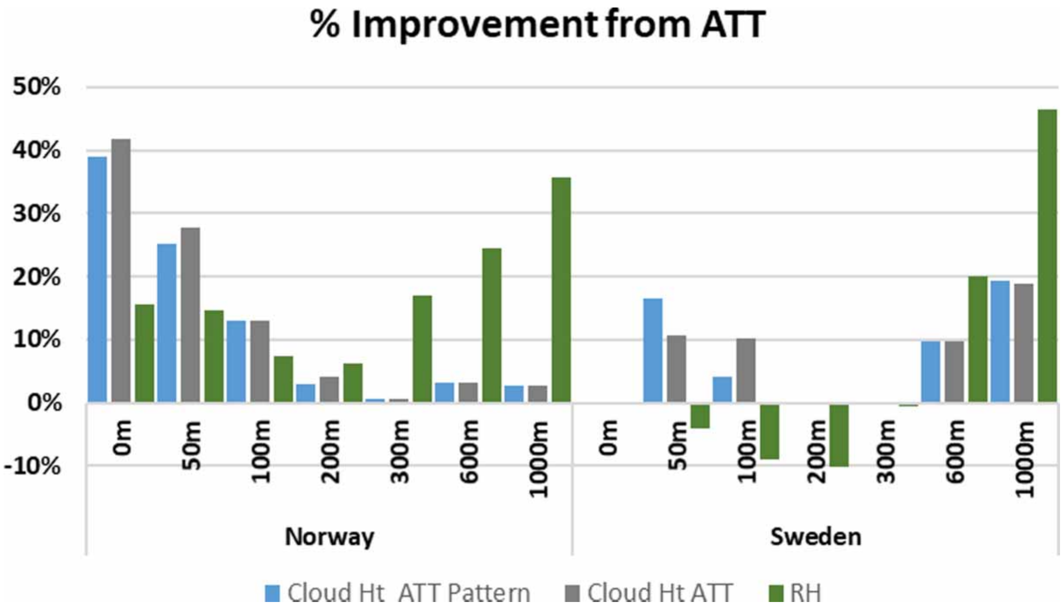

Figure 3 | Percent improvement for each cloud base height category in Norway and Sweden using cloud base height and RH precipitation phase determination methods.

Cloud base height and T_{RH} method compared for ideal dataset

A PPDS using cloud base height ATTs for cloud base height categories up to 100 m in Norway and 300 m in Sweden combined with the T_{RH} parameterization for cloud base heights above those thresholds results in the greatest decrease in misclassified precipitation from country ATTs (Figure 4). In Norway, the use of WB 0.0 °C, T_{RH}, and the combined T_{RH} cloud base height method resulted in a decrease of 19% misclassified precipitation from the use of a set country ATT. These decreases were noticeably less in Sweden than in Norway (Figure 4).

