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ICE STORMS IN A CHANGING CLIMATE

by

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June 2016

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Three known ice storm case studies were chosen to build, test, and adjust an algorithm that could predict freezing precipitation events. Once the algorithm was deemed satisfactory, it was used on four different ice storm seasons to analyze how well it identified and verified significant differences among the seasons.

This research suggests that the algorithm could continue to be adjusted for better output and tested over several ice storm seasons. Other present weather parameters could be predicted by building another algorithm, using a similar approach.

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ICE STORMS IN A CHANGING CLIMATE

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Ice storms can cause billions of dollars' worth of damage to energy infrastructure, towers, surrounding trees (that could further damage electrical structures), and transportation, and can cause deaths—either due to exposure to subfreezing temperatures or vehicular accidents. An increase in global temperatures, due to climate change, could affect the frequency, intensity, and geographic location of ice storms.

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LIST OF ACRONYMS AND ABBREVIATIONS

^{o}W	latitude degrees west
^{o}N	longitude degrees north
CFSR	Climate Forecast System Reanalysis
EPRI	Electric Power Research Institute
ESRL	Earth System Research Laboratory
GMT	Greenwich Mean Time
IPCC	Intergovernmental Panel on Climate Change
MAB	Military Advisory Board
NA	negative area
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PA	positive area
SST	sea surface temperatures
WMO	World Meteorological Organization
ZULU	time zone indicator for Universal Time

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I. INTRODUCTION

The American Meteorological Society defines an ice storm as “a storm characterized by a fall of freezing liquid precipitation” (2016). Ice storms can be especially hazardous to urban regions and the U.S. electrical grids. Freezing precipitation is formed when there is an upper layer of freezing air above a layer of warm air. An ice particle falls from the freezing air through the warm air and turns into a raindrop. Just prior to reaching the surface, it passes through a shallow layer of freezing air, causing the raindrop to freeze on contact and form a glaze of ice when it comes in contact with the ground or an object (see Figure 1) (Fletcher 1962).

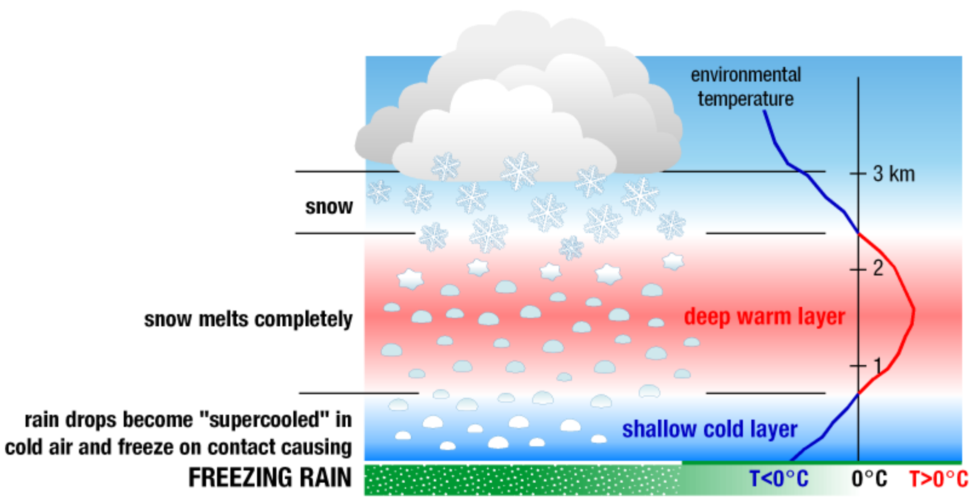


Figure 1. Schematic of a typical vertical temperature profile that will result in freezing rain. Source: National Weather Service (2013).

According to Klima and Morgan (citing work done by Changnon and Changnon in 2002 and Houston and Changnon 2006), “Ice storms can cause billions of dollars’ worth of damage and paralyze transportation, food and agricultural, water and sewers, and energy infrastructure” (2015). Klima and Morgan’s review of relevant sources showcased that ice storms can also damage electrical power and communication towers “due to the weight of ice on the pylons and poles, surrounding trees, and on the wires themselves” (2015). The accumulation of freezing precipitation can cause damage to homes and buildings. Human beings can also suffer from exposure to cold or pedestrian and vehicle accidents, which could lead to death (National Weather Service 2008).

Every year, U.S. regions east of the Rockies experience ice storms. Ice storms are a function of local topography (Millward and Kraft 2004) and the synoptic-scale environment (Ressler et al. 2011; Splawinski et al. 2011). Ice storms occur during the months of November through March. According to Klima and Morgan (citing work done by Shan et al. 1998 and Changnon and Changnon in 2002), "freezing rain generally does not fall west of the Rockies because shallow Arctic air is unable to flow over the mountains" (2015). Baldwin also agrees with Changnon and Karl (2003) showing that maximum freezing rain events take place in the Pacific Northwest but for the purposes of our research, we are focusing on regions east of the Rockies. In contrast, cold air masses sink down into valleys and can be retained, which could then be overrun by warm air thereby creating favorable conditions for an ice storm.

As the earth's climate changes, the effects of these variations could impact ice storms in frequency and severity. Climate change is forecasted to increase precipitation (Changnon and Changnon 2002; Houston and Changnon 2006). An increase in precipitation could lead to an increase in occurrences and intensity for areas that already experience ice storms. However, an increase in temperature could possibly decrease the frequency and intensity of ice storms, as warmer air can hold more precipitation (IPCC 2013; Melillo et al. 2014; Klima and Morgan 2015).

Ice storm physics has suggested that as the global temperatures warm, the occurrence of ice storms could exhibit a poleward shift to the Northeast region of the United States and a shortened season between December and January (Klima and Morgan 2015). This poleward shift targets the east and northeast regions of the country with the United States' highest population density.

Ice storms can be especially damaging to electrical grids. Everyone relies on electricity for communication, commerce, transportation, health, emergency, homeland and National Defense (CNA MAB 2015). In 2015, the CNA Military Advisory Board (MAB) released a report titled "National Security and Assured U.S. Electrical Power."

The report discusses national security and grid susceptibility in today's environment. For instance, the "current U.S. electric grid's overreliance on aging twentieth-century technology makes it susceptible to a wide variety of threats, including severe weather" (2015). The twenty-first century will see much greater energy diversity, but the grid's security vulnerabilities such as power generation, nodal distribution, and the design of power transmission "leave the U.S. open to both small / short-duration and large / long-duration power outages" (CNA MAB 2015). The CNA's MAB report discussed the ripple effect of severe weather on the United States' National Security. As we saw during Hurricane Sandy, because fuel distribution facilities did not have power, U.S. military forces were used to procure and deliver 24 million gallons of fuel to staging areas. Delivering fuel prevented these military forces from performing other, perhaps even more critical defense support to civilian authority missions (CNA MAB 2015). The U.S. power grid is made up of three major grids, Eastern, Western and Texas Interconnects. The rigid grid system is designed for power to flow in one direction. Today's electrical grid is an interdependent network with many points of failure, as the failure of one component requires power to be taken from other areas (see Figure 2). If several components fail, then there is the possibility of a cascading effect. There are 55,000 transmission substations, and according to the Federal Regulatory Commission study, the loss of just nine of these nodes could result in a regional or nationwide outage, while the damaging of two transformers could result in cascading blackouts (CNA MAB 2015).

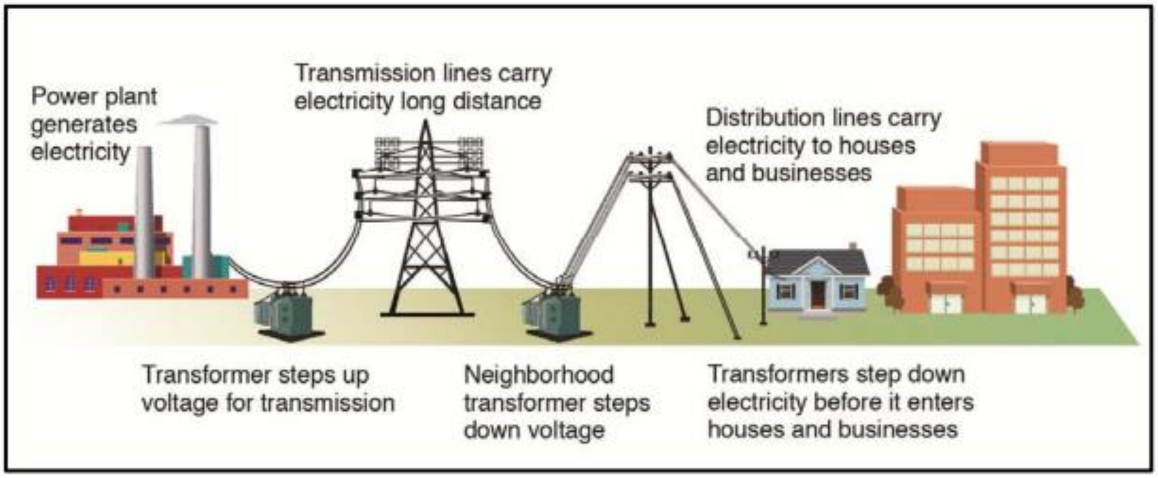


Figure 2. Electric power generation, transmission, and distribution.
Source: CNA MAB (2015).

As ice glaze accumulates on power lines and trees, it can add hundreds of pounds of weight and potentially cause serious damage or large-scale blackouts that could takes days, weeks, or possibly months to restore (Hines et al. 2009). An increase in frequency and/or severity of ice storms will leave the nation’s electrical grid system, and national security, vulnerable to ice storm events.

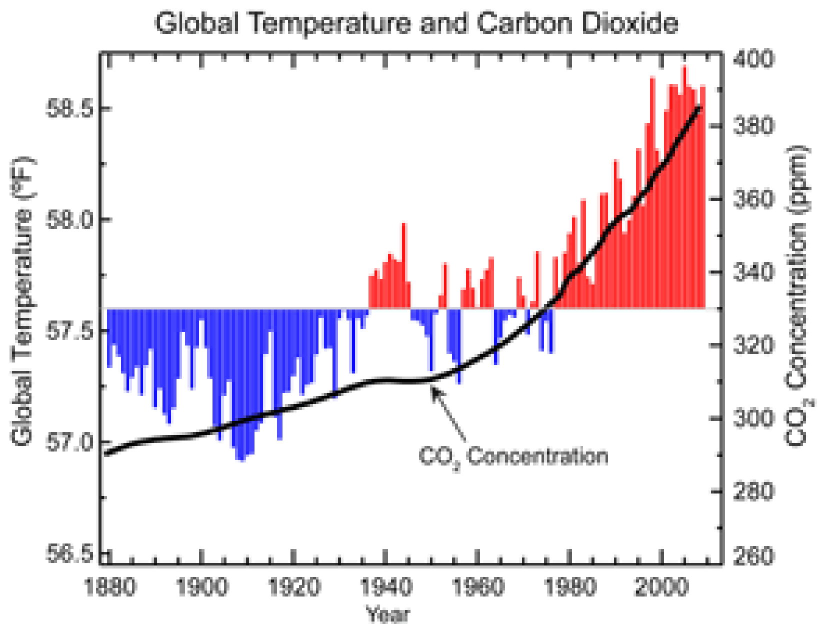
In order to help government officials, policy makers, and power companies to reduce risk and mitigate vulnerabilities, there needs to be a better understanding of how climate change will influence ice storms, especially as the changes in ice storm characteristics are not obvious due to competing climatic effects. Also, while weather models have become better at capturing storms, than in the past, predicting precipitation type is more difficult. In order to better understand ice storm frequency and intensity as climate change evolves, a robust method to accurately extract precipitation type from coarse resolution climate model prediction is needed. This will allow accurate assessment of potential ice storm impacts in projected future climate states.

II. BACKGROUND

A. CLIMATE CHANGE

The human use of fossil fuels has been modifying the earth's climate. The Intergovernmental Panel of Climate Change (IPCC) climate scientists are "95 percent certain that humans are the main cause of current global warming" (IPCC 2013). The changes that are taking place include warming global surface temperatures, sea level rising, glacial volume decreasing, ocean heat content rises, and snow cover retreat (NOAA NCEI 2016c).

Global average surface temperatures are rising as seen in Figure 3. The average temperature has increased by 1.4^{o} Fahrenheit in the last century. Observations and measurements from weather stations, ships, buoys, gliders and satellites have indicated a clear trend of warming temperatures across the globe. According to the National Oceanic and Atmospheric Association (NOAA) National Centers for Environmental Information (NCEI), "the 20 warmest years have all occurred since 1981, and the 10 warmest have all occurred in the past 12 years" (NOAA NCEI 2016c).



Red bars indicate temperatures above and blue bars indicate temperatures below the 1901–2000 average temperature. The black line shows atmospheric carbon dioxide concentration in parts per million.

Figure 3. Global annual average temperature measured over land and oceans. Source: NOAA NCEI (2016c).

As the temperatures have increased across the planet, U.S. climatology also indicates a clear rise in temperatures across the United States. The Climate Extremes Index (CEI) has also seen an increase in extreme weather events in the last four decades, as shown in Figure 4. Extreme weather events include maximum and minimum temperatures (above and below normal), severe drought and moisture surplus, a larger proportion of precipitation events, and a larger total percentage of days with and without precipitation (NOAA NCEI 2016c).

