THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF METEOROLOGY AND ATMOSPHERIC SCIENCE

Exploring Snowfall Predictability with the HRRR model for the January 16-17, 2022 Mixed Precipitation Event in Pennsylvania

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Spring 2023

A thesis
submitted in partial fulfillment
of the requirements
for a baccalaureate degree
in Meteorology and Atmospheric Science
with honors in Meteorology and Atmospheric Science

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ABSTRACT

Snowfall predictability in a mixed precipitation event is analyzed, with an emphasis on the effects of the forecasted timing and extent of the transition from snow to other precipitation-types on snowfall forecasts. This is done by comparing High Resolution Rapid Refresh (HRRR) model forecasts to observations during a winter storm that moved through Pennsylvania on January 16-17, 2022. During this storm, snowfall amounts throughout Pennsylvania were significantly overpredicted by the HRRR, with areas to the west of the storm track having the most error. Mapping the observed and forecasted precipitation transition timing shows that precipitation changed from snow to a wintry mix quicker than the HRRR forecasted, especially in areas to the west of the center of the low. These western areas also remained as sleet and freezing rain for longer than areas to the east of the low, where precipitation changed to rain after changing over from snow. Comparing the transition times at specific locations made a more quantitative analysis possible, showing that the forecast error was only in the range of one to three hours and occurred during the time of the heaviest precipitation. Analyzing soundings showed that temperatures around 850 mb were higher than forecast around the time of the transition. After the HRRR forecasted the precipitation to change over, it added additional snowfall accumulation in some locations, increasing the forecast snowfall error. An analysis of the synoptic scale progression of the storm discovered that elements such as the track and strength of the low pressure, as well as the position and strength of the high pressure to the north supplying the arctic air, were forecasted well and likely were not the primary causes of snowfall error. Overall, quicker than expected transition to sleet was a source of error, especially at initialization times farther from the storm arriving in Pennsylvania.

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ACKNOWLEDGMENTS

I first would like to thank my thesis advisor Dr. Greybush. His synoptic meteorology class inspired me to do my project on winter storms and he provided thoughtful guidance throughout the thesis process. He was always willing to answer any questions I had, and he went out of his way to provide feedback when I asked for it. I would also like to acknowledge the NASA IMPACTS program. It provided me additional observation data to analyze the storm and I was fortunate enough to go down to the Wallops Flight Facility and forecast for their flights into winter storms. I would also like to thank my parents who have always supported me and helped put me in a position to achieve this. Lastly, I would like to thank my teammates on The Legion of Broom, my curling team, as writing this paper would not have been possible without them, or at least that is what my contract says.

Chapter 1

Introduction

Winter storms are a common occurrence in the Eastern United States, causing billions of dollars in property damage every year (Insurance Information Institute, 2023). On average, the region receives twelve major storms per winter, and substantially more minor storms (Hirsch, 2001). These storms disrupt travel, commerce, and everyday life for everyone living in their path. While some of these storms bring only snow, many of them bring a variety of different precipitation-types, including sleet, freezing rain and rain. This is especially true in the study region of Pennsylvania where its varied topography and proximity to the Atlantic Ocean allow for a variety of precipitation-types to fall. While forecasting snowstorms is challenging, forecasting storms with precipitation-type changes is even more difficult, as forecasting the type and timing of precipitation transitions adds a new level of complexity. Not only is the amount of overall precipitation important, but the duration and intensity of each precipitation-type are just as important. These storms with precipitation-type transitions often have a more complex synoptic setup, such as Miller type B cyclones, as defined by Miller (1948), with precipitation moving from one storm weakening over the Ohio Valley to another storm strengthening off the Mid-Atlantic Coast. These storms often feature warmer air aloft overrunning colder air at the surface, creating mixed precipitation like sleet and freezing rain at the surface. This makes them more difficult to forecast as the speed and location of the storm transition need to be forecasted in addition to the location and strength of the center of low pressure itself (National Weather Service State College, 2018). These storms with precipitation transitions are important because each precipitation-type causes different hazards that need to be addressed differently. The impacts of a foot of snow are extremely different than the impacts of a half-inch of freezing rain or an inch of rain on a deep snowpack. For example, a long stretch of freezing rain may cause significantly more power outages than a plain snowstorm, sleet can make driving deceptively treacherous as it can behave differently than snow, and heavy rain on an existing snowpack poses an acute flooding risk (Li, 2019). One other hazard of mixed precipitation events is that communicating potential risks is more difficult than for plain snowstorms, as each precipitation-type presents different problems. Therefore, these storms are more likely to produce hazards the general public is not expecting. This means that knowing the duration and amount of each precipitation-type would help everyone subjected to these storms to prepare more effectively. This would give forecasters the ability to provide more accurate forecasts of the expected amounts of each precipitation-type and allow the public to be better informed on the hazards they will bring, helping the public make more informed decisions that reduce the likelihood of loses or injuries caused by these storms. The importance of forecasting these mixed precipitation storms correctly motivated this study on the predictability of snowfall in these mixed precipitation events.

Chapter 2

Background and Theory

2.1 Typical Precipitation Transition Pattern

In a winter storm, a common precipitation-type transition is from snow to sleet, to freezing rain, and finally to rain (Coleman, 2014). This transition is due to warm air advection being strongest around 850mb, raising temperatures at that height above freezing before the surface. The warming is responsible for changing the snow to sleet and freezing rain as the snow melts in this layer before refreezing in a colder layer near the surface (Stewart, 1992). If the precipitation freezes in the air before it hits the ground, it is sleet, and if it freezes after it hits the ground, it is freezing rain. Precipitation changes to rain once temperatures from the surface to the warmer layer in the lower atmosphere rise above freezing. Due to a spatially varying temperature profile, the transition zone is not a single line as there are pockets of different precipitation-types and areas where there are multiple precipitation-types occurring at the same time. (Coleman, 2014). For example, in an area of sleet, there is often snow mixed in on the colder side of the zone and freezing rain mixed in on the warmer side. On the backside of a storm, the precipitation changes from rain back to snow as cold air advection and latent heat absorption by melting precipitation cool the entire atmosphere below freezing (Stewart, 1992). This does not necessarily happen in reverse order of the transition on the frontside of the storm and it is often a change from rain directly to snow. The January 16-17, 2022 storm studied in this paper had transitions that roughly followed the ones described. One other aspect of precipitation transitions is that fog is typically not present where there is snow along a warm front, which is important in using visibility as a proxy for precipitation-type (Stewart, 1995). This means that precipitation would have to change to sleet, freezing rain or rain for fog to develop. Therefore, the visibility change from this transition would be apparent as the fog would not be able to form until the precipitation has fully transitioned, and by then, the visibility change would already have been noticeable.

2.2 Ways to Change Precipitation-Type

The conditions necessary for each precipitation-type are very precise creating many ways precipitation-type transitions can happen. In many cases, there is a very narrow band where each precipitation-type is occurring (Coleman, 2014). Therefore, subtle changes in temperature, precipitation rate, and water phase can move the locations of these bands significantly. One process that can move these bands is temperature advection, the transport of higher or lower temperatures by the wind. Advection of higher temperatures in an atmospheric layer can raise temperatures above freezing and cause snowflakes to melt. Warm air advection is often faster in the areas between 925 to 850 mb than at the surface (Stewart, 1995). This is because friction from the ground slows the wind at the surface, and colder air is denser than warmer air, making it harder to dislodge at the surface. Precipitation rate is another key factor that influences precipitation-type. In areas where temperatures are slightly above freezing and heavy precipitation is occurring, cooling due to the melting or sublimating of snowflakes can change precipitation from rain to snow (Kain, 2000). The opposite can occur where the latent heat release from the formation of snow in clouds can warm the layer. Also, the latent heat released by the freezing of freezing rain and sleet can raise surface temperatures above freezing (Lackmann, 2002). This can change the precipitation to rain. All these latent heating and cooling effects are most pronounced in areas with minimal horizontal temperature advection (Lackmann, 2002). However, in the January 16-17 case being studied here, there was strong horizontal temperature advection, so those effects were not the primary drivers of the heating and cooling. These factors still likely had non-negligible effects. It is also noted that freezing drizzle can occur when temperatures are below freezing in the entire atmosphere (Bocchieri, 1980). This means that when identifying precipitation-types, having temperatures below freezing in the entire atmosphere is not enough to call the precipitation snow.

2.3 Topographic Effects on Precipitation Transitions

Pennsylvania has varied topography, which produces a sizeable impact on precipitation-type across the state. In the northeast part of the state, there is a plateau called the Pocono Mountains that is about 1000 ft taller than the surrounding areas, which typically causes it to be colder that its surrounding areas. In the west central part of the state, there is a south to north oriented line of mountains called the Alleghenies that extend to the east and west a little in the northern tier of the state. These mountains are a sub range of the Appalachians, and they are generally 1000-2000 feet taller than the areas around them. The mountains commonly trap cold air on their leeward side and have temperatures several degrees lower than their surrounding valleys (Bell, 1988). These effects can cause there to be sleet and freezing rain on one side the leeward side of the mountains and plain rain on the windward side. If the temperatures in the atmosphere are highest at the surface, precipitation can remain as snow for longer periods of time on the mountains compared to surrounding areas. If there is a warmer atmospheric layer advancing into an area, the mountains can block its progression and keep one side as snow while the other side is rain (Steenburgh, 1987). This is especially apparent with taller mountains like the Washington Cascades. However, shorter mountains like those in Pennsylvania likely have similar effects. Another effect of topography on precipitation-type is that orographic lifting can lower temperatures at higher elevations and drop them below freezing (Marwitz, 1987). In a case study from the Sierra Nevadas, the ascent of air, combined with the melting of snow, lowered the freezing level around 1300 ft. This was most pronounced with a stable atmospheric layer. While the Alleghenies are not as tall as the Sierra Nevada mountains, they are tall enough for the ascending air to have some impact on the thermal profile of the atmosphere. This storm being studied by this paper also had a very stable temperature inversion during the heaviest precipitation and had peak temperatures over the Alleghenies only a few degrees above freezing. In a case with a significant sleet in North Carolina, it was determined that topographic effects enhanced a strong northeast wind underneath warmer southwesterly winds and maintained colder air at the surface due to cold air advection from an anticyclone over the Northeast United States (Keeter, 2019). Additionally, topography can enhance a cross mountain low level jet that can keep the cold air in place and cause upslope cooling (Forbes, 1987). While the mountains in Pennsylvania are shorter than the Southern Appalachians, similar effects can be felt there. In the storm analyzed in this paper, this change between snow and other precipitation-types was not primarily driven by topography, but topography still had a noticeable effect.

