Precipitation phase uncertainty in cold region conceptual models resulting from meteorological forcing time-step intervals

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ABSTRACT

Precipitation phase determination is a known source of uncertainty in surface-based hydrological, ecological, safety, and climate models. This is primarily due to the surface precipitation phase being a result of cloud and atmospheric properties not measured at surface meteorological or hydrological stations. Adding to the uncertainty, many conceptual hydrological models use a 24-h average air temperature to determine the precipitation phase. However, meteorological changes to atmospheric properties that control the precipitation phase often substantially change at sub-daily timescales. Model uncertainty (precipitation phase error) using air temperature (AT), dew-point temperature (DP), and wet-bulb temperature (WB) thresholds were compared using averaged and time of observation readings at 1-, 3-, 6-, 12-, and 24-h periods. Precipitation phase uncertainty grew 35–65% from the use of 1–24 h data. Within a sub-dataset of observations occurring between AT -6 and 6 °C representing 57% of annual precipitation, misclassified precipitation was 7.9% 1 h and 11.8% 24 h. Of note, there was also little difference between 1 and 3 h uncertainty, typical time steps for surface meteorological observations.

Key words | conceptual models, precipitation phase, snow, snow model, temperature threshold

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INTRODUCTION

An essential question for all cold region hydrological models is: was the precipitation mass in the form of rain, snow, or a mix of the solid and liquid phase (Harpold *et al.* 2017b)? To answer this question, hydrologists have used precipitation phase determination schemes (PPDS) in their surface-based conceptual models. These PPDS often apply a single rain/snow temperature threshold (T_{RS}) where all precipitation occurring in the same and cooler temperatures are assigned to the snow phase, and rain if warmer (e.g., Bartlett *et al.* 2006). Many conceptual hydrological models use either a 1-h or 24-h time steps, but the precipitation phase uncertainty related to the choice of a time step is a relatively unexplored gap in the research (Harpold *et al.* 2017b). This study intends to quantify precipitation phase uncertainty related to the time steps of 1, 3, 6, 12, and 24 hours, and explains some meteorological reasoning to support the findings.

Snowfall and rainfall have different effects on water and energy fluxes, and when misclassified can result in streamflow, surface albedo, or winter snow water storage calculation errors (Jennings *et al.* 2018). The significance of PPDS uncertainties depends on many factors, such as the intended model application, with a magnitude that can vary between precipitation events and or locations (Harpold

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et al. 2017b). In the Scandinavian Peninsula, 41.77% of annual precipitation occurred with air temperatures (AT) −3 to 5 °C in Norway, and 38.49% in Sweden with station maximum and minimum of 61.12% and 20.08%, respectively (Grigg *et al.* 2020). This abundance of precipitation occurring in near-freezing temperatures leads to a fair amount of precipitation phase uncertainty within conceptual models. Therefore, it is logical to seek ways to decrease this precipitation phase uncertainty.

Incorrect precipitation phase determination can have a cascading negative effect on both rapid response (e.g., flooding and road maintenance) and longer-term (e.g., water supply and ecosystem response) hydrological models (Harpold *et al.* 2017a). For instance, a massive snow event misclassified as rain in a model could result in: (1) a rapid response flood model indicating higher water levels due to a significant melt event which would not be observed or (2) energy loss and wetting of a modeled snowpack which would be unrepresentative of actual conditions. Rapid response models for flooding can be on a 15-min, 1-, 3-, or 6-h timescale to allow quick responses to heavy precipitation events. Other models do not require such high-temporal resolution and may have 24 h or even monthly timescales.

Conceptual hydrological models often use a set T_{RS} calibrated over a large area regardless of changes in physiography, vegetation, or other characteristics that may affect local/regional average atmospheric conditions (Grigg *et al.* 2020). Precipitation phase at the ground surface is a result of microphysical processes (melting, freezing, condensation, evaporation, ice condensation, and sublimation) between hydrometers and the atmosphere they fall through (see Stewart 1992; Thériault & Stewart 2010). The use of a set T_{RS} assumes that atmospheric conditions acting on hydrometeors falling through the lower atmosphere are invariant (Feiccabrino *et al.* 2015) and is, therefore, a source of precipitation phase uncertainty (Feiccabrino 2020). However, the use of 24-h average temperatures also assumes that atmospheric conditions over an area are static for a full day.

