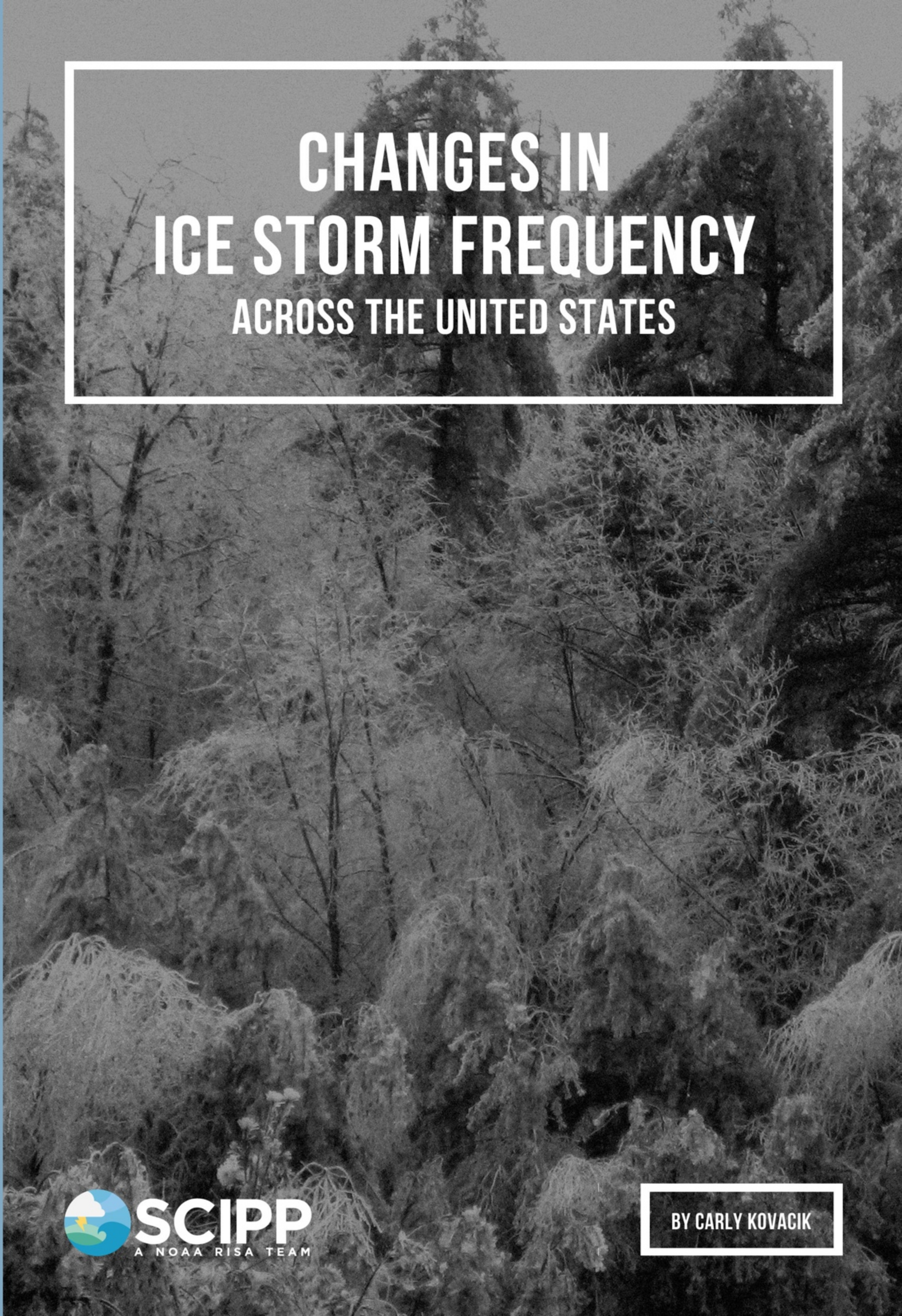

CHANGES IN ICE STORM FREQUENCY

ACROSS THE UNITED STATES

BY CARLY KOVACIK

SCIPP
A NOAA RISA TEAM

SOUTHERN CLIMATE IMPACTS PLANNING PROGRAM

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Southern Climate Impacts Planning Program

University of Oklahoma

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Changes in Ice Storm Frequency Across the United States

Carly Kovacik

Winter weather has a pronounced impact on both life and property across the United States. Numerous studies have been conducted on these types of events to better understand their meteorological features and associated hazards to improve short-term forecast ability. A majority of these studies have focused on severe snowstorm and blizzard events, however, mixed precipitation events and ice storms are also of great hazard.

Ice storms are dangerous and destructive winter weather events. Freezing rain and freezing drizzle can produce hazardous environmental conditions with significant societal impacts that may last from several days to several weeks. Industries that are most affected by these events include power, transportation, aviation, insurance, and public safety. Minor glaze accumulations typically result in pedestrian and traffic accidents, while severe ice accumulations lead to power outages, property damage, closings of ground and air transportation, and physical injury. Such harsh impacts warrant further research on this topic to improve short-term weather forecasting, to understand changes in frequency and impacts over time, and to improve public awareness.

Freezing Rain Development:

Melting process: The atmospheric characteristics of ice storms are complex and complicated to forecast, as freezing rain often forms in narrow bands contained within a broader region of precipitation. In order to understand ice storms from a meteorological or climatological perspective, the formation mechanisms must be introduced. The most common environmental setup conducive to the formation of freezing rain involves a layer of above-freezing air (commonly referred to as the "melting layer") located in the lower atmosphere that is bounded above and below by sub-freezing air (Figure 1). Initially, a precipitation particle in

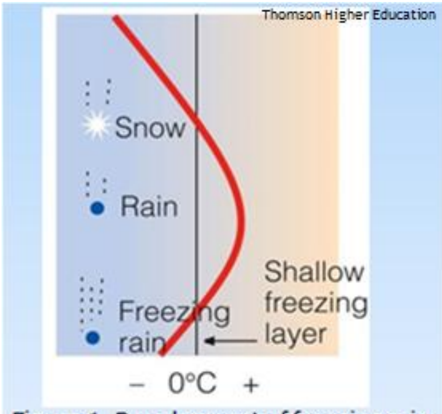

Figure 1. Development of freezing rain through the melting process. An above-freezing layer is bounded above and below by sub-freezing air.

the form of snow falls through sub-freezing air aloft until it encounters a layer of above-freezing air, where it then melts into a raindrop. As this raindrop approaches the surface, it experiences another layer of sub-freezing air. This sub-freezing layer is very shallow and does not allow the appropriate amount of time for the raindrop to freeze back into solid form. Instead, the raindrop freezes on contact with any structure or object it encounters at the surface. Multiple precipitation particles experiencing this process will cause an accumulation of ice to build over an exposed surface.

Warm rain process: Freezing rain can also form through a process referred to as "collision and coalescence" or the "warm rain process." During this process, the atmospheric temperature remains below freezing with height, however, it is common for liquid water molecules to still exist in these conditions and outnumber the amount of ice crystals (Figure 2). When liquid water exists in sub-freezing temperatures, it is said to be *supercooled*. Supercooled liquid drops occur when there is no dirt, dust, salt, or other objects in the water. When these particles exist they serve as a core around which ice can form. Shallow clouds (i.e., stratus) often supply the necessary conditions for the collision and coalescence process and supercooled water. During this process, microscopic cloud droplets collide with one another to produce supercooled liquid droplets, which eventually fall to the surface in the form of light freezing drizzle. Freezing drizzle tends to be more common during the warm rain process, whereas freezing rain tends to be more common during the melting process. While freezing drizzle can make for hazardous walking and travel conditions at the surface, it is often more hazardous to aviation aloft. Freezing drizzle can lead to rapid ice accumulation on aircraft which can impact aircraft performance and has lead to several crashes in the past (Rauber et al. 1999; Bernstein et al. 1997).

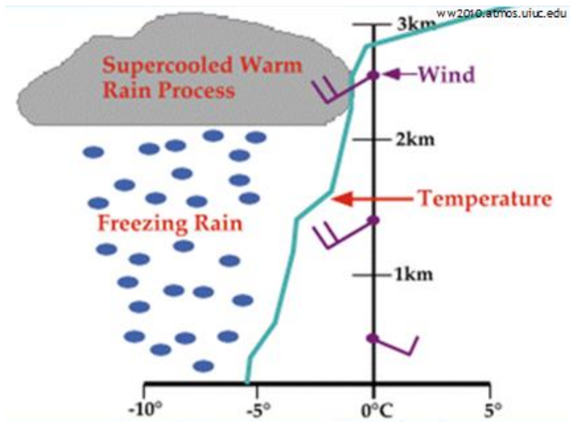

Figure 2. Development of freezing rain through the warm rain process. The atmosphere is sub-freezing, but liquid water still exists in shallow clouds. Water droplets stick together as they fall from the cloud, forming freezing drizzle.

