Examining How the Spread in the High Resolution Rapid Refresh Ensemble Translates into National Water Model Streamflow Forecasts

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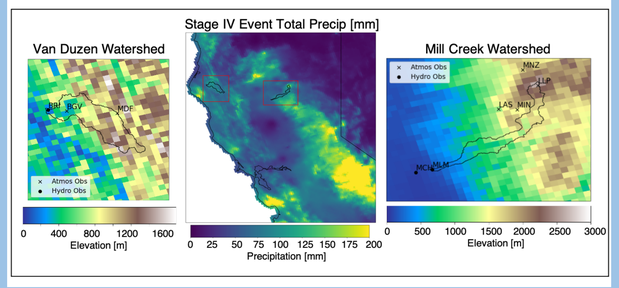
Background

The National Water Model (NWM) is a Weather Research and Forecasting Hydrologic Model (WRF-Hydro)-based operational hydrologic model producing streamflow forecasts for the continental US at high spatial and temporal resolution. The operational short-range forecast configuration is deterministic and is forced by hourly forecasts of precipitation, wind, temperature, radiation, and humidity from the operational High Resolution Rapid Refresh (HRRR) Numerical Weather Prediction Model. Currently, ensemble-based hydrologic model forecasts are forced by global models with lower spatial and temporal resolution.

In this study, we force the NWM with the experimental 9-member (plus control) HRRR Ensemble (HRRRE) to produce an experimental ensemble of streamflow forecasts for an extreme precipitation event that occurred January 26-29, 2021 in Northern California. Forecasts are initialized daily at 12 UTC using NWM operational restart files and run out to 36 hours. **The goals of this study are:**

1. **Evaluate the performance of the HRRRE against station observations in the basins of interest,**
2. **Evaluate the spread and uncertainty characteristics in the HRRRE forecasts, and**
3. **Evaluate the performance and spread of the ensemble streamflow forecasts, relating the performance and uncertainty in the HRRRE forcing variables to the NWM forecast outputs.**

For this study, we have chosen two domains of focus: The Van Duzen River in the northern Coast Range, and the Mill Creek basin in the Sierra Nevada. These basins were chosen due to their complex terrain, for the opportunity to examine ensemble forecasts of rain-snow transitions, as well as for their unimpeded streamflow, such that modeled streamflow forecasts would not be impacted by dam operations. Basin locations within the state of California are shown with event total precipitation below, with expanded maps of the basin elevation and location of available atmospheric and hydrologic observation stations included.



Takeaways

- The January 26-29 AR event was a relatively cold atmospheric river that produced snow in both of the selected basins. This complicates the evaluation of HRRRE precipitation forecasts where gauges do not measure snow.
- Where station observations are available, HRRRE typically under-forecast precipitation, and temperature forecasts were either consistent with observations or biased 1-5K low.
- The highest uncertainty in HRRRE forecasts was in the lower reaches of both basins, where the least precipitation was forecast.

- *In the Van Duzen watershed:*
  - HRRRE forecasts tended to underestimate precipitation.
  - Spread in the HRRRE members was larger in this watershed than in the Mill Creek watershed.
  - Largest spread in forecast streamflow corresponded to largest spread in forecast precipitation and snowfall at BGV.
  - Forecast streamflow had timing mismatches with observations, but typically enveloped the observations in magnitude.
  - The contributions of individual HRRR ensemble members to streamflow forecasts can be inferred to be related to specific features of the forecasts, including the distribution of rain versus snow in the basin.

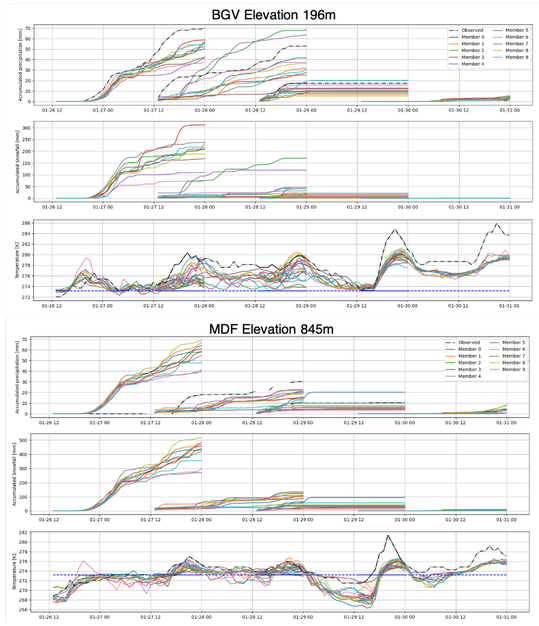
- *In the Mill Creek watershed:*
  - HRRRE precipitation performance varied with forecast run, but was overall in better agreement with observations than the forecasts in the Van Duzen watershed.
  - HRRRE consistently over-predicted snowfall, regardless of whether precipitation was over or under predicted. This implies that the snow to liquid ratio in the HRRRE was too high at this location for this event.
  - Saturated soils in the operational restart files appear to cause rapid rise and fall of the streamflow in both the operational and the experimental ensemble NWM runs.

