Winter 2007

Trends in wintertime climate variability in the northeastern United States

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TRENDS IN WINTERTIME CLIMATE VARIABILITY IN THE NORTHEASTERN UNITED STATES

BY

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BA, Wellesley College, 2003

THESIS

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DEDICATION

This thesis is dedicated to my parents, my sisters, my friends, and to everyone who appreciates the characteristic seasonality of the northeastern United States and hopes that our winters will remain snowy and white for future generations.

ACKNOWLEDGEMENTS

I would like to thank my committee members for their continued support over the past two years. Dr. Rob Braswell, for helping me to learn programming in MATLAB and performing statistical analyses, Dr. David P. Brown, for meteorological insights and assisting me in navigating the USHCN and COOP climate data websites, and Dr. Cameron Wake for providing me with inspirational outreach opportunities and encouragement to keep moving forward.

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ABSTRACT

TRENDS IN WINTERTIME CLIMATE VARIABILITY IN THE NORTHEASTERN UNITED STATES: 1965-2005

by

Elizabeth A. Burakowski

Cameron Wake, Advisor, University of New Hampshire, December, 2007

Humans experience climate variability and climate change primarily through changes in weather at local and regional scales. In this work, changes in northeastern United States winter climate are documented using meteorological observations from 1965-2005. Spatial coherence analysis is utilized to remove stations with non-climatic influences from the analysis. Trends over the past four decades in snowfall, snow-covered days, mean, minimum, and maximum temperature are estimated using linear regression.

Northeastern United States regional winter maximum temperatures (+0.43 ±.08°C/decade) are warming greater rate than minimum (+0.37 ±0.10°C/decade) and mean (+0.39 ±0.10°C/decade. Regional winter snowfall decreased by -2.5 ±0.8 inches/decade. Overall snowfall is decreases are greatest in December (-2.3 ± 0.5 inches/decade) and February (-1.1 ±0.2 inches/decade). The reduction in winter snow-covered days (-2.6 ±0.7 days/decade) is likely tied to increases in winter maximum temperature via a snow-albedo feedback. These results have important implications on the climate system, ecosystems, and society in the northeastern United States.

CHAPTER I

INTRODUCTION

Recent detailed analysis has shown that global climate change over the past three to four decades is being driven primarily by enhanced levels of greenhouse gases in the atmosphere that originate from the burning of fossil fuel and land use changes (IPCC, 2007). Warmer spring temperatures are linked to large reductions in northern hemisphere mid-latitude snow cover extent from 1966-2004 during the months of March and April (Lemke et al. 2007). Snow climatology is an important indicator of climate change at the regional scale due to its strong relationship to temperature via the albedo feedback loop (e.g., Groisman et al. 1994). The albedo (reflectivity) of snow ranges from 0.8 for fresh snow to 0.3 for old snow (Marshall 1989). A small perturbation in the climate system that leads to an increase in temperature causes snow to melt and compact, leading to a decrease in albedo. When this happens, a positive feedback loop ensues, enhancing warmer temperatures that further reduce snow cover.

Significant changes in snow cover depth and extent over time can impact a region's hydrology, ecology, climate, and economy. The northeastern United States is vulnerable to a broad range of impacts due to winter warming. In this study, historical trends in snow cover, snowfall, and temperature are developed and analyzed for the northeastern United States using surface observational data.

The Northeastern United States Changing Winter Climate

This study focuses specifically on past changes in winter climate in the northeastern United States (NE-US), which includes the states of Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. An investigation of changes in winter climate is essential for assessing regional ecological and economic impacts.

Climatic gradients in the NE-US are defined primarily by three natural factors: topography, proximity to the ocean, and latitude (Zeilinski and Keim, 2003). Orographic uplift of air masses in the mountainous zones leads to greater precipitation compared to regions at lower elevations. Higher elevations also experience colder temperatures and higher winds. The relatively warm ocean waters cause maritime zones to experience milder winters, particularly along the southern shore, which is warmed by Gulf Stream waters. Lake Erie and Lake Ontario, when not ice-covered, provide substantial moisture for lake-effect snow in northwestern Pennsylvania and western New York. The latitudinal gradient in average winter temperatures results from the lower angle of incoming solar radiation and the decrease in day length from south to north.

Analysis of NE-US observational records indicates that annual temperatures are warming, and that winter temperatures have shown the greatest seasonal rate of warming (Wake and Markham 2005; Wake et al. 2006;

Hayhoe et al. 2007). The annual and seasonal temperature trends for the region as a whole were calculated using monthly United States Historical Climatology Network (USHCN). The data are the best available and have undergone extensive quality control measures and adjustments to ensure they characterize actual variability in climate. The regional trends were obtained by calculating the mean for all station data in each of the 34 National Climatic Data Center (NCDC) climate divisions (Guttman and Quayle 1996) in the northeastern US, then using the climate division means to calculate the area-weighted regional mean. Temperature trends were represented by 73 USHCN stations covering 94% of the total area of the study region. The analysis determined that winter (December, January, February) temperatures have warmed at a rate of 0.12°C/decade over the period 1900-1999, and the rate of winter warming has increased substantially to 0.7°C/decade over the period 1970-1999 (Hayhoe et al. 2007). The snow albedo feedback mechanism may be playing a significant role in winter warming in the northeastern United States where snow pack tends to be shallow.

Surface observations taken at remote high elevation stations offer a unique perspective on regional climate change because their location subjects them to both boundary layer and free air processes. Analysis of the temperature record at Mount Washington in New Hampshire, the highest peak in the NE-US (elev. 1914 m above sea level), identified a statistically significant increase in mean temperature (~0.3°C) and a decrease in the diurnal temperature range

(~0.15°C) over the period 1932-2003 (Grant et al. 2005). Trends in the latter part of the century (1980s and 1990s) were found to be relatively warm, in agreement with North American decadal trends.

The effects of winter warming are apparent in NE-US river and lake hydrology. In rivers and streams in the northern half of the region, snowmelt dominates the pattern observed in the annual hydrological cycle. The center of volume date (the date on which half of the flow occurring between 1 January and 31 May has passed the stream gauge) for unregulated rivers in northern New England occurred 7-14 days earlier during the period 1970-2000 compared to the period prior to 1970 (Hodgkins et al. 2003). The center of volume dates were most strongly correlated with March and April air temperatures. In addition, monthly mean runoff showed increasing trends over the same period during January, February, and March, which is consistent with the advancement in the center of volume date (Hodgkins and Dudley 2006). The timing of spring lake ice-out has advanced by 9 days in northern New England and 16 days in southern New England over the period 1850-2000 (Hodgkins et al. 2002).

Annual and winter snow-to-total precipitation ratios have decreased across New England, largely due to a decrease in winter snowfall (Huntington et al. 2004). Across North America, a significant decrease in winter snow cover extent is likely a result of earlier spring melt and a decrease in the extent of deeper snow packs (Dyer and Mote 2006; Hughes and Robinson 1996; Brown 2000).

The NE-US ski industry generates approximately three billion dollars per year in visitor spending and tax revenue (Scott et al. 2007). This revenue is especially important for mountainous states like New Hampshire, Vermont and Maine, which all rank in the top ten states that benefit from winter skiing as a percentage of the state's economy (National Ski Association; US Bureau of Economic Analysis 2007). Economic impacts in the NE-US will largely be experienced in the tourism sector. For example, a successful winter tourism season in the NE depends on adequate precipitation falling as snow, and temperatures staying cold enough to keep snow on the ground. Warmer winters with less than average snowfall and snow depth have reduced profit margins of ski resorts in the NE-US because more funds have been diverted to snowmaking, which has led to the closure of many small resorts (Hamilton, 2000). New Hampshire, ranked in the top five states that benefit from the ski industry as a percentage of the state's economy, loses an average $13.1 million dollars from the decline in sales of alpine and Nordic ski tickets and snowmobile registrations during warm, slushy winters compared to cold, snowy winters (Wake et al., 2006). In the context of climate change and global warming, winter tourism and recreation in the northeastern United States will experience negative economic impacts resulting from diminished snowfall and over successive years in response to increasing winter temperatures.

Further evidence of changing wintertime climate is provided by the change in hardiness zones for plants. The 1990 USDA hardiness zones are based on average annual lowest temperatures recorded during each of the years 1974-1986, using 10°F increments. In 2006, the Arbor Day Foundation updated the hardiness zone map using average annual lowest temperature for the period 1990-2005. When compared to the USDA 1990 hardiness zone map, a northward shift in annual low temperatures is revealed (Figure 1-1). The biological response to this northward shift in hardiness zones has been documented in the earlier timing of bloom dates for a variety of NE flora, including lilacs, apples and grapes (Wolfe et al. 2005).

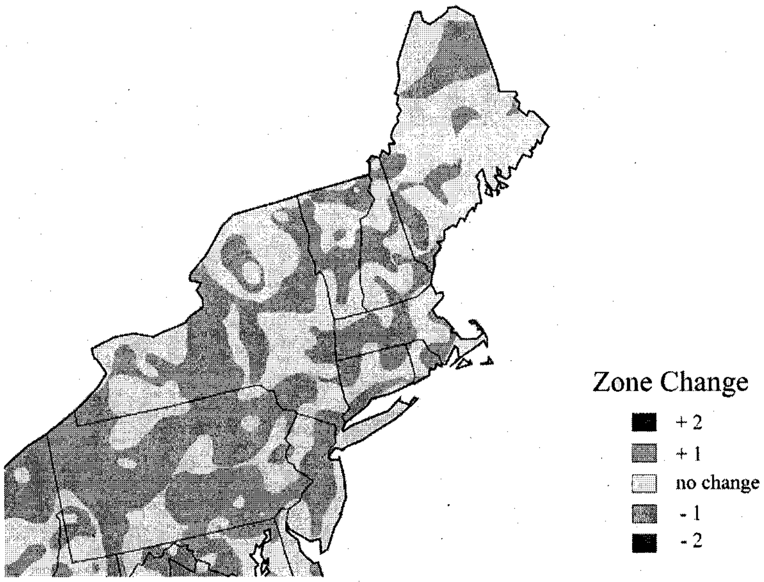

Figure 1-1. The difference between the 1990 USDA Hardiness Zone map and the 2006 Arbor Day Hardiness Zone map. The zones are created based on average annual lowest temperatures recorded at 5000 Cooperative Stations across the United States.

Projected Climate Changes

When compared to the past century's instrumental record, coupled atmosphere-ocean general circulation models (AOGCMs) accurately recreate the global climate response to a variety of natural (solar, volcanic) and anthropogenic (greenhouse gas and sulfate emissions, land-use changes) radiative forcing factors (IPCC, 2007). Trends in observed global temperature for the period 1990-2006 were found to follow the upper limit of climate projections published in the 2001 IPCC Assessment Report, despite CO_2 concentration projections following observations almost exactly (Rahmstorf et al. 2007). Given the conservative nature of climate projections, AOGCMs will continue to be integral in assessing the global ecological and economical impacts in a world warmed by anthropogenic greenhouse gases.

The coarse resolution of AOGCMs ($1^\circ \times 1^\circ$ grid cells) makes it difficult to project climate responses at the regional scale, where steep gradients in topography and coastal influences may either diminish or augment the global trend. In a recent regional study, output from nine atmosphere ocean general circulation model (AOGCM) simulations of historical climatology were compared to reanalysis and observational NE-US climate records (Hayhoe et al. *submitted*). The historical model simulations correspond to the CMIP "Twentieth Century Climate in Coupled Models", or 20C3M scenarios. These represent each modeling group's best efforts to reproduce observed climate over the past century. The AOGCM scenarios included both natural (i.e. changes in solar output, volcanic aerosols) and anthropogenic forcing (i.e. greenhouse gas emissions, sulfate aerosols from burning of fossil fuel) factors. The models reasonably reproduced regional atmospheric circulation patterns, such as the position of the jet stream and common storm tracks, and broadly simulated the long-term warming trend observed in NE-US annual temperature. However, the models failed to capture the recent (1970-1999) winter warming trend identified in Hayhoe et al. (2007). The observed linear trend in winter was 0.74°C/decade, while the model average was 0.13 ± 0.34 °C/decade. The underestimation may be due to poor resolution of snow cover in the models, and thus the models' representations of the snow-albedo feedback loop may need improvement. A regional decrease in snow cover (Wake and Markham, 2005; Wake et al. 2006) may also be linked to the rise in winter temperatures via the snow-albedo feedback loop.

The continued documentation of winter climate trends is essential to understand the cause of rapid winter warming in this region. In this study, we aim to update winter climate trends to include snowfall, minimum, maximum and mean temperature, and snow cover data through 2005. In addition, the meteorological data has undergone several extensive quality control measures to ensure that the records are of highest quality and completeness. Seasonal and monthly trend identification is evaluated with attention to the sensitivity of the time series start date, ranging from 1965 to 1975.

