
Christopher Selca
University at Albany, State University of New York, cselca@albany.edu

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AN ANALYSIS OF TEMPERATURE TRENDS IN THE NORTHEAST UNITED STATES: 1950-2019

by

Christopher Selca

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ABSTRACT

The warming signal associated with anthropogenic climate change shows a significant positive trend globally over the last century. Trends in the magnitude and frequency of annual mean and extreme events do not display a globally uniform signal, as some regions have shown negative trends. This study examines the trends in daily mean and extreme temperatures in the Northeast region of the United States. Station data was selected from the GHCN-D Version 3 data set, using a blend of stations from the weather forecast offices and the cooperative observing network. Station criteria included using a threshold of less than 5% of missing data and in which consecutive daily missing data did not exceed one season. A total of 63 stations were analyzed for the study period of 1950 - 2019.

An analysis of temperature trends for Albany, NY airport station data indicates that annual mean minimum temperatures are significantly increasing in magnitude in all seasons. Extreme temperatures defined as the 99th percentile, indicates significant trends in the magnitude of both maximum and minimum extremes. The frequency of extreme events, were also found to be significantly increasing for minimum temperatures. Additionally, results for observed trends of diurnal temperature range show a negative trend of -0.18°C dec⁻¹. The first day of frost are also presented denoting a significant trend of 3.34 day dec⁻¹, indicating that the day of first frost is occurring later in the season.

The Northeast regional results show a statistically significant trend at the 95% confidence level for both maximum and minimum temperatures at 0.10°C dec⁻¹ and 0.20°C dec⁻¹, respectively. Results indicate that the magnitudes and frequency both display positive trends for extreme minimum temperatures only. The trends in warming are not uniform as they exhibit a seasonal dependence which varies for maximum and minimum temperatures. A spatial
distribution indicates the largest warming trends occurred along the Atlantic coast for both maximum and minimum temperatures, with few outliers. Seasonal analysis shows that DJF had the greatest trend for maximum temperature while minimum temperature shows equal significant trends in both MAM and JJA. Further analysis for diurnal temperature range, indicated a trend of -0.10°C dec⁻¹ over the study region. Additionally, the dates of first frost occurrences are also examined regionally and show widespread significant trends of 2 – 4 days dec⁻¹ towards a later first day of frost. Overall, these results indicate that trends in temperature are not spatially or temporally uniform. The analysis indicates that there has been a widespread warming trend for the Northeast, United States and the changes have been greatest for minimum temperatures.
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The journey to my Master’s Degree in Atmospheric Science was not an easy one nor did it follow the typical path that most students take. As a Hudson Valley Community College student, my advisor Suzanne Garhart, helped guide me through a very difficult time in my life and helped me understand how to value everything you possibly could from it. I brought the personal life skills she instilled in me and education from the professors at HVCC, and found myself working towards my dream of obtaining a Masters degree at the University at Albany.

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Eternally Grateful,

Chris Selca

‘True love shows in everything you do’
# CONTENTS

ABSTRACT ........................................................................................................................................... ii

ACKNOWLEDGEMENTS ....................................................................................................................... iv

TABLE OF CONTENTS ............................................................................................................................. vi

LIST OF FIGURES ...................................................................................................................................... viii

1. Introduction ......................................................................................................................................... 1
   1.1 Motivation ....................................................................................................................................... 1
   1.2 Literature Review of Observed Changes ......................................................................................... 2
      1.2.1 Global Surface Air Temperatures .............................................................................................. 2
      1.2.2 Regional Surface Air Temperature Changes ............................................................................. 4
   1.3 Global Temperature Extremes ......................................................................................................... 6
      1.3.1 Temperature Extremes .............................................................................................................. 6
      1.3.2 Regional Temperature Extremes ............................................................................................... 8
   1.4 Land Use Changes and Urbanization .............................................................................................. 9
   1.5 Summary ....................................................................................................................................... 10

2. Data Selection and Statistical Methods ............................................................................................... 16
   2.1 Introduction ..................................................................................................................................... 16
   2.2 Statistical Methods and Extreme Event Criteria ............................................................................. 17

3. Albany Station Data ............................................................................................................................. 21
   3.1 Introduction ..................................................................................................................................... 21
   3.2 Annual Mean Temperature ............................................................................................................. 21
      3.2.1 Overview ................................................................................................................................... 21
      3.2.2 Annual Mean Trend Analysis .................................................................................................... 22
      3.2.3 Diurnal Temperature Range .................................................................................................... 22
   3.3 Analysis of Seasonal Annual Means ................................................................................................. 23
      3.3.1 Seasonal Analysis of Annual Mean Temperatures ................................................................... 23
      3.3.2 Seasonal Anomalies .................................................................................................................. 24
      3.3.3 Seasonal Analysis of Diurnal Temperature Range ................................................................... 25
   3.4 Extreme Temperature Analysis ....................................................................................................... 25
      3.4.1 Analysis of Trends in Extreme Temperatures ........................................................................... 25
      3.4.2 Extreme Event Frequency ......................................................................................................... 27
   3.5 Analysis of Seasonal Extreme Temperatures ................................................................................... 29
      3.5.1 Seasonal Extreme Temperature Trends .................................................................................... 29
      3.5.2 Seasonal Analysis of Extreme Event Frequency ....................................................................... 29
      3.5.3 Day of First Frost Occurrence ................................................................................................ 30
   3.6 Summary: Albany, NY ..................................................................................................................... 31
4. Annual Mean Temperatures in the Northeast, US
   4.1 Introduction.................................................................................52
   4.2 Annual Temperature Analysis......................................................52
     4.2.1 Analysis of Regional Annual Mean Temperatures.................52
     4.2.2 Regional Temperature Anomalies...........................................53
     4.2.3. Analysis of Regional Diurnal Temperature Range Trends.........54
   4.3 Regional Seasonal Analysis .......................................................55
     4.3.1 Seasonal Analysis of Annual Mean Temperatures..................55
     4.3.2 Seasonal Mean Temperature Anomalies...................................57
     4.3.3 Regional Diurnal Temperature Range.....................................58
   4.4 Feature Analysis of Selected Stations........................................59
   4.5 Summary: Regional Annual Mean Analysis..................................61

5. Extreme Temperature and Events in the Northeast, US
   5.1 Introduction.................................................................................80
   5.2 Extreme Temperature Analysis....................................................81
     5.2.1 Changes in Extreme Temperatures.......................................81
     5.2.2 Changes in Extreme Event Frequency....................................82
   5.3 Seasonal Changes in Extremes ....................................................83
     5.3.1 Analysis of the changes in Extreme Temperatures..................84
     5.3.2 Analysis of Changes in Frequency of Extreme Events...............85
   5.4 Frequency of Impact Thresholds................................................86
   5.5 Summary: Regional Extreme Temperature Analysis.....................88

6. Summary & Conclusions
   6.1 Summary of Albany, NY Station Analysis.....................................105
   6.2 Summary of Northeast Regional Analysis.....................................106
   6.3 Conclusions..............................................................................108
   6.4 Future Work.............................................................................109

References......................................................................................111
LIST OF FIGURES

1. (a) Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three datasets. Top Panel: annual mean values. Bottom panel: decadal mean values including the estimate of uncertainty for one dataset (black). Anomalies are relative to the mean of 1961–1990. (b) Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset (orange line in panel a). Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign. For a listing of the datasets and further technical details see the Technical Summary Supplementary Material. (Adapted from the IPCC AR5 Report, 2013; Figure SPM.1)

2. Global annual average land surface air temperature (LSAT) anomalies relative to a 1961-1990 climatology from the latest versions of four data sets (Berkeley, CRUTEM, GHCN and GISS) (Adapted from the IPCC AR5 Report, 2013: Figure 2.4)

3. Annual global mean surface temperature (GMST) anomalies relative to a 1961-1990 climatology from the latest version of the three combined land-surface air temperature (LSAT) and sea surface temperature (SST) data sets (HadCRUT4, GISS and NCDC MLOST). (Adapted from the IPCC AR5 Report, 2013; Figure 2.20)

4. Trends in surface temperature from the three data sets used for annual global mean surface temperature (GMST) for 1901-2012. White areas indicate incomplete incomplete or missing data. Trends are calculated only for grid boxes with greater than 70% complete records and more than 20% data availability in first and last decile of the period. Black plus signs (+) indicate grid boxes where trends are significant. Differences in coverage primarily reflect the degree of interpolation to account for data void regions undertaken by the data set providers rating non beyond grid box averaging (HadCRUT4) to substantial (GISS). (Adapted from the IPCC AR5 Report, 2013; Figure 2.21)
5. Trends in annual frequency of extreme temperatures over the period 1951-2010, for (a) cold nights (TN10p), (b) cold days (TX10p), (c) warm nights (TN90p) and (d) warm days (TX90p). Trends were calculated only for grid boxes that had at least 40 years of data during this period and where data ended no earlier than 2003. Grey areas indicate incomplete or missing data. Black plus signs (+) indicate grid boxes where trends are significant (trend of zero lies outside the 90% confidence interval). The data source for trend maps is discussed in the IPCC report therein. Also plotted for each variable are the near-global time series of annual anomalies of these indices with respect to 1961-1990 for three global indices data sets: HadEX2 (red), HadGHCND (blue), and GHCDEX (green). Global averages are only calculated using grid boxes where all three data sets have at least 90% of data over the time period. Trends are significant for all the global indices shown. (Adapted from the IPCC AR5 Report, 2013; Figure 2.32).....................15

2. Data Selection & Statistical Testing

2.1. Location of the 63 GHCN data stations used in the study. Albany, New York is marked with a star to indicate the location of the focal station analysis.............................................19

2.2. Spatial distribution of the elevation (m) at each station location used in the regional analysis........................................................................................................................................................................20

3. Northeast Annual Means Analysis

3.1. Box and whisker plots of the monthly temperature distribution for the period 1950 - 2019 for a) maximum temperature, b) minimum temperature, and c) mean temperature……33

3.2. Annual mean temperatures (°C) for Albany, NY during the period 1950 -2019 for a) maximum temperature, b) minimum temperature and c) mean temperature with annual trend line shown in black..........................................................34

3.3. Annual mean anomalies in (°C) as computed as the departure from the climatological 30 year normal 1981-2010 for the years 1950 - 2019 for Albany, New York for a) maximum temperature and b) minimum temperature..................................................................................35

3.4. Annual mean diurnal temperature trends (°C) in grey and the annual trend line shown in black for the period 1950-2019.............................................................................................................36

3.5. Seasonal annual means of daily maximum temperatures (°C) for the period 1950 -2019 for, a) DJF b) MAM c) JJA and d) SON with annual trend lines shown in black……37

3.6. Seasonal annual means of daily minimum temperatures (°C) for the period 1950 -2019 for, a) DJF b) MAM c) JJA and d) SON with annual trend lines shown in black……38
3.7. Annual mean maximum temperature anomalies (°C) during a) DJF, b) MAM, c) JJA, and d) SON for the years 1950 - 2019

3.8. Annual mean minimum temperature anomalies during a) DJF, b) MAM, c) JJA, and d) SON for the years 1950 – 2019

3.9. Annual mean diurnal temperature range (°C) shown in grey with the annual trend line (black) over the period 1950-2019 during a) DJF, b) MAM, c) JJA, and d) SON

3.10. Annual 99th Percentiles for a) maximum temperature and b) minimum temperature, over the period 1950 - 2019, with annual trend lines shown in black

3.11. Bottom 1% Percentiles a) maximum temperature, b) minimum temperature, with annual trend lines (black) for the period 1950 - 2019

3.12. Annual extreme event (top 1%) 5-year average frequency for a) maximum temperature (red) and b) minimum temperature (blue) during 1950-2019 with 5 year trend lines are shown in black

3.13. Annual extreme event (bottom 1%) 5-year average frequency for a) maximum temperature (blue) and b) minimum temperature (blue) during 1950-2019 with 5-year trend lines are shown in black

3.14. The frequency of heatwaves a) and coldwaves b) by decade, based on the consecutive frequency of occurrence for the yearly 99th and 1st percentiles, respectively

3.15. Annual 99th percentiles for maximum temperature during a) DJF , b) MAM, c) JJA, d) SON over the periods 1950-2019, with annual trend lines shown in black

3.16. Annual 99th percentiles for minimum temperature during a) DJF , b) MAM c) JJA, d) SON for the period 1950 - 2019 with annual trend lines shown in black

3.17. 5 Year Average extreme event frequencies for maximum temperature during a) DJF , b) MAM, c) JJA, d) SON during the period 1950 - 2019, with 5 year average trend shown in black

3.18. 5 Year Average extreme event frequencies for minimum temperature during a) DJF , b) MAM, c) JJA, d) SON during the period 1950 - 2019 with 5 year average trend lines shown in black

3.19. Day of year of the annual first frost occurrences (blue markers), as defined in the text, for each year in Albany, NY 1950-2019, plotted with the trend analysis shown in black

4.1. Spatial distribution of the average annual mean temperature (°C) for each station for a) maximum temperature and b) minimum temperature for the Northeast, US…………64

4.2. Annual mean temperatures (°C) averaged over all stations for a) maximum temperature and b) minimum temperature for the years 1950 - 2019 with an annual trend line shown in black. Legends that display bold text represent statistically significant trends………65