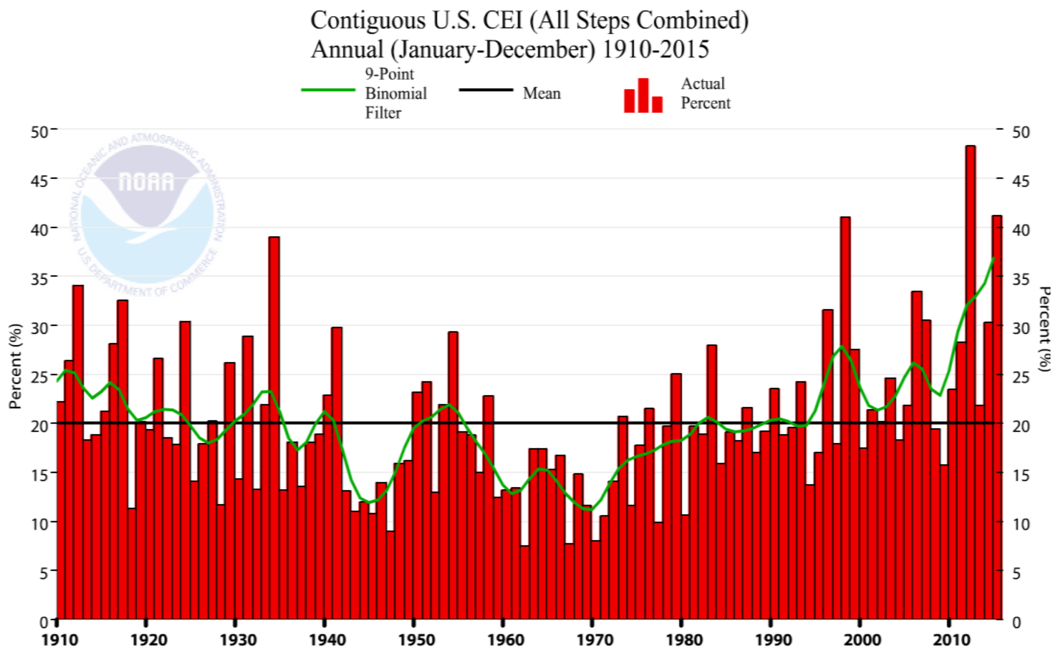


Figure 4. Annual Climate Extremes Index (CEI) value for the contiguous United States. Source: NOAA NCEI (2016c).

According to the IPCC (2013), an increase in heavy precipitation events across the mid-latitude Northern Hemisphere land masses has been observed since 1950. In addition, there is a high likelihood that these extreme precipitation events will become more frequent and intense (IPCC 2013). Given their observed trends in precipitation, assessing the frequency, coverage, and intensity of ice storms events is of great interest due to their high impact.

B. CLIMATOLOGY OUTDATED

Several freezing rain climatologies are available that include observed climatologies by Changnon (2003) and Karl (2003), the Electric Power Research Institute (EPRI) (Shan et al. 1998), Cortinas et al. (2004) and numerous others. Although there are several climatologies, they are all over a decade old and they mostly focus on national and regional climatologies of the United States and Canada (Cortinas et al. 2004; Baldwin 1973). Due to the outdated climatologies, short duration of records, and inherent variability, extracting climate trends in ice storms is very difficult. Additionally, the ability to apply their climatologies to future climate states cannot be done.

While these climatologies are old, they are all mostly in agreement with the areas that experience freezing precipitation, as well as the timeframe of most frequent occurrences in the United States. Freezing precipitation occurs between November and March, and east of the Rockies. An in-depth study done by Bennett (1959) shows that freezing precipitation occurs frequently (greater than six days per year) from Northwestern Texas and extends northeastward to New England. Bennet (1959) refers to this area as the “glaze belt” and estimates that the average ice accumulation is between 0.64 and 1.27 cm with storms occurring once every three years. Baldwin’s (1973) distribution of freezing precipitation is comparable to Changnon and Karl (2003) showing that the maximum frequency occurs in New York, Pennsylvania, eastern Appalachians, a portion of the Midwest and the Pacific Northwest. According to Cortinas et. al and other regional studies (Bernstein and Brown 1997; Bernstein 2000), the greatest “annual frequency of freezing drizzle occurs in the western portion of the Central Plains and the greatest frequency of freezing precipitation and ice pellets occurs in the Northeast U.S.” (2004).

Several severe ice storms have taken place since the climatologies were created, including the 2007 North American Ice Storm that affected the United States and Canada and caused over $380 million in damage, and the 2008 New England/New York Ice Storm that caused between $2 and $4 billion in damage (Miller et al. 2011). Also, looking at data dating back to 1996 in the Storm Events Database, on NCEI, there is significant inter-annual variability in the number and duration of ice storms, and the damage they caused. For example, in 2013 there were 11 ice storms, spread throughout 38 days and about $90 million in damage. In contrast, there were four ice storms over six days, with approximately $7 million in damage in 2012 (NOAA NCEI 2016a). The variability in annual distribution and frequency can be influenced by single events, such as the 1998 ice storm in the Northeast U.S. These large single events can cause an above normal output of freezing precipitation, or the location of the surface freezing line associated with a particular year (Cortinas et al. 2004).

C. FUTURE ICE STORMS

Because the climatology is outdated, there is very little understanding and research completed on the future of ice storms and how they will be effected by climate change. Climate change could possibly affect intensity, frequency, distribution, and a geographical shift of ice storms. A study conducted by Lambert and Hansen (2011) shows a poleward shift and a decrease of freezing precipitation events in the United States. The resolution in this study was coarse and lacked a topographic resolution, which rendered the results limited (Klima and Morgan 2015).

Klima and Morgan (2015) pointed out three general effects that climate change could have on freezing rain, due to ice storm physics. First could be a poleward shift as surface temperatures increase (IPCC 2013) and the ice storm season focusing on December and January. Second, an increase in frequency and intensity in ice storms due to an increase in precipitation (IPCC 2013). Third, topography and synoptic weather patterns may outweigh these possible changes.

To more fully assess the occurrence and coverage of ice storms and provide a tool to build a more complete climatology, extracting the precipitation type from climate analyses is useful. Numerous methods have been developed to predict precipitation type from model fields. For example, the Czys algorithm used by Klima and Morgan (2015) can predict precipitation type based on the thermodynamic profile. This method depends upon vertical temperature profiles concentrated in the eastern U.S. and southeastern Canada. In 2015, Klima and Morgan conducted a three-step thought experiment in order to recognize how increasing temperatures would influence the overall vertical temperature profile and its effects on freezing precipitation. The experiment utilized historical (1973–2013) vertical temperature profiles from the Wyoming Weather Web's archive. They implemented a uniform temperature increase (-0.5 to +5^{o}C) within the vertical temperature profile, accounting for the topographic effects, the mixing layer and other surface and aloft changes. Klima applied the Czys algorithm to forecast for where freezing precipitation would occur. As a result, Klima and Morgan found that there was a poleward shift in ice storms, with southern U.S. locations experiencing fewer ice storms throughout the season and northeast U.S. locations experiencing more during the winter months of December and January. The study did not account for other possible effects of climate change, such as a change in the jet stream location (Klima and Morgan 2015) or increases in total precipitable water available for a given storm. Other methods, such as the area method (Bourgouin 2000) may provide a more consistent distribution of precipitation type when applied to coarse resolutions model data. Any of these methods applied to large-scale climate analyses can provide a direct assessment of the variability of ice storms over time.

While a complete assessment over a 30-year climatology is desirable, the robustness of this approach can be tested using select years. Typical climate variations, such as El Nino / La Nina are known to produce variation in precipitation. Applying the precipitation type algorithm to these years provides an ability to relate key synoptic features to ice storm coverage and locations. Hence, the various contributions to ice storm impacts for a given year can be separated. Frequency, area of coverage, duration, and location can be assessed as they relate to climate pattern shifts.

D. OBJECTIVES

The overall goal of this study is to apply an algorithm to climate projections to predict ice storm variability. The algorithm will be tested and tuned with observations using select cases to optimize its accuracy with respect to observations. A proxy climatology of ice storms can then be developed by applying this to multiple years. This assumption will provide a reference for the future of ice storm occurrence when applied to climate prediction. Chapter III describes the data and methodology used in this study to develop an algorithm. Chapter IV describes the analysis and results, and Chapter V lists the conclusions from this research and recommendations for future analysis.

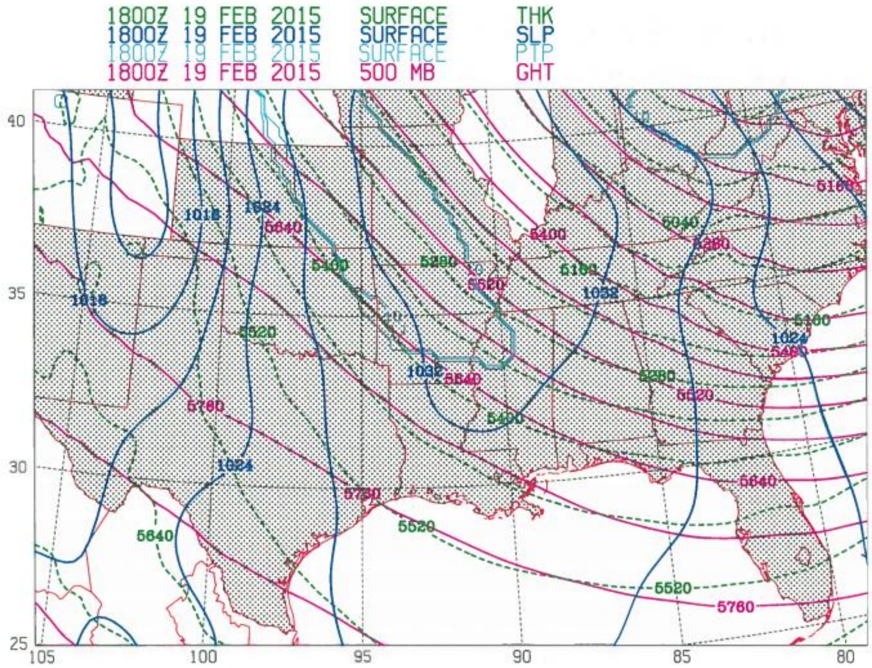
III. DATA AND METHODOLOGY

In order to try and identify a method for forecasting the precipitation type that results in ice storms, three significant storms were identified based on intensity. The historical data for these storms was obtained via the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR). The "area" algorithm, to determine precipitation type from a temperature profile, was coded and applied into VISUAL (a diagnostic and display program), along with specific weather parameters and surface observations to understand the mesoscale and synoptic weather patterns.

A. DATA ACQUISITION AND STRUCTURE

The data was acquired from NCEP's CFSR model. The NCEP CFSR was completed over the 31-year period of 1979 to 2009 and was extended as an operational, real time product to March 2011. Per NCEP's webpage, "The CSFR was designed and executed as a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system to provide the best estimate of the state of these coupled domains over this period" (NOAA NCEI 2016b). The current CFSR model has a global atmosphere resolution of ~38km with 64 levels extending from the surface to 0.26hPa. The model also considers "observed variations in carbon dioxide, changes in aerosols and other trace gases and solar variations to estimate climate changes due to these factors" (Saha et al. 2010).

A program called VISUAL was used to display and diagnose the CFSR data. VISUAL was developed by Nuss and Drake in 1995 as a way for users to display several plots using little effort. The program is a diagnostic display program that uses Graphical Kernal System (GKS) primitives and NCAR graphics to examine meteorological grids and observations (Nuss and Drake 1995). Most of the code for common data sets (i.e., sea level pressure, geopotential heights, temperature, etc.) has already been programmed into VISUAL. Figure 5 shows an analysis produced by VISUAL.



Surface thickness depicted in green, sea level pressure depicted in blue, precipitation depicted in light blue and 500 mb geopotential height depicted in magenta.

Figure 5. CFSR data for 1800 UTC on February 19, 2015.

In order to account for precipitation in the form of freezing rain, a new diagnostic routine was programmed into VISUAL to display types of precipitation to include no precipitation, rain, freezing rain, ice pellets and snow. Each type of precipitation was assigned a number of zero, five, ten, 15 and 20, respectively. The algorithm that was used to code this data set, within VISUAL, is discussed in the Methodology portion of this chapter.

Once the precipitation parameters were programmed into VISUAL, a VISUAL script was written to compare observations to model data. We used this process to verify if the algorithm was validating freezing precipitation events or if the algorithm needed to be adjusted. VISUAL assigned a number for the predicted weather phenomena, observed weather phenomena, a calculated error between the model forecast and observation, and a World Meteorological Organization (WMO) numeric weather code to show what weather phenomena had taken place at each station. This helped to decipher the consistency and intensity of any freezing precipitation that fell at individual stations. Table 1 displays an example of those results. Fuchsia represents when the model forecast validated with the observation. Green represents an observation of freezing precipitation, but not being forecast in the model. Red represents the model forecasting freezing precipitation, but it was not observed.

Table 1. Model versus Observation data using WMO numeric weather code to decipher types of present weather.