Now that the common mechanisms and temperature profiles conducive for the formation of freezing rain and freezing drizzle have been introduced, it is important to understand the features in the atmosphere and Earth's surface that are commonly associated with these weather events. Warm fronts, arctic cold fronts, mountains, and oceans all provide the necessary conditions for the development of freezing rain and freezing drizzle. It is important to note that freezing precipitation is not always guaranteed with these features, but during the appropriate time of year and under the right conditions, they are a good first estimate as to where freezing rain or freezing drizzle may develop. Each feature is treated individually and discussed in greater detail for the remainder of this section.

Warm fronts: A warm front marks the boundary between the advancement of warm air towards an area of cooler air (Lackmann 2011). During warm frontal occurrences, the wind direction is favorable for the transport of warmer air from southern latitudes over top of cooler air already in place north of the warm front. This condition is favorable for the development of a melting layer in the lower atmosphere. When freezing rain develops, it may also be accompanied by sleet and/or snow as the front moves north. This is due to the gentle, sloping nature of the warm front with height, which contributes to the production of a broad area of precipitation. Freezing rain development in the vicinity of a warm front is most common across the United States in the Great Lakes region, the South, and the Northeast (Rauber et al. 2001).

Arctic fronts: An arctic front is a very shallow, intense cold front that commonly develops during the winter across high latitudes of North America, where air temperatures tend to be the coldest (Lackmann 2011). As an arctic front moves polar air southward from higher latitudes, warmer air in middle latitudes is forced to rise over top of it. The forcing of the warm air over the polar air is relatively weak and usually only produces shallow clouds just behind the front. This allows for the development of freezing drizzle. If the forcing is stronger, deeper clouds may develop, in which case freezing rain would likely occur. The development of freezing rain or freezing drizzle through the propagation of an arctic front is most common across the United States in the Northern and Central Plains (Rauber et al. 2001).

Marine and terrestrial features: In some cases, a weather feature, such as a front, does not act alone to produce freezing precipitation. Mountains and oceans often aid in the development of freezing rain and freezing drizzle. In the case of mountains, very shallow cold air can be too dense to rise over this terrestrial barrier. This cold air then becomes trapped against the mountains where a weather feature may interact with it to produce freezing rain or freezing drizzle. This is especially common on the eastern side of the Appalachian Mountains during the winter, when cold air from the Northeast moves south and becomes trapped against the mountains, while low pressure moving north/northeastward from the Gulf or western Atlantic Ocean supplies warm, moist air that can move over top the cold air. Depending on the cloud depth and the intensity of the forcing of the warmer air over colder air, freezing rain or freezing drizzle can be expected. This setup is also common across the Pacific Northwest near the Columbia River Basin (Rauber et al. 2001).

Global Temperature Changes:

Shown in Figure 3 are the annual global temperature anomalies between 1950-2012, in reference to global temperature data recorded over the past century. Global temperature anomalies associated with each phase of the El Nino-Southern Oscillation (El Nino, La Nina, and Neutral) have been increasing over time. Although, on average, El Nino years are associated with warmer temperature anomalies than La Nina years, the more recent La Nina years have become associated with higher global temperature anomalies than earlier La Nina years (NOAA National Climatic Data Center 2013).

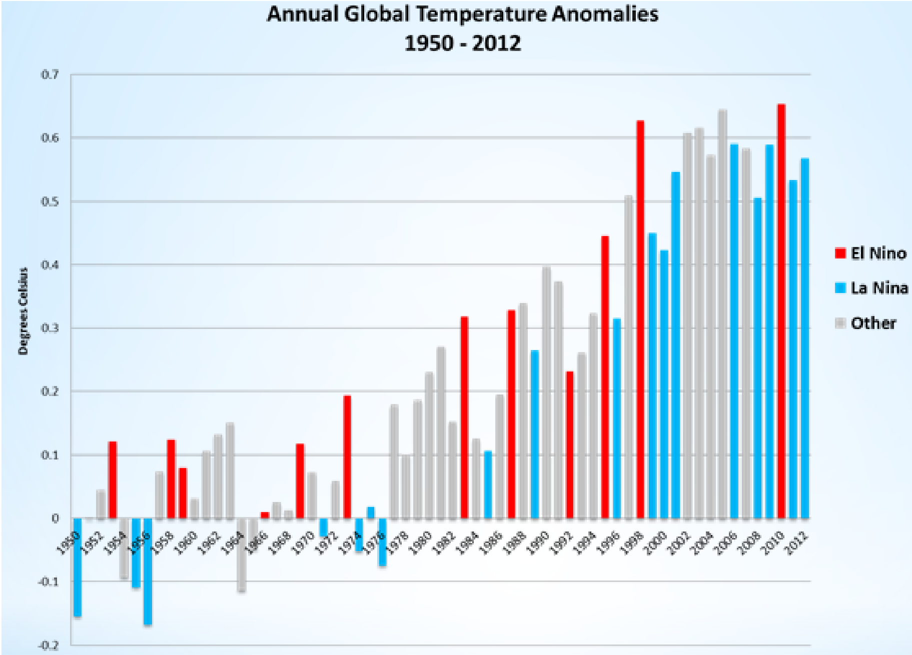

Figure 3. Annual global temperature anomalies associated with El Nino (red), La Nina (blue), and Neutral (grey) seasons. Global temperature anomalies have been increasing over time and, although El Nino years are associated with warmer temperature anomalies than La Nina years, the more recent La Nina years have become associated with higher global temperature anomalies than earlier La Nina years (NCDC 2013).

Ice Storm Frequency Across the U.S. in Response to Global Temperature Changes:

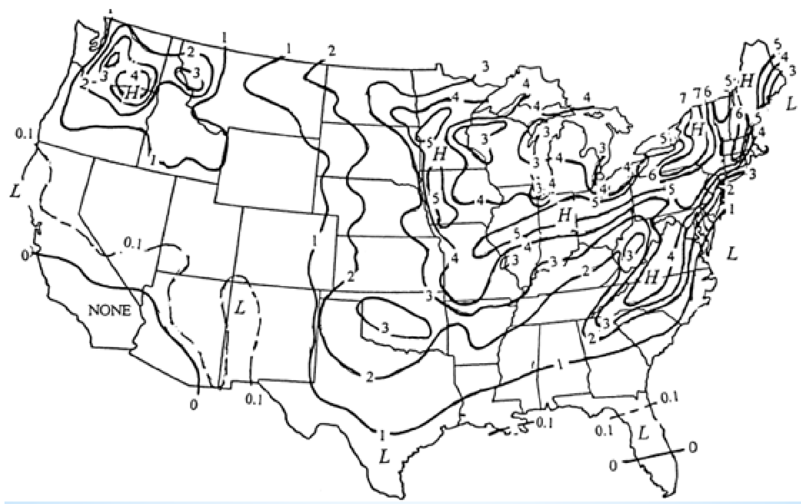

Figure 4. The average number of freezing rain days across the U.S. between 1949-2000 (Changnon 2002). The highest average is in the Northeast, extending down into the Appalachians and west into the Central U.S.

Previous Work: Not many studies have been conducted on ice storms, especially from a climate standpoint. Perhaps the most well-known ice storm climatology was completed by Stanley Changnon in 2002, who documented all significant freezing rain events between the years of 1949-2000. Changnon concluded that the national loss total between 1949-2000 from all freezing rain events was estimated at $18 billion, with an annual average of $187 million. Changnon also determined the average number of days with freezing rain across the United States (Figure 4). The maximum was found over the Northeast with an average of 5-7 freezing rain days per year, although it is unclear whether this was influenced by population density. Higher averages were also found over the upper Midwest, but Changnon concluded that, although this region experiences frequent freezing rain days, it usually does not result in large property losses. Higher averages were also noted in the Appalachians and Pacific Northwest, with relatively few freezing rain days found in the Southwest and the Rockies. Several other studies, including Robbins and Cortinas (2001) and Changnon and Karl (2003), found similar results to Changnon's 2002 study using a similar method.

Current Work: While several studies have indicated that the Northeast, Midwest, Appalachian Mountain region, and the Pacific Northwest have experienced the highest number of ice storms over the past several decades, there has yet to be a comparison on how ice storm frequency across the United States is changing over time, particularly in response to the notable global temperature changes. To account for this, two time periods were chosen based upon the information provided in Figure 3 and the length of the National Climatic Data Center's (NCDC) detailed weather event database, *Storm Data*. One time period represents ice storm frequency before the temperature anomaly shift: 1966-1977, and the other period represents ice storm frequency after the temperature anomaly shift: 1998-2011.

The total number of ice storms during the winter season (December, January, and February) across the United States when global temperature anomalies were lower (i.e., 1966-1977) reveals a strong maximum located across the northern portion of the Northeast, where over 30 ice storms were documented (Figure 5, top). Several other areas of higher frequency are seen in the Chesapeake Bay area, the Appalachian Mountains of North Carolina and Virginia, eastern Oklahoma, and the Columbian River Basin of Washington and Oregon. Storm tracks, frontal positions, terrain, and the frequency of reporting are largely responsible for this distribution.

