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Accuracy of Precipitation Type in the HREF Model for the January 12/13, 2018 Winter Storm

Celia Werner

University at Albany, State university of New York, celiawerner71@gmail.com

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Accuracy of Precipitation Type in the HREF Model for the January 12/13, 2018 Winter Storm

An honors thesis presented to the
Department of Atmospheric and Environmental Sciences,
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and
graduation from the Honors College

Celia Werner

Research Advisor: Justin Minder, Ph.D.

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Abstract

Accurately predicting the type of precipitation in a given winter storm remains a forecast challenge. High-resolution numerical weather prediction models, such as those that make up the operational High-Resolution Ensemble Forecast (HREF) system, are an important tool in the forecast process. However, there is still a large amount of discrepancy between individual members of the forecast ensemble and between the numerical forecasts and observations. These discrepancies can be caused by small differences in the vertical temperature profile leading to large inconsistencies between observational precipitation type (p-type) and the model output. This study will investigate near-freezing precipitation during a winter storm to evaluate the accuracy of the simulated p-type, examine what synoptic or local meteorological features contribute to model errors, and explore how the performance of specific HREF members depends on choices of model physics and initial/boundary forcing conditions. HREF forecasts will be compared to observations from meteorological Phenomena Identification Near the Ground (mPING), the New York State (NYS) Mesonet, and Automated Surface Observing System (ASOS). The winter storm that will be investigated took place on 12-13 January 2018. The large storm entered western NYS the morning of the 12 January, bringing heavy rain, but with a strong cold front moving southeast through the state came a mix of ice pellets, freezing rain, and snow. Even just one day out from the storm, the Buffalo National Weather Service Forecast Office was unsure of the strength and placement of the cold front so the transition areas between precipitation types was uncertain. Initialized at 1200 UTC 12 January, the different HREF ensemble members were inconsistent (about 8 hours from the first observation of mixed precipitation) with the transition areas of rain to ice pellets/freezing rain mainly around 2000-2300 UTC. Due to this forecast uncertainty in western NY, this area and time will be the main focus of this study. The most accurate member in this time frame was found to be the NAMNEST since the temperatures in western NY in this model were closest to observed. The other models that had cooler temperatures than observed had rain moving through western NY much earlier than observed.

Keywords: *Model verification, Winter weather, Mixed precipitation*

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Introduction

Precipitation (p-type) forecasting can be difficult because only small changes in the vertical temperature profile can result in drastic changes in surface p-type in winter storms. (e.g., Ikeda 2017; Rauber et al. 2001; Reeves 2016; Thériault et al. 2010). In near-freezing weather events, what typically causes these slight changes is latent heating effects due to phase changes of water or warm air advection (WAA) at mid-levels. As the precipitation falls through the atmosphere, it can fall into warm layers from WAA and melt and absorb heat, making the surrounding air cooler. If it subsequently falls into below-freezing layer, the melted ice particle, can re-freeze, which would release latent heat, increasing the temperature at that level. These latent heat and temperature advection interactions with falling precipitation result in a complex temperature and humidity profile (e.g., Stewart 1985; Lackmann et al. 2002). As the precipitation falls, other dictating factors of the resulting surface precipitation type are drop size distribution, precipitation rate, interactions of the different types of precipitation as they fall, and the composition of the initial phase of the precipitation (Thériault et al. 2010). Typically though, the primary factor in determining the surface precipitation type is the vertical profile of the wet-bulb temperature. Varying types of winter precipitation are usually observed along a warm front since warm air rises over the cold air out ahead of the front resulting in a temperature inversion (Thériault et al. 2010). This rising warm air can be seen on a temperature profile as a warm nose (warm layer of air above a temperature inversion) at mid-levels in the atmosphere in which can change the type of precipitation as it falls through this layer. The strength and depth of this warm layer is important since only a couple of degrees of difference in any part of the temperature profile can result in varying p-types (Stewart et al. 2015). These intricate atmosphere conditions associated with p-type require model temperature accuracy to result in a more precise forecast of p-type.

There is a wide-range of p-types that can reach the ground in a near-freezing precipitating event. The main categories of p-type can be defined as ice pellets, snow, rain, and freezing rain. The atmospheric profile or conditions that leads to freezing rain over ice pellets is mainly the depth and strength of the mid-level warm layer. A freezing rain profile typically has a warmer and deeper warm layer above the surface and is below freezing right at the surface, so any ice or snow is completely melted in the warm layer, becomes supercooled in the sub-freezing near-surface air, and only refreezes as it touches the ground. An ice pellet profile does not have as deep/warm of a warm layer, so the ice core remains, which serves as an effective ice nuclei allowing the liquid to re-freeze, once it falls below freezing, as an ice pellet and not just be a supercooled water droplet. (Stewart et al. 2015). Each main category of p-type has sub-categories of aggregations or degree of melting (Stewart et al. 2015). Aggregates can fall when ice particles begin to melt and combine with each other or supercooled water droplets as they fall. Even if the particles are of the same type but not size and distribution, the interactions between these particles and different fall speeds can lead to varying p-types at the surface (Crawford and Stewart 1995). Ice pellets can also be categorized by a liquid core in which the ice completely melted but then just the outside re-froze and partially melted snow can also fall as wet snow (Thériault & Stewart 2007). Due to limitation in model outputs of p-type, just the main p-type categories listed above will be plotted and compared to surface observations in thus study.

The HRRR is a high-resolution model, which is included in the operational High-Resolution Ensemble Forecast (HREF) ensemble v2.1 so understanding the capabilities of high-resolution models in general can be helpful in diagnosing the biases in HREF. The HREF model forecast maps can be found on the Storm Prediction Center's (SPC's) website (https://www.spc.noaa.gov/exper/href/). Each ensemble member can be viewed individually and easily compared to the other member's outputs at the same time. Ikeda et al. (2013) investigated the accuracy of the HRRR model in near-freezing precipitation events. In the 2013 study, the HRRR model did well in predicting the overall extent of the snow and rain compared to the Automated Surface Observing System (ASOS) data (Ikeda et al. 2013). The model also quantitatively performed well compared to observations in rain to snow transition and freezing precipitation areas when looking at spatial coverage and temporal uniformity. However, the model was not as accurate in areas of mixed precipitation, showing the need to focus on more of these mixed areas than rain-snow areas. There was roughly a 2°C warm bias when the temperature was near freezing and rain was forecasted but mixed precipitation was observed. There a was about a 2°– 4°C cold bias when snow was forecasted but mixed precipitation was observed. (Ikeda et al. 2013) So, even in a high-resolution model, the temperature accuracy, even just at the surface, is often not precise enough to accurately predict the varying mixed precipitation types. With this said, there is very little information about HREF model and the other individual ensemble member biases, especially when diagnosing precipitation type, which is why this paper will look to further analyze HREF accuracies/biases compared to a winter mixed p-type storm on 12/13 January 2018.

Data and Methodology

A. Synoptic Analysis

To better understand what caused this storm, upper-air conditions were analyzed using the NCEP/NCAR Reanalysis data and Climate Forecast System Reanalysis (CFSR). The NCEP/NCAR uses an analysis forecast system to perform data assimilation from 1948 to the present (Kalnay 1996). The CFSR is a global, high-resolution coupled system at 38km resolution to provide data from the atmosphere, ocean, land surface, and sea ice levels (National Center for Atmospheric Research Staff 2017). The 250-hPa winds, 500-hPa vorticity, and 850/700-hPa temperature advection were plotted using this dataset to understand the forcing behind the storm. National Weather Service soundings retrieved from the Wyoming upper air sounding archive (http://weather.uwyo.edu/upperair/sounding.html) were analyzed in Buffalo and Albany to get a sense of the temperature profiles causing the surface precipitation type. Surface maps were retrieved from the Weather Prediction Center's archive (https://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php) to get an overview of the placement and movement of the low-pressure system and associated cold front.

B. Station Observations

Observational data was inspected to verify what the overall storm pattern showed and what the national weather service forecasts were predicting (Figure 8). NYS Mesonet, mPING, and ASOS data were plotted (temperature, wind direction/speed, precipitation/snow totals, and precipitation type) on various NYS maps and in time series to get a spatial and temporal understanding of the event (Figures 6 and 9). Each observational data set serves a slightly different purpose and each added a unique angle to verification of this storm. The NYS Mesonet (Brotzge et al. 2020) was established in 2014, initially as the Early Warning Severe Weather Detection network, and provides real-time data, updated every 5 minutes, to operational forecasters with 126 stations, about 17 miles apart, across the state as seen in Figure 7. This is the most widespread data available for NYS and can be found at https://www2.nysmesonet.org/.

ASOS data (NWS 1998) is collected by 52 automated sensor stations across NYS, as seen in Figure 7, with 1 and 5 minute data reported hourly. However, special weather observations are reported more frequently since the type of weather (such as p-type) can change rapidly. The ASOS data was downloaded from the Iowa State University, Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu/request/download.phtml?network=NY_ASOS).