ICAO	Latitude	Longitude	Date / Time	Model	Observation	Error	WMO Code	WMO Code description
YSC	45.43	-71.68	980109/0000	10	10	0	2529	ground fog, light freezing rain
YGK	44.22	-76.6	980109/0000	10	10	0	3933	light freezing rain, light rain
YTR	44.12	-77.53	980109/0000	10	10	0	49	light freezing rain
YQA	44.97	-79.3	980109/0000	10	10	0	53	light freezing drizzle
MKE	42.95	-87.9	980104/0600	0	10	10	49	light freezing rain
MSN	43.13	-89.33	980104/0600	0	10	10	19	freezing drizzle
WLD	37.16	-97.03	980104/0600	0	10	10	2529	ground fog, light freezing rain
DRO	37.15	-107.75	980104/0000	10	0	-10	0	none
DSM	41.53	-93.65	980104/1200	10	0	-10	31	ground fog
DBQ	42.4	-90.7	980105/0000	10	0	-10	2521	ground fog, light freezing rain

B. CASE STUDY CRITERIA

To start the research process of developing a precipitation type algorithm for forecasting ice storms, three storms were identified. The three storms that were chosen were also in three separate locations, to account for topography and local surface effects, and also took place years apart to account for a changing climate. The first storm took place February 9–12, 1994, in the Southeast United States and mostly affected Tennessee, Mississippi, and Alabama (NOAA NCEI 2016a). The second storm, the North American Ice Storm of 1998, focused on the northeast United States and southeast Canada happening on Jan 5–10, 1998. Upstate New York, northern New Hampshire and Vermont, and much of Maine were the states that received the most damage in the U.S. (NOAA NCDC 1999). The last storm chosen occurred Feb. 20–21, 2015, mainly concentrating on Tennessee.

1. February 9–12, 1994

In early February 1994, a typical set-up for an ice event was taking place over the southeast United States. A quasi-stationary front was over the Gulf of Mexico and overrunning the Arctic air that was north of the front. The ice storm that took place produced large amounts of precipitation and covered several states in the southeast.

The unusual ice storm that took place in February 1994 offered a large areal extent of ice and high precipitation amounts (some reports exceeding 125 mm), not normally associated with such an event. Figure 6 shows total precipitation accumulations over the state of Tennessee. Ice accumulations of 20 mm up to 150 mm were reported. The storm caused an estimated $3 billion in economic damage and 9 fatalities. Over 2 million customers were without electricity, with some residents losing power for over a month after the storm (Lott and Sittel 1996).

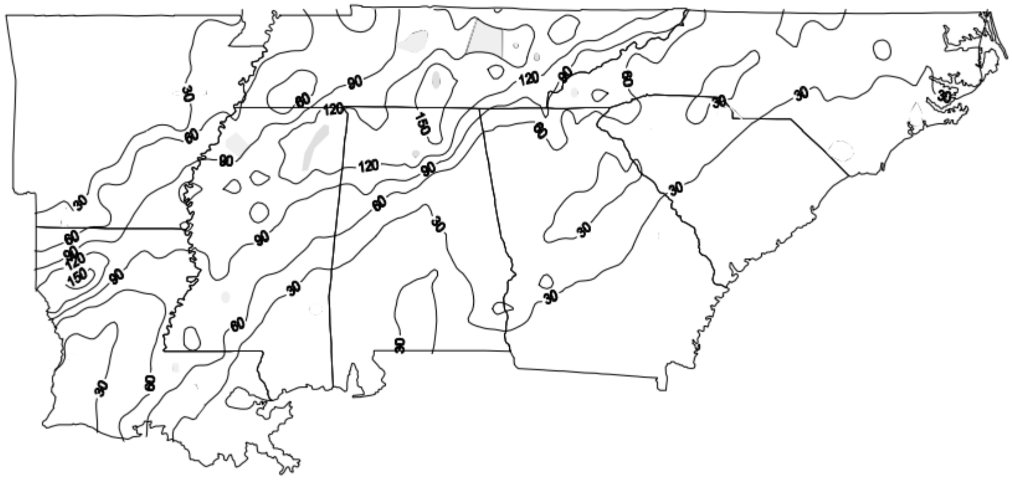


Figure 6. Total precipitation in millimeters, February 9–13, 1994. Source: Lott and Sittel (1996).

2. January 5–10, 1998

In January 1998, a low pressure system with warm moist air was pushing toward the northeast Unites States from the Tennessee Valley. A cold front along New England with an associated Arctic high pressure system provided a disastrous set-up for one of the worst ice storms in North America.

The 1998 ice storm, which devastated regions of the northeast United States and southeast Canada, dropped over 76 mm of freezing rain over a 5-day period. Figure 7 shows total freezing rain accumulations from January 4-10, 1998. Radial ice thicknesses of 25 to 76 mm were reported, with the greatest amounts along the Canada and New York borders.

Most of the economic damage was attributed to the loss of power due to downed power lines because of ice accumulation. According to Gyakum and Roebber (citing 1999 data from NOAA NCDC), “approximately 3 million customers were left without power in Canada, while 500,000 customers were without power in the northeast and New England area, including 80% of Maine’s population. Economic damage was estimated at $3 billion in Canada and at least $1.4 billion in United States. The total fatalities that were attributed to the ice storm event were 28 in Canada and 16 in the United States” (2001).

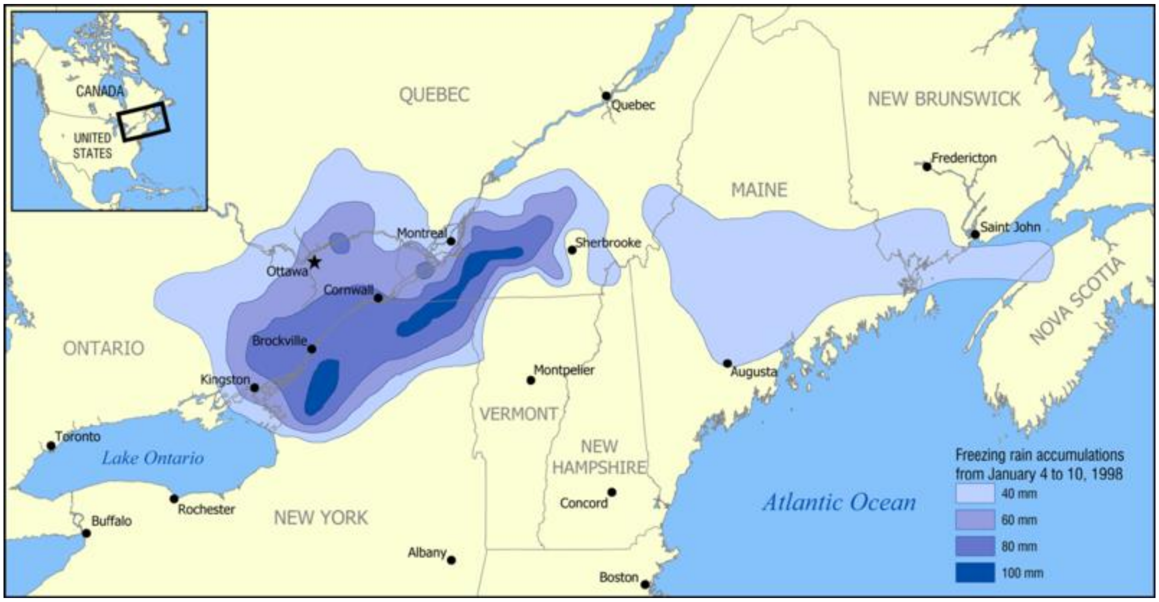


Figure 7. Freezing Rain accumulations in millimeters from January 4–10, 1998. Source: Einstein (2006).

3. February 20–21, 2015

The historic winter storm that affected Tennessee happened 4 days after a separate winter storm struck the area and 2 days after a major snowfall. A low-level jet at 850 mb measuring at 44 meters per second, accompanied by a warm front located over Arkansas, brought warm air advection aloft into the area ultimately causing the surface to warm. The snowfall became sleet and eventually transitioned to freezing rain, as the temperatures remained at or below freezing. Still recovering from the previous storms along with 13-22 meters per second wind gusts, ice accumulations were reported up to 25 mm.

Parts of Tennessee lost power for two weeks and up to one month in some areas. Less than five fatalities were reported. According to the NOAA NCEI storm events database, "an estimated $64.8 million of economic damage to the State of Tennessee was attributed to this winter storm" (2016a).

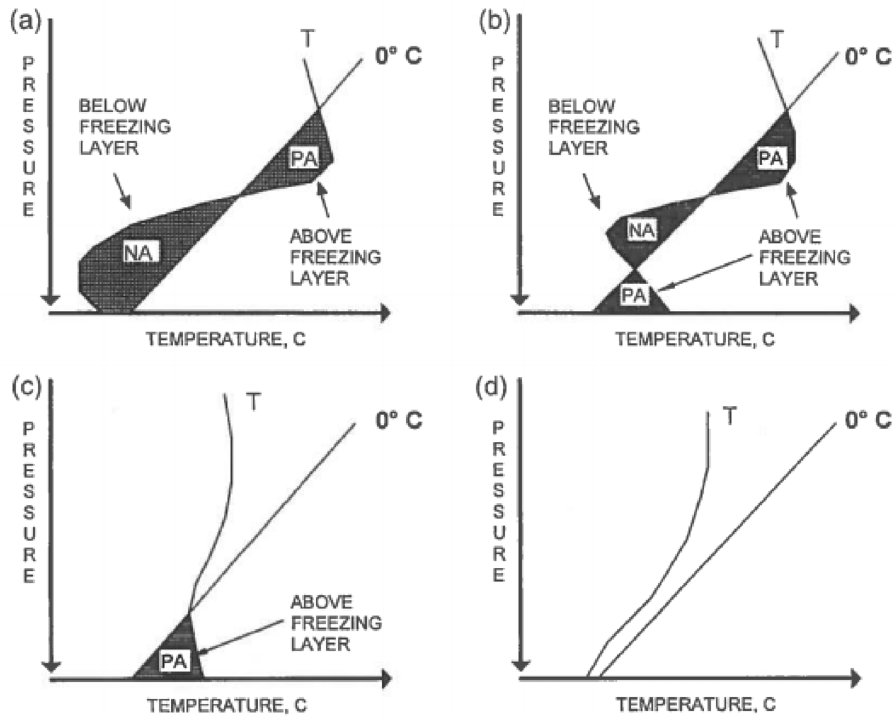
C. METHODOLOGY

The purpose of the research was to try to identify an automated methodology or algorithm that could be used to forecast freezing rain. Once developed, this algorithm would then be used to analyze other known ice storms using climatology data. The algorithm would be used to analyze freezing precipitation data compared to warming and cooler temperatures to see if warming global temperatures will affect the frequency and severity of ice storms.

The vertical temperature profile is the determining factor when forecasting for precipitation type. Precipitation will fall as snow if the temperature remains at or below freezing (0^{o} Celsius). Ice pellets and freezing rain are possible when there is a freezing layer above a warm layer. For ice pellets to form, snow partially melts as it falls through a shallow warm layer and refreezes as it passes through a deep cold layer prior to hitting the surface. For freezing rain to reach the surface the vertical profile is similar to the ice pellets profile, however there is a deep warm layer above a shallow cold layer. If the warm layer is too small, the precipitation will fall as snow (Bourgouin 2000; National Weather Service 2013). According to Bourgouin, "Ice pellets or freezing rain occurs when warm air advection, generally associated with extratropical cyclones, is stronger aloft than near the surface and low-level cold air advection is present, frequently associated with topographically induced cold air drainage or cold air trapped in valleys" (2000).

First, to program the precipitation data set into VISUAL, an algorithm was used based on the "area" method developed by Bourgouin (2000). Bourgouin describes the area method is as a new predictor that "is used to establish different statistical relationships to diagnose different precipitation types from a vertical temperature profile" (2000). In order to define a new predictor, Bourgouin determined that the type of precipitation is dependent on the mean temperature of the layer and the resident time that a hydrometeor is in that layer. Bourgouin determined that the resident time is dependent on the height of the layer. Both the temperature and height parameters are easily accessible through observed or forecast vertical temperature profiles.

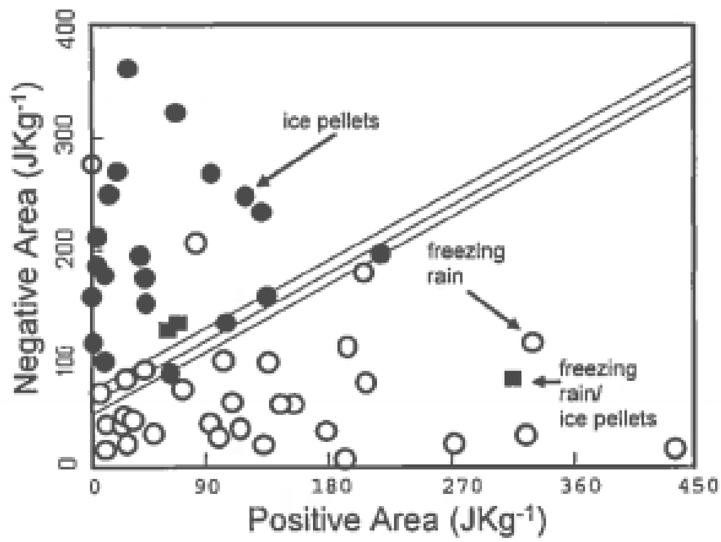
Bourgouin also determined that positive and negative thermal heat capacity areas could be used as predictors for precipitation type. A positive (negative) area is defined as the area between the 0^{o} C isotherm and the environment temperature in the above (below) freezing layer shown on a Skew-T or tephigram (Bourgouin 2000). These predictors showed that with a small positive area (PA), freezing rain is possible, as long as the negative area (NA) remains small. If NA becomes too large, then freezing rain is no longer expected. Figure 8(a) shows an example of a PA and NA ratio that would produce freezing rain.



(a) freezing rain or ice pellets, (b) ice pellets or rain, (c) snow or rain, and (d) snow. PA and NA areas are indicated.

Figure 8. Schematic diagram showing typical vertical temperature profiles. Source: Bourgouin (2000).