- *Future Work:*
  - Identify additional cases and basins for study
  - Initialize NWM several days earlier to allow for soil moisture to regulate.
  - Include snow pillow observations to better quantify snowfall.

Results: Van Duzen Watershed

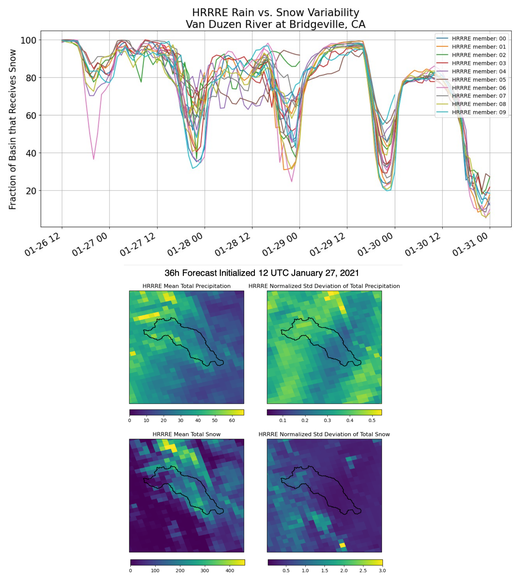
HRRRE Evaluation

Precipitation and temperature observations are available at two stations in the Van Duzen watershed: Bridgeville (BGV) and Mad River (MDF). HRRRE under-forecasts precipitation at both locations, particularly for the heaviest precipitation on January 27. Note that the MDF site did not measure precipitation on January 26; likely due to the occurrence of frozen precipitation, as the observed temperatures were below freezing during this time. HRRRE temperature forecasts were in line with the observations early in the forecast, but have a 2-4K cold bias at BGV on January 27-28, and at both stations after 12 UTC on January 29.



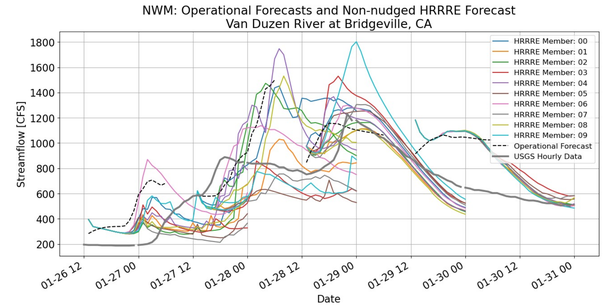
HRRRE Spread

At both MDF and BGV, there is large disagreement in accumulated precipitation at 24+h lead times for the 12 UTC January 26 forecast. Over the remainder of the event, forecasts at MDF exhibit fairly low spread. There is large disagreement among the HRRRE members at BGV, in both accumulated precipitation and snowfall (left). There is also a large spread in temperature forecasts from the 12 UTC forecasts on January 27 and 28, resulting in large variability in the fraction of the basin receiving rain versus snow (below). Maps of the ensemble mean and standard deviation of total precipitation and snowfall from the12 UTC January 27 forecast show the largest precipitation totals and ensemble spread in the NW part of the basin. In the lower part of the basin, there are generally low mean snowfall totals, but the normalized standard deviation of the ensemble is over 100% of the mean.



NWM Evaluation

Below we compare the NWM forced with HRRRE to both the operational NWM forecast and the USGS gauge observation. Both the HRRRE-forced and the operational NWM forecasts show a timing mismatch and a general tendency to overestimate streamflow when compared to the observations. The forecasts forced with HRRRE initialized at 12 UTC on January 27 and 28 tend to envelope the observed streamflow, providing an improved representation versus the operational NWM. The periods with the highest uncertainty in precipitation, snowfall, and the fraction of the basin receiving snow correspond to the periods with the largest spread in the NWM ensemble forecasts.