The total number of ice storms across the United States when global temperature anomalies were higher (i.e., 1998-2011) also reveals a strong maximum across the Northeast, however, the highest frequency is found across the southern portion of this region, particularly eastern Pennsylvania, northwest New Jersey, and eastern New York (Figure 5, bottom). Other areas of higher frequency include the Chesapeake Bay region, the Appalachian Mountain region of North Carolina, the Midwest, Southern Plains, and the Columbia River Basin of Washington and Oregon.

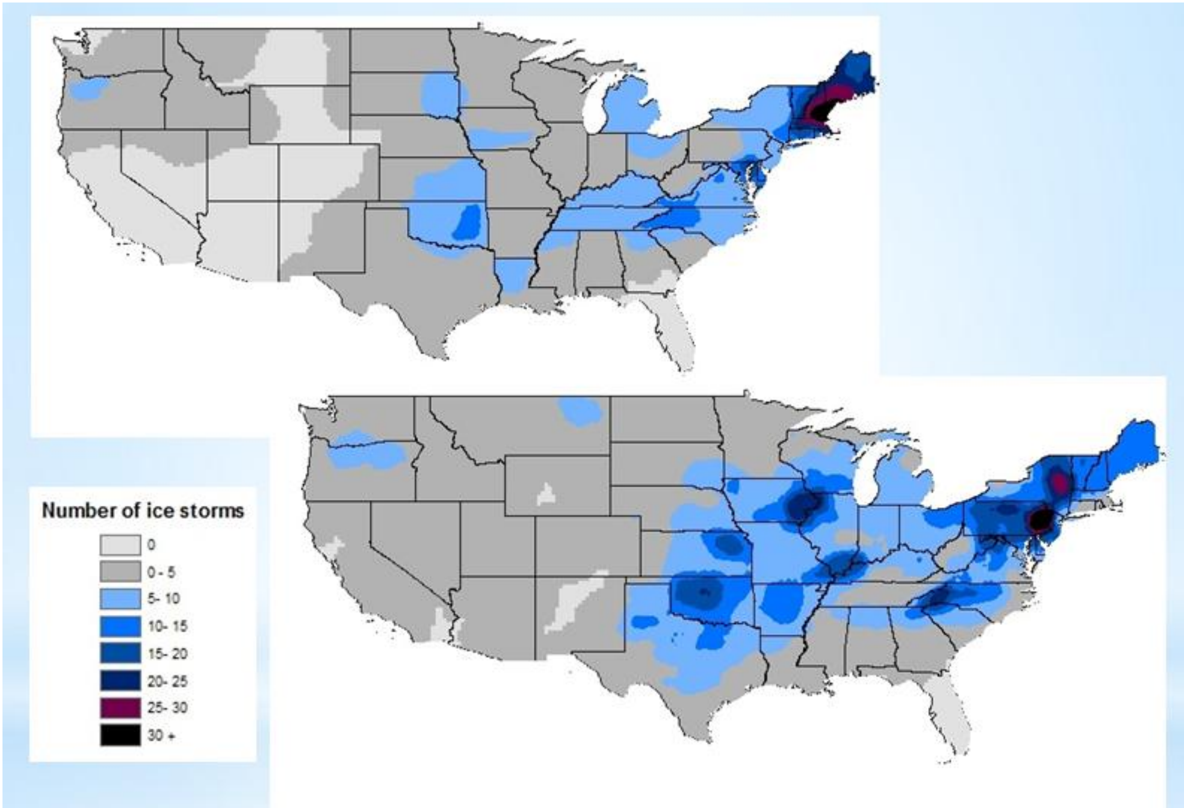

Figure 5. The total number of documented ice storms across the U.S. between the winters of 1966-1977 (top) and 1998-2011(bottom). The Northeast experienced the highest frequency during both periods, with a westward shift evident.

Despite a difference in the length of the two time periods compared above, the most notable changes in ice storm frequency occurred across the Northeast, the Midwest, and the Southern Plains. Figure 6 shows the difference in ice storm frequency between the two periods, with warmer colors indicating a higher ice storm frequency when global temperature anomalies were lower and cooler colors indicating a higher ice storm frequency when global temperature anomalies were higher. The largest difference is seen across the Northeast, where a higher frequency of ice storms occurred during the winter seasons of 1966-1977 across the northern portion of the Northeast, while a higher frequency of ice storms occurred across the southern portion of the Northeast during the winter seasons of 1998-2011. Across most of the central United States, more ice storms were documented between the winter seasons of 1998-2011. West of the Rocky Mountains, there has been a slight increase in ice storm frequency in recent years, but due to the low frequency found during both periods it does not appear to be significant compared to other regions of the United States. It is speculated that the distinct westward and southward shift in ice storm frequency across the Northeast is due to changes in global air circulation, while the increase in ice storms across the central United States is likely related to improvements in ice storm reporting.

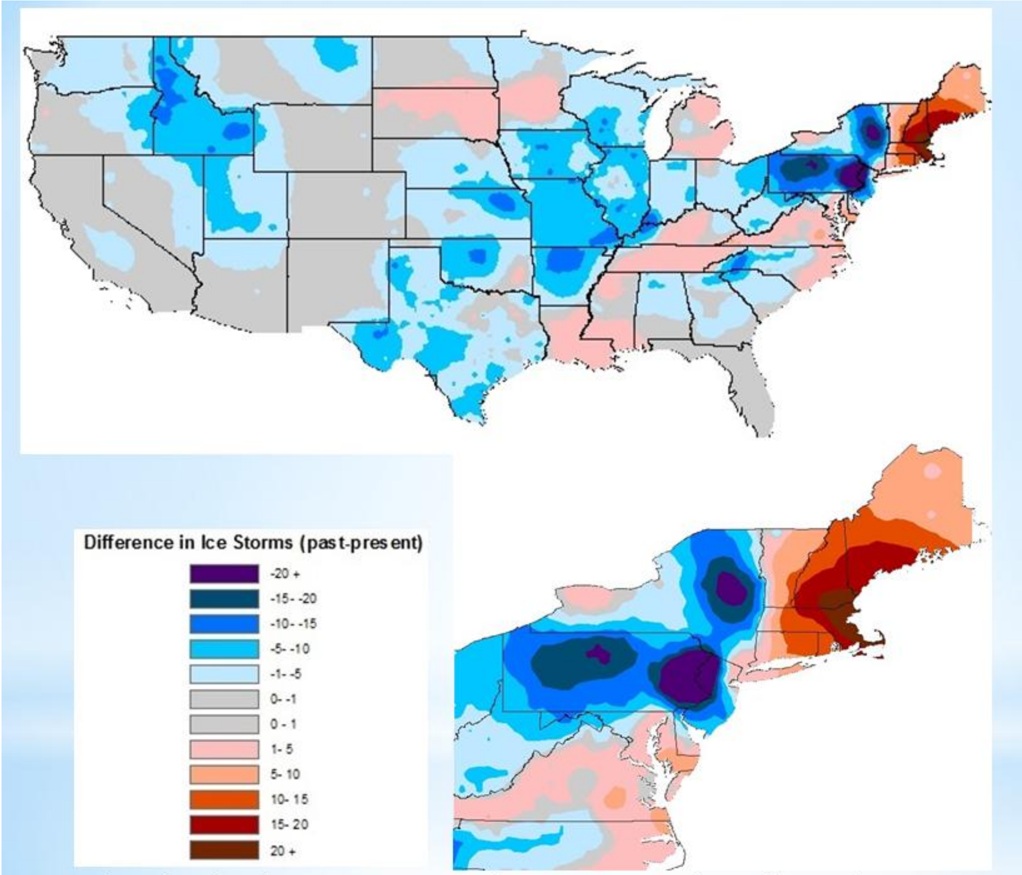

Figure 6. The total number of winter season ice storms between 1998-2011 subtracted from total winter season ice storms between 1966-1977. Red colors indicate more ice storms between 1966-1977 and blue colors indicate more ice storms between 1998-2011. A notable shift is seen across the Northeast and an increase in ice storms is found across the Midwest and Central U.S.

Based on the aforementioned speculation, further research was conducted on ice storm frequency across the northeastern United States. Figure 7 shows the average number of winter season ice storms per decade across the Northeast. Ice storm frequency was determined in this manner to pinpoint a timeframe in which a regional shift in ice storm frequency may have occurred.

During the late 1960s (1966-1969), the highest average is found over far eastern Vermont, central and southern New Hampshire, southern Maine, and eastern Massachusetts, with 2-3 ice storms. A relatively high frequency of ice storms is also found over the northern Chesapeake Bay area, with an average of 1-2 ice storms. A minimum is found over western Pennsylvania, with no reported ice storms.

