Investigating Regional Climate Change in Northeastern United States

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Although climate change has global ramifications, the planet's geographical regions will not be identically affected by climate change. Without understanding regional climate patterns, accurate predictions about the future regional climates cannot be made. This inhibits governments from establishing appropriate measures to mitigate and adapt to climate change. The goal of this project was to create a functional representation of the Northeastern United States climate using the relatively new statistical method of climate indexing. The Northeast was defined as including Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, and Pennsylvania. The climate indicators of maximum and minimum temperature, precipitation, and snowfall were analyzed to create the Northeast Climate Index over annual and seasonal timeframes. The results suggest that the Northeast has been in a period of higher than normal warming and precipitation, with lower than normal snowfall for the past few decades. The amplitudes of this warmer and wetter climate have not been observed anywhere else in the studied period of record (1900-2009).

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INTRODUCTION

Global climate change has recently become a key topic of discussion in the scientific, political, economic, and social realms of society. Although climate change is mainly presented to the public on a global scale, geographic regions around the planet will not be affected by global climate change in an identical manner. As stated by Frumhoff et al., "climate change is a global challenge, but the impacts are experienced locally".[1] Without understanding the regional impacts of climate change, local and state policy makers are flummoxed on the best plan of action with regards to climate change adaptation and mitigation policies. The scientific community must be able to systematically research regional climate change so that local policy makers have tangible information with respect to the impacts of climate change in their area of jurisdiction. Without a robust method for detecting regional climate change, sound governmental polices cannot and will not be made to help mitigate or adapt to climate change.

Although much research has focused on global climate change, more research must be done to better understand regional climate change so that accurate small-scale predications can be made. Unfortunately, quantitative methods for detecting regional climate change are challenging due to a number of underlying problems related to regional climate change detection:

I. Climate systems are naturally noisy with lots of variation,
II. Regional climate data tends to be lacking sufficient sampling locations,
III. A lack of clarity exists around which sampling sites best indicate climate change, and

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[1] Frumhoff, et al., "An integrated climate change…," 420.

IV. Insufficient data records mean that the amplitude of natural climate variations cannot be represented by a baseline. [2]

This thesis attempts to negotiate these problems associated with detecting regional climate change by using a relatively new and seldom used data analysis technique: climate indexing. The method of climate indexing involves identifying and graphically representing principal indicators of the climate, such as minimum temperature, maximum temperature, and precipitation.

This project complements an ongoing study of the Pacific Northwest climate by focusing on the geographical region of Northeastern United States (NE). The Northeast is defined as including the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, and Pennsylvania.[3] The purpose of this thesis was to examine the nature of climatic variation of the Northeast since 1900. Data for the climate indicators of interest were collected, analyzed, and used to create a climate index for the regional climate of Northeastern United States. The creation of this climate index for the Northeast has the potential to assist in detecting any signals of anomalous climate trends in the past century, which suggests a change in climate beyond the usual climatic variation. The key questions posed were:

1. What is the general climate pattern of the Northeastern United States over the time scale of a century (i.e. Northeast Climate Index)?
2. Once the Northeast Climate Index (NEI) is created, does the NEI suggest any shifts in the long-term climate trends within that region?
3. If yes, which of the climatic indicators analyzed, if any, have the greatest impact on the NEI trend?

The primary findings of this study indicate that the Northeast has been in an extended climate phase of warmer and wetter than average, which has not been observed elsewhere in the 20th century in terms of temporal length and amplitude. The following

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[2] Professor Gregory Bothun.
[3] Northeast Climate Impacts Assessment, *Climate Change in the U.S. Northeast*, 1.

section provides more background on the topics of climate, climate change, and the Northeast region of the United States. The methodology behind this research will be addressed immediately following the brief overview of key topics related to this project. The second half of this thesis reviews the results of the climate research and discusses the potential implications of those results.

BACKGROUND

CLIMATE SYSTEM

The Earth's climate system is comprised of four separate parts: "the atmosphere, the hydrosphere, the cryosphere, and the land surface of the biosphere".[4] The interactions that occur within and between these components govern the output of the climate system and make the system exceedingly complex. The figure below tries to capture the complicated and multi-layered interacts that occur within the Earth's climate system:

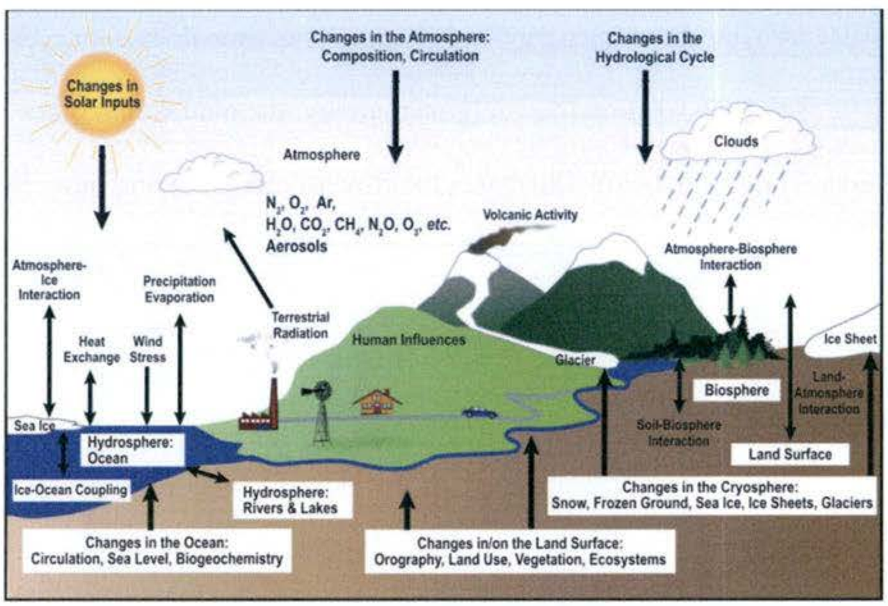

Figure 1**: Components of the Climate System** – depicts the processes of and interactions between the four components of the climate system.[5]

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[4] Baede, A.P.M. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 943.
[5] Le Treut et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 104

Because of the climate system's intricate *internal dynamic* and other external forcings, the system is in a constant state of change. External forcings are factors outside of the climate system that have the ability to change the dynamics of the climate system. Variation in insolation (i.e. incoming solar radiation) and volcanic eruptions are the primary examples of naturally occurring external forcings. Anthropogenic (i.e. human-caused) changes, such as increasing the amount of greenhouse gases in the atmosphere, are also considered external forcings.[6]

The Earth's climate system derives its energy from solar radiation, which powers the multitude of processes within the climate system. The incoming and outgoing energy from the sun creates the energy balance of the Earth. This radiation always moves "between the Earth's surface, atmosphere, and space" to create the energy budget of the Earth.[7] Although the overall temporal and spatial balance must equal zero, the Earth's energy budget any given time does not necessarily equal zero. If there is more insolation than outgoing energy, the planet undergoes warming, and visa versa. The figure below illustrates the flow of incoming and outgoing solar energy.

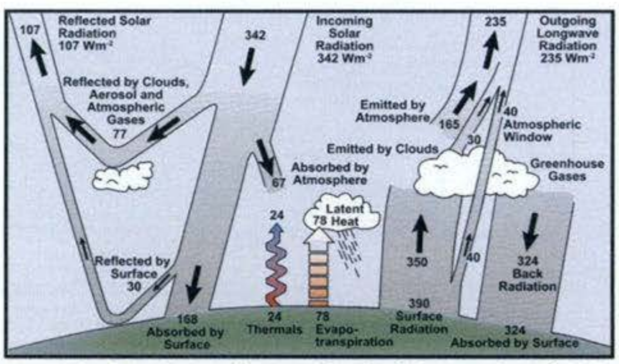

***Figure 2*: Energy Balance of the Earth** – estimates the Earth's annual and global mean energy balance[8]

[6] Le Treut et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 96.
[7] Anderson and Strahler, *Visualizing Weather and Climate*, 73.
[8] Le Treut et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 96.

Incoming solar radiation enters the Earth's atmosphere as shortwave radiation. Some of this shortwave radiation does not reach the Earth's surface because clouds, aerosols, and atmospheric gases reflect it back into space. The shortwave radiation that does make it to the Earth's surface is either absorbed by the surface or reflected as longwave radiation back to the atmosphere. Some of this longwave radiation goes past the atmosphere into space, while most is absorbed by the atmosphere and reradiated to the surface, as well as space.

This process of longwave radiation being absorbed by the atmosphere and reradiated back the Earth's surface is called the greenhouse effect. The absorption of longwave radiation by the lower atmosphere depends on the presence of greenhouse gases such as water vapor, carbon dioxide, methane, and ozone. Water vapor and carbon dioxide are the dominant molecules in the lower atmosphere that absorb longwave radiation. Without the presence of any greenhouse gasses the Earth's surface would be effectively much cooler. However, the addition of more greenhouse gasses into the atmosphere causes more longwave radiation to be absorbed and reradiated back to the surface, consequently altering the energy balance of the Earth.

CLIMATE VARIABILITY

Within the global climate system, climate controls influence the climate variability at smaller scales across the globe, creating a diverse composition of climates on Earth. These climate controls influence the annual and seasonal temperature and precipitation for a given region. The major climate controls that influence air temperature at a given location are latitude, elevation, and coastal-continental location. Precipitation is also influenced by those controls and other controls including: annual and monthly air temperatures, prevailing air masses, prevailing wind and ocean currents, topography, and position of persistent high- and low- pressure centers.[9] The interactions between these numerous climate controls cause climate to vary "from region to region".[10] Regional climate is defined as the average weather characteristics (i.e. temperature, precipitation) of that given region over a long period of time.[11]

Although climate controls define regional climate types around the planet, each of these regions is ultimately influenced by the entire climate system. Because the climate system experiences a large range of spatial and temporal variability due to the fluctuating nature of "its own internal dynamics" and to "changes in external forcings that affect climate", the planetary regions are influenced by climatic patterns that have multiple degrees of oscillation (i.e. daily, seasonal, decadal, millennial).[12] For example, climate has daily cycles that influence daily temperature and precipitation due to the rotation of the Earth on its axis. This rotation causes regions to have dynamic levels of daily insolation (incoming solar radiation) throughout a 24-hour time period. Daily insolation at a given location depends on the duration of exposure to the sun's rays and the angle of the sun's rays when they hit the Earth.[13]

On a larger temporal scale, climate undergoes natural internal processes in interannual and decadal timeframes as observed by the El Nino/ Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), Atlantic Multi-decadal Oscillation (AMO), etc. For instance, the NAO primarily influences the

[9] Anderson and Strahler, *Visualizing Weather and Climate*, 300.
[10] Christensen et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 865.
[11] Anderson and Strahler, *Visualizing Weather and Climate*, 7.
[12] Le Treut et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 96.
[13] Anderson and Strahler, *Visualizing Weather and Climate*, 90.

Northern Hemisphere and is the "dominant pattern of near-surface atmospheric circulation variability over the North Atlantic".[14] The NAO fluctuates between positive phases characterized by intensified Azores high and Iceland low and negative phases characterized by reduced Azores high and Iceland low. Although an annual pattern, the strongest NAO signature occurs during the winter as shown in the figure below.

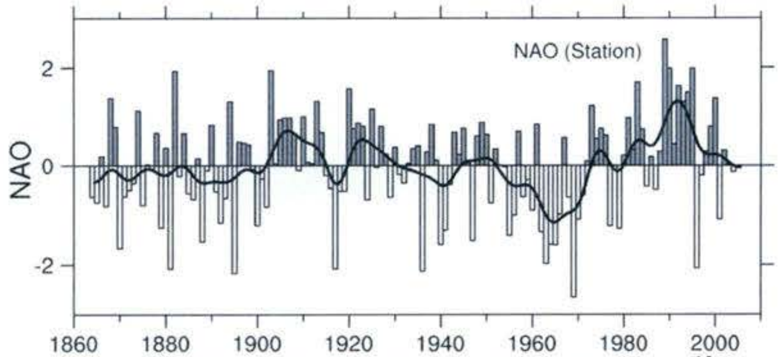

***Figure 3*: Winter (Dec-Mar) North Atlantic Oscillation**[15]

The two phases influence the temperature and precipitation patterns "extending from eastern North America to western and central Europe" by causing "basin-wide changes in the intensity and location of the North Atlantic jet stream".[16] For example, the eastern United States is marked by higher than normal temperatures when the NAO enters into a strong positive period.[17] In contrast, the negative phase correlates with colder and drier conditions in the eastern United States.

The Atlantic Multi-decadal Oscillation (AMO) is a climatic phenomenon, which follows a cyclic pattern that fluctuates between positive and negative phases approximately every 60-80 years.

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[14] Trenberth et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 290.
[15] Ibid., 292.
[16] Climate Prediction Center, *National Weather Service*, http://www.cpc.noaa.gov/data/teledoc/nao.shtml.
[17] Ibid.

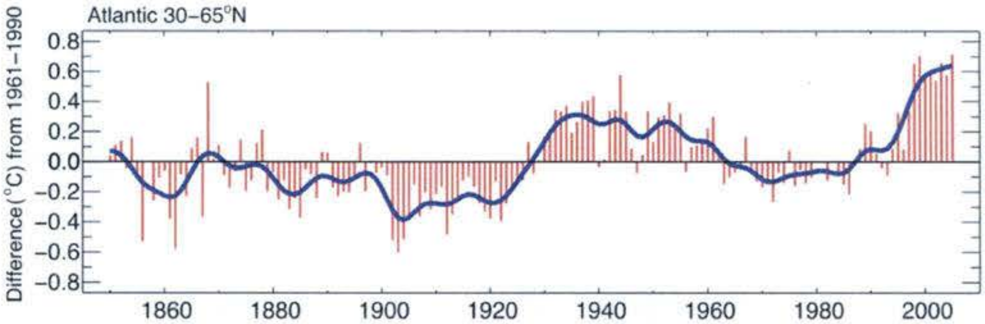

***Figure 4*: Atlantic Multi-decadal Oscillation (AMO)[18]**

The AMO is driven by the sea surface temperatures (SSTs) "in the North Atlantic Ocean between the equator and Greenland".[19] The positive phase has warmer than average SSTs, while the negative phase has cooler than average SSTs. Also, changes in precipitation and river flow in North American have been linked to the AMO.[20]

Furthermore, these climatic cycles do not occur in accordance with one another, thus complicating climate by introducing even more variability. Each of these decadal cycles affects the climate differently depending on what point each is in their oscillations. For example, the Pacific Decadal Oscillation (PDO) and AMO cause different climate patterns across the United States depending on where they are at in their cycles (positive or negative). *Figure 5* depicts the relationship between the PDO and the AMO during the various modes of oscillation.

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[18] Trenberth et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 294.

[19] Glenn Carrin, "The Relationship Between Sea…," 4.

[20] Trenberth and Shea, "Atlantic hurricanes…," 1.

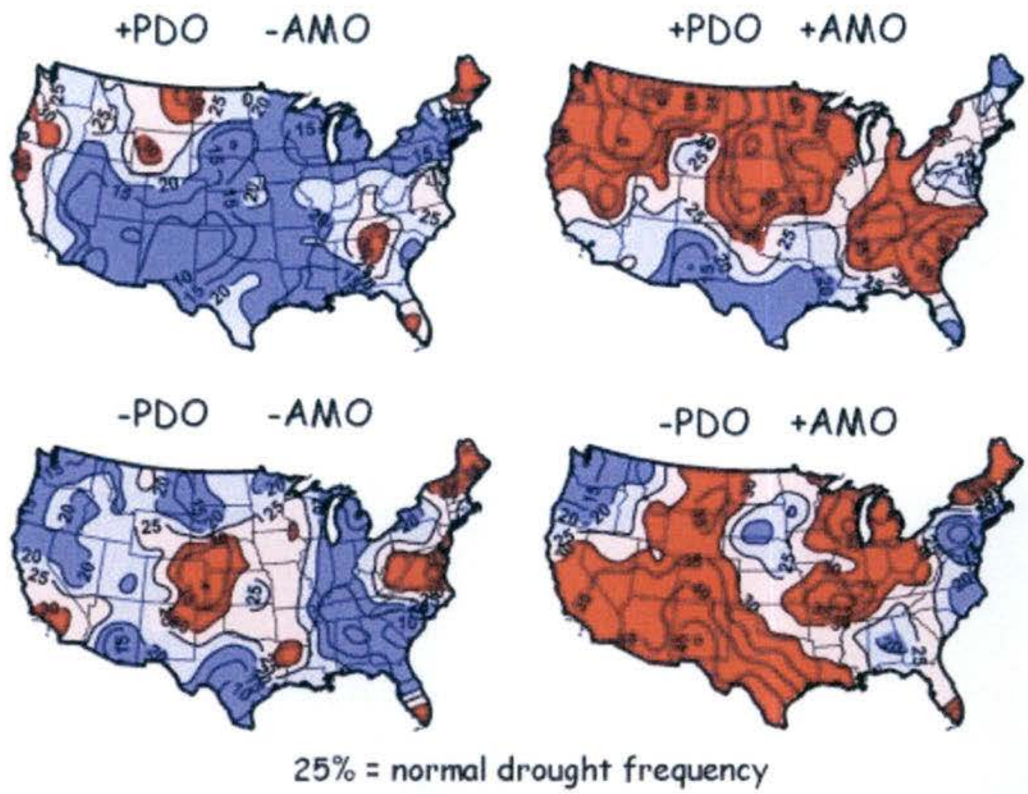

***Figure 5*: Combined Modes of the PDO and AMO** – Areas of high (red > 25%) and low (blue < 25%) drought frequencies associated with complimentary modes of the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO).[21]

There are also climate variations on the millennial scale. For example, shifts in the Earth's rotation and revolution influence the earth's climate. However, this is not a primary concern of this thesis due to the much smaller timescale being analyzed. The importance of referencing these varying lengths of cycles is to show that climate does have internal variability and is always changing, which adds to the difficulty of quantitatively detecting regional climate change. To detect accurate regional climate change among this intrinsic variability means that it is necessary to detect a shift in the patterns of variability within the climatic system.

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[21] McCabe et al. *Past Research Highlights* http://wwwpaztcn.wr.usgs.gov/rsch_highlight/articles/200404.html.

CLIMATE ANE GEOGRAPHY OF NORTHEASTERN UNITED STATES

The Northeast falls within the latitudes of 38 to 48 degrees north and within the longitudes of 66 to 81 degrees west. The Appalachian Mountain Range cuts through the middle of the Northeast, which causes the region to range in elevation from 0-1,524 meters. The figure below illustrates the elevation pattern of the Northeast. The central high-elevation pattern that extends from the bottom of Pennsylvania through the top of Maine highlights the Appalachian Range.

***Figure 6*: Northeast Elevation** – Dark green represents the lowest elevation (0-152 m) and tan represents the highest elevation (610-1524).[22]

Although the Northeastern United States has "one of the most varied regional climates in the nation", it is broadly defined as a moist continental climate.[23] This climate type has a large seasonal variation with cold winters and warm summers. Throughout the year, precipitation in the Northeast stays fairly constant with a slight increase in precipitation during the summer due to incoming maritime tropical air masses. Continental arctic and continental polar air masses influence the cold winters.[24]

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[22] U.S. Geological Survey, "Topographic Relief," http://www.learnnc.org/lp/media/maps/usa_toporelief_1968_o.jpg.
[23] Northeast Climate Impacts Assessment, *Climate Change in the U.S. Northeast*, 4.
[24] Anderson and Strahler, *Visualizing Weather and Climate*, 340.

Figure 7 below represents the seasonal variation of temperature and precipitation for a moist continental climate, such as the Northeastern United States.