A 24 h time step does not account for many regular atmospheric changes two of which are: (1) diurnal changes in temperature which are affected by clear skies, overcast skies, partly cloudy skies, or changes in the cloud cover through the day and (2) frontal boundaries and troughs which separate air-masses with often vastly different atmospheric properties.

Typically, on a cloud-free day, the near-surface air and the boundary layer are warmed by incoming short-wave solar radiation and cooled overnight as long-wave radiation is emitted from Earth. On an overcast day, the incoming short-wave radiation is reduced by cloud cover, which in turn reduces daytime high temperatures, and nighttime long-wave radiation is reradiated by the clouds moderating nightly low temperatures. If clouds move over an area in the morning after a full night of cooling, the typical daily pattern will be disrupted by a cold night and a cool day. If clouds move over an area in the evening after a full day of warming, the daily pattern will be disrupted by a warm day and a cool night. Both examples above run a chance of not being adequately represented by a 24-h average temperature.

Many meteorological changes take place on sub-daily time steps, therefore making 24-h averaged meteorological inputs into a model unrepresentative (e.g., Figures 1–4). Cyclones, described in the Norwegian cyclone model (Bjerknes 1919) and many updates to this model, e.g., the conveyor belt model (Browning 1986), describe the atmospheric interactions at air-mass boundaries causing a majority of winter precipitation (Stewart *et al.* 1994). Fraedrich *et al.* (1986) showed that 82.7% of winter precipitation mass in Germany was generated by cyclones. The most common of these air-mass boundaries are cold fronts and warm fronts, but there are also troughs, occlusions, and arctic fronts (reviewed in Feiccabrino *et al.* 2012).

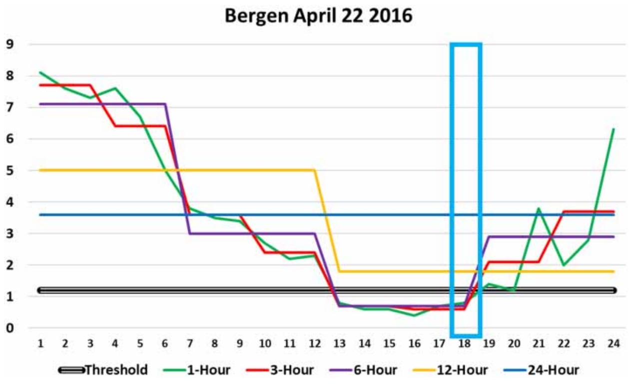


Figure 1 | 2.4 mm water equivalent/4 cm snow (blue box) misclassified as rain in 12- and 24-h time steps. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2020.080.

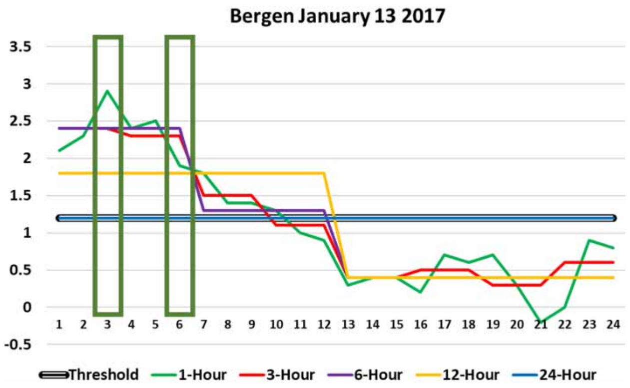


Figure 2 | 0.8 and 0.4 mm rain events (green boxes) misclassified as snow by a 24-h time step. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2020.080.

