The Changing Character of Winter Climate in the Northeast United States

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Introduction

The winter of 2007-2008 will go down in memory as one of the snowiest winters in the northeast. Skiers and snowboarders enjoyed natural snow conditions as early as mid-November and continued the season through May. Outdoor enthusiasts enjoyed snowshoeing in the Green Mountains of Vermont, cross-country skiing along the coast at Ordiorne Point State Park in New Hampshire, and snowy winter hikes in the White Mountains.

When compared to previous winters, the 2007-2008 winter makes people in the northeast appreciate the capricious nature of their winters, but also reminds them that the cold, snowy winters are becoming more of a rarity. The warmer winters of recent years remind us that the character of our winters is at stake, and we that we have the opportunity to partake in a global effort to help preserve it.

Detailed analysis of meteorological records has determined that global temperatures rose 1.3^{o}F over the past 100 years, and that the rate of warming over the past 50 years has more than doubled the 100-year trend[1]. In addition, the eleven warmest years on record (since 1850) have occurred since 1995[1]. Scientists agree that the increased rate of warming is being driven primarily by increases in levels of greenhouse gases in the atmosphere that originate from the burning of fossil fuel and land use changes[1].

Regions around the world are responding differently to the impacts of a warming globe. In the northeastern United States, winter temperatures have warmed much faster than in any other season over the past four decades. Communities in the northeast, which includes the states of Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont, generally experienced cold winters during the first half of the 20th century (Figure 1). In more recent decades, warmer winter temperatures have lead to changes in snowfall and snow cover, which have resounding impacts on the region's climate, ecosystems, and economy.

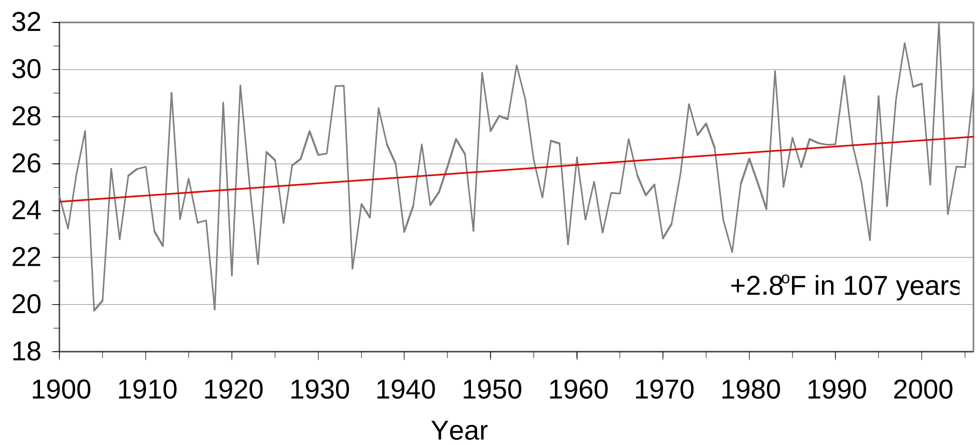

Figure 1. Time series of northeastern United States winter temperature, 1900-2006. The temperature change (+1.7°F) was estimated using linear regression (red line). The regional average was calculated as the area-weighted mean, weighted by NCDC climate division area.

This report contains a summary of findings from research conducted at the Climate Change Research Center at the University of New Hampshire (and published in peer reviewed scientific literature[2]) and includes trends in regional winter temperature over the period 1965-2006, days with snow cover (snow depth > one inch) and snowfall over the period 1965-2005. This time period was chosen because it coincides with the increased rate of warming identified in the global record that is linked to increased levels of anthropogenic greenhouse gases[1].

The data in this study come from the United States Historical Climate Network (USHCN)[3] and the National Weather Service Cooperative Observer Program (COOP) [4](Figure 2). Extensive quality assurance and quality control measures have been applied to the data set used to increase confidence in the findings[2]. In the northeastern United States, the month of March is included in the winter analysis because it is typically colder and snowier than December.