2.4 Precipitation Rate in Transition Regions

In general, the heaviest precipitation rates in winter storms are in precipitation transition regions (Stewart, 1990, 1988). By analyzing rain-snow boundaries, the strongest updrafts were almost always in the rain-snow boundary (Stewart, 1990). Since areas with updrafts typically have high precipitation rates, heavy precipitation typically often occurs in these transition regions. Therefore, if the models misplace the transition, there could be significantly more or less snowfall than forecast as snow is likely falling at a high rate in these areas. The heavy precipitation also exaggerates the effects of latent heating and cooling as there is more precipitation freezing and melting, transferring heat faster.

2.5 Important Model Biases and Sources of Error in Winter Storm Forecasts

Model representation of precipitation transition regions is often problematic and there are many known biases and sources of error. An analysis of thermal profiles in winter storms revealed that while the models represent the general profile fairly well, when warm air is overriding cold air at the surface, the layer of cold air at the surface is often forecasted to be too thin (Ellis, 2022). This commonly occurs in areas with lots of synoptic driven upward motion. This would theoretically cause the model to forecast rain in situations where there should be freezing rain and forecast freezing rain in areas where there should be sleet. The size of this cold layer does not have a significant impact on the snow to sleet transition as that is more impacted by the warmer layer aloft and not the colder air at the surface. In an analysis of winter storms in the winter of 2010 to 2011, it was determined that the High Resolution Rapid Refresh (HRRR) model forecasted the location and extent of the precipitation well, but forecasted precipitation-type in precipitation transition zones less well (Ikeda, 2013). This study did not go into details on the causes of the error but only discovered that there is more error in the transitions than in other parts of the storm. Another cause of error in model winter storm forecasts is small deviations in the storm track (Greybush, 2017). Even if the models forecast the location of the precipitation-type relative to center of the storm correctly, if the models incorrectly forecast the track of the storm, the placement of the different precipitation regions will be incorrect. When analyzing model forecasts of storm track, it is sometimes stated that there is a trend where storms move to the right of the modeled storm track. In a study of hundreds of major east coast winter storms, Burg (2019) concluded that this trend does not exist. Another area the models incorrectly forecast winter storms is with quantitative precipitation forecasts and snow liquid equivalent forecasts. However, data on those aspects was inconclusive for the storm being studied, so they were not extensively analyzed. In winter storms, the models can also errantly predict the timing of the precipitation transitions. This is specifically the amount of time that a location spends in each precipitation-type before it transitions. If the transition from one precipitation-type to another precipitation-type is quicker than forecast, then less of the original precipitation type will fall than forecasted. In this paper, using the HRRR, the snowfall predictability in these mixed precipitation events will be analyzed with an emphasis on exploring how forecasts on the timing of the transition from snow to the other precipitation-types affects forecasted snowfall error.

Chapter 3 Case Description

3.1 Life of the Storm

The storm being analyzed formed over the Deep South on January 16, 2022, on a trough that dipped south from Canada. The storm tracked northward along the Eastern Seaboard slightly inland from the coast. It entered southeast Pennsylvania moving straight north out of Maryland. By the time, it reached Pennsylvania it was starting to occlude, and as it moved through the state, it slowed down and moved more northeasterly (Figure 1). This coincided with a low that formed at the triple point off the New England coast. While the storm behaved like a Miller Type A cyclone, it had some Miller Type B characteristics. There was a weak low over the Great Lakes that helped advect in warmer air before the precipitation entered the state, especially west of the Alleghenies where temperatures were close to freezing in many areas (Figure 2). This resulted in temperatures being much lower over central and eastern regions as the precipitation entered the state, despite those areas being closer to the center of the low. This weak low over the Great Lakes slowly fell apart as the main storm moved up the coast, but its effects were still noticeable throughout the storm. Another source of warm air for Pennsylvania was the high pressure off the Canadian Coast. It had originally been supplying the arctic air to the region, but by the time the storm reached Pennsylvania, it moved far enough eastward that it started to advect warmer air into the region with easterly winds off the Atlantic Ocean (Figure 2).

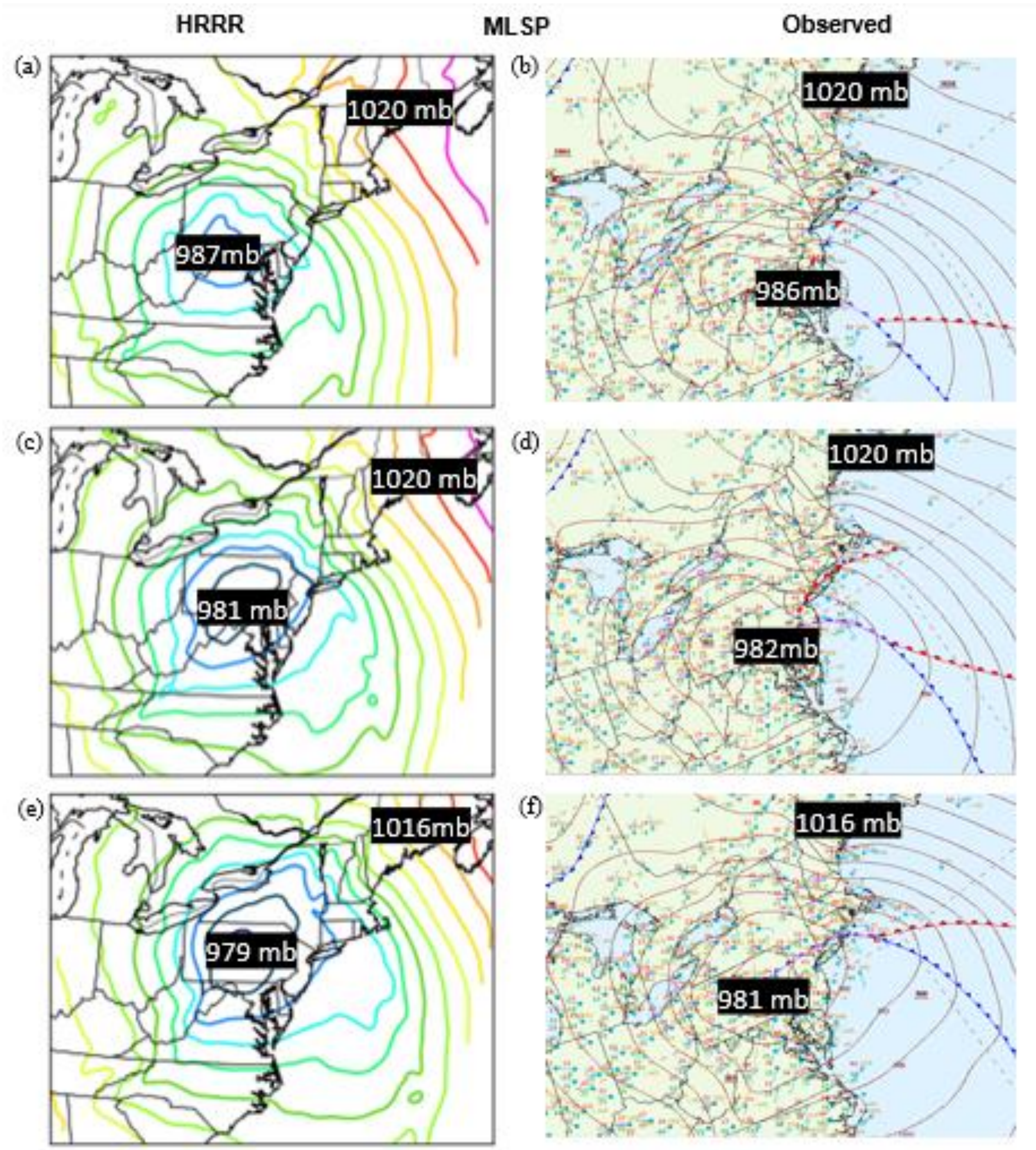

Figure 1: Sea level pressure at selected hours after precipitation entered the state (1/16 18z). Panels (a) and (b) are at 12 hours after the precipitation arrived, (c) and (d) are at 14 hours after, and panels (e) and (f) are at 18 hours after. Panels (a), (c), and (e) are HRRR data, and panels (b), (d), and (f) are observed data provided by the Weather Prediction Center. The number below 1000 mb represents the pressure at the center of the low and the number above 1000 mb represents pressures over Eastern Maine, the location of the arctic high.