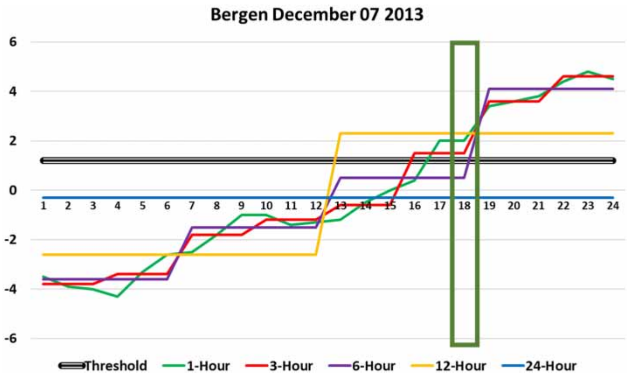


Figure 3 | 7.3 mm warm frontal rain event (green box) misclassified as snow by 6- and 24-h time steps. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2020.080.

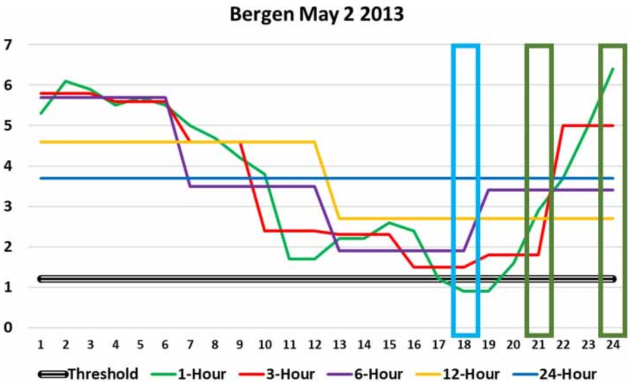


Figure 4 | 5.8 mm water equivalent snow event (blue box) misclassified by all but 1-h time step on a day with multiple precipitation phases (green rain boxes) observed. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2020.080.