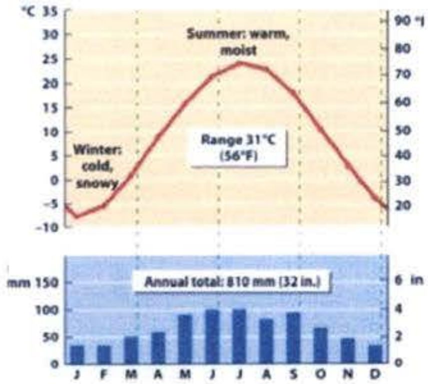

***Figure 7*: Moist Continental Climate (monthly temperature and precipitation)** – Represents the annual variation of the Northeast climate. The red line shows temperature and the blue bar graph depicts precipitation.[25]

The snow season in the Northeast ranges primarily from October through April, with the heaviest snowfall occurring from November to March. Snowfall and snow cover varies within the Northeast due to the range of latitudes and elevations. For example, the southeastern (south of 42ºN) area and the area along the coast generally have 0-60 snow covered days, while the more inner-continental area north of 42ºN has between 60-121 snow covered days.[26]

NORHTEASTERN LIFE

The climate of a region unavoidably influences the livelihoods of those inhabiting that region. Since any shift in climate has strong potential to "impact urban and rural life, agriculture, industry, tourism, and natural ecosystems", the livelihoods of those living there, human and non-human, will be altered, for better or worse.[27] Climate change in the Northeast has the potential to impact one in five Americans due to the

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25 Anderson and Strahler, *Visualizing Weather and Climate*, 340.
26 Burakowski and Wake, "The Changing Character…," 6.
27 Hayhoe, et al., "Past and future changes…," 28.

approximately 57,000,000 people that live in the Northeast.[28] A majority of that population lives to the east of the Appalachians along the seaboard.

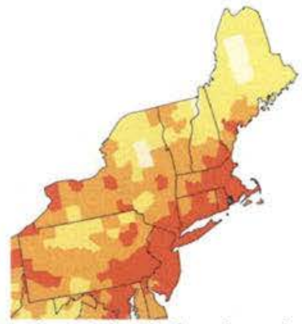

***Figure 8*: Northeast Population Density** – The darker the color, the more densely populated the area. Less than one person per square mile = white and over 1040 persons per square mile = red.[29]

Because a majority of the NE population lives along the coast, a large amount of investment (in terms of homes, public services and buildings, and businesses) is vulnerable to any changes in sea surface. In fact, "New York alone has more than $2.3 trillion in insured coastal property".[30]

The economic sectors in the Northeast that are most vulnerable to climate changes include recreation, tourism, fisheries, forestry, and agriculture.[31] One of the most important sectors in agriculture is the dairy industry, which has an annual yield of $3.6 billion.[32] Other notable agricultural industries that are vulnerable to climate change include: fruits (blueberries, apples, cranberries) and maple syrup.

Winter recreational activities, such as downhill skiing, cross-country skiing, snowshoeing, snowmobiling, and ice fishing, are another important economic sector in the Northeast. These winter activities bring in approximately $7.6 billion dollars annually to the Northeast. Snowmobiling has grown in popularity in recent years to now

[28] Northeast Climate Impacts Assessment, *Climate Change in the U.S. Northeast*, 4.
[29] HowStuffWorks, Inc., *US States Population Density Map*, http://maps.howstuffworks.com/united-states-population-density-map.htm.
[30] United States Global Change Research, 109.
[31] Northeast Climate Impacts Assessment, *Climate Change in the U.S. Northeast*, 4.
[32] United States Global Change Research, 108.

make up about $3 billion of the annual revenue, while the other snow related activities comprise the other $4.6 billion.[33] All snow-related winter activities bring wealth into the region while supporting an expected way of life in the Northeast. Any shifts in the amount of snowfall could negatively or positively affect the livelihoods of those that depend on winter sports for recreation or occupation.

BRIEF HISTORY OF GLOBAL CLIMATE CHANGE RESEARCH

As more attention has been directed toward global climate change, more resources and energy have gone into the comprehensive understanding of the climate system in all of its complexity. The more understanding we have of the climate system, the greater our ability to understand the driving causes of that change, whether it be caused by the *internal dynamics* of the climate system or due to natural or anthropogenic external forcings. The Intergovernmental Panel on Climate Change (IPCC) has been the leading task force since 1990 that compiles global scientific research pertaining to the climate system, synthesizes that information, and publishes detailed assessment reports about the past, present, and future state of the climate. The reports focus on research that investigates the detection and attribution of climate change.

With the level of scientific knowledge of climate in 1990, the first IPCC report timidly suggested that, "there is concern that human activities may be inadvertently changing the climate of the globe through the enhanced greenhouse effect".[34] By the publication of the Third IPCC Assessment Report in 2001, more understanding of the

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[33] United States Global Change Research, 110.
[34] Intergovernmental Panel on Climate Change, *Climate Change: The IPCC Scientific Assessment*, 1990, viii.

climate system led to the conclusion that, "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities".[35] Around this time, figures like the *Figure 9* shown below were frequently referenced when discussing global climate change. *Figure 9* illustrates the long-term temperature trends of the planet over centennial and millennial scales. Both figures signal an increase in global temperatures in the past century compared to the historical trends.

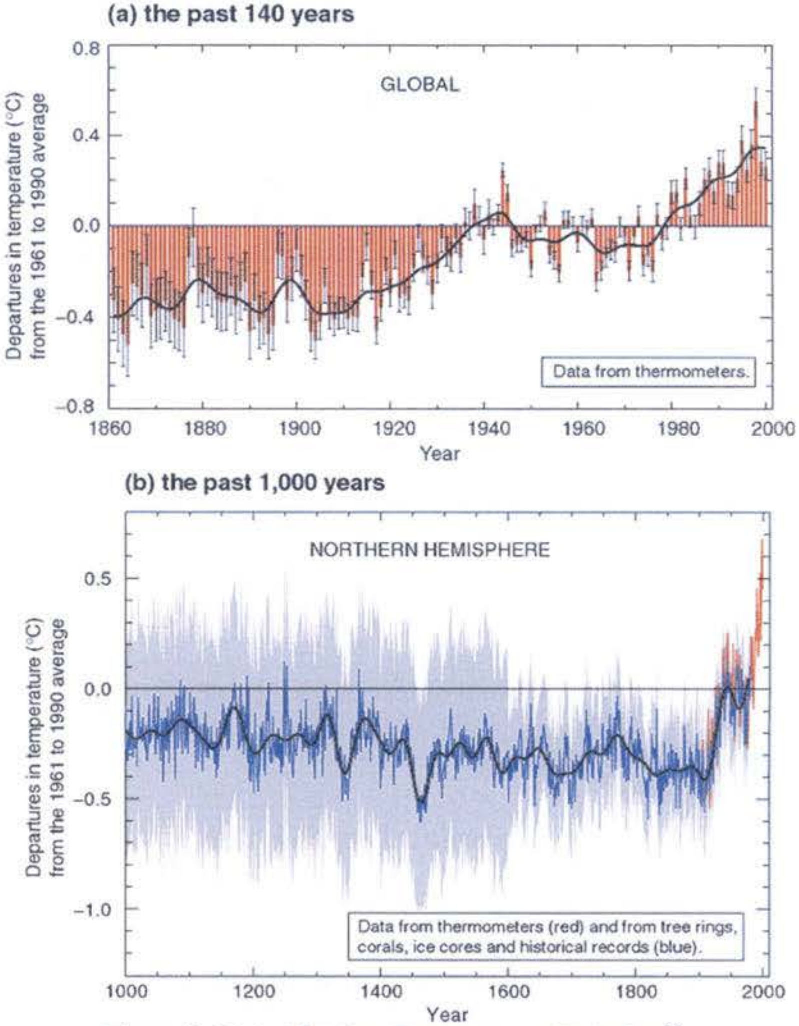

***Figure 9*: Global Surface Temperature Variation**[36]

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[35] Intergovernmental Panel on Climate Change, *IPCC Third Assessment Report*, 2001, http://www.grida.no/publications/other/ipcc_tar/. Summary for Policy Makers.
[36] Ibid.

The Fourth IPCC Assessment Report released in 2007 marked a shift of public thinking away from the modest question, "is [anthropogenic] climate change occurring?", to the urgent one, "what are we going to do about it?".[37] The Fourth Assessment states,

> It is extremely unlikely (<5%) that the global pattern of warming during the past half of the century can be explained without external forcing, and very unlikely that it is due to natural external causes alone. The warming occurred in both the ocean and the atmosphere and took place at a time when natural external forcing factors would likely have produced cooling. Greenhouse gas forcing has very likely caused most of the observed global warming over the last 50 years.[38]

To make a statement of this caliber, there has to be a significant understanding of the climate system and the internal and external processes associated with it. Although there is still much more to investigate concerning the climate system, inherent climate variation, and human influences, the scientific community has made large advancements since the 1990s in the ability of climate models to capture the complexity of the climate system, as shown below.

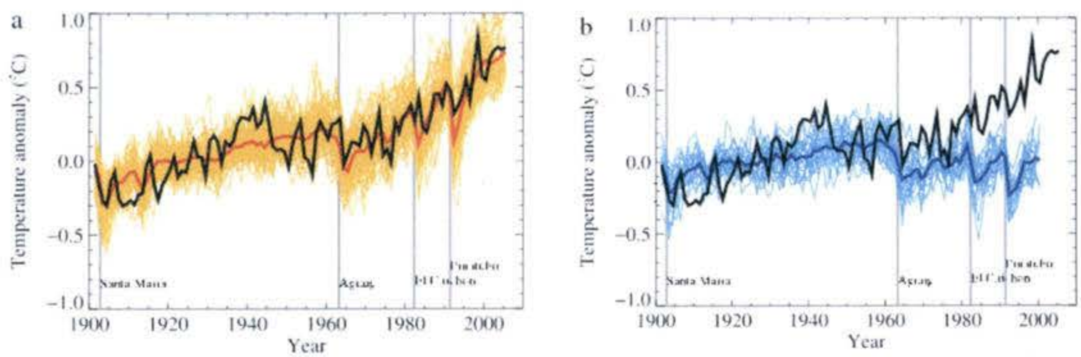

***Figure 10*: Global Climate Models vs. Observed Global Temperature** – Compares global climate models (colored lines) to global mean surface temperature anomalies (black line): a) model includes both anthropogenic and natural forcings, b) model includes natural forces only[39]

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[37] Intergovermental Panel on Climate Change, "IPCC Expert Meeting on Assessing and Combining Multi Model Climate Projections," 77.

[38] Hegerl et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 665.

[39] Ibid., 684.

The graphs compare the observations of the past century (black line) to Global Climate Models (color). The left image illustrates the model that includes both anthropogenic and natural forcings, while the right image shows the model that only includes natural forces. The model does not match the observed global temperatures unless anthropogenic and natural forcings are included in the model. The conclusions drawn from comparing global climate models to observations have enabled scientist to not only detect climate change, but also to determine the broad causes of that change. Although extensive scientific progress has been made on the topic of global climate change, uncertainty still remains at the global scale, however, more uncertainty exists at the continental, regional, and local scales.

REGIONAL CLIMATE CHANGE IN NORTHEASTERN UNITED STATES

A number of climate change analyses for the Northeast have been published in the past decade. These analyses consistently indicate an increase in annual temperature since the 1970s.[40] In addition to annual warming, most reports have emphasized that the greatest warming in the NE over the past forty years has occurred during the winter.[41] The Northeast Climate Impact Assessment states that the observed warming in the NE "has been correlated with many noticeable changes across the Northeast, including:

- More frequent extreme-heat days (maximum temperatures greater than 90°F)
- A longer growing season
- Earlier leaf and bloom dates for plants
- Shifts in the mating cycles of frogs to earlier in the year
- Earlier migration of Atlantic salmon in northeastern rivers
- An increase in heavy rainfall events
- Earlier breakup of winter ice on lakes and rivers
- Earlier spring snowmelt resulting in earlier high spring river flows
- Less precipitation falling as snow and more as rain

[40] Northeast Climate Impacts Assessment, *Climate Change in the U.S. Northeast*, 10.
[41] Christensen et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 850.

- Rising sea surface temperatures and sea level
- Reduced snowpack and increased snow density".[42]

In addition to observed changes in temperature trends over the past forty years, the analyses also describe annual precipitation trends over the past century. Unlike temperature, the scientific community is not fully unanimously about observed precipitation trends. The Northeast Climate Impact Assessments stated in 2006 that annual precipitation since 1900 has been increasing, with the least amount of increase occurring during the winter. However, this trend reversed a few decades ago, to show a minor decease in annual precipitation, but an increase in winter precipitation.[43] Another study agrees that precipitation has been increasing over the past century (by +9.5±2 mm/dec), but warns that the evidence for the shift in the trend over the past few decades is not very robust.[44]

The observed increase of winter precipitation in the past few decades suggests that there is more precipitation falling as rain and less as snow.[45] More evidence indicates that snow has been decreasing in amount and cover, while increasing in density.[46] Burakowski's dissertation, which focused specifically on winter trends in the Northeast, suggests that the greatest decrease in snowfall has been during December months. In addition, the study claims that snowfall may not correspond to the warming winter temperatures as well as snow cover.[47]

Although temperature and precipitation are both important indicators of climate change in the NE, Hayhoe et al. recommend that, "due to the large inter-annual

[42] Northeast Climate Impacts Assessment, *Climate Change in the U.S. Northeast*, 15.
[43] Ibid.
[44] Hayhoe et al., "Past and future changes…," 10.
[45] Frumhoff et al., *Confronting Climate Change…,* 107.
[46] Hayhoe et al., "Past and future changes…," 1.
[47] Burakowski and Wake, "The Changing Character…," 7.

variability and uncertainty in estimated [precipitation] trends, more weight should be attached to temperature-driven change than precipitation".[48] The paper further explains that it is challenging to "distinguish consistent long-term trends from natural fluctuations" because of the "large interdecadal variability in precipitation" in the NE.[49] Regardless of the questionable robustness of precipitation trends, the indicators of climate change mentioned above (i.e. temperature, precipitation, biological, etc.) signify that the NE is already experiencing some of the repercussions of climate change.

MEASURING CLIMATE

As more attention has been given to global and regional climate change, more funds have been allocated to researching climate. Consequently, the complexity of the global climate models have become increasingly more complex in the past decade as more collaboration and effort goes into this topic. *Figure 11* below pictorially represents the increased complexity of global climate models over the past forty years:

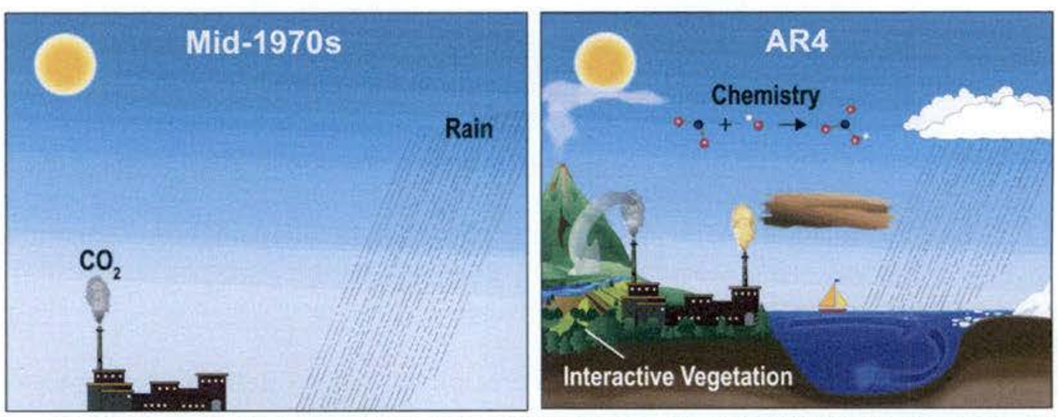

***Figure 11*: Complexity of Global Climate Models Overtime** – Illustrates the increased complexity of models from the 1970s (left) to present (right)[50]

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[48] Hayhoe et al., "Past and future changes…," 11.
[49] Ibid.,10.
[50] Le Treut et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 99.

Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) are today's most advanced climate models. These models attempt to represent the multi-layered complexity of the climate system and "have been demonstrated to reproduce observed features of recent climate and past climate changes".[51] The IPCC feels that the AOGCMs are most robust in quantitatively measuring climate change at continental, hemispherical, and global scales.[52] However, AOGCMs are not reliable for quantitatively measuring regional climate scales because the techniques to downscale these global climate models have yet to be fully developed and applied.[53] Climate indexing, the methodology used in this project, is significantly more simplistic than these complex AOGCMs, but the implications made from this statistical method may be no less powerful in its ability to quantitatively measure change on a regional scale. Although, unlike climate indexing, AOGCMs are also tools that attempt to discover the explicit causes of any observed changes. Consequently, AOGCMs investigate detection (i.e. statistically demonstrating that climate has changed) and attribution (i.e. finding the most likely causes of that detected change) of climate change, while climate indexing only addresses detection.

A weakness of many climate models, including complex global models, lies in the method for defining what length of time defines normal climate. A common method to define a climate baseline, or the normal climate, is to average thirty years of weather, such as temperature or precipitation. Although this method is suggested to "remove year-to-year fluctuations" because "thirty to forty years" is a "relatively long period of

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[51] Randall et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 591.
[52] Ibid.
[53] Christensen et al., Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 918.

time", the outcome of this method is the creation of a climate baseline that is somewhat arbitrary due to natural variation of the climate at the decadal scale.[54] Consequently, using a thirty-year baseline to represent the normal climate becomes unreasonable when accounting for the naturally occurring variability in climate because this thirty-year baseline that is suppose to represent the *normal* climate might not accurately represent that climate. For example, in the 1960s a drought occurred in the Northeast that was "a multi-year event estimated to be the most severe drought to occur in that region in the observational record" (i.e. since the late 19th century).[55] If scientists wanting to create a thirty-year climate baseline to represent long-term precipitation trends averaged a thirty-year period that included this severe drought, the consequence could lead to an inaccurate assumption about the current and future precipitation trends in that region. Hayhoe et al. warn that, "care must be used in estimating long-term precipitation trends, as any trends that begin or end near a major drought event (or an extended wet period) will be biased by this strong event".[56] The same warning applies to other climate indicators being analyzed, such as snowfall, minimum temperature, maximum temperature, etc. This raises the question of how to define a normal climate when the natural climate cycles cannot be defined in a set number of years.