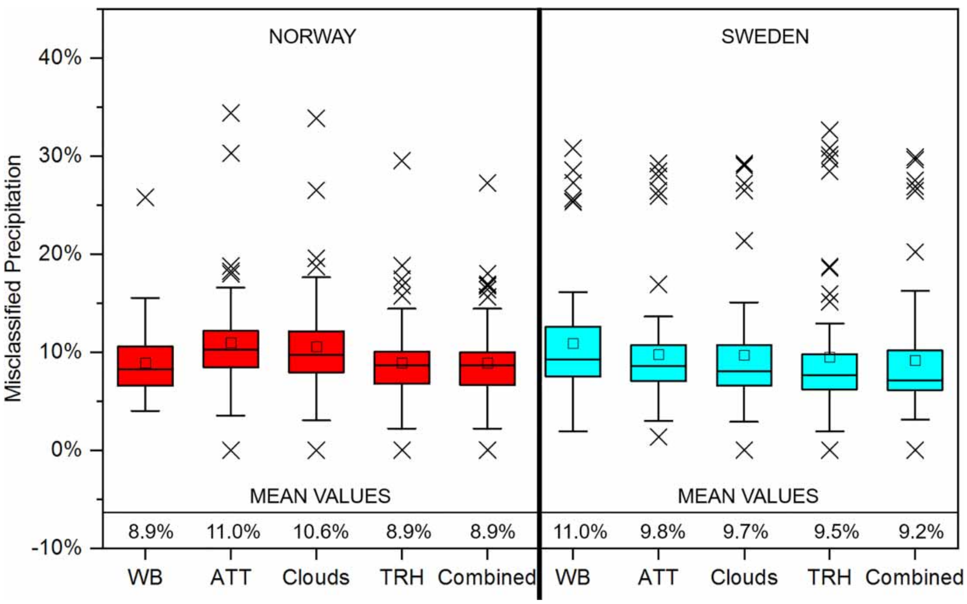

Figure 4 | Misclassified precipitation percentages for the labeled precipitation phase determination schemes in Norway (red/left) and Sweden (blue/right). Box plots cover the 25–75% probabilities with a small box indicating mean percentage, a line indicating the median value, whiskers showing the 95% confidence interval, and X marking all outliers from the 95% confidence intervals. Please refer to the online version of this paper to see this figure in color: https://doi.org/10.2166/nh.2021.072.

Cloud base height and T_{RH} method results for physiographic groups

In all Norwegian physiographic categories, the T_{RH} PPDS method reduced much more misclassified precipitation than cloud base height ATTs. However, in Norway, both T_{RH} and cloud base height methods decreased misclassification from the country ATT in all physiographic categories (Figure 5). In Sweden, cloud base height ATTs lead to an increase in precipitation phase error at coastal stations, whereas the T_{RH} method increased misclassified precipitation in fjord stations when compared with the Sweden country ATT (Figure 5). Of note, the T_{RH} method produced over 2% decreases in misclassified precipitation for the Norwegian hill and mountain stations. These high relief areas have the greatest misclassified precipitation percentages for all land categories in Norway.

Cloud base height and T_{RH} method results using full dataset

Using all precipitation observations, except mixed phase and freezing events, occurring in air temperatures between −3 and 5 °C, the use of cloud base height ATTs reduced misclassified precipitation, but that reduction was less than 1/3 of the reduction found using T_{RH} (Table 3).

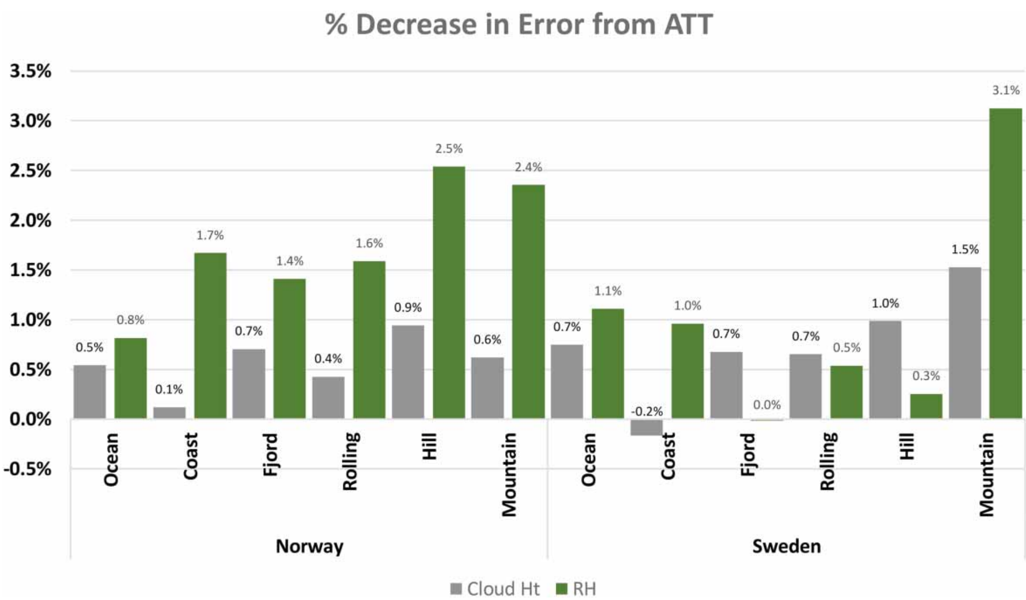

Figure 5 | Percent decrease in precipitation phase determination using T_{RH} and cloud base height ATT methods compared with a country ATTs for each identified physiographic category in Norway and Sweden.

Table 3 | Decrease in misclassified precipitation phase observations from ATT for each dataset using the labeled precipitation phase determination schemes

	Norway				Sweden			
Datasets	**Cld Ht**	**RH**	**RH > 100 m**	**ATT**	**Cld Ht**	**RH**	**RH > 300 m**	**ATT**
Cld Ht	864	2,389	2,690	**17,109**	447	639	935	**7,638**
No Cld Ht	N/A	466	466	**1,634**	N/A	613	613	**7,183**
Cld Ht > 1 km	N/A	79	79	**238**	N/A	156	156	**667**
No RH	N/A	N/A	N/A	**1,153**	N/A	N/A	N/A	**294**
Total	864	2,934	3,235	**20,134**	447	1.408	1.704	**15,782**
% Less error	4.29%	14.57%	16.07%		2.83%	8.92%	10.80%	

Bold values indicate methods that could not be applied to a given dataset.