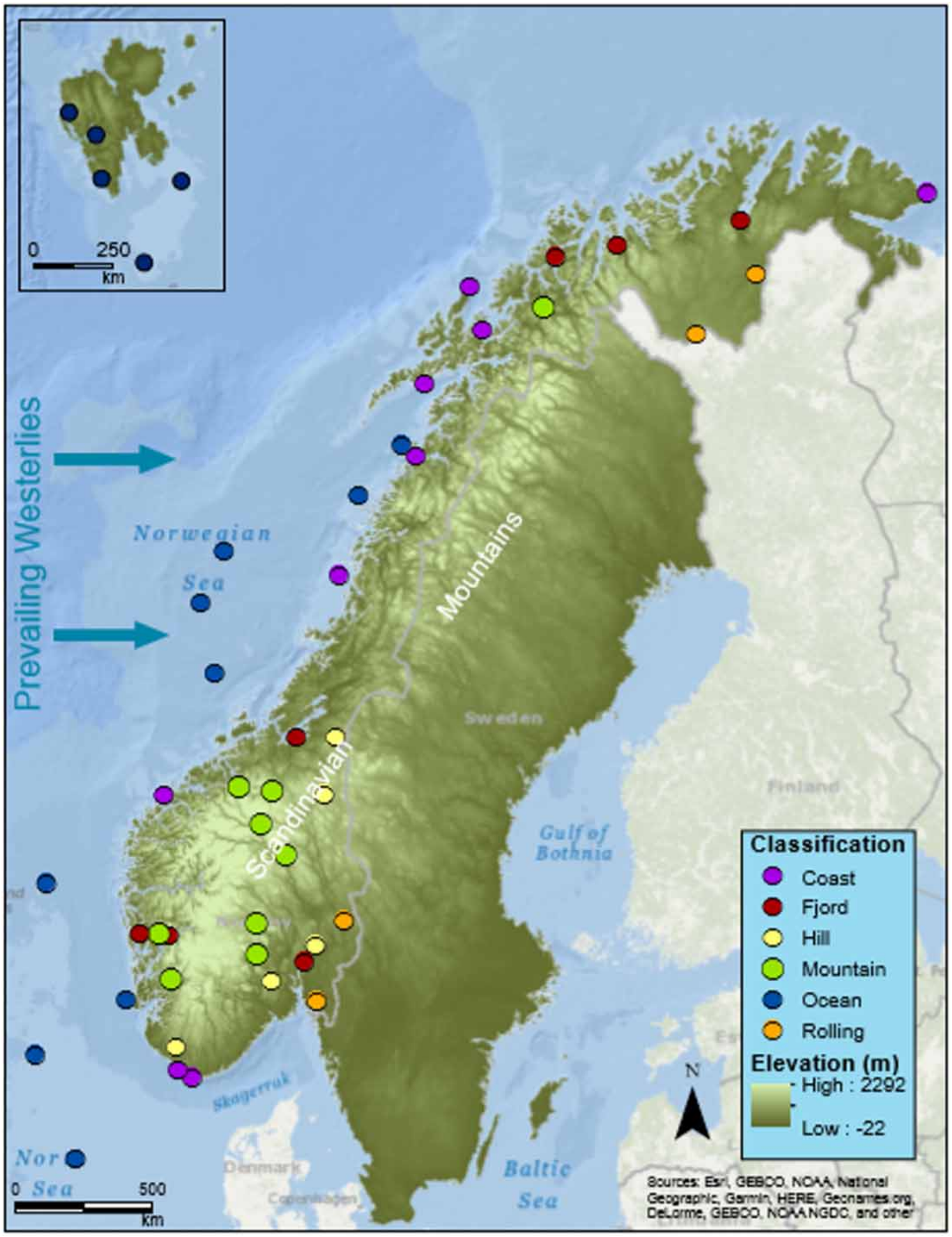
Occlusions and warm fronts characteristically have shallow frontal slopes with warm air rising over denser cold air near the surface. This causes a broader precipitation field (see Hanesiak *et al.* 1997; Venne *et al.* 1997) allowing hours of steady precipitation before warm frontal passage. Cold fronts have a much steeper frontal slope than other fronts causing stereotypically heavier precipitation and showers due to increased lift (Browning 1986; Bjerknes 1919; Venne *et al.* 1997). Cold fronts, troughs, and arctic fronts with steeper frontal slopes typically take less time than warm fronts to pass over a station. All including showers typically occur well under the daily timescale unless the storm path drags an air-mass boundary parallel to a station.

With many winter precipitation events occurring on a sub-daily time step, this paper will compare misclassified precipitation rates for 1-, 3-, 6-, 12-, and 24-h time steps for all stations analyzed together. This addresses misclassified precipitation events resulting from the assumption of constant atmospheric conditions over a daily time step. The misclassified precipitation findings from this climatological study should translate to model uncertainty when applied in a cold region hydrological model.

METHOD

Hourly meteorological observations from 48 publicly available Norwegian weather stations (NMI 2019; Figure 5) representing diverse physiographic categories (Grigg *et al.* 2020) of ocean platform (6), island (5), Svalbard (3), coast (9), fjord (7), rolling (4), hill (5), and mountain (9) stations having 98,849 liquid or solid precipitation events/observations used in this study.

Observations with AT, dew-point temperature (DP), and wet-bulb temperature (WB) between −6 and 6 °C accounted for 57% AT and 63% DP and WB precipitation observations in each of the 1-, 3-, 6-, 12-, and 24-h datasets. This is the temperature range over which PPDS is most uncertain. Mixed-phase precipitation (4,782 observations) was excluded from the datasets due to a lack of information on rain/snow ratios and many prior studies disregarding this phase, e.g., Bartlett *et al.* (2006). Frozen precipitation (247 observations) was included as the liquid in this analysis. However, frozen precipitation can be considered either



Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, DeLorme, GEBCO, NOAA NGDC, and other

Figure 5 | Map of meteorological stations and their physiographic classification created by Laurie Grigg.

rain or snow, depending on the intended use of a model (Feiccabrino 2020).