Established in 2012, mPING (Elmore et al. 2014) is a citizen science project that collects geotagged, time stamped reports of precipitation type and intensity at the surface reported through an app on any mobile device. The data was retrieved directly from mPING's website (http://mping.ou.edu/mping/api/v2/reports). The use of all three of these observational data sets minimized data gaps when verifying the model forecasts.

ASOS data provides the most reliable and consistent p-type data however, there are some notable gaps in the spatial coverage of ASOS stations. In a storm like this, where p-type varies greatly over a small area, some details of the storm can be lost. The most widespread coverage of data comes from the NYS Mesonet stations but there is no specific p-type sensor so p-type is harder to diagnose accurately with this data. mPING data, although not collected from an official station and can be inconsistent, helps to fill in the gaps of ASOS data if enough people report. The inconsistencies come from under-reporting of rain since that is more commonplace and the bias towards ice pellet reports compared to ASOS observations (Reeves 2016). This ice pellet bias is most likely a result of confusion among reporters of what ice pellets are since many people the term sleet is in the same category as ice pellets and many places use the term sleet to refer to wet snow. It was also found to have a delay in freezing rain reports since it takes a little while to notice ice build-up from rain freezing when hitting the surface (Reeves 2016). Particularly in the 2000-2300 UTC window of this storm, mPING reports were critical for observing the mixed p-types falling between Buffalo and the Finger Lakes where less ASOS stations had reports.

C. HREF Model Data

The HREF ensemble model v2.1 produces ensemble products from 5 models with 3-km grid spacing. Time-lagging is utilized resulting in a total of 10 outputs available. The HREF data was attained from the National Severe Storm Laboratory (NSSL), via their THREADDS server (https://data.nssl.noaa.gov/thredds/catalog/FRDD/HREF.html). The 5 ensemble members available for this model are the high-resolution WRF (HRW) NSSL, HRW Nonhydrostatic Multiscale Model on B-grid (NMMB), Weather Research and Forecasting - Advanced Research Weather (HRW-ARW), the North American Model (NAM) 3 km CONUS nest, and High-Resolution Rapid Refresh (HRRR). Each model has a 12-hour lag version as well except the HRRR which includes a 6-hour lag version. As can be seen in Table 1, the NMMB and NAMNEST have similar configurations, each with an NMMB dynamical core, Ferrier and Ferrier-Aligo microphysics schemes respectively and the MYJ boundary layer scheme. WRF-ARW and NSSL are similar in that they both have the WRF-ARW dynamical core and WSM6 microphysics scheme. However, they differ in boundary layer schemes. The WRF-ARW is the only member to have the YSU boundary layer scheme while NSSL has the MYJ scheme like the other three. The HRRR, which will not be analyzed in this study, is slightly different to the rest with a WRF-ARW core, Thompson microphysics scheme and MYNN boundary layer scheme. HREF v2.1 became operational beginning 1 April 2019 which includes the HRRR and is processed out to 48 hours. HREF v2.0 was used at SPC from 11 November 2017 to 31 March 2019, which only has a total of 8 members processed out to 36 hours. That is what was used for this case since it took place in 2018, so the HRRR ensemble was not available for this case.

Meteorological overview

A. Synoptic Forcings

In Figure 4, beginning 12 January at 1200 UTC, there was a weak line of low pressure at the surface just northeast of New England. The strongest low pressure was in the Southeastern United States. Along this line of low pressure was a strong cold front that progressed southeastward through NYS throughout 12 January into 13 January. The upper-level forcings were fairly weak over NYS starting at 1200 UTC 12 January. In Figure 1, looking at the 250mb winds, there was a short-wave trough over Arkansas/Louisiana with a strong jet east of the trough axis with max winds just north of New England. As the trough moved northeast, the jet intensified with the equatorward jet entrance region moving more over NYS by 13 January at 1200 UTC providing more upper-level divergence and forcing for upward motion. However, the location for the best forcing for upward motion for the time of mixed precipitation in western NY between 2000-2300 UTC was to the southeast where that low was more in line with the jet equatorward entrance region and downstream of the shortwave trough. Now in Figure 2, looking at the 500mb vorticity advection, there was a ball of curvature vorticity over Missouri on the 1200 UTC, with the positive vorticity advection maximum over the southeastern US, too far south to provide forcing for the storm hitting New York. By 13 January, the curvature vorticity moved northward providing more forcing for upward motion along with the strengthening and placement of the 250-hPa jet at this time as well.

The 850-hPa temperature advection at 12 UTC 12 January and 0000 UTC 13 January (Figure 3) shows strong warm air advection (WAA) throughout all of NYS at mid-levels. By 0000 UTC, there was strong cold air advection (CAA) passing through western NY and WAA over the Binghamton area where the cold front had already passed through but there was some warmer air aloft. At 0000 UTC 13 January the 700-hPa temperature advection was also plotted since in the Albany and Buffalo soundings (Figure 5), that seemed to be where the majority of mid-level WAA was occurring. This is also about the time when mixed p-type was falling in western NY and there is clear WAA over this area in which the surface cold front has already passed through, but WAA is seen at 700-hPa, which lines up with the 800-700-hPa warm layer in the Albany sounding and having mixed p-type (mainly ice pellets at this time) falling.

B. Storm Observations

Rain had already begun in most of the northern half of NYS by the morning of 12 January as can be seen in Figure 9. In Figure 6, by around 2100 UTC, the cold front passed through most of western NY with surface temperatures near freezing after the cold front passed through. Buffalo reported first reported freezing rain, ice pellets, then snow and this pattern generally progressed eastward through NYS overnight (Figure 9). By the morning of 13 January, most precipitation in Western New York had turned to snow, with some local exceptions of freezing rain, such as Fulton, NY (Figure 9). Western NY ended up receiving 2-4’ of rain, with snow melt on top of this amount and ice jamming, there was significant flooding and 10-16’ of snow with some local enhancements in Rochester due to lake effect snow from northeasterly winds blowing over Lake Ontario (Erdman et al., 2018). In the soundings provided in Figure 5, the timing of Buffalo’s mixed precipitation happened between 1200 UTC 12 January and 0000 UTC 13 January. However, Albany’s sounding at 1200 UTC 13 January clearly shows environmental conditions favorable for ice pellet formation with a small warm layer between 700-600 hPa and temperatures well below freezing at the surface. Locations further to the south, such as New York City and Long Island, received only rain so Western NYS will be the main focus of this paper.

C. NWS Forecasts

Just 24 and 48 hours out from the start of this storm, the NWS Buffalo office was still uncertain of the timing of the transition from rain to mix to snow (Figure 8). There was higher confidence in the maximum amount of snow to fall around Rochester with the lake-effect snow (about 12”-18”) from Friday into Saturday. The Finger Lakes and the Buffalo regions were the lowest confidence areas for snow amounts since the lower confidence in mixed p-types could lead to uncertainty in snowfall amounts. The Binghamton office was forecasting lower amounts of ice (0.08”) and more snow (8”-12”) but just southeast, around Binghamton, more ice (0.20”) was expected than snow (2”-3”). The Buffalo NWS office’s area forecast discussion (AFD) released 11 January at 9pm discussed the 1200 UTC HREF run and was able to give a general timing of the freezing rain and then ice pellets: “the surface front will cross the forecast area Friday afternoon, ushering in sub-freezing temperatures, while the mid-level front lags slightly behind. This will produce rain changing to freezing rain behind the surface front, then to sleet as the cold air continues to deepen near the surface. This phase of mixed precipitation will last about 3 or 4 hours.” (retrieved from Iowa Environmental Mesonet archive: https://mesonet.agron.iastate.edu/wx/afos/list.phtml). A flood watch and a winter storm warning were in effect for Friday morning into the afternoon and Friday afternoon into Saturday respectively.

Results

A. HREF Temperature vs. Observation

The NYS Mesonet-observed temperature at each station is compared with each HREF member forecast averaged from 2000-2300 UTC 12 January in Figure 10. There were some clear discrepancies in the temperature forecast between models. In general, the WRF-ARW was the only model to resolve the warm temperatures in southeastern NY and has a very strong temperature gradient, which is very different to how the other three model temperature maps look. This could be due to the fact that the WRF-ARW is the only model to have the YSU boundary layer scheme while all the others use the MYJ. Also, the NMMB and NAMNEST were the two members closest to resolving the temperatures in western NY. The most notable differences in the WRF-ARW and NSSL forecasted temperatures compared to the observations were near the coast of Lake Ontario and Lake Erie where the model was much cooler than observed, about 8°C and 5°C respectively.

Although the NMMB and NAMNEST resolved the warm temperatures in southeastern NY the worst out of all four models, with over a 10°C difference between model and observed temperatures, these two were most accurate around the Great Lakes regions and western New York. These two ensemble members also resolved the transition area from cold to warm in western NY better than the WRF-ARW and NSSL. Overall, the gradient of temperatures across NYS in the WRF-ARW and NSSL were much steeper and had a clear cold bias in the areas around the Great Lakes so it would be expected for these two members to have greater p-type inaccuracies. In contrast, it would be expected that the NMMB and NAMNEST perform similarly and have a more accurate p-type forecast, especially in transition areas as the cold front passes through and temperatures at the surface drop quickly.