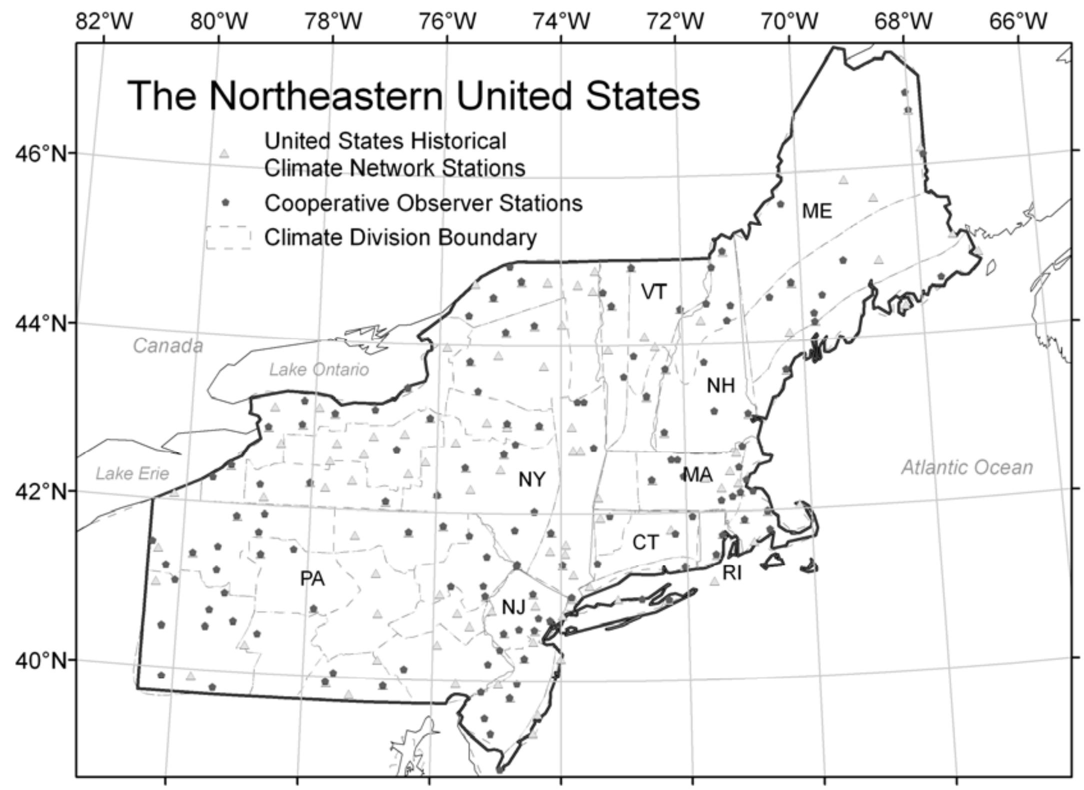

Figure 2. Distribution of northeastern United States climate stations used in this study. United States Historical Climate Network (USHCN) stations are shown as light grey triangles, Cooperative (COOP) Network stations are shown as dark grey circles. National Climatic Data Center (NCDC) climate division boundaries within each state are delineated with dashed lines. Here we define the Northeast US as the six New England states, New York, Pennsylvania, and New Jersey.

Temperature

Analysis of winter temperature records provides a first-order measure of how winter climate in the northeastern United States has changed in recent decades. For the period 1965-2006, the average winter temperature in the northeastern

United States was about 27°F. The 32°F isotherm, or the threshold between below and above freezing mean winter temperatures, is located approximately between 41°N and 42°N (Figure 3).