The average of all hourly temperature values within a 24-, 12-, 6-, 3-, and 1-h temporal resolution was calculated and assigned to each observation within the period. Observation datasets for each time resolution were then created. The phase of precipitation from the manual observation was compared to the assigned precipitation phase for AT, DP, and WB PPDS for each possible T_{RS} at 0.1 °C intervals between -3 and 5 °C. A precipitation event was considered erroneous in a PPDS if the liquid or solid phase assigned by the T_{RS} did not match the manually observed phase. The sum of errors divided by the total number of observations gave a station's percent misclassified precipitation for each

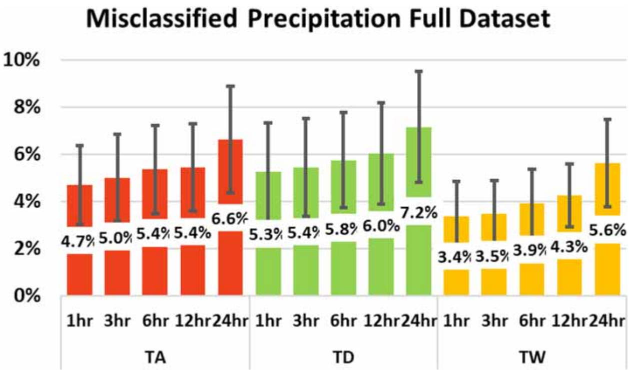


Figure 6 | Average misclassified precipitation per station for each full dataset with standard deviation error bars.

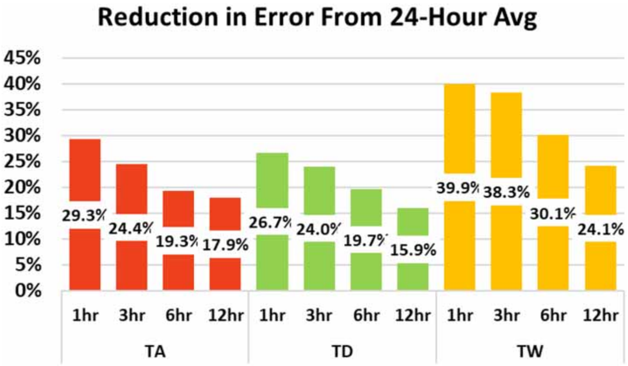


Figure 7 | Average reduction in misclassified precipitation when comparing the labeled dataset to the matching 24-h dataset for air temperature (AT), dew-point temperature (DP), and wet-bulb temperature (WB).

possible T_{RS}. The temperature corresponding to the lowest average station misclassified precipitation was the T_{RS} value for all stations analyzed together. Results for decreases in error between time steps refer to the absolute difference in precipitation points. Reduction in error results represents the relative change in error between two time-step options.

RESULTS AND DISCUSSION

Harpold *et al.* (2017b) stated in their review that PPDS accuracy is generally increased at finer timescales and or with the inclusion of RH data. There has not been a hydrological study focused on model PPDS uncertainties related to the temporal resolution of meteorological inputs. However, there have been some discussion comments, e.g., Harder & Pomeroy (2013) mentioning that there was little change in uncertainty between 15-min and 1-h time steps, but a vast difference between those datasets and a 24-h dataset. Here (Figure 6), misclassified precipitation for AT, DP, and WB all decreased for each shortening of the time resolution from 24 to 12, 6, 3, and 1 h. The misclassified precipitation results for AT and DP are similar for all temporal resolutions. However, misclassified precipitation resulting from

Table 1 | Temperature range (Range) between 90% snow fraction (90% SF) and 10% snow fraction (10% SF) and the percent misclassified precipitation occurring with temperatures cooler than −6, warmer than 6, and between −6 and 6 for air temperature (AT), dew-point temperature (DP), and wet-bulb temperature (WB) thresholds in 1, 3, 6, 12, and 24 h time-step datasets