CHAPTER II

DATA AND METHODS

Climate Data

Monthly USHCN Data (NDP-019)

The United States Historical Climatology Network (USHCN) is a high-quality data set compiled by the National Climatic Data Center (NCDC), and is available for download at the Carbon Dioxide Information and Analysis Center (CDIAC) (Easterling et al., 1996; Williams et al., 2006). The USHCN has been developed over the years to assist in the detection of regional climate change, and has been widely used in analyzing U.S. climate (e.g., Easterling, D. R. 2002; Huntington et al. 2004; Hayhoe et al. 2007). The period of record and availability of climate variables differs for each station. USHCN stations are selected using a number of criteria including length of period of record, percent of missing data, number of station moves and other station changes that may affect data homogeneity, and spatial coverage.

Monthly data consist of monthly averaged maximum, minimum, and mean temperature and total monthly precipitation from 138 stations in the NE-US (Figure 2-1). Data records generally include the period from 1900 through 2003.

Monthly data have been corrected for station relocations (Karl and Williams 1987), instrument changes (Quayle et al 1991), urbanization effects (Karl et al. 1988), and time of observation differences (Karl et al. 1986).

Daily USHCN Data (NDP-070)

The USHCN data set includes daily meteorological data for 109 stations for four climate variables: (1) minimum temperature, (2) maximum temperature, (3) snowfall, and (4) snow depth (Figure 2) (Williams et al. 2006). The mean daily temperature record is calculated as the mean of daily minimum and maximum temperature, and is used only for filling missing daily snow depth values in this study. The longest USHCN station record comes from Eastport, Maine, whose current temperature record commences in 1873 and ends in 2005. Fifty-eight percent of the 109 station records begin prior to 1927; all station records commence prior to 1949. Eighty-two percent of the records have daily data through 2005; the remaining 18% terminate between 1985 and 2000. Not all stations have data available for all five variables covering the same period.

NCDC performs quality assurance (QA) procedures on raw (observed) daily data. The main NCDC quality assurance checks performed on daily data collected after 1982 are as follows:

1. Monthly mean values of maximum and minimum temperature,computed from the HCN/D data, were compared to their respective unadjusted monthly means from the HCN. All

conflicts were investigated and resolved, with verification based on manuscript or published sources.

2. Checks were performed to ensure that no monthly mean values of maximum and minimum temperature calculated from a station's daily data were above (below) the monthly state extremes of maximum (minimum) temperature.
3. Any daily precipitation total exceeding 5 in. was verified against manuscript or published sources.
4. Checks were implemented to ensure that maximum temperatures were never less than minimum temperatures on the day of occurrence, the preceding day, and the following day. Conversely, checks were performed to ensure that minimum temperatures were never greater than maximum temperatures on the day of occurrence, the preceding day, and the following day.
5. Temperature data from stations that took readings during the morning over some period have been checked for any date shifting resulting from observers assigning readings to the calendar day of occurrence (the previous day in the case of maximum temperature) rather than the observation day. Such readings were switched back to the day of observance as part of the manual QA checks on the HCN/D data.

In addition to NCDC quality assurance measures, CDIAC applied its own set of QA measures. These include:

1. Elements pertaining to nonexistent dates were checked to ensure that they contained missing data indicators with blank flag spaces (the prescribed conventions).

2. A few data measurement and data quality flags were found in the data that are not detailed in NCDC's SOD documentation. Records containing these were submitted to NCDC. In some cases, consultation with NCDC determined that meanings of a few unknown data measurement flags could not be resolved by NCDC. NCDC acknowledges these flag caveats in the following passage from the SOD documentation: "Other values occasionally appear in Data Measurement Flag 1 for which documentation is not currently available, e.g., "C" and "s".
3. All data records were checked to ensure that the number of days in the month (specified in each record) was correct for the year and month of each record.

Daily temperature and precipitation records provide the longest, most continuous station records. Snowfall and snow depth records are largely continuous from 1970-2005, however data gaps still exist in some records. Methods used to address the data gaps are described later.

Cooperative (COOP) Station Data (DSI-3200)

The DSI-3200 database contains over 300 stations in the NE-US (Figure 2-1), and is comprised primarily of stations in the National Weather Service (NWS) cooperative station network. The vast majority of the observers are volunteers (non-paid, private individuals). However, the cooperative (COOP) network also includes the NWS principal climatological stations, which are operated by highly trained observers. The observing equipment used at all of the stations, whether at volunteer sites or federal installations, are calibrated and maintained by NWS field representatives, Cooperative Program Managers and Hydro-Meteorological Technicians.

The NCDC provides daily climate data for 370 COOP stations in the NE-US for the following four climate variables: (1) minimum temperature, (2) maximum temperature, (3) snowfall, and (4) snow depth. NCDC includes the following quality statement with regard to the DSI-3200 dataset:

> These data have received a high measure of quality control through computer and manual edits. These data are subjected to internal consistency checks, compared against climatological limits, checked serially, and evaluated against surrounding stations. Quality control "flags" are appended to each element value to show how they fared during the edit procedures and to indicate what, if any, action was taken. The historical data prior to 1982 were converted from existing files then placed in the element file structure format after being processed only through a gross value check. In November 1993 the entire historical period of record was processed through a stringent quality control. Another round of quality control in November 2000 increased the data set's quality still more.

Additional quality controls are performed to remove outliers that NCDC may have missed during gross value checks.

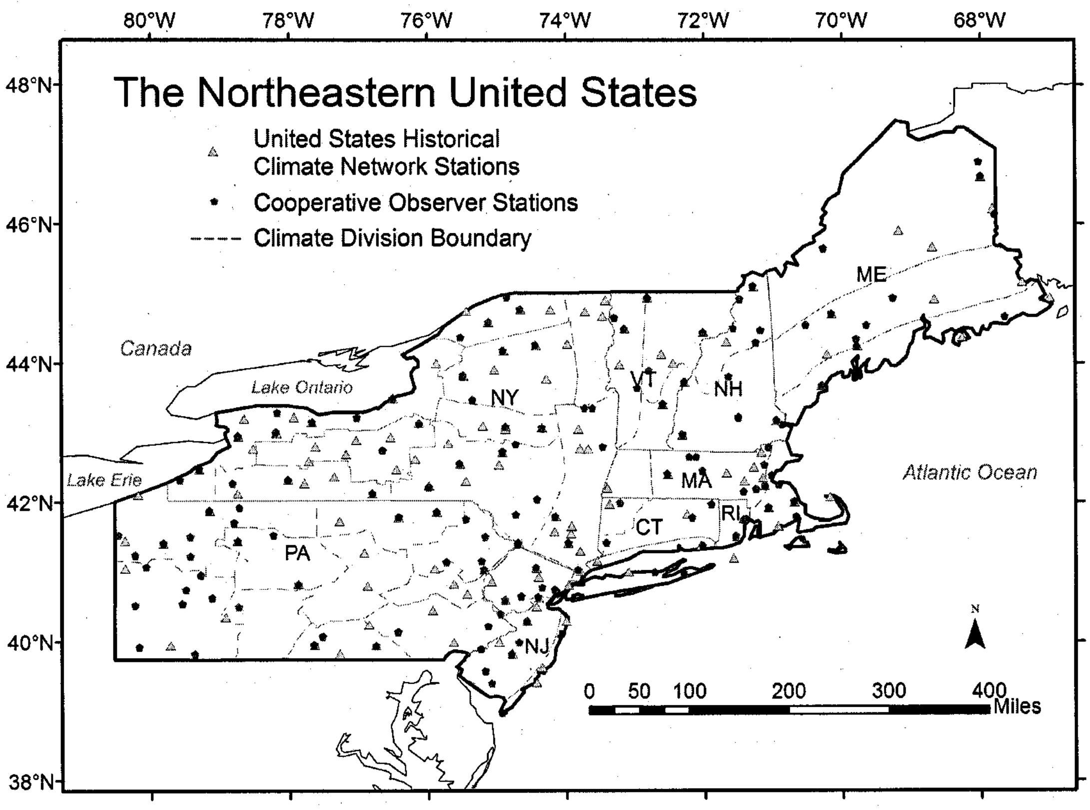

Figure 2-1. Distribution of northeastern United States climate stations used in this study. United States Historical Climate Network stations are shown as blue triangles, Cooperative Network stations are shown as red circles. Climate division boundaries within each state are delineated with dashed lines.

Climate Data Processing

We perform in sequence four major data processing steps to prepare data for trend analysis. The first step fills missing daily mean temperature data, which is later used in estimating missing snow depth values. The second step evaluates total snowfall and total snow covered day records for spatial coherence with nearest surrounding stations. The purpose of the spatial coherence analysis is to identify and remove stations with non-climatic biases from further data processing and subsequent trend analysis. The third step fills missing monthly snowfall totals. The fourth and final data processing step fills missing daily snow depth values based on available daily mean temperature and snowfall data. The sequential climate data processing steps ensure that only the highest quality and most complete data records are utilized in seasonal and monthly trend analysis.

Daily Mean Temperature Gap Filling

Daily mean temperature values are calculated as the mean of daily maximum and minimum temperature. Missing daily mean temperature values are filled with the average of the three nearest neighbor's mean daily temperature values.

Spatial Coherence Analysis: Snowfall and Snow Covered Days:

Kunkel et al. (2007) emphasize that non-climatic issues (i.e. station moves, instrument changes, observer changes, or land-use changes) can significantly influence trends identified in snowfall and snow depth. To address these data quality problems in this study's dataset, data inhomogeneities are identified and resolved using spatial coherence analysis. The method is essentially a comparison of surrounding station anomalies to determine whether non-climatic influences are introducing non-climatic biases to the long-term record. A spatially coherent station is expected to have minimal differences in anomalies with its neighboring stations.

Winter total snowfall and total snow-covered days (snow depth > one inch) for the period 1965-2005 are calculated using the merged USHCN and COOP daily data for stations with less than 20% missing winter data. The winter totals are converted to anomalies by subtracting the long-term mean (1965-2005) from the winter total. The annual anomaly *A(y)* is defined as

$$A(y) = s(y) - \left[\frac{\sum_{y=1965}^{2005} F(y) * s(y)}{\sum_{y=1965}^{2005} F(y)} \right],$$

where F(y) is a flag equal to 1 if data exist for year *y* or 0 if data do not exist, and *s(y)* is the winter snowfall or snow-covered day total. Stations are evaluated for spatial coherence by plotting as a time series the difference between a given station's winter snowfall anomaly and the ten nearest neighbor's winter snowfall anomalies (Figure 2-2).

A station is considered spatially coherent with its neighbors if no major shifts can be identified in the time series. If a station is not spatially coherent with its neighbors, the non-climatic influences manifest themselves in the time series as a coherent negative or positive shift in anomaly differences. Shifts are preliminarily identified by visual inspection of the anomaly difference time series. For any stations that do show a shift, a student's t-test is performed on the hypothesis that the data in the time series before and after the shift come from a distribution with a mean zero. If more than 3 out of the 10 neighboring stations fail the t-test at the 95% confidence interval, the primary station is removed from further analyses. When possible, the timing of the shifts are compared to metadata records to identify the source of the inhomogeneity (i.e. station move, instrument change, change in observer). Unfortunately, most metadata records are incomplete, so the source of the error was not routinely identified.

Of the 168 stations with greater than 80% of daily snowfall and SCD data available over the period 1965-2005, 88 snowfall stations and 123 SCD stations were found to pass for spatial coherence. This refined set of stations then undergoes further data processing to fill missing data values, described below.

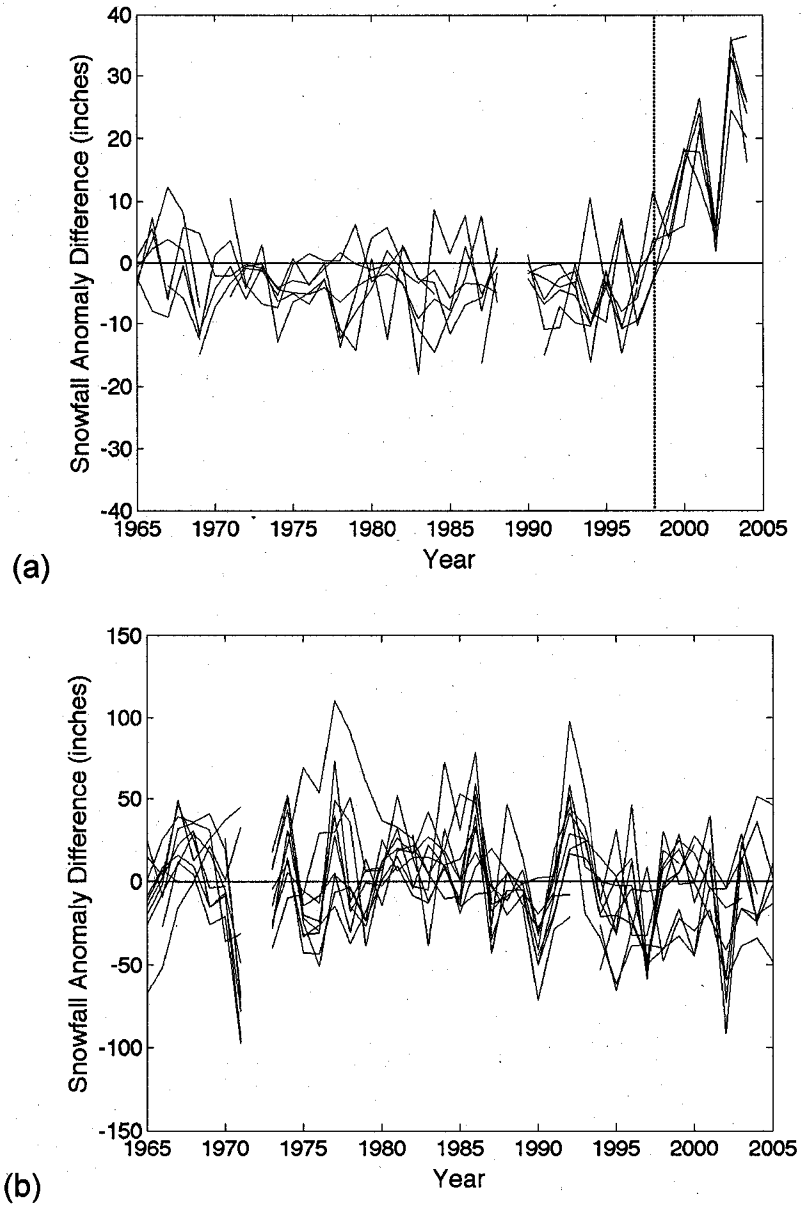

Figure 2-2. Time series of station winter (DJFM) snowfall anomalies minus neighboring station snowfall anomalies are shown for (a) Plainfield, NJ and (b) Lowville, NY. Thin solid lines show time series of nearest neighbors minus the primary station anomalies. Plainfield, NJ was removed from further trend analysis due to the major shift in 1998. Lowville, NY remains synchronized with its neighbors throughout the time series and was retained for trend analysis.