In order for the algorithm to be used in VISUAL, code was written into the program to account for freezing rain. The area method parameters that were used to discriminate between freezing rain and ice pellets were calculated from verified vertical profiles of temperature. Figure 9 shows a plot of positive area (x-coordinate) versus negative area (y-coordinate) in joules per kilograms. The solid lines represent the criteria that were used to differentiate between freezing rain, freezing pellets and a combination of the two. From the figure we can see that if the NA is small (less than about 80 J kg^{-1}) then freezing rain is possible. However, it the NA becomes larger than 200 J kg^{-1}, and then we should not expect freezing rain. The equation that was used to represent the solid line is NA = 56 + 0.66PA. To accommodate the transitioning of freezing rain to ice pellets, 10 J kg^{-1} was subtracted from 56 to account for freezing rain and added to account for ice pellets. This calculation was used in the code for the freezing precipitation algorithm in VISUAL.



The solid lines represent criteria to discriminate between freezing rain and ice pellets.

Figure 9. Plot of freezing rain, ice pellets, and mixed freezing rain and ice pellets as a function of positive and negative areas.
Source: Bourgouin (2000).

Once an algorithm was developed, observations were compared to model data for verification. This analysis was used to fine tune the algorithm. The WMO numeric weather code was used to identify the weather that was observed. All types of observed freezing precipitation were assigned a value of 10 based on the WMO code was used to identify the exact weather phenomena, intensity (light, moderate, heavy) and consistency (constant or intermittent). For example, light freezing rain, heavy freezing drizzle, fog, or snow showers, to name a few. This allowed direct comparison of all (freezing precipitation type) observations to the model which only produces one category of freezing precipitation. The next chapter will go into more detail about how the algorithm was adjusted and tuned.

IV. ANALYSIS AND RESULTS

A. INITIAL RESULTS FROM THREE CASE STUDIES

Three case studies were used to test and tune the algorithm by comparing the observations and model data. For each analysis time where freezing precipitation was observed, hits, misses, false alarms and correct negative numbers were calculated. All of the observations bounded by 25^{o}N and 50^{o}N latitude and 105^{o}W and 65^{o}W longitude were included in the analysis. The hits were all of the freezing precipitation observations where the algorithm successfully predicted freezing precipitation. The misses were the observations where the algorithm did not predict freezing precipitation, but it was observed. False alarms were freezing precipitation that the model had forecast, but it was not actually observed. Correct negatives consisted of all the other observations where neither freezing precipitation was predicted nor observed. This includes both non-precipitation observations, as well as other types of precipitation. For purposes of this study, the other precipitation type categories were not verified separately.

For the purposes of tuning the algorithm, correct negatives were ignored. Hits, misses and false alarms were the only factors taken into account, with more hits than misses being ideal for a more reliable algorithm. To assess this, the hit rate and critical success index were calculated for the 3 cases. The hit rate is the amount of hits divided by the hits plus misses. The critical success index is the amount of hits divided by the hits plus misses and false alarms. The algorithm was adjusted to attempt to maximize these values. The verification script was run every six hours GMT (i.e., 00Z, 06Z, 12Z, 18Z), over days when a known freezing event happened (i.e., January 4–January 11, 1998). No non-event days were included in adjusting the algorithm.

The initial algorithm, based on Bourgouin's area method (2000), set relative humidity at 90% at the 700mb level, to account for possible precipitation occurring at a particular gridpoint. While vertical velocity was considered when adjusting the algorithm, this seemed to reduce the precipitation areas too much and was not added to the algorithm. The algorithm was run on the three initial cases. Table 2 shows the initial findings. The algorithm provided less than 50% accuracy in picking up observed freezing precipitation events, for each of the cases, with the 2015 case being the most successful at 49% accuracy. Comparing actual observed events to the algorithm output, it was realized that while the algorithm was picking up some events, the area of coverage was not sufficient based on the large number of misses. In addition, shallow precipitation events were not identified at all by the 700 mb relative humidity.

Table 2. Initial run of three case studies used to tune the algorithm.

Initial Run			
	1994	Observed	
	Forecast	Hits	False Alarms
		68	357
		Misses	Correct Negatives
		198	5287
Accuracy	26%		
Hit Rate	0.256		
Critical Success Index	0.109		
	1998	Observed	
	Forecast	Hits	False Alarms
		140	1206
		Misses	Correct Negatives
		275	11675
Accuracy	34%		
Hit Rate	0.337		
Critical Success Index	0.086		
	2015	Observed	
	Forecast	Hits	False Alarms
		57	546
		Misses	Correct Negatives
		59	9134
Accuracy	49%		
Hit Rate	0.491		
Critical Success Index	0.086		

The algorithm was then adjusted to use 75% relative humidity averaged between the 950mb and 700mb levels as the criteria for the occurrence of precipitation. Again, the vertical velocity component was considered, but a direct input was not added to the algorithm. Table 3 shows the results of the second run, with the adjusted algorithm, on the three initial cases. Although the results were still not perfect, the accuracy of the algorithm had increased significantly for all cases. Overall, these results produced more hits than misses that greatly influenced the instantaneous accuracy. Looking at individual six hourly results, some six-hourly reports had more reports than others (i.e., 1 observation versus 30 observations). Some of the analysis times showed 1 observation, 1 miss which resulted in 100% inaccuracy. Other events produced for example, 17 hits and 4 misses, which resulted in 81% accuracy. For a majority of the results, the algorithm succeeded in picking up more hits of observed freezing precipitation events, especially events that had 16 observations or more.

Table 3. Second run of three case studies used to tune the algorithm.

Second Run			
	1994	Observed	
	Forecast	Hits	False Alarms
		142	708
		Misses	Correct Negatives
		124	6591
Accuracy	53%		
Hit Rate	0.534		
Critical Success Index	0.146		
	1998	Observed	
	Forecast	Hits	False Alarms
		270	2774
		Misses	Correct Negatives
		156	16717
Accuracy	63%		
Hit Rate	0.634		
Critical Success Index	0.084		
	2015	Observed	
	Forecast	Hits	False Alarms
		87	1079
		Misses	Correct Negatives
		29	13105
Accuracy	75%		
Hit Rate	0.75		
Critical Success Index	0.073		

While the number of hits increased, the number of false alarms increased, as well. The false alarms were attributed to three factors observed while looking at these case studies. First, as we increased the average relative humidity over the 950mb through 700mb levels, we increased the total favorable area of coverage. The initial run seemed to be blocking the areas for favorable conditions for precipitation due to the relative humidity being limited in the vertical. Second, the algorithm has no way to extract where the model is producing precipitation. Lastly, because we are only running the algorithm to compare to a single hourly observation coincident with the model data, there is the possibility of one station observing freezing precipitation within the six-hour window, around the model analysis time. This would be missed in the verification. There is also the possibility of stations that are experiencing freezing rain and not reporting it. For example, the model may have forecast freezing precipitation over the state of Tennessee. One station reports several observations of freezing precipitation in the six-hour window, but not at the analysis time. One station is experiencing freezing precipitation but is not reporting it, while another station 30 km east is reporting freezing precipitation during the six-hour analysis period. The algorithm was only verified with the observed freezing precipitation for the observations that exactly matched the analysis time, but it missed the other observations that might also verify.

Although the second run output produced accuracy outputs of less than 75% for all of the cases, the amount of hits did improve overall. The 2015 case showed only a 53% overall accuracy. Most of the hits and misses occurred when there were only a few reported observations (<5). Analysis times that produced more than 12 observations showed an 81% accuracy and analysis times that produced more than 16 observations yielded a 79% accuracy. The 1998 case yielded accuracy between 67% and 69% for greater than 12 but less than 20 observations per analysis time respectively. The 1994 case yielded accuracy between 48% and 69% for greater than 12 but less than 20 observations respectively.

Overall, while not 100% accurate, the algorithm proved to be satisfactory in picking up the majority of freezing precipitation events, but it still yielded a high output of false alarms. Up to this point, the algorithm only required a warm layer to occur over a sub-freezing layer for the profile to be flagged as freezing precipitation.Bourgouin’s area method (2000) required a negative cold area to be less than 0.66 of the positive warm area plus an offset. This was added to our algorithm by requiring the negative area be greater than $3Jkg^{-1}$ and the positive area be greater than 1.4 times the negative area. This eliminates very shallow cold layers while keeping the positive to negative ratio consistent with the Bourgouin (2000) method. After applying the newly adjusted algorithm to the initial cases, the hits and misses remained mostly the same (a change of 1 or less to hits and misses), but reduced the amount of false alarms overall (Table 4).

Table 4. Final run of three case studies used to tune the algorithm.

Final Run			
	1994	Observed	
	Forecast	Hits	False Alarms
		142	649
		Misses	Correct Negatives
		124	6653
Accuracy	53%		
Hit Rate	0.534		
Critical Success Index	0.155		
	1998	Observed	
	Forecast	Hits	False Alarms
		203	1461
		Misses	Correct Negatives
		223	18070
Accuracy	48%		
Hit Rate	0.477		
Critical Success Index	0.108		
	2015	Observed	
	Forecast	Hits	False Alarms
		86	991
		Misses	Correct Negatives
		30	13198
Accuracy	74%		
Hit Rate	0.741		
Critical Success Index	0.078		

B. RESULTS FOR 4 DIFFERENT ICE STORM SEASONS

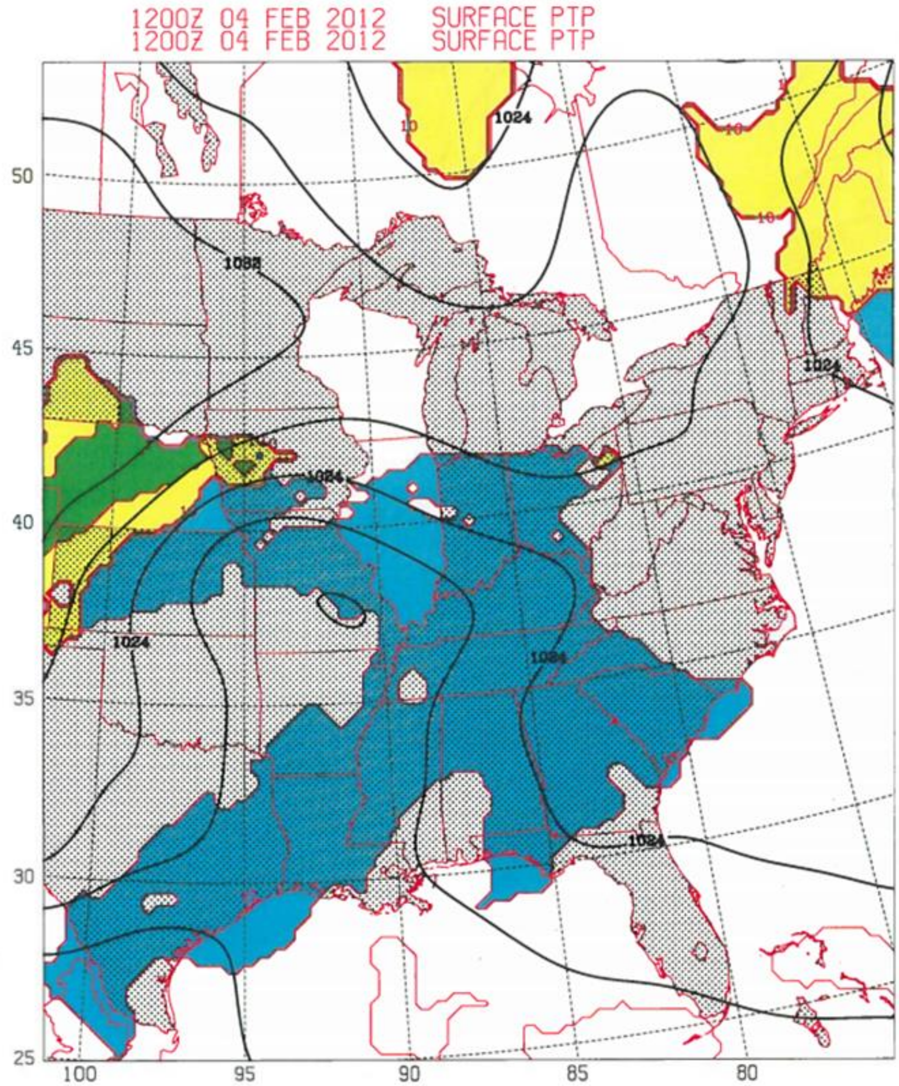
Next, 4 ice storm seasons (December 1–March 31) were chosen based on significance (high amount of ice storm events), insignificance (low amount of ice storm events), and years that experienced strong La Nina and El Nino characteristics. The 4 seasons that were selected were 1988–1989 (La Nina), 1997–1998 (El Nino), 2011–2012 (insignificant) and 2012–2013 (significant). Initially, the algorithm was applied to only two of the seasons in order to establish a threshold of gridpoints that reported freezing precipitation in order to be considered an event. The 2011–2012 and 2012–2013 seasons were used and the output was put into graphs to define a threshold above which a freezing precipitation event occurs. The threshold was used for further adjustment of the algorithm, as there were significant jumps between times of known ice storm events and times when no ice storm event took place. We chose a threshold of 120 for the number of gridpoints that recorded ice storm events. Everything below 120 gridpoints was considered a non-event and everything above 120 were considered a possible ice storm event.

Once a threshold was established and the algorithm was deemed satisfactory, the algorithm was run on all 4 seasons' of analysis data. After these graphs were produced, actual ice storms needed to be verified and compared to what the algorithm had identified as a freezing precipitation event. The NCEI Storm Events database, the Plymouth State Weather Center archives and METAR data from the University Corporation for Atmospheric Research (UCAR) Unidata program were used to verify ice storms. Using the NCEI database, the dates for each season and year were entered (i.e., December 1, 1997–March 31, 1998). Search criteria included all U.S. States (although we were only concerned about freezing precipitation events east of 105^{o} west longitude), ice storms, blizzards, sleet, winter weather, and winter storms. Because these types of weather events can be associated with producing freezing precipitation, in addition to other types of precipitation, they were used in the search and verified by reading individual episode narratives. The Plymouth State Weather Center archives were used to plot present weather on surface data maps. The archives only date back to July 1998, therefore they were not usable for all four seasons. The archives proved useful, as there were some events that were not included in the database, but present weather observations did indicate freezing precipitation. For the 1988–1989 data set, the GEMPAK Analysis and Rendering Program (GARP) was used to view observations for verification.