B. HREF P-Type vs. Observation

In Figures 11 and 12, it is evident that the general cold bias in western NY in the WRF-ARW and NSSL members led to a favoring of forecasted ice pellets or freezing rain when rain was observed. In Figure 11, the main discrepancy between the WRF-ARW member and ASOS/mPING observation was that a much wider area of mixed p-type was forecasted than the much more concentrated, ice pellets and freezing rain falling in close proximity, mixed p-type observed. The areas of rain were generally forecasted to move out much quicker than what was observed during these three hours and there are several mPING and ASOS rain observations in the forecasted ice pellet region. The transition from ice pellets to snow was also not forecasted well at 2300 UTC when observations had turned to snow but the model still had ice pellets just east of Buffalo.

The NSSL member (Figure 12), which was similar to the WRF-ARW in its dynamical core and microphysics configuration and temperature bias in western NY, had similar p-type inaccuracies to the WRF-ARW. Mainly, the forecasted areas of freezing rain and ice pellets were much larger than what was observed and the rain moved through western NY much quicker than observed as well. The NSSL member also had snow falling too soon at 2100 and 2200 UTC (earlier than the other 3 models had it falling) but handled the transition from ice pellets to snow at 2300 UTC better than the WRF-ARW.

The NMMB (Figure 13) and the NAMNEST (Figure 14), which were similar in dynamical core and boundary layer scheme and temperature bias, did seem to perform generally better than the other two ensemble members. Starting with the NMMB, the area of rain was forecasted well in the first two times, coming up much further north than the previous members. However, there is and ASOS and mPING report of rain off the Erie coast which could be outliers or an error in observations. At 2100 UTC, the area of mixed p-type was more concentrated and closer to what was observed, but then in the next two times, it was spread too far southeast. Also, the model's transition from ice pellets to snow at 2300 UTC was too far northeast as compared to observations. The NAMNEST, although very similar to the NMMB with well forecasted areas of rain, still differed from the NMMB mainly in ice pellet transition. The transition from ice pellets to snow at 2300 UTC was more accurate in the NAMNEST and it was the only ensemble member to pick up the very quick transition from ice pellet to freezing rain to rain at 2200 UTC around the Rochester area. It was also the most accurate member at 2100 UTC in resolving the rain to freezing rain pattern around the Buffalo area, although none of the models had rain in Dunkirk or freezing rain in Buffalo.

Discussion

Looking ahead, some next steps that could be taken if this research were to be continued would be to look at more cases, especially a more recent case that would include the HRRR model. It would be helpful to look at cases with different p-type biases, such as rain vs. snow to see if certain members forecast more accurately for certain p-types. This would address some of the main limitations of this paper since it is limited to a specific case, time, and location. An overall look at the members' p-type forecast accuracy in even just this storm could give more insight to each member's accuracies and biases. A deeper look into the different HREF members' configurations could help explain consistent biases in each model.

Conclusion

The 12-13 January 2018 storm had a wide range of p-types fall in western NY over just a three-hour period from 2000-2300 UCT. There was uncertainty in NWS forecasts 1 to 2 days out and in the HREF ensemble members less than 12 hours before the mixed p-type fell. Overall, the WRF-ARW and NSSL members forecasted much colder temperatures in western NY during the 2000-2300 UTC time period which led to large areas of mixed p-type forecasted in areas of observed rain. The NMMB and the NAMNEST members were able to resolve the temperatures in western NY better so the areas of rain were better forecasted and the NAMNEST resolved the transition from ice pellets to snow better. Overall, the NAMNEST outperformed the other three models, especially in transition zones from rain, to freezing rain, to ice pellets, and finally to snow. Since, especially during this three-hour time frame, the upper-level forcings for upward motion and a strong low pressure were not around NY, the main forcing mechanism for this storm was temperature advection and the strength/placement of the cold front. The WRF-ARW and NSSL forecasted the cold front to be much stronger than it was since the temperatures were much cooler than observed after the cold front had passed. The front also was forecasted to move through western NY quicker since the rain falling within the warm sector of the storm moved out much faster than observed. These temperature and front placement inaccuracies led to more p-type discrepancies in the WRF-ARW and NSSL members than in the NMMB and NAMNEST.

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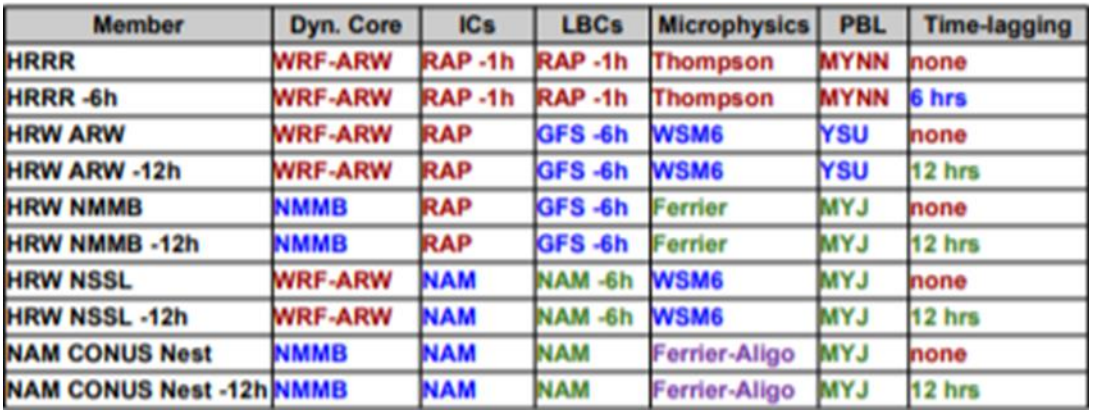
Appendix

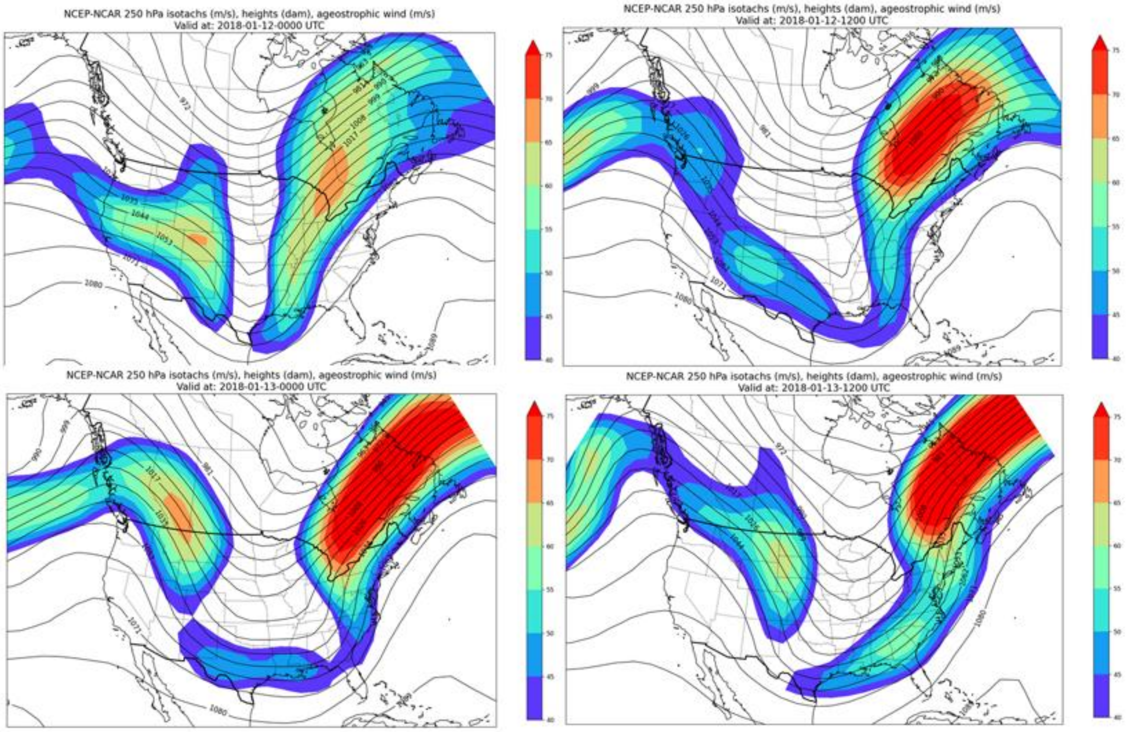
Table 1

HREF v2.1 member configurations



Member	Dyn. Core	ICs	LBCs	Microphysics	PBL	Time-lagging
HRRR	WRF-ARW	RAP -1h	RAP -1h	Thompson	MYNN	none
HRRR -6h	WRF-ARW	RAP -1h	RAP -1h	Thompson	MYNN	6 hrs
HRW ARW	WRF-ARW	RAP	GFS -6h	WSM6	YSU	none
HRW ARW -12h	WRF-ARW	RAP	GFS -6h	WSM6	YSU	12 hrs
HRW NMMB	NMMB	RAP	GFS -6h	Ferrier	MYJ	none
HRW NMMB -12h	NMMB	RAP	GFS -6h	Ferrier	MYJ	12 hrs
HRW NSSL	WRF-ARW	NAM	NAM -6h	WSM6	MYJ	none
HRW NSSL -12h	WRF-ARW	NAM	NAM -6h	WSM6	MYJ	12 hrs
NAM CONUS Nest	NMMB	NAM	NAM	Ferrier-Aligo	MYJ	none
NAM CONUS Nest -12h	NMMB	NAM	NAM	Ferrier-Aligo	MYJ	12 hrs

Note. Retrieved from https://www.spc.noaa.gov/exper/href/ ICs and LBCs refer to the parent model providing initial and lateral boundary conditions, respectively. PBL is the planetary boundary layer scheme.