During the 1970s, the highest average number of ice storms is still located over the northern portion of the Northeast. Southern Maine, central and southern New Hampshire, and northern and eastern Massachusetts averaged 2-3 ice storms. There is a slight increase in the average number of ice storms across southern New York and eastern Pennsylvania, with a slight decrease in ice storm frequency over northern Maryland. Overall, the winter season ice storm frequency and distribution across the Northeast during late 1960s and

1970s is very similar, with the highest averages found over the northern portion of the Northeast, and relatively lower averages over the southern portion.

During the 1980s, there is a noticeable change in both ice storm frequency and the location of the highest frequency across the Northeast. Not only is the average number of ice storms lower in the 1980s, but the maximum in frequency shifted westward into New York and Pennsylvania. The highest average is located over eastern and southern New York, eastern Pennsylvania, and parts of southern New Hampshire, where an average of 1-2 ice storms was documented. The remaining areas of the Northeast experienced an average of around one ice storm. It seems that the westward shift that was discussed earlier may have occurred sometime during the 1980s.

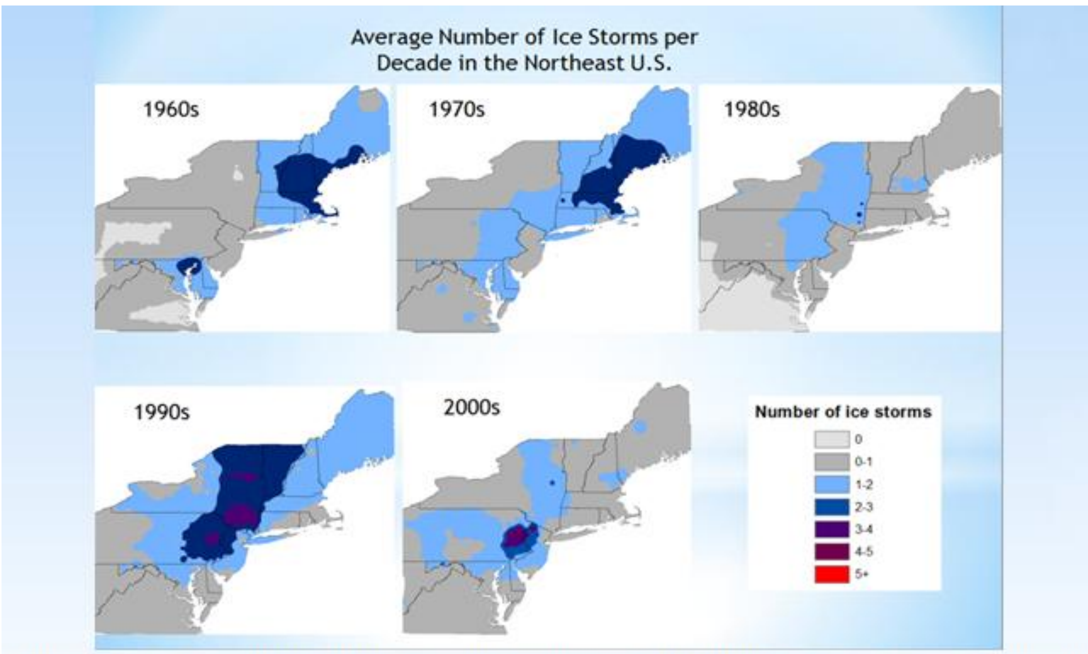

Figure 7. The average number of ice storms by decade across the Northeast. Higher averages occurred in the northern Northeast until the 1980s, where highest averages then shifted westward. Higher frequencies overall have occurred since the 1990s across southern portions of the Northeast.

The winter seasons during the 1990s were very active across much of the Northeast as compared to the previous decades. The location of the maximum in frequency matches that seen during the 1980s, albeit more intense**.** The greatest frequency of ice storms is found during this decade, with nearly all portions of the Northeast experiencing a higher average number of ice storms than previous decades. The highest frequency is found over Vermont, eastern and southern New York, eastern Pennsylvania, and far northwest New Jersey, where some locations averaged 4-5 ice storms. The minima in frequency are seen across western Pennsylvania, near the Lake Ontario shore of central and western New York, coastal Delaware and Maryland, and coastal New England, where an average of one ice storm occurred.

During the most recent decade, there seems to be a noticeable decrease in the spatial coverage of the higher frequencies of ice storms across the Northeast, compared to the

1990s. Despite this decrease in coverage, higher frequencies than were seen prior to the 1990s are still evident. The maximum number of ice storms is found over a small portion of eastern Pennsylvania and northwest New Jersey near the Poconos Mountains, with an average of 4-5 ice storms. The remainder of the region reported 1-2 ice storms. The westward shift still appears evident, however, the broad coverage of higher frequency that was seen over previous decades, especially the 1990s, has noticeably declined to only include a small section of the southern Northeast.

Overall, it appears that a westward shift in ice storm frequency likely occurred sometime during the winter seasons of the 1980s. Prior to this decade, the higher frequencies were seen across the northern portion of the Northeast, particularly New Hampshire, Maine, and Massachusetts. During and after the 1980s, the higher frequencies were found across the southern portion of the Northeast, particularly New York, Pennsylvania, and New Jersey. Ice storm frequency also seems to have increased since the 1990s, mostly across the southern portion of the Northeast. Discussed next are climatological reasons as to why ice storm frequency across the Northeast may have changed and might still be changing.

A Comparison of Northeast U.S. Ice Storm Frequency and Global Air Circulation:

Global air circulation can be affected by a number of natural oscillations associated with the ocean and atmosphere. These natural oscillations are commonly referred to as teleconnections and include, but are not limited to, the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), and the El Nino-Southern Oscillation (ENSO). All of these teleconnections are associated with a positive and negative phase that alternate on daily, seasonal, or annual time scales. A change in phase of all of the aforementioned teleconnections commonly alters temperature and precipitation patterns across the United States throughout the entire year, but is usually most strongly noticed during the winter.

A Closer Look at the AMO:

The AMO is generally defined as a measure of the change in sea surface temperatures over the North Atlantic Ocean, which consists of a warm phase and a cool phase that alternate over a time period ranging from 20-40 years (Figure 8). Since the mid-1990s, a warm phase of the AMO has been present (NOAA Physical Oceanography Division). The AMO is relatively new to climate science and not much is known about its long-term effects on the ocean and the atmosphere. Recent studies have suggested that the AMO may affect air temperature and rainfall over much of North America and Europe, particularly midwest and southwest United States drought and Florida rainfall (Knudsen et al. 2011). Despite this speculation, some controversy exists regarding the magnitude of the effect of greenhouse gas emission on the natural sea surface temperature variability that currently determines the phase of the AMO. Therefore, in addition to its recent discovery, many previous studies have yet to compare the phase changes of the AMO to atmospheric phenomena frequency due to the skepticism of its representation (Knudsen et al. 2011).

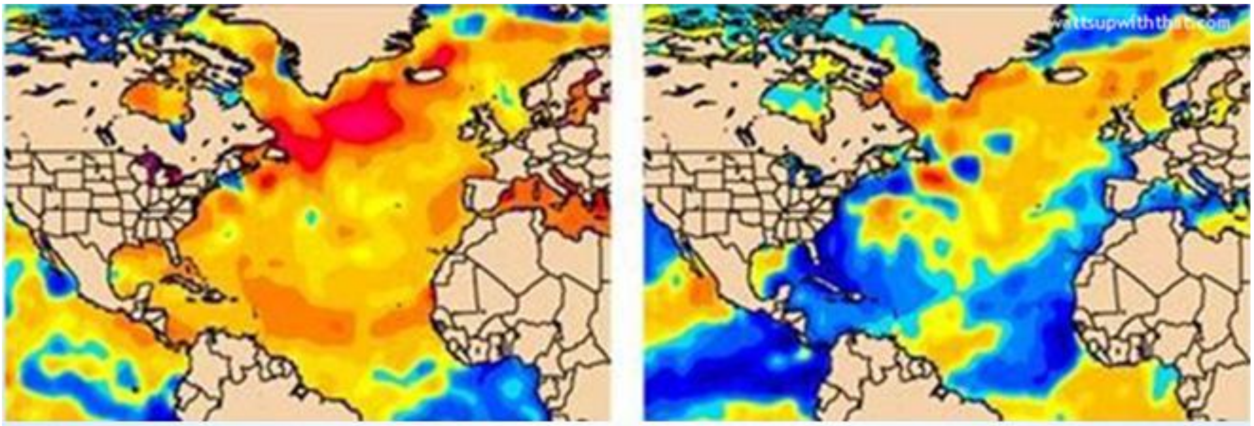

Figure 8. Sea surface temperatures (shaded) over the North Atlantic Ocean. These figures do not correspond to an actual phase of the AMO, rather they show the general area where the signal exists.