Mean monthly and seasonal temperature records from 138 meteorological stations across the northeastern US exhibit region-wide winter warming trends on

	Mean Temperature		Snow Covered Days		Snowfall	
	°F	°F/decade	days	days/ decade	inches	inches/ decade
December	+1.9	+0.5	-3.0	-0.7	-5.5	-1.3
January	+3.7	+0.9	-3.1	-0.8	+2.4	+0.6
February	+4.6	+1.1	-2.0	-0.5	-2.8	-0.7
March	+1.4	+0.3	-0.3	-0.01	+2.1	+0.5
Winter	+2.9	+0.7	-8.6	-2.1	-3.2	-0.8

Table 1. Summary of northeastern United States regional average winter climate trends calculated for the period 1965-2005. For each climate variable, the first column represents the total change over the 41-year period, and the second column represents the decadal rate of change over the 41-year period.

the order of +2.9°F over the period 1965-2006 (Table 1). All but two (New Bedford, MA and Lowville, NY) of the 138 stations included in the analysis exhibit winter warming trends (Figure 4).

At the monthly level, strong temperature increases in January (+3.7°F) and February (+4.6°F) are nearly twice than that observed for December (+1.9°F) and March (+1.4°F). A sensitivity analysis using a range of 30-year windows over the period 1965-1994, 1966-1995 ... 1977-2006 shows that winter temperatures are warming regardless of the start and end date used for the time series, and that statistically significant winter warming trends predominate after 1970 (See Appendix I).

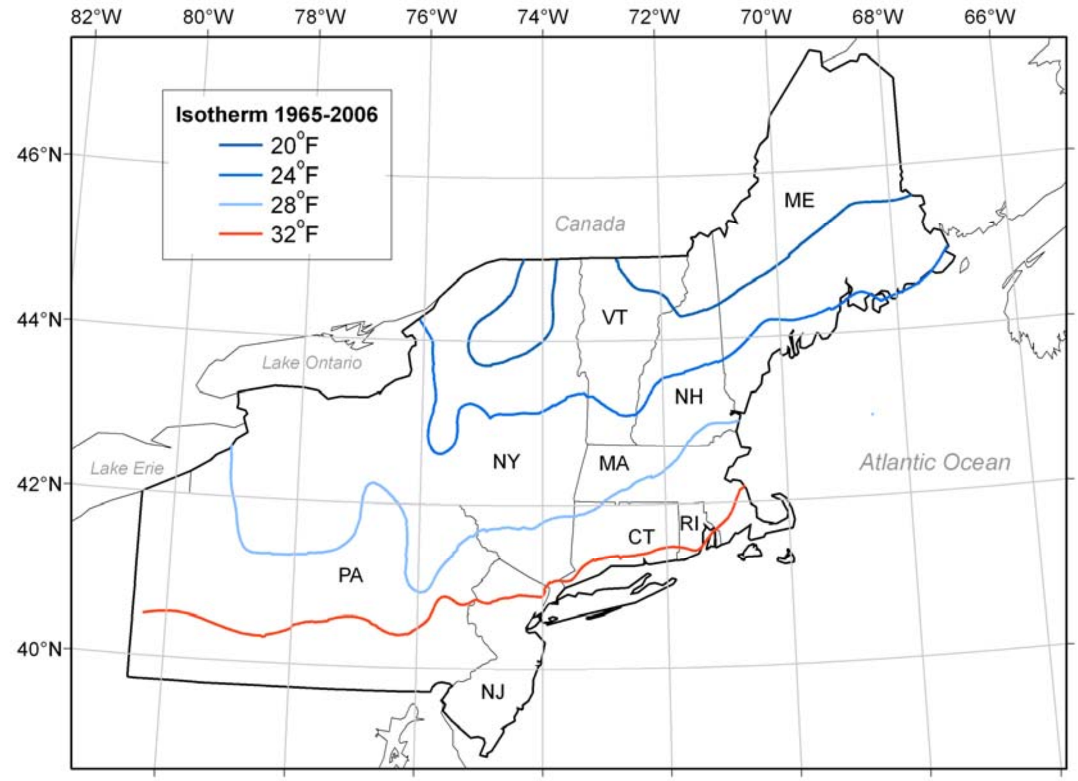

Figure 3. Mean winter (Dec-Mar) temperature isotherms derived from station-based data over the period 1965-2006. The red line marks the 32^{o}F isotherm, or the freezing point threshold. Stations with average winter temperatures below freezing are located north of the 32^{o}F isotherm, and stations with average winter temperatures above freezing are located south of the 32^{o}F isotherm.