Monthly Snowfall Gap Filling

Missing monthly snowfall values are filled using a linear relationship between nearest neighbor surrogate station within 60km of the primary station (Helfrich and Robinson, 1997). First, monthly snowfall totals are calculated for the set of 88 spatially coherent stations with no more than 10% of the daily observations missing from any given month. If greater than 10% of the daily observations are missing, the monthly total is flagged as missing data. Of the 14432 months in the 88-station data set, 4.8% were flagged as missing. Next, surrogate stations are identified using Pearson correlation (r^2) statistics. A station qualifies as a surrogate station if the correlation between the primary and surrogate station's monthly records is greater than 0.7. A maximum of three stations with the highest correlations are retained as surrogate stations. A linear regression on the primary and surrogate monthly snowfall totals is done to obtain the slope (a) and intercept (b) between the two stations. The results are then applied to the surrogate station's monthly total for the year in which the primary station's month is missing, using the following equation:

$$Y=(M)a+b \qquad (1)$$

Where Y is the missing monthly snowfall for the primary station and M is the monthly snowfall for the surrogate station. In the event that both the primary and surrogate stations are missing the same month, the surrogate station with the next highest correlation is selected. Any missing values that could not be filled using a surrogate regression are subsequently filled with the primary station's 1965-2005 mean monthly snowfall.

To evaluate the use of the monthly snowfall gap-filling model, modeled monthly snowfall totals are cross validated with observed monthly snowfall totals. Each observed monthly value from 1965-2005 is iteratively changed to a missing value. The missing values are then filled using the monthly snowfall gap-filling model. Once filled, the original data values are compared to the modeled values (Figure 2-3), and the error residuals between the two monthly values is quantified to estimate the 95% confidence intervals for each month (Figure 2-4). Based on the range of 95% confidence intervals (±8.1 to ±8.7 inches) in the cross validation, the monthly snowfall gap-filling model was chosen as an acceptable means to fill the missing data values. Less than 5% of the December-March snowfall totals required filling for the period 1965-2005. Using surrogate station linear regression, 3.1% of monthly total snowfall records were successfully filled. The remaining missing snowfall records, which represented less than 1.7% of the total monthly totals, were subsequently filled using primary station's 1965-2005 mean monthly snowfall total.

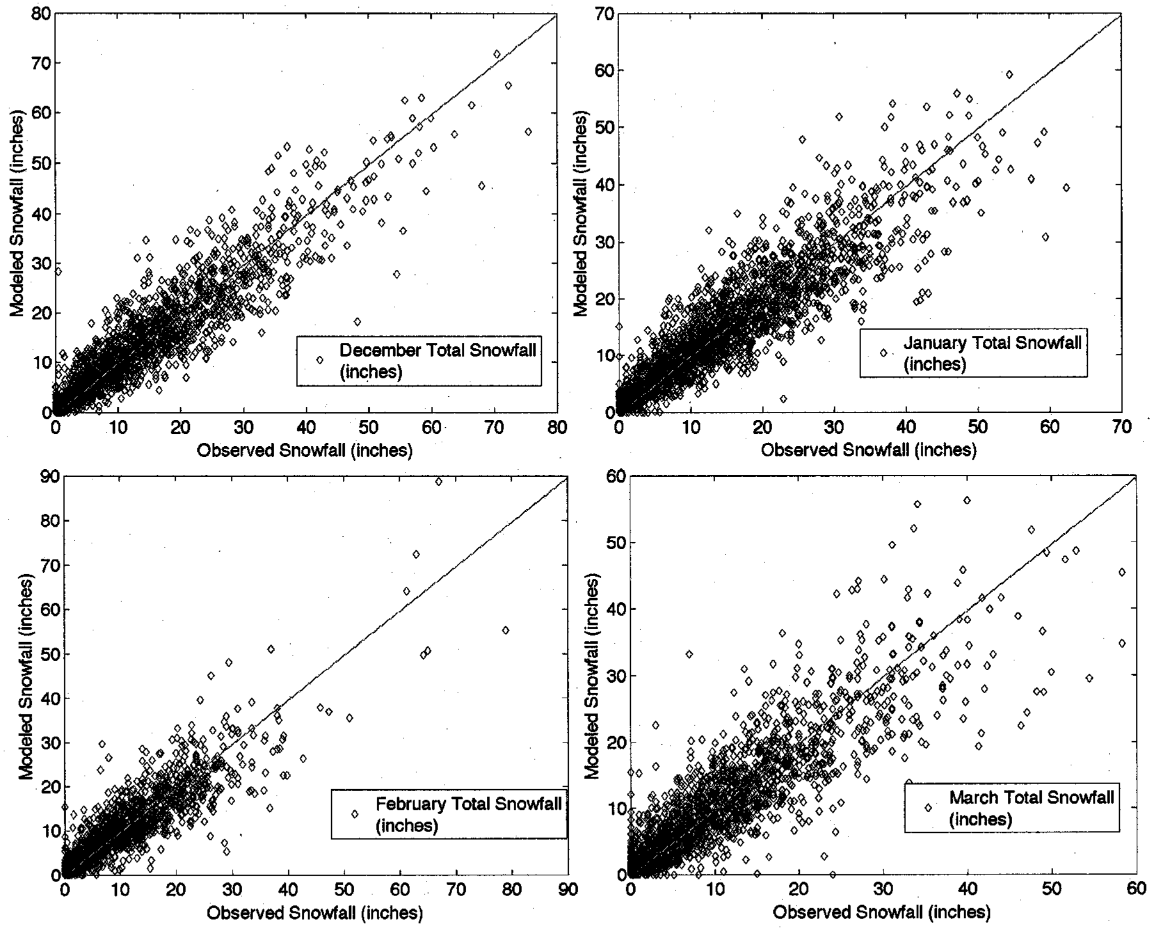

Figure 2-3. Cross validation of observed versus modeled monthly snowfall using the nearest neighbor gap-filling model.

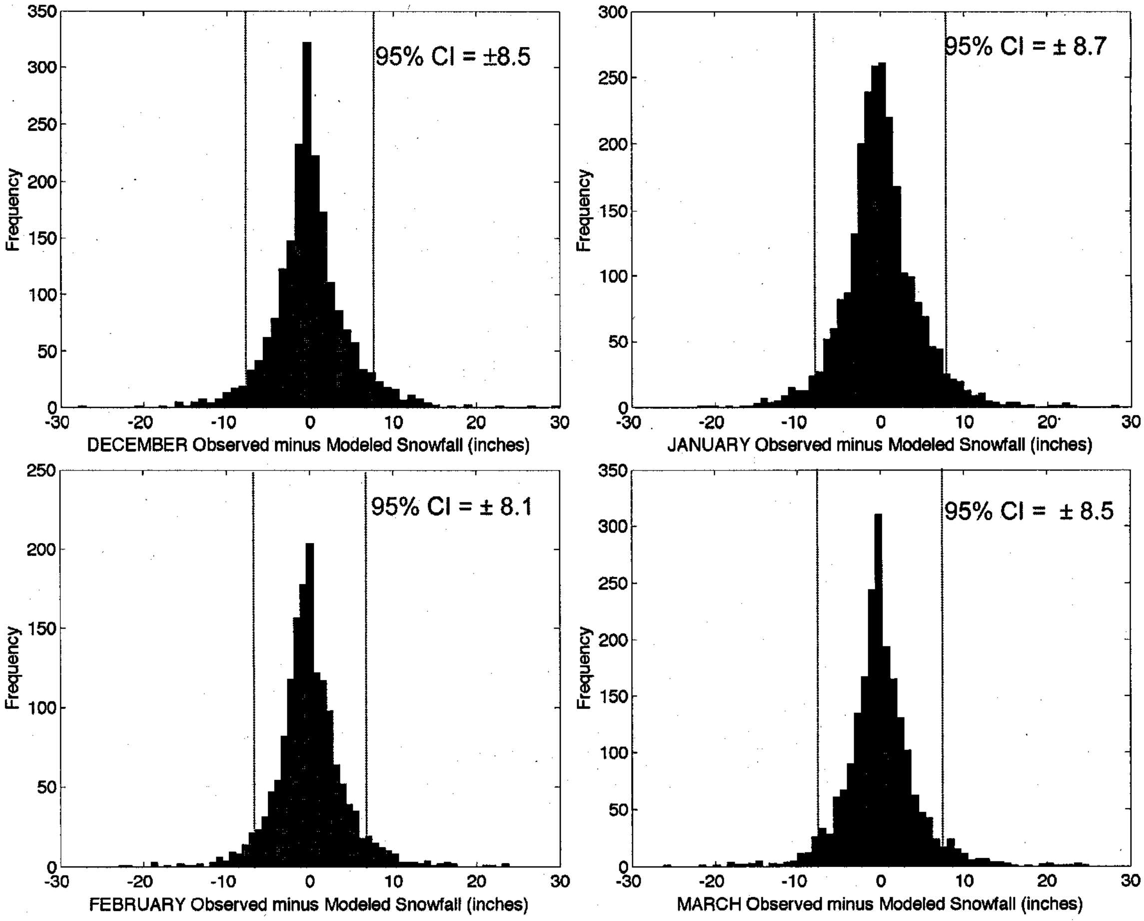

Figure 2-4. Observed minus modeled snowfall totals for December, January, February, and March. The 95% confidence intervals are estimated as two standard deviations of the error residuals.

Daily Snow Depth Gap Filling

In the merged USHCN and COOP 123-station spatially coherent daily snow depth dataset, 5.7% of the daily snow depth values are missing. Missing snow depth values are filled using the depth change (DC) method developed by Hughes and Robinson (1993) that computes changes in snow depth based on the empirical relationship between changes in snow depth and daily mean temperature within depth change regions in the northeastern US. The NE-US is divided into four regions based on the range and mean daily winter snow depth values over the period 1965-2005 (Figure 2-5).