We also included 300 mb vector wind composite mean plots for each of the 4 seasons by month to account for the jet stream location. They were produced by NOAA's Earth System Research Laboratory (NOAA ESRL 2009). This was done to characterize climate for the year.

After verifying actual ice storm events to events the algorithm had recognized, there were some noticeable discrepancies with the algorithm. Many of the freezing precipitation events that were being produced by the algorithm, taking place over the

Northern and Central Plains, and Upper Midwest states, did not verify. The events that verified in those areas were snow, wet snow, ice pellets or rain. Most of the images produced in VISUAL displayed a rain area geographically south of a snow area and a freezing precipitation within the snow area, as seen in Figure 10. Figure 11 shows a cross-section taken along 100^{o}W on February 4, 2012 at 12Z. The cross section shows a shallow sub-freezing layer with a shallow warm layer above. This geographical area is higher in elevation. The vertical resolution of CFSR data and a ground level above 1000mb make the determination of the depth of a shallow cold layer very sensitive to small changes. Resolving this problem may not be feasible with coarse vertical resolution and was not addressed in the present study.



Snow is represented by yellow color fill, rain is blue color fill and freezing precipitation is green color fill.

Figure 10. Freezing precipitation located in the Central Plains that did not verify.

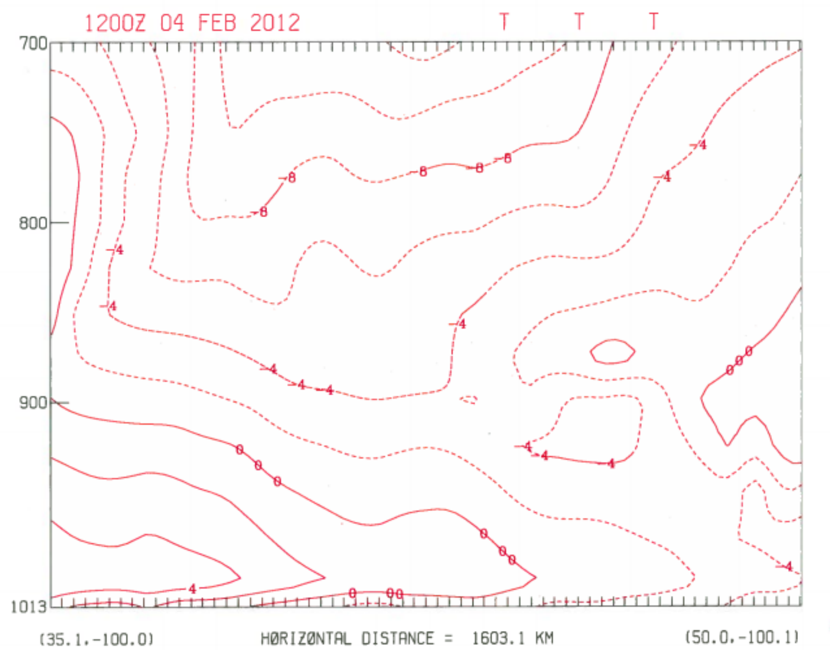
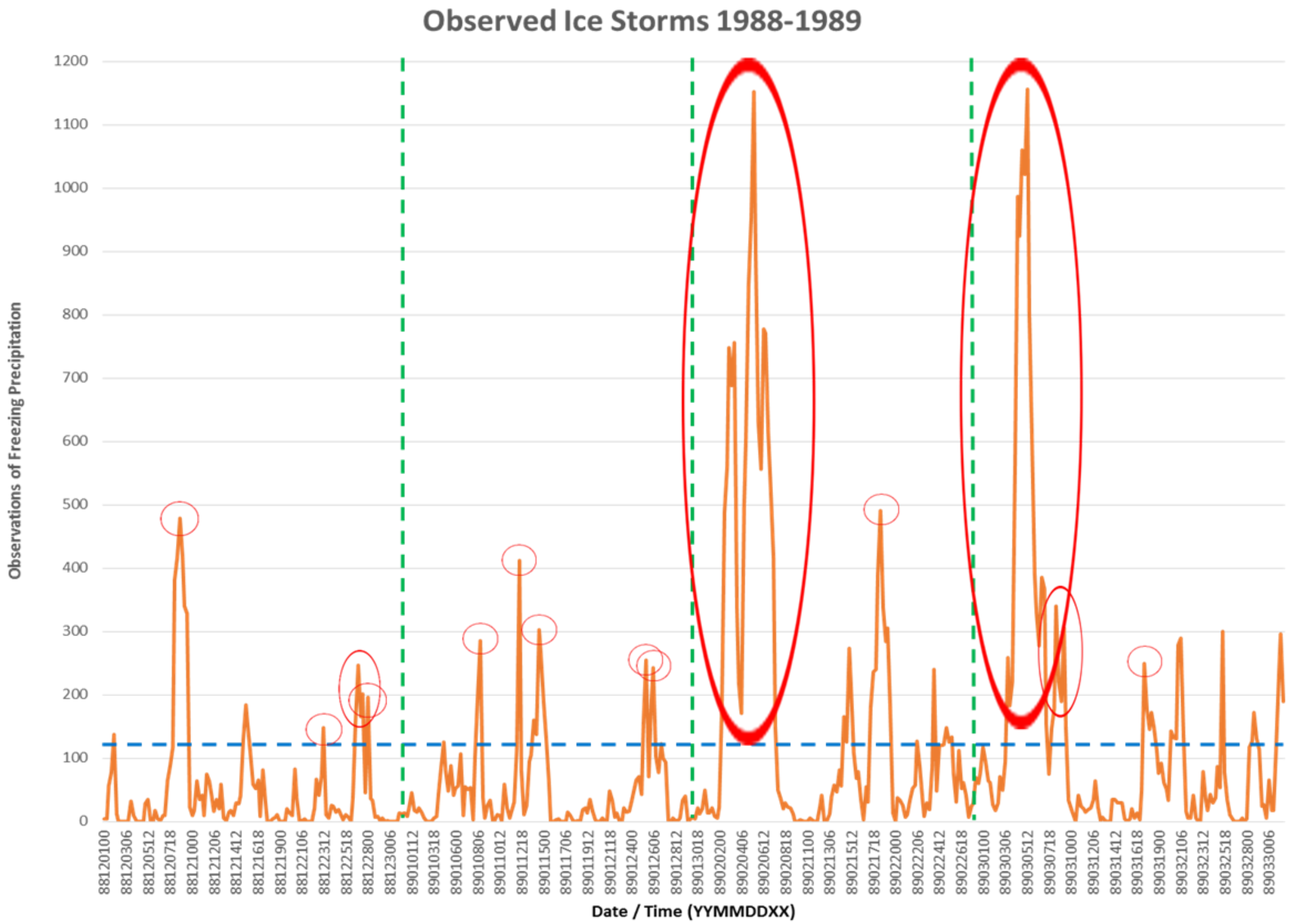


Figure 11. Cross-section (surface to 700mb) of area 100°W longitude and between 35°N and 50°N latitudes showing temperature in degrees C.

1. 1988–1989: La Nina

1988 and 1989 was considered a strong La Nina year. The Oceanic Nino Index (ONI) is used to identify El Nino and La Nina events. La Nina years are characterized by cool sea surface temperatures (SST) over a 3-month consecutive period, based on a threshold of -0.5°C. Weak, moderate, and strong La Nina events are further categorized as 0.5–0.9 SST, 1.0–1.4 SST, 1.5–1.9 SST, and ≥2.0 SST, respectively (NOAA Climate.gov 2009).

Throughout the majority of this season a strong jet stream sat over the Mid-Atlantic and Northeast regions of the United States and along the southeast Canadian border as seen in Figure 13. A major difference seen in this year's data set from the other years, is that January was not an active month. February and March were the more active months as seen in Figure 12.



Red circles identify verified ice storm events.

Figure 12. December 1, 1988–March 31, 1989, freezing precipitation events recognized by the algorithm.

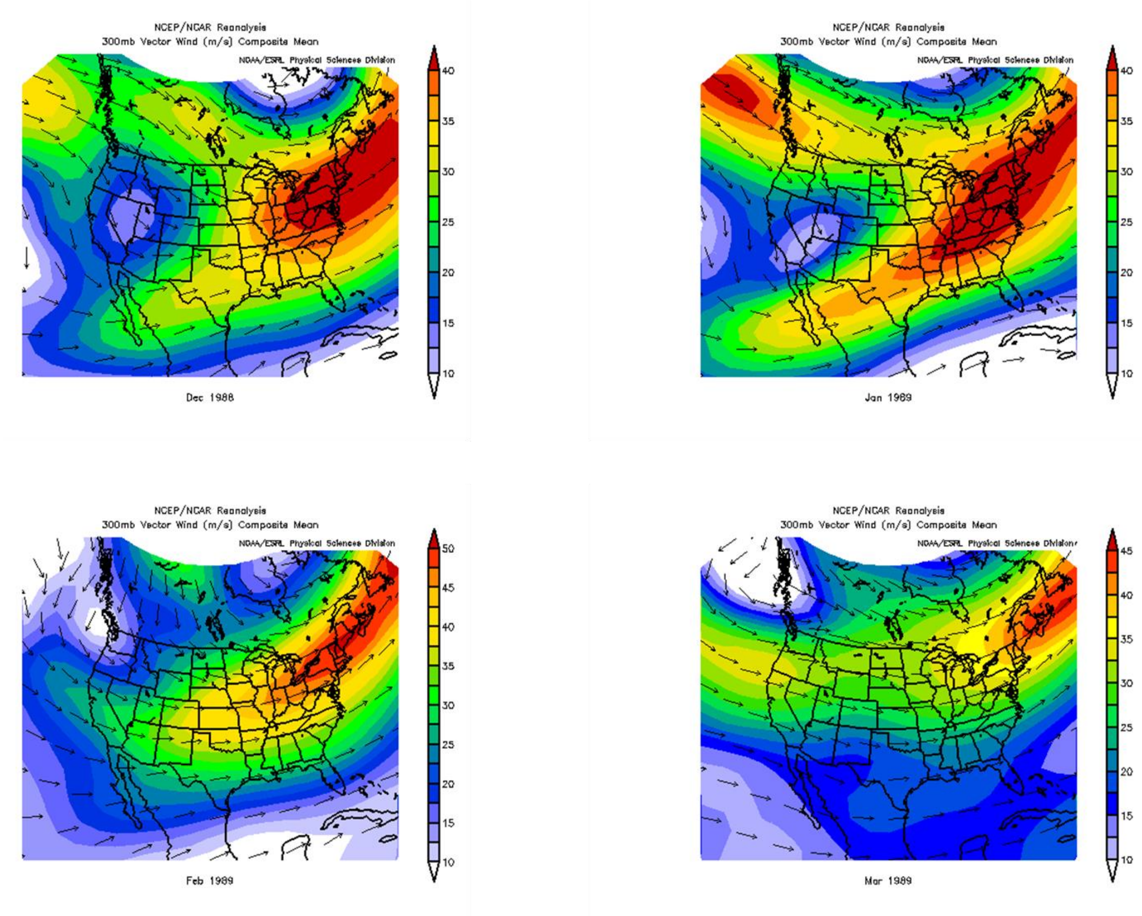


Figure 13. 300 mb vector wind (m/s) composite mean (December 1988–March 1989). Source: NOAA ESRL(2016).

Looking at the observations, a station or set of stations in an area would report freezing precipitation during one 6-hour analysis, then it would not be observed during the next 6-hour observation period, but would return in the following 6-hour reporting period. This happened in numerous locations throughout the verification period. While a majority of the storms did validate, the two storms (one in February, one in March) that the algorithm recognized with a large numbers of gridpoints, did seem to over predict on the areas that it reported freezing precipitation. These two storms were both cases where freezing precipitation was reported during one 6-hour period, not reported during the next 6-hour period, and then would return in later reporting periods. Also, if both of these storms did cover such a large area of the United States (eastern Texas up through the Tennessee Valley to the Mid-Atlantic region), there was not much historical information on them. In contrast, the algorithm under predicted the verified freezing precipitation events in areas in the northeast and Mid-Atlantic.

During the month of December the mean jet stream stayed over the Mid-Atlantic and New England regions. The first storm that validated was over the panhandles of Oklahoma and Texas. As mentioned previously, the freezing precipitation observations were not consistently reported every 6 hours, but the observations were reported at stations all in close proximity to each other and in areas that the algorithm predicted freezing precipitation. Although the algorithm did well on recognizing some events in the Central Plains region, it did not verify for a few areas in that region. The algorithm verified well on storms at the end of the month over the Ohio Valley and New England regions.

The mean jet stream did remain over the New England and Mid-Atlantic regions during the month of January, but it did move further inland over the Tennessee Valley. For the majority of the events that verified in January, the algorithm did over predict in area of coverage. However, the observations did not seem consistent. Freezing precipitation would be observed, then not observed during the next reporting period, but stations within 200 km would report observations of freezing precipitation. The following reporting period would show the freezing precipitation returning to the previous reporting station.