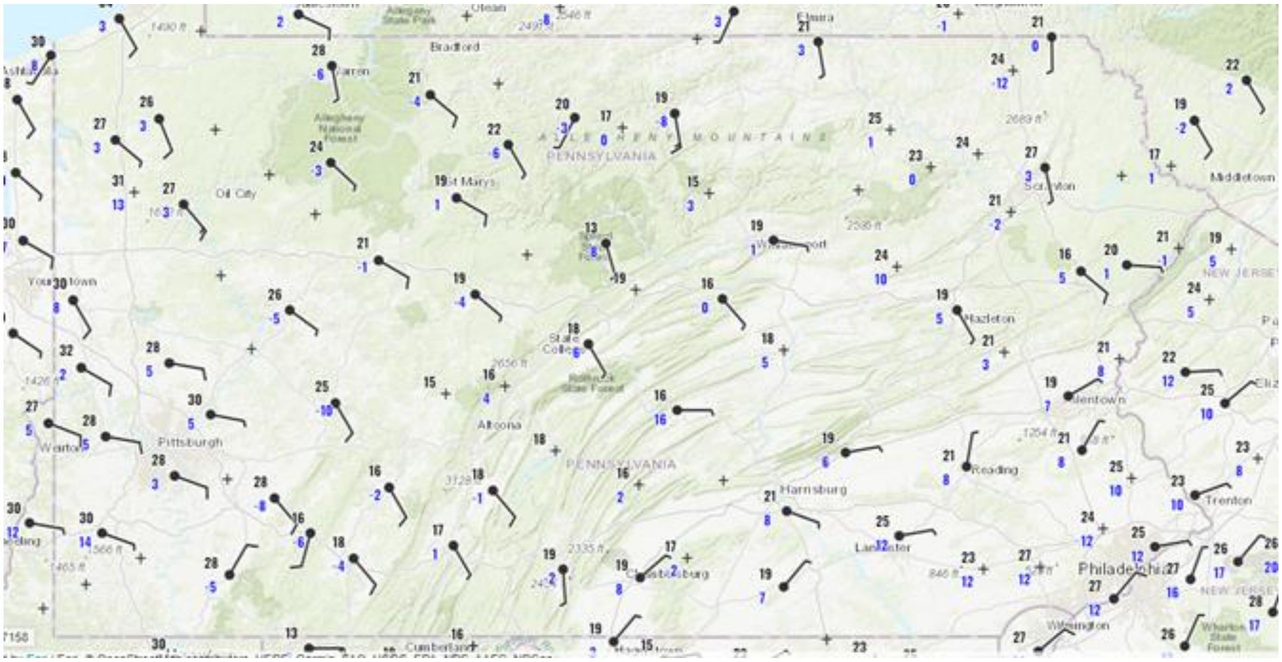

Figure 2: Stational model data at 17z 1/16/22, an hour before precipitation entered the state. Temperatures (black, °F), dew points (blue, °F), and winds (barbs, kt).

3.2 Precipitation Transitions over Pennsylvania

The storm brought a variety of precipitation types to Pennsylvania. As the storm reached the state, the precipitation west of the Alleghenies started off as a mix of snow and sleet as temperatures were generally around freezing. As the heavier precipitation arrived, it quickly transitioned all snow in those areas. East of the Alleghenies, where temperatures were lower, the storm started as all snow. As the center of the storm moved into the state, the precipitation transitioned from snow to sleet, freezing rain, and rain from southeast to northwest (Figure 3). Areas east of the low transitioned to rain quickly while areas to the west of the low remained as sleet and freezing rain much longer before transitioning to rain. However, far northwestern areas remained all snow or only had a brief transition to sleet. As the low moved north of the state, the precipitation transitioned back to snow from west to east, but east of the Alleghenies, the precipitation became very light by the time it transitioned back.

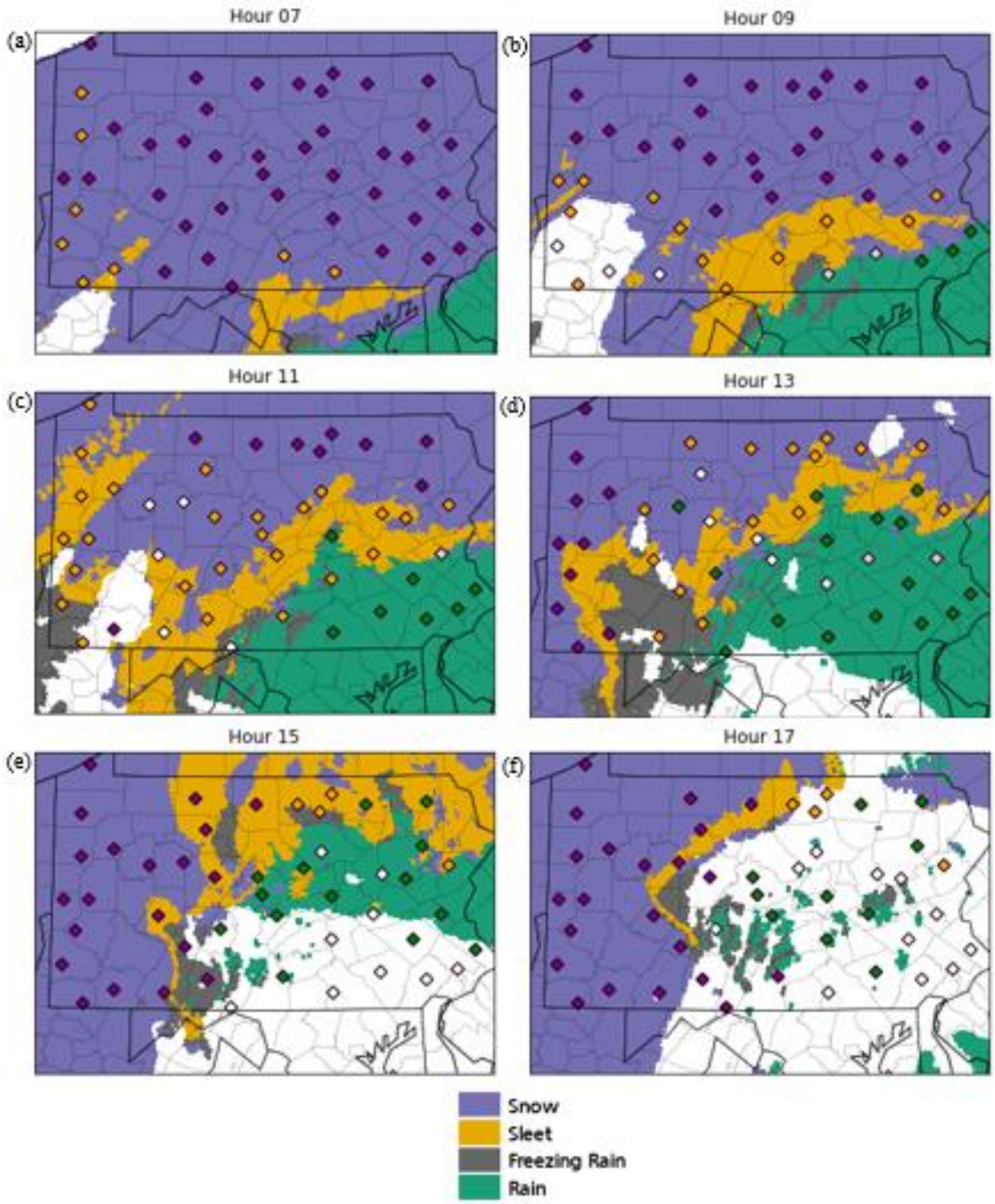

Figure 3: HRRR precipitation-type forecast (background) vs observed totals (points) for Pennsylvania at 7, 9, 11, 13, 15, and 17 hours from the time the precipitation entered the state (1/16 18z). Observed data is from ASOS and PennDOT weather sensors. In areas of precipitation-type overlap, precedence was given to freezing rain, sleet, snow and rain in that order.

While the storm brought many types of mixed precipitation, this was not a classic cold air damming situation where the warmer air in the west is being forced upward by terrain as it moves into eastern areas. In this case, once the heavy precipitation entered the state, the lower temperatures were on the western side of the state and the higher temperatures were in the east. Also, the precipitation transitions were influenced more by position and distance in relation to the center of the low pressure than topography. The storm left between six and twelve inches of snow in northern and western areas, between three and seven inches in central areas, and between two and five inches in eastern areas (Figure 4b). Higher elevations generally received more snow than lower elevations, especially in western areas.

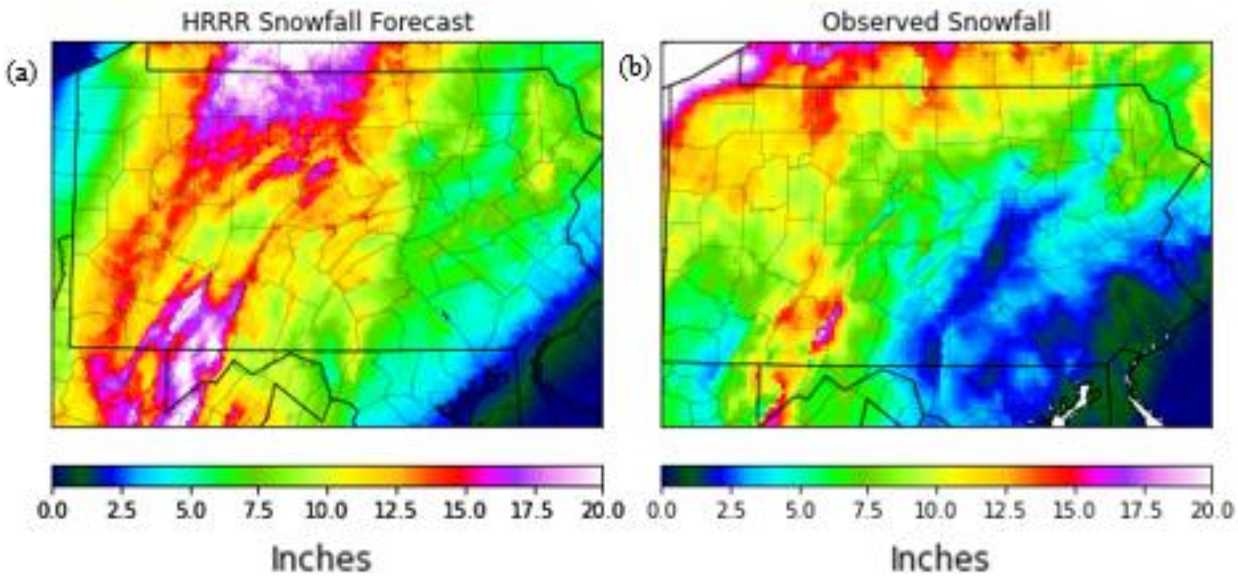

Figure 4: HRRR snowfall forecast (1/16 12z - 1/18 00z) and NOHRSC interpolated snowfall observations (1/16 12z - 1/18 00z). Areas along Lake Erie should be ignored as there was a Lake Effect component that occurred as the storm was still over Northeast Pennsylvania.

Chapter 4

Data and Methods

Between 18z on January 16, 2022 and 18z on January 17, 2022, we compared HRRR model data against a variety of observations. We chose this storm because it had a large precipitation transition area and had NASA Investigation of Microphysics and Precipitation for Atlantic Coast Threatening Snowstorms (MPACTS) upper air data to supplement the observational datasets. The start time was chosen to be 18z on January 16 because that was about an hour before precipitation entered the state. The end time is 18z on January 17 because precipitation was primarily lake effect snowfall after that time and was not from the storm itself. We chose Pennsylvania as the location of study because precipitation-types varied greatly across the state during the storm and we chose the HRRR for the model data because it provides high resolution data that is commonly consulted by forecasters making winter storm forecasts.