4.3. Spatial distribution of annual mean decadal trends (°C/dec) for a) maximum temperature and b) minimum temperatures. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant………………………………………………………………………………………..66

4.4. Annual mean temperature anomalies (°C) averaged all stations in the Northeast for a) maximum temperatures and b) minimum temperatures…………………………………….66

4.5. Annual mean diurnal temperature range (°C) averaged over all stations in the Northeast (grey), with an annual trend line shown in black. Legends that display bold text represent statistically significant trends………………………………………………………………………………………..68

4.6. Spatial distribution of the annual mean decadal trends (°C/dec) of diurnal temperature range. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant…………………..69

4.7. Annual mean temperatures (°C) averaged over all stations for maximum temperature during a) DJF, b) MAM, c) JJA and d) SON, for the years 1950 – 2019. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends………………………………………………………………………………………..70

4.8. Spatial distribution of seasonal annual mean maximum temperature trends (°C/dec) for a) DJF, b) MAM, c) JJA and d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant………………………………………………………………………………………..71

4.9. Annual mean temperatures (°C) averaged over all stations for maximum temperature during a) DJF, b) MAM, c) JJA and d) SON, for the years 1950 – 2019. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends………………………………………………………………………………………..72

4.10. Spatial distribution of seasonal annual mean minimum temperature trends (°C/dec) during a) DJF, b) MAM, c) JJA and d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant………………………………………………………………………………………..73
4.11. Seasonal annual mean maximum temperature anomalies (°C) for a) DJF, b) MAM, c) JJA, d) SON for the Northeast, United States. Anomalies were computed using the climate normal (1981-2010) baseline for each station and then averaged over all years. ................................................................. 74

4.12. Seasonal annual mean minimum temperature anomalies (°C) for a) DJF, b) MAM, c) JJA, d) SON for the Northeast, United States. Anomalies were computed using the climate normal (1981-2010) baseline for each station and then averaged over all years. ................................................................. 75

4.13. Seasonal annual mean diurnal temperature range (°C) for a) DJF, b) MAM, c) JJA and d) SON. Annual mean trend lines are shown in black. Legends that display bold text represent statistically significant trends. ................................................................. 76

4.14. Spatial distribution of seasonal annual mean diurnal temperature range decadal trends. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant. ................................................................. 77

4.15. Annual mean maximum temperatures (°C) for six specified stations: a) Rutland, VT, b) Central Park, NY, c) Indian Lake, NY, d) Cape May, NJ, e) Edgartown, MA and f) Warren, PA. Annual trend lines are shown in black. ................................................................. 78

4.16. Annual mean minimum temperatures (°C) for six specified stations: a) Rutland, VT, b) Central Park, NY, c) Indian Lake, NY, d) Cape May, NJ, e) Edgartown, MA and f) Warren, PA. Annual trend lines are shown in black. ................................................................. 79
5. Analysis of Changes in Extreme Temperatures and Events in the Northeast US

5.1. The averaged annual mean (°C) 99th percentile at each station for a) maximum and b) minimum temperature………………………………………………………………………90

5.2. Annual mean 99th percentile (°C) averaged over all stations for a) maximum temperature and b) minimum temperature. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends……………………………………91

5.3. Spatial distribution of the decadal trends in the 99th percentile (°C/dec), at each station for a) maximum temperature and b) minimum temperature………………………………………92

5.4. Annual extreme event frequency averaged (events/dec), over all stations for a) maximum temperature and b) minimum temperature. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends…………………93

5.5. Extreme event frequency trends (events/dec) as defined in the text for a) maximum temperature and b) minimum temperature. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant…………………………………………………………………………………………………………………………………………………………………………………94

5.6. Seasonal mean 99th percentiles (°C) averaged over all stations for a) DJF, b) MAM, c) JJA, and d) SON. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends…………………………………………………………………………………………………………………………………………………………………………………95

5.7. Spatial distribution of the decadal trend in the 99th percentile (°C/dec) for maximum in a) DJF, b) MAM, c) JJA, d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant…………………………………………………………………………………………………………………………………………………………………………………96

5.8. Seasonal mean trends in 99th percentiles (°C) of minimum temperatures averaged over all stations for a) DJF, b) MAM, c) JJA, and d) SON. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends………97

5.9. Spatial distribution of the decadal trend in the 99th percentile (°C/dec) for minimum temperatures in a) DJF, b) MAM, c) JJA, d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant…………………………………………………………………………………………………………………………………………………………………………………98

5.10. Seasonal mean extreme event frequency (events/dec) for maximum temperature averaged over all stations for a) DJF, b) MAM, c) JJA, and d) SON. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends………99
5.11. Spatial distribution of the decadal trend (°C/dec) in the extreme event frequency for maximum temperatures in a) DJF, b) MAM, c) JJA, d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant………………………………………………………………………..100

5.12. Seasonal mean extreme event frequency (events/dec) for minimum temperature averaged over all stations for a) DJF, b) MAM, c) JJA, and d) SON. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends……..101

5.13. Spatial distribution of the decadal trend (°C/dec) in the extreme event frequency for maximum temperatures in a) DJF, b) MAM, c) JJA, d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant………………………………………………………………………..102

5.14. Extreme Event thresholds frequency trends (°C/dec) for a) 29.4°C, b) 32.2°C and c) 35°C. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant………………………………………………………………………..103

5.15. Spatial distribution of the decadal trend (days/dec) in the first frost occurrence. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant………………………………………………………………………..104
1. Introduction & Motivation

1.1 Motivation

A prominent characteristic regarding climate change studies focuses on the concerns associated with the sudden rise in surface air temperatures (SAT) that have been well documented in the scientific literature for the past several decades. Global mean SAT trends have been found to be correlated and casually attributed with a rise in anthropogenically produced GHG’s altering the mean state radiative forcing at the top of the atmosphere (TOA) and thereby directly and indirectly influencing the temperatures at the surface (IPCC, 2013, Trenberth et al, 2007, Hansen et al, 1981). The current observed changes are not simply just attributed to just a rise in SAT’s as they are a combination of several dynamical and feedback processes (Hawkins et al, 2017).

Large scale feedbacks within the climate system drive further changes that may either act positively or negatively on the mean state climate often amplifying the effects of anthropogenically driven changes (Hansen et al, 1981, IPCC, 2013). Various changes in climate variables including temperature, precipitation, and specific humidity are not well recorded homogeneously globally making attribution very complex. (IPCC, 2013). In the fifth assessment report released in 2013 the IPCC stated explicitly that warming of the climate system is unequivocal, and since the 1950’s, many of the observed changes are unprecedented over decades to millennia. Furthermore, the IPCC AR5 report states that it is extremely likely that human influence has been the dominant cause of the observed warming since the mid twentieth century.

The motivation behind this research thesis is to analyze how SAT trends and extremes have shifted regionally in the northeastern United States. Weather extremes such as warm and
cold waves continue to lead the attention of the more immediate tangible effects of climate change. Heat related illness and deaths are a leading cause of weather related fatalities and health hazards and much work is needed to encourage adaptability to future changes (Shuber and Hubert, 2010). A regional analysis of annual temperature trends, extreme events, seasonality, temporally and spatially will help to better understand how temperatures are evolving under a warming climate.

1.2 Literary Review of Observed Changes in Temperature and Extremes

1.2.1 Global Surface Air Temperatures

Global surface air temperature trends offer insight into how the overall planetary changes are occurring and how temperatures evolve spatially and temporally to understand their evolution at a regional scale. While consensus as to the causes and catalysts of climate change are well understood and accepted, the worldwide data set is incomplete and non-homogenous offering particular challenges studying how SAT’s have evolved (Hawkins et al, 2016, Trenberth et al, 2007, IPCC 2013). The dynamics of the climate system including feedback processes, regional topography, ocean currents and vegetation types all play a component in regional temperature trends, thus each region of the planet may not exhibit the same trends in warming (IPCC, 2013, Hansen et al, 1982, Lim et al, 2008). However, it is implicitly stated by the IPCC 2013 report that each of the past three decades has been successively warmer at the Earth’s surface than all the previous decades in the instrumental record, with the first decade of the 21st century has been the warmest.

The IPCC AR5 report (2013) describes a significant increase in globally averaged temperature increases when combing both trends from land and ocean surface data calculated by a linear trend denoting a value range of 0.85 [0.65 to 1.06] °C, over the period 1880 to 2012 and
with the inclusion of multiple data sets the calculated linear average is just over a tenth of a degree less at 0.72 [0.49 to .89] °C for the referenced period of 1951-2012. While other various data sets and pentads give slightly variant trends of temperature increases, this has been the accepted calculated linear average in the AR5 report (Fig 1.1).

In addition to caveats regarding the methodologies employed by the IPCC to determine how temperatures have changed, other studies have shown that the rate of increase may be even more significant and highlights the various trend results that can be obtained based on the selection of data sets and the time periods analyzed (Karl et al, 2015, Hawkins et al, 2017). Land surface air temperatures (LSAT) exhibit more consistency between various analyses, however the data assimilation of methods used between ship and buoy ocean air temperatures vary and tend to skew the data sets (IPCC 2013, Hawkins et al, 2017, Karl et al, 2015). The IPCC AR5 report does highlight these caveats but are in good agreement that the overall premise is uniform that globally averaged temperatures are in fact increasing regardless of the database chosen.

Figure 1.2 illustrates the trend in the respective period chosen by the IPCC AR5 report of global annual LSAT’s of the four global assimilated data sets used within the analysis. The trends of the various data sets are fairly harmonious from the 1950’s onward primarily attributed to more uniform station data observations assimilation methods and show consistency prior to this period if albeit more skewed. As illustrated in the Fig. 1.2, the rate of increases in the trends is not very prominent until the early 1920’s where an upward trend is apparent before a leveling off from the 1940’s through the mid century until the 1970’s where a very prominent upswing in the anomalous trend in temperatures is shown. Additionally, the amplitude of the seasonality of LSAT anomalies is far greater throughout the period of 1850’s to the 1940’s (Fig. 1.2).
When coupling the data analysis for both LSAT’s and ocean surface temperatures, the trend shows less of a seasonal amplitude in the data as can be seen in Fig.1.3 which is the global mean surface air (GMST) anomalies from the IPCC’s AR5 report, 2013. Most notably, the data is not cohesive through the same period and yet the signal is still clear with increasing trends from the 1920’s onward, with a steadying during the mid-century through the 1980’s in which an upswing in GMST’s is seen thereafter. In comparison, the LSAT’s exhibit stronger anomalies through the period in the trends than that of the coupled GMST’s (Fig. 1.2, Fig. 1.3). These results reinforce the conceptual theory that temperatures over land would exhibit a larger anomalous trend than that of the global ocean and land air temperature trend which lends to implications in how regional trends globally may vary.

1.2.2 Regional Surface Air Temperature Changes

Spatial distributions of temperature trends have not been uniform across the planet due to a variety of coupled atmosphere-ocean interactions and feedbacks, inducing changes in upper air circulation patterns that have influenced a variety of regional impacts in temperature and climate variable trends such as cold nights and warm days (Trenberth et al, 2007, IPCC 2013). This is an imperative factor that trends in average temperatures are not solely impacted by the increasing greenhouse gas concentrations as various feedbacks amplify and modify the system thus regions may experience variant trends based on the local synoptic climatology.

Predominant increases in SAT trends are most consistent over land masses and especially within the regions in the northern hemisphere northern latitudes and is attributed to the lower specific heat capacity of land over water basins, thus offering a larger trend in temperatures (IPCC 2013, Trenberth et al, 2007). This inconsistency between heat capacity over the oceans and the continental masses plays an important role in the circulation patterns of the atmosphere
and in addition can alter how specific localized trends in temperature may be altered such as coastal regions (Trenberth et al, 2007).

Figure 1.4 from the IPCC AR5 report illustrates the spatial distribution of (SAT) for the three primary datasets for combined land and ocean surface used within the report including the HadCRUT4, MLOST, and GISS data sets for the period 1901 - 2012. As seen in this figure the most pronounced warming trends on the order of nearly 2.5ºC are in the northern hemisphere high latitudes with maximums in trends being denoted over the northern north America, over the Sahel region in Africa, portions of the Arctic region, and the central region of the Eurasian regions and eastern China in both MLOST and GISS map projections (Fig. 1.4). The most notable cooling trend is evident over the extreme northern portion of the Atlantic Ocean south of Greenland.

Various studies have examined regional temperature annual mean temperature trends and trends in extreme events offering various results. An analysis of temperature trends for the last century in China, it was found that positive increases are seen in all seasons with the most predominant warming occurring during the winter, although the overall trend in warming is not as significant as found globally (Li et al, 2010a). Additionally, Bohm et al, 2010 and Brazdil et al, 2010 both used various reconstructed data sets of temperature trends and find similar results of increases in SAT trends but find that they are not spatially or temporally consistent with greater increases found in winter than summer. Similar results have been found in Africa, Australia and India highlighting the spatial and temporal dependence of each region that show increasing overall global SAT however, they are not spatially or temporally uniform as specific regions are actually experiencing cooling trends (IPCC, 2013).
One such region that is that of the west coast of South America that has actually experienced a cooling in average temperatures trends along coastal regions yet inland within the Andes mountains the net trend is positive suggesting localized trends can vary within hundreds of kilometers, based on regional influences such as topography and sea surface temperatures (Falvey and Garreaud, 2009). This reinforces that non uniform spatial distributions make attribution and temperature trend analysis difficult especially if regions lack adequate instruments for data collection and data assimilation processes. Another region that is inconsistent with observed global warming trends is in the southeastern United States, where changes in land use have seemingly resulted in cooling of temperature trends in this region however, it is not distributed evenly throughout the data period and is more prominent in the earlier part of the record (Ellenburg et al, 2016). Additionally, these results indicate that the seasonality of SAT trends and subsequently extremes are an important indicator in regional changes.