In February, the algorithm seemed to over predict for the area of coverage for a storm that lasted several days at the beginning of the month. The mean jet stream did move further north over the New England region and over the southeast Canada coastline as seen in Figure 13. The two largest storms, according to the gridpoint analysis (one at the beginning of the month and the other beginning February 17 at 12Z), showed large areas of coverage. When the verification was complete, there was an ice event that did cover several states, but the areas that the algorithm predicted as ice events were not verified. According to the observations, there were several small-scale freezing precipitation events that happened over several states, but not a large line of freezing precipitation. There could have been a major storm at the beginning of the month that did cover a large area, as predicted by the algorithm, but there is not a lot of historical information to verify, other than the Unidata observations.

Going into the month of March, the mean jet stream continued to move northward over Maine and over the southeast Canadian coastline. The major ice event that the algorithm predicted at the beginning of the month was similar to the major event in February, in that the algorithm over predicted for the area of coverage. It still did verify in the vicinity of where the algorithm identified, but some areas were snow and some areas were rain. The last four events, in the month of March that included over 120 gridpoints, were all observed as snow events.

Overall, there were 22 freezing precipitation events, above the 120 gridpoint threshold. Many of the false alarm events had areas of coverage just above the 120 gridpoint threshold and so the performance might already be better than 64%. Of those 22 events, we were able to verify 14 resulting in a 64% accuracy rate.

2. 1997–998: El Nino

One of the strongest El Nino years ever recorded happened in 1997 and 1998. El Nino years are characterized by warm sea surface temperatures (SST) over a 3-month period, based on a threshold of +0.5^{o}C (NOAA Climate.gov 2009). Weak, moderate, strong, and very strong El Nino events are categorized similarly to La Nina. The jet stream represented the El Nino characteristics by staying far south during the winter season (Figure 14).

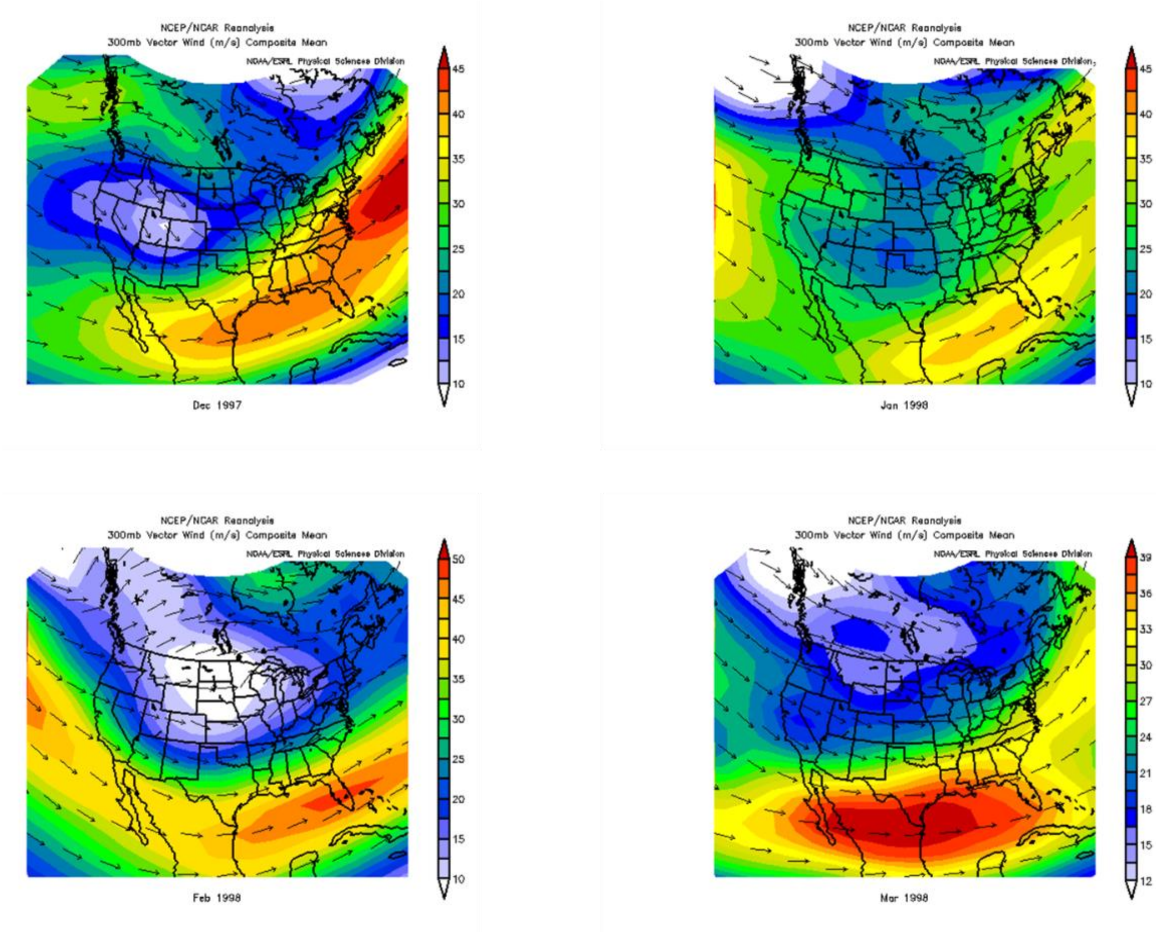
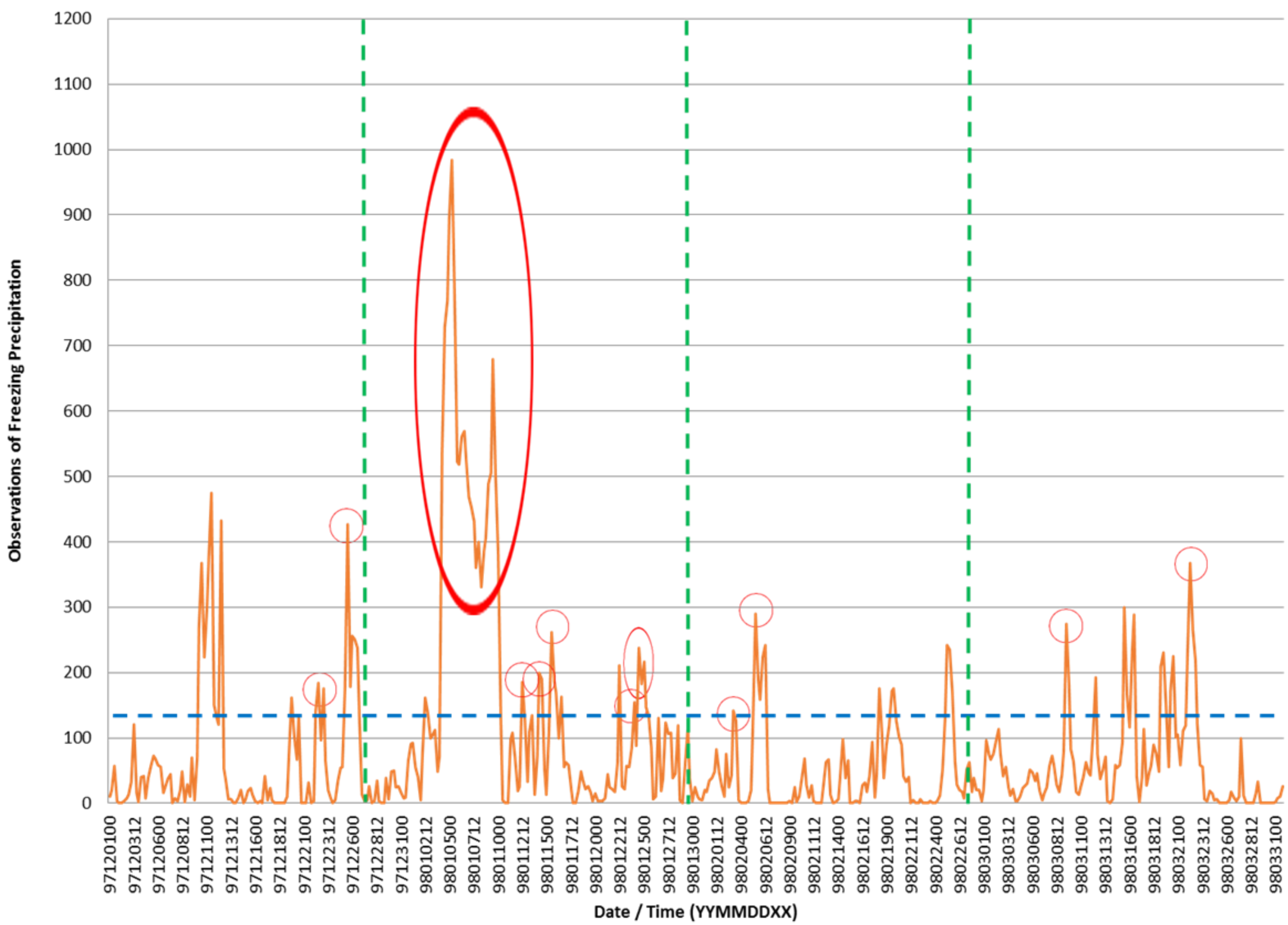


Figure 14. 300 mb vector wind (m/s) composite mean (December 1997–March 1998). Source: NOAA ESRL (2016).

It was difficult to compare this strong El Nino ice storm season to any of the other data sets, other than having an active storm month in January, as seen in Figure 15. The ice storm that took place in January 1998 would become one of the most historic ice storms to date. This data set was similar to the 1988–-1989 data sets, in that there were not as many observations available for verification or climatology information. It is possible that more storms could have been verified. The jet stream remained mostly south of the United States throughout this period of time as seen in Figure 14.



Red circles identify verified ice storm events.

Figure 15. December 1, 1997–March 31, 1998 freezing precipitation events recognized by the algorithm.

The strongest mean jet stream remained off the northeast coastline and extended down to southern Texas for the month of December. The majority of rain events stayed at or below the jet, while snow events remained north and west of the jet latitude. The month of December did not verify as well as expected. Although the algorithm did recognize and verify a small-scale ice storm in western Nebraska, it over predicted on the area of coverage. This was attributed to the algorithm not doing very well at deciphering between snow, rain and freezing precipitation events over the Central and Northern Plains areas. There were three ice storms that did verify, towards the end of December. They were located in the northeast United States.

As previously mentioned, all of the data sets show an active ice storm month for the month of January. This January set was no different. The algorithm picked up 10 freezing precipitation storms, above 120 gridpoints, in January. Seven of those events were verified. It also included one of the most damaging storms in U.S. history. This storm took place January 4 through January 10. The algorithm did extremely well in recognizing this ice storm, as well as deciphering between the snow and rain.

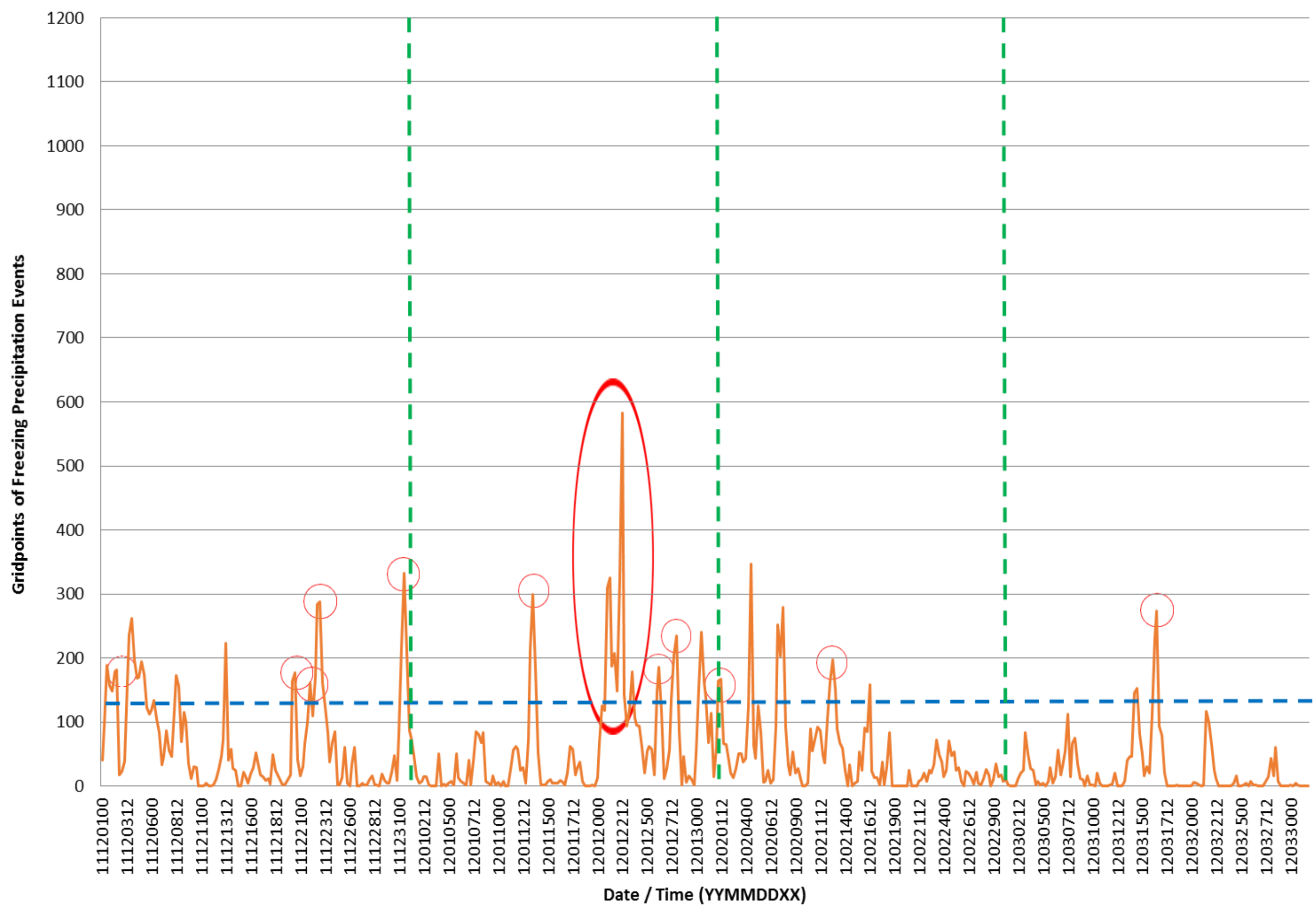
In February, only two storms were verified. The jet stream was still far south and increased in strength. Similar to December, the algorithm recognized another verified small-scale storm in Nebraska, but over predicted for the area of coverage. The other storm that verified was part of a large mixed precipitation storm that extended from the Tennessee Valley up towards New England. Most of the over verified events happened in the New England region. There was another area that the algorithm identified in the Ohio Valley, but it did not verify and was geographically north of the snow line by looking at the observations, therefore it was mostly likely snow, not freezing precipitation.