NCEP-NCAR 250 hPa isotachs (m/s), heights (dam), ageostrophic wind (m/s)
Valid at: 2018-01-12-0000 UTC

NCEP-NCAR 250 hPa isotachs (m/s), heights (dam), ageostrophic wind (m/s)
Valid at: 2018-01-12-1200 UTC

NCEP-NCAR 250 hPa isotachs (m/s), heights (dam), ageostrophic wind (m/s)
Valid at: 2018-01-13-0000 UTC

NCEP-NCAR 250 hPa isotachs (m/s), heights (dam), ageostrophic wind (m/s)
Valid at: 2018-01-13-1200 UTC

Figure 1 *250 hPa Winds*

Note. 250-hPa winds shaded, height contoured beginning at 0000 UTC 12 January 2018, advancing every 12 hours. Data retrieved from NCEP-NCAR archive

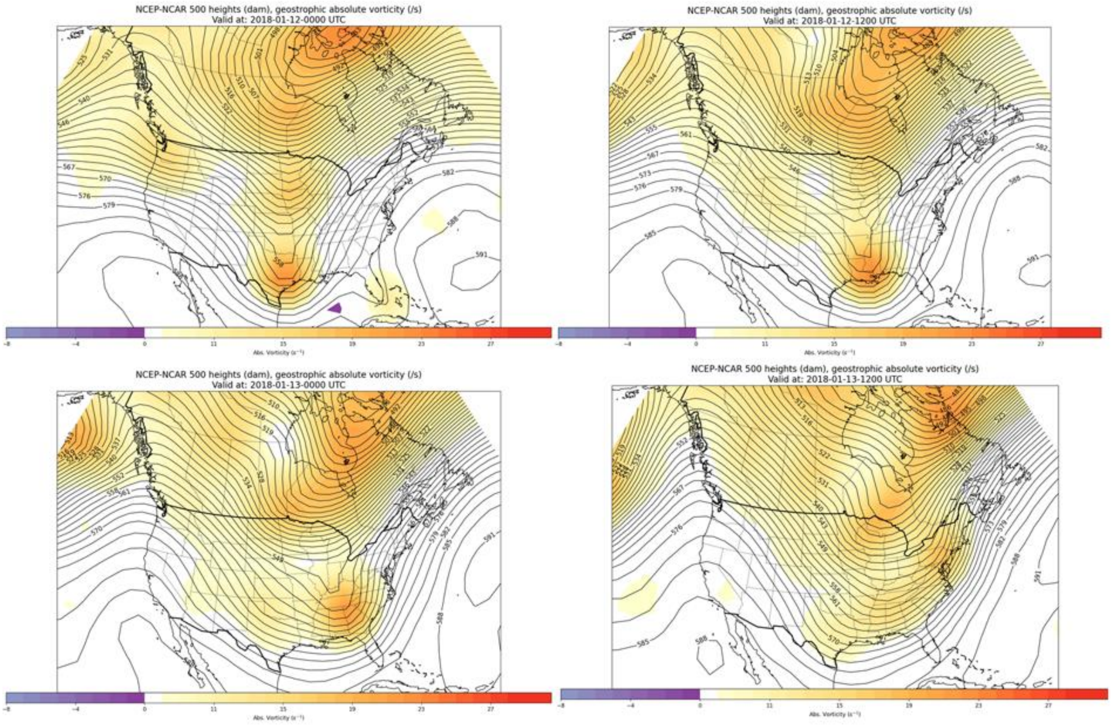
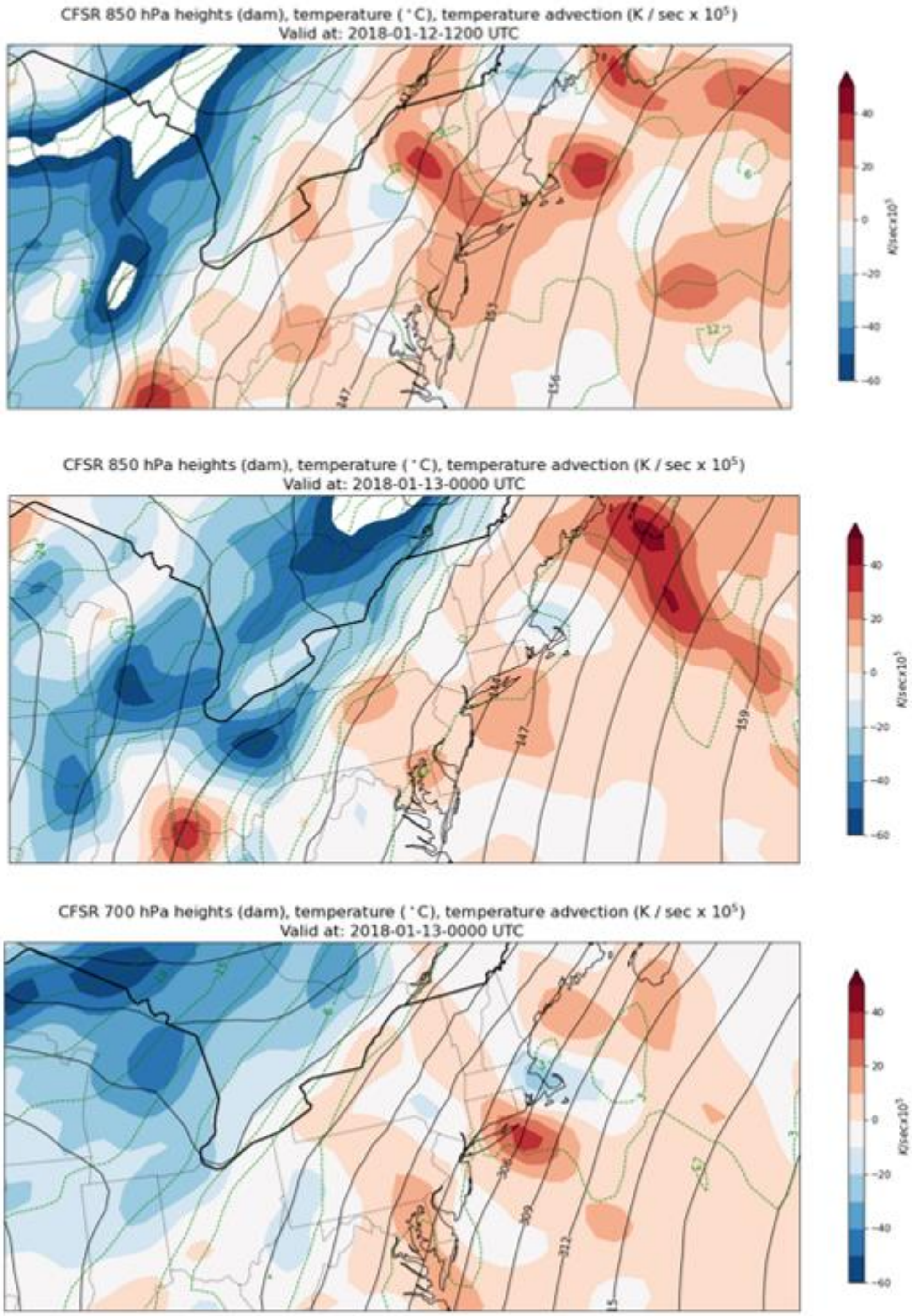


Figure 2 *500 hPa Vorticity*

Note. 500-hPa vorticity shaded, heights contoured beginning at 0000 UTC 12 January 2018 advancing every 12 hours. Data retrieved from NCEP-NCAR archive



CFSR 850 hPa heights (dam), temperature (°C), temperature advection (K / sec x 10^5)
Valid at: 2018-01-12-1200 UTC

CFSR 850 hPa heights (dam), temperature (°C), temperature advection (K / sec x 10^5)
Valid at: 2018-01-13-0000 UTC

CFSR 700 hPa heights (dam), temperature (°C), temperature advection (K / sec x 10^5)
Valid at: 2018-01-13-0000 UTC

Figure 3 *850/700 hPa Temperature Advection*

Note. 850-hPa temperature advection shaded (positive red, negative blue) at 1200 UTC 12 January and 0000 UTC 13 January. 3rd plot is of 700-hPa temperature advection at 0000 UTC 13 January 2018. Data retrieved from CFSR