1.3 Global Extreme Temperatures

1.3.1 Global Temperature Extremes

Climate and weather extremes are used to evaluate how the mean state climate is evolving throughout a period from the result of anthropogenic climate change and often has implications that are specific to a localized region that may be influenced by number of factors and have multiple affects on society and economy (IPCC 2013, Lee et al, 2014, Peterson et al, 2008). Climate extremes are expected to increase and become more variable both spatially and temporally in the future under increased warming of the climate system (Donat et al, 2014, IPCC 2013,). Measuring changes in extremes globally and regionally poses unique challenges as they are uniquely sensitive to the time period analyzed, the data sets used and the conceptual

The IPCC AR5 2013 report indicates that changes in extremes in both minimum and maximum temperatures indices are both warming. This is supported by various previous studies including Donat et al, (2013c) that shows that analyzed data of global land areas have increased with warming trends of maximum and minimum temperatures extremes since the 1950’s. Figure 1.5 is a global analysis on spatial and temporal trends extreme anomalies for cold nights (1.5a), cold days (1.5b), warm nights (1.5c), and warm days (1.5d), which provides both a spatial and temporal perspective on how the global extremes have evolved with time over the reliable record based upon the three main global gridded data sets used in their comprehensive analysis, in which at least 90% data observations are available during the period per regional grid box, as seen in the IPCC AR5 report (IPCC, 2013).

As can be seen from the results in Fig. 1.5 indicate that the number cold days and nights have substantially decreased, especially since the 1970’s with a greater increase in variability and decrease in amplitude however, these trends are not consistent spatially as various regions lack reliable data (grey areas) and certain regions are seeing increases in the number of cold days as can be seen in northern North America. This is consistent with the results of (Donat et al, 2013c, DeGaetano and Allen 2002, Peterson et al, 2008), among others.

Conversely, the number of warm nights and days that are increasing during this period with varied spatial signatures within Fig. 1.5c and Fig 1.5d, respectively; an overall increasing trend in the anomalous number of days with less variability with a larger increase in overall trends than that of the decrease of cold days and nights. As discussed previously, cooling trends can be seen in regions in the southeast US, as shown as the number of warm days and the
western Pacific coast of South America while robust large increases are apparent over much of Europe and northern North America and are associated primarily with day time maximums (Fig. 1.5,d), while modest trends are found in much of China, Australia, and the western US.

Analysis of the trends as it pertains to warm nights, large scale robust increases in trends over the last few decades can be seen throughout many regions where substantial data is available. Distributions of nighttime (minimum) temperatures demonstrate greater trends than that of the daytime temperatures (maximum) but are not fully understood and remains an active area of research for global and regional locations and exhibit faster increase in minimum temperature extremes than maximum temperature extremes (IPCC 2013, Hansen et al, 2012, Donat et al, 2014, Peterson et al, 2008).

1.3.2 Regional Temperature Extremes

Regional trends in various extreme indices are expected to increased under future anthropogenic warming with high confidence that cold night extremes will likely decrease and warm nights increase in north and central America, Europe, southern Africa, south-east Asia and Oceania and medium confidence in South America, central-northern Africa and Middle East for the respective indices (IPCC, 2013, Donat et al, 2014). Furthermore, there is high confidence in all regions experiencing an increase in the number of warm days and decrease in cold days in north and central America, Europe, southern Africa, south-east Asia and Oceania and medium confidence in South America, central-northern Africa and Middle East (IPCC, 2013). Regions with medium confidence in changes are where data is substantially poor to indicate past and or future trends (IPCC, 2013).

Studies that have examined the trends in extreme temperatures in the United States have found that there is a divide amongst trends between western and eastern zones appearing to be
spatially and temporally robust within seasons and even specific city locations and is mainly attributed to large scale forcing both internal and externally based (Donat et al, 2014, Hansen et al, 2012, DeGaetano and Allen, 2002). Various results regardless of the methodology and data sets indicate that there is an overall trend emerging that extremes are overall in agreement that the number of warm days and nights are increasing while cold days and nights are decreasing. These results indicate the importance of regional studies in the US are needed to closely examine both the spatial and temporal evolution of changes in trends and extremes in particular regions that are affected by local climate, atmospheric processes and dynamics as to understand how these variables will change with time in a warming climate.

1.4 Land Use & Urbanization

It has been found by some that the large temperature trends tend to appear within cities with high levels of urbanization (DeGaetano and Allen, 2002, Peterson et al, 2008). Additionally, it is found that land use and land changes (LULC), and urban heat island (UHI) effect defined as a change in surface albedo altering transfer and storage of heat, water and air flow, have both been shown to alter the mean state radiative forcing locally adding to additional anomalies outside of city centers that have potentially created certain temperature anomalies that are outside the overall trend (Hansen et al, 2010, IPCC 2013), yet many studies show different variances in these results. It was found through post analysis that the effects of these urban nighttime influences on the overall trends in SAT’s trends was nominally only 0.01°C when compensating for these effects (Hansen et al, 2010) and moreover these overall de-trended analyses show less than a 10% reduction in the overall trends of global SAT’s despite the tangible effects on observed and future temperature trends (IPCC 2013). Once reconciled, temperature trends are consistently apparent.
1.5 Summary

The result of the literature review relied heavily on the results of the IPCC 2013 report for its comprehensive analysis globally of trends in annual mean temperatures, the changes of the 90th and 10th percentiles and the frequency of these threshold events. This review displayed that the results for global analysis indicates that changes in the trends are not uniform spatially or temporally and thus highlight the complexities and analyzing the trends and attributing explanations for trends. Further research indicated that many regions are experiencing cooling trends and varying trends in the magnitude and frequency of extreme events. Additionally, recent studies have shown that localized urban heat island effects and changes in land use can lead to localized trends. This suggests that the examination of temperatures for the Northeast may show differences in trends when analyzed spatially and temporally.
Figure 1.1: (a) Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three datasets. Top Panel: annual mean values. Bottom panel: decadal mean values including the estimate of uncertainty for one dataset (black). Anomalies are relative to the mean of 1961–1990. (b) Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset (orange line in panel a). Trends have been calculated where data availability permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a + sign. (Courtesy of IPCC AR5 Report, 2013; Figure SPM.1)
Figure 1.2: Global annual average land surface air temperature (LSAT) anomalies relative to a 1961-1990 climatology from the latest versions of four data sets (Berkeley, CRUTEM, GHCN and GISS) (Courtesy of IPCC AR5 Report, 2013; Figure 2.4)
Figure 1.3: Annual global mean surface temperature (GMST) anomalies relative to a 1961-1990 climatology from the latest version of the three combined land-surface air temperature (LSAT) and sea surface temperature (SST) data sets (HadCRUT4, GISS and NCDC MLOST) (Courtesy of IPCC AR5 Report, 2013; Figure 2.20)
Figure 1.4: Trends in surface temperature from the three data sets used for annual global mean surface temperature (GMST) for 1901-2012. White areas indicate incomplete or missing data. Trends are calculated only for grid boxes with greater than 70% complete records and more than 20% data availability in first and last decade of the period. Black plus signs (+) indicate grid boxes where trends are significant. Differences in coverage primarily reflect the degree of interpolation to account for data void regions undertaken by the data set providers rating non beyond grid box averaging (HadCRUT4) to substantial (GISS). (Courtesy of IPCC AR5 Report, 2013; Figure 2.2f)
**Figure 1.5:** Trends in annual frequency of extreme temperatures over the period 1951-2010, for (a) cold nights (TN10p), (b) cold days (TX10p), (c) warm nights (TN90p) and (d) warm days (TX90p). Trends were calculated only for grid boxes that had at least 40 years of data during this period and where data ended no earlier than 2003. Grey areas indicate incomplete or missing data. Black plus signs (+) indicate grid boxes where trends are significant (trend of zero lies outside the 90% confidence interval). The data source for trend maps is discussed in the IPCC report therein. Also plotted for each variable are the near-global time series of annual anomalies of these indices with respect to 1961-1990 for three global indices data sets: HadEX2 (red), HadGHCND (blue), and GHCDEX (green). Global averages are only calculated using grid boxes where all three data sets have at least 90% of data over the time period. Trends are significant for all the global indices shown. (*Courtesy of the IPCC AR5 Report, 2013; Figure 2.32*)
2. Data Selection and Statistical Analysis Methods

2.1 Introduction

The selection of data used in this study was prominently focused on two contributing factors; the length of the observational record and spatial distribution of stations within the region. The definition of Northeast region of the United States varies and for the purpose of this study is defined by the states of Pennsylvania, New York, New Jersey, Connecticut, Massachusetts, Vermont, New Hampshire, Rhode Island and Maine. The Global Historical Climate Network (GHCN-D) version 3 was used for the data’s historical expansive availability and quality controlled data assurance measures. Stations that were selected for this study from this dataset were from First Order National Weather Service stations and the U.S. Cooperative Observing Network. The GHCN data set is not held to the same criteria as the USHCN dataset although much is derived from the former offering a larger range of available station data (Menne et al, 2012). The use of the GHCN data set does come with some limitations as it is not as meticulously maintained as the US Historical Climate Network (USHCN), however it offers a present day range of daily maximum temperatures, daily minimum temperatures, precipitation, snowfall and snow depth for each station within the networks. Additionally, the GHCN data set has as set of procedures and tests to ensure the data is quality assured and logistically accurate.

In selecting the stations in the study region for the data analysis several factors were included to create a spatially cohesive range of stations that would maximize the temporal evolution of temperatures at each station. Adapting the work of previous studies in climate variable trends and extremes, stations were only included if they met the condition of less than 5% of the missing data in which consecutive missing days of data did not exceed more than one season as to not skew seasonal analyses. Additionally, stations that moved or that were not
restructured into a new station name were also omitted. All consideration and criteria led to a final determination that a seventy year study period from 1950 - 2019 be used, as station density drops significantly beyond 1948. The resulting set of sixty-three stations met the above criteria for stations within the study region, offering a consecutive seven decade perspective at maximum and minimum daily temperature trends and changes in extremes in the Northeast region of the United States. The geographical distribution of stations is shown in Fig. 2.1. It is well accepted that temperatures vary with elevation (m) and for this reason a supplemental spatial distribution of the station location is provided in Fig. 2.2 to deduce if any outlying trends in the spatial distribution may be explained by the elevation of the station.

2.2 Statistical Methods and Extreme Events Criteria

An extreme temperature event in our study was defined as the 99th percentile, which varies slightly from the 90th percentile as set by the IPCC (IPCC, 2013) and offers a focused view of how the most extreme of events are changing with time. The annual extreme event frequency for each station was based on the 99th percentile value for that station averaged over all years. Heatwaves were defined to be a minimum of three consecutive days in which the extreme temperature event was met and coldwaves being the bottom 1% (or 1st percentile) in which the most extreme cold events were computed. Temperature anomalies were computed as the departure from the mean and using the climatological norm as defined by the 30 year period 1981-2010 daily average for each station.

In addition to annual trends and extreme events in both daily maximum and minimum temperatures are examined seasonally using their respective meteorological seasons as defined as winter including the months December, January and February (DJF), spring including the
months March, April, and May (MAM), summer including the months June, July and August (JJA), and autumn including the months September, October, and November (SON).

A linear regression analysis was performed on the station data to compute the best estimated trend for both maximum and minimum daily temperatures in a variety of definitions (such as diurnal temperature range, first frost days). Statistical tests were performed using a standard Student-test approach using Wald-T assumptions and methods to provide the statistical significance of any trends at the 95% confidence level. Results from the regional data analysis that were averaged over all stations was not normalized, as to show the actual apparent changes based on the criteria already set prior to data assimilation methods above.

The analysis begins with a focused view of Albany, New York Airport station data for its nearly perfectly homogenous observational record. This focused single station analysis allowed for a thorough examination of how temperatures were changing and evolving with time. This methodology offered a basis to approach the regional data set analysis based on first trends and changes in seasonality that provided a template to analyze the pertinent results to best describe changes in trends and extremes in the Northeast region of the United States.
Figure 2.1: Location of the 63 GHCN data stations used in the study. Albany, New York is marked with a star to indicate the location of the focal station analysis.
**Figure 2.2:** Spatial distribution of the elevation (m) at each station location used in the study.
3 Albany, New York: Analysis of Temperature Trends

3.1 Introduction: Albany, NY

The motivation for using a single station as a primer for the analysis of temperature changes in the Northeast region of the United States, (US) was to conduct a preliminary analysis to deduce what overall trends were the most prominent for a single station. The temperature record from 1950 – 2019 for Albany, New York, is a nearly homogenous record of daily values for maximum and minimum temperatures that offer a distinct view, at a single station, of trends and evolution over the last seventy years. Albany’s airport station location is located at 42.47° latitude and -73.80° longitude and is at an approximate elevation of 95.1 meters. This geographical location offers a centered focal point for the study region as it lies within the northern and southern boundaries of the region as shown in Fig. 2.1.