During the month of March, the jet continued to strengthen and remain south extending from the Baja Peninsula over the Gulf of Mexico to Florida. There were two storms that verified over the New England region. Most of the events that did not verify were snow events over the North and Central Plains, the Upper Midwest and the Ohio Valley.

For the 1997–1998 freezing precipitation season, there were 27 freezing precipitation events, above the 120 gridpoint threshold. 13 ice storms were verified resulting in a 48% accuracy rate. Again, many of the incorrectly forecast events were just above the threshold, suggesting that accuracy may be higher if a higher threshold were used.

3. 2011–2012: Insignificant Ice Storm Season

The 2011–2012 ice storm season was chosen as an insignificant storm season based on the storm events database, not including mixed precipitation (i.e., snow, rain, ice pellets, etc.), based on 3 days of observed events. As our research evolved, we noticed that there was not a significant difference between this season and the 2012–2013 season, discussed next. Both of these seasons, as well as the previously discussed El Nino season, experienced a higher amount of large-scale ice storms in January. Figure 16 and later in the 2012–2013 section, Figure 18 shows a higher frequency of ice storms during the month of January. The jet stream remained mostly over the Mid-Atlantic region and along the New England coastline, but in March the jet stream moved north as seen in Figure 17.



Red circles identify verified ice storm events.

Figure 16. December 1, 2011–March 31, 2012 freezing precipitation events recognized by the algorithm.

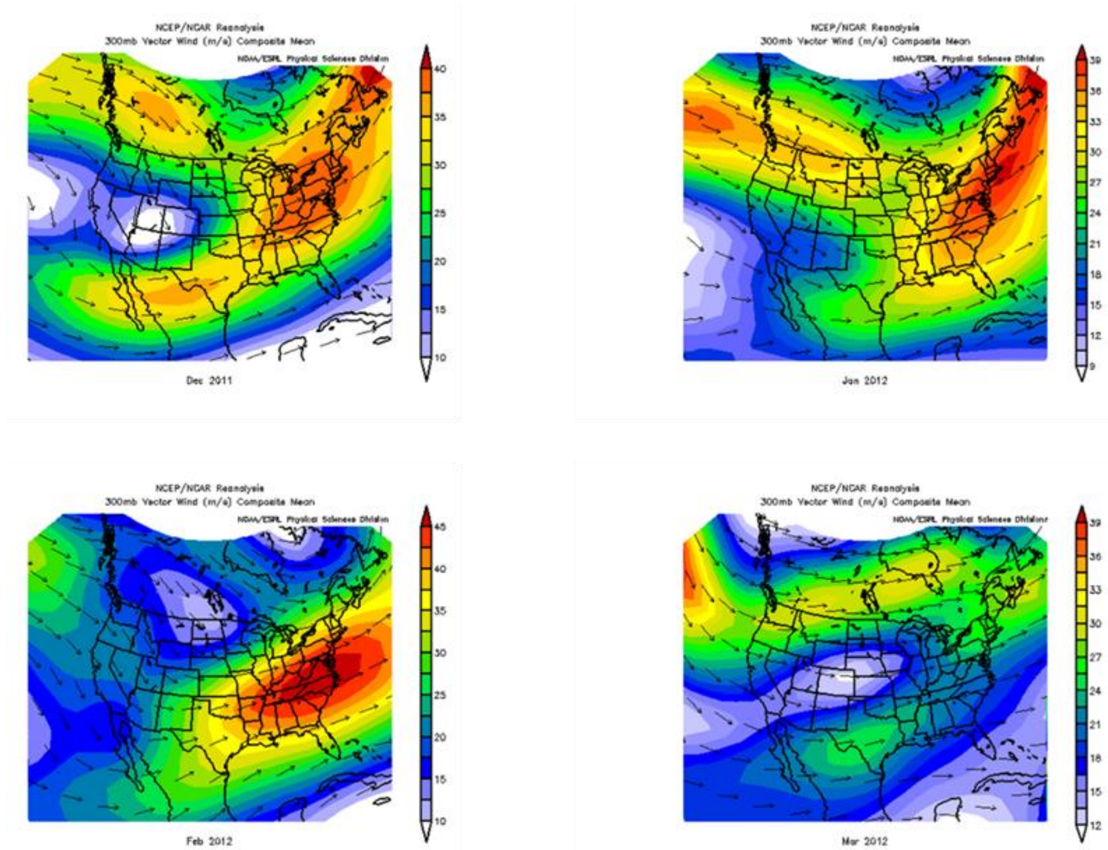


Figure 17. 300 mb vector wind (m/s) composite mean (December 2011–March 2012). Source: NOAA ESRL (2016).

The majority of storms that the algorithm identified, during the month of December, took place in the Central Plains states. The two storms that verified were in the Central and Southern Plains regions, which was not consistent with a lot of the other data sets, in that the algorithm did do well in this region. The ice events took place at the beginning of the month over the Oklahoma and Texas panhandles and towards the end of the month over the two panhandles and Kansas. There were also two events in the Northeast that were confirmed. The mean jet stream was split in December, but the strongest winds were over the Mid-Atlantic and southern New England regions.

The mean jet stream moved east and aligned along the Mid-Atlantic and Northeast coastline. At the beginning of the month, there was a confirmed ice storm in New Hampshire and Maine. A large-scale storm that began over the Mississippi and Ohio valleys, and moved east over the Mid-Atlantic States, was also identified by the algorithm. Rain events remained at or below the mean jet stream, while snow events took place mostly in the Northern Plains and Upper Midwest regions. Towards the end of January, most of the verified ice events took place in western Ontario and the Northeast.

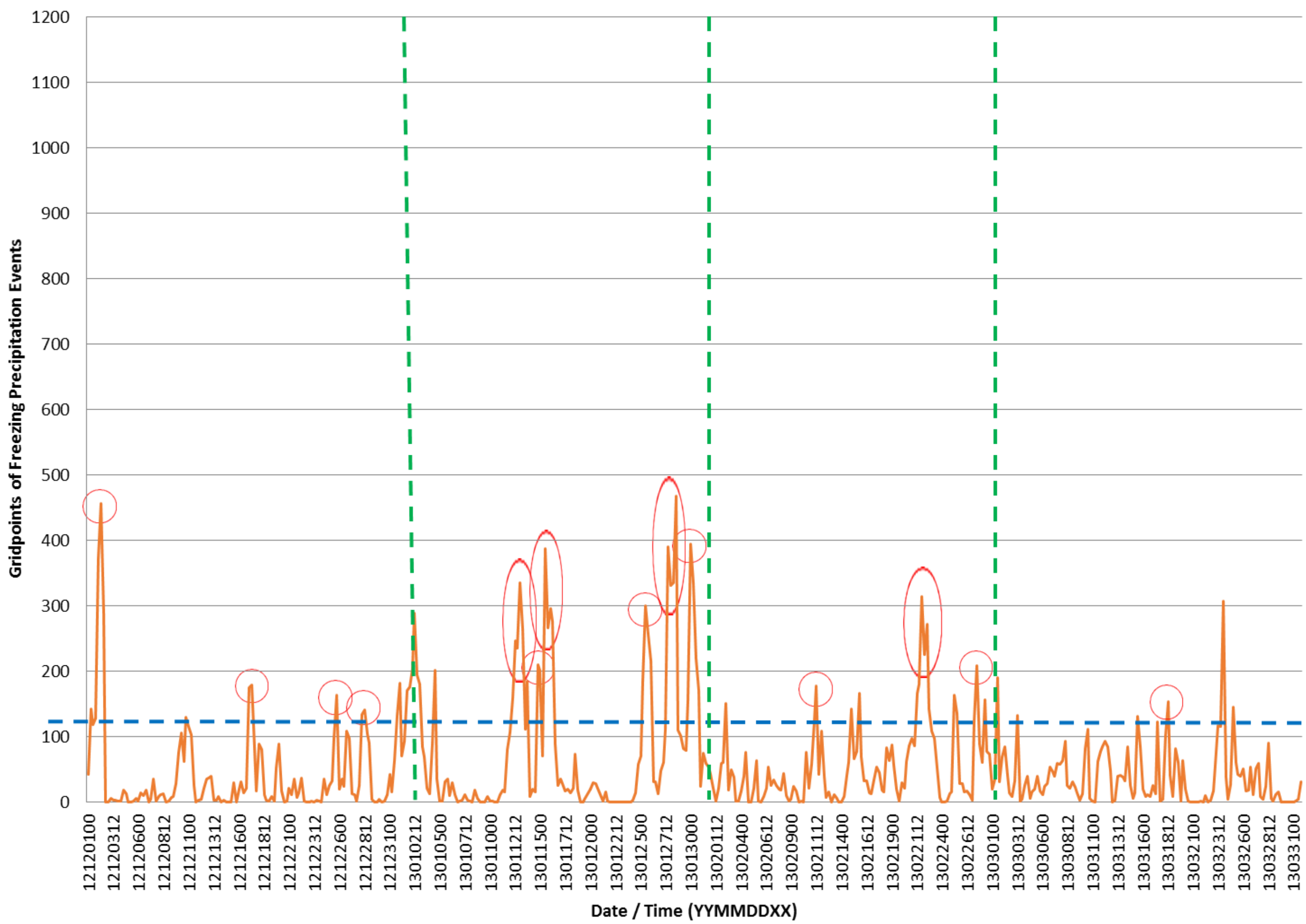
The jet stream mean remained mostly stationary over the Mid-Atlantic region during February. Snow events took place over the Northern and Central plains, upper Midwest and New England regions. In sync with the jet stream, rain events took place south of these areas. Most of the events that the algorithm identified as freezing precipitation were, again, in those Central Plains areas, therefore they did not verify. The events that did verify were in those that took place in the New England region.

There were two ice events that the algorithm recognized for our research in the month of March. The only event, being the larger event on March 16, was verified through surface weather observations. As previously stated, the weaker mean jet stream remained mostly north of the United States extending from the Hudson Bay down towards the Pacific Northwest United States. During the month of March, the ice storms that were predicted took place in southeastern and eastern Canada, below and east of the mean jet stream.

The algorithm predicted 21 freezing precipitation events during the 2011–2012 seasons. 13 ice storms were verified resulting in a 62% accuracy rate. The incorrectly predicted events in this year often well exceeded the 120 gridpoint threshold and so this year seemed to be handled less accurately overall.

4. 2012–2013: Significant Ice Storm season (Polar Vortex)

Prior to our research, just considering ice storms in the storm events database, not including mixed precipitation (i.e., snow, rain, ice pellets, etc.), and the 2012–2013 seasons was deemed as a significant storm season based on 17 days of observed events. As previously mentioned in the 2011–2012 research, the 2012–2013 seasons was similar in freezing precipitation events that the algorithm recognized as seen in Figure 18. Figure 19 shows December and February saw similar jet stream placement with the mean extending from the northeast and Mid-Atlantic region down to Texas. In January and March the mean jet stream was situated along the east coast.



Red circles identify verified ice storm events.

Figure 18. December 1, 2012–March 31, 2013, freezing precipitation events recognized by the algorithm.