Climate indexing negotiates this thirty-year baseline problem by using all of the data over the timescale being measured to define the *normal* climate. For example, this thesis uses the recorded minimum temperature, maximum temperature, and precipitation beginning in 1900 to create the climate baseline, as opposed to some randomly selected thirty years of data within that period of record to serve as the

[54] Northeast Climate Impacts Assessment, *Climate Change in the U.S. Northeast*, 9.
[55] Hayhoe et al., "Past and future changes…," 9.
[56] Ibid.

climate baseline. This enables the climate analysis to represent more clearly the inherent variability of climate. Climate indexing is a relatively new statistical method for quantitatively measuring climate that was developed in the mid-1990s by C.C. Ebbesmeyer and R.M. Strickland from the University of Washington. They used climate indexing to supplement their research on fluctuations of oyster populations in the Pacific Northwest and how those fluctuations correlate with temperature and precipitation trends.[57] The climate index that Ebbesmeyer and Strickland created for the Pacific Northwest is shown below:

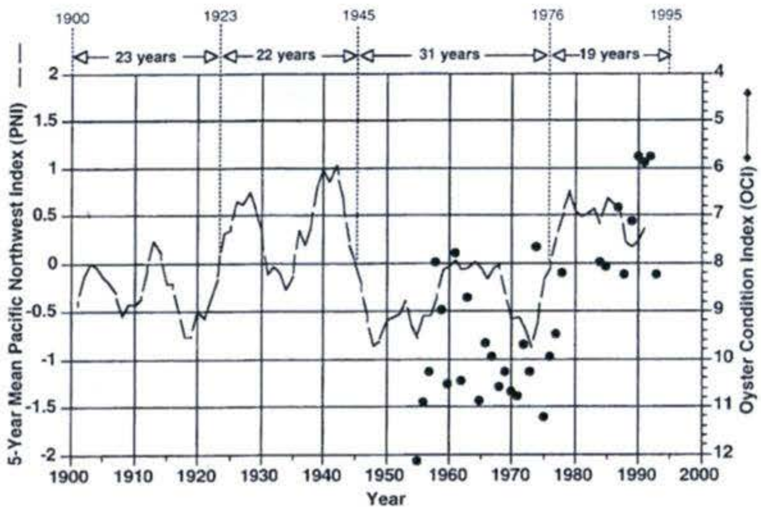

***Figure 12*: Original Pacific Northwest Index (PNI)** – The dashed black line represents the PNI.[58]

The Pacific Northwest Index (PNI) is composed of three parameters: snowpack depth at Paradise on Mount Rainier, precipitation at Cedar Lake in the Cascade Mountains, and air temperature at Olga in the San Juan Islands.[59] A clearer, and more current representation of the PNI, made by another study is shown in *Figure 13*. This figure

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[57] NOAA, "NOAA Response to Congressional…," 6.
[58] Ibid., 5.
[59] University of Washington, *Columbia River Dart Data Access in Real Time*, http://www.cbr.washington.edu/data/pni.html.

highlights the cyclic pattern of the Pacific Northwest climate from warm/dry periods (shown in red) to cool/wet periods (shown in blue).

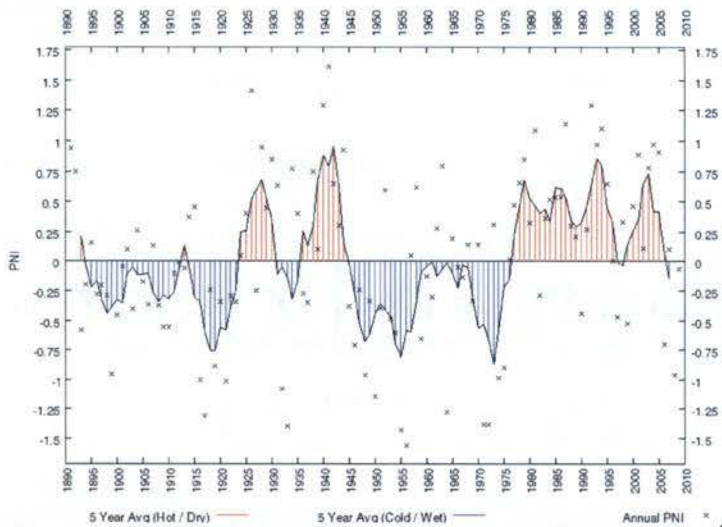

Figure 13: **Updated (1891-2009) Pacific Northwest Index (PNI)**[60]

In 2004, Dr. Gregory Bothun advised an Honors College student, Harvey Rogers, to test the robustness of the PNI, thinking that the PNI would not be a good representation of the Pacific Northwest because it is composed of three arbitrary locations. However, the results of Rogers's thesis suggested otherwise. To test the robustness of the PNI, Rogers ran numerous trials by randomly selecting three sites in the Pacific Northwest, creating indexes, and comparing those indexes to the original PNI.[61] After confirming the robustness of the PNI, Rogers fit a model to the PNI using sine waves. The model suggests that the Pacific Northeast should be entering into a cool/wet period based on the historical climate record, however, the opposite is occurring towards a trend of hot/dry.[62] As seen in *Figure 14* below, Rogers fit a model to an improved PNI, called the RNWI, which used more sites to create the climate

60 University of Washington, *Columbia River Dart Data Access in Real Time*, http://www.cbr.washington.edu/data/pni.html.
61 Harvey Rogers, "Assessing the robustness…," 42.
62 Ibid., 51.

index, but shows this same trend of the current observable data diverging from the model.

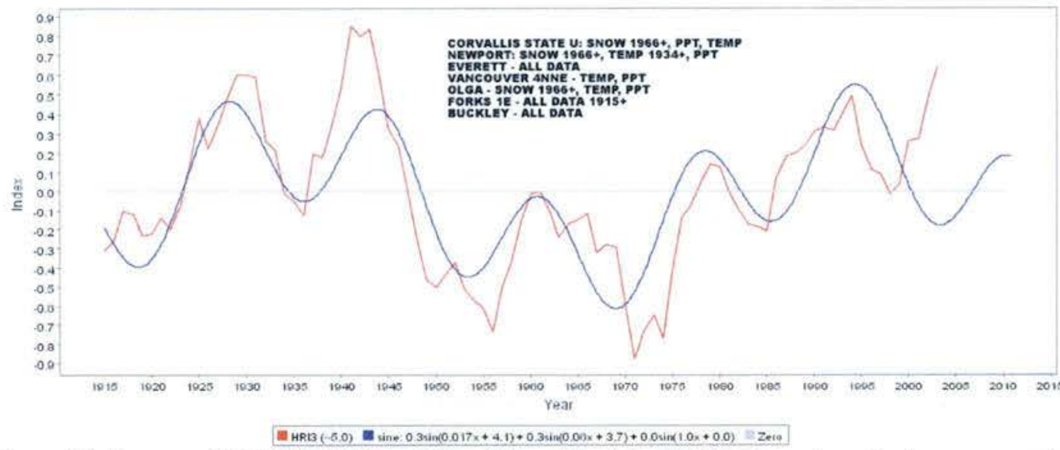

***Figure 14*: Improved PNI (RNWI) and Sine Wave Model** – RNWI shown in red; sine wave model fitted to RNWI shown in blue. Note that the model matches the RNWI waveform until approximately 2000.[63]

In the last couple of years, Stephanie Ostrander has been working with Dr. Bothun to further investigate the PNI. They have identified some errors with the PNI, such as the manner in which the PNI measures snowpack (i.e. only on March 15). Ostrander has reproduced a climate index for the Pacific Northwest (SHI) that is more robust than the initial PNI and Roger's RNWI. Using the techniques employed by Rogers, Ostrander, and Dr. Bothun, a climate index of Northeastern United States will be made. There is yet to be a published climate analysis in the Northeast that uses the statistical technique of climate indexing. Although "true climate shift is subtle and difficult to define and measure" due to noisy and incomplete data, this thesis will hopefully add clarity to the long-term climate trend of the Northeast.[64]

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[63] Harvey Rogers, "Assessing the robustness…," 50.
[64] Professor Gregory Bothun.

METHODS

DATA COLLECTION

The critical first step of this research project was to compile the climate data needed for analysis: maximum temperature, minimum temperature, precipitation, and snowfall. The data used for the parameters of maximum temperature, minimum temperature, and precipitation, is available on the United States Historical Climatology Network (USHCN) website. The USHCN makes available to the public "high-quality" data records from a multitude of climate stations located across the nation. Data from the USHCN are frequently used, particularly to analyze and detect long-term climate trends in the United States.[65] The USHCN stations meet a number of quality-control criteria such as, "length of record, percent of missing data, number of station moves and other station changes that may affect the homogeneity, and resulting network spatial coverage".[66] The maximum and minimum temperature data for this analysis came from 137 stations across the Northeast and have complete monthly records from January 1900 to September 2010. The precipitation data set is composed of data from 136 sites. Of these stations, 128 have complete precipitation records from January 1900 to September 2010. The remaining eight stations start no later than 1908 and have no more than three missing months of data from January 1908 to September 2010. *Figure 15* illustrates the locations of the 137 USHCN stations in the Northeast.

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[65] NOAA Regional Climate Centers, "The RCC Report," 2.

[66] Menne et al. *USHCN*, http://cdiac.ornl.gov/epubs/ndp/ushcn/background.html.

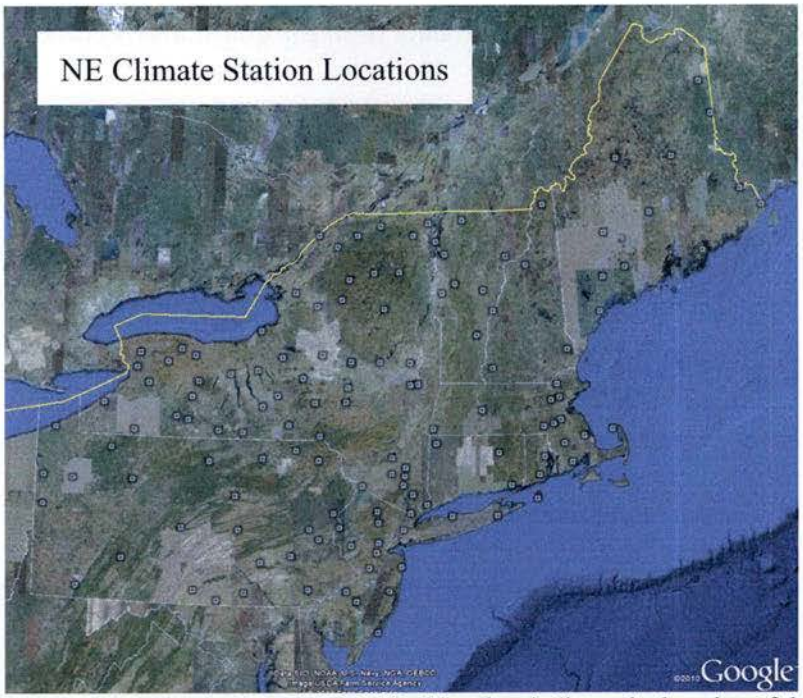

***Figure 15*: USHCN Stations in the Northeast** – The blue dots indicate the location of the stations used in this analysis.[67]

Unfortunately, snowfall records are significantly less complete than the other parameters being analyzed. Although climate record keeping in the Northeast began in the late 19th century for variables such as temperature and precipitation, snowfall did not become consistently recorded until decades later.[68] The snowfall data used in this analysis came from the National Weather Service's Cooperative Station Network (NWSCoop) accessed via the National Climatic Data Center's (NCDC) website. Even though the snowfall data did not come directly from the USHCN database, the monthly snowfall records used came from the same stations as the other three parameters because the USHCN is comprised of mostly U.S. Cooperative Observing Network stations.[69] Consequently, the Station IDs (i.e. CoopID) correspond for all four variables

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[67] Created by Professor Gregory Bothun using Google Earth.
[68] Hayhoe et al., "Past and future changes…," 18.
[69] Menne et al. *USHCN*, http://cdiac.ornl.gov/epubs/ndp/ushcn/background.html.

being examined. The snowfall data used for this analysis comes from a total of 49 stations that fit the following station criteria:

- the data record starts prior to 1960,
- the data record ends no earlier than 2008,
- the data is at least 90% complete from start date to end date, and
- the station is not located near the Great Lakes.

In addition to these 49 stations having the most complete records of snowfall in the Northeast in terms of longevity and completeness of the data, the stations are not heavily impacted by lake-effect snow caused by the Great Lakes. Lake-effect snow occurs during the winter when cold wind passes across large expanses of warmer lake water causing water vapor to accumulate. This accumulated water vapor is deposited on the leeward land from the body of water as snow. Stations influenced by this effect (i.e. stations located in western New York and extreme northwestern Pennsylvania) were excluded from the snowfall analysis to avoid skewing the snowfall results for the entire NE region.

It should be noted that although urban heat island effect was initially taken into consideration when compiling the sites used in the analysis, no station was removed from the original analysis for its proximately to large, urban centers. An urban heat island is an area at the center of a city that has higher temperatures than surrounding regions due to human induced alterations of the landscape's albedo (i.e. reflectivity of solar radiation).[70] For example, New York City reflects less solar radiation than a deciduous forest, thus the city absorbs more heat during the day. This urban influenced microclimate could distort the measurements made at stations located in the heavily built environment compared to measurements made at stations in the less built and more

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[70] Anderson and Strahler, *Visualizing Weather and Climate*, 103.

natural environments. However, the USHCN claims that a majority of their stations are located in rural areas or small towns, with only some of the stations being located in more urbanized environments.[71]

DATA ANALYSIS

The variables analyzed in this thesis to create a climate index for the Northeast include maximum temperature, minimum temperature, precipitation, and snowfall. For this project, the primary tool for analysis was the extensive use of Excel, with some separate elements of computer programming. The data analysis involved the creation of four climate indices that are composed of stations based on different criteria:

- Northeast Climate Index (NEI),
- Filtered Northeast Climate Index (FNCI),
- Non-Urban Northeast Climate Index (UNEI), and
- Northeast Coastal Climate Index (NECI).

The reasoning for creating these four different climate indices and the methodology for selecting sites for the indices will be discussed in further detail below.

Creating the NEI

The Northeast Climate Index (NEI) is comprised of data for every existing station in the NE for temperature and precipitation. Snowfall data comes from all the stations within the NE that meet the previously stated criteria. *Figure 16* on the following page illustrates the distribution of NE climate stations used in this analysis, as well as highlights the stations used for the analysis of snowfall:

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[71] Menne et al. *USHCN*, http://cdiac.ornl.gov/epubs/ndp/ushcn/background.html.

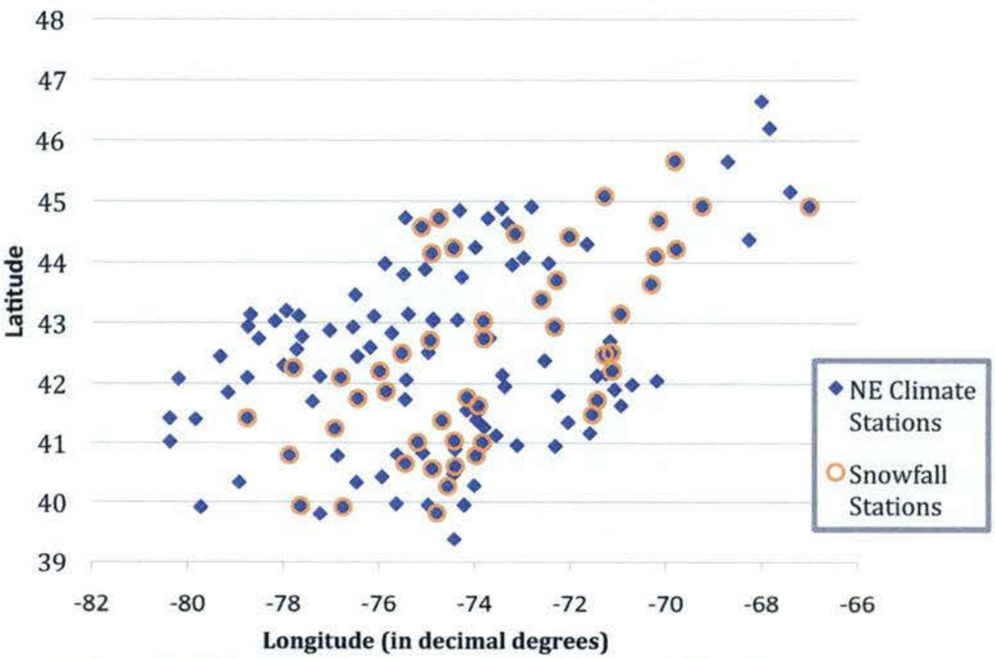

***Figure 16*: Spatial Distribution of Northeast Climate Stations** – Blue diamonds represent sites used for temperature and precipitation data; orange circles indicate sites used for snowfall data.

After collecting the data for the variables of interest (maximum temperature, minimum temperature, precipitation, and snowfall), the statistical method of climate indexing was applied to create the NEI. This method involves the use of a statistical technique called a *Z-score*. The *Z-score* is a powerful tool used for measuring the "relative standing of a measurement in a dataset".[72] More clearly, it measures the "distance between an observation and the mean, measured in units of standard deviation".[73] To calculate the *Z-Score* three values are needed: an observational value, the mean of the population from which the observational value came, and the standard deviation of that population.

$$\textit{Z-Score} = (x - \mu) / \sigma$$

Where:

x = an observation within a population
μ = mean of the population
σ = standard deviation of the population

[72] Mendenhall et al. *Introduction to Probability*...,75.
[73] Ibid.

For each variable, a *Z-score* was calculated for every individual site by month over the period of record. For example, when calculating the *Z-scores* for maximum temperature at hypothetical Site A, there should be *Z-scores* for all twelve months for every year from 1900-2010. This procedure was repeated for all sites and all four variables.

Once the monthly *Z-scores* for every site had been calculated, these monthly *Z-Scores* were averaged together to produce annual and seasonal *Z-scores* for every site over the period of record. For example, to calculate the annual *Z-scores* for the period of record for Site A, the *Z-scores* for January through December would be averaged together by year until the most recent complete record for that year (i.e. 1900, then 1901… then 2009). This results in *Site A* having an annual *Z-score* for every year in that data record. The above procedure was repeated for all of the sites associated with minimum temperature, maximum temperature, and precipitation.

The annual average *Z-scores* for snowfall does not include all twelve months because it does not snow in the NE for the entire calendar year. This project has defined the annual snowfall season as including only seven months: January, February, March, April, October, November, and December. In the snowfall data used in this analysis, there exists no record of snowfall during the months of July and August. Although there have been instances of snowfall in June and September, the occurrence is extremely rare and insignificant to this project. For example, the records show that it has only snowed during June once from 1931-2010 in one of the forty-nine stations located in the NE. The snowfall amount at that site was only 0.3 inches, which had a standard deviation of 8.8. A snowfall event with this standard deviation of 8.8 is considered very rare because "observations with *Z-scores* exceeding 2 in absolute value happen less than 5% of the time and are considered somewhat unlikely… [and] observations with *Z-Scores* exceeding 3 in absolute value happen less than 1% of the time and are considered very unlikely".[74] September snowfall is not as rare as in June, but is still extremely uncommon. In the past eighty years it has snowed during one or two Septembers in only seven of the forty nine sites with standard deviations for those events ranging from 2.4 to 8.7.

The month of May could be included in future snowfall analyzes, but was excluded from this analysis. One primary reason for this exclusion was to simplify the annual and spring calculation of the snowfall *Z-scores*. When initially calculating the monthly snowfall *Z-scores*, it appeared that a majority of the snowfall sites had scarce to no snowfall during May. However, upon further investigation, it has snowed during May in thirty-five of the forty-nine sites with the yearly occurrence rates ranging from one to thirty-one times in the snowfall record depending on the site location. Despite this seemingly high rate of snowfall occurrence, only 9 sites of the 35 sites that have at least one record of snowfall above zero have snowfall occurring for more than ten years in the eighty-year record. It should be further noted that these nine sites have higher elevations compared to the majority of sites. In conclusion, due to calculation efficiency and efforts to represent the NE climate as best as possible, the month of May was not included in the defined annual snowfall season for this project.

The climate seasons are defined as: winter (November – February), spring (March-June), and summer (July-October). The primary reason for only having three climate seasons, with four months per season, was to match the climate research already

[74] Mendenhall et al. *Introduction to Probability…*,76.

in progress on the Pacific Northwest. This enables more direct comparisons of climate variability between the Pacific Northwest and the Northeast.

The next step in creating the NEI was the averaging of the annual and seasonal *Z-scores* for a given year of every site. This step combined all sites used in the analysis together to give a more statistically relevant representation of the regional Northeastern climate. The calculation resulted in the annual and seasonal Z-scores for all four variables over the period of record (1900-2010): $MaxTempDev_{time}$, $MinTempDev_{time}$, $PrecipDev_{time}$, and $SnowFDev_{time}$.