Shown in Figure 9 is the average number of ice storms across the Northeast when the AMO is in a negative phase (left) and a positive phase (right). During a negative AMO, most of the Northeast averages 1-2 ice storms. The maximum of 2-3 ice storms is found over the southern portion of New York and several counties across eastern Pennsylvania and southern New Hampshire, while a minimum of around one ice storm occurs over western New York, western and central Pennsylvania, and most of the northeast Atlantic coast. With the exception of few isolated areas, a broader region of higher frequency is mostly confined to the northern portion of the Northeast during a negative AMO.

During a positive AMO, most of the Northeast averages at least one ice storm. The maximum frequency is located over the Poconos Mountain region of eastern Pennsylvania and northwest New Jersey with an average of 2-3 ice storms, with isolated areas averaging 4-5 ice storms. The minimum frequency is located across most of the northern portion of the region, as well as western New York and most coastal locations. A comparison of the two phases of the AMO suggests there is a westward shift in ice storm frequency, as a higher ice storm frequency is seen across the northern portion of the Northeast during a negative AMO, and a higher ice storm frequency is seen across the southern portion of the Northeast when the AMO is positive.

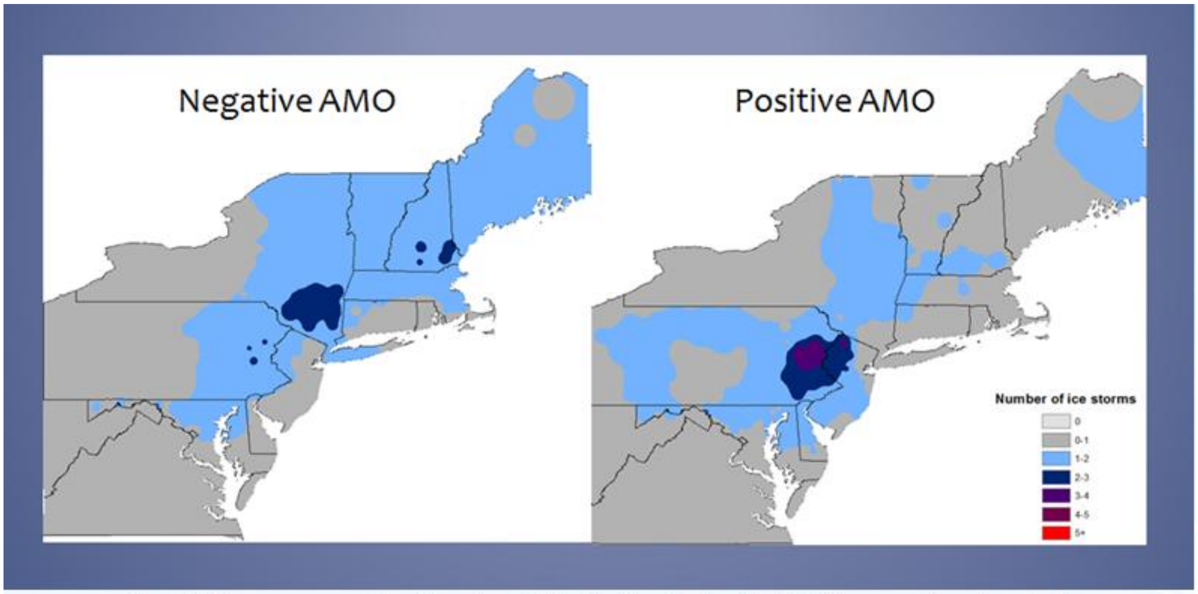

Figure 9. The average number of ice storms in the Northeast when the AMO is in a negative phase (left) and a positive phase (right). Higher averages are seen in the northern Northeast during a negative phase, while higher averages are seen in the southern Northeast during a positive phase.

A Closer Look at the NAO:

The NAO is defined as the strength of the air pressure difference between Iceland and the Azores region. Typically, lower air pressure is found near Iceland and higher air pressure is found near the Azores (State Climate Office of North Carolina). The NAO expresses seasonal variability, meaning it changes phase throughout each season, however, it tends to be most useful and representative during the winter. The phase changes of the NAO tend to be oscillatory, but have trended towards a more positive phase since the early 1990s (State Climate Office of North Carolina).

During a negative phase of the NAO, both the Icelandic low and the Azores high weaken, which suppresses the jet stream over the North Atlantic region (Figure 10, left). This weakening of the jet stream allows cold, arctic air, initially confined to polar latitudes, to penetrate further south into middle latitudes and into most of the United States (State Climate Office of North Carolina). The strongest effects are noted across the eastern U.S., where below average temperatures and below average precipitation are commonly observed. The negative phase was most dominant from the mid-1950s through about 1980, although the most recent winter seasons (i.e., 2009-2012) have trended strongly negative (State Climate Office of North Carolina).

During a positive phase of the NAO, both the Icelandic low and the Azores high strengthen, which has the opposite effect on the jet stream than during a negative NAO (Figure 10, right). A strengthening of the jet stream over the North Atlantic region keeps arctic air confined to polar latitudes and away from the United States. The effects of a positive NAO remain strongest across the eastern portion of the U.S. where above average temperatures and above average precipitation are common. The positive phase has been most dominant from 1990-2008 (State Climate Office of North Carolina).

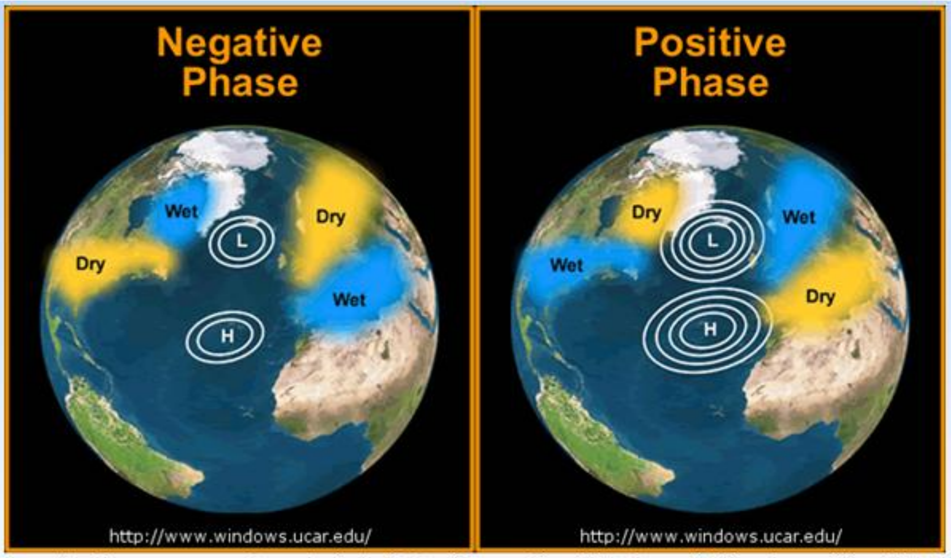

Figure 10. The common meteorological effects of a negative NAO phase (left) and a positive NAO phase (right) over the Northern Hemisphere. A negative phase is usually associated with both below normal temperatures and precipitation over the eastern U.S., while a positive phase is usually associated with both above normal temperatures and precipitation across the eastern U.S.

Comparing ice storm frequency across the Northeast to a negative and positive phase of the NAO, there is not a distinct difference, as most of the region averages at least one ice storm (Figure 11). During a negative NAO, ice storm frequency is highest across eastern Pennsylvania, far Northwest New Jersey, and isolated sections of southern New York, where an average of 2-3 ice storms is common. Ice storm frequency is lowest across western New York, western and central Pennsylvania, and coastal locations, with an average of around one ice storm.

During a positive NAO, the highest frequency is across southern New York, with an average of 2-3 ice storms, and the lowest frequency is very similar to that found during a negative NAO. Overall, ice storm frequency does not seem to be strongly affected by a phase change in the NAO, as the higher frequencies for both phases extend northeastward from Maryland to Maine, with isolated portions of New York and Pennsylvania experiencing the highest averages. This is somewhat contrary to some of the concluding results of previous studies, which have suggested that winter weather across the eastern United States is strongly influenced by the phase of the NAO. Perhaps the NAO has more of an influence on frozen precipitation frequency (snow) than freezing precipitation frequency (freezing rain and sleet).