	Air temperature			**Dew-point temperature**			**Wet-bulb temperature**		
	90% SF	**10% SF**	**Range**	**90% SF**	**10% SF**	**Range**	**90% SF**	**10% SF**	**Range**
1 h	0.1 °C	2.7 °C	2.6 °C	−2.4 °C	0.3 °C	2.7 °C	−0.8 °C	1.2 °C	2.0 °C
3 h	0.1 °C	2.8 °C	2.7 °C	−2.6 °C	0.2 °C	2.8 °C	−0.9 °C	1.1 °C	2.0 °C
6 h	0.0 °C	3.0 °C	3.0 °C	−2.8 °C	0.1 °C	2.9 °C	−1.0 °C	1.2 °C	2.2 °C
12 h	0.0 °C	3.0 °C	3.0 °C	−3.0 °C	0.1 °C	3.1 °C	−1.1 °C	1.2 °C	2.3 °C
24 h	−0.2 °C	3.1 °C	3.3 °C	−3.6 °C	0.1 °C	3.7 °C	−1.6 °C	1.2 °C	2.8 °C

Percent misclassified precipitation in each category

	AT < −6	**AT > 6**	**−6 ≤ AT ≤ 6**	**DP < −6**	**DP > 6**	**−6 ≤ DP ≤ 6**	**WB < −6**	**WB > 6**	**−6 ≤ WB ≤ 6**
1 h	0.3%	1.2%	98.6%	1.2%	0.2%	98.6%	0.6%	0.5%	99.0%
3 h	0.3%	1.2%	98.6%	1.4%	0.2%	98.4%	0.6%	0.5%	98.9%
6 h	0.2%	1.1%	98.7%	1.2%	0.2%	98.7%	0.5%	0.4%	99.1%
12 h	0.3%	0.9%	98.9%	1.4%	0.2%	98.5%	0.5%	0.3%	99.2%
24 h	0.5%	1.1%	98.5%	2.1%	0.1%	97.8%	0.8%	0.3%	98.9%

the use of WB is much lower than AT and DP in all temporal resolutions. All three temperature measurements have similar reductions in misclassified precipitation as time resolutions are decreased (Figure 7). For example, AT, DP, and WB all had 60% of the error reduction from 24 to 1 h occur with a time step decrease to 12 h.

These results indicate that a majority of the daily variability in average temperature measurements affecting misclassified precipitation using T_{RS} was eliminated by cutting a 24-h time period in half. Interestingly, for AT, DP and WB, every reduction in time step produced a reduction in misclassified precipitation (Figures 6 and 7).

These results (Figure 6) along with many previous studies, e.g., Matsuo *et al.* (1981), have found WB to be a better indicator of the surface precipitation phase than AT. Other studies, e.g., Marks *et al.* (2013), have found DP to be a better precipitation phase indicator than AT alone. However, AT is still used in many models and is available at almost every station reporting environmental measurements. WB and DP require RH, and other observation elements not always measured by stations for their calculation. Due to availability issues for RH and the continued use of AT in many models, improvement of AT methods have elevated importance. However, RH methods to include WB, consistently identify precipitation phase better than AT in the model PPDS.

98% misclassified precipitation occurred in AT, WB, and DP temperatures between −6 and 6 °C, for 1-, 3-, 6-, 12-, and 24-h datasets (Table 1). The daily time resolution has the greatest T_{RS} difference (Figure 8(a)), largest misclassified precipitation percentages (Figures 6 and 9), and greatest mixed precipitation range (90% SF–10% SF) (Table 1) for AT DP and WB. As time resolution increased toward 1 h (Figure 8(a)–8(e)), the T_{RS} for DP warms from −1.9 to −0.7 °C and T_{RS} for AT cool slightly from 1.4 to 1.2 °C, bringing AT and DP T_{RS} closer to WB ≅ 0.0 °C. As time resolutions increase from daily to hourly, misclassified precipitation decreases in each time step (Figure 9), while the mixed-phase temperature range (Table 1) stays steady or decreases. This leads to noticeable decreases (Figure 10) and reductions in error (Figure 11) for AT, DP, and WB.