Long-term snow bias from PPDS methods

The use of a set ATT or cloud base height ATT results in the least change in percentage snow assigned by the compared PPDS (Figure 6). The methods resulting in the greatest decrease in misclassified precipitation (Figure 4) result in the greatest imbalances in the assigned percentage of snow events. The use of WB 0.0 °C resulted in a −9.5% and −6.9% mean change in snow events, whereas T_{RH} resulted in a 10.6 and 11.7% mean increase in snow events assigned to precipitation in this climatological study (Figure 6).

DISCUSSION

The techniques of using T_{RH} or adjusting ATT for cloud base heights between 0 and 1,500 m could be incorporated into conceptual models to improve precipitation phase determination from the standard, often criticized (Daly *et al.* 2000; Harpold *et al.* 2017a) practice of using a set ATT (Figures 2 and 4). With Feiccabrino (2016), this is now a second and third independent dataset in which ATTs calibrated for cloud base heights between 0 and 1,500 m were found to warm with an increase in the depth of the near-surface unsaturated atmospheric layer (Table 2).

Surface RH is often greater with low cloud base heights compared with high cloud base heights. The T_{RH} equation increases ATT at lower RH, in agreeance with cloud base height ATTs being warmer with high cloud base heights. This indicates that cloud base height could be used as a proxy for RH in a PPDS. However, ATTs calibrated to cloud base heights reduced misclassified precipitation events by 864 (447) compared with 2,934 (1,408) using T_{RH} in Norway (Sweden) (Table 3).

The use of cloud base height ATTs reduced more misclassified precipitation than T_{RH} when cloud base heights were at and below the 100 m category in Norway and the 300 m category in Sweden (Figures 2 and 3). Once cloud base heights were at or above 200 m in Norway and 600 m in Sweden (Figure 3), the T_{RH} method reduced much more misclassified precipitation than ATTs calibrated to cloud base height.

This finding could indicate that in moist environments with a maritime onshore flow (Norway), surface RH is a much better indicator of precipitation phase (Figure 3) than in drier environments (Sweden). The calibrated ATT for Norway 1.2 °C was warmer than Sweden 0.9 °C, which would seem to contradict the T_{RH} method which would predict lower ATTs for higher RH environments. Meanwhile, these country ATT values would support onshore advection of warmer ATTs from oceans 1.9 °C than land 1.2 °C (Dai

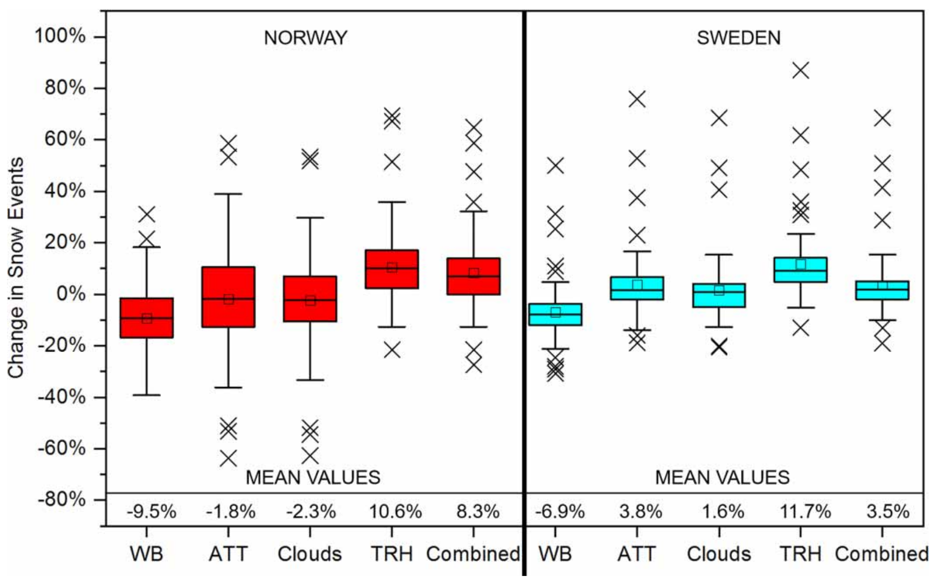

Figure 6 | Percentage change in snow events for the labeled precipitation phase determination schemes in Norway (red/left) and Sweden (blue/right). Box plots cover the 25–75% probabilities with a small box indicating mean percentage, a line indicating the median value, whiskers showing the 95% confidence interval, and X marking all outliers from the 95% confidence intervals. Please refer to the online version of this paper to see this figure in color: https://doi.org/10.2166/nh.2021.072.