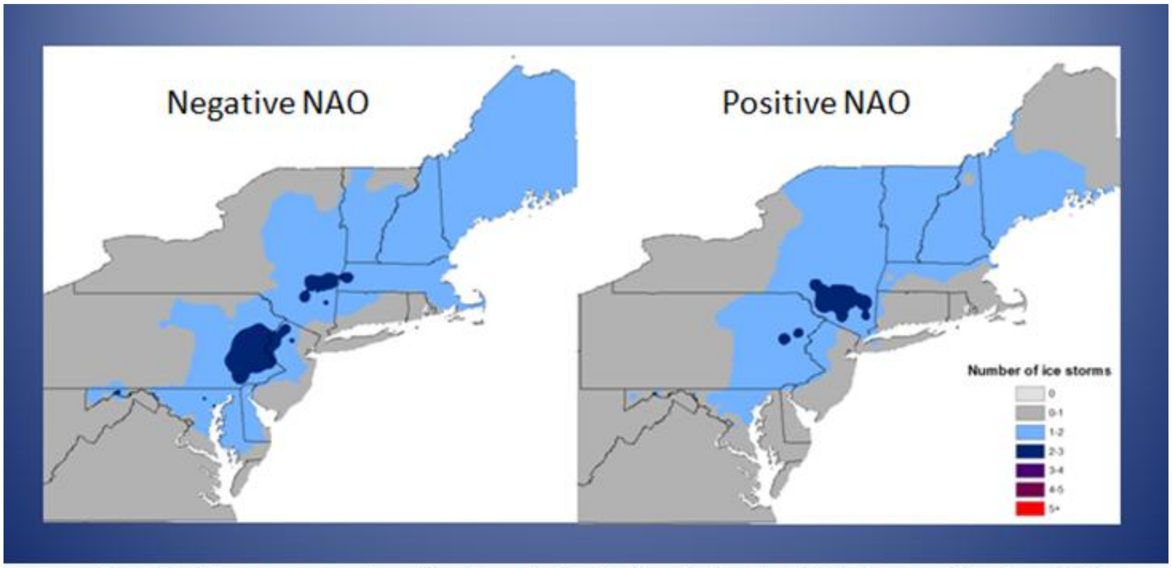

Figure 11. The average number of ice storms in the Northeast when the NAO is in a negative phase (left) and a positive phase (right). Not much change in ice storm frequency is found between the two phases, as higher frequencies extend northeastward from Maryland to Maine in both cases.

A Closer Look at the AO:

The AO is characterized as an opposing pattern of air pressure between high and middle latitudes. Alternatively, it can be thought of as a measure of how much arctic air can penetrate southward into middle latitudes. Higher than normal air pressure over the arctic region indicates that lower than normal air pressure exists over middle latitudes and vice versa. Similar to the NAO, the AO expresses seasonal variability and tends to be strongest during the winter. The AO also consists of both a negative phase and a positive phase (State Climate Office of North Carolina; Climate Prediction Center).

During a negative phase of the AO, the semi-permanent low pressure system (the polar vortex) over the Arctic region weakens and warms (Figure 12, left). This reduces the temperature difference between polar and middle latitudes, which causes the polar jet stream to weaken and allow cold, arctic air to penetrate southward into the United States. The effects are generally confined to regions east of the Rocky Mountains, where below average temperatures are commonly observed during this phase (State Climate Office of North Carolina).

During a positive phase of the AO, the low pressure system over the Arctic region strengthens and becomes colder, which strengthens both the polar circulation and the jet stream by increasing the temperature difference between polar and middle latitudes (Figure 12, right). A strengthening of the polar jet stream keeps arctic air confined to high latitudes, typically resulting in above or near normal temperatures across regions of the United States east of the Rocky Mountains (State Climate Office of North Carolina).

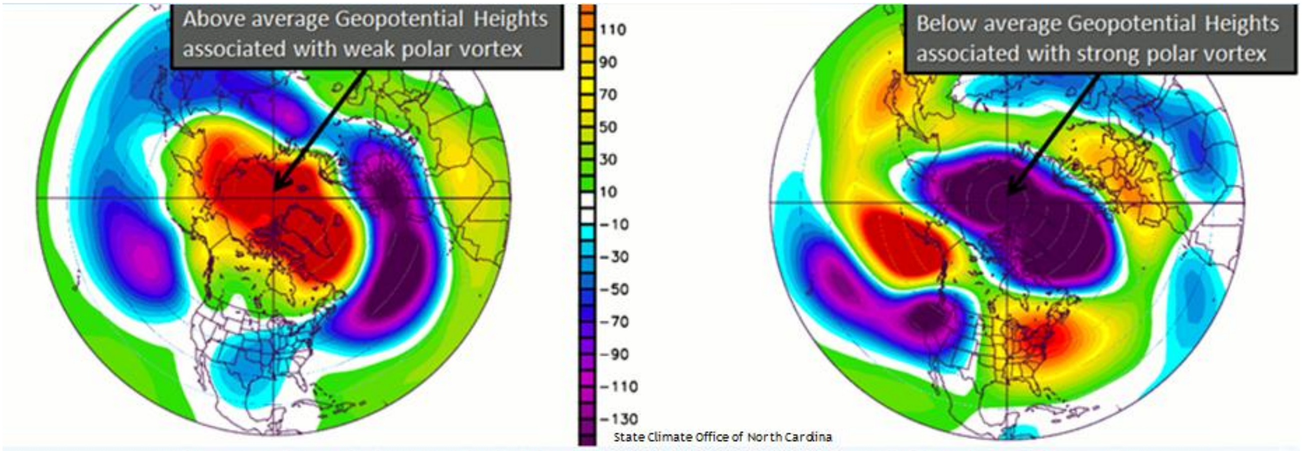

Figure 12. The typical meteorological development of a negative AO phase (left) and a positive AO phase (right). During a negative AO, the polar vortex weakens, which brings cold air south into the U.S. During a positive AO, the polar vortex strengthens, which keeps cold air away from the U.S.

Similar to the phases of the NAO, no distinct change in ice storm frequency is evident between either phase of the AO (Figure 13). During a negative AO, the highest frequency is found in an isolated region near the Poconos Mountains of eastern Pennsylvania, where an average of 2-3 ice storms is common. The remainder of the region experiences an average of between 1-2 ice storms. The ice storm frequency distribution seen during a negative AO is not too different from the distributions seen during both a positive and negative NAO, as slightly higher frequencies extend northeast from Maryland to Maine (refer back to Figure 11).

During a positive AO, ice storm frequency is slightly higher than that during a negative AO over eastern New York, where an average of 2-3 ice storms is reported. In addition to eastern New York, a broader area of eastern Pennsylvania experiences a slightly higher number of ice storms during a positive AO as compared to a negative AO. The remaining area experiences an average of 1-2 ice storms. Despite slightly higher averages across eastern New York, the ice storm distribution during a positive AO is similar to both the negative AO and both phases of the NAO, as the northeast trail of higher frequencies from Maryland to Maine is evident.

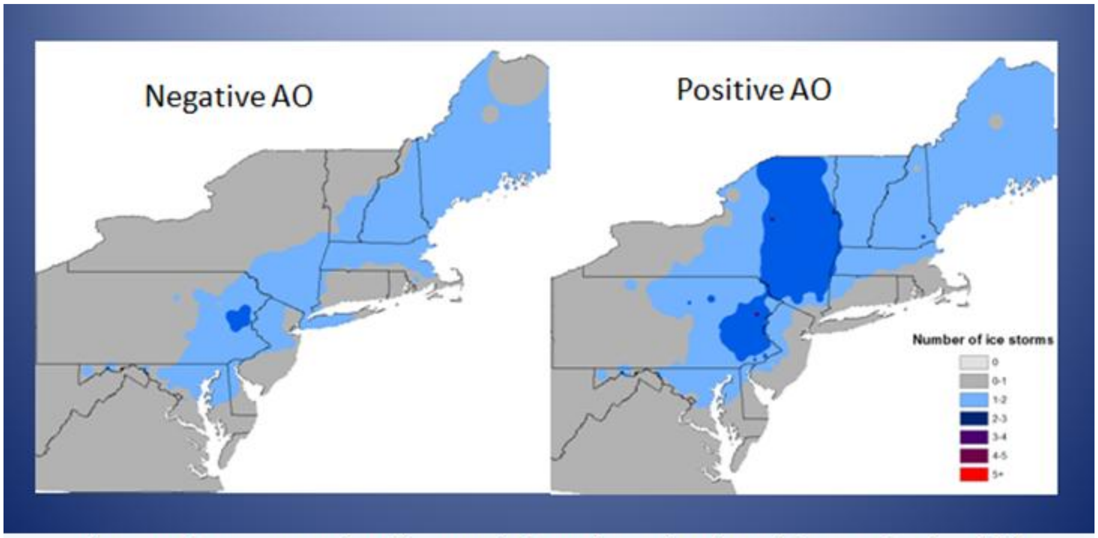

Figure 13. The average number of ice storms in the Northeast when the AO is in a negative phase (left) and a positive phase (right). A large difference in not evident overall, except across eastern New York where more ice storms are common during a positive AO. Both phases of the AO yield a similar ice storm distribution as both phases of the NAO.