Snow Covered Days

Snow-cover depth and duration are important to the climate, ecology, and economy of the northeastern United States. Deep, long-lasting, natural snow cover can be a boon to the cross-country and snowmobiling industry, and also provides an insulating cover for frost-sensitive plants like wild blueberries. Snow cover also results in cooler air temperatures, as the white snow reflects much of

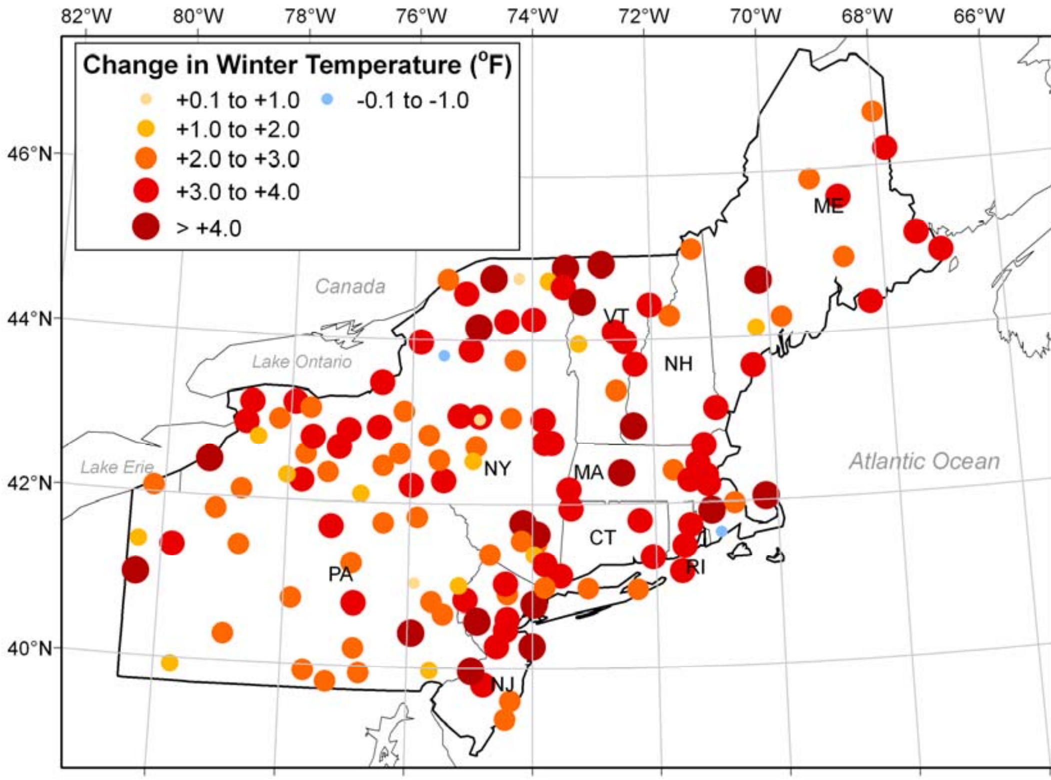

Figure 4. Spatial distribution of winter warming trends, 1965-2006. Trends are calculated using the slope of the linear regression applied to the time series. Warm colors indicate warming trends; cool colors indicate cooling trends. The size and hue of the dot indicates magnitude.

the incoming solar radiation back into space[5]. Communities in the northeastern United States located near the coast and south of 42°N typically experience between 0-60 snow covered days (snow depth > one inch), while inland stations north of 42°N typically experience between 60-121 snow covered days.