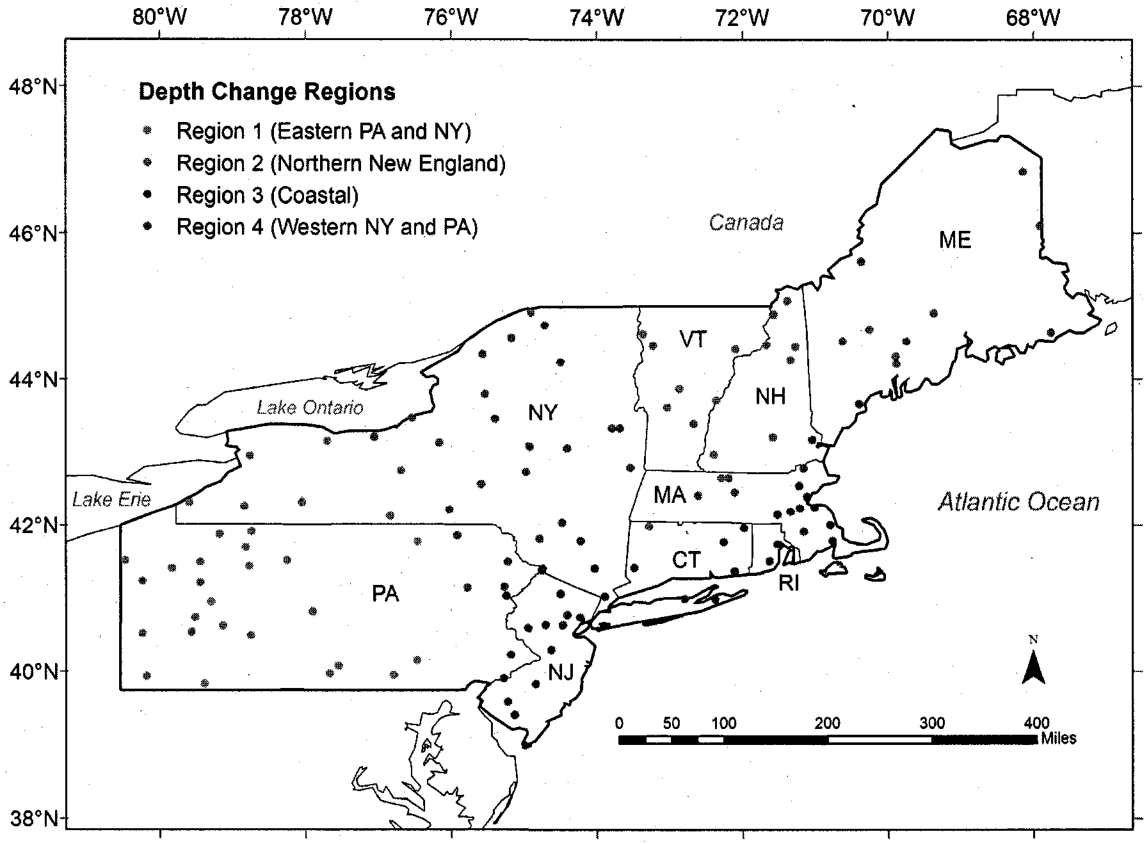

Figure 2-5. Depth Change model regions for the northeastern United States.

The empirical relationship between the change in snow depth and mean daily temperature is established as follows. For each station in a given region, the previous day's snow depth is compared to the current day's snow depth for days on which there was no observed snowfall. If a decrease in snow depth has occurred, the depth change value and the associated mean daily temperature are recorded. Depth change values were recorded at 1°F intervals for mean daily temperatures ranging from 14°F to 41°F. The weighted average change in snow depth at each temperature interval is computed for each region, weighted by the number of days snow cover is observed, but no change in snow depth occurred. The regression analysis is performed using the change values and associated mean daily temperatures to develop the appropriate statistical snow depth change model for each region. The regional regression equations are used to estimate missing snow depth values at stations within a given climate division using available daily mean temperature.

To evaluate the efficacy of the depth change model, each daily snow depth value is iteratively changed to a missing value and subsequently filled using the depth change model. The observed values are compared to the modeled values in a binary cross validation matrix to determine how well the model can predict whether there is or is not snow cover greater than one inch on the ground (Table 2-1). The difference between the observed daily snow depth and the modeled daily snow depth is not quantified because the authors only require the method to model the presence or absence of snow cover. For all four regions, the model correctly filled the missing snow cover value greater than 98% of the time. Based on the binary cross validation, the depth change model was chosen as an acceptable means for filling missing daily snow cover values.

	Region 1	Region 2	Region 3	Region 4
Yes_{obs} , Yes_{mod}	2190	9163	2282	4122
No_{obs} , No_{mod}	9657	3278	15041	2813
Yes_{obs} , No_{mod}	5	10	17	2
No_{obs} , Yes_{mod}	55	167	41	26
% Correct	99.5%	98.6%	99.7%	99.6%

Table 2-1. Binary validation of the depth change method for modeling missing daily snow depth values.

For each region, the relationship between mean change in snow depth and mean daily temperature is described by a quadratic fit (Figure 2-6). Region 2 (Figure 2-6b) and Region 3 (Figure 2-6c) experience similar changes in snow depth at a given mean temperature. Region 1 (Figure 2-6a) and Region 4 (Figure 2-6d) experience greater decreases in snow depth at a given daily mean temperature than Region 2 and 3.

Missing snow depth values are filled sequentially in one of three ways. (1) If the daily mean temperature of the current day is greater than 41°F, there is no recorded snowfall, and the previous day's snow depth was zero, then the missing day's value is filled with zero. (2) If the mean daily temperature for the current day is below -10°C and snowfall is equal to zero, the current day's snow depth is set equal to the previous day's snow depth. (3) If the mean temperature is greater than -10°C, the current day's snow depth is estimated to be the previous day's snow depth plus the current day's snowfall, less the change in snow depth as calculated from region regression equation. The depth change method filled an average of 2.3 days/per year for missing daily snow depth values, less than 0.5% of the daily snow depth values.

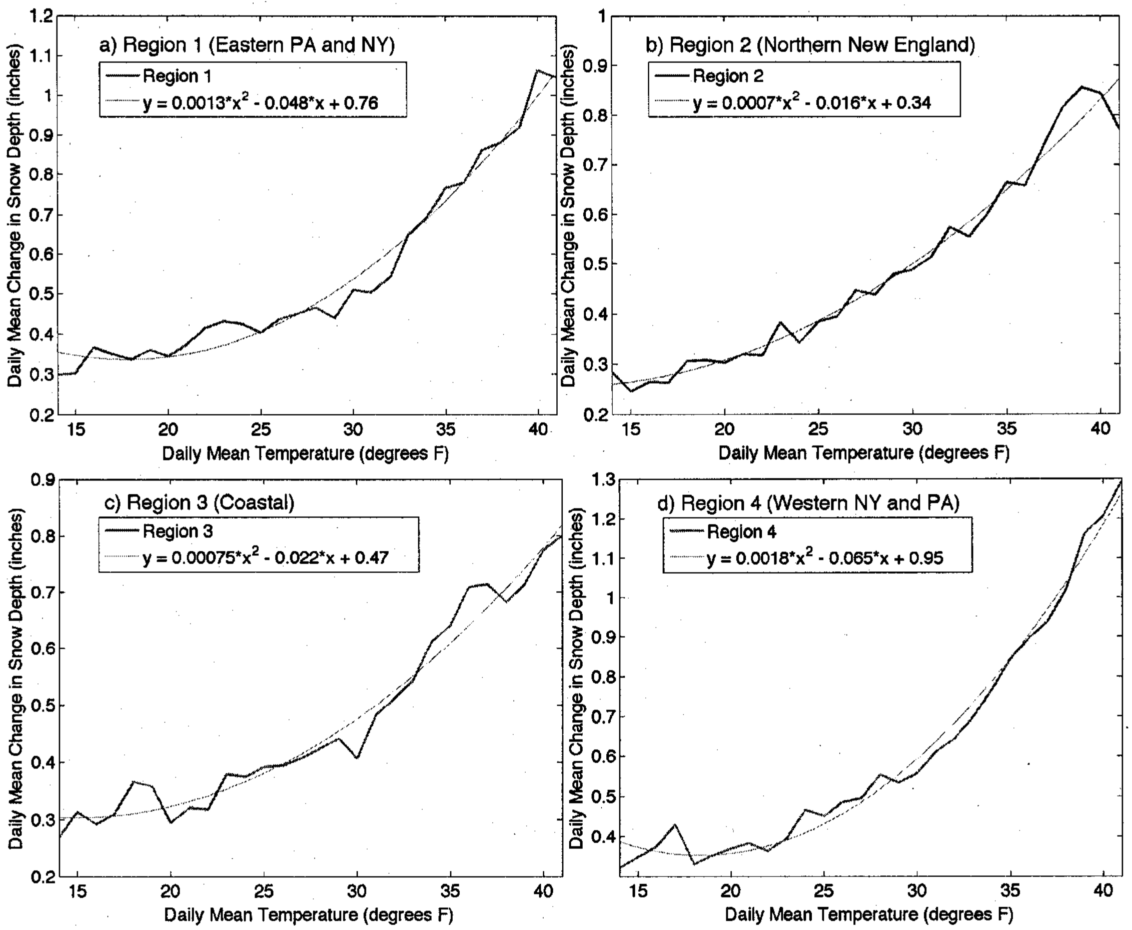

Figure 2-6. Relationship between change in daily snow depth and change in daily mean temperature for depth change regions in the northeastern United States.

Climate Data Analysis

Station trends in wintertime climate variables are estimated using linear regression analysis on the monthly and seasonal time series for snowfall, snow-covered days, and minimum, maximum, and mean temperature. Total snowfall and snow covered days in March often exceeds December totals, therefore all winter trends include the months of December, January, February, and March. To account for the trend's sensitivity to the start year of the time-series, we calculate the mean of trends estimated from eleven time-series with start years ranging from 1965 to 1975, and ending in 2005 (eg., decadal rates were calculated for 1965:2005, 1966:2005, ... 1975:2005). Trends were only calculated for stations with less than 10% of years missing from the time series.

Regional trends in winter climate were calculated by creating an area-weighted (by NCDC Climate Division) average time series from 1965-2005 for each variable. The mean regional trend is calculated as the average of eleven trends from time series starting in 1965 through 1975 and ending in 2005 (e.g. 1965:2005; 1966:2005; ... 1975:2005). A regional trend is considered statistically significant if 10 or more of the 11 trends had a $p < 0.05$, and weakly significant if $0.05 < p < 0.20$.

CHAPTER III

TRENDS IN WINTERTIME CLIMATE VARIABILITY IN THE NORTHEASTERN UNITED STATES: 1965-2005

PAPER TO BE SUBMITTED TO *JOURNAL OF GEOPHYSICAL RESEARCH*

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Abstract

Humans experience climate variability and climate change primarily through changes in weather at local and regional scales. One of the most effective means to track these changes is through detailed analysis of meteorological data. In this work, monthly (December, January, February, and March) and seasonal trends in recent winter climate of the northeastern United States (NE-US) are documented. Snow cover and snowfall are important components for the region's hydrology, ecosystems, water management, travel safety, and winter tourism and recreation. Temperature, snowfall, and snow depth data were collected from the United States Historical Climate Network (USHCN). Monthly and seasonal time series of snow covered days (snow depth

> one inch) are constructed from snow depth data. The National Climatic Data Center and Carbon Dioxide Information Analysis Center perform extensive quality assurance and quality control measures for monthly temperature data. However, daily snowfall and snow depth data have not been adjusted for station relocations, instrument changes, or time of observation biases. To address these data quality issues, we evaluate daily data for spatial coherence with nearest neighbors, and remove stations with non-climatic influences from regional analysis. Monthly and seasonal trends in mean, minimum and maximum temperature, total snowfall, and days with snow on the ground are estimated using linear regression over a range of start years, stepping annually from 1965-2005 through 1975-2005.

Northeastern United States regional winter maximum temperatures (~+0.43°C/decade) are warming at a greater rate than minimum temperatures (~+0.37°C/decade). Regionally averaged winter snowfall has decreased by ~-2.5 inches/decade, with the most significant decreases in snowfall occurring in December and February. The strong reduction in number of snow-covered days (~-2.6 days/decade), particularly at stations located between 42°N and 44°N, is likely tied to strong increases in winter maximum temperature via a snow-albedo feedback. These results have important implications for the impacts of regional climate change on the northeastern United State's hydrology, natural ecosystems, and economy.

Introduction

Recent detailed analysis has shown that global climate change over the past three to four decades is being driven primarily by enhanced levels of greenhouse gases in the atmosphere that originate from the burning of fossil fuel and land use changes (IPCC, 2007). Warmer spring temperatures are linked to large reductions in mid-latitude northern hemisphere snow cover extent from 1966-2004 during the months of March and April (Lemke et al. 2007). Changes in snow cover can be an important indicator of climate change at the regional scale due to its strong relationship to temperature via the albedo feedback loop (e.g. Groisman et al. 1994).

Significant changes in snow cover depth and extent over time can impact a region's hydrology, ecology, climate, and economy. The northeastern United States (NE-US) is vulnerable to a broad range of impacts due to winter warming. In this study, historical trends in snow cover, snowfall, and temperature are developed and analyzed for the NE-US using surface observational data.

A recent analysis of northeastern United States observational records over the period 1970-2000 has shown that annual temperatures are warming (+0.25°C/decade), and that winter temperatures have shown the greatest seasonal rate of warming (+0.70°C/decade) (Wake and Markham, 2005; Wake et al. 2006; Hayhoe et al. 2007). The snow albedo feedback mechanism may be playing a significant role in winter warming in the northeastern United States, where snow pack tends to be shallow.

Surface observations taken at remote high elevation stations offer a unique perspective on regional climate change because their location subjects them to both boundary layer and free air processes. Analysis of the temperature record at Mount Washington in New Hampshire, the highest peak in the northeastern United States (elev. 1914 m ASL), identified a statistically significant increase in mean winter (December, January, February) temperature (~0.71°C) and a decrease in the diurnal temperature range (~-0.12°C) over the period 1932-2003 (Grant et al. 2005).

The effects of winter warming are apparent in NE-US river and lake hydrology. In rivers and streams in the northern half of the region, snowmelt dominates the pattern observed in the annual hydrological cycle. The center of volume date (the date on which half of the flow occurring between 1 January and 31 May has passed the stream gauge) for unregulated rivers in northern New England occurred 7-14 days earlier during the period 1970-2000 compared to the period prior to 1970 (Hodgkins et al. 2003). The center of volume dates were most strongly correlated with March and April air temperatures. In addition, monthly mean runoff showed increasing trends over the same period during January, February, and March, which is consistent with the advancement in the center of volume date (Hodgkins and Dudley 2006). The timing of spring lake ice-out has advanced by 9 days in northern New England and 16 days in southern New England over the period 1850-2000 (Hodgkins et al. 2002).