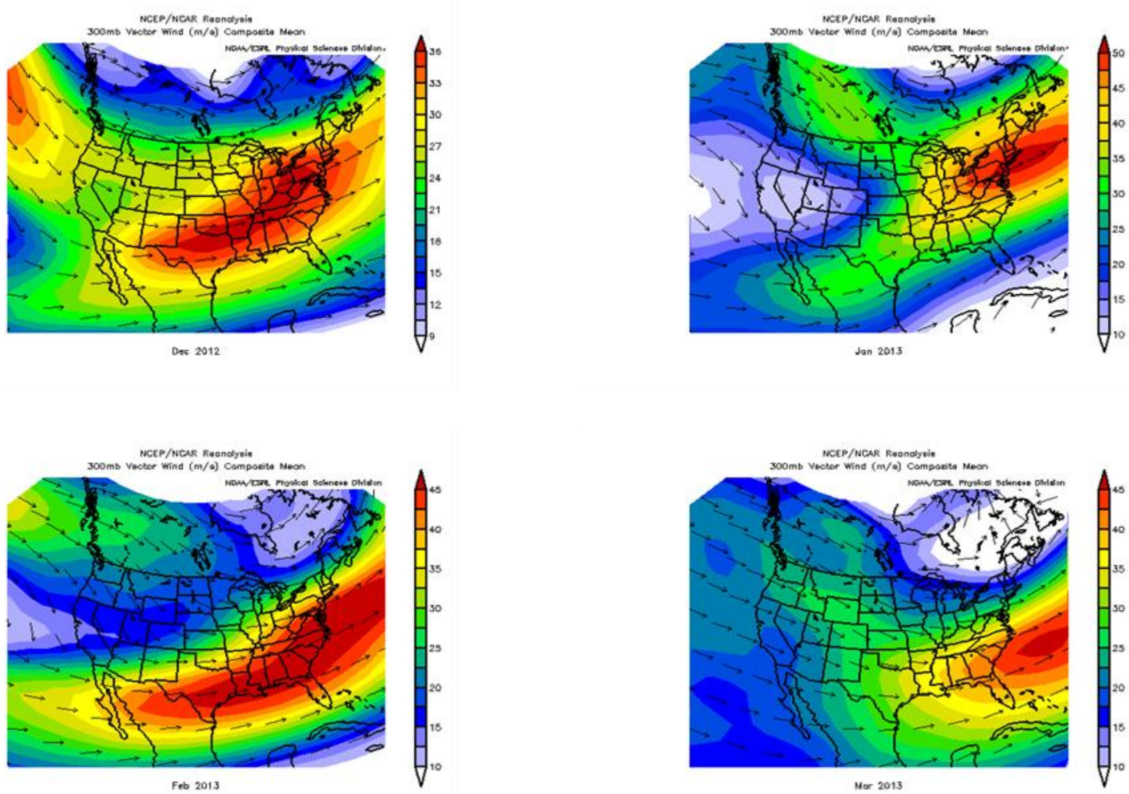


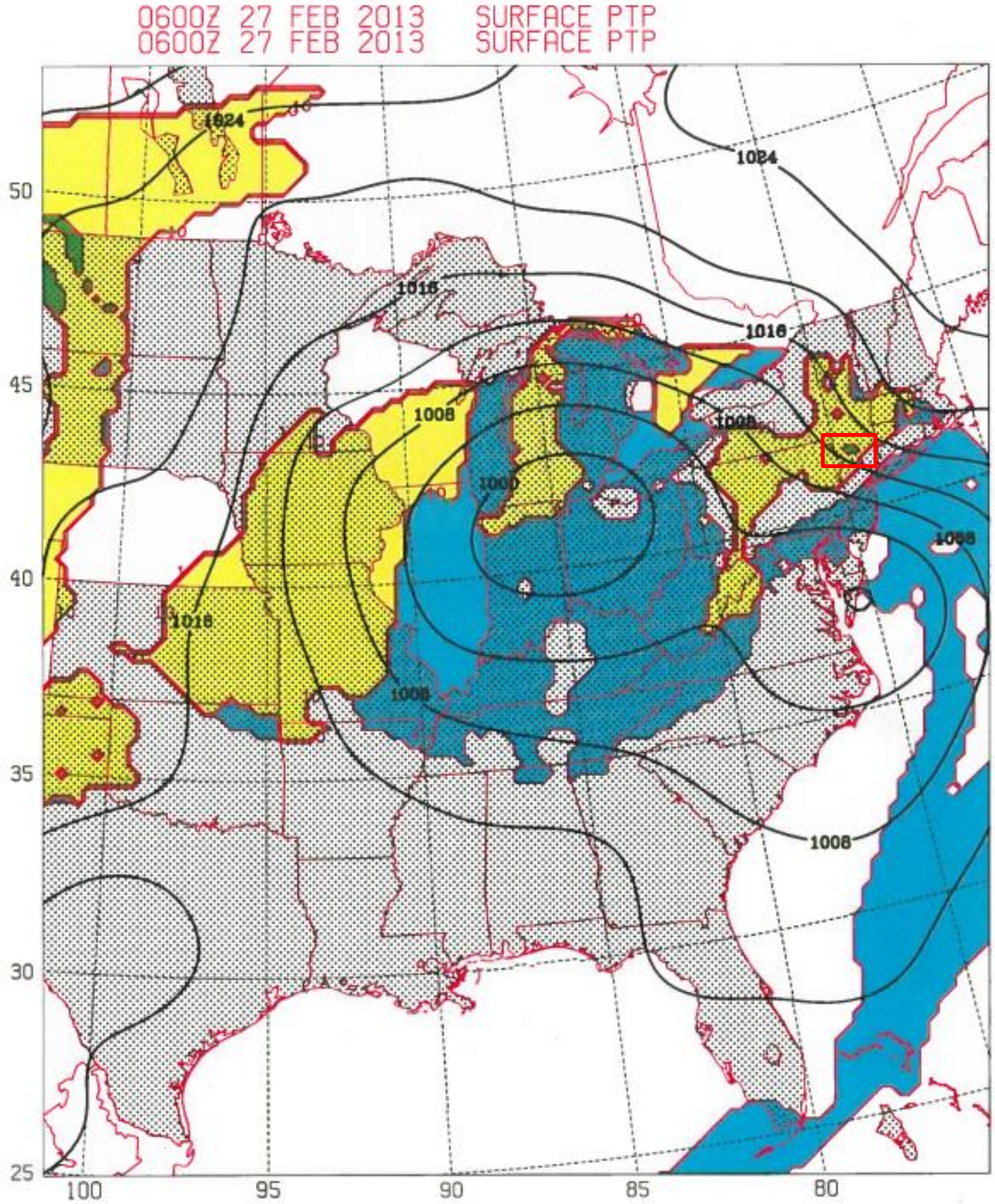
Figure 19. 300 mb vector wind (m/s) composite mean (December 2012–March 2013). Source: NCEP / NCAR Reanalysis (NOAA ESRL 2016).

During the month of December the strongest jet stream extended from west Texas up to New England. During this month, the majority of the freezing precipitation events that the algorithm recognized took place over western Ontario, southern Quebec and New England, just north of the jet. Snow remained in southern Canada and New England and rain events took place south of these regions. Towards the end of December, as winter set upon the United States snow moved over the upper-half of the country, while rain remained in the south, which was confirmed by looking at precipitation plots for each day. A freezing precipitation event was picked up by the algorithm and verified in north Arkansas.

The month of January experienced more large-scale ice storms than the other three months in the 2012–2013 for our research. The mean jet stream composite has the strongest winds over the Northeast. The majority of the precipitation events that the algorithm recognized had snow in Canada and northern regions of the United States. Rain events mostly extended along the southern split portion of the jet stream. Again, the events that the algorithm recognized at the beginning of the month were over the Central Plains. There were some small-scale events in New Hampshire, Maine and southeast Canada that the algorithm did recognize, but the algorithm produced a larger area than what was observed. Overall, the algorithm did well picking up on large-scale freezing precipitation events that took place in January, hitting 6 out of 7 storms.

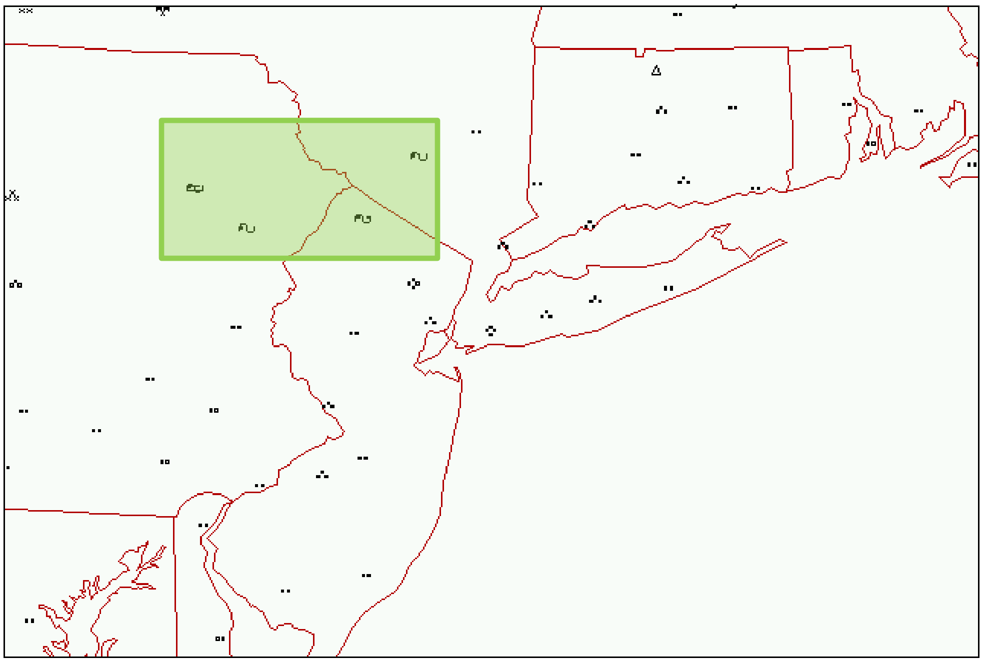
In February, the jet stream pushed further south again extending from northern Mexico over to the Mid-Atlantic region. Snow events took place over the northern and central plains, upper Midwest and New England regions. In sync with the jet stream, rain events took place in areas of the strongest mean jet stream (along the Gulf Coast and Mid-Atlantic).

The algorithm did extremely well identifying ice storm events during February 2013, with the exception of the Central Plains region. There were two small-scale events that took place in New England, and the algorithm recognized both occurrences. Figures 20 and 21 show one particular example that verified a small-scale event that took place over northeast Pennsylvania, southern New York state and northwest New Jersey. The algorithm also confirmed a freezing precipitation event that took place February 21 at 1800Z through February 22 at 1800Z in Arkansas/Missouri moving northeast towards Pennsylvania, Maryland and Virginia.



Freezing precipitation is represented red box with green color fill.

Figure 20. Verified small-scale freezing precipitation event in south New York State.



Green box represents actual freezing precipitation observations.

Figure 21. Verified small-scale freezing precipitation event in south New York State. Source: Plymouth State Weather Center (2016).

For our research purposes, there were only two freezing precipitation events above the 120 gridpoint threshold in March 2013. Looking at the analysis of precipitation events, the Southeast and Mid-Atlantic were dominated by rain and the Northern and Central Plains, Upper Midwest, Ohio Valley and the Northeast experienced snow events. The jet stream was situated over the southeast during March, which correlates to the weather events, as most of the rain stayed over the south, southeast and off the east coast, while the snow and freezing precipitation events took place in the Northern Plains, Upper Midwest and northeast. Of the two events that the algorithm recognized, one was verified.

For the 2012–2013 freezing precipitation season, there were 24 freezing precipitation events, above the 120 gridpoint threshold. Fourteen ice storms were verified resulting in a 58% accuracy rate. As with some of the other years the incorrect events were often just about the threshold and the accuracy may be better than 58%

We analyzed four different seasons using the freezing precipitation algorithm that we created. Overall, we were satisfied with the algorithm's performance. The accuracy rate for all sixteen months of data is 57%, with the 1988–1989 season having the most hits that verified at 64%, and the 1997–1998 season having the least at 48%.

The highest number of misses that were found in the analysis took place over the Great Plains. We found that this could be attributed to the topography and that the CFSR vertical resolution may be insufficient to resolve this issue.

The last item that we recognized in this analysis is that the mean jet stream located does correlate to precipitation weather events. Wherever the mean jet stream was located, snow events stayed north or west of the location, while rain stayed south and east of the location. Freezing precipitation events usually occurred just slightly north of the mean jet stream maximum.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The purpose of this research was to identify a signature for predicting ice storms. Ice storms can cause billions of dollars in damage and death. As the climate continues to change, it is difficult to know how these changes will affect ice storms. The algorithm that was developed to identify freezing precipitation events during this research is satisfactory, but it could be adjusted to produce a higher rate of accuracy for all freezing precipitation seasons.

The algorithm to identify freezing precipitation, while not 100% accurate, showed that inter-annual variability of ice storms can be assessed by applying it to CFSR data The vertical resolution of the CFSR is limiting, but the algorithm shows promise. A long term "quasi" climatology of ice storms can be derived from the algorithm.

When comparing the four years, the variability in ice storm occurrence was less than expected from other climatologies (i.e., NCEI Storm events database). The frequency of storms seemed to be minimally dependent on climate variation. However, the locations of storms clearly correlated with mean jet stream position which varied from year to year.

Over the four seasons that were used for this research, January was consistently an active month amongst three of the four more recent seasons. The La Nina season that was used has data that is over 25 years old. In 1988–1989 the storm events database did not keep records of ice storms. The observations that were used to verify freezing precipitation events may also be less plentiful and inaccurate. The El Nino season produced a large amount of ice storms that lasted more than 24 hours at a time, including the devastating ice storm in January 1998, a major storm that lasted nearly six days and caused significant damage. The insignificant season (2011–12) did not produce an insignificant amount of ice storm events, but they were short-lived and smaller-scale storms. The significant season (2012–2013) had a mixture of more days with ice storms, some short-lived and some lasting 2–3 days at a time. It would be fair to say that as the climate changes and global temperatures continue to increase, the jet stream would experience a poleward shift and more ice storms would take place in more northern locations.

B. RECOMMENDATIONS

Three areas of further research were uncovered during the process of developing an algorithm to predict freezing precipitation events and using it on data sets from four different seasons. First, the algorithm could be further adjusted. Although the algorithm is satisfactory, there were some issues with it recognizing events that took place over the Northern and Central Plains regions. It verified extremely well in the northeast United States, but there were some areas that it over and under predicted ice storm events. In addition, testing a slightly higher threshold might resolve some false alarms. Next, the algorithm could be used on however many years of climatology data. The research that we conducted only focused on four different seasons, but the algorithm could be used on several years of data to possibly expose any significant changes that could be attributed to climate change. Lastly, this research focused on one parameter. Another area of research could be writing another algorithm to predict another parameter such as visibility conditions.

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