3.2 Annual Mean Temperatures

3.2.1 Overview

As an initial exploration for the distribution of temperatures over the study period for Albany, a statistical analysis of the distribution of monthly temperatures is shown in Fig. 3.1 and provides a monthly perspective of how temperatures typically vary. There is a strong seasonal signal evident in the mean distribution with big differences between summer and winter as expected (Fig. 3.1). The results for maximum temperatures show that there are larger spread of temperatures in MAM and SON (Fig.3.1a). Conversely, the distribution is smaller for minimum temperatures during these seasons; however, they are larger for DJF and JJA (Fig. 3.1b). It is notable that there is greater spread in minimum temperatures highlighting a more uniformly distribution of temperatures seasonally (Fig. 3.1c). These results in the spread of daily
temperatures above suggest that particular seasons may also exhibit different trends in annual means and extreme trends in different seasons for each threshold as this cycle is evident in the monthly distribution.

3.2.2 Annual Mean Trend Analysis

Annual mean temperature trends were analyzed over the study period for daily maximum and minimum temperatures to offer insight on how temperatures changing and if any trends were present. Positive temperature trends are clearly seen for annual mean maxima (Fig. 3.2a), annual mean minima (Fig 3.2b) and annual mean temperatures (Fig. 3.2c). There are notable differences in the magnitude of these trends as maximum temperature exhibit larger variability with a slightly less trend of 0.12° C dec⁻¹(Fig. 3.2a). Conversely, the minimum temperature trend was greater at 0.30 °C dec⁻¹. It also shows a cooling phase into the 1970’s before beginning a steady warming trend into the 1990’s (Fig. 3.2b). The mean temperature for this study is defined as the average between the maximum and minimum temperature and produced a trend of 0.21 °C dec⁻¹ which suggests the magnitude of the warming in the later decades of the study period in the minimum temperature time series, plays a stronger influence on the mean temperature value. All three trends tested statistically significant at the 95% confidence level (Fig. 3.2).

Temperature anomalies offer another perspective on trends as they denote a measure of how anomalous temperatures are based on the average baseline period. Anomalies offer a more distinct view of the relative changes in temperatures. Temperature anomalies were computed using the climate normal baseline (1981-2010) for both maximum and minimum temperatures for Albany, NY and the results are shown in Fig. 3.3. Annual mean maximum temperature anomalies range from approximately -1.4°C to 1.6°C and show a trend of positive anomalies
since the late 1990’s (Fig. 3.3a). Conversely, the trend of minimum temperatures is far more prominent with a very distinct shift to positive anomalies from the 2000’s on, after primarily cold anomalies since the 1950’s (Fig. 3.3b). It is interesting to note that the cold anomalies are greater in magnitude than the warm anomalies, suggesting that the magnitude of warming has been greater for minimum temperature. Minimum temperature anomalies range from approximately -1.7°C in 1977, to approximately 2°C in 2012 (Fig 3.3b). The period 1960-1990 shows over a dozen years with cooler anomalies suggesting that the shift in minimum temperatures is very pronounced in the record.

3.2.3 Diurnal Temperature Range

Another important measure to examine is the diurnal temperature range defined as the difference between the maximum and minimum temperature. The annual mean diurnal temperature trend analysis for Albany, NY indicates a statistically significant negative trend of approximately -0.18°C dec⁻¹ with a total change of -1.27 °C over the period (Fig. 3.4). The negative trend in the diurnal temperature range is most apparent after the 1970’s through the 2010's, after an abrupt warming trend within the 1960’s. It is clear that for Albany, NY, the annual mean diurnal temperature range is decreasing due to a larger rise in minimum temperatures than maximum temperatures. A comprehensive seasonal analysis including diurnal temperature range is discussed in the following sections.

3.3 Analysis of Seasonal Temperatures

3.3.1 Seasonal Trend Analysis

A seasonal analysis of mean temperatures will help to deduce how the overall trend of temperatures has evolved both annually and seasonally. Figure 3.5 shows the annual mean
maximum temperatures for DJF, MAM, JJA and SON. The greatest trends were found for the seasons DJF and MAM which show statistically significant trends of 0.21°C dec⁻¹ and 0.18°C dec⁻¹, respectively (Fig. 3.5a, b). Trends are not significant for JJA (Fig. 3.5c) or SON (Fig. 3.5d). This suggests that the DJF and MAM seasons mean temperatures are warming more than that of rest of the year, suggesting that extremes may be increasing as well. This result is also true for the seasonal distribution of annual mean minimum temperatures in which all seasons are statistically significant with trends 0.35 °C decades for DJF (Fig. 3.6a) and JJA (Fig. 3.6c) showing the highest values followed by 0.23 °C dec⁻¹ and 0.25 °C dec⁻¹ for MAM (Fig 3.6d) and SON (Fig. 3.6d), respectively. Particular interest is noted in Figure 3.6d for SON for the large inter-annual swing in temperatures on the order of 2-3 °C during the 1970’s into the very early 1980’s. This feature in variability is also noted within the minimum mean trends in Figure 3.2b, suggesting that the signal from the SON season was strong enough to influence the overall annual mean trend.

3.3.2 Seasonal Anomalies

The results of a seasonal analysis are presented for maximum temperature anomalies in Fig. 3.7. The results show that distribution of anomalies over the study period show a greater range in the magnitude for both DJF and MAM (Fig. 3.7a,b). The overall results in this analysis indicate the warming trend in Albany is most pronounced in DJF and MAM. The variability is very apparent in the time series of anomalies and indicates the magnitude of greatest warming is occurring after the 1990’s (Fig. 3.7).

Similarly, a seasonal analysis for minimum temperature anomalies is shown in Fig. 3.8. The results indicate that many of the most anomalous extreme temperatures are occurring in DJF
with a range of -6° to 4°C degrees a 10°C anomaly range (Fig. 3.8a). The results for JJA and SON also show a warming trend, however the range in magnitudes between seasons is not as pronounced. A shift to more frequent warm anomalies is apparent in DJF, JJA and SON which suggests that the warming signal is increasing most recently. Nonetheless, the consistent signal in the analysis is that there are notable changes in minimum temperatures in DJF, JJA and SON.

3.3.3 Seasonal Analysis of Diurnal Temperature Range

Results indicated in section 3.2.3, that the diurnal temperature range is decreasing in association with the warming trend found in all seasons, for minimum temperatures. This would ultimately suggest that diurnal temperature range has shifted through the time series seasonally as well. A diurnal temperature range seasonal analysis is shown in Fig.3.9. The range in maximum and minimum temperatures is decreasing in DJF, JJA and SON and these trends were found to be statistically significant with the highest trend appearing in JJA at -0.34 °C dec⁻¹ (Fig. 3.9c). Further inspection shows that the inter-annual variability is quite large for both MAM and SON and potentially could explain why there is no significant trend in MAM.

3.4 Extreme Temperature Analysis

3.4.1 Analysis of Trends in Extreme Temperatures

The approach used to define an extreme event for the purpose of our study was to examine how the most extreme outliers are changing. The IPCC 2013 report used a 90th/10th percentile distribution for their analysis of maximum and minimum temperatures in which the top 90th percentiles were examined as warm days (or nights) and 10th percentile were defined as cool days (or nights), for maximum and minimum values respectively (IPCC, 2013). For the purposes of demonstrating this change for Albany, NY we examined both the 99th percentile (and
top 1%) and the 1st percentile (bottom 1%) for both maximum and minimum temperature. This approach allows analysis of how the cool (coldest temperatures) and warm (hottest temperatures) extremes are changing. This offers insight into the magnitude of the range distribution of daily temperatures. The approach for the use of the 99th percentile to define an extreme was based on the desire to look at how only the most extreme events were changing regionally, whereas the broader approach used by the IPCC was necessary as it was a global data set prone to large spatial distributions of temperatures. For clarity of reference ‘warm extremes’ will be referenced as those at and above 99th percentile threshold, while ‘cool extremes’ will be used for the 1st percentiles for both maximum and minimum temperature analyses.

Figure 3.10 shows an annual 99th percentile trend analysis for annual mean temperatures. Warm extremes show a statistically non-significant negative trend of -0.09°C dec⁻¹ for a total change of -0.61°C over the period with a larger range of variability (Fig. 3.10a). As to be expected from the analysis in section 3.2, minimum temperatures do exhibit a positive trend in magnitude at a rate of 0.29°C per dec⁻¹ for a total change of 2.05°C which was the only statistically significant trend (Fig. 3.10b). The mean value also shows the same pattern of minimum temperatures representing most of the changing mean trend at 0.12°C dec⁻¹ for a total of 0.84 °C per decade (Fig. 3.10c). These results indicate that warm extremes for maximum temperatures are not showing any significant trends. However, warm extremes for minimum temperature are warming at a steady significant rate indicating the coldest nights are warming.

The same approach was used for the 1st percentile, highlighting the change in cool extremes. The overall trend in the 1st percentile for maximum, minimum and mean temperatures all show positive trends at 0.3°C dec⁻¹, 0.72°C dec⁻¹ and 0.51°C dec⁻¹ respectively, with all testing statistically significant (Fig. 3.11a,b,c). This provides further support that the major changes
appearing in the temperature distribution, relates to minimum temperatures with trends in the coldest minimum temperatures increasing overall about 5.0°C (Fig. 3.11). It is interesting to note that overall while the magnitude of maximum temperature warm extremes is not changing significantly, the magnitude of cool extremes for maximum temperature are suggesting that the range of variability in extreme maximum temperatures is decreasing.

3.4.2 – Extreme Event Frequency Trends

The following analysis uses an extreme event threshold that is computed as the 99th percentile for warm extremes and 1st percentile for cool extremes, for both maximum and minimum temperatures. This offers us a view of how the frequency of an extreme event is changing over time for both warm and cool extremes. To do this analysis the mean of the 70 years of 99th percentile values was calculated and used to count the number of days that met this threshold each year, and these results were then averaged in five year bins (Fig.3.12). The frequency of maximum temperature extreme events has decreased by a statistically insignificant -0.11 events dec⁻¹ consistent with the results in maximum warm extremes which showed no trend in magnitude. In contrast, the frequency of minimum temperature extremes has increased by a statistically significant 5.29 events dec⁻¹, noting that many of the most extreme outliers occur from 2000-2019 (Fig.3.12a,b). This denotes that the number of times the minimum temperature’s 99th percentile threshold was reached has increased, suggesting the number of warm extremes for minimum temperature have increased in frequency in addition to the magnitude. This is consistent with the trends found in the annual mean minimum temperatures where many of the largest positive anomalies and yearly means were found in the later part of the study period.
Further exploration of the cool extremes indicates that for maximum temperature, the extreme events are not showing a significant trend. Conversely, the minimum temperature extreme event trends were at decreasing at \(-2.47\) events dec\(^{-1}\) (Fig. 3.13a,b). This provides a larger perspective that the cool extremes of maximum and minimum temperatures are indeed decreasing in both magnitude and frequency for Albany, NY.

In addition to how the frequency of extreme events is changing it is important to look at how many times these thresholds occur in consecutive days over a period as well, as it represents the occurrences of the phenomena of heatwaves and coldwaves, where the societal impact is most prevalent. The definitions of these phenomena can differ, however it is most commonly known to be defined as three consecutive days of temperatures in excess of 90°F (or 29.44°C). The definition of heatwaves and cold waves for this single station analysis was to use the 99\(^{th}\) percentile derived from Fig. 3.10 as the extreme event threshold to deduce the frequency of consecutive multi day events. The results for any multi day events in which our threshold definition was met for heatwaves and coldwaves in Albany are presented in Fig. 3.14. These results indicate that heatwaves have not exhibited a notable change in frequency (Fig. 3.14a), however, coldwaves (Fig. 3.14b) have decreased in frequency over the last few decades. The results of this analysis suggests that periods of cool extremes for minimum temperatures are decreasing in frequency suggesting that the overall change in minimum temperatures over the study period is very coherent.
3.5 Seasonal Analysis of Extreme Temperatures

3.5.1 – Seasonal Extreme Temperature Trends

The previous results are explored further by looking at the trends in each specific season to deduce the sensitivity to the time of year. Fig. 3.15 shows the 99th percentiles for maximum temperature for the seasons as previously defined, a) DJF, b) MAM, c) JJA and d) SON. Statistically significant warming trends exist in DJF (0.38 °C dec⁻¹, Fig. 3.15a) and in MAM (0.3 °C dec⁻¹, Fig. 3.15b), while JJA and SON (Fig. 3.15c,d), did not show significant trends (Fig. 3.15). These results indicate that the overall trend for the annual analysis is skewed from the negative trends in maximum temperature warm extremes in JJA and SON.

The seasonal trend analysis of the 99th percentile for minimum temperatures is shown in Fig. 3.16. The results show that MAM, JJA, and SON show significant trends (3.16b,c,d). The variability between seasons is also not as uniform as DJF and SON exhibit a larger variability, while MAM and JJA suggest a smaller range of variability. This is interesting as the MAM season leads the trend at 0.3 °C dec⁻¹ for maximum extreme temperatures and yet has a smaller range of value over the period (Fig. 3.16b). It should be noted that results in particular seasons that have no significant trends may be due to a larger range in variability thus reducing overall trend and significance. These results may suggest that the results in seasons that show no trends may become a significant trend over time.