Finally, to generate the composite NEI, the *Z-Scores* of the existing variables for every year were averaged. Because there is no snowfall data from 1900-1931 the NEI equation for 1900 through 1930 is as follows:

$$\mathbf{NEI_{year} = (MaxTempDev_{year} + MinTempDev_{year} + PrecipDev_{year}) / 3}$$

For the remaining years (1931-2010), the equation to calculate the composite NEI incorporated all four parameters:

$$\mathbf{NEI_{year} = (MaxTempDev_{year} + MinTempDev_{year} + PrecipDev_{year} + SnowFDev_{year}) / 4}$$

When graphed, a point above the baseline (i.e. 0) indicates that the year is warmer and wetter than the overall average. Likewise, if the point is below the baseline, it indicates a cooler and drier year than normal. The equation above will always follow this pattern.

In contrast to the Northeast climate, the Pacific Northwest has little precipitation during the summer, but ample precipitation and snow in the winter. Because low temperature corresponds with high precipitation and snow in the Pacific Northwest, the

PNI is calculated with the temperature deviations having the opposite sign as precipitation and snow, as shown below:[75]

$$\mathbf{PNI_{year} = [(-TempDev_{year}) + PrecipDev_{year} + SnowDev_{year}] / 3}$$

The result of this sign change makes the points above the baseline represent years that are warmer and drier than the norm, while the points below the baseline represent years that are colder and wetter than the average. To better compare the NEI to the PNI, the NEI was also calculated to match the PNI, with above the baseline equaling warmer/drier and below the baseline equaling cooler/wetter. The equations to calculate the composite NEI that matches the PNI (NEI^p) is shown below:

$$\mathbf{NEI^{p}_{1900\text{-}1930} = [MaxTempDev_{1900\text{-}1930} + MinTempDev_{1900\text{-}1930} + (-PrecipDev_{1900\text{-}1930})] / 3}$$

and

$$\mathbf{NEI^{p}_{1931\text{-}2010} = [MaxTempDev_{1931\text{-}2010} + MinTempDev_{1931\text{-}2010} + (-PrecipDev_{1931\text{-}2010}) + (-SnowFDev_{1931\text{-}2010})] / 4}$$

To graphically visualize both the NEI and the NEI^p, the years were graphed on the x-axis and the NEI values were graphed on the y-axis. A 5-year moving average was applied to the data to reduce the noise of the data points by smoothing out the short-term fluctuations, while highlighting the longer-term trend/ cycles. This statistical technique helps reveal multi-year or decal trends within the dataset.

In addition to graphing the composite NEI, each variable that creates the index (minimum temperature, maximum temperature, precipitation, and snowfall) was graphed independently and then compared to the composite NEI. A five-year moving average was also applied to the independently graphed variables. Graphing $MaxTepDev_{1900\text{-}2010}$, $MinTempDev_{1900\text{-}2010}$, $PrecipDev_{1900\text{-}2010}$, and $SnowFDev_{1931\text{-}2010}$

[75] Harvey Rogers, "Assessing the robustness…," 31.

independently of each other allows for better visualization of those particular long-term trends. Also, to determine which, if any, variable was the primary driver of the NEI waveform, the variable was then graphed alongside the composite NEI.

Site Comparisons to NEI

An important, but more peripheral step following the completion of the NEI, was to graph each variable for the individual sites in comparison to the $MaxTepDev_{1900-2010}$, $MinTempDev_{1900-2010}$, $PrecipDev_{1900-2010}$, and $SnowFDev_{1931-2010}$. The results of this procedure were used to determine which sites to exclude from FNEI. If the variable's waveform of the individually graphed site fails to correspond to the waveform of the $VarDev_{years}$, then one of two conclusions is likely.

First, this difference might suggest that a calculation error occurred when determining the average or standard deviations of that site. For example, *Figure 17* on the following page shows the minimum temperature trends in Connecticut (colored lines) compared to the $NEI_{MinTemp}$ (black line). All of the sites shown coincide with the $NEI_{MinTemp}$, except for one site (red line). This site is isolated from the other sites but still follows the same waveform as the other sites. This suggests that an error occurred when calculating the standard deviation for that site. Before continuing with the analysis, any errors were corrected and the NEI was recalculated.

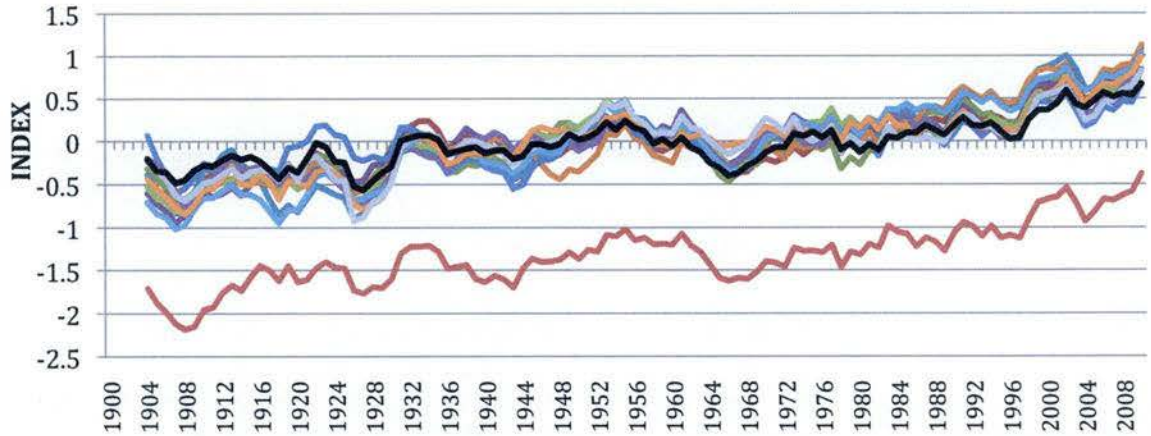

***Figure 17*: Calculation Error: Connecticut Sites$_{MinTemp}$ versus NEI$_{MinTemp}$** – Compares the minimum temperature data at individual Connecticut stations to the overall averaged minimum temperature waveform.

If a site intersected with the other sites or the NEI, but varied greatly from the general trend, then a *Z-score* calculation error was less likely. Rather, the parameter being investigated for that site was anomalous to the Northeast region. For example, the figure below illustrates the minimum temperature for two sites in Vermont compared to the overall NEI$_{MinTemp}$. The orange site coincides well with the NEI$_{MinTemp}$, however, the blue site varies greatly from the NEI$_{MinTemp}$. When creating the FNEI, the blue site was omitted from the analysis due to its anomalous form, although this site was included in the original index (NEI).

***Figure 18*: Anomalous Sites: Vermont Sites$_{MinTemp}$ Compared to NEI$_{MinTemp}$** – Compares the minimum temperature for two sites in Vermont to the overall minimum temperature.

Creating the UNEI, FNEI, and NECI

To further analyze and test the robustness of the NEI, three additional climate indices were made using different criteria to determine which stations should be incorporated in that analysis. These climate indices were calculated using the same procedure as described above for the original NEI.

UNEI

The Less-Urban Northeast Climate Index (UNEI) is comprised of the stations used for the NEI, with the exclusion of stations located in heavily urbanized areas. The purpose of creating this index was to investigate the potential influence of urban heat island effect on the NEI. To determine whether a site was a heavily urbanized site, three primary criteria were assessed:

- the type of land surrounding the station,
- the human population of the place surrounding the station, and
- the proximity of the station to the largest cities in the NE.

To determine the topography surrounding the climate station, GoogleEarth was used to observe each site from an aerial view of approximately 25,000 feet from the ground. The basic location of the climate stations were known because the USHCN and NCDC made available the coordinates on their on their websites. (However, the two resources published slightly different coordinates for climate stations having the same identification number. If an urban setting did not surround the station, it was considered less-urban and used in the analysis. If the station appeared to have an urban setting, then it was put through another filter. *Figure 19* demonstrates the most common aerial views seen for the 137 climate stations: wilderness, rural, suburban, and heavily urbanized. These four examples are the best example of each classification. Consequently, not all of the sites fit perfectly into one of the four categories, but rather fell between two of the classifications.

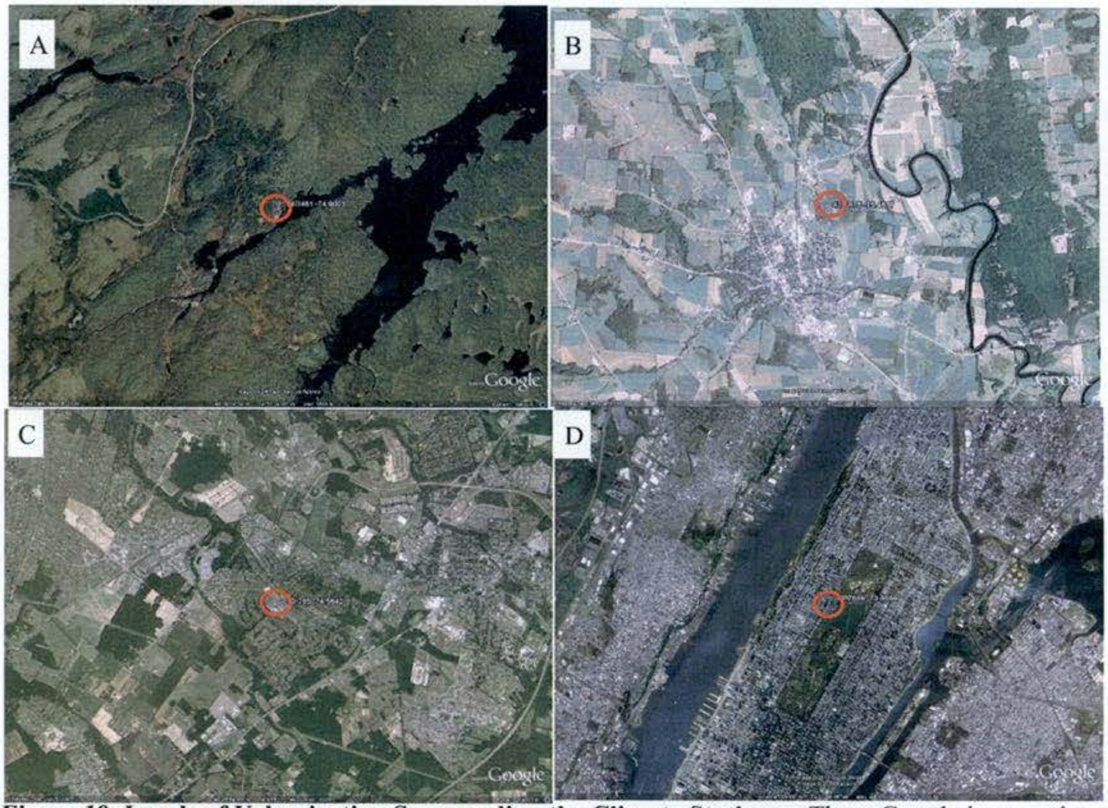

***Figure 19*: Levels of Urbanization Surrounding the Climate Stations** – These Google images show the aerial view from approximately 25,000 feet above the ground. Red ring indicates location of climate station. (A): site surrounded by only natural environment, (B): site located in a rural area, (C): site located in a suburban area, (D): site located in a heavily urbanized area.

If the site fell between the categories of suburban (c) or heavily urbanized (d), the population of the area was then researched. The population was found using the name giving to the station by the USHCN. If the climate station was located inside the city center and the population exceeded 70,000, then the station was considered heavily urbanized. For example, (c) on the figure above shows Hightstown, New Jersey, which has a population of about 5,500. In contrast, (d) on the figure above is New York City, which has a population of approximately 8.5 million.

Occasionally, the location of the climate station would be in a place that had less than 70,000 people, but surrounding that area was a large, continuous expanse of built environment. For example, *Figure 20* below represents the aerial view of Moorestown, NJ, which falls between the classifications of suburban and heavily urbanized. The population of Moorestown is approximately 65,000, but it is located only ten miles east of Philadelphia, which was ranked by the Census Bureau as one of the top ten largest cities in the United States in 2000.[76]

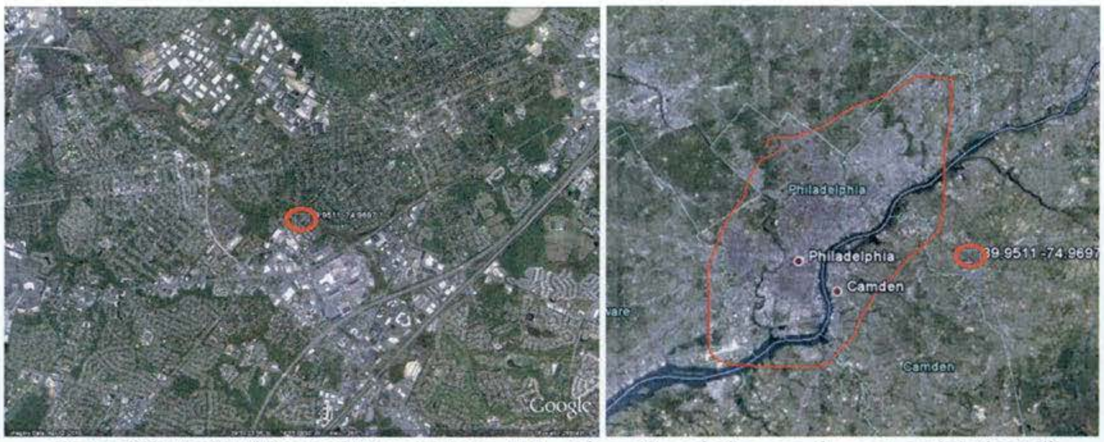

***Figure 20*: Aerial Views of Moorestown, NJ** – These Google images show an aerial view of Moorestown, NJ at approximately 5 miles above the ground (left) and approximately 60 miles above the ground (right). Philadelphia is thinly outlined in red, and a small, thick, red circle outlines the climate station.

Because of the size of Moorestown's population and its proximity to a large city center, this site was deemed heavily urbanized, thus not used in the analysis of the UNEI.

After evaluating all the climate stations in the Northeast, sixteen sites qualified as heavily urbanized sites and were excluded from the UNEI analysis for all four variables. The red highlighted stations in Figure 21 on the following page represents the sites excluded from the analysis based on the criteria described above.

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[76] Frank Hobbs and Nicole Stoops, *Demographic Trends in the 20th Cenury*, A-6.

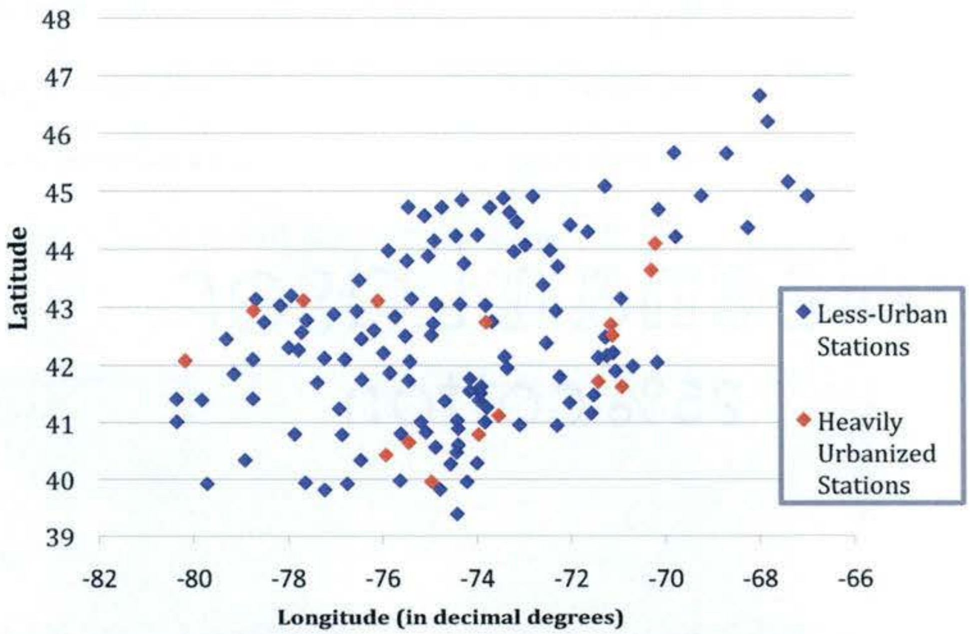

Figure 21: Stations Located in Heavily Urbanized Areas – This figure illustrates the spatial distribution of the climate stations. Red = stations omitted from the UNEI analysis due to their proximity to heavily urbanized areas.

FNEI

The Filtered Northeast Index (FNEI) was created to further test the robustness of climate indexing. The FNEI utilized information gained from the UNEI analysis and the site comparison to the NEI. This index is similar to the UNEI in that it excluded the sixteen sites classified as heavily urbanized. In addition, sites that were observed to be anomalous to the original $NEI_{Variable}$ during the site comparison procedure were also excluded from this analysis. An example of an anomalous site for minimum temperature can be seen in Figure 18 on page 34. In total, 26 of the 137 sites for maximum temperature, 24 of the 137 sites for minimum temperature, 34 of the 136 sites for precipitation, and 7 of the 49 sites for snowfall were omitted from this analysis.

NECI

The final climate index created in this study of the Northeast was the Northeast Coastal Climate Index (NECI). During the site comparisons to the NEI, it became evident that there may exist climatic sub-regions within the NE. The Northeast is said to have a multitude of microclimates although the entire region is broadly defined as having a moist continental climate regime. The NECI was the first step in exploring more closely the climates of sub-regions in the NE. The Appalachian Mountain Range cuts all the way through the NE, essentially dividing the region into two major geographic sections. This major geographical barrier lead to question of how the climate of the eastern sub-region of the Appalachians compared to the entire NE region. To address this question, the NECI was composed of climate stations located east of the Appalachians with an elevation no greater than 235 meters. *Figure 22* below illustrates the division made between the western and eastern half of the NE. The climate stations east of the red boundary line were used in the NECI analysis. Examining the eastern versus the western side of the Appalachian Mountains was of greater interest because a majority of the population in the Northeast lives along the seaboard.

***Figure 22*: Eastern Boundary of Appalachian: Sites Used in NECI** – The red line marks the eastern boarder of the Appalachian Mountain Range. All sites located to the right of this line are used in the NECI analysis. All sites to the left of the red line are NOT used in the NECI analysis.

Weight Machine

After creating the NEI, UNEI, FNEI, and NECI, weights were given to each variable to determine if the climate indices were influenced more by one variable than the others. The weighted generated data (WGD) for each index was compared to the original un-weighted indices. This comparison gave insight into how the four variables impact the NE climate indices. The weight machine helped assess which, if any, variable had the greatest influence on the shape of the line, in terms of amplitude. When making the weight machine, the weights of each variable had to sum to one. A variety of weights were applied to the climate indices as shown in the figure below:

	Parameter			
	MinTemp	**MaxTemp**	**Precip**	**Snowfall**
WMAX	0.25	0.25	0.25	0.25
WGD1	0.4	0.4	0.1	0.1
WGD2	0.3	0.3	0	0.4
WGD3	0.3	0.3	0.4	0
WGD4	0.01	0.01	0.97	0.01
WGD5	0.01	0.01	0.01	0.97
WGD6	0.45	0.45	0.05	0.05
WGD7	0.2	0.1	0.6	0.1
WGD8	0.5	0.5	0	0
WGD9	0.04	0.03	0.03	0.9
WGD10	0.49	0.49	0.01	0.01
WGD11	0.1	0.1	0.4	0.4
WGD12	0.97	0.01	0.01	0.01
WGD13	0.01	0.97	0.01	0.01

***Figure 23*: Weight Machine Values** – This figure details the weights given to each parameter to create the Weighted Generated Data (WGD) trials run through the Weight Machine.