Annual and winter snow to total precipitation ratios have decreased across New England, largely due to a decrease in winter snowfall (Huntington et al. 2004). Across North America, a significant decrease in winter snow cover extent is likely a result of earlier spring melt and a decrease in the extent of deeper snow packs (Dyer and Mote 2006; Hughes and Robinson 1996; Brown 2000).

The northeastern US ski industry generates approximately three billion dollars per year in visitor spending and tax revenue (Scott et al. 2007), especially for mountainous states like New Hampshire, Vermont and Maine, which all rank in the top ten states that benefit from winter skiing as a percentage of the state's economy (National Ski Association; US Bureau of Economic Analysis 2007). Warmer winters with less than average snowfall and snow depth have reduced profit margins of ski resorts in the NE because more funds have been diverted to snowmaking, which has led to the closure of many small resorts (Hamilton et al. 2003). New Hampshire, ranked in the top five states that benefit from the ski industry as a percentage of the state's economy, loses an average $13.1 million dollars from decreased sales of alpine and Nordic ski tickets and snowmobile registrations during warm, slushy winters compared to cold, snowy winters (Wake et al., 2006). In the context of climate change and global warming, winter tourism and recreation in the northeastern United States will experience negative economic impacts resulting from diminished snowfall and over successive years in response to increasing winter temperatures.

The potential impacts of climate change are assessed primarily based on projections from coupled atmosphere-ocean general circulation models (AOGCMs). In a recent regional study (Hayhoe et al. 2007), output from nine AOGCM simulations of historical climatology were compared to reanalysis and observational northeastern United States climate records. The AOGCM scenarios included both natural (i.e., changes in solar output, volcanic aerosols) and anthropogenic forcing (i.e.,greenhouse gas emissions, sulfate aerosols from burning of fossil fuel) factors. The models reasonably reproduced regional atmospheric circulation patterns, such as the position of the jet stream and common storm tracks, and broadly simulated the long-term (1900-1999) warming trend observed in annual temperature. However, the models failed to capture the recent (1970-1999) winter warming trend identified in Hayhoe et al. (2007). The observed linear trend in winter was 0.74°C/decade, while the model average was 0.13 ± 0.34 °C/decade. The underestimation (~0.61°C/decade) may be due to poor resolution of snow cover in the AOGCMs. A regional decrease in snow-covered days (-0.5 days/month/decade) may also be linked to the rise in winter temperatures via the snow-albedo feedback loop ((Wake and Markham, 2005; Wake et al., 2006).

More detailed analysis of winter climate trends is essential to understanding the cause of rapid winter warming in the northeastern United

States. In this study, we aim to update winter climate trends to include snowfall, temperature, and snow cover data through 2005. Because snowfall and the number of snow-covered days (SCD) in March often exceed December snowfall and snow covered days, winter trends include the months of December, January, February and March. In addition, the meteorological data has undergone several extensive quality control measures to ensure that the records are of the highest quality and completeness. Seasonal and monthly trend identification is evaluated with attention to the sensitivity of the time series start date, ranging from 1965 to 1975.

Data and Methods

We complied snowfall, snow depth, and mean temperature data from two daily surface datasets containing observations collected at over 300 National Weather Service First Order stations and Cooperative Observer Program (COOP) stations in the northeastern US over the period 1965-2005. For this study, the northeastern US includes Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island and Vermont (Figure 3-1). The USHCN provides a high-quality daily dataset, denoted as NDP-070, compiled by the National Climatic Data Center (NCDC), and is available for download at the Carbon Dioxide Information and Analysis Center (http://cdiac.ornl.gov/ftp/ndp070/) (Easterling et al., 1999; Williams et al., 2005).

The NCDC provides the digitized COOP dataset, DSI-3200 (http://cdo.ncdc.noaa.gov/pls/plclimprod/somdmain.somdwrapper). From the merged daily data sets, we examine trends in monthly and seasonal snowfall and days with snow on the ground (daily snow depth greater than 0, 1, and 3 inches). Daily data have not been corrected for station moves, instrument changes, urbanization effects, and time-of-observation differences.

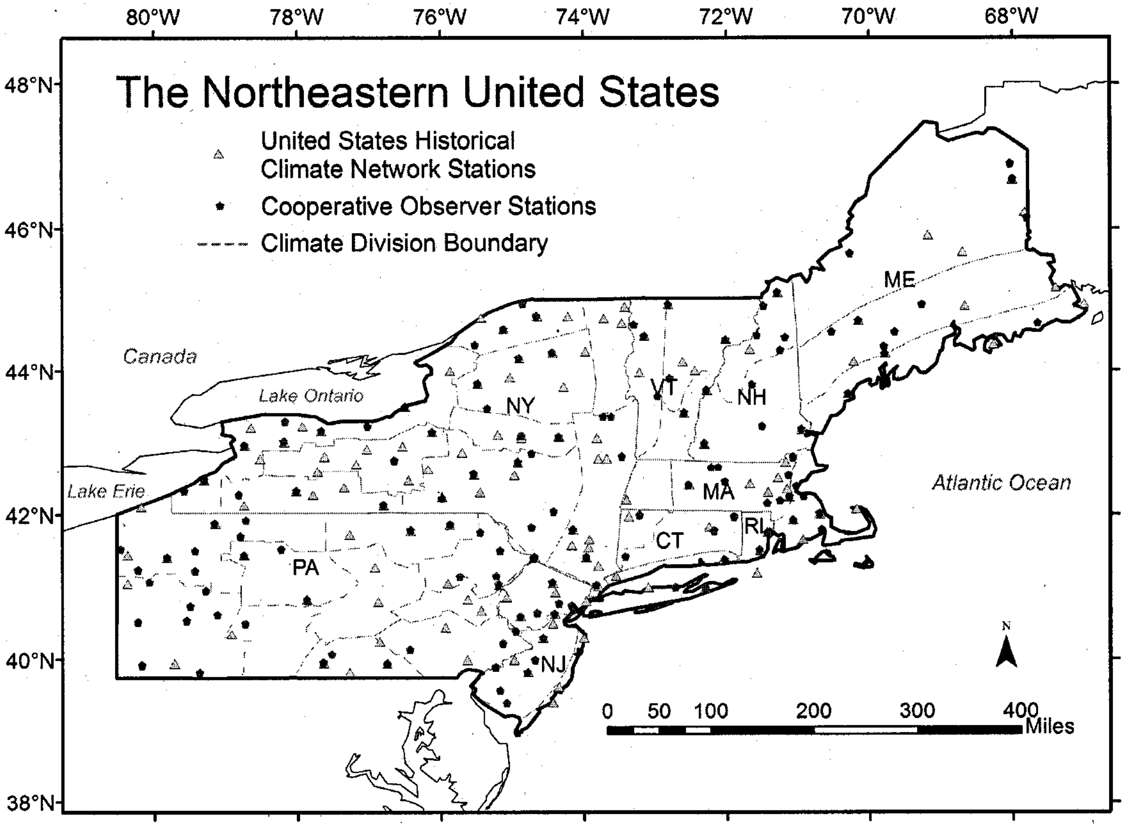

Figure 3-1. Distribution of northeastern United States climate stations used in this study. United States Historical Climate Network stations are shown as blue triangles, Cooperative Network stations are shown as red circles. Climate division boundaries within each state are delineated with dashed lines.

Monthly and seasonal temperature trends were analyzed from the USHCN monthly dataset (NDP-019), which consists of monthly averaged maximum, minimum, and mean temperature from 138 stations in the NE-US. Monthly data have been corrected for station moves, instrument changes, urbanization effects, and time-of-observation differences.

We used daily USHCN and COOP snowfall and snow depth data to analyze trends in monthly and seasonal trends in snowfall and the number of snow covered days with snow depth greater than 0, 1, and 3 inches (SCD0, SCD1, and SCD3). In order to address non-climatic issues that can significantly influence trends identified in snowfall and snow depth. (eg: station moves, instrument changes, observer changes, or land-use changes), we analyze the data using a spatial coherence method developed and tested by Kunkel et al. (2007). The method compares neighboring annual station anomalies to determine whether non-climatic influences are introducing non-climatic biases to the long-term record. A spatially coherent station is expected to remain synchronized with its nearest neighbors throughout a long-term time series of seasonally averaged observations of snowfall and SCD. Stations determined to have undergone major shifts relative to their neighbors were removed from further snowfall and snow depth and SCD trend analyses. Of the 168 stations with greater than 80% of daily snowfall and SCD data available over the period 1965-2005, 88 snowfall stations and 123 SCD stations were found to pass for spatial coherence.

Although the NCDC and the USHCN provide the highest quality climate data available, observational records still contain a significant number of missing daily. Missing daily mean temperature values are filled as the average of the three nearest neighbor's mean daily temperature values.

For the 123 stations with spatially coherent SCD records, missing daily snow depth values are filled when daily values of snowfall and mean temperature are present, using the depth change method developed by Hughes and Robinson (1993). The method uses daily snowfall, snow depth and mean temperature data to develop regionally specific regression equations relating changes in snow depth to changes in temperature. The regression equations were developed and tested successfully for four sub-regions within the northeastern US (Burakowski 2007). The depth change method filled an average of 2.3 days/per year for daily snow depth values.

Using the 88 spatially coherent snowfall stations, monthly snowfall totals are flagged as missing for stations with more 10% of daily observations missing from any given month. The missing monthly snowfall totals for stations with no more than 10 missing months over the period 1965-2005 are filled using a linear regression between the three nearest surrogate neighbors having a Pearson correlation greater than 0.7. Less than 5% of the December-March snowfall totals required filling for the period 1965-2005. Using surrogate station linear regression, 3.1% of monthly total snowfall records were successfully filled. The remaining missing snowfall records (1.7%) were subsequently filled using primary station's 1965-2005 mean monthly snowfall total. Based on the range of 95% confidence intervals (±8.1 to ±8.7 inches) in the cross validation, the monthly snowfall gap-filling model was chosen as an acceptable means to fill the missing data values (Burakowski 2007).

For each station, winter (December of one year through March of the following year) and monthly time series are computed for the following climate variables: (i) total snowfall, (ii) snow covered days (SCD) greater than 0", 1", and 3" of snow depth, (iii) minimum temperature, (iv) maximum temperature, and (v) mean temperature. For snowfall and SCD, seasonal and monthly values were calculated for stations with fewer than 10% of daily values missing from any given winter or month to create the time series from 1965-2005. The decadal rate of change in these wintertime climate variables are estimated using linear regression analysis on the monthly and seasonal time series for snowfall, SCD and minimum, maximum and mean temperature for stations with no more than 10% missing data over the period 1965-2005. To account for the trend's sensitivity to the start-year of the time-series, we calculate the mean of the decadal rate of change estimated from linear regression of eleven time-series with start-years ranging from 1965 to 1975, and ending in 2005 (eg., decadal rates of change were calculated for 1965:2005, 1966:2005, ... 1975:2005). The significance of trends is evaluated by computing p-values for Pearson's correlation of the series. Stations with 10 or more trends with $p < 0.05$ were considered statistically significant. If 10 or more of the trends had p in the range of 0.05-0.20, the station trend was considered weakly significant.

Regional trends in winter climate were calculated by creating an area-weighted (by NCDC Climate Division) average time series from 1965-2005 for each variable. The mean regional trend is calculated as the average of eleven trends from time series starting in 1965 through 1975 and ending in 2005 (e.g. 1965:2005; 1966:2005; ... 1975:2005). A regional trend is considered statistically significant if 10 or more of the 11 trends had a $p < 0.05$, and weakly significant if $0.05 < p < 0.20$.

Results and Discussion

Temperature

The mean winter temperature in the northeastern United States is -2.6°C ± 2.8°C. Stations in the southern part of the region (New Jersey and Pennsylvania) and along the coast (Connecticut and Rhode Island) tend to have a mean winter temperature above freezing, while stations in the north (Maine, Massachusetts, New Hampshire, New York, and Vermont) are typically below freezing. The mean winter temperature 0°C threshold lies at approximately 42°N.

Analysis of maximum, minimum, and mean temperature trends indicates a region-wide winter warming trend in the northeastern United States that is coherent across all latitudes (Figure 3-2). Figure 3-2a, 3-2c, and 3-2e show the mean decadal rate of change by latitude with error bars of the standard deviation. In Figure 3-2b, 3-2d, 3-2f, the magnitude and direction of the mean decadal rate of change is illustrated by dot size and color, respectively. Warming trends are represented by warm colors, cooling trends by cool colors. Stronger trends have larger dots, and weaker trends have smaller dots. For example, a large red dot indicates a strong warming trend in temperature; a small blue dot indicates a weak cooling trend. Statistically significant trends are classified into two groups: statistically significant ($p < 0.05$) and weakly significant ($0.05 < p < 0.20$).