3.5.2 Seasonal Analysis of Extreme Event Frequency

A seasonal analysis was used to continue the examination of the trends in extremes events. The 99th percentile averaged over all years is used as the extreme frequency threshold and the frequency of occurrence averaged over five years is shown for each season in Fig. 3.17
for maximum temperature. The statistically significant trend is found in MAM at 0.88 events dec$^{-1}$, (Fig. 3.17b). This suggests that not only is the range of the magnitude of maximum temperatures changing, but the frequency at which they occur is as well for MAM. Results for JAA and SON for maximum temperature show both a decrease in magnitude and frequency in events, albeit not strongly enough to be considered statistically significant trend.

The results for the extreme frequency analysis for minimum temperatures are shown in Fig. 3.18, and indicate that warm extreme event frequency has increased. These positive increases in frequency support the observed increase in the magnitude of the 99th percentile annually (Fig. 3.10). The trends were statistically significant for DJF, MAM and JJA. Changes in extremes are found most prominent for minimum temperatures throughout the study period for Albany and displaying a small negative trend in maximum temperatures. This detailed seasonal analysis of extreme magnitude and frequency trends demonstrated that changes are seasonally dependent for maximum temperatures.

3.5.3 Day of First Frost Occurrence

An alternative definition of an extreme event is based on a specific threshold that measures an anomalous event that may have large societal impacts. Such a threshold may be determined by a specific application such as farming and agriculture. For example, there is a lot of interest in the timing of the first frost occurrence, the date when crops and the growing season to an end for the year. A trend in such a measure wouldn’t be considered an extreme event, but it is a threshold with extreme implications as an early first frost could end a growing season earlier, potentially causing damage and economic losses. It is important to distinguish the first ground
frost versus the first 2m frost. For the purpose of this study we are examining the first 2m frost, or that is to say the first occurrence below 0°C during the SON season.

A first frost analysis was performed to analyze a trend in how this threshold is potentially changing. Figure 3.19 shows the first day of frost each year. A trend analysis on the first frost occurrence indicates that the first frost day is trending 3.34 days later in the season. Further examination of these trends denotes that the first frost shifts from an October 1st to October 20th, occurrence based on 5 year averages over the seventy year period. This has strong implications for the growing season, as the latest first frost day in this time series record was November, 3rd 2019 (Fig. 3.19). These findings are not inclusive of all thresholds that may have implications for society such as energy production forecasts and efficiency measures, but these results do highlight the importance of individual thresholds pertinent to a specific determining cause

3.6 Albany Station Summary

The results from this analysis show that the evolution of annual mean trends, anomalies, and changes in extremes are most profound overall for minimum temperatures. These results indicate that the greatest amount of change in temperatures over the study period for Albany, NY has occurred for minimum temperatures. The following key results are listed below:

• An annual mean temperature analysis for maximum temperature showed a significant trend of $0.12 \degree C \text{ dec}^{-1}$ and seasonal trends are found in DJF and MAM.

• Minimum temperature show a significant trend annually of $0.30 \degree C \text{ dec}^{-1}$, and shows trends in all seasons.
• A diurnal temperature range trend analysis shows that there is a significant negative trend annually of -0.18 °C dec⁻¹ and trends exist in DJF, JJA and SON seasons.

• Extreme temperatures were defined as the 99th percentile and show that no significant trend exists for maximum temperatures annually, while trends exist in DJF and MAM. Minimum temperatures do show a significant trend annually of 0.29 °C dec⁻¹ and also in MAM, JJA and SON.

• Extreme event frequency analysis for Albany was based on the 99th percentile of the series; maximum temperature extreme results show no annual trend, but a significant trend in MAM exists. Minimum temperature shows a significant trend annually of 5.29 events dec⁻¹ and trends are also apparent in DJF, MAM, and JJA.

• An analysis of trends in the date of the first frost occurrence shows a statistically significant positive trend of 3.34 days dec⁻¹. These results signify that the date of first frost shifts from an October 1st to October 20th, occurrence based on 5 year averages.

These key findings indicate that trends in temperatures in Albany, NY do not exhibit a uniform signal seasonally. These results are consistent with the findings of previous studies which showed that trends in temperature varied by both season and location for maximum and minimum temperatures (Donat et al, 2013c, Hansen et al, 2012, IPCC 2013). The analysis of daily mean temperatures shows they are driven by the minimum temperature trends and thus will not be included in the regional study. The approach for the Albany station analysis sets the groundwork for the analysis in the following chapters discussing the results for the Northeast, United States.
Figure 3.1: Box and whisker plots of the monthly temperature distribution for the period 1950 - 2019 for a) maximum temperature, b) minimum temperature, and c) mean temperature.
Figure 3.2: Annual mean temperatures (°C) for Albany, NY during the period 1950-2019 for a) maximum temperature, b) minimum temperature and c) mean temperature with annual trend line shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.3: Annual mean monthly time anomalies in (°C) as computed as the departure from the climatological 30 year normal 1981-2010 for the years 1950 - 2019 for Albany, New York for a) maximum temperature and b) minimum temperature.
**Figure 3.4:** Annual mean diurnal temperature trends (°C) in grey and the annual trend line (black) for the period 1950-2019. Legends that display bold text represent statistically significant trends.
Figure 3.5: Annual mean distribution of daily maximum temperatures (°C) for the period 1950-2019, for the seasons a) DJF b) MAM c) JJA and d) SON with annual trend lines shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.6: Annual mean distribution of daily minimum temperatures (°C) for the period 1950-2019, for the seasons a) DJF b) MAM c) JJA and d) SON with annual trend lines shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.7: Annual mean maximum temperature anomalies (C) during a) DJF, b) MAM, c) JJA, and d) SON for the years 1950 - 2019.
Figure 3.8: Annual mean minimum temperature anomalies during a) DJF, b) MAM, c) JJA, and d) SON for the years 1950 - 2019
**Figure 3.9:** Annual mean diurnal temperature range (°C) shown in grey with the annual trend line (black) over the period 1950-2019 during a) DJF, b) MAM, c) JJA, and d) SON. Legends that display bold text represent statistically significant trends.
Figure 3.10: Annual 99th Percentiles for a) maximum temperature, b) minimum temperature over the period 1950 - 2019, with annual trend lines shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.11: 1st Percentiles a) maximum temperature, b) minimum temperature with annual trend lines (black) for the period 1950 - 2019. Legends that display bold text represent statistically significant trends.
Figure 3.12: Annual extreme event (99th percentile) 5-year frequency for a) maximum temperature (red) and b) minimum temperature (blue) during 1950-2019 with 5 year trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.13: Annual extreme event (1st Percentile) 5-year average frequency for a) maximum temperature (blue) and b) minimum temperature (blue) during 1950-2019 with 5-year trend lines (black). Legends that display bold text represent statistically significant trends.
Figure 3.14: The frequency of heatwaves a) and coldwaves b) by decade, based on the consecutive frequency of occurrence for the yearly 99th and 1st percentiles, respectively.
Figure 3.15: Annual 99th percentiles for maximum temperature during a) DJF, b) MAM, c) JJA, d) SON over the periods 1950-2019 with annual trend lines shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.16: Annual 99th percentiles for minimum temperature during a) DJF, b) MAM, c) JJA, d) SON for the period 1950 - 2019 with annual trend lines shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.17: 5 Year Average extreme event frequencies for maximum temperature during a) DJF, b) MAM, c) JJA, d) SON during the period 1950 - 2019, with 5 year average trend shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.18: 5 Year Average extreme event frequencies for minimum temperature during a) DJF, b) MAM, c) JJA, d) SON during the period 1950 - 2019 with 5 year average trend lines shown in black. Legends that display bold text represent statistically significant trends.
Figure 3.19: Day of year of the annual first frost occurrences (blue markers), as defined in the text, for each year in Albany, NY 1950-2019 with the annual trend analysis shown in black. Legends that display bold text represent statistically significant trends.
4. Annual Mean Temperature Trends in the Northeast, US.

4.1 Introduction

The regional analysis begins by examining the spatial distribution of the mean annual temperature at each station in our study region. This provides an overall view of how mean temperatures are distributed geographically and if any local signals are prevalent. The spatial distribution is shown in Fig. 4.1 which denotes that mean maximum temperatures (Fig. 4.1a) exhibit a pattern of warmer temperatures in southern portion of the study region with cooler temperatures in the northern region with the exception that seemingly all coastal regions are a bit warmer than inland. Additionally, the minimum temperature distribution shows a similar spatial pattern with warmer minimum values along the coast and a north south gradient in temperatures inland (Fig. 4.1b). These results suggest that coastal mean temperatures are moderated by the proximity of the ocean.

4.2 Annual Mean Temperatures: Northeast, US

4.2.1 Analysis of Regional Annual Mean Temperatures

Annual mean temperatures for the entire region were averaged over all the stations to produce a trend analysis for temperatures offering a perspective of how temperatures have changed overall in the Northeast US. These results show a decadal trend of 0.10°C dec⁻¹ for maximum temperature with an amplifying pattern of inter-annual variability (Fig. 4.2a). This is consistent with the findings of Albany (Fig. 3.1a), which trended slightly larger at 0.12°C dec⁻¹ and also had amplified variability. The overall trend in minimum temperatures for both analyses
shows a subtle cooling in the 1960’s – 1970’s before a consistent warming trend into the 1990’s (Fig. 4.1b). These results also indicate that overall, the minimum temperature trend of 0.20°C dec\(^{-1}\) is twice the rate of warming for maximum temperatures (Fig. 4.1b).

To further examine this averaged trend for the Northeast, the spatial distribution of decadal trends in annual mean temperatures for each station was created to examine how trends varied locally (Fig. 4.3). These results show that many of the coastal locations have experienced statistically significant warming trends in excess of 0.2°C dec\(^{-1}\). The distribution of maximum temperatures indicates that 52 of the 63 stations indicate a positive trend, 33 of which tested statistically significant. The highest trend rates are found clustered along the Northeast coastline and southern Pennsylvania (Fig. 4.3a). Trends in minimum temperature are far more coherent spatially denoting 53 of 59 positively trending stations displaying trends that were statistically significant across the study region (Fig 4.3b).

Minimum temperature only showed one significant negative trend which was in Rutland, VT and only 3 stations for maximum temperature show a statistically significant negative trend (Fig. 4.3b). These results also demonstrate that localized trends of weak cooling in maximum temperatures are found in a cluster of stations in north-western Pennsylvania, Maine and upstate New York near Lake Champlain, and Vermont. Referencing the elevation map for each station shows no apparent relationship between trends and elevation, and thus must be the results of localized forcing (Fig. 2.2).

4.2.2 Regional Temperature Anomalies

Temperature anomalies were computed using the calculated climate normal’s (baseline 1981-2010) for each station. Annual anomalies were then averaged over all stations annually,
providing a clear signal of how much temperatures have changed. Figure 4.4 shows the calculated annual mean temperature anomalies averaged over the Northeast region. Maximum temperature anomalies show a trend towards warm anomalies over the Northeast with more positive temperature anomalies from the 1990’s onwards (Fig. 4.4a). These results show that there has been a substantial change in maximum temperature over the whole region as the range of the magnitude of anomalies is roughly 2.5°C in which the warm anomaly maxima exceeds the minima by 0.5°C (Fig. 4.4a)

The signal is larger in the minimum temperature anomalies as the overall range is greater than that of maximum temperature by approximately 0.5°C (Fig.4.4b). The transition to increasing warm anomalies is also found after the 1990’s. The spread of anomalies show that there were many years of more frequent cold anomalies for minimum temperature prior to the 1990’s. These results support a larger change in the temperature distribution of minimum temperatures over the Northeast, than maximum temperatures with a larger range of roughly 3.0°C (Fig. 3.2b).

4.2.3. Regional Diurnal Temperature Range Trends

Consistent with the observation that minimum temperature trends are greater than trends in maximum temperatures, a notable shift in the regional diurnal temperature range is seen. An analysis of diurnal temperature range was performed on all stations and averaged annually and is shown in Fig. 4.5. The results indicate that the trend is a negative 0.10°C dec⁻¹ which implies the diurnal temperature range is decreasing over the study region (Fig. 4.5). Furthermore, the variability for most of the study period shows a relatively steady decrease with only anomalous outliers in the mid 1960’s and late 2010’s (Fig. 4.5).
The spatial distribution of the decadal trends in diurnal temperature range shown in Fig. 4.6, indicates that 51 stations show a decrease in the range, 41 of them testing statistically significant (Fig.4.6). Many of the stations that exhibit the greatest magnitude in negative trends tend to be inland. Interestingly, statistically significant increases are found distributed throughout regions clustered with stations that exhibit negative trends such as the Boston, Massachusetts region, Rutland Vermont, Cape May, and New Jersey. These locations may be experiencing varied trends in mean temperatures than the majority due to localized forcing, as geographic effects such as elevation doesn’t appear to explain the variation. It is interesting to note that three of the stations that do exhibit positive significant increases are in fact coastal locations (Fig. 4.6). These stations show no trend and negligible change for minimum temperatures and a weak significant increase in maximum temperatures, thus it explains why the analysis denotes positive trends for these locations (Fig. 4.3a,b).