4.1 HRRR Data

For the model data, HRRR categorical precipitation-type, snowfall accumulation, sea level pressure, wind, snow liquid equivalent, and temperature data were analyzed. For calculating model precipitation-type, outputted categorical precipitation-type was used, but for areas with overlapping precipitation-types, the most hazardous precipitation-type was used. In this case, the order of most hazardous to least hazardous precipitation is freezing rain, sleet, snow and then rain. These overlapping areas were small and their impacts to the data were generally insignificant. Modeled snowfall data was also taken directly from the model output which uses a varying snow liquid ratio that depends on temperature and a few other atmospheric variables

(Banjamin, 2021). Forecasted mean sea level pressure, 850 mb wind speed, and 850 mb wind direction are directly from model output. 850 mb winds were converted to vectors and then plotted on maps to show both relative speed and direction. HRRR soundings from Lancaster, PA, Pittsburgh, PA and Elmira, NY are from the Iowa State BUFKIT archive. HRRR snow liquid equivalents were calculated by summing the forecasted liquid equivalent of the precipitation before it forecasted a transition.

4.2 Observation Data

Observed sea level pressures are from Weather Prediction Center archived surface analyses. The pressures are from the drawn isobars and stated central pressures of lows and highs. The observed 850 mb data is from the Storm Prediction Center's hourly mesoscale analysis. This is point observation data that was interpolated in areas where there were no observations. Observed surface temperature and wind data are from Automated Surface Observing System (ASOS) sites and Pennsylvania Department of Transportation (PennDOT) sensors. For the map, some other sources of the data appear, but they were not used in any of the calculations. Observed snowfall data is from two sources. At point locations, National Weather Service (NWS) reported snowfall data from trained spotters or NWS employees was used. For the statewide snowfall map, National Operational Hydrologic Remote Sensing Center (NOHRSC) interpolated snowfall data was used. This NOHRSC data is from reports, and it is supplemented with radar estimates where there are no reports. Observed soundings in Pittsburgh, PA were from National Weather Service balloon launches. Observed soundings in Lancaster, PA and Elmira, NY were from Millersville University and Stony Brook University respectively as part of the NASA IMPACTS field campaign. These special soundings were recorded as a supplement to the atmospheric profiles being collected by the airplanes flying into the storm. However, the planes flew north of PA, so data collected from them was not consulted. These sounding locations were selected because they were the only locations in the target area that had sounding data around the time of the precipitation transition and BUFKIT soundings to compare them too. Observed snow liquid equivalents were calculated by adding up all the precipitation data recorded by the ASOS stations before the precipitation changed over from snow. However, the ASOS Users' Guide states that liquid totals from frozen precipitation are generally undercounted, so the data is not fully trustworthy. A major reason for this is evaporation caused by the application of heat to melt the frozen precipitation. If less heat is used, sometimes the frozen precipitation does not all melt and this can block the opening where precipitation falls into. Therefore, storm quantitative precipitation data and snow liquid ratios were analyzed with caution.

4.3 Determining Observed Precipitation-Type

For the observed precipitation-type data, ASOS and PennDOT sensor data were both used. PennDOT sensor data was used in areas without ASOS stations and for areas where nearby ASOS stations did not provide data. These stations form a network of forty-seven locations across Pennsylvania where observed precipitation-type was recorded during the storm. These two sensor sources were used because they provided both precipitation-type and visibility data. These observations were needed because sensor derived precipitation-type data was generally untrustworthy in the precipitation transitions due to sensor error. This unreliability has been noted where snow can be diagnosed as rain or freezing rain and where sleet can be diagnosed as rain or snow (Reeves, 2016). Some examples include the sensors reporting freezing rain at temperatures well above freezing and reporting long periods of snow when sleet was occurring (Figures 5,6). This required that ASOS data to be supplemented with radar and visibility observations to determine the actual precipitation-type. This was a three-step process. The first step was to determine whether the station observed any precipitation. If it did, the sensor precipitation-type was recorded from the station observation. The second step was to record visibility data for the same time. Based off the results of a study that linked visibility to snowfall rate, snow produces much lower visibility than all other precipitation-types and any visibilities greater than one statue mile are considered very light snow or non-snow (Rasmussen, 1999). The third step was to collect radar reflectivity data and analyze the change in radar reflectivity from the hour or two surrounding that time. If there was moderate or high reflectivity values and visibility over a mile, it was determined that the precipitation was not snow. Looking at visibility data, it was determined that a change in visibility corresponded to a change in either precipitation intensity or precipitation-type. If the radar reflectivity generally remained constant during this visibility change, it was clear that it was due to a precipitation-type change. It is typically noted that in precipitation, the melting snowflakes that occur during sleet, freezing rain and rain can have much higher reflectivity than plain snow rain, and effect commonly called bright banding (Farby, 1995). However, if there was melting precipitation, there would be higher visibility, so high reflectivity and high visibility would still be counted as non-snow precipitation. This means that this bright banding would not cause an error in determining precipitation type. Using all the steps for determining precipitation-type was only necessary in areas where the visibility had large changes and where there was a precipitation transition region nearby. If there were very low visibilities and little precipitation, it was determined that fog was present. That data was either discarded or interpreted as rain if temperatures were significantly higher than freezing. Throughout the entire state, there were only a few areas near the Pennsylvania-New York border that had fog around the precipitation transitions. There was enough supplemental data to determine the precipitation-type at these locations though. Using this visibility and radar-based precipitation-type discrimination method also fits personal experience determining the precipitation transition lines using visibility.

Date/Time (L)	Temp. (°F)	Dew Point (°F)	Relative Humidity (%)	Wind Chill (°F)	Wind Direction	Wind Speed (mph)	Visibility (miles)	Weather	Clouds (x100 ft)
Jan 17, 12:10 am	32	28	86	24	E	10	6.00	Lt snow, Mist	OVC020
Jan 17, 12:05 am	30	27	86	23	E	7	6.00	Lt snow, Mist	OVC020
Jan 17, 12:00 am	28	27	93		E	3	5.00	Lt snow, Mist	OVC020
Jan 16, 11:55 pm	27	25	93		N	0	4.00	Lt snow, Mist	OVC020
Jan 16, 11:54 pm	27	23	85		N	0	4.00	Lt snow, Mist	OVC020
Jan 16, 11:50 pm	25	21	86		N	0	3.00	Lt snow, Mist	OVC020
Jan 16, 11:45 pm	25	19	80		N	0	3.00	Lt snow, Mist	OVC020
Jan 16, 11:40 pm	23	19	86		N	0	3.00	Lt snow, Mist	OVC020
Jan 16, 11:35 pm	23	19	86		N	0	3.50	Lt snow, Mist	OVC020
Jan 16, 11:32 pm	23	19	85		N	0	4.00	Lt snow, Mist	OVC018
Jan 16, 11:30 pm	23	19	86		N	0	4.00	Lt snow, Mist	OVC018
Jan 16, 11:25 pm	23	19	86		N	0	2.50	Lt snow, Mist	FEW009 OVC018
Jan 16, 11:20 pm	21	19	93		N	0	2.00	Lt snow, Mist	SCT009 OVC018
Jan 16, 11:15 pm	21	19	93		N	0	1.50	Lt snow, Mist	SCT009 OVC018
Jan 16, 11:10 pm	21	19	93		N	0	0.75	Lt snow, Mist	BKN009 OVC016
Jan 16, 11:05 pm	21	19	93		N	0	0.50	Snow, Freezing Fog	VV009
Jan 16, 11:00 pm	21	19	93		N	0	0.50	Snow, Freezing Fog	VV008
Jan 16, 10:55 pm	21	18	86		N	0	0.50	Snow, Freezing Fog	VV009
Jan 16, 10:54 pm	22	18	84		N	0	0.50	Snow, Freezing Fog	VV009
Jan 16, 10:50 pm	21	18	86		N	0	0.50	Snow, Freezing Fog	VV008
Jan 16, 10:45 pm	21	18	86		N	0	0.50	Snow, Freezing Fog	VV008
Jan 16, 10:40 pm	21	18	86		N	0	0.50	Snow, Freezing Fog	VV008
Jan 16, 10:35 pm	21	18	86		N	0	0.50	Snow, Freezing Fog	VV008

Figure 5: ASOS data from Williamsport, PA at the time of the transition from snow to sleet. Everything after 11:05 PM (0405z) was primarily sleet and not snow despite the sensor recording it as snow. The transition corresponds to the sharp increase in visibility.

Figure 6: Radar reflectivity at 1/17/22 4z. The blue areas of lighter precipitation to the south of Williamsport are due to well-known radar holes and not lightening precipitation.

Chapter 5

Results and Discussion

5.1 Snowfall Error

Looking at the snowfall totals across the state, the HRRR forecasted significantly more snow than actually fell (Figure 4). This is most pronounced in the central and western areas of the state, the same areas that were west or north of the center of the low pressure (Figure 1). The only extensive areas that the HRRR underpredicted were the higher elevations of Northeastern Pennsylvania, most notably the Pocono Plateau. The areas right along Lake Erie should not be considered as their totals contain a large lake effect component we are not analyzing. An analysis of the snowfall at slected cities across the state again shows that the HRRR overpredicted the most in the central and western parts of the state, while doing better in the eastern parts of the state (Figure 7).