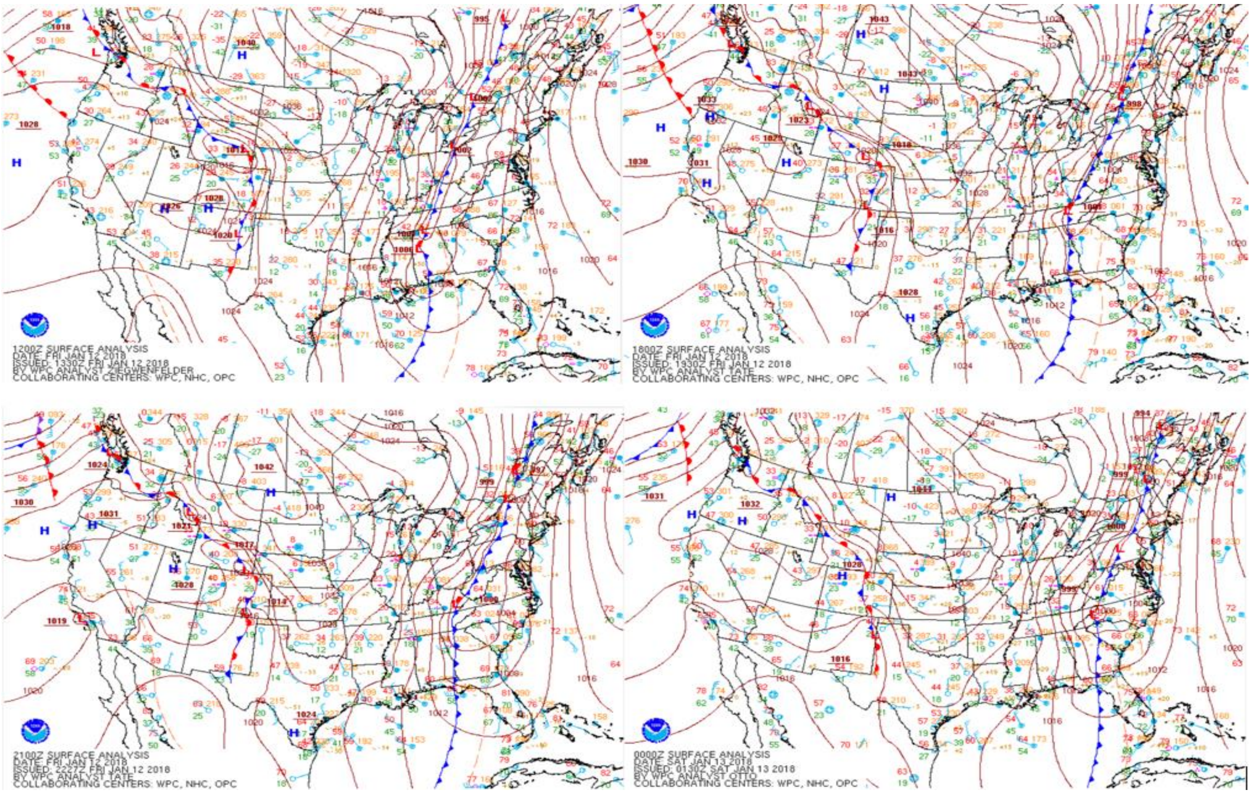


Figure 4 *Surface Maps*

Note. Surface analyses from WPC archive beginning at 1200 UTC 12 January.

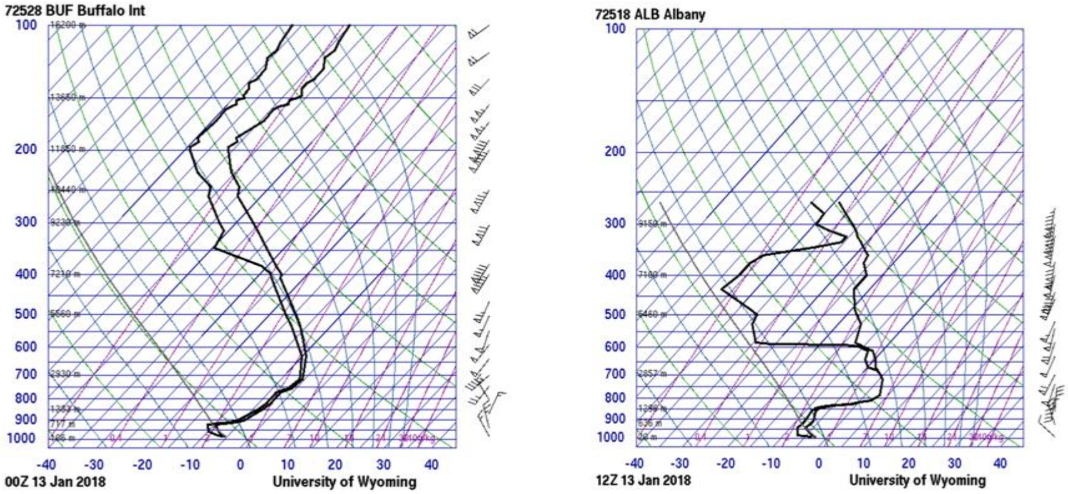


Figure 5 *Soundings*

Note. Albany and Buffalo NWS soundings retrieved from University of Wyoming Upper Air.

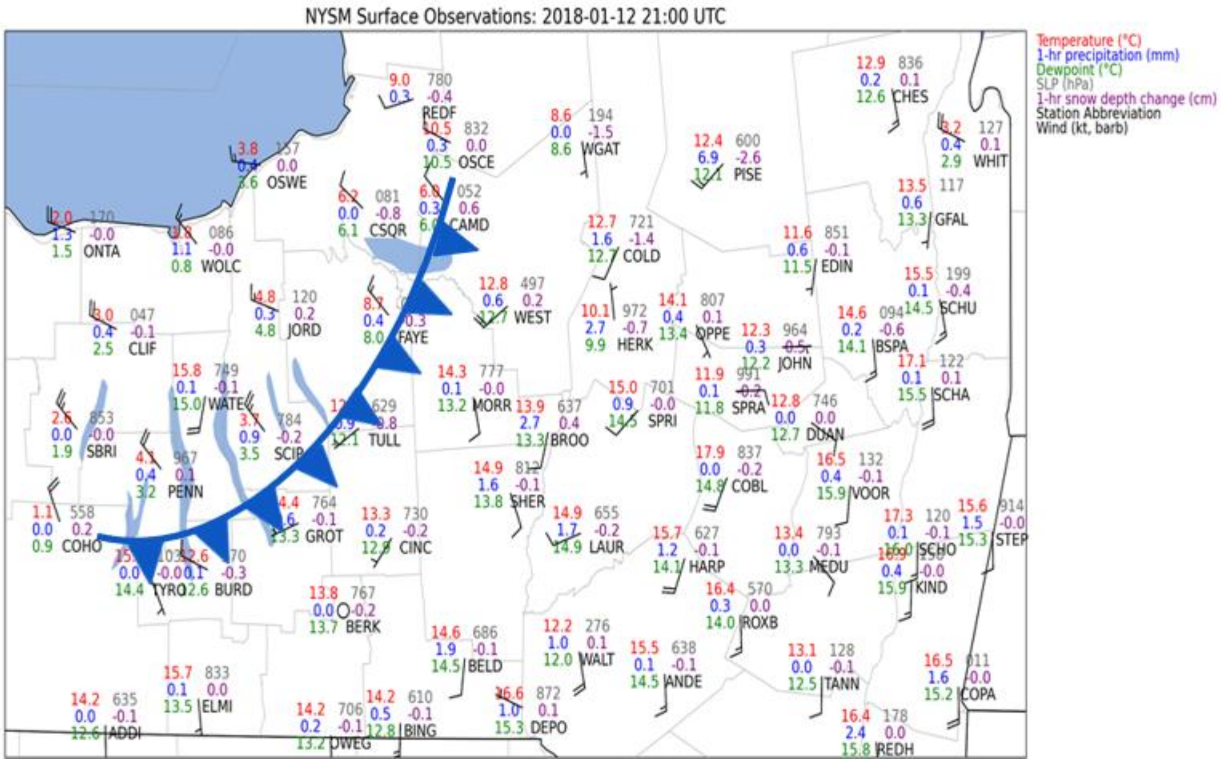


Figure 6 *NYS Mesonet Surface Station Map*

Note. NYS Mesonet station plot at 2100 UTC 12 January 2018 with cold front analyzed in blue.