RESULTS AND DISCUSSION

NORTHEAST CLIMATE INDICES COMPARED

The primary goal of this project was to create a climate index of the Northeast. To test the robustness of the NEI originally created, three additional indices were also produced: UNEI, FNEI, NECI. Although these four climate indices were based on different criteria for selecting the climate stations used in the analysis, very little differences can be observed in the indices. *Figure 24* below compares the $NEI_{combined}$, $UNEI_{combined}$, $FNEI_{combined}$, and $NECI_{combined}$ to each other:

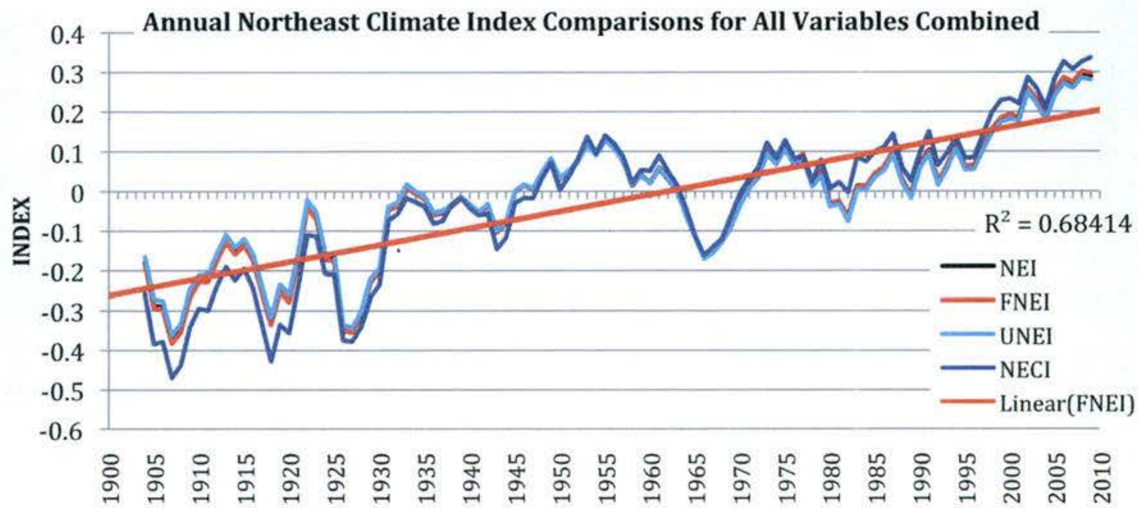

***Figure 24*: Annual Northeast Climate Index Comparisons for All Variables Combined** – Compares the annual NEI, UNEI, FNEI, and NECI when all four variables are combined (minimum and maximum temperature, precipitation, and snowfall).

The four climate indices have congruent waveforms and have almost perfectly corresponding amplitudes throughout the past century. The NEI, FNEI, and UNEI are statistically similar, with differences in the values of each year being only tenths or hundredths away from each other. However, of these three indices, the FNEI, has an amplitude slightly greater than the NEI, and the NEI has an amplitude slightly greater than the UNEI.

The UNEI suggests that urban heat island effect has little impact on the accuracy of climate analyses in the NE because it is statistically similar to the NEI. This result parallels the scientific opinion of the USHCN, which states that the "impact of urbanization and other changes in land use is likely small" in USHCN version 2 data because the "change-point detection algorithm" for version 2 data "accounts for any 'local' trend at any individual station".[77] The minor effect of urbanization on the regional climate measurements is encouraging because the population density of the Northeast, particularly along the eastern seaboard, makes it challenging to have climate stations in the NE located solely in rural areas and small towns. After observing the aerial view of the climate stations, it seems common for the climate stations to be situated near or amongst moderately sized expanses of suburban sprawl, rather than isolated wilderness areas.

In future climate studies of the NE, it would be interesting to employ a more stringent definition of heavily urban stations or to broaden the exclusion of sites to also omit moderately urbanized stations. However, the level of urbanization should not be thought as mutually exclusive with urban heat island effect and its potential to influence climate measurements. Some of the largest urban centers in the NE have been urbanized for longer than the period of record used in this analysis. For example, in 1900 Manhattan had a population of 1,850,093 compared to the 1990 population of 1,487,536.[78] If urban heat island effect does impact that site, it has likely done so for the length of this study. This suggests that any shift in climate trends for that site has a cause other than urbanization.

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[77] Menne et al., *USHCN*, http://cdiac.ornl.gov/epubs/ndp/ushcn/monthly_doc.html.
[78] Campbell Gibson, *Population of the…*,
http://www.census.gov/population/www/documentation/twps0027/twps0027.html.

The NECI varies from the other three indices the most because of the larger range of amplitude, as seen on the figure above. This result suggests that the NE does have climatic sub-regions within the larger NE region. From observing individual waveforms of the climate stations during the site-NEI comparison procedure, a few sub-regional patterns emerged. For example, sites off the coast of the Atlantic Ocean seem to have increased amplitudes in temperature from the NEI, while sites in western New York have waveform patterns similar to each other, but do not coincide as precisely with the NEI.

Although initial results from the NECI and singular site observations indicate that the NE does have climatic sub-regions, these sub-regions are not dissimilar enough to cause a complete reconstruction of the defined NE region. For instance, in Harvey Roger's study of the PNI, the analysis originally incorporated all of Washington and Oregon, but as the research progressed, it became apparent (as expected) that the region west of the Cascade Range differed greatly from the eastern region.[79] The climate in the Pacific Northwest (PNW) is well documented as having different climate signatures for western and eastern Washington and Oregon, primarily due to the rain shadow effect of the Cascades. Consequently, the PNW is generally defined as the region west of the Cascades in Oregon and Washington. Although this clear climate distinction does not appear as strongly in the NE from the western and eastern sides of the Appalachians or from the northern to southern latitudes, it would still be relevant to research more closely the climatic sub-regions of the NE. These sub-regions could be determined by geographical criteria, such as elevation, longitude, latitude, proximity to lakes and ocean, etc.

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[79] Harvey Rogers, "Assessing the robustness…," 39.

To further explore the similarities and differences of the composite climate indices, each variable was directly compared to one another. The next few figures compare the maximum and minimum temperature, precipitation, and snowfall indices:

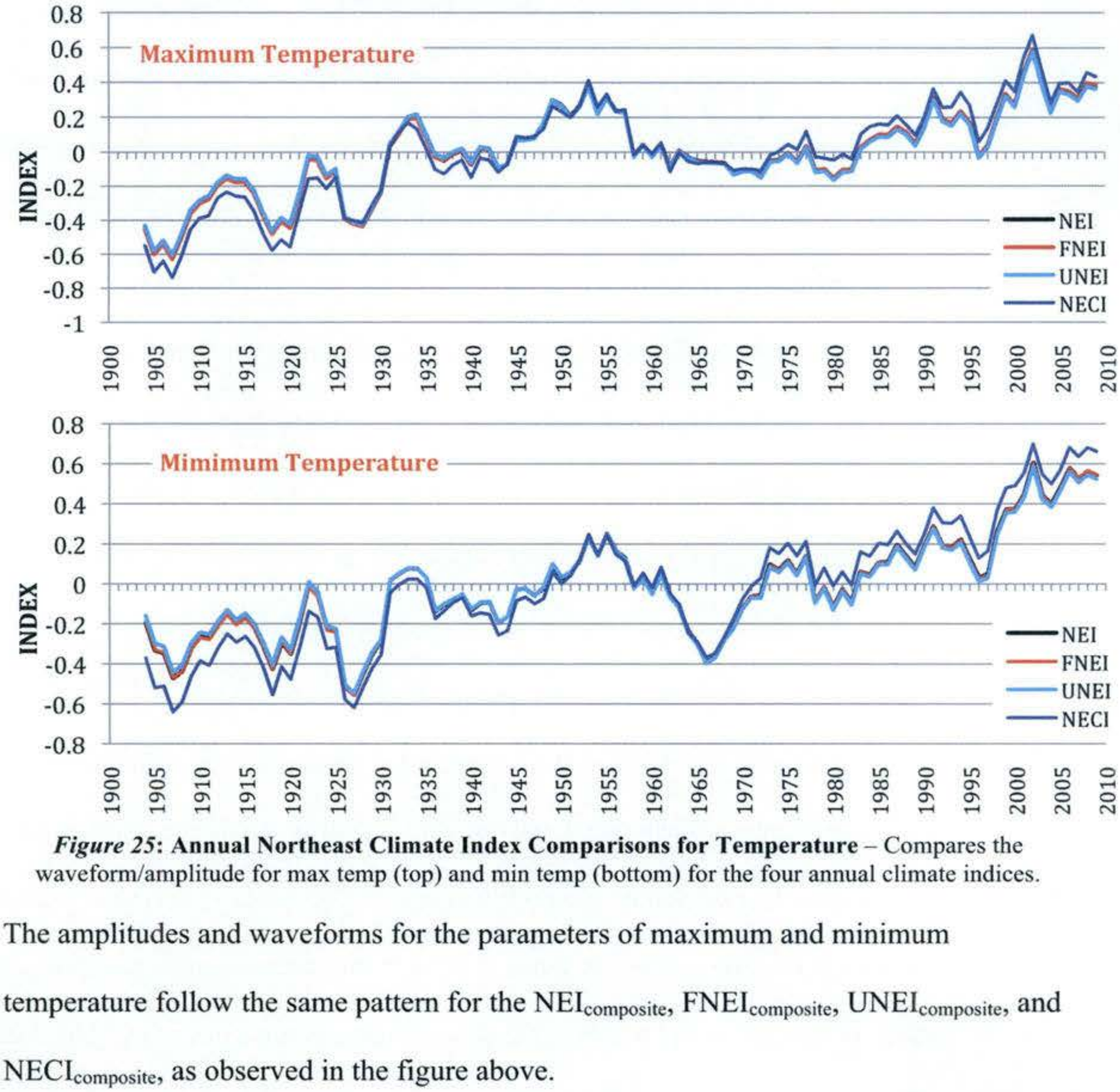

***Figure 25*: Annual Northeast Climate Index Comparisons for Temperature** – Compares the waveform/amplitude for max temp (top) and min temp (bottom) for the four annual climate indices.

The amplitudes and waveforms for the parameters of maximum and minimum temperature follow the same pattern for the $NEI_{composite}$, $FNEI_{composite}$, $UNEI_{composite}$, and $NECI_{composite}$, as observed in the figure above.

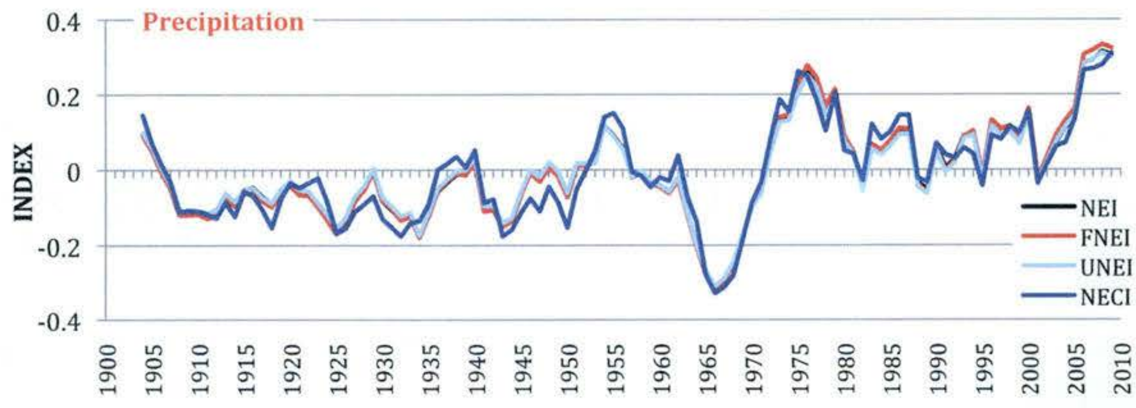

***Figure 26*: Annual Northeast Climate Index Comparisons for Precipitation** – Compares the waveform and amplitude of precipitation for the four annual climate indices.

The climate indices for precipitation shown above all have essentially the same amplitudes, unlike the composite indices (*Fig. 24*). The NECI has basically the same amplitude as the NEI, FNEI, and UNEI rather than having a greater amplitude as seen in the composite figure. Although the amplitude better matches all four indices, the waveforms do not compare as well as the composite or temperature indices. The slight waveform difference of the NECI from the other indices can be primarily seen in the figure above at years 1920, 1935, 1995, and 2010. Precipitation is possibly more variable than temperature across the Northeast due to a greater number of influencing climate controls, such as prevailing air masses, prevailing wind and ocean currents.[80]

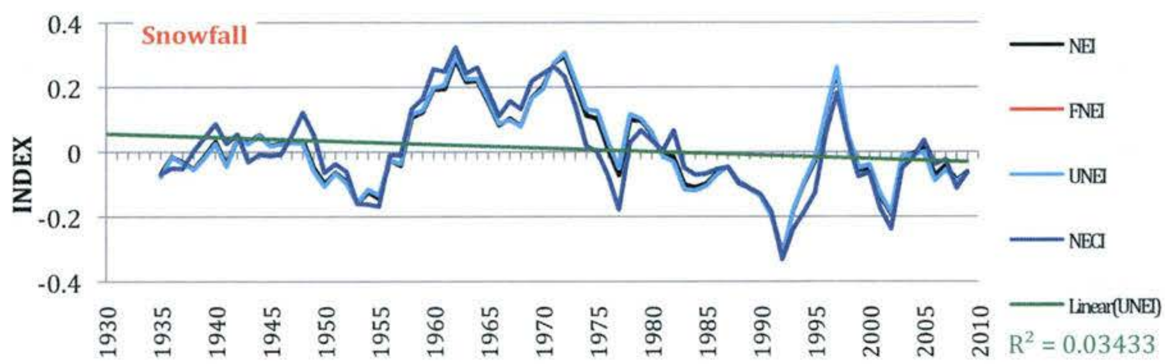

***Figure 27*: Annual Northeast Climate Index Comparisons for Snowfall** – Compares the waveform and amplitude of snowfall for the four annual climate indices.

[80] Bruce Anderson and Alan Strahler, *Visualizing Weather and Climate*, 300.

The snowfall indices (shown on the previous page in *Figure 27*) have the least matching amplitudes and waveform of all four parameters. Please note that the FNEI cannot be identified in the above figure because it has an identical waveform and amplitude as the UNEI. The snowfall data for the FNEI and UNEI analysis was identical so both indices should be the same. The snowfall indices vary most in waveform as compared to the other three parameters. The most likely cause of this stems from the much smaller sample size of the snowfall data as compared to temperature and precipitation, as well as, the less complete dataset as compared to temperature and precipitation.

PARAMETER COMPARISONS PER ANNUAL & SEASONAL TIME FRAMES

The figures referenced for this section will come from the FNEI climate analysis. Because the NEI, FNEI, UNEI, and NECI resulted in very similar waveforms and amplitudes for the composite and individual parameters, it should be assumed that figures depicting the FNEI are also representative of the other indices. The four NE climate indices were analyzed seasonally, as well as annually, in attempts to better understand the region's climate trends. Are the trends observed in the annual climate analysis also observed in four-month seasons or is one season influencing the annual results more than another?

It is also important to note that years with positive index values are warmer and wetter than average, while years with negative index values are colder and drier than average. This contrasts the PNI, which has positive values representing warmer/drier phases and negative values representing the opposite. The reason for departing from the PNI methodology arose from the nature of the Northeast climate trends. The scientists who created the PNI developed their climate index to have temperature the inverse of precipitation and snow because low temperature in the PNW "corresponds to high precipitation and snow".[81] In other words, the PNW receives the most precipitation and snow during winter months and little precipitation and no snow during the summer. The NE contrasts the PNW in this way because the NE receives higher amounts of precipitation during the summer, while low temperatures still corresponds to high snowfall. Because the relationship between temperature and precipitation in the NE is opposite from the PNW, I chose to depart from the PNI methodology by not reversing the sign of the temperature *Z-scores*. This is why positive values equate to warmer and wetter rather than warmer and drier as seen in the PNI.

Also, unlike the climate analysis on the PNW by Dr. Bothun and Stephanie Ostrander, which mainly focuses on the composite climate index of the PNW, I have given more emphasis to the signatures of each parameter, in addition to the composite index. The primary reason for this relates to the contrasting correlations between temperature and precipitation and temperature and snowfall. Because the trends of precipitation and snowfall do not parallel one another, each signature is subsequently suppressed in the composite index. For example, *Figure 28* on the following page illustrates the impact of snowfall on the amplitude of the composite FNEI.

[81] University of Washington, *Columbia River Dart Data Access in Real Time*, http://www.cbr.washington.edu/data/pni.html.

Figure 28: $FNEI_{Composite}$ Compared to $FNEI_{NoSnow}$ (Annual) – Compares the NE climate index when averaging together all four parameters (minimum and maximum temperature, precipitation, and snowfall) and when snowfall is excluded from the composite climate index.

The FNEI with snowfall and the FNEI without snowfall have identical climate signatures until 1929 because the snowfall data in this analysis does not start until 1930. Once snowfall starts being averaged into the composite FNEI, it reduces the overall amplitude of the index due to the inverse waveform of snowfall from the other three parameters. Because of this, it is important to independently review the indices of each parameter in addition to studying the composite index.

Annual

The annual $FNEI_{composite}$ and individual parameter climate signatures are depicted in *Figure 29* on the following page:

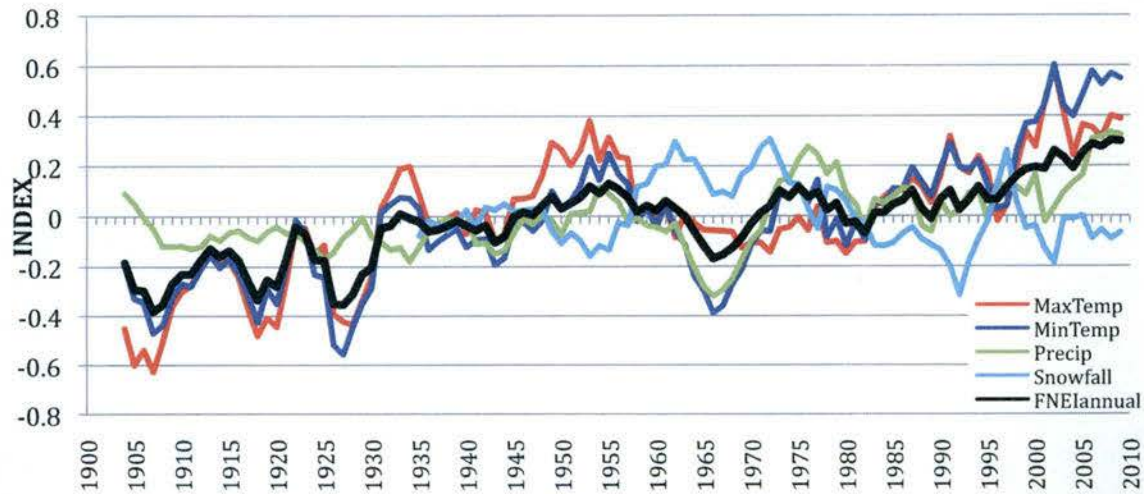

Figure 29**: Annual FNEI** – Illustrates the annual climate signatures of the composite FNEI (black), maximum temp (red), minimum temp (dark blue), precipitation (green), and snowfall (light blue).

In a brief summary, the NE seems to be experiencing more periods of warmer than average maximum and minimum temperature, more periods of increased amounts of precipitation, and more periods of reduced snowfall as compared to the length of the analysis from 1900-2009. In this section, the composite index and individual parameters of temperature and precipitation will be more closely examined, while snowfall will be discussed in more detail in the Winter Section.