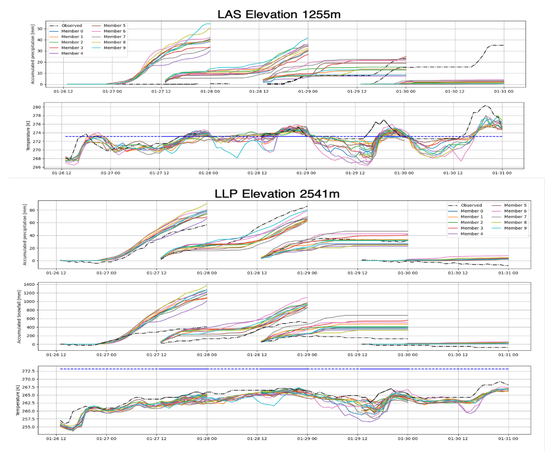
The effect of individual members of the HRRRE on the HRRRE-forced NWM forecasts is apparent in several instances. For example, at ~18 UTC on January 26, HRRRE member 6 is much warmer than the remaining members, resulting in a smaller fraction of the basin receiving snow (i.e. more of the basin is receiving liquid precipitation). This translates to member 6 having higher streamflow than the other members just after 00 UTC on January 27. Similarly, on January 28, HRRRE members 4 and 5 both have low snow fraction, but member 4 indicates high precipitation, whereas member 5 has very low precipitation (particularly at BGV). The result of this is a maximum streamflow forecast from member 4, with member 5 having the minimum forecast streamflow during this period. At 00 UTC January 29, HRRRE member 9 produces a much higher streamflow than the other ensemble members. While member 9 does not stand out at either surface station, the increased streamflow is due to this member producing heavy precipitation at the lower elevations during this run (not shown).

Results: Mill Creek Watershed

HRRRE Evaluation

There are 4 surface stations in and just outside of the Mill Creek Watershed, however they are all located above 1250m, and likely received the majority of their precipitation as snow. The lowest elevation station is Lassen Lodge (LAS) at 1255m. Observed precipitation at this station is 0 through January 28, after which increases in accumulated precipitation are associated with periods when the temperature rises above freezing, indicating snowmelt into the gauge.

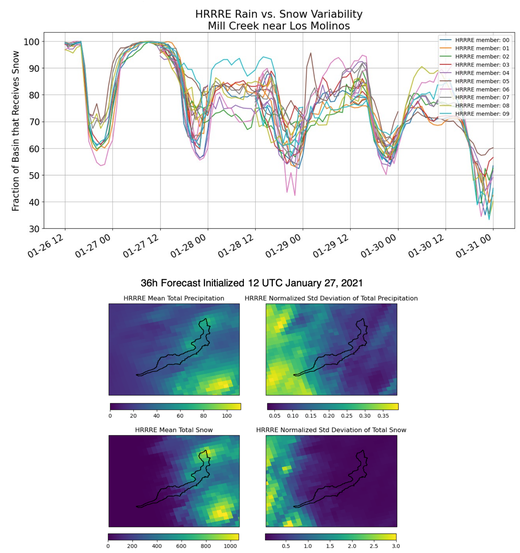
The highest elevation station is Lower Lassen Peak (LLP) at 2541m. Measurements at this station include snow depth and snow water content, which we use here as a proxy for accumulated liquid precipitation. During the first two forecast periods when precipitation was the heaviest, the HRRRE members overestimate accumulated snowfall, while they overestimate precipitation in the 12 UTC January 26 forecast and underestimate precipitation the last 12h of the 12 UTC January 27 forecast. The underestimation of accumulated snowfall regardless of over- or underestimated precipitation suggests that the HRRRE snow to liquid ratio is too high. HRRRE SLR is greater than 10:1, while the observations suggest SLR closer to 7:1. HRRRE tends to have a low bias in forecast temperature compared to the observations. Late in the event, observed SWE and snow depth decrease at LLP, indicating melting and settling of the snow pack, and we do not make any evaluation of the HRRRE during this period.



HRRRE Spread

Similarly to the Van Duzen watershed, the highest uncertainty in HRRRE forecasts is seen at the 24+h lead times for the 12 UTC forecast January 26, primarily at the lower elevation site (LAS). At LLP, ensemble spread is relatively low. With regard to the fraction of the basin receiving snow, the ensemble members agree relatively well through ~18 UTC on January 27, when member 9 becomes a high outlier, both in snow fraction and temperature at LAS.

Maps of the ensemble mean and normalized standard deviation of the total precipitation and total snow from the 12 UTC January 27 forecast show that this region received twice the precipitation as the Van Duzen watershed, but with much smaller normalized standard deviations. In the Mill Creek Basin, the normalized standard deviation of precipitation is less than ~15% for most of the basin, with higher values at the lower elevations where precipitation totals are also lower. Similar patterns are seen in the snowfall.



NWM Evaluation

In the Mill Creek watershed, both the operational and HRRRE-forced NWM behave questionably. The operational forecasts start each period near the observation, before rapidly dropping to a low base flow value. Meanwhile, the HRRRE-forced forecasts have a rapid increase in flow followed by a rapid decrease, with little to no ensemble spread. Forecasts produced at other unmanaged basins in California showed similar questionable results from both the ensemble and operational NWM output. This appears to be due to saturated soils in the restart file that quickly route excess water down the channel. The lack of response to continued inflows due to precipitation remains under investigation.