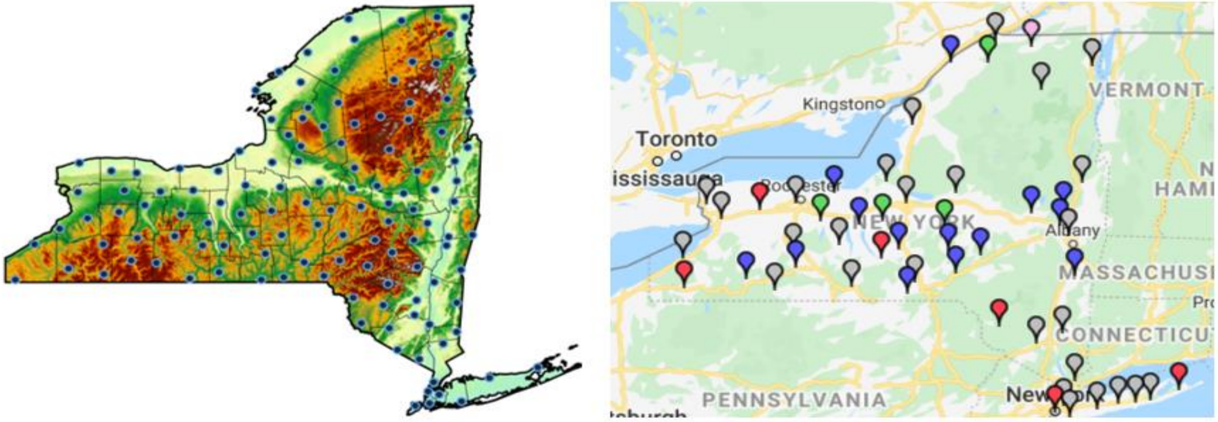


Figure 7 *NYS Mesonet and ASOS Surface Maps*

Note. NYS Mesonet and ASOS location of stations. On the ASOS map, the colored cites are AWSOS stations while the gray is ASOS stations. Retrieved from https://www2.nysmesonet.org/ and https://www.faa.gov/air_traffic/weather/asos/

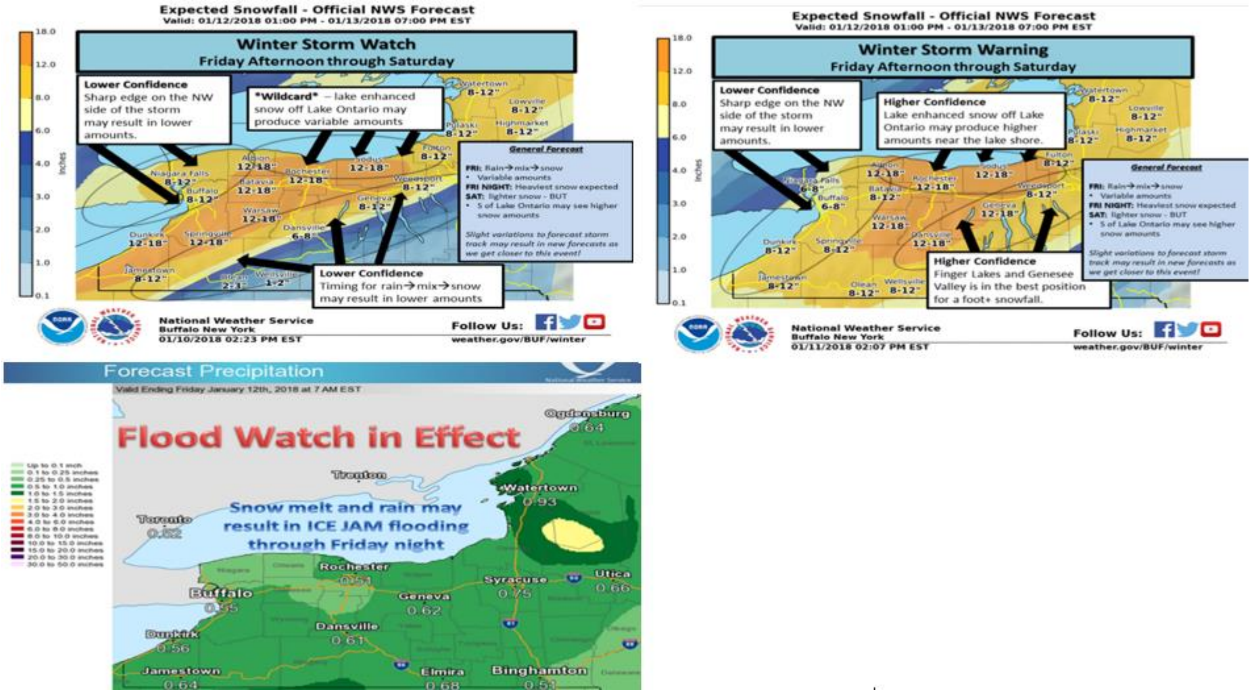


Figure 8 *NWS Buffalo Forecast Maps*

Note. NWS Buffalo forecast products from 11 and 12 January.

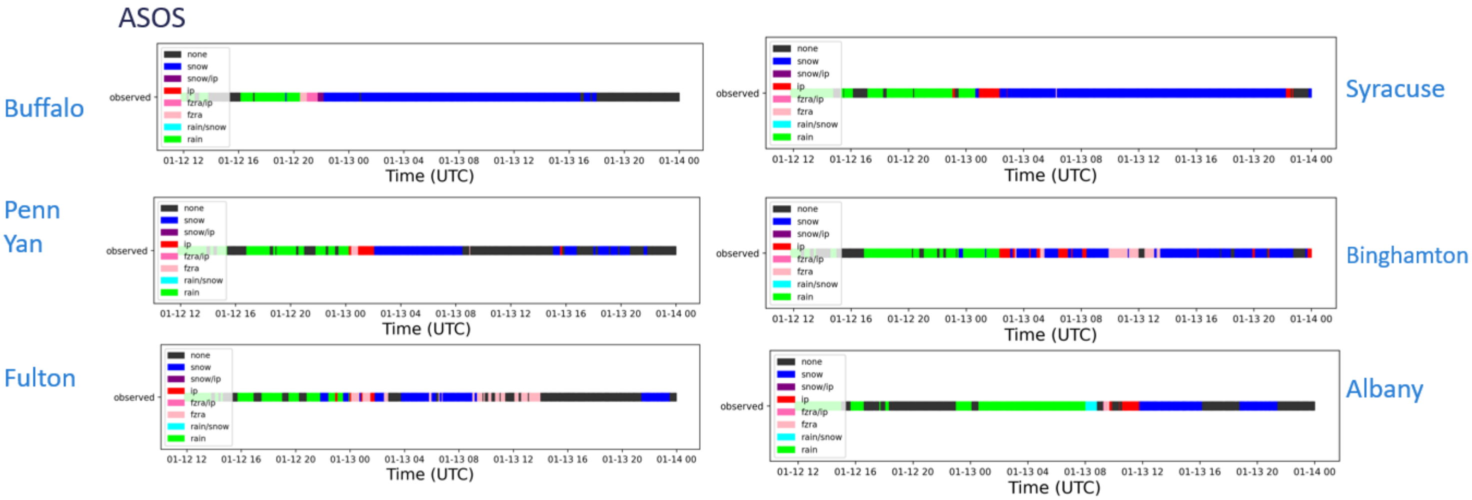


Figure 9 *ASOS p-type time series*

Note. ASOS p-type time series from 1200 UTC 12 January to 0000 14 January 2018.