Regional winter maximum temperature (+0.43°C/decade) increased at a faster rate than the regional winter minimum temperature (+0.37°C/decade) or regional winter mean temperature (0.39°C/decade) (Table 3-1). Given the interannual variability of the spatially averaged regional time series, it is not surprising to find that so few of the regional trends were found to be statistically significant. The significance of the region wide warming trend is more apparent on an individual station basis. Out of the 138 stations in the northeastern United States, 52 (10) stations showed statistically significant ($p < 0.05$) increasing trends in winter maximum (minimum) temperature. None of the stations showed statistically significant decreasing trends in winter or monthly temperatures.

The greatest monthly maximum temperature increases are occurring in February (+0.61°C/decade), followed by January (+0.47°C/decade) (Table 3-1). March (+0.33°C/decade) and December (+0.32°C/decade) maximum temperatures are also increasing, though at slower rates compared to January and February. Monthly increases in minimum, maximum, and mean temperature are coherent across the region. Increases in February minimum and maximum temperature were nearly equal. The increase in January minimum temperature is greater than the increase January maximum temperature. For December and March, maximum temperatures are increasing at faster rates than minimum temperature.

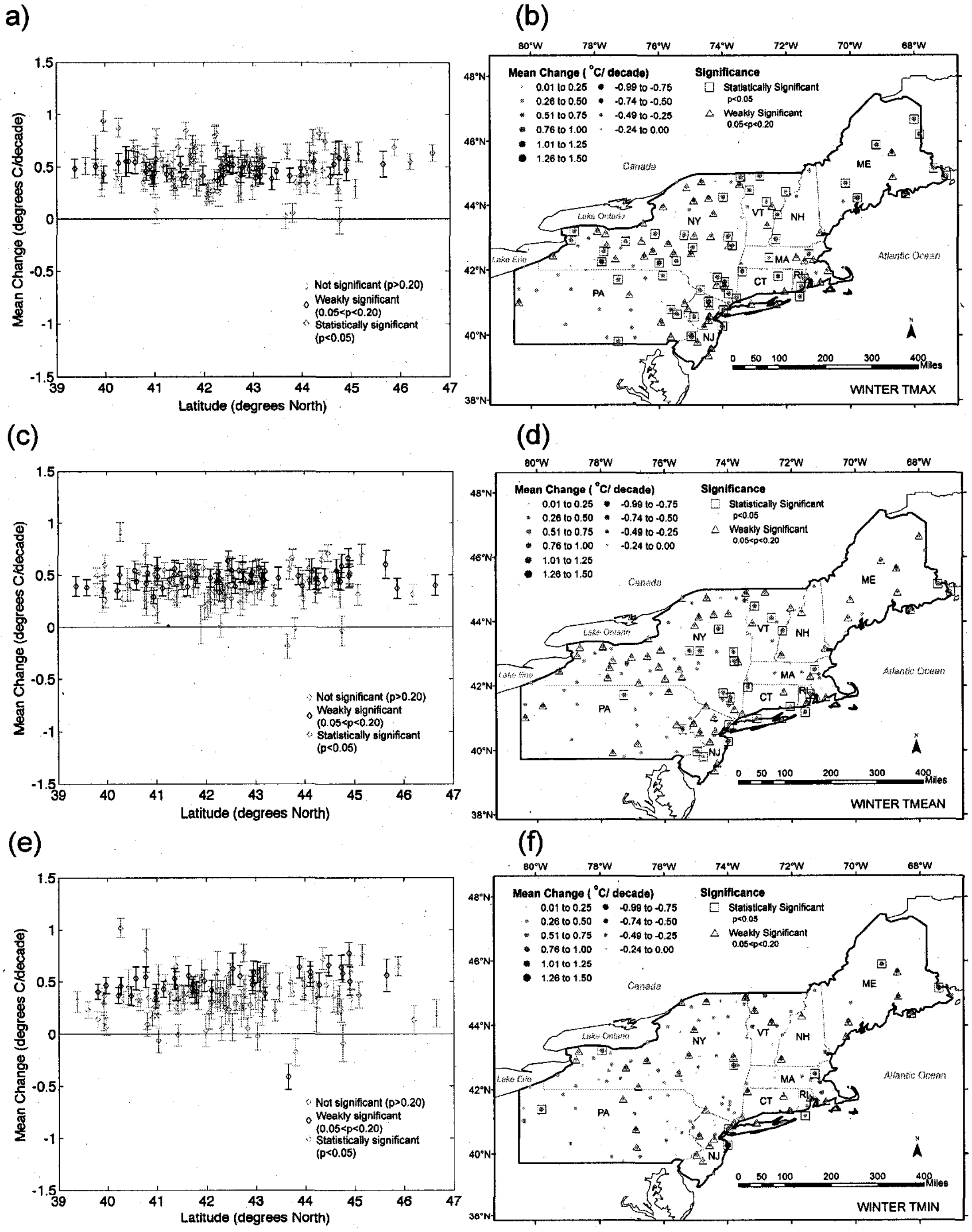

Figure 3-2. Mean decadal rate of change in winter (a,b) maximum, (c,d) mean, and (e,f) minimum temperature. Error bars (a,c,e) are one standard deviation of mean trend. On maps (b,d,f), size of dot indicates magnitude and color represents direction (warming vs. cooling) of trend. Statistically significant ($p<0.05$) trends are shown in red (a,c,e), or boxed (b,d,f). Weakly significant trends ($0.05<p<0.20$) are shown in black (a,c,e), or enclosed in triangles (b,d,f).

	TMAX (°C/ decade)	TMIN (°C/ decade)	TMEAN (°C/ decade)	SNOW (inches/ decade)	SCD1 (days/ decade)
December	+0.32 ±0.12	+0.18 ±0.15	+0.24 ±0.13	**-2.3 ±0.5**	-0.6 ±0.2
January	+0.47 ±0.12	+0.62 ±0.12	+0.54 ±0.12	+0.4 ±0.1	-1.0 ±0.4
February	+0.61 ±0.16	+0.60 ±0.17	+0.59 ±0.16	-1.1 ±0.2	-0.8 ±0.2
March	+0.33 ± 0.06	+0.08 ±0.08	+0.19 ±0.06	+0.3 ±0.3	-0.4 ±0.2
Winter	**+0.43 ±.08**	+0.37 ±0.10	+0.39 ±0.10	-2.5 ±0.8	-2.6 ±0.7

Table 3-1. Summary of regional trends in maximum (TMAX), minimum (TMIN), and mean (TMEAN) temperature, snowfall (SNOW), and snow covered days >1 inch (SCD1). Trends in bold are weakly significant ($0.05 < p < 0.20$).

Snowfall

The mean total winter (December, January, February, and March) snowfall at stations in the NE-US ranges from 13.5 inches (Cape May, NJ) to 137.6 inches (Oswego, NY). High-elevation stations (>3000ft ASL) such as Mount Mansfield, VT and Mount Washington, NH were excluded from regional snowfall trend analysis for two reasons: 1) lack of comparable neighboring stations made it difficult to check for spatial coherence, and 2) high elevation stations are subject to both boundary layer and free air processes. Total winter snowfall during the winter months (December, January, February, and March) has decreased at stations across much of the northeastern US over the period 1965-2005 (Figure 3-3). In general, stations south of 42°N consistently show decreasing trends (~-2.3 inches/decade), although only Putneyville, PA exhibits a statistically significant (p <0.05) trend of -5.7 inches/decade. The New England states (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont) show the strongest decreases in winter snowfall (~-3.0 inches/decade), with five out of 31 stations showing weakly significant trends ($0.05 < p < 0.20$). Stations with increasing winter snowfall trends tend to be located primarily near the Great Lakes, though this is not true of all stations downwind of the Great Lakes. Based on the spatial coherence analysis, we believe the trends at these stations are real, but a more detailed analysis of individual station trends is needed to understand why certain Great Lake stations show decreasing snowfall trends while others show increasing trends.

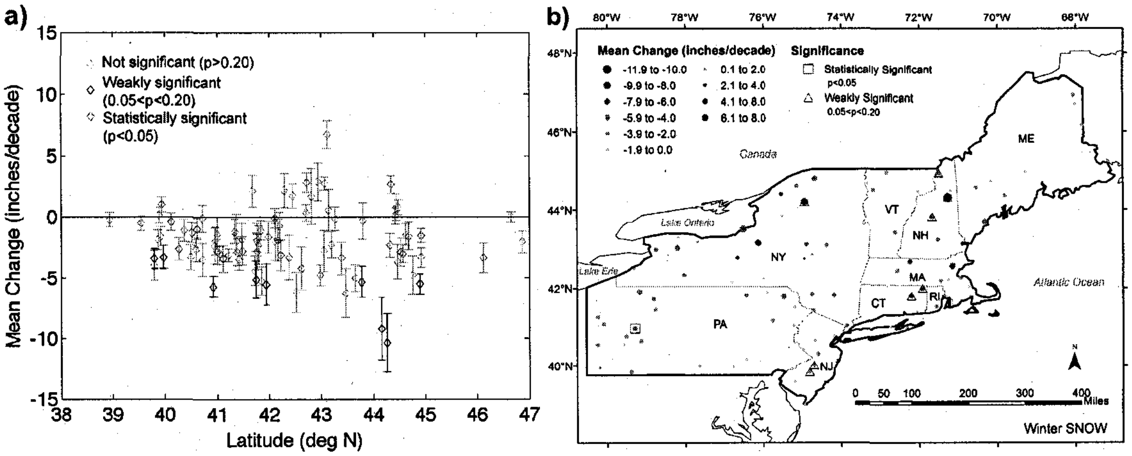

Figure 3-3. Mean decadal rate of change in winter snowfall, by station latitude (a) and station location (b). Statistically significant (p<0.05) trends are shown in red (a), or boxed (b). Weakly significant trends (0.05<p<0.20) are shown in black (a), or enclosed in triangles (b).

December shows the greatest monthly rate of decrease in snowfall, particularly in the northern part of the region (Figure 3-4). All 19 stations north of 44°N show decreasing trends (~3.6 inches/decade), with three of these northern stations showing statistically significant trends and nine showing weakly significant trends. The two stations (Buffalo, NY and Oswego, NY) showing increasing trends greater than one inch/decade were not found to be significant.

No statistically significant trends in January snowfall were identified (Figure 3-4). Weakly significant decreasing trends in New Jersey, Connecticut, Rhode Island, and Long Island, NY point to decreasing January snowfall in the southern part of the NE-US. One station in central New York (Cherry Valley) exhibited a weakly significant increasing trend (+4.2 inches/decade).

Changes in February snowfall are weakly decreasing across much of the northeastern US (Figure 3-4). No stations were found to have statistically or weakly significant increasing trends. The largest decreasing trend in February snowfall occurred at Oswego, NY, but was not found to be significant. Putneyville, PA shows a statistically significant decreasing trend (-2.5 inches/decade), and 11 stations exhibit weakly significant decreasing trends. A cluster of stations with significant trends in Western Pennsylvania shows an average decrease of -2.1 inches/decade.

The month of March is characterized by generally increasing trends in snowfall, especially north of 42°N (Figure 3-4). Snowfall has increased on average ~1.3 inches/decade at stations north of 44°N in Vermont, New Hampshire, and Maine. However, only one station (Corinna, Maine) showed a statistically significant increasing trend (+2.5 inches/decade) in March snowfall. Pemberton, New Jersey and Mercer, Pennsylvania both had weakly significant decreasing trends of -1.1 and -1.5 inches/decade, respectively.