The annual composite climate index suggests that the NE has been consistently in a period of warmer/wetter since the mid-1980s, which has not been observed in terms of the length of the period (25 years) over the past century, as seen in *Figure 30*.

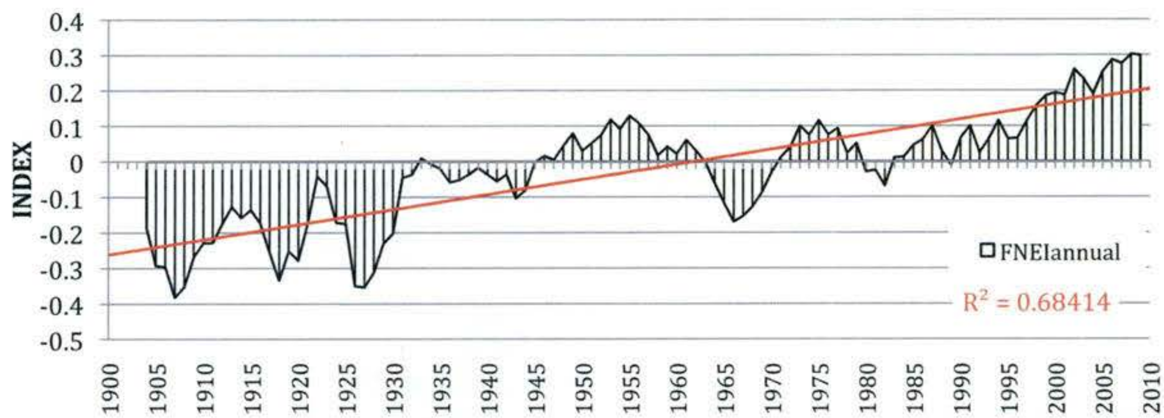

Figure 30**: FNEI$_{\text{Annual Composite}}$**

Also, the continued overall increase in amplitude over that 25-year time frame cannot be observed elsewhere on the period of record. In contrast to the present, the first 33 years of the 20th century were dominated by a strong period of cooler/drier than average climate. A question that arises from this is whether or not the current period of warm/dry is just a part of the historical cyclic pattern of the NE climate? However, one very important difference exists between the two periods: the 1900-1933 period, although entirely below the baseline, has a very different waveform than the 1985-2010 period. The 1900-1933 period has within it three major amplitude fluctuations that range from approximately -.35 deviations to about -0.1 deviations. This strong rise and fall in amplitude is not present in the 1985-2010 period. The difference between the waveforms of the two periods raises the question of how the index would be altered if the normal climate were defined as the average of 1900-1985 data versus the entire period of record? How much would this change the calculation of the FNEI to amplify the most current period of warmer/wetter? And, how much would the 1900-1933 waveform shift upwards? Would it shift up enough to raise parts of the period above the baseline? Although this index raises a number of questions, the take home message is that there is a clear trend of increasing temperature and precipitation over the past century.

The indices of maximum temperature and minimum temperature look very similar to the composite FNEI, thus the same questions from the composite index apply. The amplitude of annual temperature is consistently greater (above and below the baseline) than the $FNEI_{composite}$, except for maximum temperature during the time range from 1963-1977. Additionally, the maximum and minimum temperatures have very similar waveforms to one another with the greatest discrepancy between the two occurring from the early 1960s to late 1970s.

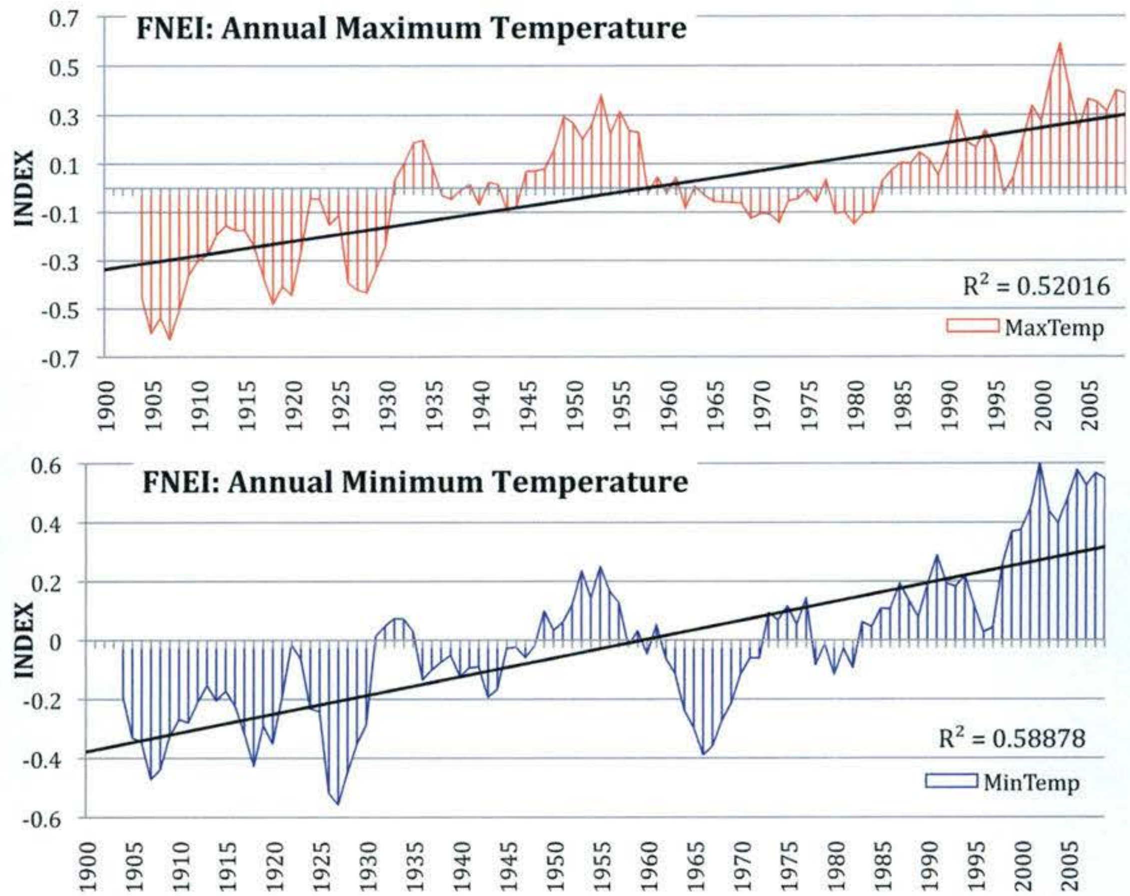

***Figure 31*:** **FNEI** $_{\text{Annual Temperature}}$ – Illustrates the climate signature of annual maximum temperature (top) and annual minimum temperature (bottom) since 1900. The linear regression of the minimum and maximum temperature are shown in black.

The annual precipitation signature follows the same increasing trend and basic waveform as minimum temperature. A major difference between precipitation and temperature is that the precipitation amplitudes are much lower than temperature, which suggests that there is less precipitation variability than temperature variability within the Northeast. However, attention must be given to the largest amplitudes on the annual precipitation index (observed at years 1965, 1975, and 2009). Interestingly, the largest negative amplitude occurring in 1965 corresponds to a well-documented fact that 1962-

1965 was dominated by the worst drought to have occurred in the Northeast since before the beginning of the 20th century.[82] The amplitude of this mid-1960s severe drought is only observable two other times in the period of record. Both of these other times occur after 1970 and have a positive sign (wetter than average), unlike the 1965 drought amplitude of -0.3. Furthermore, the precipitation index strongly indicates that the NE has been experiencing an extended period of higher than average precipitation since 1970 because the waveform barely dips below the baseline during that time. However, in contrast to the past few decades, the time frame from 1900 until 1970 only has a couple periods above the baseline (i.e. 1955). This seventy-year period of primarily drier than average climate has maximum amplitudes of -0.15 (excluding the anomalous drought event that occurred during the 1960s, which has an amplitude of -0.3). The climate change signal for annual precipitation in the Northeastern United States is quite strong as seen on the figure below.

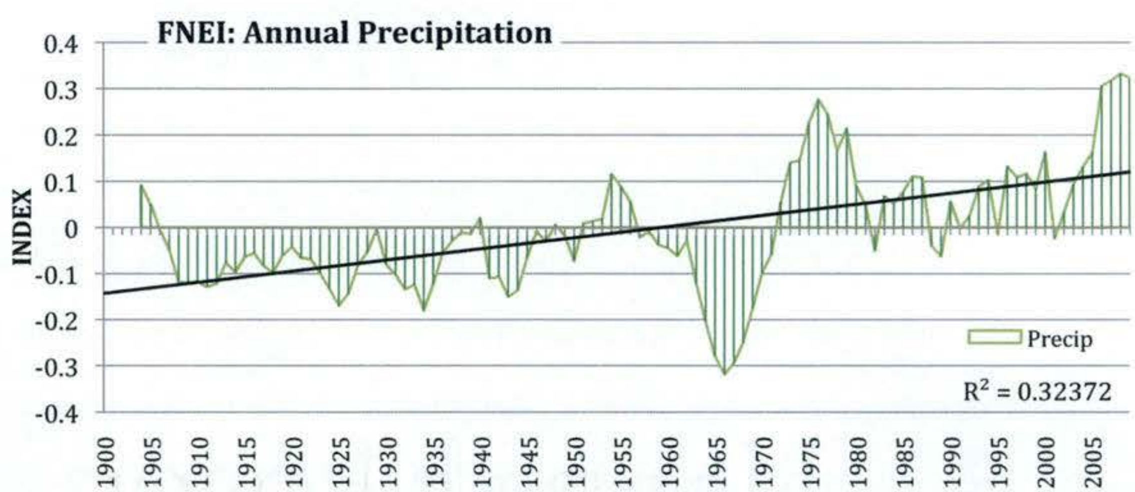

***Figure 32*:** **$FNEI_{Annual\ Precipitation}$** – Illustrates the annual precipitation climate signature from 1900-2009. The linear regression of the precipitation index is shown in black.

[82] Hayhoe, et al., "Past and future changes…," 16.

Winter

While the waveform of the winter composite index follows the basic waveform of the annual composite index, the amplitude ranges of the winter composite, winter temperature and winter precipitation are greater than those of the annual index. The winter minimum and maximum temperatures have climate signatures very similar to one another throughout the entire period of record, with the greatest divergence from one another occurring in 1970.

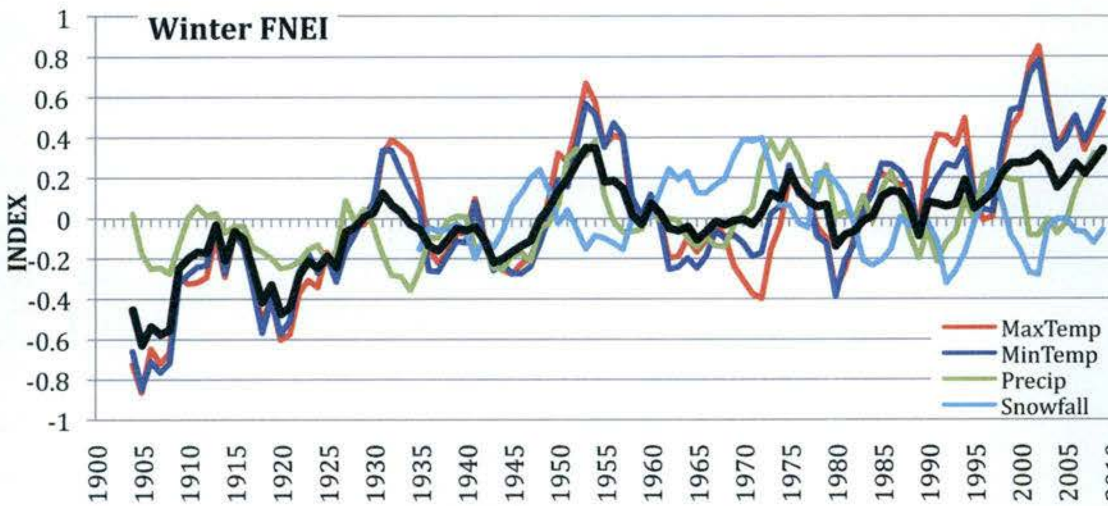

***Figure 33*: Winter FNEI** – Illustrates the winter climate signatures of the composite FNEI (black), maximum temp (red), minimum temp (dark blue), precipitation (green), and snowfall (light blue).

The winter composite, like that of the other seasons analyzed, indicates a shift in climate to a warmer and wetter state. The winter climate since 1950 has been primarily been above the baseline, while prior to then, a majority of the waveform is below the baseline. Because snowfall has an inverse index as temperature and precipitation (i.e. as temperature increases, snowfall decreases), the signature of snowfall becomes washed out in the FNEI, while also reducing the composite amplitude of the FNEI.

To better investigate the long-term trend of snowfall, it must be graphed independently of the other parameters. Winter shows the strongest signal of a shift in the pattern of snowfall since 1930. As *Figure 34* below illustrates, snowfall from 1930 until approximately 1985 fluctuates between seven to twelve year periods of drier than average states to wetter than average states. However, since the start of the dry period in 1980, the snowfall index has remained almost entirely below the baseline, except for a few year-period above the baseline starting in 1995. This means that approximately twenty-five of the past thirty years (83% of years) have received less snowfall than the average from 1930-2009. In comparison, the time frame from 1930 to 1985 had approximately only 25 years below the baseline (drier), which is only 45% of the time. This marks a substantial divergence in trend from the beginning of the data record.

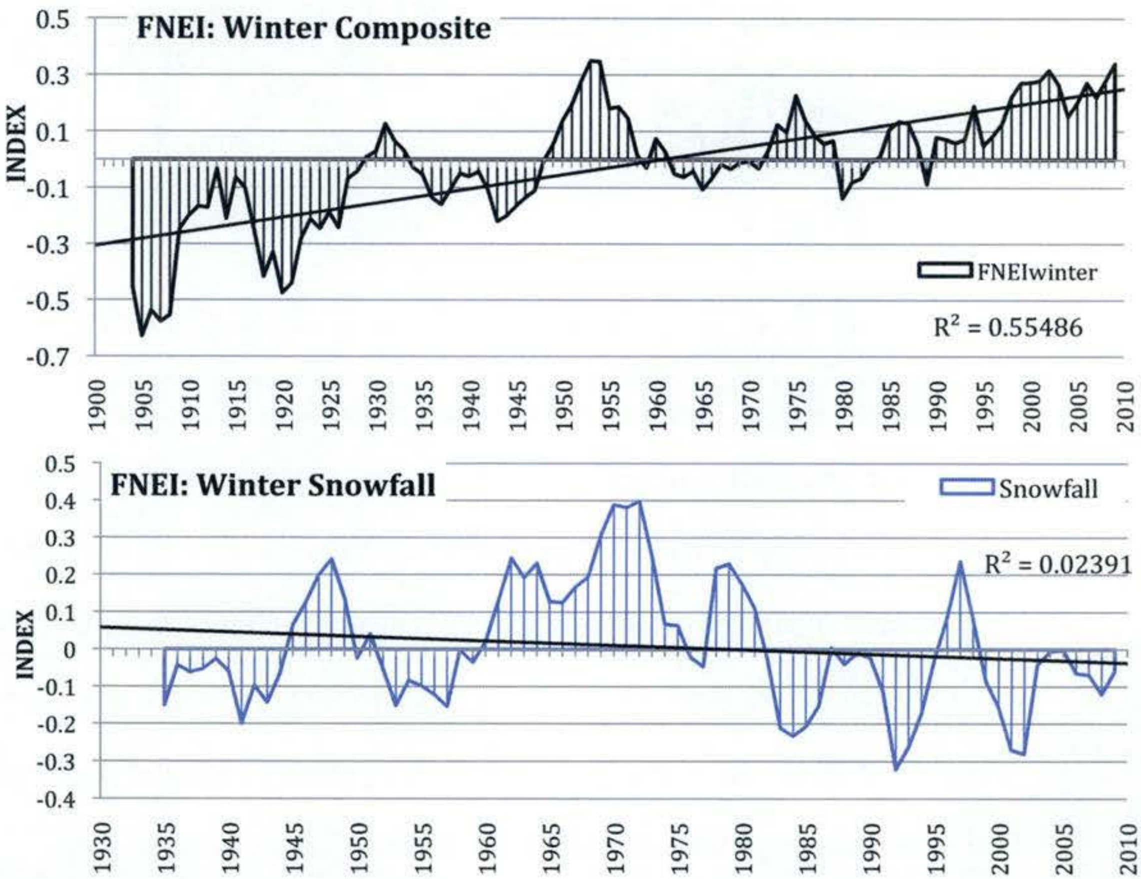

***Figure 34*: FNEI$_{\text{Winter Composite}}$ and FNEI$_{\text{Winter Snowfall}}$** – Depicts the winter climate signatures of the FNEI$_{\text{composite}}$ (top) and FNEI$_{\text{snowfall}}$ (bottom). The linear regression line for each index is shown in black.

Spring

The most interesting element of the spring analysis is the $FNEI_{composite}$. It fluctuates from negative to positive phases from the beginning of the record until approximately 1973, with large negative amplitudes during the first thirty years. An important aspect, as observable in the other seasonal indices, is the astounding lack of cold/dry periods after 1973. For the past thirty-seven years, the composite climate signature has only once barely dropped below the baseline in about 1982. This large extent of a warmer/wetter period had not been observed prior to this in the data records, nor had there been a colder/drier period in the past century that matches the longevity of the current period. The spring composite index once again shows an increasing trend.

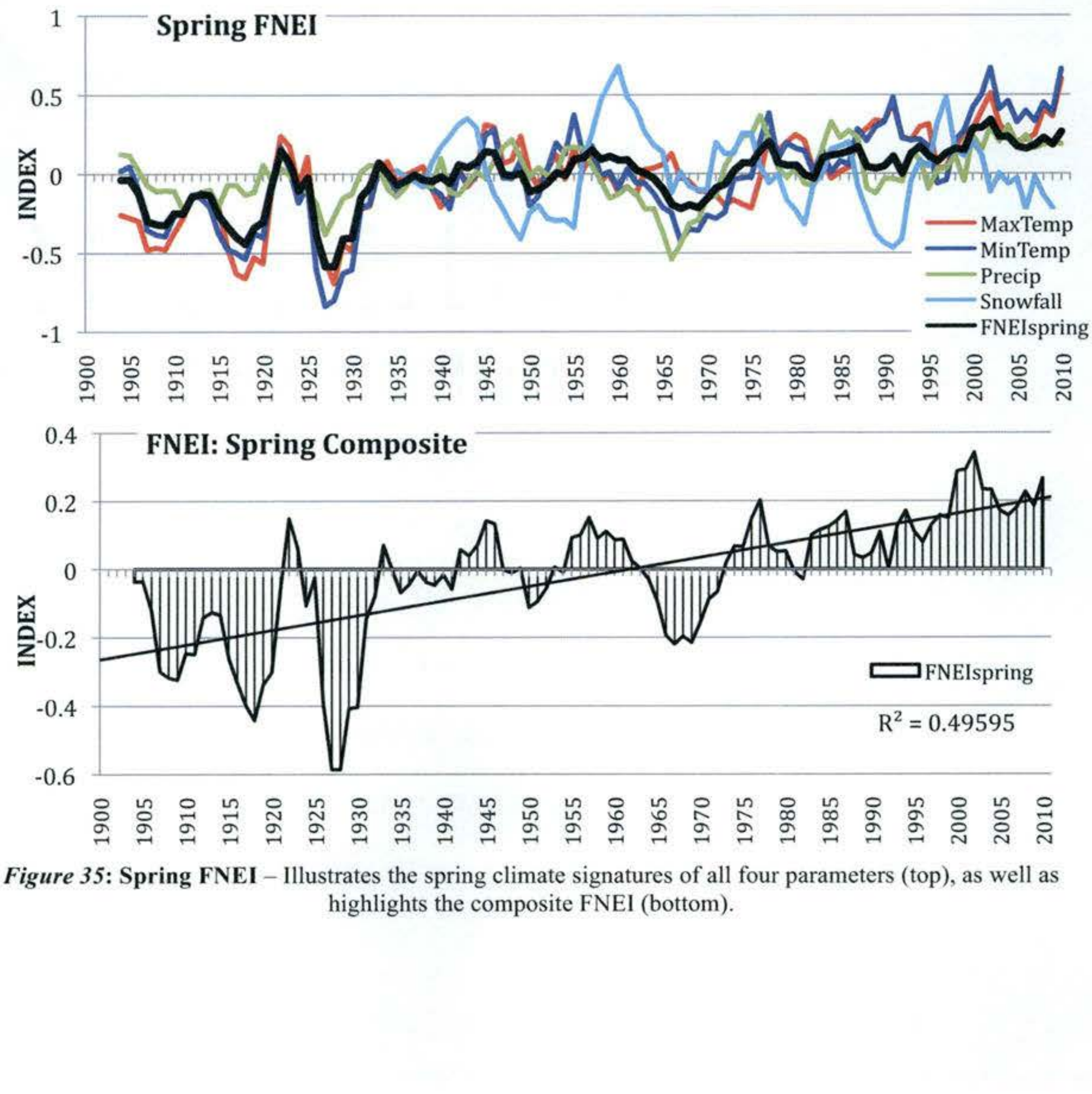

***Figure 35*: Spring FNEI** – Illustrates the spring climate signatures of all four parameters (top), as well as highlights the composite FNEI (bottom).