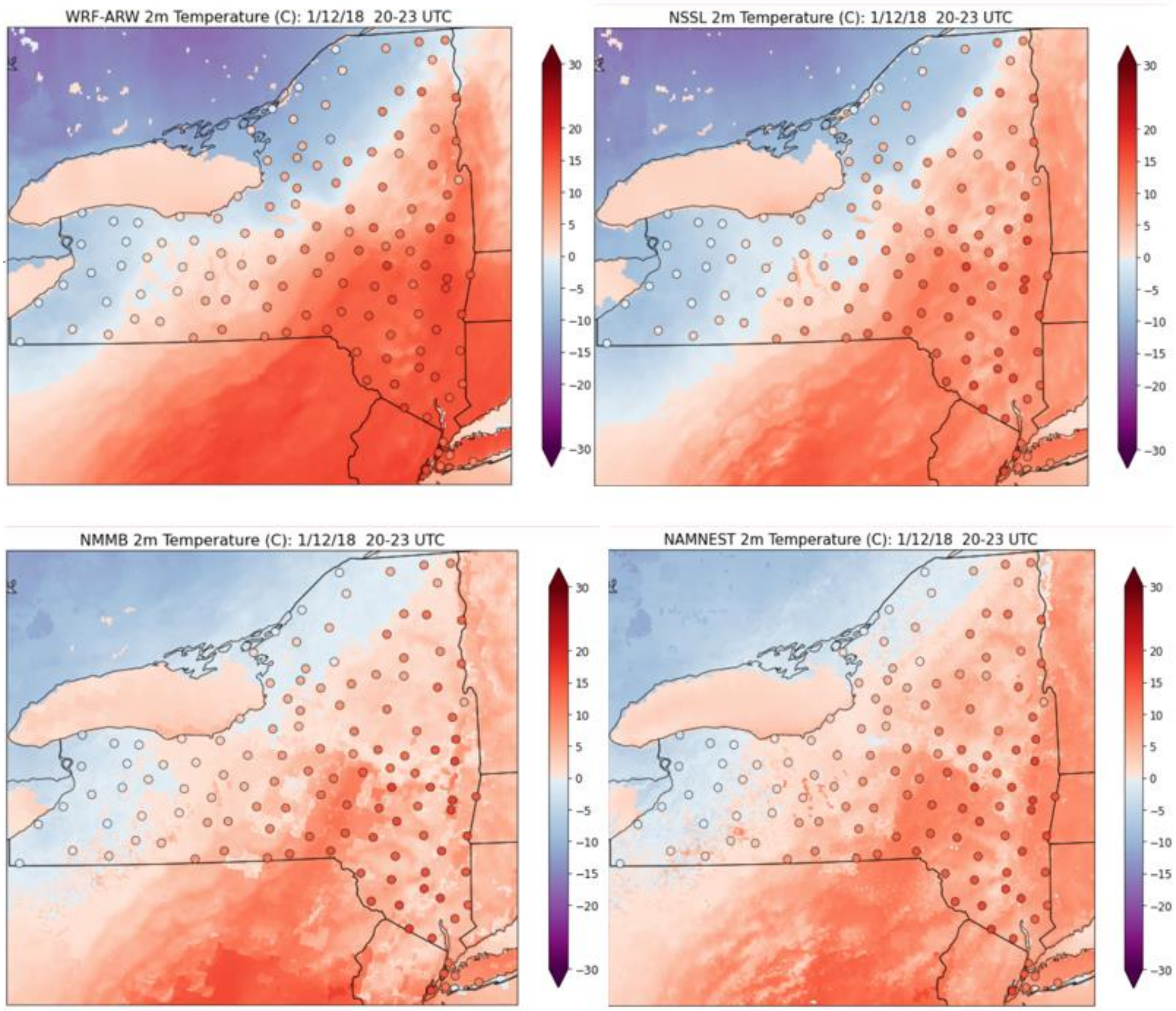


Figure 10 *HREF temperatures vs. NYS Mesonet observations*

Note. HREF 3-hour averaged (12 January 2000-2300 UTC) 2-m temperature shaded with NYS Mesonet 3-hour averaged temperature at each station shaded in the dots

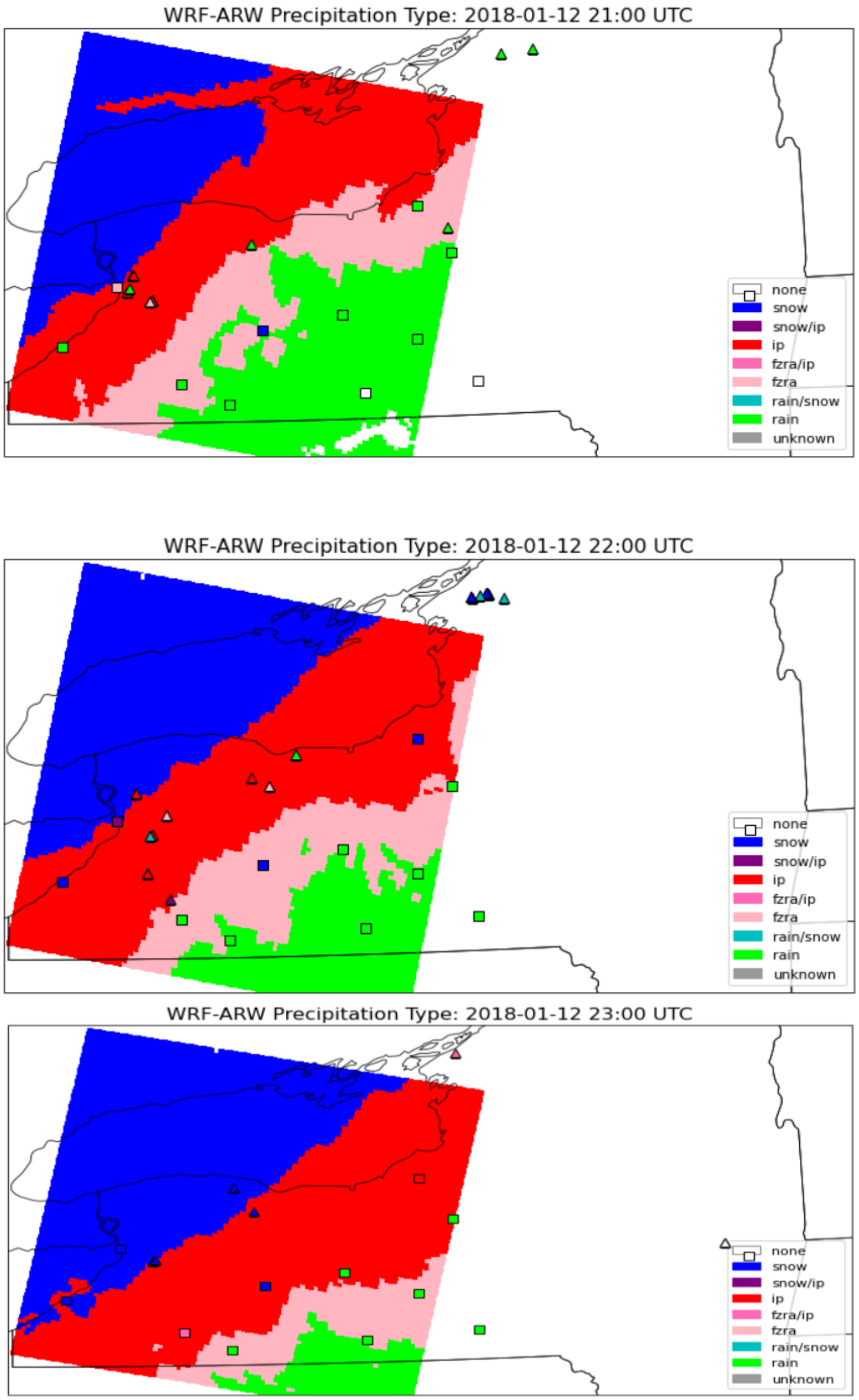


Figure 11 *WRF-ARW p-type vs ASOS and mPING observations*

Note. WRF-ARW p-type shaded with mPING p-type plotted as triangles and ASOS as squares.

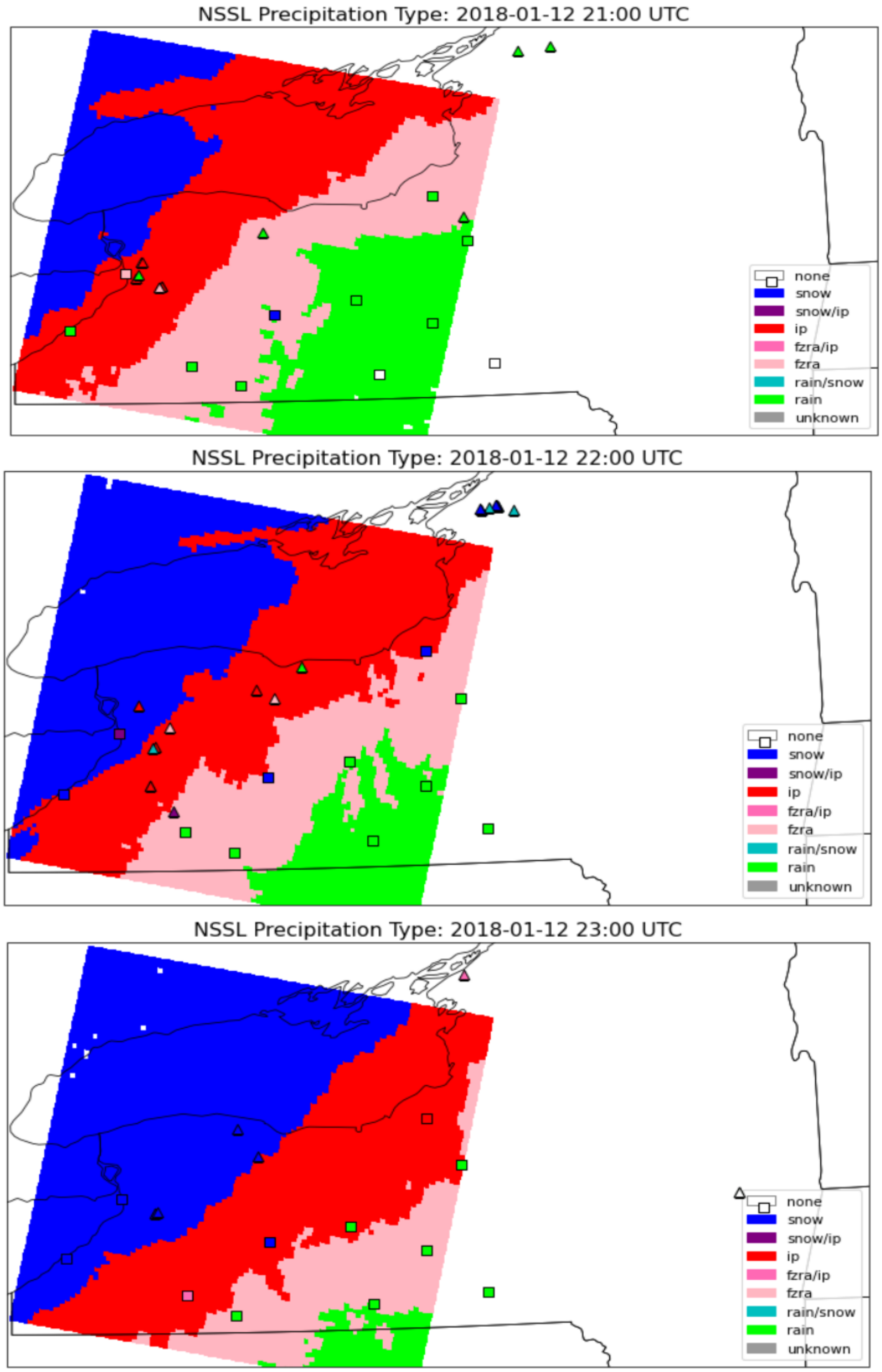


Figure 12 *NSSL p-type vs ASOS and mPING observations*

Note. NSSL p-type shaded with mPING p-type plotted as triangles and ASOS as squares