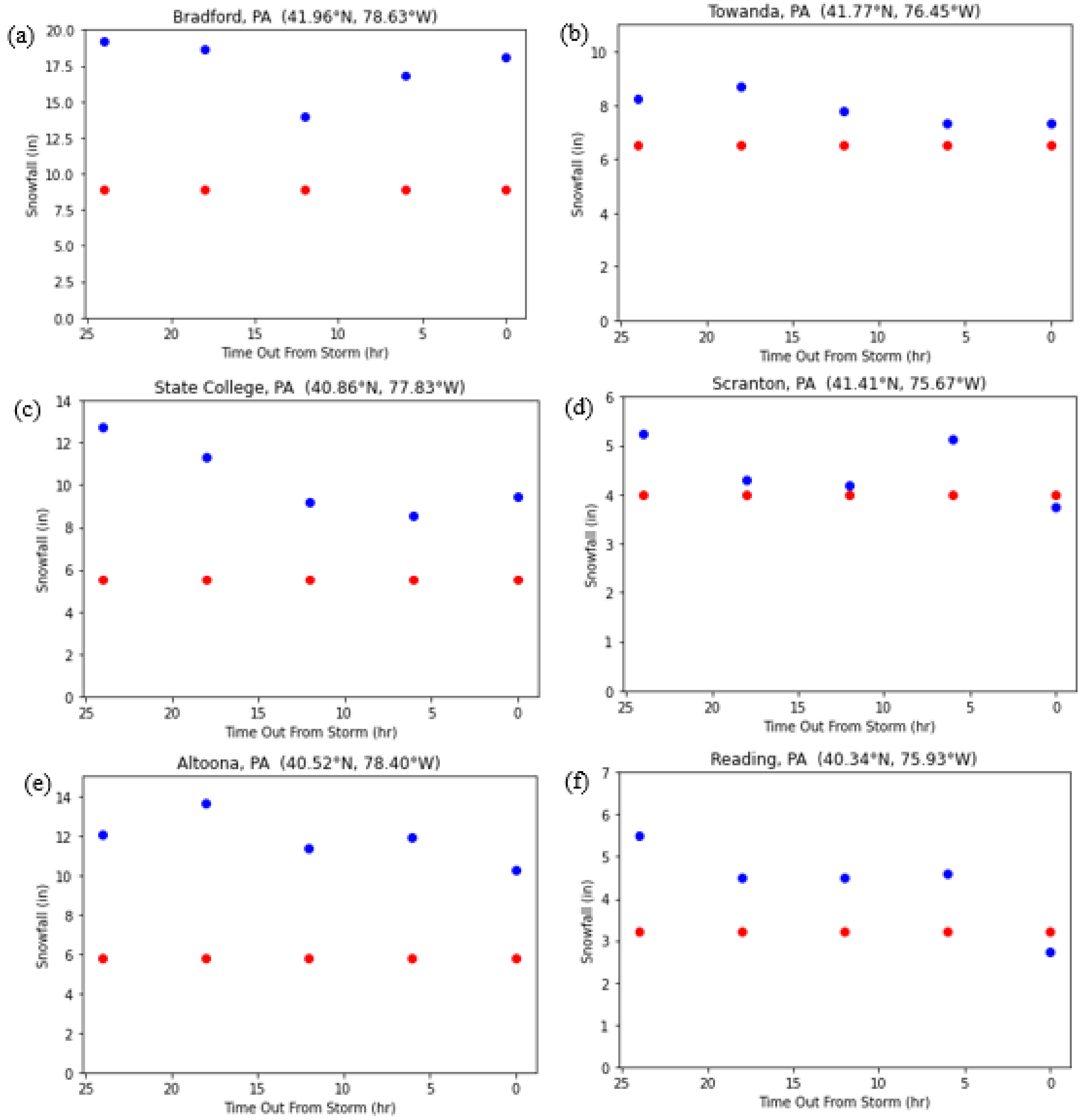

Figure 7: HRRR snowfall forecast (blue) vs observed totals (red) for different locations at different initialization times relative to the precipitation entering Pennsylvania (1/16/ 18z). Observed data is snowfall totals reported by the NWS from trained spotters. Cities to the west of the storm track are on the left and cities to the east of the storm track are on the right.

5.2 Snowfall Forecasts at Different Initialization Times

Looking at snowfall forecasts from different initialization times at six-hour intervals, the HRRR snowfall forecasts improved as the precipitation moved closer to the state, with the best forecasts at the time the precipitation entered the state (Figure 7). The timing implies that the predictability of the precise transition timing and extent are limited to the few model runs before precipitation entered the state. This would mean the predictability horizon is around twelve hours from the precipitation entering the state. Because the snowfall forecasts were generally too high at every initialization time, this improvement was from forecasting less snow at times closer to the start of the storm. In eastern areas, this decrease in forecasted snow was enough to drop the forecasts close to the observed values. However, in the central and western areas, the forecasted totals were still much higher than the observed amounts. While almost every case had lower snowfall forecasts when the storm reached Pennsylvania storm comapred to forty-eight hours out, the difference between the two times was different depending on the location. For doing analysis farther from out from the storm entering the state, ensemble data would likely be much more beneficial.

5.3 Precipitation Transitions Relative to the Track of the Low

The progression of the precipitation transition was different depending on the location relative to the track of the center of the storm, which likely impacted snowfall error. On the eastern side of the low, where the precipitation transitioned to sleet and then rain more quickly, snowfall error was lower (Figures 1, 6). However, in central, western, and northern Pennsylvania, where the precipitation remained as sleet and freezing rain for much longer, the snowfall error was generally higher (Figure 3). In western areas, there were even a few places that never changed to freezing rain or rain. Instead, they only briefly changed over to sleet. In these areas, the snowfall error was still similar to other western areas.

5.4 Topographic Effects

The precipitation transition from snow to other precipitation types did not appear to be significantly affected by topography. The transition was not signficantly blocked or enhanced by the mountains. Instead it was mostly due to the proximity to the center of the low and the side of the low it was on (Figure 3). However, this was not the case for the precipitation transitions from mixed precipitation to rain. Generally, the higher elevations generally stayed at freezing rain and sleet instead of rain, likely due to being at lower temperatures (Figure 3). Higher elevations of the central and western areas also transitioned back to snow more quickly than in lower elevation areas (Figure 3).

5.5 Transition Timing

From the precipitation transition maps, for areas west of the storm track, the preicpitation changed over to sleet one to three hours earlier than the HRRR forecasted (Figure 3). In eastern areas there was less of a time difference between the observed and modeled transition, but there was still some error. For clarification, this map wide analysis was only performed on the 1/16 18z initialization time because it was the only run to correctly predict the timing of the precipitation entering the state. Going out six and twelve hours from the time the precipitation entered the state, the HRRR predicted the storm to arrive around an hour later than it did. This provides a problem because it would make it appear that the HRRR had the precipitation change over from snow an hour late, when the issue was that the storm moved through the state an hour quicker than forecasted. This error would not affect snowfall totals as the same amount would fall, it would just fall an hour earlier than forecasted. The storm timing was not an issue with the 18z run because it had the snow overspread the state at the correct time.

5.6 Transition at Different Initialization Times

As the initialization times moved earlier and farther from the time the precipitation entered the state, the forecasted transition time became increasing later than the observed transition time in many areas, causing a forecast for a longer period of snow than occurred (Figure 8). This corresponded to an increase in error in the snowfall forecasts in many areas, even after correcting for the precipitation arriving earlier than forecasted in many of these areas. For example, for the run initialized at 06z, in State College, the HRRR predicted the transition a full two hours earlier than the 18z run (Figure 8b). This correlated to an eight inch snowfall overprediction instead of a five inch overprediction (Figure 7b). However, this is not the case everywhere. The forecasts from the earlier initialization times were typically only an inch or two higher, but this would be somewhat equivalent to one or two more hours of snowfall before the transition. An important aspect here is that even though the forecasts at the time the storm entered the state were much more accurate, the less accurate forecasts farther out were the ones that had to be used by people preparing for the storm, so their error is still important.

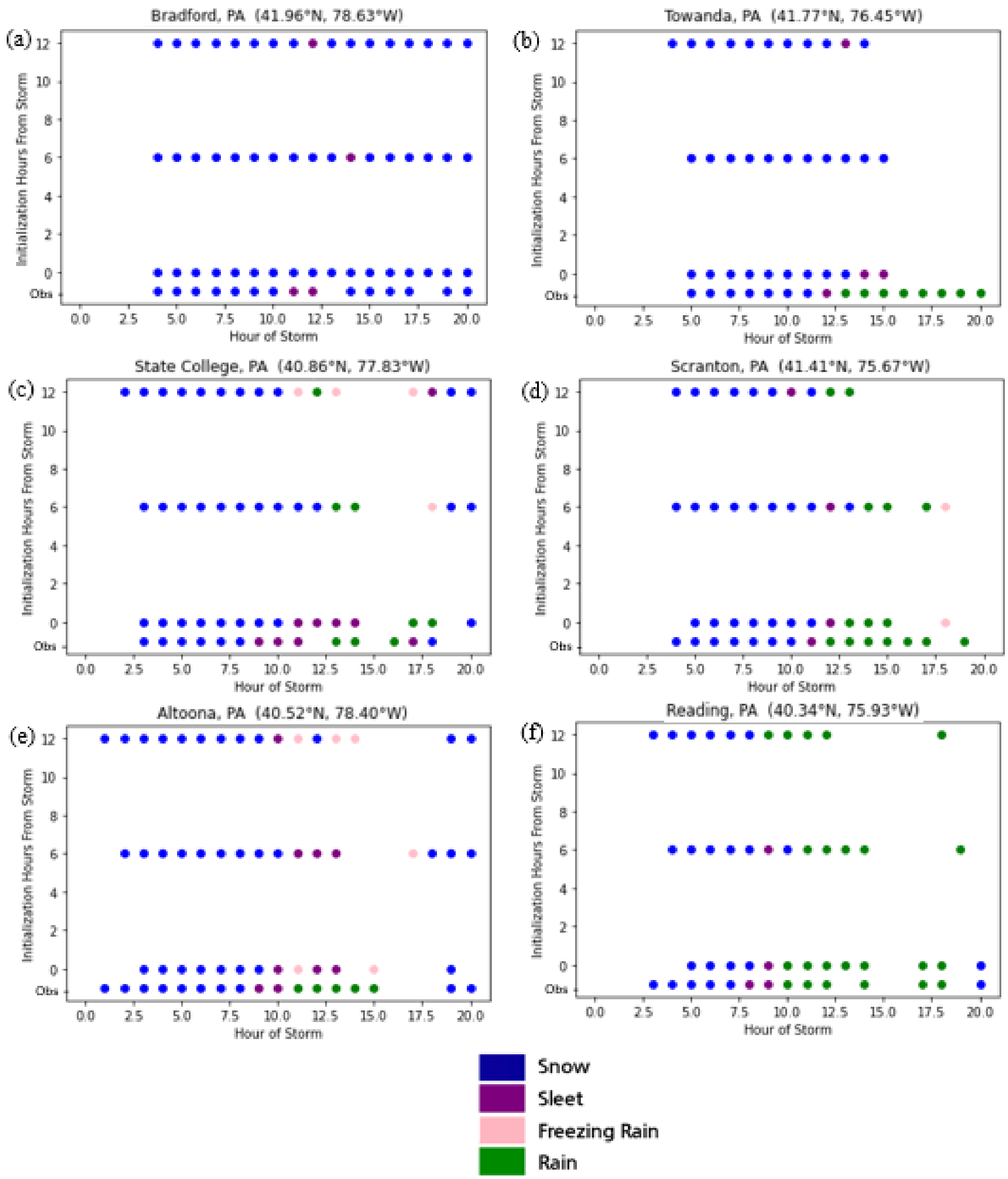

Figure 8: HRRR and observed precipitation-type at selected locations for different model initialization times relative to the precipitation entering Pennsylvania (1/16 18z). Hours are the number of hours since the precipitation arrived in Pennsylvania. Blank areas are when no precipitation was forecasted or observed. The accuracy of transitions between different mixed precipitation-types is not assured so only consult the transitions from snow and back to snow.