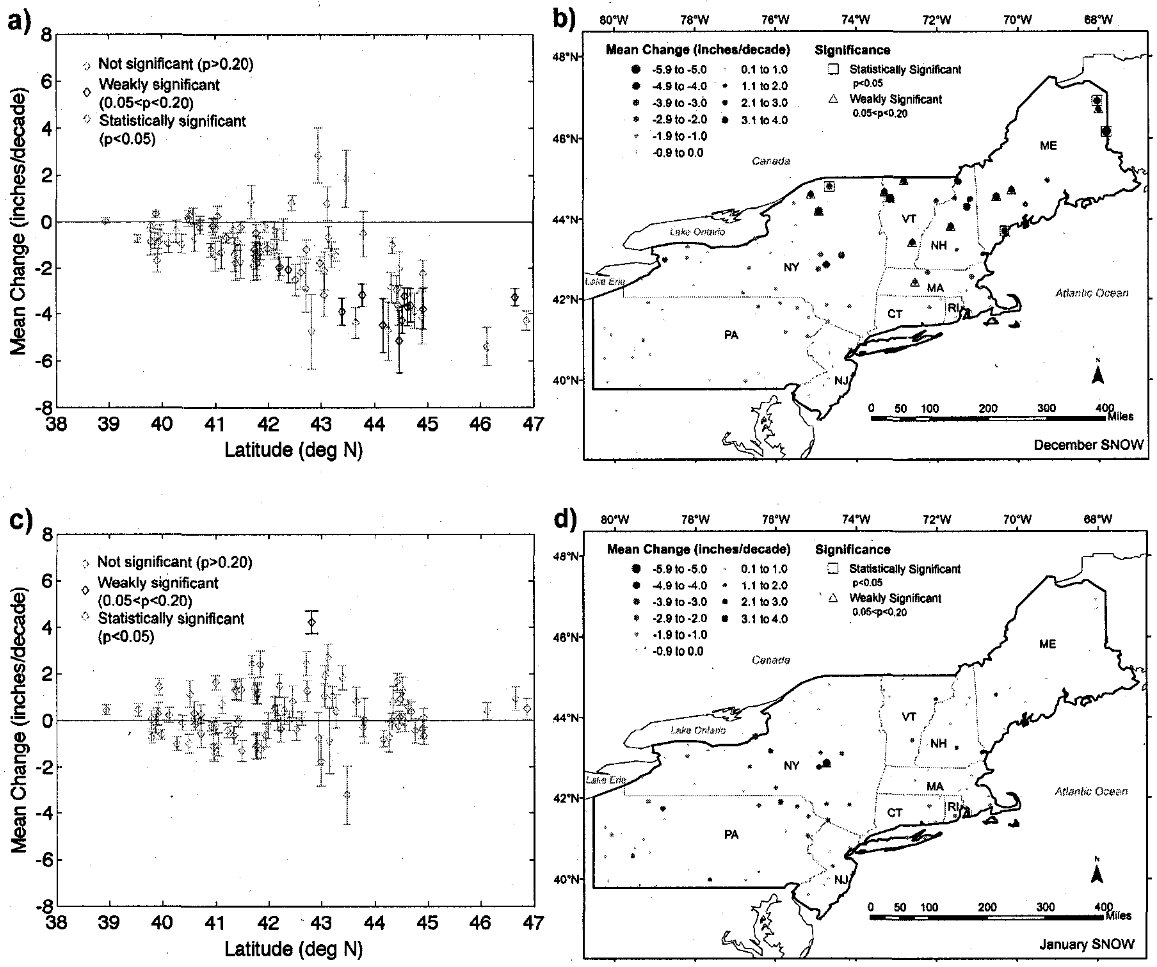

Figure 3-4. Mean decadal rate of change in monthly snowfall, by station latitude (a,c,e,g) and station location (b,d,f,h). Statistically significant ($p<0.05$) trends are shown in red (a,c,e,g), or boxed (b,d,f,h). Weakly significant trends ($0.05<p<0.20$) are shown in black (a,c,e,g), or enclosed in triangles (b,d,f,h).

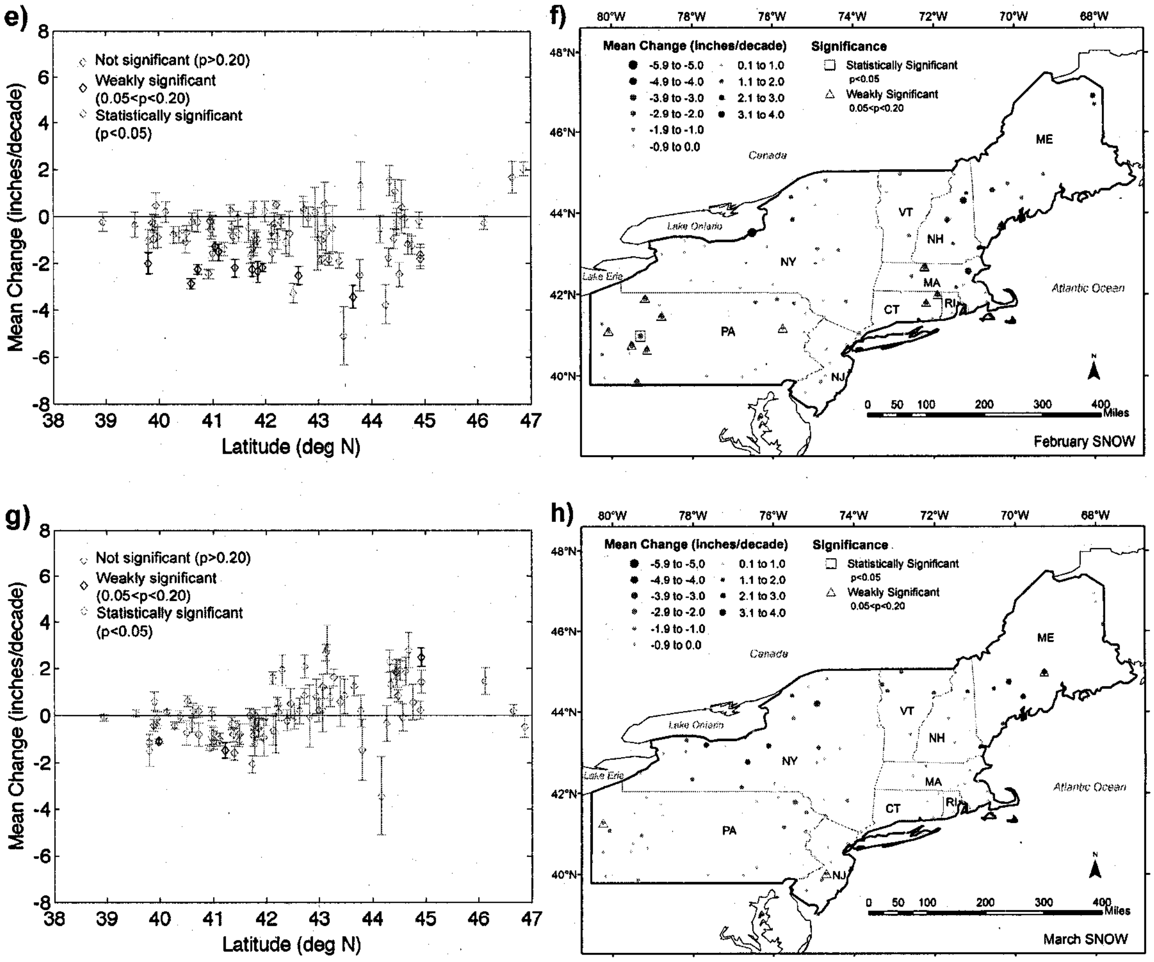

Figure 3-4 (continued). Mean decadal rate of change in monthly snowfall, by station latitude (a,c,e,g) and station location (b,d,f,h). Statistically significant ($p<0.05$) trends are shown in red (a,c,e,g), or boxed (b,d,f,h). Weakly significant trends ($0.05<p<0.20$) are shown in black (a,c,e,g), or enclosed in triangles (b,d,f,h).

Based on the individual station and regional trend analysis, snowfall trends can be characterized by an overall decrease in winter snowfall (~2.5 inches/decade) that is consistent across the region except for several stations downwind of the Great Lakes. The reduction in winter snowfall occurs primarily as strong decreases in December (-2.3 inches/decade) and moderate decreases in February (-1.1 inches/decade), which are considerably greater than the insignificant increases observed in January (+0.4 inches/decade) and March (+0.3 inches/decade). The snowfall data for the COOP and USHCN data analyzed here support the decreasing trend in the snow to total precipitation ratio identified by Huntington et al. (2004). Other studies of snow data in the northeastern United States also report decreasing trends in snowfall and snow water equivalent (Hayhoe et al. 2007; Hamilton et al. 2003). Although significant non-climatic influences may exist in USHCN and COOP data, the care taken in this study to remove stations with such biases from the analysis gives the authors greater confidence in the snowfall results presented above.

The increasing winter snowfall trends at stations downwind of the Great Lakes may be related to increased lake-effect snow. Analysis of air temperature, water temperature, and lake ice records in the vicinity of the Great Lakes suggest that observed increased in lake-effect snow during the twentieth century may be the result of warmer Great Lakes surface water temperature and decreased ice cover (Burnett et al. 2003). Annual maximum ice cover average over the period 1998-2001 is the lowest four-winter average over the period1963-2001, and Lake Erie was virtually ice-free in 1998 (Assel et al. 2003). Stations located in lake-effect snow belts from this study include Syracuse, NY (+6.8 inches/decade) downwind of Lake Ontario, and Buffalo, NY (+2.9 inches/decade) downwind of Lake Erie.

A significant inverse relationship between the winter North Atlantic Oscillation (NAO) index and regional winter snowfall by Hartley and Keables (1998) and Bradbury et al. (2002) may explain the decreasing trend in northeastern United States winter snowfall. The winter (DJFM) NAO index, defined as the normalized pressure difference between Libson, Portugal and Stykkisholmur/Reykjavik, Iceland, is the dominant mode of variability in Northern Hemisphere atmospheric circulation (Hurrell, 1995). The reductions in winter snowfall identified in this study coincide with a statistically significant upward trend in the North Atlantic Oscillation (NAO) index from 1970 through the 1990s (Thompson et al. 2000a,b; Gillet et al. 2001; Feldstein, 2002; Hurrell et al. 2003).

Snow Covered Days (SCD)

Over the period 1965-2005, stations near the coast and south of 42°N have typically experienced 0-60 days with snow depth greater than 1 inch (SCD1), while stations north of 42°N typically have between 60-121 SCD1 days (Figure 3-5). We calculate the number of snow covered days (SCD) by summing the number of days with snow depth greater than 0 inches (SCD0), 1 inch (SCD1), and 3 inches (SCD3). Only trends in SCD1 are presented here because winter and monthly trends in SCD0, SCD1, and SCD3 are similar.

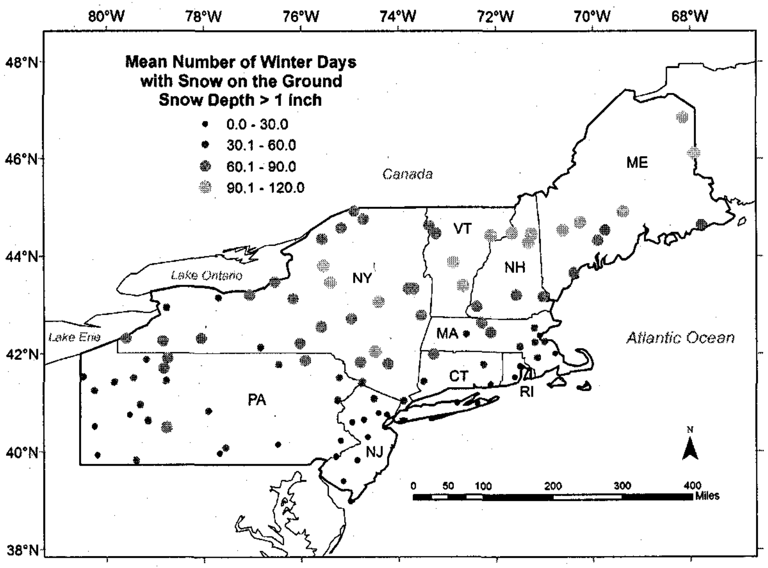

Figure 3-5. Mean number of winter snow covered days (snow depth > 1 inch). Winter includes December, January, February, and March.

The number of snow covered days in winter is broadly decreasing throughout the region (Figure 3-6). The greatest decreases have occurred at stations located between 42°N and 44°N (average ~-5.0 days/decade). Seven stations in New England (CT, RI, MA, VT, NH and VT) show statistically significant ($p<0.05$) decreasing trends (average ~-10.2 days/decade), and 14 stations in New England and New York show weakly significant ($0.05<p<0.20$) decreasing trends. No significant increasing trends in winter SCD1 were identified.

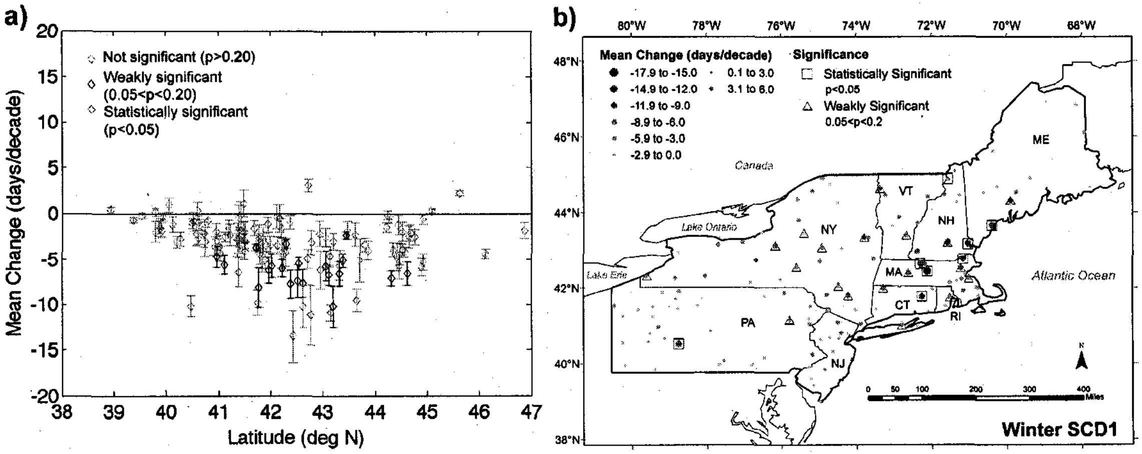

Figure 3-6. Mean decadal rate of change in winter snow covered days, by station latitude (a) and station location (b). Statistically significant (*p*<0.05) trends are shown in red (a), or boxed (b). Weakly significant trends (0.05<*p*<0.20) are shown in black (a), or enclosed in triangles (b).