Interestingly, the proportion of observations in each −6 and 6 °C dataset for AT (57%), DP (63%), and WB (63%) remained constant while the percent misclassified

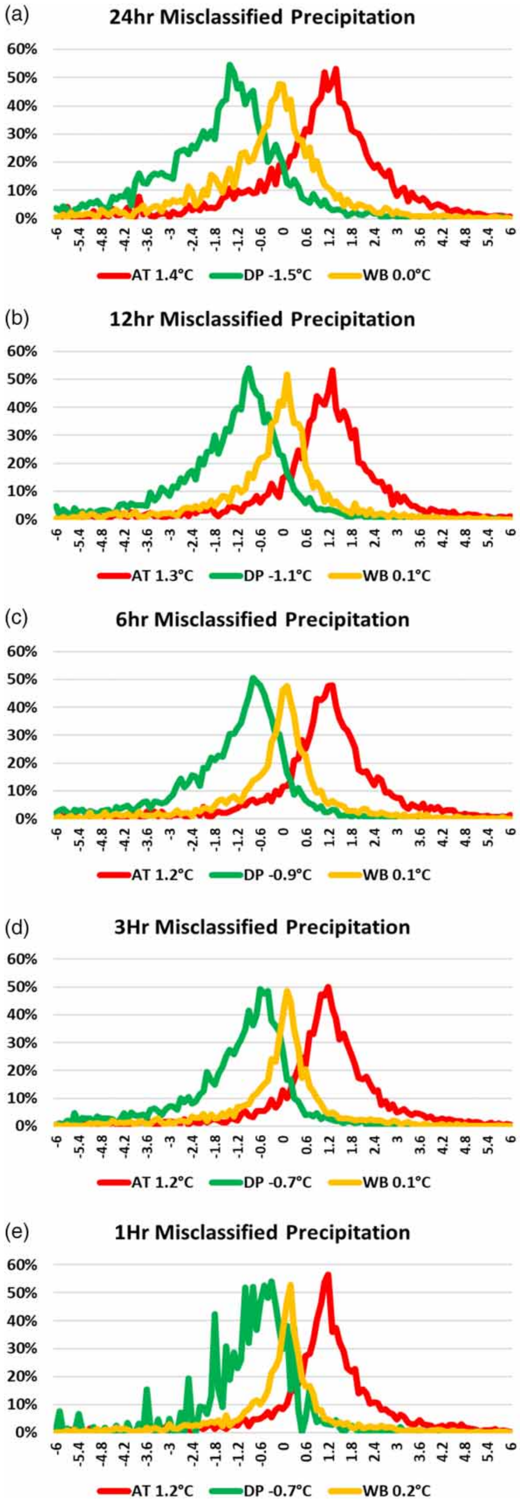


Figure 8 | (a–e) Percent misclassified precipitation occurring at each 0.1 °C between −6 and 6 °C with labeled threshold temperatures for air temperature (AT), dew-point temperature (DP), and wet-bulb temperature (WB) for datasets of 24, 12, 6, 3, and 1 h.

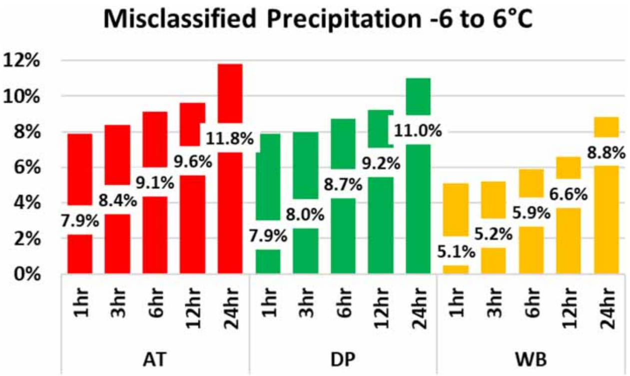


Figure 9 | Average misclassified precipitation for precipitation observations between −6 and 6 °C.