Summer

The summer season has a very intriguing climate index for $FNEI_{composite}$, $FNEI_{mintemp}$, and $FNEI_{precip}$ because these summer indices strongly signal that a climate shift has occurred in the Northeast over the past century. Once again, this seasonal index also shows an increasing trend of temperature and precipitation over the period of record. (Please note that the summer climate index does not include snowfall because snowfall during summer months is essentially nonexistent for July, August, and September and negligible for October.)

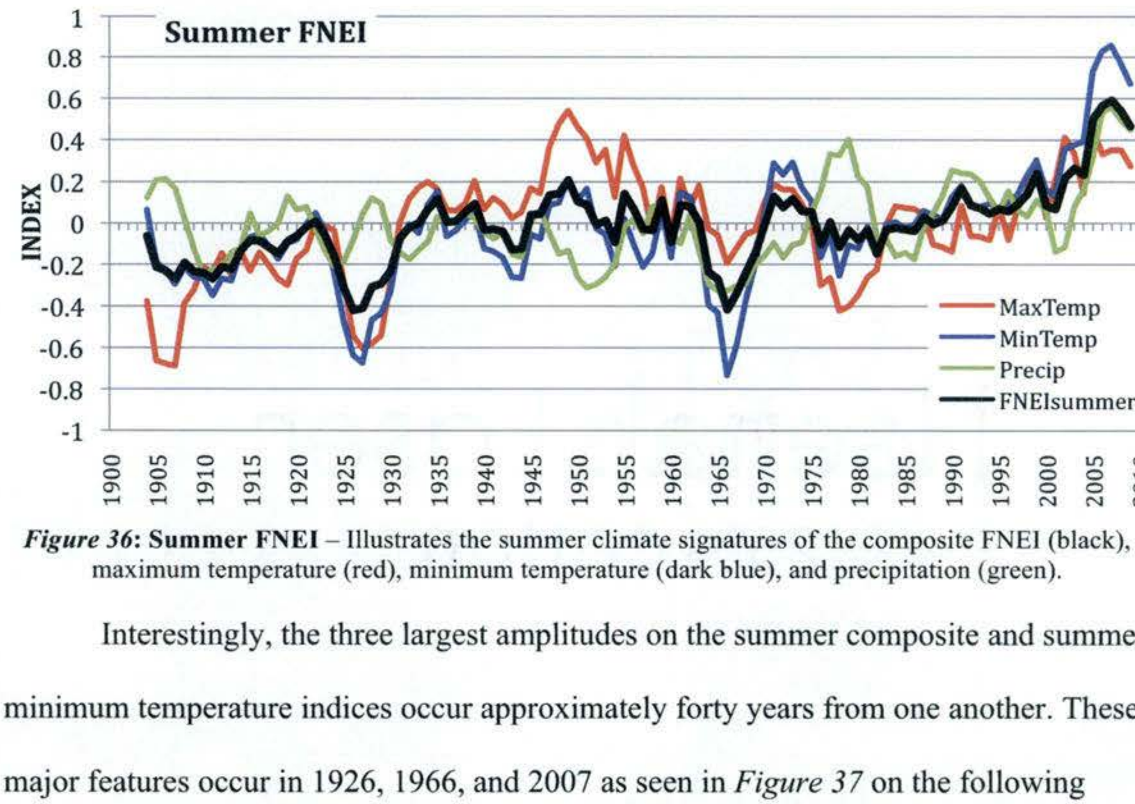

***Figure 36*: Summer FNEI** – Illustrates the summer climate signatures of the composite FNEI (black), maximum temperature (red), minimum temperature (dark blue), and precipitation (green).

Interestingly, the three largest amplitudes on the summer composite and summer minimum temperature indices occur approximately forty years from one another. These major features occur in 1926, 1966, and 2007 as seen in *Figure 37* on the following page. The significant difference between these features is the sign and amplitude of the 2007 feature. The 1926 and 1966 features have an amplitude of about negative 0.4, where as, the 2007 feature has an inverse amplitude of positive 0.6. A wet period of this magnitude is not observable elsewhere over the period of record. In addition, the multi-decadal cycle of the index suggests that the mid-2000s should have experienced another pronounced phase of cold/ dry, but quite the opposite happened. Furthermore, when looking at the composite index, the mid-2000s mark the highest absolute value amplitude over the period of record by approximately 0.2 deviations.

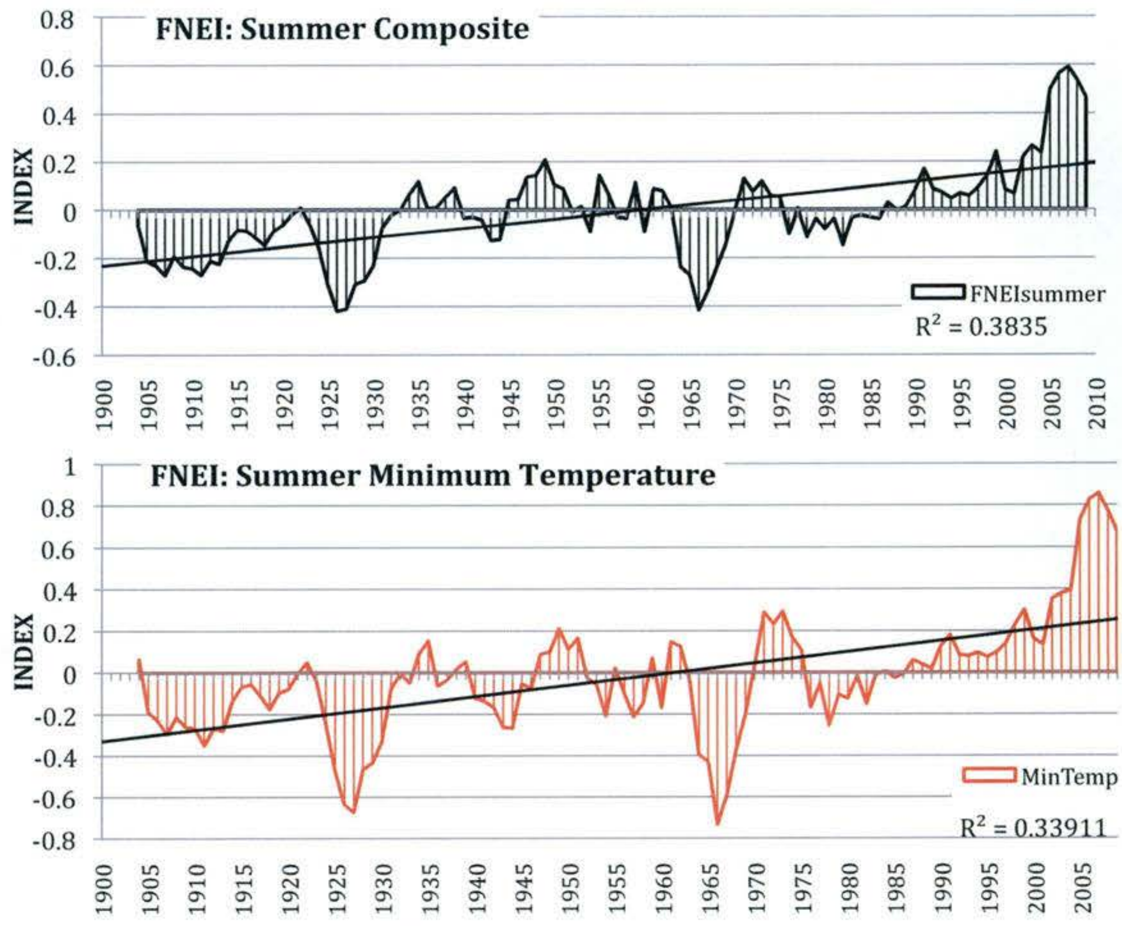

Figure 37**:** **$FNEI_{Summer\ Composite}$ and $FNEI_{Summer\ Minimum\ Temp}$** – Depicts the summer climate signatures of the $FNEI_{composite}$ (top) and $FNEI_{mintemp}$ (bottom). The linear regression line of the index is shown in black.

The summer climate signature for precipitation follows a general waveform from 1900 until 1975 that fluctuations between wet and dry states with a majority of the years falling into drier than average periods. This waveform shifts, however, from approximately 1975 until present. As seen in *Figure 38*, the past thirty-five year span is characterized by the majority of the years having periods above the baseline with only two minor dips below the baseline occurring in 1985 and 2000. The $FNEI_{precip}$ index strongly signals that the past thirty-five years have been dominated by notable periods of wetter than normal states as compared to the past century.

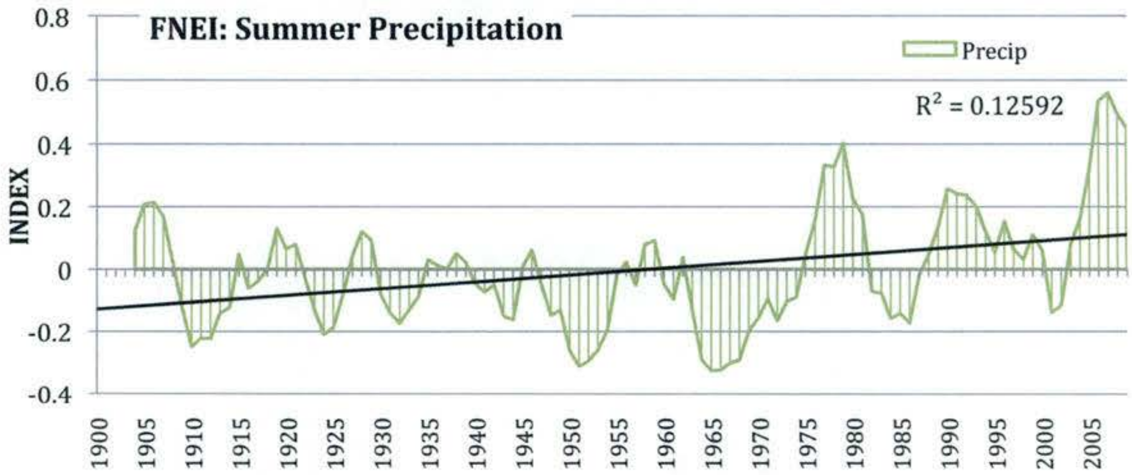

Figure 38**:** $\mathbf{FNEI_{Summer\ Precipitation}}$ – Depicts the summer climate signature of $FNEI_{precip}$. The linear regression line of this index is shown in black.

WEIGHT MACHINE

The purpose of running the composite FNEI through a weight machine was to determine whether one of the parameters analyzed was the primary driver of the index or whether maximum and minimum temperature, precipitation, and snowfall were equally weighted. The results of the Weighted Generated Data (WGD) are shown in *Figure 39* on the following page. The detailed description of the parameter weights given to each WGD# can be referenced on page 40 in *Figure 23*.

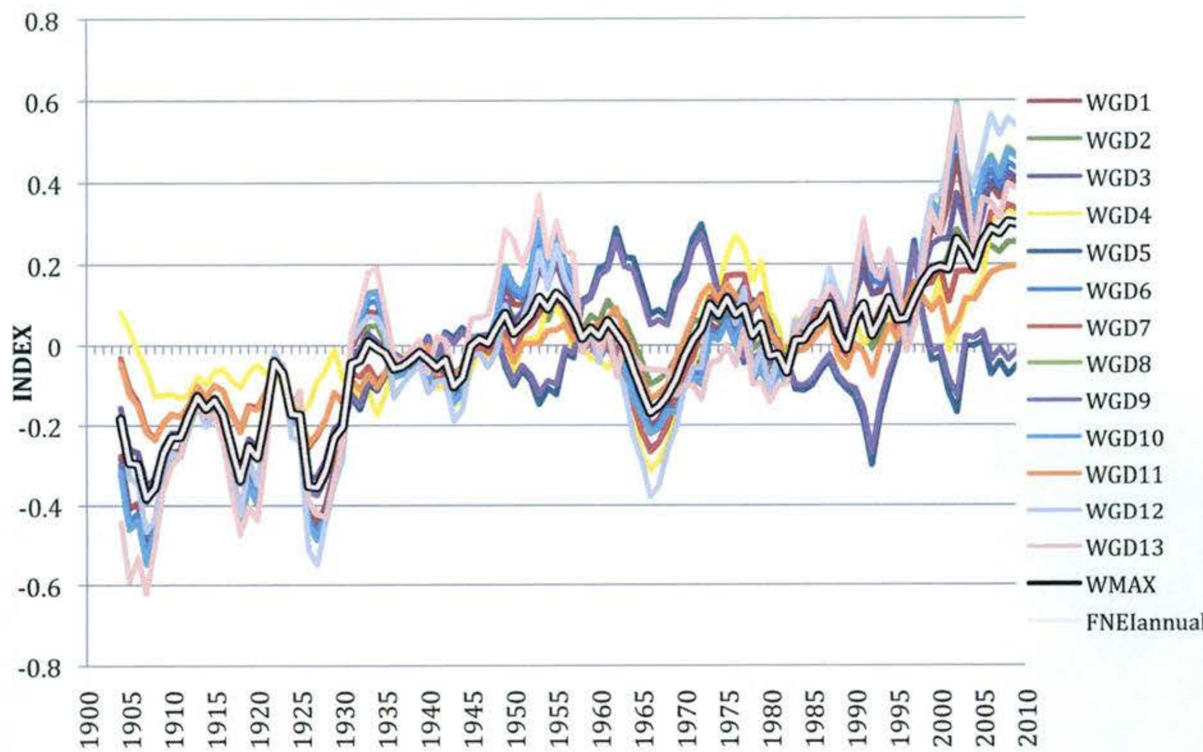

***Figure 39*: Weighted Generated Data for $FNEI_{Annual}$** – Depicts the results from the Weight Machine. The original NE index is shown in grey and the equally weighted variables shown in black (WMAX). The WGD# represents different trials of various weights given to the data.

The positive peaks with the highest amplitude in the early-1930s, mid-1940s to mid-1950s, and late-1980s through 2000s are driven by temperature, primarily maximum temperature. The negative peaks with the highest amplitude in the early 20th century and late teens are also primarily driven by maximum temperature. Minimum temperature drives the negative peaks with the highest amplitude in the mid to late 1920s and the mid-1960s. However, precipitation is also an influential factor in the large amplitude of the mid-1960s negative peak, most likely due to the record-breaking drought during that time. WGD5 and WGD9 (purple and dark blue lines) are heavily weighted toward snowfall, which explains their anomalous waveforms to the rest of the indices.

The Weight Machine analysis of the NE climate indices suggests that the NE and PNW are primarily influenced by different climate parameters. Research done by Dr. Bothun and Stephanie Ostrander indicate that the Pacific Northwest climate indices are most affected by snowfall.[83] In contrast, the FNEI is most sensitive to minimum and maximum temperature. In the Weight Machine analysis the waveforms of indices heavily weighted toward snowfall are misleading because of the inverse relationship it has with precipitation. To better understand the influence of snowfall on the composite index, the $FNEI^P$ is put through the Weight Machine, which reverses the sign of snowfall and precipitation *Z-scores*. This makes the indices heavily weighted toward precipitation (WGD4 and WGD11), rather than snowfall, have the most anomalous waveforms from the un-weighted $FNEI^P$. The results still suggest that minimum and maximum temperature are still the most influential parameters to the composite index.

NORTHEAST CLIMATE INDEX COMPARED TO PNW CLIMATE IDEX

To compare the FNEI to the SHI (updated and improved version of the PNI), the original assumption was to just convert the FNEI to match the SHI. As discussed previously, positive values on the SHI represent years that are warmer and drier than normal, while negative years are colder and wetter than normal. In theory, to make the FNEI compatible with the SHI, the *Z-scores* of precipitation and snowfall are multiplied by negative one, which reverses the signs. This alters the NE index to match the SHI by changing the meaning of the FNEI index values. Positive values change from warmer/wetter to warmer/drier, while negative values change from colder/drier to colder/wetter. For example, on *Figure 40*, the climate signature for precipitation is

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[83] Professor Gregory Bothun.

graphed to match the SHI. The resulting waveforms are simply the inverse of one another, except that the implication of the positive and negative values has changed. When the $FNEI_{precip}$ climate signature has positive values, the climate is wetter than average, while negative values represent drier than average years. In contrast, the $FNEI^{P}_{precip}$, which matches the SHI, means drier than average will be above the baseline and wetter than average below the baseline. Both climate signatures, as they should, suggest the same increasing trend of precipitation in the Northeast. The length and amplitude of this recent wet phase has not been observed in the first seven decades of the 20th century.

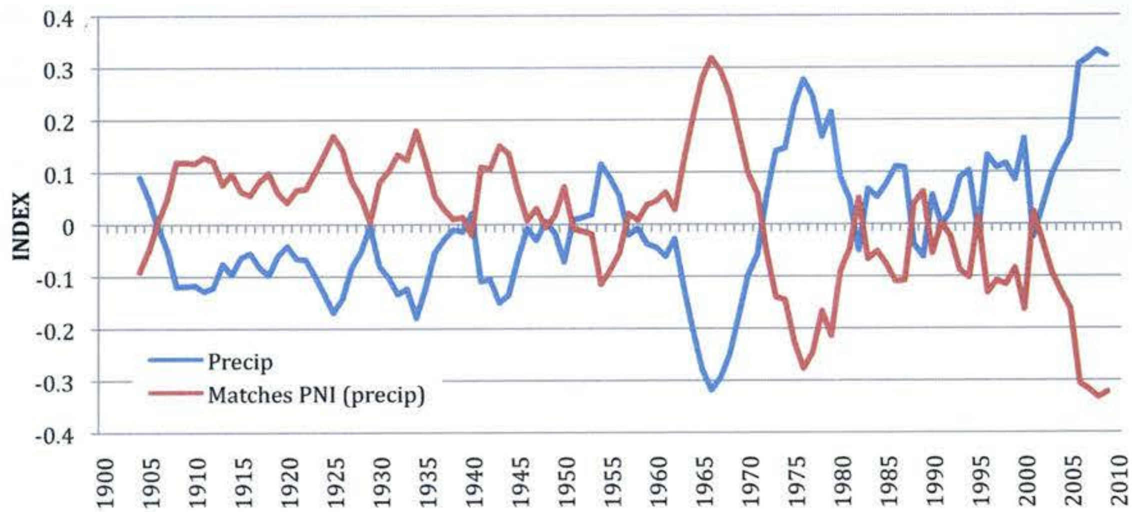

***Figure 40*: $\mathbf{FNEI_{Precip}}$ Compared to $\mathbf{FNEI^{P}_{Precip}}$** – Illustrates the difference between the original precipitation and the precipitation made to match the PNI. Blue line represents original, where positive values means wetter than normal. In contrast, the negative values on the red line, which matches the PNI, means wetter than normal.