A Closer Look at the ENSO:

ENSO is a measure of both air pressure fluctuations and ocean temperature changes across the equatorial Pacific Ocean. The Southern Oscillation refers to the large-scale changes in surface air pressure between the eastern tropical and western tropical Pacific Ocean and is calculated from fluctuations in the surface pressure between Tahiti and Darwin, Australia. A negative Southern Oscillation corresponds to below normal pressure over Tahiti and above normal pressure over Darwin, which reduces the strength of the surface winds and creates low pressure over the eastern equatorial Pacific. Low atmospheric pressure is associated with warm ocean water and high atmospheric pressure is associated with cold water, so El Nino conditions develop when the Southern Oscillation is negative. For a positive Southern Oscillation, the opposite conditions occur and La Nina develops. When ocean temperatures remain warmer than normal across the eastern equatorial Pacific for an extended period of time, El Nino is defined and when ocean temperatures remain cooler than normal across the eastern equatorial Pacific for an extended period of time, La Nina is defined. Near average ocean temperatures within this region that exist for an extended period of time are referred to as ENSO-neutral conditions (State Climate Office of North Carolina).

During the development of an El Nino event, the near-surface winds near the equator decrease, allowing warmer waters of the western tropical Pacific Ocean to shift east. This warmer ocean water characterizes an unstable environment in the lower atmosphere, which is favorable for the enhancement of thunderstorms and heavier rain (referred to as convection) across most of the equatorial Pacific. This convection alters the orientation of polar and subtropical jet streams, often leading to warmer than average temperatures across the Pacific Northwest and Northeast regions of United States and cooler than average temperatures and above average precipitation across much of the southern United States (Figure 14). The orientation of the these jet streams typically results in unfavorable conditions for hurricane development across the Atlantic Ocean and Caribbean Sea during the summer and fall, as upper-level winds speeds are too strong to allow for the proper organization of these storms. In general, El Nino is strongest during the Northern Hemisphere winter season, where ocean temperatures tend to be warmest worldwide (State Climate Office of North Carolina).

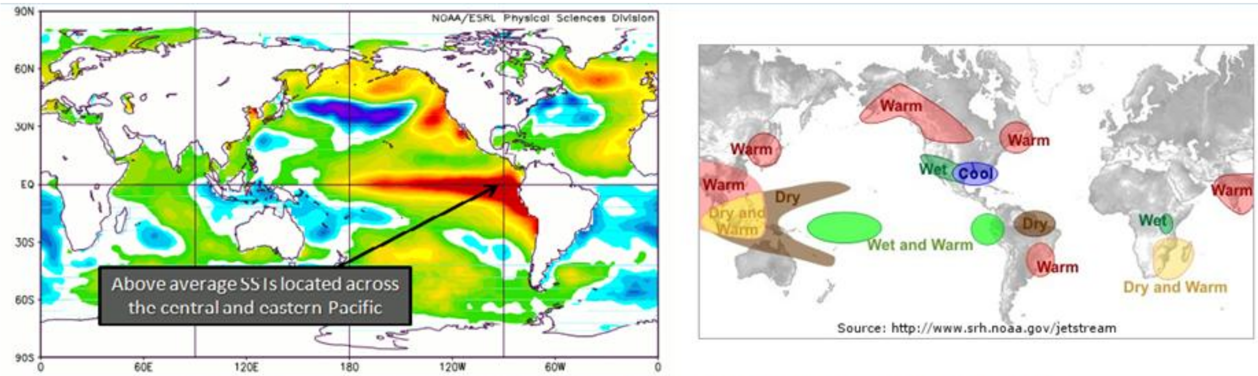

Figure 14. Warmer than normal ocean waters characteristic of El Nino in the equatorial Pacific Ocean (left) and the common weather patterns associated with it across the world (right). In the U.S., effects are strongest during the winter and result in warmer than normal temperatures across the Northwest and Northeast, and cooler and wetter than normal conditions across the South.

The cooler than normal sea surface temperatures that define a La Nina event are driven by an increase in the near-surface wind speeds, which causes an upwelling of colder water across the eastern tropical Pacific Ocean. With a colder ocean surface in place, the lower atmosphere tends to remain stable, which decreases storm development in the eastern Pacific and a both a weakening of the subtropical jet stream and a reorientation of this jet from westerly to southwesterly. This reorientation typically leads to cooler than normal temperatures and above average precipitation to the Pacific Northwest region of the United States and above average temperatures and below normal precipitation to much of the southern United States (Figure 15). The reorientation of the jet stream is also favorable for hurricane development over the Atlantic Ocean during the summer and fall months, as upper-level winds are weaker in this region. Despite La Nina's effect on hurricane season, its effects are typically strongest during the winter season in the Northern Hemisphere, similar to El Nino (State Climate Office of North Carolina).

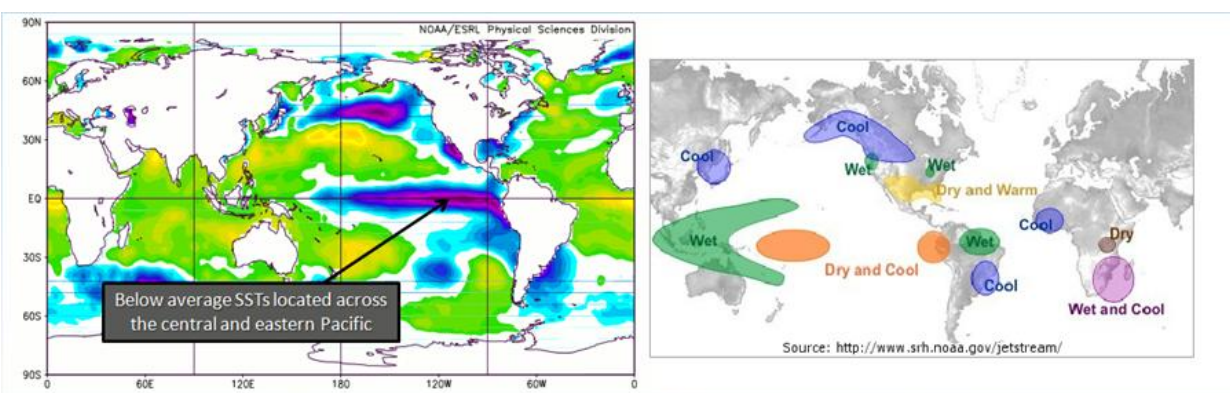

Figure 15. Cooler than normal ocean waters characteristic of La Nina in the equatorial Pacific Ocean (left) and the common weather patterns associated with it across the world (right). In the U.S., effects are strongest during the winter and result in cooler and wetter than normal conditions across the Northwest and warmer and drier than normal conditions across the South.

ENSO-neutral events mark the transition between El Nino and La Nina conditions. Sea surface temperatures across the eastern equatorial Pacific are near average during this phase and global atmospheric air patterns are controlled more by other climate patterns and oscillations that vary on shorter timescales. Examples of these may include the Pacific North American Oscillation (PNA), the NAO, the AO, etc.

During El Nino conditions, the highest frequency of ice storms across the Northeast is seen across the northern portion of the Northeast, particularly across Vermont, New Hampshire, Maine, and Massachusetts, where an average of 2-3 ice storms is common. Some locations across southern New Hampshire and southern Maine average 3-4 ice storms. Across the southern portion of the Northeast, around one ice storm is common during El Nino, except the mountainous regions of eastern Pennsylvania, northwest New Jersey, and eastern New York where 1-2 ice storms are common (Figure 16 top left).

During La Nina conditions, the highest frequency of ice storms is seen across the southern portion of the Northeast, where 2-3 ice storms are common across eastern Pennsylvania, northwest New Jersey, and eastern New York. Isolated higher frequencies of 3-4 ice storms are seen across this region as well. A majority of the northern portion of the Northeast averages around 1-2 ice storms during La Nina. Comparing La Nina ice storm frequency to El Nino ice storm frequency, higher averages tend to be confined to the northern portion of the Northeast during El Nino events, while higher averages tend to be confined to the southern portion of the Northeast during La Nina events (Figure 16 top right).

ENSO-neutral conditions are associated with relatively low ice storm frequencies across the entire region, as most areas experience anywhere between 1-2 ice storms. The Poconos Mountain region of eastern Pennsylvania experiences the highest average of 2-3 ice storms during ENSO-neutral conditions. Comparing the ENSO-neutral ice storm distribution to all of the other teleconnection phases, it is fairly similar to that found during a negative AO and not too different from both phases of the NAO (Figure 16 bottom).