5.7 Model Forecasted Snow After Transition

Looking at Figure 9, another problem with the modeled snowfall is that after the HRRR changed from snow to other precipitation-types, it still forecasted a couple more inches of snow accumulation at some locations. The additional accumulation would inflate snowfall totals because snowfall at these times is not physcially possible. There were areas where the HRRR forecasted snow and sleet at the same time, and the categorical precipitation calculations would indicate that only sleet is occurring. However, these areas were very narrow, and the mix of sleet would drastically reduce the snowfall rate that there would likely be no significant snowfall accumulation in those areas. Even if the HRRR was counting some of the sleet accumulation as snow, sleet falling on snow has a tendency to pack the snow down and not add any height to the snow on the ground anyway. This means that the HRRR forecasting snow and sleet accumulation in different categories would be ideal.

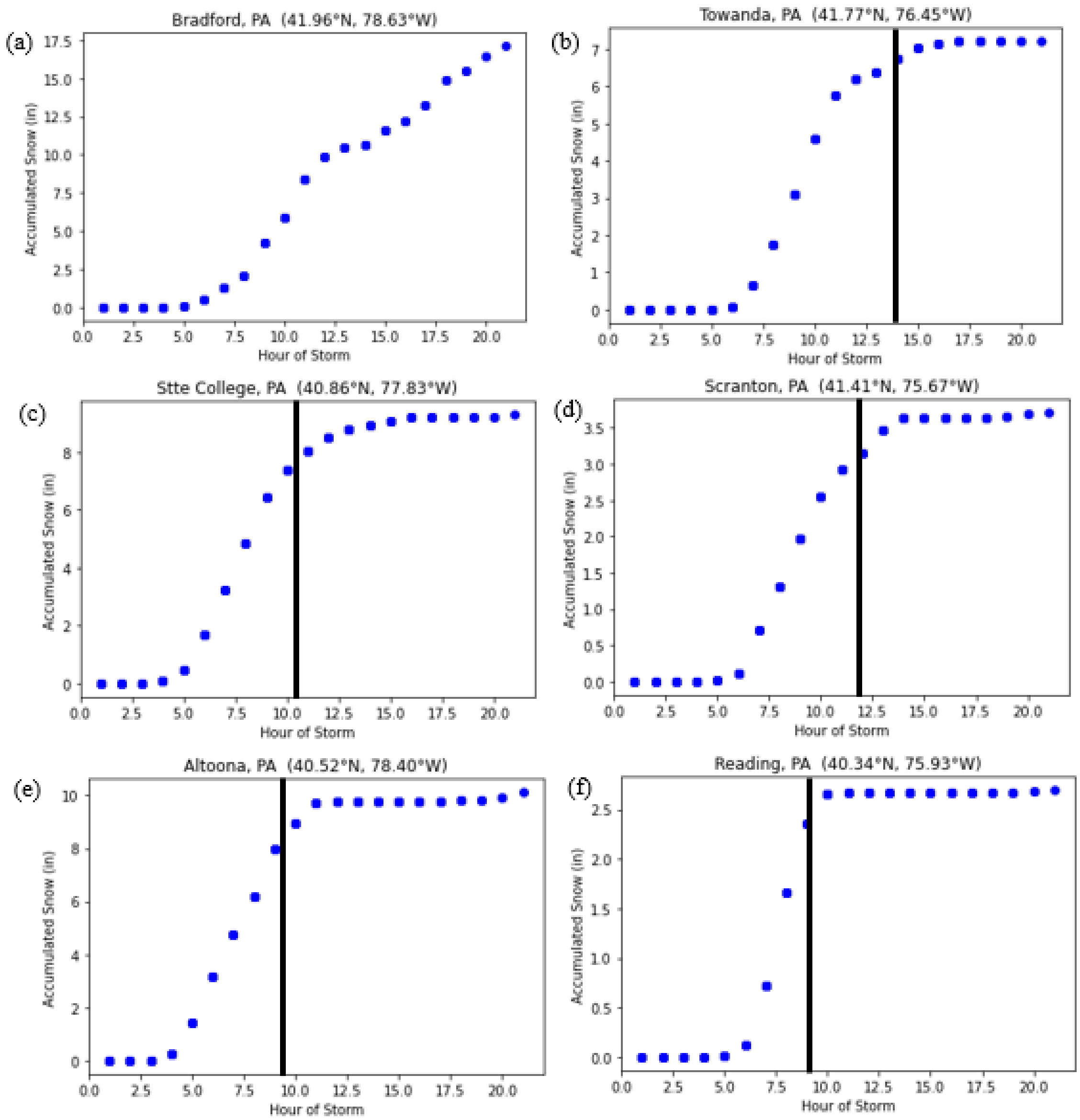

Figure 9: Snowfall accumulation throughout the storm HRRR (initialized at Hour 0) accumulated snowfall (blue) compared to the forecasted transition from snow to other precipitation-types (black line). Accumulation to the right of the line is forecast snow during forecasted non-snow precipitation. In the case of Bradford, the HRRR did not forecast a transition so there is no bar. Models did change the precipitation back to snow in the last couple hours in some of the locations so increases there are not necessarily from forecasted accumulation in non-snow precipitation-types.

5.8 Sounding Analysis

Looking at the modeled and observed soundings, it is clear that one of the main reasons the precipitation changed to sleet faster than the HRRR predicted is that the warm nose aloft moved into Pennsylvania faster than forecast (Figure 10). At 00Z in Lancaster, PA, the HRRR had the warmest temperatures in the atmopshere at a couple degrees below freezing (Figure 10 a, b). However, the observed sounding had a region where temperatures in the atmosphere were slightly above freezing (Figure 10d). The location of the observed sounding, Millersville Univeristy, is 10 miles south of Lancaster Airport, the location of the modeled sounding. However, due to close proximity, and with a lack of significant topography change between the two, a major change in the atmopsheric profile between the two locations is unlikely. The 01z HRRR sounding at Lancaster Airport was also a little colder than the 00z observed sounding at Millersville. In Elmira New York, on the northwestern side of the storm, the same pattern is clear (Figure 10 c, d). The HRRR sounding was again colder than the observed sounding, despite being taken twenty-seven minutes after the observed one and being a couple miles farther south. Elmira is a good representative of North-Central Pennsylvania as it is close to the Pennsylvania border and had a similar precipitation transition.