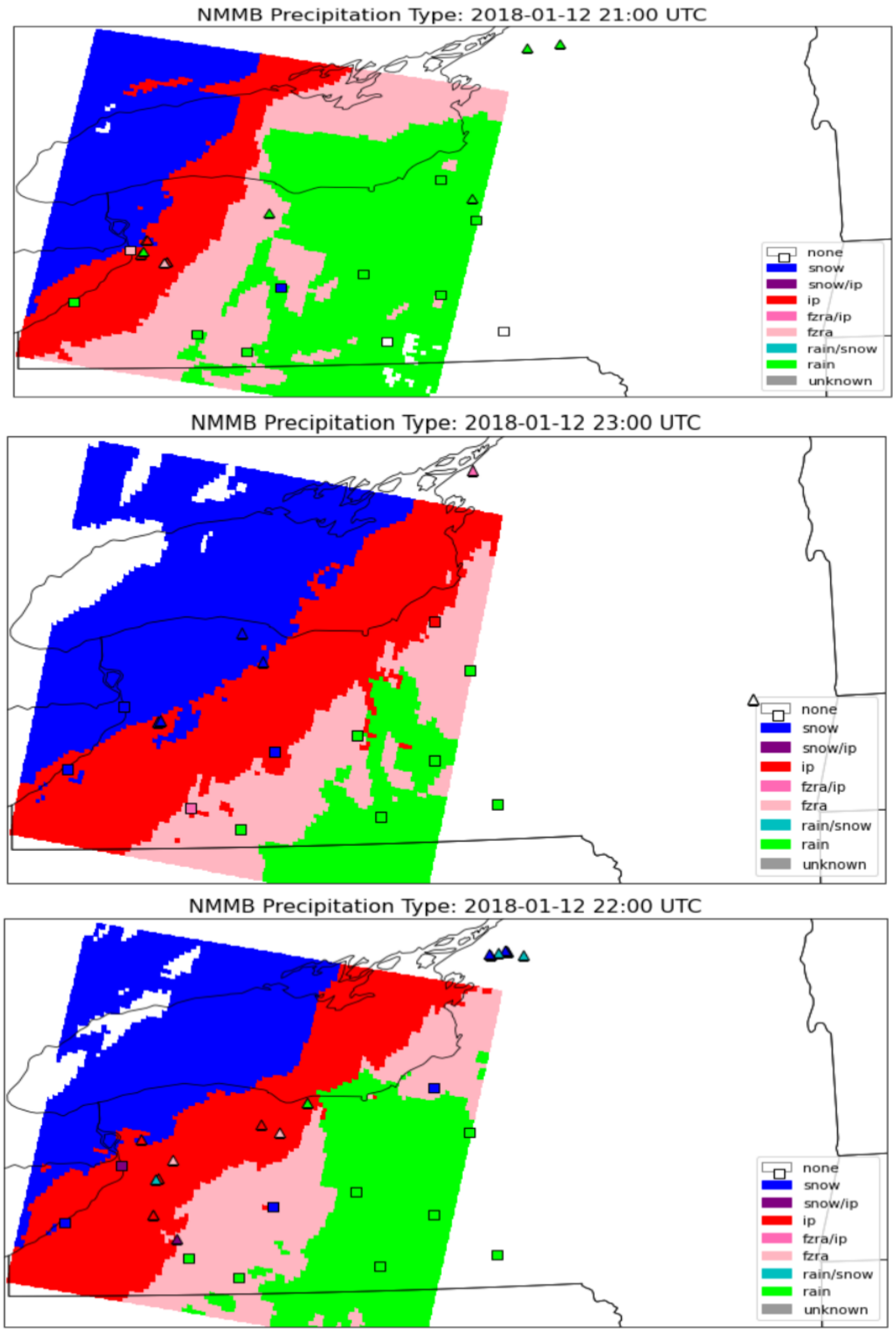
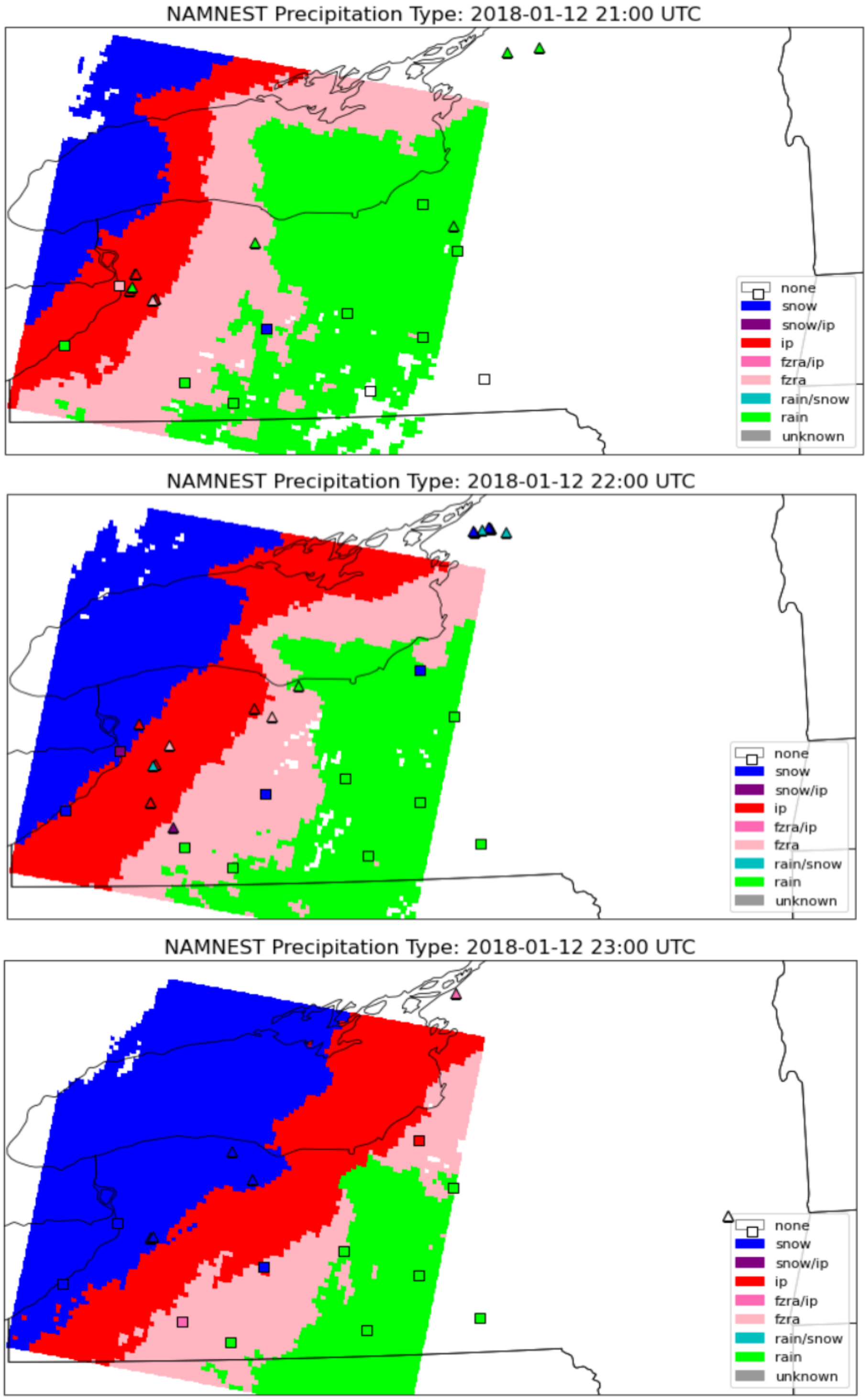


Figure 13 *NMMB p-type vs ASOS and mPING observations*

Note. NMMB p-type shaded with mPING p-type plotted as triangles and ASOS as squares


NAMNEST Precipitation Type: 2018-01-12 21:00 UTC

NAMNEST Precipitation Type: 2018-01-12 22:00 UTC

NAMNEST Precipitation Type: 2018-01-12 23:00 UTC

Figure 14 *NAMNEST p-type vs ASOS and mPING observations*

Note. NAMNEST p-type shaded with mPING p-type plotted as triangles and ASOS as squares