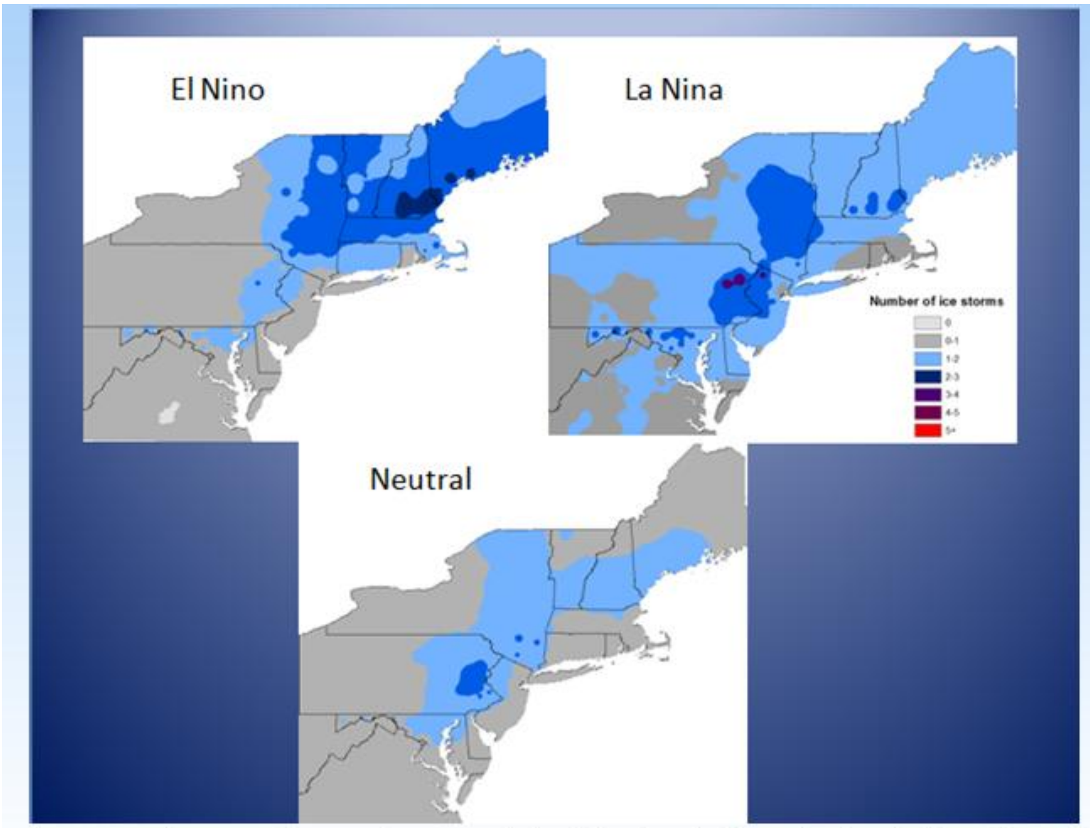

Figure 16. Northeast U.S. ice storm frequency during El Nino (top, left), La Nina (top, right), and neutral (bottom, center) conditions. Higher averages are confined to the northern Northeast during El Nino, while higher averages are confined to the southern Northeast during La Nina. Neutral conditions do not show much of any trend.

AMO and ENSO:

The distribution of ice storm frequency across the northeast United States during negative AMO conditions and El Nino conditions are quite similar, as well as the ice storm distribution during positive AMO conditions and La Nina conditions. Figure 17 shows the distribution of ice storm frequency when a negative AMO is present with El Nino conditions (left) and when a positive AMO is present with La Nina conditions (right). During winter seasons when the AMO is negative and present with El Nino conditions, the highest ice storm frequency across the Northeast is confined to northern sections, particularly New Hampshire, southern Maine, and eastern Massachusetts where an average of 3-4 ice storms is common. Some areas across southern New Hampshire and very far southern Maine experience an average of 4-5 ice storms when these conditions are present together. Areas across the southern portion of the Northeast only experience around one ice storm during these conditions.

During winter seasons when the AMO is positive and La Nina is present, the highest frequency is located across the southern portion of the Northeast, particularly eastern Pennsylvania, northwest New Jersey, and eastern New York. These areas experience an average of anywhere between 3-5 ice storms during these conditions, with some isolated areas within the Poconos Mountain region of eastern Pennsylvania and northwest New Jersey averaging over 5 ice storms. Relatively few ice storms (around one) are found across the northern portion of the Northeast. All other teleconnections were compared with one another and no significant pattern was found. Therefore, it is possible that ice storm frequency shifts from northern to southern portions of the Northeast U.S. when a negative AMO becomes a positive AMO and El Nino becomes La Nina during the same time period.

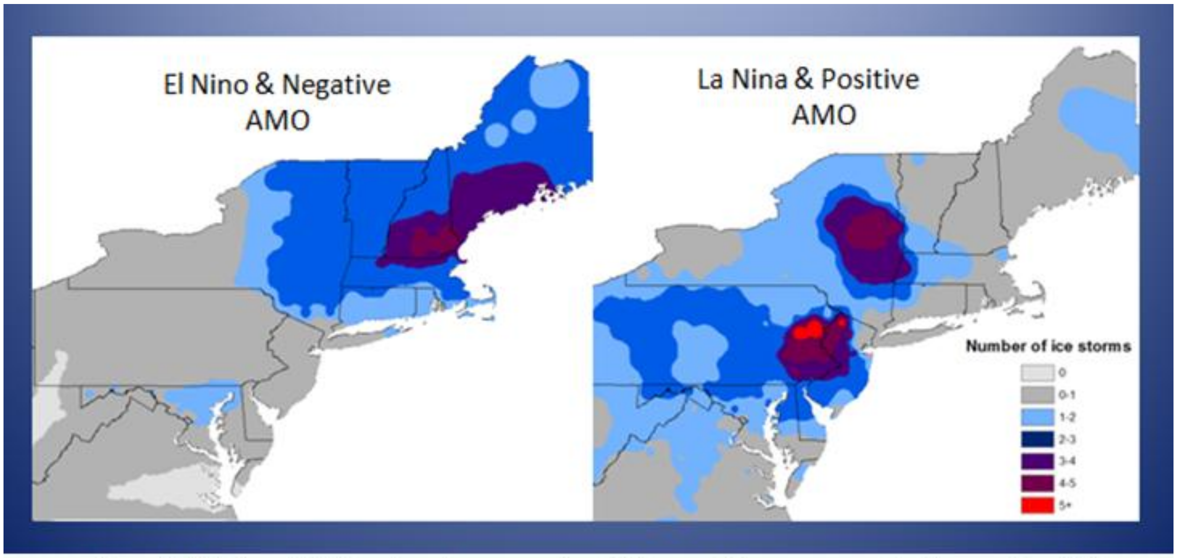

Figure 17. Northeast U.S. ice storm frequency when El Nino conditions are present with a negative AMO phase (left) and when La Nina conditions are present with a positive AMO phase (right). El Nino and negative AMO together tend to confine more ice storms to the northern Northeast, while La Nina and positive AMO confine more ice storms to the southern Northeast.

Summary:

Freezing rain poses significant societal impacts across many regions of the United States. The development of freezing rain commonly occurs near warm fronts, arctic cold fronts, terrestrial barriers, and marine bodies. These features often allow for the development of a low-level warm layer that is bounded above and below by sub-freezing air or the development of a sub-freezing layer capable of producing supercooled liquid water. Freezing rain is often associated with a low-level melting layer, while freezing drizzle is often associated with a sub-freezing atmosphere, although this is not always the case.

It was found that global temperature anomalies associated with ENSO have been increasing over time. Comparing ice storm frequency between a time period when global temperature anomalies were lower (1966-1977) to a time period when global temperature anomalies were higher (1998-2011) suggested that the northeast and central United States have been affected the most. In the Northeast, ice storm frequency was higher across the northern portion of the region when global temperature anomalies were cooler and was higher across the southern portion of the region when global temperature anomalies were warmer. Across the central region of the country, ice storm frequency has increased during recent years. It was speculated that the change in ice storm frequency across the Northeast was meteorologically induced, whereas the change across the central United States was influenced by an improvement in ice storm reporting. This is not to say that ice storm frequency in the central United States cannot be affected by changes in global air circulation, but for this particular study it was not investigated.

It is possible that Northeast ice storm frequency is largely influenced by changes in global air circulation, particularly via teleconnection patterns. Phase changes in several teleconnections including the AMO, NAO, AO, and ENSO were compared to ice storm frequency and distribution across the Northeast in an effort to isolate any trends or notable areas of high and/or low frequency. Both the AMO and ENSO seemed to show distinct areas of higher ice storm frequency across the Northeast during different phases. During both negative AMO and El Nino conditions, a higher ice storm frequency was confined to the northern portion of the United States, particularly New England. When these conditions were plotted together, this became strikingly evident. Similarly, during positive AMO and La Nina conditions, a higher ice storm frequency was confined to the southern portion of the Northeast, particularly mountainous areas of eastern Pennsylvania, northwest New Jersey, and eastern New York. When plotted together, this was also very evident. Neither phase of the NAO and AO showed distinct results, as a general "belt" of slightly higher ice storms frequency extended northeast from Maryland to Maine, with a few isolated locations experiencing slightly higher frequencies.

Overall, changes in the phases of the natural oscillations may play a key role in the ice storm distribution over the Northeast, especially the AMO and ENSO. It is currently less clear as to what affects long-term ice storm frequency across other regions of the United States. Keeping an eye on current patterns and future changes in these patterns will hopefully yield fully representative results in the years to come. A better understanding of how and why ice storm frequency is changing across the United States will eventually lead to better forecasting and public preparation strategies, and short-lived or less intense impacts.

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