4.3 Seasonal Analysis of Regional Temperatures

4.3.1 Seasonal Analysis of Regional Annual Mean Temperatures

An analysis of annual mean temperature trends for maximum temperature over all stations in the Northeast shows that the only statistically significant trend is MAM at a rate 0.16°C dec⁻¹(Fig. 4.7b). The lack of significant trends in the other seasons indicates that the statistically significant trend in maximum temperatures over the Northeast stations is driven by the trend found during MAM (Fig. 4.2b). The spatial distribution of seasonal annual mean maximum temperature decadal trends is shown in Fig. 4.8. A consistent warming trend is found in all four seasons along the coastal areas for annual mean maximum temperature (Fig. 4.8a). Consistent with the analysis for MAM, 38 of 55 stations had statistically significant positive
trends (Fig. 4.8a). It is interesting to note that many inland stations show a slight weakening trend, primarily in western New York, Pennsylvania, and Maine one of which is a coastal location and is most pronounced during JJA and SON (Fig. 4.8c,d). Additionally, the significant warming trend observed along the coasts implies that the overall mean for the season is being dampened by the widespread negative trends found inland (Figs 4.8c, Fig. 4.7c). These results highlight the spatial and temporal signals evident in the trends in temperatures.

The results of the analysis of average annual minimum temperature in Fig. 4.9 shows that all four seasons have statistically significant warming trends of 0.2°C dec⁻¹ in DJF, 0.14°C dec⁻¹ in MAM, 0.25°C dec⁻¹ in JJA and 0.17°C dec⁻¹ in SON. It is interesting to note that the greatest trend is found in JJA denotes that overnight minimum temperatures are warming more than any other season. Additionally, strong variability is displayed within DJF and MAM seasons and yet indicates significant trends. This is an important observation as it indicates that variability alone cannot explain whether a trend is significant or not.

Figure 4.10 shows the minimum temperature trends spatially for the seasons and shows that the signal is indeed strongest in nearly all stations in JJA. In fact, all but Rutland, VT show strong positive trends and of these 62 stations, 57 of them were statistically significant (Fig. 4.10c). This is consistent with previous findings supporting that the evolution of minimum temperatures is more prominent than that of maximum temperatures. The results also show a widespread distribution in trends over the region with many clustered around the Atlantic Ocean and Great Lakes. Interestingly, DJF had the least number of stations that tested statistically with 28. Additionally, MAM displayed statistical significance for 37 trends of the 57 stations (Fig.4.10b). The season with the most stations showing trends were found in SON, with 43
trends of the 55 stations testing statistically significant. These results show that the changes in minimum temperatures are most profound for the region in JJA and SON.

4.3.2 Seasonal Mean Temperature Anomalies

Further analysis considered the annual mean temperature anomalies averaged over all stations and the results of this analysis are shown in Figure 4.11. The positive trend is very apparent in DJF, where maximum temperature anomalies show negative anomalies until the 1990’s and shift to warmer anomalies through the 2010’s is apparent (Fig. 4.11a). MAM shows more year to year variability and the trend is not apparent, however there are more cases of large anomalies >= 2.5°C, which may reflect the higher variability in this season (Fig. 4.11b). The signal is not as clear in JJA as the anomalies are weakest during this season and denote that there has been little change in the variability or magnitude (Fig. 4.11c). SON shows slightly larger variability in anomalies but there is not a clear signal (Fig. 4.11d). These results reveal that the changes in maximum temperature over the Northeast region are most prevalent in DJF and MAM.

The results of the seasonal minimum temperature anomalies show a slightly more consistent change in all four seasons, as shown in Fig. 4.12. In DJF, there is a very clear change in the magnitude of temperature anomalies including a range of variability of -3.75 – 3.5°C (Fig. 4.13). MAM shows warm anomalies trending greater in magnitude and occurring more frequently since the 1980’s, although several years in the 1990’s were cool anomalies highlighting the presence of marked inter-annual variability in this season (Fig. 4.12b). The clearest trend in this analysis was in JJA showing a weaker trend but a consistent shift to positive anomalies as demonstrated by generally cooler anomalies prior to the 1990’s (Fig. 4.12c). The
JJA anomalies highlight a marked trend and show a clear change in contrast to the other seasons which showed strong inter-annual variability. There is a clear signal in changing temperatures in SON as well; however, there appears to be more of consistent change since 2000 – 2019 into a period of warmer minimum temperatures (Fig. 4.12d).

4.3.3 Regional Diurnal Temperature Range

The seasonal analysis of annual mean temperatures and anomalies suggests that changes in diurnal temperature range would also be more prominent in particular seasons such as JJA. This suggests that the trend during JJA for diurnal temperature range over the regional stations should visualize these projected results. Figure 4.13 shows the annual mean diurnal temperature range trend analysis by season. As expected, the most significant decrease is found in JJA at -0.2°C dec⁻¹ (Fig.4.13a). The trend decreases are significant for both DJF at -0.07°C dec⁻¹ and SON at -0.12°C dec⁻¹ (Fig. 4.13a,d).

An analysis of how the diurnal temperature range is changing regionally is presented in Fig. 4.14. This seasonal analysis shows that statistically significant negative trends exist broadly in the seasons of DJF, JJA, SON. The trends are the most prominent in JJA, exhibiting the largest magnitudes and in all, 56 stations denoting positive trends and 48 of which were statistically significant (Fig. 4.14c). SON has the second largest number of stations showing significant trends at 39 of 44 positive trends (Fig. 4.14d). It is interesting to note that for DJF there is a significant trend overall as discussed in Fig. 4.13a, however, the spatial distribution is a bit different, as only 25 significant trends of 30 stations that show negative trends (Fig. 4.13a).

It is interesting to note that for JJA, there are 4 stations that show statistically significant positive trends in diurnal range implying that the difference between maximum and minimum
temperatures is increasing. Interestingly, the positive trend comprises a bit more than half of the spatial signal in MAM, as 33 stations denote a positive trend in which 14 tested statistically significant (Fig. 4.14b). These effects do not to appear to be explained by elevation or proximity to a body of water as they are scattered amongst the distribution and suggest that regional local climates and terrain effects must be influencing the stations locally.

Further examination shows that many of the largest negative magnitudes in trends are observed within inland locations in DJF, JJA, and SON. The distribution of the results also show they are clustered in the western and northern areas of the Northeast study region with the exception again being the MAM season (Fig. 4.14). Further analysis on individual stations would need to be applied to determine if it is an increasing or decreasing trend in maximum or minimum temperatures.

4.4 Feature Analysis of Selected Stations

As an additional focus for the study region, further analysis of annual mean temperature trends was created for the purpose of examining several more individual station trends across the Northeast. Stations were chosen based on prominent trends. Fig. 4.15 shows 6 stations from the study region for maximum temperature. There are no trends found in the analysis for Rutland, Vermont or Central Park, NY (Fig. 4.15a,b). The regional spatial analysis of annual mean temperatures showed a station in northern interior New York, identified as Indian Lake, as having a negative trend annually and could be due to the high elevation of 509 meters (Fig. 4.3, Fig. 2.2). The results for this annual mean trend analysis in Fig. 4.15c indicates a significant trend of -0.12°C dec⁻¹ for the Indian Lake, NY station.
The southernmost station in our data set in Cape May, NJ, shows a positive trend for maximum temperatures with a cooling phase from the 1960’s through the 1990’s, in which a increase in annual mean temperatures is noted with an overall trend of 0.13°C dec\(^{-1}\) (Fig.4.15d). It should be noted that this location is also situated on the Atlantic coast as is the Edgartown, MA station which is located in the proximity of Martha’s Vineyard. This station also shows significant trends at 0.22°C dec\(^{-1}\) and also exhibits the same cooling trend through the 1950’s and then an increase through the 1990’s (Fig. 4.15e). This is a highly interesting result at is implies that coastal locations during this period may have been influenced by modes of variability with regards to sea surface temperatures. The last focused analysis shows an outlier negative trend in Warren, in northeastern Pennsylvania which was examined and is showing a trend of -0.09°C dec\(^{-1}\). The variability within this region increases after the 1990’s. These results would require further exploration to deduce the exact cause of the trends displayed locally, however they do offer that geographical factors such as coastal proximity, elevation and terrain may play contributing roles.

Further analysis of these stations for annual means in minimum temperatures are shown in Fig. 4.16. The analysis for Rutland, VT (Fig. 4.16a) denotes a significant negative trend of -0.11°C dec\(^{-1}\) and as was shown in Fig. 4.3 in the spatial analysis, this station is an outlier to the surrounding stations that show a statistically signal trend in minimum temperatures. This decrease in minimum temperatures creates a positive diurnal temperature trend signal for this station as the range is increasing between maximum and minimum temperatures. Central Park, NY (Fig. 4.16b) also indicates a strong trend of 0.2°C dec\(^{-1}\), and recall this station does not show a trend for maximum temperatures. The station in Indian Lake, NY that indicated a negative trend in maximum temperature shows a strong positive trend in minimum temperatures of 0.34°C
dec$^{-1}$, and thus a decrease in diurnal temperature range which is the strongest of the significant stations (Fig. 4.16c). Conversely, the coastal locations in this focused analysis such as Cape May, NJ shows no trend of minimum temperatures but a strong trend in maximum temperatures thus resulting in an increase in the diurnal temperature range (Fig. 4.16d). The strongest trend in minimum temperature in the spatial distribution of trends is in Edgartown, MA and indicates a trend of 0.48°C dec$^{-1}$, which recall is on the Atlantic coast near Martha’s Vineyard. It should be noted here that this location’s geographic shape is similar to a peninsula, thus the station being surrounded by the ocean influence offers a higher influence similar to the Cape May, NJ station which is also surrounded by the Atlantic coast. Our last focused analysis features a positive trend in Warren, PA of 0.11°C dec$^{-1}$, where the maximum temperatures were decreasing and thus shows a decrease in the diurnal temperature range.

Further analysis could be approached for the coastal locations of Lake Ontario which also show variations in maximum and minimum trends depending on the location. These results support the previous analysis of maximum temperature stations in which regional and local influences can drive the temperature changes. Further exploration of these mechanisms would need to be conducted to deduce the causes of these trends at specific stations.

4.4 Summary

An analysis of annual mean temperatures, annual mean anomalies, and diurnal temperature range were examined both spatially and seasonally. The analysis shows that there is a large coastal signature in warming trends and a weaker cooling trend inland which have been noted due to the differential between the specific heat capacity between the ocean and the land
which may act to increase or decrease trends (Trenberth et al, 2007). Additionally, key results are summarized below:

- Annual mean temperature trend analysis denotes that maximum temperature has increased significantly at 0.10°C dec⁻¹ and a trend is only found in MAM.

- Minimum temperature shows twice the rate of warming at 0.20°C dec⁻¹, and exhibit significant trends are shown in all seasons with JJA denoting the strongest trend.

- Spatial analysis of trends in the Northeast show 33 significant positive trends for maximum temperature and 53 significant positive trends for minimum temperature.

- Spatial analysis shows trends are most consistently positive along coastal regions and negative inland dampening the signal. This signature is seen seasonally for maximum temperature as well. Minimum temperature spatial analysis shows widespread trends in all seasons.

- Analysis of trends in diurnal temperature range indicate that 41 stations show a significant negative trend which was computed as -0.10°C dec⁻¹ for the overall region. Seasonal analysis showed significant trends in DJF, JJA and SON. The spatial analysis seasonally showed widespread distribution of negative trends. Stations that display positive trends see no change in minimum temperature.