2008). Surprisingly, it was found that the mean RH for the over 150,000 Norwegian precipitation observations was 88 ± 4%, 5% lower than the mean RH for the over 71,000 Swedish precipitation observations, 93 ± 2%. This additional finding, while unexpected, allows the country ATT findings to be supported by both the T_{RH} method and Dai's (2008) results.

In Sweden, a drier environment than Norway, cloud base height ATTs indicate precipitation phase better than T_{RH} through a greater depth of unsaturated layer (Figure 3). This could be due to the differences in latent and sensible heat fluxes between a hydrometeor and the environment in a moist/low cloud base height environment compared with a dry/high cloud base height environment.

In a mountain environment often saturated (in cloud), Marks *et al.* (2013) found WB ≈ DP ≈ AT, and a DP 0 °C to be a better indicator of precipitation phase than ATTs, often calibrated warmer than 0 °C. Swedish cloud base height ATTs near the ground start closer to 0 °C than Norwegian cloud base height ATTs (Table 2), while the T_{RH} method only warms from a saturated threshold of 0.75 °C. This warmer T_{RH} threshold in saturated environments could explain the results of (1) T_{RH} method not reducing as much misclassified precipitation as cloud base height ATTs when cloud base heights are low and (2) Swedish cloud base height ATTs decreased more misclassified precipitation than T_{RH} through a thicker near-surface unsaturated layer than in Norway.

In Norway, cloud base height ATTs and T_{RH} improved precipitation phase determination in all landscape categories, to varying effect, with T_{RH} being the most effective in all physiographic classifications. However, in Sweden results using cloud base height ATTs, and T_{RH} depended on the physiographic group, but generally improved (Figure 5) with some exceptions in the coastal environments. Perhaps a future addition of onshore or offshore influence could help in these coastal areas.

Since assigning a precipitation phase is a crucial first step in cold region hydrological models (Kongoli & Bland 2000), improvements in PPDS skill should result in better information driving water resource management decisions. Here, using all observations with or without a RH or cloud base height, misclassified precipitation between −3 and 5 °C was reduced from 10.62% (9.86%) to 10.16% (9.58%) using cloud base height ATTs, 9.07% (8.98%) using T_{RH} and 8.91% (8.79%) using a combination of T_{RH} and cloud base height ATT methods in Norway (Sweden) (Table 3). This indicates that either method or both combined could be used to reduce precipitation phase determination errors in conceptual surface-based models. There is also potential to improve future studies by filling data gaps (removed observations) and expand station selection options by using simulated RH values (averaged winter grid-square RH) in a reanalysis step as was done by Jennings *et al.* (2018).

CONCLUSIONS

1. Precipitation phase determination in conceptual models using ATTs can improve miss-rates by applying cloud base height ATTs and/or a linear ATT RH formula $(T_{RH}) = 0.75 * 0.085(RH - 100)$. Here, cloud base ATT and T_{RH} reduced 4.29% (2.83%) and 14.57% (8.92%) error in Norway (Sweden), respectively.
2. The T_{RH} formula was much more effective at reducing misclassified precipitation than cloud base height ATTs, except when cloud base heights were below 200 m above the ground in Norway and 600 m in Sweden. Applying the T_{RH} formula with cloud height ATT in low cloud conditions resulted in 16.07% and 10.80% improvements to miss-rate for model precipitation phase determination in Norway and Sweden, respectively.
3. Improvements to precipitation phase determination from traditional ATT by applying T_{RH} and cloud base height ATT should yield fairly universal improvements across diverse landscapes because they indirectly adjust for the atmospheric properties that control phase change before precipitation reaches the ground.
4. Short of adding atmospheric datum, the PPDS in conceptual hydrological models could be improved by adding surface observational data that act as proxies for the atmospheric conditions a hydrometeor must interact with as it falls to the ground.

DATA AVAILABILITY STATEMENT

All meteorological RAW data used in this study is public information available at no charge through the Norwegian Meteorological Institute and the Swedish Meteorological and Hydrological Institute.

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