Although this methodology of matching the PNI does work with the individual indexes of temperature, snowfall, and precipitation, the composite FNEI that matches the PNI ($FNEI^{P}$) is visually misleading. On the following page, *Figure 41* illustrates the differences in the FNEI and the new index that matches the SHI ($FNEI^{P}$):

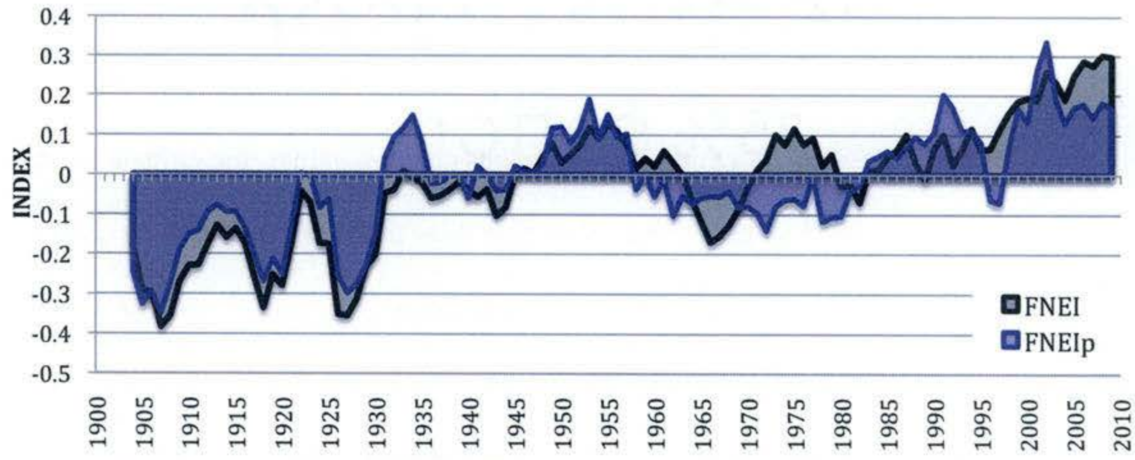

***Figure 41*: FNEI$_{Composite}$ Compared to FNEI$^{P}_{Composite}$** – Compares the NE climate indices when positive values equal warm/wet (FNEI) or warm/dry (FNEI^{P}) and when negative values are cold/dry (FNEI) or cold/wet (FNEI^{P}).

If only the composite FNEI^{P} were taken into consideration, one would conclude that in the 2000's the Northeast experienced a period of warmer and drier than normal because the climate signature is above the baseline. However, from looking at the climate signature of precipitation on the previous page, we know that the 2000's actually mark one of two wettest periods (in terms of rain) since the beginning of the data record in 1900. This trend, however, is being washed out primarily by the strength of the temperature amplitudes. It should be noted that the 2000's are also marked by less than average amounts of snowfall, but this dry signal is not strong as the wet signal given by precipitation. This uncorrelated cycle between snowfall and precipitation in the Northeast makes the composite FNEI not as directly informative as the SHI. The moisture trends of precipitation and snowfall are suppressed by one another so it becomes important to analyze the individual parameter's climate signatures as well as the composite.

Because of the problems associated with illustrating the composite FNEI^{P}, it does not make sense to directly compare the FNEI^{P} to the SHI, which was the purpose of making the FNEI match the PNI in the first place. Due to the complications mentioned above, an indirect comparison between the FNEI and SHI makes more sense than directly comparing the two. When graphing the FNEI and the SHI on the same axis, it is very important to remember the meaning of positive and negative index values for each composite climate index. Again, positive values represent warmer/drier for the SHI and warmer/wetter for the FNEI, while negative values mean colder/wetter for the SHI and colder/drier for the FNEI.

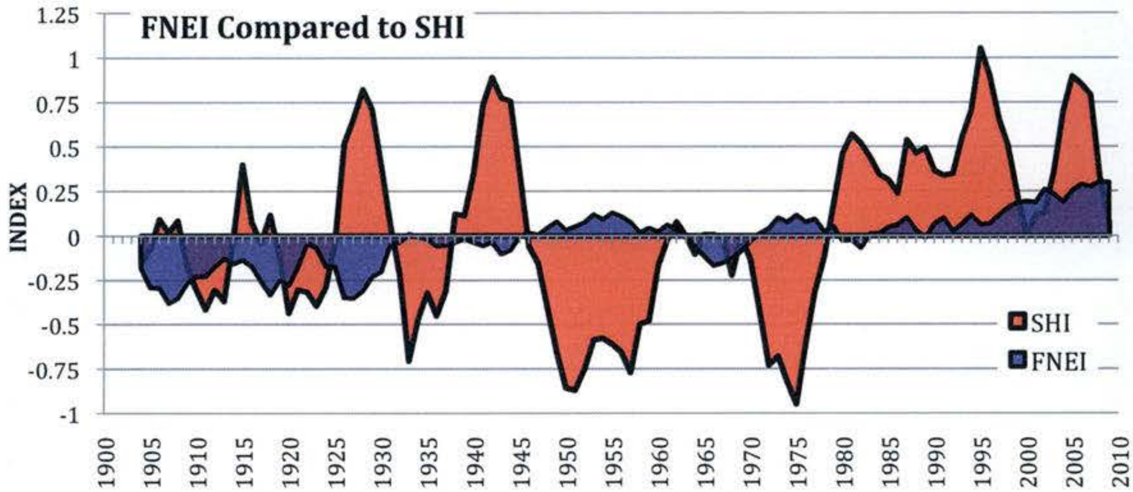

Figure: Indirectly compares the FNEI and the SHI[84]

The most important observation made from this figure is the striking differences in amplitude throughout the entire index. The composite FNEI has a much smaller amplitude range (approximately ± 0.3 deviations) compared to the SHI's amplitude range (approximately ± 1.0 deviations). The reasoning for this remains moderately unclear. However, the results indicate that the Northeast has less overall climate variation than the Pacific Northwest, at least in terms of these four parameters.

The two waveforms appear to follow patterns that are loosely the inverse from one another until the late 1900s. For example, the troughs of the FNEI tend to

[84] Data for SHI provided by Stephanie Ostrander.

correspond to the peaks of the SHI as seen in the periods 1905-1910, 1925-1930, 1945-1960, and 1970-1980. This suggests that when the Pacific Northwest undergoes a period of warmer/drier, the Northeast undergoes a period of colder/drier. However, since the late 1900s, the PNW and NE have been in a similar period of warming, with the PNW having a dry phase and the NE having a relative wet phase (increased precipitation, but decrease snowfall). A change in the relationship between the PNW and NE has potential implication of further supporting the argument for regional and global climate change.

CONCLUSION

SUMMARY OF RESULTS

The Northeast is experiencing a trend of increasing temperature and precipitation over the past century. This trend is strongly influenced by the warm/wet phase that has dominated for approximately the past forty years. This signal of climate change is observable in the annual index, as well as the seasonal indices. Although the NE has been in a phase of wetter than average climate, not all forms of precipitation are increasing in amount. Snowfall has primarily been in drier than normal phases for the past thirty years, which is not observed elsewhere in the 80 year snowfall data record. This decreasing trend in snowfall is consistent with the increasing trend of temperature.

In conclusion, the results of this study further support the evidence suggested in other Northeast climate studies. Many studies expressed a concern for conclusions made about long-term precipitation trends due to its high variability. However, this study shows no indication that the index for precipitation is any less robust than that of temperature. In fact, precipitation throughout the past century underwent less climatic variability than temperature as seen by the smaller range of precipitation index amplitudes (i.e. standard deviations). The visual display of climate indexing makes clear the climate changes occurring in the Northeast: increasing temperature, increasing precipitation, and decreasing snowfall.

IMPLICATIONS FOR NORTHEASTERNERS' LIVELIHOODS

The results of this study have many implications for all living organisms in the Northeast. If this anomalous phase of higher minimum and maximum temperature, more precipitation, and less snowfall, continues to dominate the 21st century, how will the livelihoods of those living in the Northeast be impacted? Increases in temperature could cause a location move in the agricultural sectors if the primary commodities (i.e. fruit, trees used for maple syrup) can no longer survive in their current areas. In addition, warmer temperatures could negatively impact the dairy sector (the most vital agricultural industry) because of the sensitivity of cows to heat: "heat stress in dairy cows depresses both milk production and birthrates for periods of weeks to months.[85]

The consequences of higher maximum temperatures could exacerbate health concerns in metropolitan centers. People will also be more susceptible to heat stress. The Northeast has below average air conditioning infrastructure, with only "58% of homes… [having] some form of air conditioning, compared with 77% of homes nationwide". [86] This could further exacerbate the concerns of heat stress, unless urban planning and development prioritized the installation of more air conditioning units. Another health risk related to increased temperatures has to do with the potential increase of exposure to ozone pollution, which is amplified during hotter days.

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[85] Frumhoff et al., *Confronting Climate Change in the U.S. Northeast*, 108.
[86] Ibid.

A positive implication of more precipitation is the increase of water inputs into the soil, streams, and the agricultural system, which are "dependent on natural rainfall".[87] However, Northeasterners should research how the primary sources for their water consumption are regenerated. If the revitalization of the primary water sources is dependent on springtime snowmelt rather than precipitation, then the reduction of snowfall could lead to water shortages, even though precipitation has increased.

The winter recreational economy will also be strongly influenced by any shifts in snowfall amounts. Downhill skiing can adapt to reduced snowfall, to a point, by increasing the artificial production of snow, but this adaption technique does not work for snowmobiling, which rivals the combined revenue of other winter sports.[88] The Northeast's established winter tourism and recreational culture thrives on the continuation of winter snowfall, frozen lakes, and freezing temperatures. A shift away from that climate would require a change in the traditional winter economy and culture.

Although these points have focused mostly on the anthropocentric implications of climate change, all other biological life associated with the Northeast will also be impacted by changes in climate. Climate change has the potential to alter the range distribution of species, which could impact the predator-prey-parasite relations between species. Because of the interconnected nature of ecology, the affects of climate change on the non-human species in the Northeast will ultimately impact the lives of humans inhabiting that region for better or worse.

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[87] Hayhoe, et al., "Past and future changes...," *16*.
[88] Frumhoff, et al., "An integrated climate change...," 422.

FUTURE DIRECTION OF RESEARCH

To improve and expand the base of this project, a number of topics should be examined more closely. The most basic steps to further this analysis of the NEI would be to update the climate index to include data from the second half of 2010. The longer the period of record used in the climate indexing analysis, the more informative the index becomes. Also, the sign of the *Z-scores* for snowfall could be inversed to add more clarity to the composite index. This would address the concerns of precipitation and snowfall suppressing each other's signal. If the sign of $SnowFDev_{year}$ were reversed in the calculation process, points above the baseline in would mean higher temperatures and more precipitation, but less snowfall. Considering that increased temperatures logically suggest decreased amounts of snowfall, reversing the sign of snowfall might strengthen the signal of the composite Northeast index.

Fitting a model to the NEI is another necessary procedure that must be examined to make the analysis more relevant to policy makers and citizens of the Northeast. Professor Bothun and Harvey Rogers de-convolved the PNI into harmonics to create a representative model of the observed climate pattern in the Pacific Northwest. If the model fits with the historical climate record, as shown by the PNI model (*Figure 14*), then any recent deviation of the model from the observed data further strengths the climate change signal. The model increases the ability to detect climate change beyond natural climate variability. This methodology of manipulating sine waves to match the cyclic variations of the PNI may not work as well for the NEI as the PNI because of the different waveform of the NEI.

Upon observing the waveforms of individual stations and the results from the Northeast Coastal Climate Index (NECI), it is evident that the Northeast is not perfectly homologous in terms of climate, but rather, has climatic sub-regions. Climate indexing can be applied to these sub-regions, which will lend even greater understanding of the climate patterns within the Northeast over the last century. Because of the relatively well-distributed locations of the USHCN stations, each sub-region would have a handful of data sources, which improves the reliability of the analysis. These climatic sub-regions would be determined based on a number of geographical criteria such as: elevation, longitude, latitude, and proximity and positioning to bodies of water.

Although many narrowed questions arose by the end of this investigation, a broader question also came to light. The comparison of the Pacific Northwest climate to the Northeast climate resulted in initially intriguing observations, but went no further. This component could be explored in more detail by comparing the climate parameters between these two climate regions more closely. In addition, the relationship between the PDO/AMO and the influences these two established cycles have on the Northeast and the Pacific Northwest might assist in the comparison of the NEI and PNI. By creating a climate index of the Northeast, it became apparent that the NE is influenced by the warming and cooling phases of sea surface temperature in the Atlantic Ocean, as observed by the Atlantic Multi-decadal Oscillation (AMO). *Figure 43* on the following page compares the NEI and the AMO:

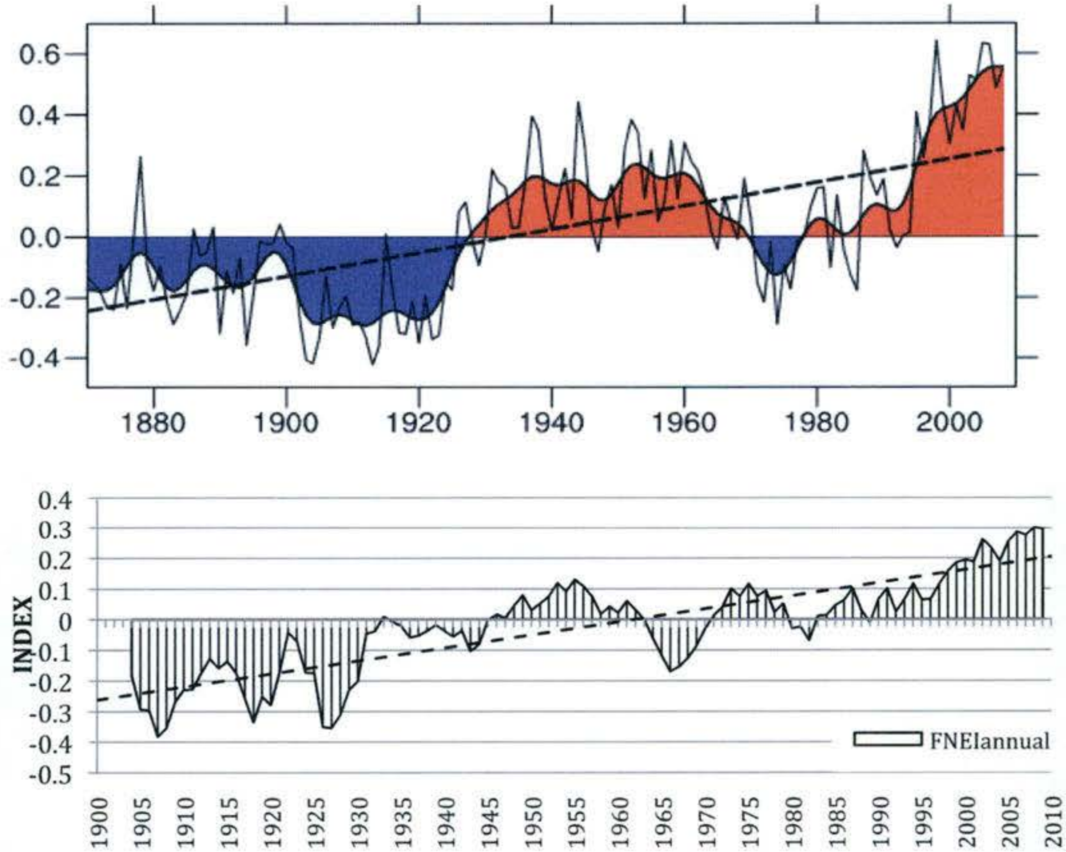

***Figure 43*: FNEI Compared to AMO** – Compares the composite FNEI (bottom) to the AMO[89] (top). The linear regression line is a dashed black line for both the FNEI and AMO.

Although the FNEI and AMO cannot be compared directly to on another because of the timescale and data smoothing differences, both have waveforms that fluctuate from negative to positive phases. Interestingly, the warm phase that has dominated the past few decades is clearly visible in the AMO and the FNEI. Furthermore, a warming trend over the past century is not limited to the Northeast, but also is apparent in the surface temperatures of the Atlantic Ocean. Being able to directly compare the Northeast Climate Index, Atlantic Multi-decadal Oscillation, Pacific Northwest Climate Index, and Pacific Decadal Index to one another could give insight to what larger scale systems influence the regional PNW and NE climates.

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[89] Dennis Shea, http://www.cgd.ucar.edu/cas/catalog/climind/AMO.html.

IMPORTANCE OF THIS STUDY

Because climate is inextricably tied to human lives and livelihoods, the Northeast will have to adapt to its changing climate regardless of the causes of that change (i.e. natural and/or anthropogenic). Adaptation policy depends heavily on what the anticipated long-term change will be, so a robust method for detecting and projecting regional climate change trends must be available. Although the International Panel on Climate Change (IPCC) has published volumes of information on the evidence and future projections of global climate change, regional climate change tends to be neglected. This creates a major disconnect between the dissemination of knowledge to adaptation and mitigation action because "many response strategies [to climate change], both for adaptation and for mitigation, are best designed and implemented at local to regional scales".[90] In the most recent IPCC report, more emphasis was given to regional climate change than previous reports, but the robustness of the results were limited due to the complex analysis technique of downscaling already existing global climate models to represent regional scales.[91] Compared to the process of using AOGCMs to downscale them to regional scales, climate indexing is a simple statistical technique that has the ability to detect regional climate change through the natural climatic variability. Because of the power and simplicity of climate indexing, this regional climate change analysis method should become a baseline procedure for all regional assessment reports. The results of climate indexing provide tangible representations of the climate, which policy makers can use as a starting point to make important adaptation policies that will impact millions of people across multiple generations.

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[90] Frumhoff et al., "An integrated climate change…," 420.
[91] IPCC, "IPCC Expert Meeting…," 59.

APPENDIX

GLOSSARY OF ACRONYMS

AMO – Atlantic Multi-decadal Oscillation

AOGCMs – Atmospheric-Ocean Global Climate Models

FNEI – Filtered Northeast Climate Index

FNEI^P – Filtered Northeast Climate Index that matches the PNI

IPCC – Intergovernmental Panel on Climate Change

NAO – North Atlantic Oscillation

NCDC – National Climatic Data Center

NE – Northeastern United States

NECI – Northeast Coastal Climate Index

NEI – Northeast Climate Index

NEI^P – Northeast Climate Index that matches the PNI

NWSCoop – National Weather Service's Cooperative Station Network

PDO – Pacific Decadal Oscillation

PNI – Pacific Northwest Climate Index

PNW – Pacific Northwest

RNWI – Harvey Rogers's Improved PNI

SHI – Improved Pacific Northwest Climate Index

UNEI – Reduced-Urban Northeast Climate Index

USHCN – United States Historical Climatology Network

WGD – Weighted Generated Data

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