- An analysis of six individual stations that showed prominent or unique trends show that geographical influences such as elevation, proximity to a coastline, or terrain do not produce a one solution cause for various trends.
The regional analysis of annual means from a seasonal perspective offered us insight into how the temperatures have changed. Additionally, spatial distributions showed that most coastal locations are warming for both maximum and minimum values. These results in mean temperatures may suggest that extreme temperatures are also trending positively. An analysis of extreme temperatures, extreme event frequency and various impact thresholds is discussed in the following chapter.
Figure 4.1: Spatial distribution of the average annual mean temperature (°C) for each station for a) maximum temperature and b) minimum temperature for the Northeast, United States.
Figure 4.2: Annual mean temperatures (°C) averaged over all stations for a) maximum temperature and b) minimum temperature for the years 1950 - 2019 with an annual trend line shown in black. Legends that display bold text represent statistically significant trends.
**Figure 4.3:** Spatial distribution of annual mean decadal trends (°C/dec) for a) maximum temperature and b) minimum temperatures. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 4.4: Annual mean temperature anomalies (°C) averaged all stations in the Northeast for a) maximum temperatures and b) minimum temperatures.
Figure 4.5: Annual mean diurnal temperature range (°C) averaged over all stations in the Northeast (grey), with an annual trend line shown in black. Legends that display bold text represent statistically significant trends.
Figure 4.6: Spatial distribution of the annual mean decadal trends (°C/dec) of diurnal temperature range. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 4.7: Annual mean temperatures (°C) averaged over all stations for maximum temperature during a) DJF, b) MAM, c) JJA and d) SON, for the years 1950 – 2019. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 4.8: Spatial distribution of seasonal annual mean maximum temperature trends (°C/dec) for a) DJF, b) MAM, c) JJA and d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 4.9: Annual mean temperatures (°C) averaged over all stations for minimum temperature during a) DJF, b) MAM, c) JJA and d) SON, for the years 1950 – 2019. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 4.10: Spatial distribution of seasonal annual mean minimum temperature trends (°C/dec) during a) DJF, b) MAM, c) JJA and d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 4.11: Seasonal annual mean maximum temperature anomalies (°C) for a) DJF, b) MAM, c) JJA, d) SON for the Northeast, United States. Anomalies were computed using the climate normal (1981-2010) baseline for each station and then averaged over all years.
Figure 4.12: Seasonal annual mean maximum temperature anomalies (°C) for a) DJF, b) MAM, c) JJA, d) SON for the Northeast, United States. Anomalies were computed using the climate normal (1981-2010) baseline for each station and then averaged over all years.
Figure 4.13: Seasonal annual mean diurnal temperature range (°C) for a) DJF, b) MAM, c) JJA and d) SON. Annual mean trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 4.14: Spatial distribution of seasonal annual mean diurnal temperature range decadal trends. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 4.15: Annual mean maximum temperatures (°C) for six specified stations: a) Rutland, VT, b) Central Park, NY, c) Indian Lake, NY, d) Cape May, NJ, e) Edgartown, MA and f) Warren, PA. Annual trend lines are shown in black.
Figure 4.16: Annual mean minimum temperatures (°C) for six specified stations: a) Rutland, VT, b) Central Park, NY, c) Indian Lake, NY, d) Cape May, NJ, e) Edgartown, MA and f) Warren, PA. Annual trend lines are shown in black.
5. Extreme Temperatures and Events in the Northeast, US

5.1 Northeast Mean Extreme Temperatures

The regional analysis for changes in extreme temperatures in the Northeast, US is examined using the same analytical approach for the Albany, NY station data analysis. To define an extreme temperature we used the 99th percentile for each station in the data set for both maximum and minimum temperatures. The regional analysis computed the mean of the 99th percentile of each year over all stations to compute a trend for the Northeast, US. Additionally, the spatial analysis shows individual trend analysis for the 99th percentile at specific stations. Further analysis of cool extremes defined as the 1st percentile, were not implemented in this analysis.

The overall station averaged annual mean 99th percentile distribution in the Northeast provides a perspective on how the extreme values are distributed across the region for each station. Figure 5.1 displays the mean 99th percentile over all years for each station for a) maximum temperature and b) and minimum temperature. Consistent with the results found in section 4.1.1, the spatial distribution of average station temperature shows the maxima values occur near or along the Northeast coastline and in southern Pennsylvania (Fig. 5.1). A notable hotspot is found in the cluster of stations in and around the New York City region and potentially displays the urban heat island effect as does the cluster near Boston, MA, although these means are not as large for both maximum and minimum temperatures (Fig. 5.1). These results highlight a gradient in the spread of values of warmer temperatures along the coastal regions and cooler mean inland suggesting that the trends of the magnitude of extreme events may be larger along coastal zones.
5.2 Extreme Temperature Analysis

5.2.1 - Changes in Extreme Temperatures

An analysis of the mean 99th percentile averaged over all the stations in the Northeast gives us an overall trend for the region and is shown in Fig. 5.2. It is of interest to note that the maximum extreme temperatures are not trending positive, but the overall annual mean temperature has increased (Fig. 4.2). This might suggest that there is a shift in the frequency of warmer temperatures that do not exceed this 99th threshold, suggesting a warming trend in annual means, but not extremes. As expected, the magnitude of extremes has increased for minimum temperatures at a statistically significant rate of 0.20°C dec⁻¹ which shows a total change of about 1.4°C over the study period.

Further analysis of the spatial distribution of the decadal trends in the 99th percentiles indicate that for maximum temperature, only 9 stations have a positive trend while 6 display a negative trend (Fig. 5.3a). Many of the larger trends in the 99th percentile for maximum temperature were along the Atlantic coast with the negative trends appearing further inland (Fig. 5.3). This distribution acted to mute the combined regional average trends.

The distribution of trends for minimum temperature shows a very prominent positive significant trend in nearly all stations. One case of a statistically significant negative trend was once again found in Rutland, VT for minimum extreme temperature trends (Fig. 5.3b). The distribution for extreme minimum temperatures denotes 51 positive significant trends (Fig. 5.3b). The largest trends are found in eastern Massachusetts, Rhode Island, and southern Vermont. This analysis shows that the annual mean minimum temperatures are not only trending warmer, but the magnitude of the extremes is also changing which was not the case for maximum
temperatures in the Northeast. This suggests that the warmest overnight minimum temperature’s, are increasing in the last seventy years.

5.2.2 Changes in Extreme Event Frequency

To further explore how the frequencies of extreme events have changed; an analysis was performed where the average 99th percentile over all the stations for all years was used as a threshold definition. The maximum temperature threshold is 31.95°C and the minimum threshold was computed as 19.85°C. These values are used to count the number of times a year this threshold is met. These results are shown for maximum and minimum temperatures in Fig. 5.4. The trend analysis denotes no significant change in maximum temperatures. Conversely, minimum temperature extreme frequencies show impressive significant trend of .85 events dec\(^{-1}\) for a total change of 5.95 events for the study period (Fig. 5.4b). These results support the evolution of maximum temperatures extremes to be minute in both magnitude and frequency however, significant trends in the magnitude and frequency of extreme events is evident for minimum temperature (Fig. 5.4b). This implies that the numbers of extreme warm nights are increasing in frequency over the Northeast, US on average.

The spatial distribution of decadal trends in extreme event frequencies shows that maximum temperature extremes are increasing in magnitude most significantly along the coastal regions, while inland regions show negative trends (Fig.5.5a). Scattered increases are found in minimum temperature extreme events but most positive significant increases are found along the coastal region as was the case for maximum temperatures (5.5b). These results show how the average evolution of temperatures is influenced by geography as many of these trends appear to be the result of influence by sea surface temperatures (Trenberth et al, 2007).
5.3 Seasonal Changes in Extreme Temperatures

5.3.1 Analysis of the Changes in Extreme Temperatures

Seasonal analysis of extreme temperatures provides further insight regarding the evolution of extremes for maximum and minimum temperatures through the year. The case study for Albany, NY demonstrated that trends in extremes were seasonally dependent for maximum temperature showing no overall annual trend but statistically significant trends exist in DJF and MAM (Section 4.3). Fig. 5.6 provides a seasonal perspective of the 99th percentile for maximum temperature averaged over all stations. These results show that both DJF and MAM show trends that are both statistically significant at rates of 0.29°C and 0.21°C dec⁻¹, respectively. This demonstrates that the distribution of the maximum extremes is increasing in only two seasons but is substantial enough to increase the annual mean extreme trend for maximum temperature.

Figure 5.7 shows the spatial distribution of decadal trends and highlights the prominent warming signal for maximum temperature warm extremes in DJF where all stations exhibit a positive trend (Fig 5.7). The magnitudes of these trends however, are not consistent spatially as many of the significant positive trends are distributed along the coastal states and interior New York, eastern Pennsylvania, Vermont and New Hampshire. In all, 31 stations show a statistically significant warming trend in DJF, supporting the results found above in Figure 5.6a. Consistent with these findings, MAM denotes that 27 stations show statistically significant warming?. Stations located north of 43°N exhibit cooling in stations during MAM which dampens the overall average regional signal. The spatial distributions for JJA and SON show that most of the western inland stations show moderate to strong cooling trends. These trends are nearly non-existent in Fig.5.6c,d). The coastal warming signature of extremes and inland cooling of extremes where localized trends are masked by the annual mean signal (Fig. 5.7,c,d)
The seasonal analysis for minimum temperature extremes presents a more cohesive signal with all seasons displaying positive trends and tested statistically significant except for DJF, despite the trend of 0.19°C dec⁻¹ being within the range of the other seasons (Fig.5.8). The signal is strongest in both MAM and JJA at 0.22°C dec⁻¹, yet the variability in the two seasons are different (Fig. 5.8b,c). Results did not show a trend for SON. These results indicate that the warming signal is notable in all seasons with maximum trends found in MAM and JJA.

The 99th percentile decadal trends for minimum temperature are shown in Fig. 5.9 and show a positive trend at nearly all stations in all seasons. There is a subtle north-south trend gradient seen in DJF, where northern latitude stations exhibit a cooling trend or very weak warming trends in the extremes (Fig. 5.9). Moreover, the stations south of the 42°N latitude favor warming trends with 15 statistically significant trends (Fig. 5.9a). There were 30 statistically significant trends found in 60 of the warming stations for MAM and of the 61 stations in JJA of which fifty of the stations show a statistically significant trend (Fig.5.9a,b). These results imply that the warmest overnight minimum temperatures are increasing in magnitude. SON features 25 statistically significant trends displaying the stronger magnitude of change along the coastal stations consistent with JJA.

This implies that extremes are not only increasing in magnitude by season, they are regionally dependent as well. This may be indicative of localized signals for stations near the coast suggesting again thermodynamic influences are trends along the coast in both mean and extreme temperatures. Additionally, our results show increases in the magnitude and frequency of extreme events clustered around major city centers where the effects of the urban heat island may act to amplify these trends (DeGaetano and Allen, 2002 , Peterson et al, 2008). Further analysis is required to deduce the cause of these local trends.
5.3.2 Analysis of Changes in Frequency of Extreme Events

The previous analysis presented results in trends of maximum and minimum extreme temperature magnitudes giving insight into how the average 99th percentile was evolving by season. These results however, do not offer a perspective on how the frequencies of these events have changed over the different seasons. To further explore how the frequency of extreme events have changed over the study region a single threshold was derived based on the seasonal mean 99th percentile value at each station averaged over all stations. Figure 5.10 presents results of this analysis that the range of frequency of events shows that the number of days that this extreme threshold for maximum temperature is met is increasing in DJF and MAM at 0.28 and 0.25 events dec⁻¹ respectively (Fig. 5.10a,b). The frequency of events meeting this threshold do not show significant trends for JJA or SON consistent with the results of the analysis magnitude of extreme events as discussed in the previous section (Fig 5.10c,d).

The spatial distribution of these results is shown in Figure 5.11 for decadal trends for each location over all seasons. The results indicate that the frequency of extreme events is increasing most consistently at stations within proximity to the Atlantic coast in all seasons that show increasing statistically significant trends (Fig. 5.11). The spatial pattern of trends is consistent in DJF and MAM showing subtle non-significant trends to slightly negative trends in northern latitudes but increases in southern latitudes and in stations within proximity to the coast (Fig. 5.11a,b). While the coastal signal is consistent for increases in JJA, the interior Northeast shows a large number of stations with weak cooling among many stations in which several denote significant trends (Fig.5.11c). The spatial trends in SON support the findings in Fig. 5.10d, where the trend is nearly nonexistent at most stations with only a few notable statistically
significant trends scattered along the coast. The trends in coastal locations should be noted for their upper limit trend values in JJA, as this signal is very strong considering nearly half the stations show a decreasing trend in the frequency of warm extreme events.

The same approach as used for minimum temperatures to deduce how extremes are changing in frequency over the seasons and the results of an averaged analysis are shown in Fig. 5.12. Trends are found to be positive and statistically significant in each season at 0.27 events dec\(^{-1}\), 0.33 events dec\(^{-1}\), 0.75 events dec\(^{-1}\) and 0.23 events dec\(^{-1}\) for DJF, MAM, JJA and SON respectively (Fig. 5.12). These results show the number of times the extreme event threshold for each season was met is increasing for minimum temperatures. The spatial distribution of the frequency of these events, are shown in Fig. 5.13. A prominent result from the analysis is that the range of trends is highly skewed in this presentation and denotes that the largest shift in frequency of minimum temperatures is JJA as to be expected with a station averaged trend of 0.75 events dec\(^{-1}\) (Fig. 5.13c, Fig. 5.12c). The signal is dampened in the other seasons and yet, the increases in frequency of extreme events in DJF is consistent with maximum temperature extremes in that they are along the coastal regions and southern portions of the study region. These results indicate that once again, the biggest change in the magnitude and frequency of extreme temperatures is occurring for minimum temperature in JJA and the strongest trends occur along the Atlantic coast indicating that the overnight minimum temperatures along the southern Northeastern Atlantic coast are experiencing more extreme warm nights during JJA.

5.4 Frequency of exceeding impactful thresholds

The definition used in the above analysis shows how the distribution of the most extreme events occurred as using a threshold defined as the 99\(^{th}\) percentile. This computed value for the threshold is just a bit larger than that of a widely recognized 90°F (32.2°C) temperature threshold
commonly noted as a threshold value for heatwaves. Further inspection of various thresholds is shown in Fig. 5.14 in which common warm day Fahrenheit thresholds of 85°F (Fig. 5.14a), 90°F (Fig. 5.14b) 95°F (Fig. 5.14c) are shown in degrees Celsius (°C) as trends in extreme event frequencies. The results support the frequency event distribution for maximum temperatures shown above in Fig. 5.13 in which many of the interior northeast stations show decreases and coastal areas are showing increases once again further supporting the influence of the Atlantic ocean on warming means, extremes and frequency of extreme events (Trenberth et al, 2007).