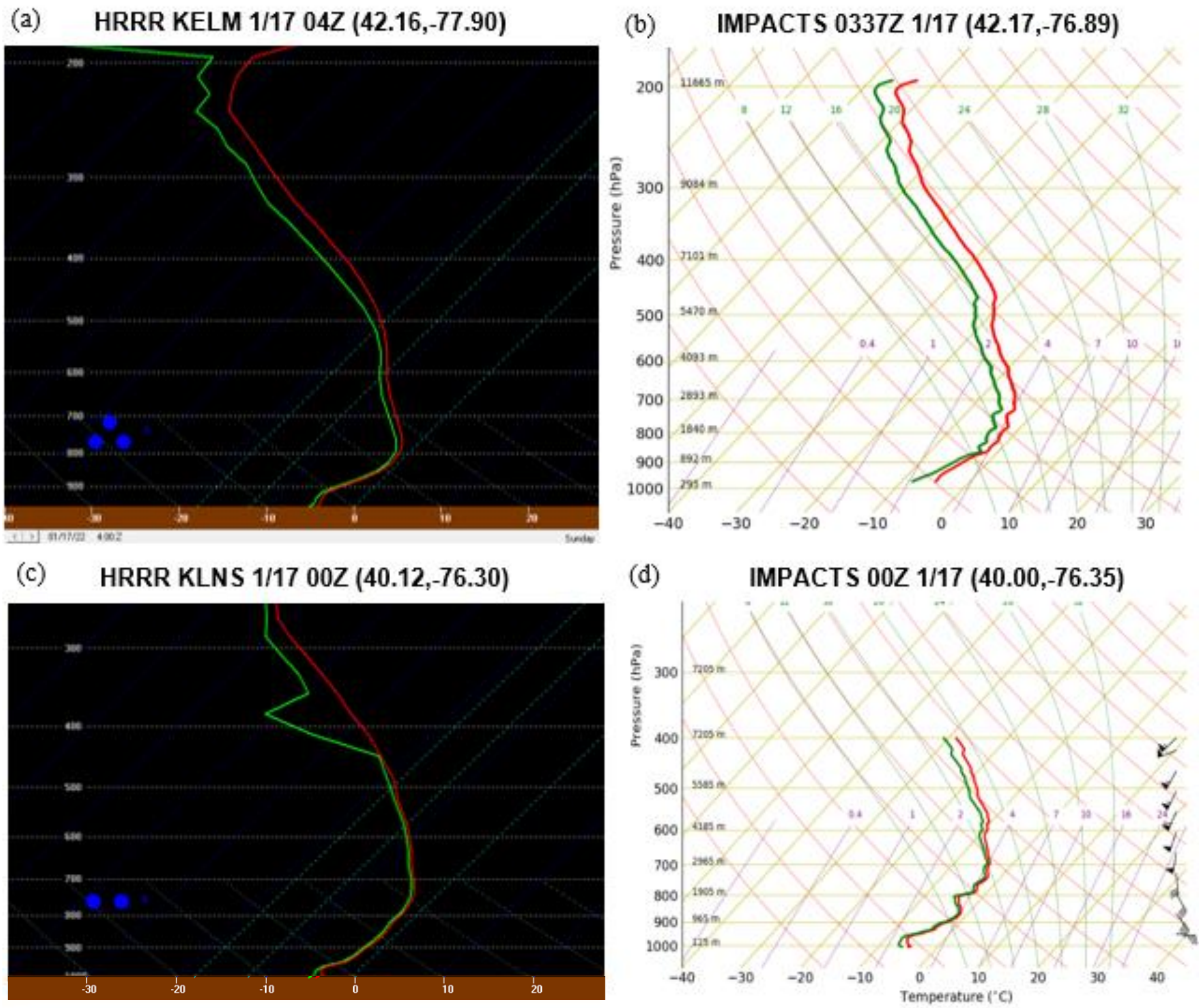

Figure 10: Select HRRR (initialized 1/16 18z) and observed soundings. Panels (a) and (b) are from Elmira, NY at 04z and 0337Z on 1/17 respectively. Panel (a) is a HRRR sounding, and it is from about two miles south of (b), the observed sounding. Panel (b) was recorded by a Stony Brook University group as part of the NASA IMPACTS Program. Panels (c) and (d) are from Lancaster, PA at 00z. Panel (c) is the HRRR sounding, and it is from a location 10 miles north of panel (d), the observed sounding. Panel (d) was recorded by a group from Millersville University as part of the NASA IMPACTS Program.

While this analysis is not particularly concerned with areas west of the Alleghenies due to slightly different synoptic influences, the Pittsburgh soundings at 00z are another example of the warm nose being forecasted too slow (Figure 11). The modeled and observed soundings were taken in the exact same place and at the exact same time, yet the HRRR forecast was colder again. The HRRR had the warmest part of the warm nose reach around freezing, but the observed sounding had it a couple degrees above freezing. In summary, in all the soundings, the HRRR was forecasting the temperatures aloft around 850 mb to be lower than was observed. This lines up with the map data showing that the precipitation changing from snow to other precipitation-types occurred faster than the HRRR forecasted.

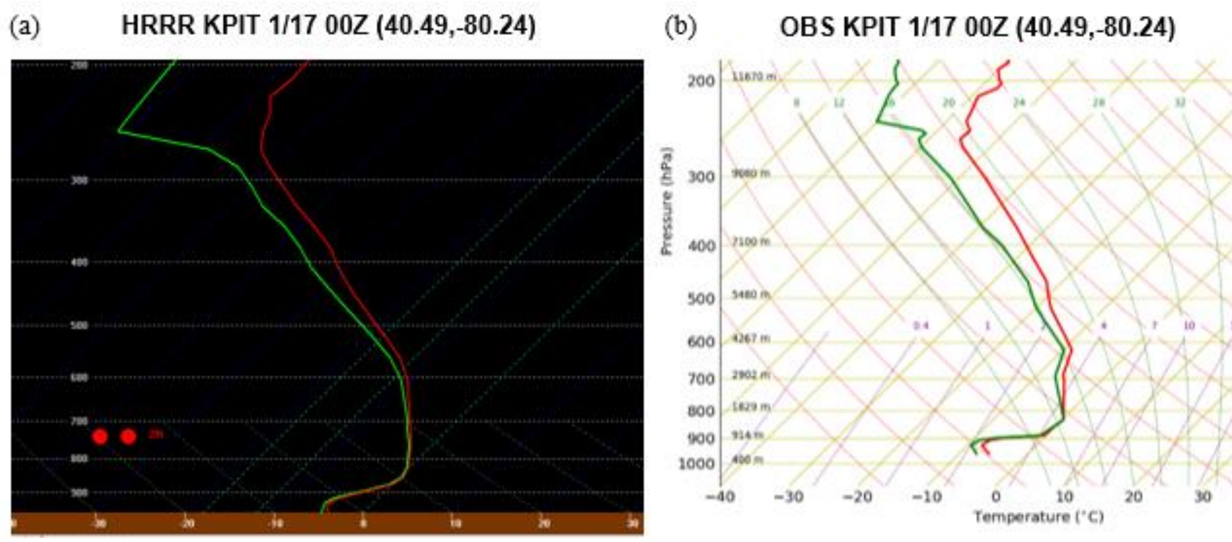

Figure 11: HRRR (initialized 1/16 18z) sounding vs observed sounding at 00z 1/17 for Pittsburgh, Pennsylvania. The observed sounding is from a NWS Pittsburgh balloon launch.

5.9 Backside Precipitation Transition

While the backside precipitation transition is not the primary focus of the study, it is still worth a brief mention. While the HRRR forecasted the transition away from snow too late on the frontside of the storm, on the backside of the storm, this was not the case. Along the Allegheny Front and in south-central areas of the state, the HRRR was one to two hours behind in predicting the transition back to snow (Figure 3). In a period of about an hour, the non-snow precipitation disappeared from everywhere west of the Alleghenies, something that was forecasted to take a couple hours. However, at this point, the precipitation was much lighter. An hour two of error here would not affect the snowfall totals in the way an hour or two would affect them in the first transition. This incorrect timing did not continue in the central or eastern areas. Here, the transition occurred close to the time that the HRRR predicted it. However, this does not simply mean the storm was moving faster than forecast as it entered the state at the correct time.

5.10 Precipitation Intensity in the Transition Region

For the areas that had a couple hours of mixed precipitation instead of snow, there was a significant impact on snowfall totals because this transition occurred in the part of the storm with the heaviest precipitation (Figure 6). Here snowfall rates were around or even exceeded an inch per hour before the transition to sleet. This earlier than forecast transition was therefore enough to take a couple inches off the snow totals in many areas, underscoring the importance of correct precipitation transition forecasts at this time. When the precipitation changed to snow on the backside of the storm, the precipitation was significantly lighter so an error in timing here would not have the same effect as an error with the initial transition.

5.11 Synoptic Effects

Synoptic elements of the storm were analyzed to determine if they were the cause of the transition, but they did not appear to have a significant effect. The first element was temperature advection at 850 mb. The observed wind speeds, direction, and temperatures at that level were close to forecasted (Figure 12). The warmer air was generally advected off the Atlantic Ocean by an east to southeasterly wind that moved in ahead of the storm. The HRRR predicted this correctly and if anything, the observed winds had a slightly more northerly component than the forecasted winds, something that implies slower warm air advection and therefore a colder storm. From here, it made sense that the HRRR generally had the correct placement of both the low, and the arctic high over the Atlantic Ocean (Figure 1). During the storm, the HRRR correctly forecasted that the high would move offshore and strengthen the southeast wind advecting higher temperatures into the state. It had the low strengthen at the correct rate, preventing calmer or stronger winds from changing the rate of the temperature advection. If anything, the HRRR forecasted the low to track to be slightly farther west than was observed. This would cause the transition to be slower and keep it farther east than forecast, the opposite of what occurred. In all, there were likely no analyzed synoptic scale factors that caused the higher temperatures at the 850 mb level.