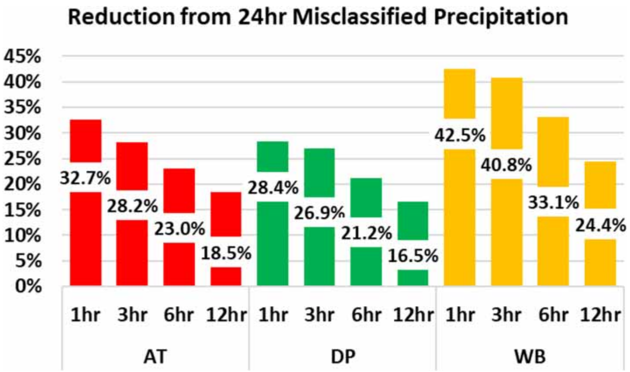


Figure 11 | Average reduction in misclassified precipitation when comparing the labeled dataset to the matching 24-h dataset for air temperature (AT), dew-point temperature (DP), and wet-bulb temperature (WB).

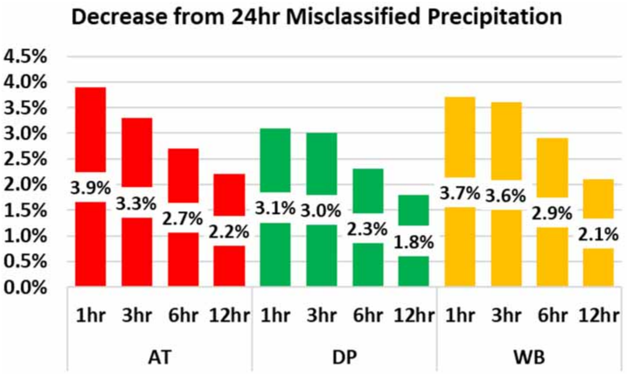


Figure 10 | Average decrease in misclassified precipitation when comparing the labeled dataset to the matching 24-h dataset for air temperature (AT), dew-point temperature (DP), and wet-bulb temperature (WB).

precipitation (Figure 9), and the mixed-phase temperature range (90% SF–10% SF) (Table 1) increased with decreasing time resolutions. The fact that the sample size was relatively constant, while misclassified precipitation and the mixed-phase temperature range increased with time steps suggests that precipitation occurring within the −6 to 6 °C range become more poorly characterized as the time resolution becomes more course.

One result of concern for further studies is the relatively large standard deviations ranging from one-third to one-fourth of the averaged misclassified precipitation for each temperature measurement in all time steps (1.7–2.3%) (Figure 6). These large standard deviations could be a result of averaging all station results together without regard for expected changes in the lower atmosphere caused by, for example, ocean heating of near-surface air, diurnal maritime cloud changes affecting daily heating and cooling patterns, or other physiographic effects on locations (Grigg *et al.* 2020).

CONCLUSIONS

- Reducing the temporal resolution of meteorological forcing data in hydrological models from 24 to 1 h greatly reduced misclassified precipitation for air temperature (AT) (29.3%), dew-point temperature (DP) (26.7%), and wet-bulb temperature (WB) (39.9%) thresholds.
- In almost all cases, reducing the temporal resolution between 24, 12, 6, 3 and hourly meteorological forcing reduced misclassified precipitation. However, the most significant decreases were between 24 and 12 h. Surprisingly, 60% of the decrease between 24 and 1-h time resolutions could be attained for AT, DP, and WB by only cutting the daily temporal resolution in half.
- It is here suggested that if attempting to reduce precipitation phase uncertainty in a cold region hydrological model with a daily air temperature time step, the best two options would be to either switch to using wet-bulb temperature or reduce the time step to 3 or 1 h for more representative meteorological forcing.

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