Decreases in monthly SCD1 (Figure 3-7) are greatest during the months of January and February, consistent with the greater increase in temperature during those months. In New England and NY, nine stations show statistically significant decreasing trends in January SCD1 (~-3.5 days/decade) and 13 exhibit weakly significant decreasing trends. Stations showing significant trends in February SCD1 are located primarily in Massachusetts and New York (~-2.4 days/decade). Stations in northern Maine exhibit weak increasing trends in February SCD1, however none were found to be significant. For March, one station (First Connecticut Lake, NH) was found to have a statistically significant increasing trend of +0.5 days/decade; this was the only statistically significant increasing trend identified in monthly SCD1.

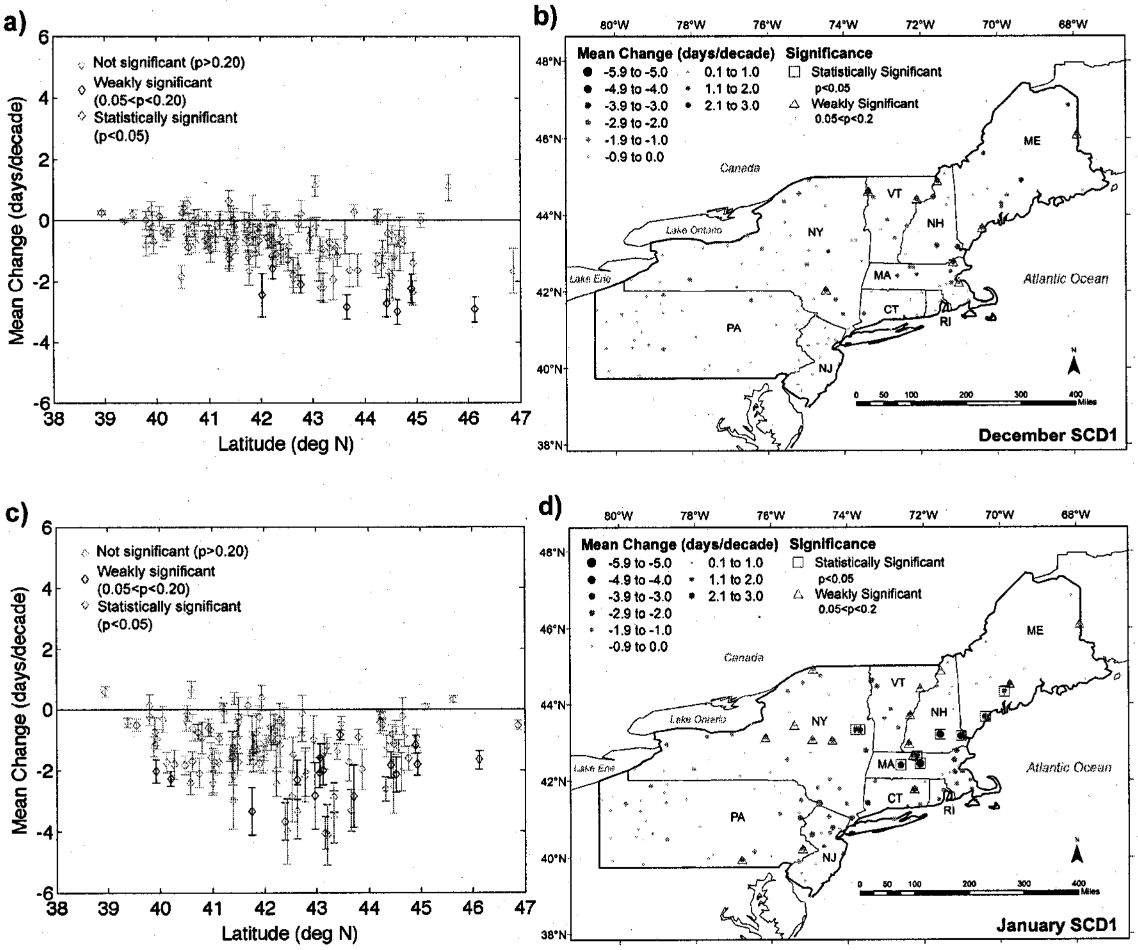

Figure 3-7. Mean decadal rate of change in monthly snow covered days, by station latitude (a,c,e,g) and station location (b,d,f,h). Statistically significant (p<0.05) trends are shown in blue (a,c,e,g), or boxed (b,d,f,h). Weakly significant trends (0.05<p<0.20) are shown in black (a,c,e,g), or enclosed in triangles (b,d,f,h).

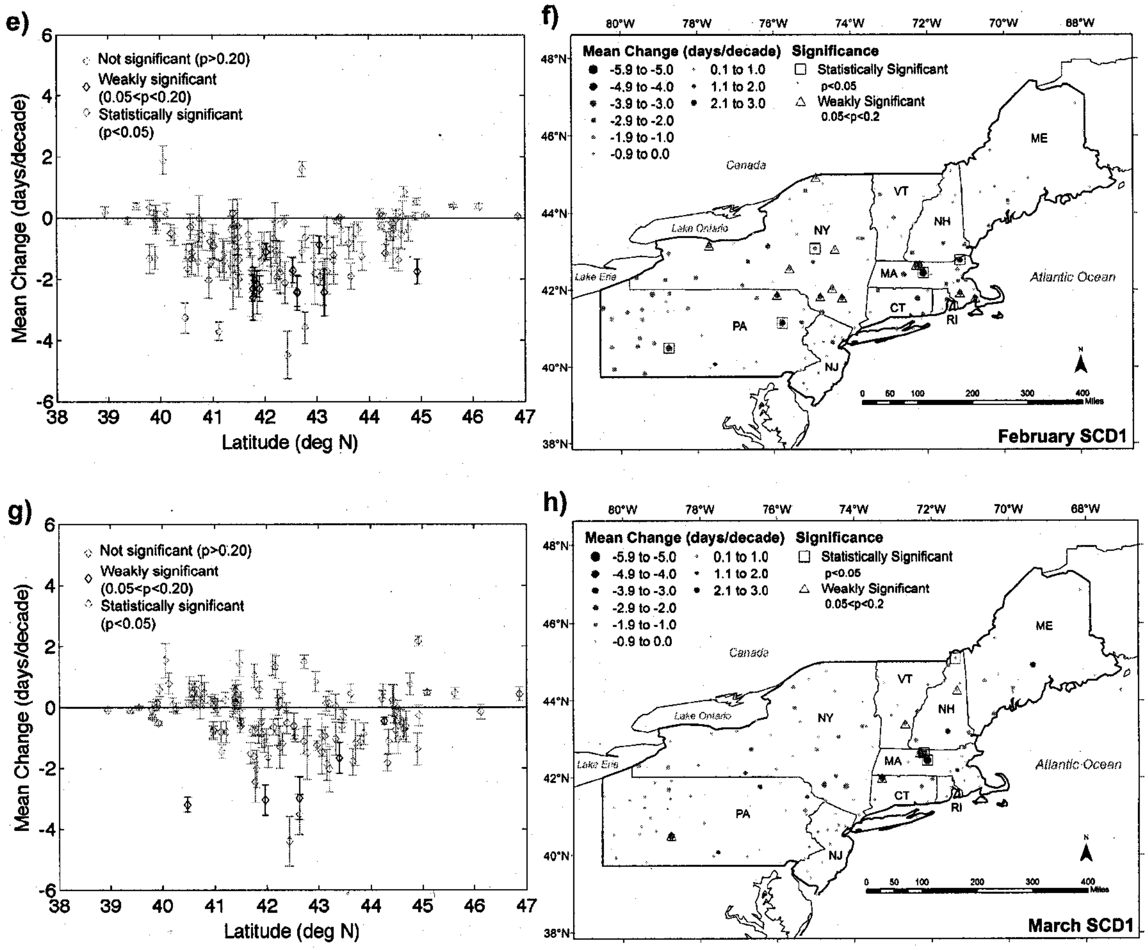

Figure 3-7 (continued). Mean decadal rate of change in monthly snow covered days, by station latitude (a,c,e,g) and station location (b,d,f,h). Statistically significant (*p*<0.05) trends are shown in blue (a,c,e,g), or boxed (b,d,f,h). Weakly significant trends (0.05<*p*<0.20) are shown in black (a,c,e,g), or enclosed in triangles (b,d,f,h).

Over the period 1965-2005, many stations in the northeastern United States have experienced a decrease in the total number of winter days with snow on the ground. The regional average decrease in total winter SCD1 (~-2.6 days/decade) is largely due to strong decreases in January and February.

Stations in New England and New York are experiencing the greatest reductions in winter SCD1 (~-5.0 days/decade). The significant decreases in January snow covered days are consistent with strong increases in January maximum temperatures, and only slight increases in January snowfall. This suggests that in our current climate, the presence of snow cover depends more on temperature and less on snowfall, which has also been suggested by Lemke et al. (2007) and Hayhoe et al. (2007). The potential for a snow-albedo feedback is large between 41°N and 43°N, where mean winter snow depths are shallow (<10 inches) and the mean winter temperature hovers around ~0°C. As temperatures increase above the freezing point, the likelihood of maintaining snow cover decreases. Without snow cover, the surface absorbs more incoming solar radiation, which increases the surface temperature. Given the documented strong increase in winter maximum temperature, it is not surprising that the greatest decreases in snow-covered days are occurring in this latitudinal band.

Conclusions

Time series analysis of temperature, snowfall and days with snow on the ground indicate a region-wide winter warming trend in the northeastern United States over the period 1965-2005. Winter temperatures have increased, with winter maximum temperatures increasing significantly faster than minimum temperatures. At a monthly level, December and March maximum temperatures have increased at a faster rate than minimum temperatures, while February maximum and minimum temperature rates of warming were almost equal. In January, minimum temperatures are warming faster than maximum temperatures.

Warmer winter temperatures have coincided with a decrease in total winter snowfall and a reduction in the number of snow covered days in winter. Decreases in monthly snowfall have been greatest in December, followed by February. Slight increases in January and March snowfall were not found to be significant. The months of January and February have experienced the greatest decrease in snow covered days, which coincide with the greatest increases in maximum temperature. These documented changes in wintertime climate have and will continue to impact the region's natural ecosystems, hydrology, and winter tourism industry. Regional climate models are one of the most promising tools for projecting climate changes into the future and assessing regional impacts. A regional climate modeling system (RCMS) that coupled the Penn State/NCAR MM5 atmospheric component with the land surface transfer model (Pollard and Thompson 1995) accurately predicted precipitation trends over the period 1991-1999. The use of a similar RCMS setup can be utilized to output trends in snowfall and snow cover, and to investigate the link between snow cover and temperature.

In this study, extensive quality control and quality assurance measures were taken to ensure that only the best available data were used. Missing data values and incomplete documentation of station moves, instrument changes, and observer changes complicate trend analysis of climate data. Stringent and consistent operational practices among USHCN and COOP stations would improve the certainty of trends derived from the observational record.

The extent to which snow-albedo feedback may be influencing winter temperature and snow covered days requires further research. Major discrepancies between observed and modeled northeastern United States historical climatology (Hayhoe et al. 2007) could possibly be resolved through quantification of the magnitude of warming generated by reductions in regional snow cover extent. Although trends in snow-covered days at individual stations are important, they do only provide a proxy measure of changes in snow cover area. Improved quantification of trends in regional snow cover extent are necessary to better understand the region's sensitivity to changes in surface albedo. Satellite imagery combined with station observations revealed a decreasing trend in spring snow cover extent over North America since the 1980s (Frei and Robinson 1999). The introduction of high-resolution (500m) daily satellite snow maps from NASA's Earth Observing System Moderate Resolution Imaging Spectroradiometer (MODIS) in February 2000 will be useful in creating a time series of snow cover extent for future studies at the regional scale.

In addition, the important complex links between northeastern United States winter climate trends and the NAO identified by Hartley and Keables

(1998) and Bradbury et al. (2002) may help explain the warming trends identified in this study. Future studies should include quantifying the extent to which the recent warming trends identified here are due to hemispheric-scale climate oscillations like the NAO.

CHAPTER IV

CONCLUSIONS AND FUTURE WORK

Time series analysis of temperature, snowfall and days with snow on the ground indicate a region-wide winter warming trend in the northeastern United States over the period 1965-2005. Winter temperatures have increased, with winter maximum temperatures increasing significantly faster than minimum temperatures. At a monthly level, December and March maximum temperatures have increased at a faster rate than minimum temperatures, while February maximum and minimum temperature rates of warming were almost equal. In January, minimum temperatures are warming faster than maximum temperatures.

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In addition, the important complex links between northeastern United States winter climate trends and the NAO identified by Hartley and Keables (1998) and Bradbury et al. (2002) may help explain the warming trends identified in this study. Future studies should include quantifying the extent to which the recent warming trends identified here are due to hemispheric-scale climate oscillations like the NAO.

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