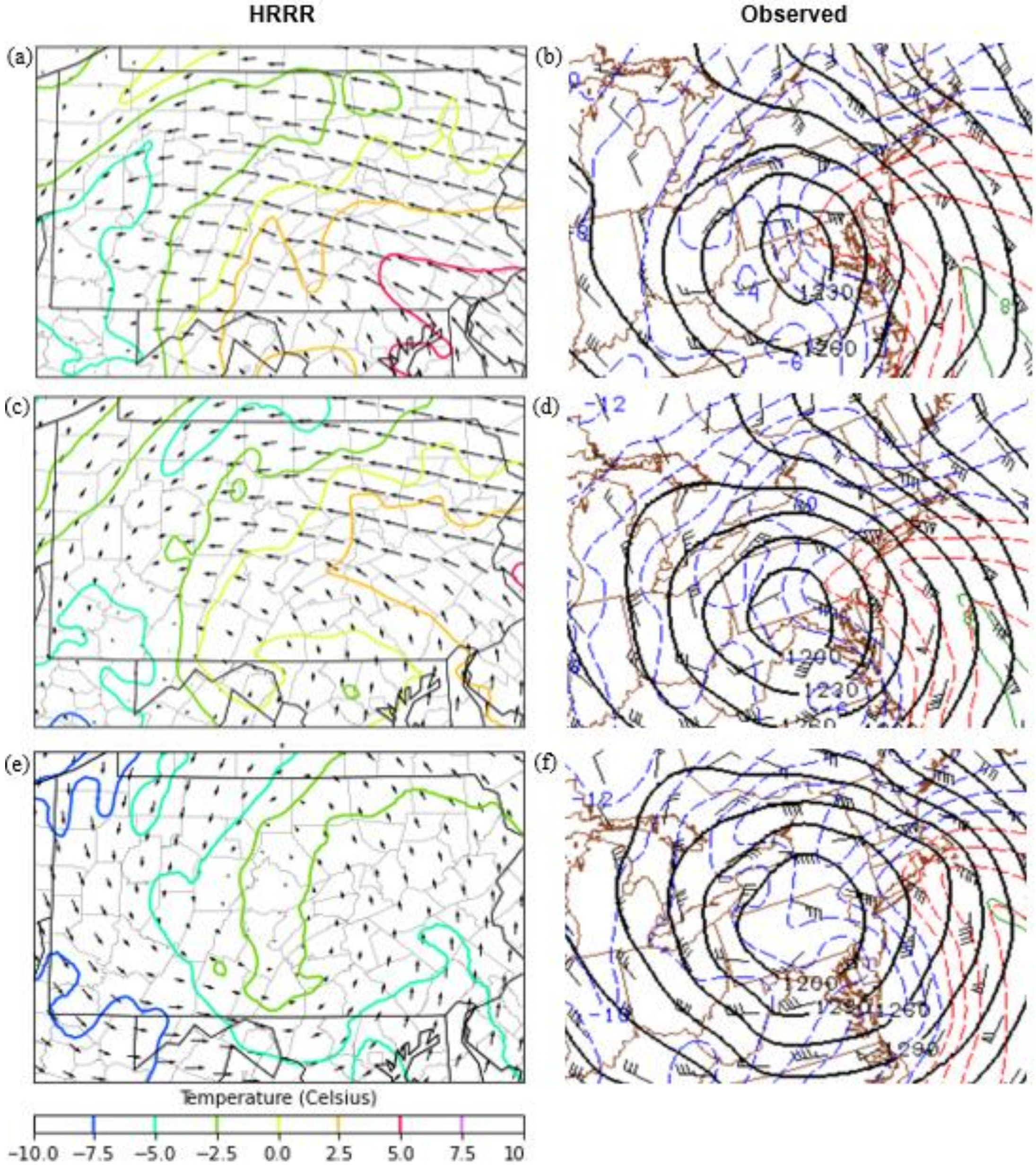

Figure 12: HRRR and observed 850 mb temperatures and winds. Panels (a) and (b) are from 12 hours after precipitation entered the state at 1/16 18z, panels (c) and (d) are from 14 hours after, and panels (e) and (f) are from 18 hours after. Panels (a), (c), and (e) are HRRR forecasts and panels (b), (d), and (f) are observations from the Storm Prediction Center Mesoscale Analysis. The observed values are from observed data at points and are interpolated for areas in between. For the observed data, the blue lines represent temperatures below freezing and the red lines represent temperatures above freezing. The black lines are isobars. Arrows in the left panels represent winds and wind barbs in the right panels represent winds.

5.12 Snow Liquid Equivalent

The observed liquid precipitation data is not fully trustworthy, meaning the snow liquid equivalent and snow water ratios cannot be fully trusted either. The ASOS observations are known to record less liquid from frozen precipitation than actually falls (ASOS User's Guide). Also, it was difficult to be precise in retrieving the model data as the transition typically happened between hours. Comparing observed snow liquid totals to the model forecasts, the liquid equivalents of the snow were generally less than forecasted (Table 1). However, this was not true across the state. For example, in Williamsport, PA, the HRRR forecasted 0.37 inches compared to the 0.52 inch total that was observed. Also, the HRRR greatly overpredicted the snowfall here. Due to the known bias of ASOS underreporting liquid equivalent precipitation for frozen precipitation, and no complete trend, it is difficult to explain the effects of snow liquid equivalents errors on the snowfall error. At the same time, the fact that the HRRR appeared to underpredict the liquid equivalent of the snow in some places does imply that this was not the primary issue that caused it to overpredict the snow. Another limiting factor that stems from this is snow liquid ratios. With the lack of quality observation data, the observed snow liquid rations had highly variable and unrealistic data (Table 2). That partially led to the 46/1 snowfall ratio in Reading.

Table 1: Snow Water Equivalent (SWE) for different locations in Pennsylvania. SWE was calculated by adding up the liquid equivalent precipitation before the precipitation changed away from snow. Model data was QPF and observed data was from the ASOS.

City	Forecasted SWE (in)	Observed SWE (in)	Forecasted - Observed SWE (in)
Altoona, PA	0.54	0.46	0.08
Bradford, PA	0.47	0.37	0.1
Dubois, PA	0.6	0.27	0.33
Harrisburg, PA	0.2	0.33	-0.13
Reading, PA	0.126	0.07	0.056
Scranton, PA	0.34	0.35	-0.01
Williamsport, PA	0.37	0.52	-0.15

Table 2: Snow Liquid Ratios (SLR) for different locations in Pennsylvania. SLR is snowfall totals /snow liquid equivalent at the time of the initial transition. There is no data for observed SLR in Bradford and Dubois because there were no snowfall reports from after the initial transition as significant snowfall fell on the backside.

City	Forecast SLR	Observed SLR
Altoona, PA	17.6	12.6
Bradford, PA	22.3	X
Dubois, PA	13.3	X
Harrisburg, PA	21	9.1
Reading, PA	20.6	45.7
Scranton, PA	10.3	11.4
Williamsport, PA	20.3	10.6

Chapter 6

Conclusion

During the mixed precipitation event of 1/16 - 1/17/22, snowfall predictibility was explored by comparing the HRRR model forecasts to observations. Overall, the HRRR overpredicted the snowfall totals throughout Pennsylvania, with the central and western regions of the state having the largest snowfall error. One reason for this was a faster transition from snow to other precipitation types than was forecasted. This was supported by categorical precipitation observations and soundings from the NASA IMPACTS program that showed a warm nose progressing through Pennsylvania faster and farther than forecasted. The most overpredicted areas were in the central and western parts of the state, the areas that were on the western side of the low. These areas generally remained sleet and freezing rain for longer than areas to the east. These eastern areas changed to rain quickly after changing to sleet. The timing of the transition was only off by one to three hours in western areas, but it occurred at the times that the heaviest precipitation was falling. This means that snowfall rates were likely exceeding one inch per hour, causing the error to have a noticeable impact on snowfall totals. After the HRRR changed the precipitation from snow, it still accumulated snow in some of the locations, likely adding to the overprediction error. A synoptic scale analysis did not reveal any significant errors in the HRRR forecasts that might have contributed to the overprediction. These findings allign with personal experience forecasting on this topic where many cases, it appears the HRRR is sometimes too slow in advancing a precipitation transition in winter storms. However, this was not the only factor that led to the snowfall overprediction, and the explicit reasons the HRRR had the incorrect thermal profile causing this incorrect precipitation transition timing are still unclear. There did not appear to be any specific topographic effects that caused the overprediction, but topography definitely played a role in the precipitation transitions. A place for further research could be looking deeper into the snow liquid equivalents and snow water rations as those were not fully analyzed here due to untrustowrthy data. There could have been less precipitation than was forecasted or incorrect snow water ratios, but with the limited data analyzed, this does not appear to be the clear cause. Understanding model biases in the precipitation transition regions is important as many impactful winter storms in Pennsylvania progress through precipitation transitions and each precipitation-type brings different hazards that should be communicated to the public. Improving the forecasting of the precipitation-type transitions would help the public prepare for the storms better and minimize damage caused by the storms.

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Education

Bachelor of Science: May 2023
Major: Meteorology and Atmospheric Science
Certificate: Geographic Information Systems (GIS)
Schreyer Honors College
The Pennsylvania State University, University Park, PA

Experience

NWS Pathways Intern – Mid Atlantic RFC (Fall 2022 – Present) (7 Hours per week)
-Using ArcGIS to compare Flood Inundation Mapping (FIM) to impact statements and flood pictures to determine its reliability in different areas of the forecast region
-Helping create an office-wide system for FIM reviews ahead of its Fall 2023 public release
-Acting as a liaison between the MARFC and the National Water Center to address any FIM questions, potential concerns and issues from the RFC
-Presented my FIM analysis to MARFC and National Water Center teams
-Shadowed MARFC and NWS State College forecasters

NASA IMPACTS – Forecaster (Winter 2023)
-Provided forecasts, both remotely and at the Wallops Flight Facility, for pilots flying planes into winter storms for scientific research
-Forecasted flight target areas and provided updates when planes were airborne

NWS Pathways Intern – National Water Center (NWC) (Summer 2022) (40 hours per week)
-Analyzed countrywide FIM to document and explain its errors to developers
-Used Python to convert remote sensed flooding images to be used as benchmarks for FIM to be compared against
-Analyzed the effects of model precipitation forecasts on the inundation mapping
-Anticipated public response and usage of FIM ahead of its public release by providing feedback on the FIM interfaces that will become available to the public
-Used QGIS to visually compare remote sensed flooding images to the NWC FIM

NWS Caribou Student Volunteer (Summer 2021) (20 hours per week)
-Used Python and ArcGIS to determine patterns and causes of NDFD precipitation forecast error in different forecast regions and presented the results to regional offices
-Calculated the average error, error as percent of total rainfall, error at various intervals before storms, absolute error and the percent of times storms were either overpredicted or underpredicted
-Shadowed short-term and long-term forecasting shifts, and activities like balloon launches
-Participated in various meetings with partners including local Emergency Management and the Maine Forest Service
-Completed various forecasting training modules and exercises including winter weather, radar, GOES satellites, and warnings

Skills

Python - Analyzed and displayed data for the NWS, my honors thesis, and classwork
Matlab - Classroom experience performing data analysis and displaying it on maps
ArcGIS - Experience plotting, manipulating map layers, and using detailed symbology
Linux - Experience operating python and Matlab in Linux environments

Honors Thesis Using Python to analyze HRRR snowfall error in mixed precipitation events by comparing the model output to observational datasets

Leadership/ Activities

Penn State Curling Club League Director (Present)
-Create IM curling regular season and playoff team schedules, update official scores and standings, help recruit new members, and settle rules disputes
-Play in the weekly IM league throughout the school year

Campus Weather Service Forecasting and Communication (CWS) (Fall 2019-Present)
-Analyzed weather patterns and created forecasts for Pennsylvania as part of the largest student-run forecasting organization in the country
-Provided live and pre-recorded radio discussions about the weather for several local radio stations and presented detailed forecasts on television-style video segments
Shift Leader - taught freshman forecasting skills and coordinated forecast coverage for regions throughout Pennsylvania in person and remotely

Penn State Marching Blue Band (Current)
-Performed at all football games including Rose Bowl and Outback Bowl

Penn State Athletic Bands (Current)
-Perform at all hockey games and select basketball and women's volleyball games

Connecticut Bird Atlas – Block Leader (Spring 2018-Spring 2022)
-Leader of bird surveys in several towns for the State Department of Energy and Environmental Protection to helps determine land use and climate change adaptation

Classes

Meteorology/Major

- Atmospheric Dynamics
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- Synoptic Meteorology
- Principles of Atmospheric Measurements
- Atmospheric Chemistry and Cloud Physics
- Forecasting Practicum
- Climate Dynamics
- Mesoscale Meteorology
- Meteorological Map Analysis
- Forest Fire Management
- Intro to Environmental Engineering

GIS/Certificate

- Intro to GIS
- Remote Sensing Image Analysis
- Cartography
- Python in GIS