To expand the analysis from section 3.3 of the first frost occurrence for Albany, the same analysis was applied to deduce decadal trends in the first frost occurrence at each station in the study region. The findings are presented in Fig. 5.15 and show a very distinct and positive trend in 31 stations that of to be statistically significant trends. Additionally, it should be noted that a large majority of the stations indicate a trend of greater than 3 days dec⁻¹ suggesting that as an approximate estimate the total change of the first frost occurrence has been about 21 days (Fig. 5.15). The distribution of magnitudes in the rate of change for the first frost occurrences do not seem to show any pattern other than a north – south gradient with very few outliers of weak or negative trends. These results have certain implications regarding the changes in the length of the growing season in the Northeast. It should be highlighted that these results only represent that of the seventy0year period chosen and are not indicative of first frost occurrences outside this time period and other records may exist that change this distribution over a longer period. From this analysis it is clear however, that the trend in the first frost occurrence is trending towards a later date in most of the region.
5.5 Summary

The analysis in this chapter has shown that for the seventy year period chosen for the stations included in this Northeast analysis, the magnitude positive trends in extreme events is seasonally and spatially dependent. A summary of the key findings is noted below:

• Analysis of extreme temperatures, defined as the 99th percentile, denote no trend for maximum temperatures but significant trends in DJF and MAM. Results display a significant trend for minimum temperatures of 0.20°C dec⁻¹, and trends exist in MAM, JJA and SON.

• Spatial analysis indicates a warming signal along the Atlantic coast in which 30 stations show a positive trend and cooling signal inland. Minimum temperatures denote 53 stations show positive trends a widespread 53 positive trends.

• Seasonal analysis shows trends in DJF and MAM for maximum temperature and spatial station analysis shows 31 and 27 positive trends, respectively. Trends exist in MAM, JJA and SON for minimum temperatures and show 50 stations with positive trends for JJA.

• Analysis of extreme event frequency show that maximum temperatures are increasing in frequency in DJF and MAM, but no trend annually. Minimum temperatures show trends in all seasons and an annual trend of .85 events dec⁻¹

• Spatial seasonal analysis of extreme event frequency shows the greatest change is in JJA, with stations exhibiting strong trends clustered mostly along the Atlantic coast.

• There is an evident coastal signal where the there are positive trends in the frequency of extreme events, many of which are found at coastal stations.

• Analysis of the first frost occurrence over the region show 31 significant positive trends in a later first frost over the Northeast. Most stations indicate a trend of 2 – 4 days per decade across the region.
The regional spatial analysis showed anomalous outliers in the trends of the data geographically offer further opportunity for study to deduce how localized effects are affecting the individual stations that show varied trends in changes. Such an example is Rutland, Vermont in which a statistically significant negative trend in minimum temperature is found amongst a region of warming signal. The results of the increase in extreme temperatures is consistent with the findings of previous studies which found that increases in the magnitude and frequency of extreme events would be dependent upon local, regional and seasonal influences (IPCC 2013, DeGaetano and Allen, 2002, Donat et al, 2014, Hansen et al, 2012). The results of this analysis conclude that the changes in extreme magnitude and events are most significant and prevalent for minimum temperatures.
Figure 5.1: The averaged annual mean (°C) 99th percentile at each station for a) maximum and b) minimum temperature.
Figure 5.2: Annual mean 99th percentile (°C) averaged over all stations for a) maximum temperature and b) minimum temperature. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 5.3: Spatial distribution of the decadal trends in the 99th percentile (°C/dec) at each station for a) maximum temperature and b) minimum temperature.
Figure 5.4: Annual extreme event frequency averaged (events/dec) over all stations for a) maximum temperature and b) minimum temperature. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 5.5: Extreme event frequency trends (events/dec) as defined in the text for a) maximum temperature and b) minimum temperature. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 5.6: Seasonal mean 99th percentiles (°C) averaged over all stations for a) DJF, b) MAM, c) JJA, and d) SON. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 5.7: Spatial distribution of the decadal trend in the 99th percentile (°C/dec) for maximum in a) DJF, b) MAM, c) JJA, and d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
**Figure 5.8:** Seasonal mean trends in 99th percentiles (°C) of minimum temperatures averaged over all stations for a) DJF, b) MAM, c) JJA, and d) SON. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 5.9: Spatial distribution of the decadal trend in the 99th percentile (°C/dec) for minimum temperatures in a) DJF, b) MAM, c) JJA, and d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 5.10: Seasonal mean extreme event frequency (events/dec) for maximum temperature averaged over all stations for a) DJF, b) MAM, c) JJA, and d) SON. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 5.11 Spatial distribution of the decadal trend (°C/dec) in the extreme event frequency for maximum temperatures in a) DJF, b) MAM, c) JJA, and d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 5.12: Seasonal mean extreme event frequency (events/dec) for minimum temperature averaged over all stations for a) DJF, b) MAM, c) JJA, and d) SON. Annual trend lines are shown in black. Legends that display bold text represent statistically significant trends.
Figure 5.13 Spatial distribution of the decadal trend (°C/dec) in the extreme event frequency for maximum temperatures in a) DJF, b) MAM, c) JJA, and d) SON. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 5.14: Extreme Event thresholds frequency trends (°C/dec) for a) 29.4°C, b) 32.2°C and c) 35°C. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
Figure 5.15: Spatial distribution of the decadal trend (days/dec) in the first frost occurrence. Stations indicated by a star marker denote a statistically significant trend and circle markers represent trends that are not statistically significant.
6. Summary and Conclusions

6.1 Summary of Albany, NY Station Data Analysis

This analysis provided a focused perspective of temperature changes for Albany, NY. A comprehensive analysis of temperature trends of annual means, extremes and thresholds were studied. A summary of the key findings for Albany are:

- Annual mean temperatures in Albany, NY show positive trends for maximum and minimum temperatures. A greater increase in minimum temperatures has resulted in a negative trend in the diurnal temperature range.

- Extreme maximum temperatures show no trend annually, but they do have a positive trend in spring. Extreme minimum temperature showed a significant positive trend annually.

- The frequency of extreme events show a trend during spring for maximum temperature and a strong for minimum temperature extreme events and seasonal trends are shown in winter, spring and summer.

- An analysis of trends in the date of the first frost occurrence shows a statistically significant positive trend of 3.34 days dec$^{-1}$, indicating that the first date of frost is later in the fall. This result has significant implications for agriculture and energy production.

The prominent findings from this analysis for Albany, NY were that trends in the magnitude of mean and extreme temperatures were not changing uniformly for maximum and minimum temperatures. Additionally, trends were shown to be different across seasons. The overall results for Albany showed that the greatest changes were found for trends in minimum temperatures. These results were consistent with the findings of previous studies that indicated
changes in the magnitude of mean and extreme temperatures were not consistent globally, or even regionally (IPCC 2013,

6.2 Summary of Northeast Regional Analysis

The analysis of stations in the Northeast, US highlighted regional variations in annual mean temperature trends and extremes. The analysis included analysis of anomalies and diurnal mean temperature range. This analysis was also performed from a seasonal perspective. The analysis shows that for the Northeast, US maximum and minimum temperatures were found to be increasing at a rate of 0.10˚C dec⁻¹ and 0.20˚C dec⁻¹ respectively. Seasonal analysis shows that the mean for maximum temperatures is driven by the changes in MAM while minimum analysis shows positive statistically significant trends in all season but SON.

Changes in extreme temperatures were explored by analyzing trends in the 99th percentiles for maximum and minimum temperatures. The increase in the magnitude of events is more prominent in DJF and MAM for maximum temperatures. The positive trend is apparent in all seasons for minimum temperatures suggesting that the changes are more coherent for minimum temperature. Moreover, it is shown that trends in maximum temperature extremes are occurring more frequently and in greater magnitude along the Northeastern coast of the study region suggesting that extreme temperatures are being influenced by local sea surface temperatures. A summary of key findings for the regional analysis is presented below:

• Annual mean trend analysis for maximum temperature denotes a significant trend of 0.10˚C dec⁻¹ and a trend is only found in spring. Spatial analysis shows the greatest trends in many cases are found in proximity to the Atlantic coast or the Great Lakes although interior positive trends do exist as well.
• Annual mean trend analysis for minimum temperature show a significant warming trend of 0.20°C dec⁻¹, and trends are found in all seasons. The spatial analysis shows widespread warming trends both in the interior and along the coasts of the study region.

• Trend analysis for the diurnal temperature range show a negative trend although trends do not occur in all seasons. A spatial analysis showed widespread decreases in the diurnal range across the region with the weakest signal of change during spring.

• Maximum extreme temperature trend analysis displayed that the magnitude of extremes were increasing in winter and spring. Additionally, the frequency of these events also show an increase in both winter and spring.

• Minimum extremes temperature trend analysis displayed the greatest increases in magnitude in spring, summer and fall. The frequency of these minimum extreme events show positive trends in all seasons.

• The spatial distribution of the trend in the magnitude and frequency of extreme events shows that for maximum temperatures there is a coastal warming signal and for minimum temperature the signal is widespread across the region.

• An analysis of the first frost occurrence was performed and found 31 stations with significant positive trends indicating that the first frost is now occurring later almost all over the region.

These results indicated that the changes in temperature trends in the Northeast, US were not spatially or temporally uniform and exhibit even localized differences in trends. Minimum temperatures showed the most consistency annually and seasonally over all stations; with
frequent warming trends. The results are consistent with previous findings that minimum temperatures are warming more steadily than maximum temperatures (Donat et al, 2014, Hansen et al, 2012, IPCC, 2013).

In addition to regional trends the spatial distribution indicated that there are greater increases in the magnitude and frequency of extreme events along the Atlantic and Great Lakes coasts. Additionally, previous studies have also indicated that regional changes in maximum and minimum temperature trends varies on large scale, to regional to local scales and shows no temporal or spatial uniformity (DeGantaeo and Allen, 2012, Hansen et al 2012, Lee et al 2014, IPCC 2013). These results support the consensus that warming trends are not regionally uniform.

**6.3 Conclusions**

The research presented in this thesis focused on the evolution of temperature trends and changes in annual mean temperatures, extreme temperatures, extreme thresholds, and the frequency of extreme events over the Northeast, US. The study region included New York, Pennsylvania, New Jersey, Connecticut, Rhode Island, Massachusetts, Vermont, New Hampshire and Maine. The objective of balancing the spatial density of station data with the temporal time series was important in maximizing the analysis of change in temperatures. The period 1950 - 2019 was chosen as the number of stations beyond the 70 year period decreased spatial distribution too greatly. The data set included 63 stations from the GHCN data network including both weather stations and cooperative observing network sites in which less than 5% of the data was missing and consecutive data gaps didn’t extend beyond a full season. This multi-decadal analysis of trends in temperatures provided an analysis of how temperatures have evolved over the last 70 years. The following key findings are presented as follows:

- Maximum temperatures are increasing at half the rate of minimum temperature annually.
Minimum temperature shows the most widespread increase in all analyses in all seasons. The greatest change is found in summertime minimum temperatures.

Trends are not uniform spatially or temporally. Warming signals are noted along Atlantic and the Great Lakes coastlines; most significantly for extreme temperatures.

Trends in threshold events that represent warm temperatures are increasing in frequency most prominently along the Atlantic coast and trends in cold temperatures such as the first frost occurrence show a significant trend later for the first day of frost occurrences over the region.

The research presented in this thesis presents that minimum temperatures are changing the greatest over the Northeast region in all trends and at the rate of twice that of maximum temperatures. This trend of warming minimum temperatures is noted in the literature and is attributed to a number of factors including, but not limited to localized changes in cloud cover, soil moisture, land use and urban heat island effect (Dai et al, 1999, Hansen, 2010, IPCC 2013, Patterson et al, 2008). It has also been found that the minimum temperatures are more prone to the changes in radiation balance due to increases in concentration of greenhouse gases in the planetary boundary layer and are noted to be more sensitive to greenhouse gases in the planetary boundary layer (Dai et al, 1999 and Davy et al, 2017). These results support further inspection of regional analysis and changes of temperature trends and the attribution to what is causing the observed changes to deduce how temperatures may continue to change.

6.4 Future Work

Future work motivated by this analysis could include a more comprehensive view of the extreme temperatures for cool extremes as was done for Albany, NY. This would require the same approach as the regional analysis with the 1st percentile for both maximum and minimum
temperatures which would then offer a broader perspective of how the changes in cold and warm days and cold and warm nights were changing over the study period. Increasing the study period with less spatial density and conversely, decreasing the study period by increasing station density could offer additional insight how regional temperatures are changing. Additionally, further research for outlier stations such as Rutland, VT is needed to deduce the cause of the localized outlier trends. Furthermore, analysis of consecutive day threshold events could be expanded in scope for the study region on multiple thresholds and length of days. Lasly, further research into the mechanisms causing the regional and localized trends in temperatures may offer a perspective on how future temperatures will change in the Northeast, US.

The results have shown that temperatures are not changing uniformly as there are differences at the regional and local scale. The results indicate that further research is needed on regional and local scales to fully capture the evolution of annual mean temperatures, extremes, and the frequency of extreme events. The results found in this research offer further support that regional changes in temperatures are not spatially or temporally uniform and offer a perspective of how temperatures may continue to change in the Northeast, US under anthropogenic climate change.
REFERENCES


https://doi.org/10.1175/1520-0442(2002)015%3C3188:TITCTE%3E2.0.CO;2


https://doi.org/10.1175/1520-0442(1990)003%3C1254:LSACFO%3E2.0.CO;2


https://doi.org/10.1175/JCLI-D-13-00405.1