Since 1965, most stations in the northeastern United States have experienced an overall decrease in the total number of winter snow covered days. Regionally averaged, the number of snow covered days has decreased by more than week (-8.6 days) over the period 1965-2005, and is largely the result of strong decreases during the months of December (-3.0 days), January (-3.1 days) and February (-2.0 days). The stations with the greatest decreases in days with snow cover days are primarily located between 42°N and 44°N, or just north of the threshold between above and below freezing average winter temperatures (Figure 5). In addition, the decrease in January and February snow-covered days coincides with strong increases in January and February temperatures

(Table 1), a possible indication that snow cover may depend more on temperature than on snowfall[6,7]. In addition, the documented decrease in the snow to total precipitation ratio[7] suggests that increasing winter rainfall over the period 1949-2000 may also be involved in melting shallow snow cover and exposing bare ground.

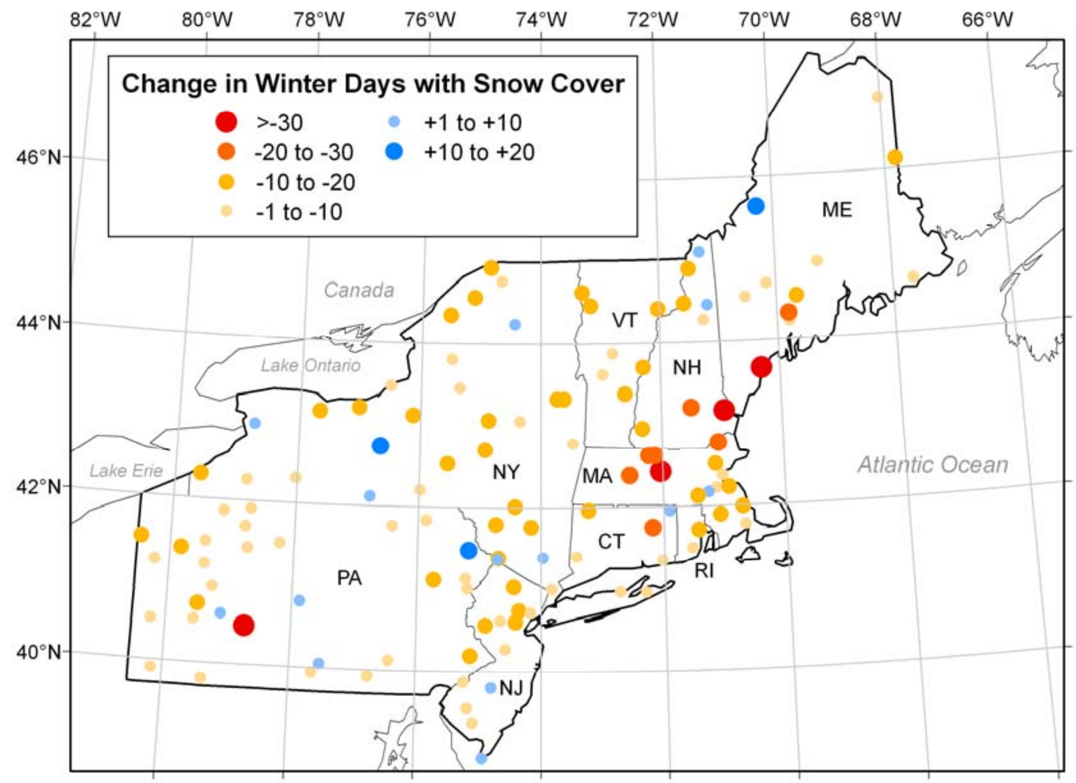

Figure 5. Spatial distribution of winter (Dec, Jan, Feb, Mar) snow-covered days trends in the northeastern United States, 1965-2005. Trends are calculated from applying linear regression to the time series. Warm colors indicate decreasing trends; cool colors indicate increasing trends. The size and hue of the dot indicates the magnitude of the trend.

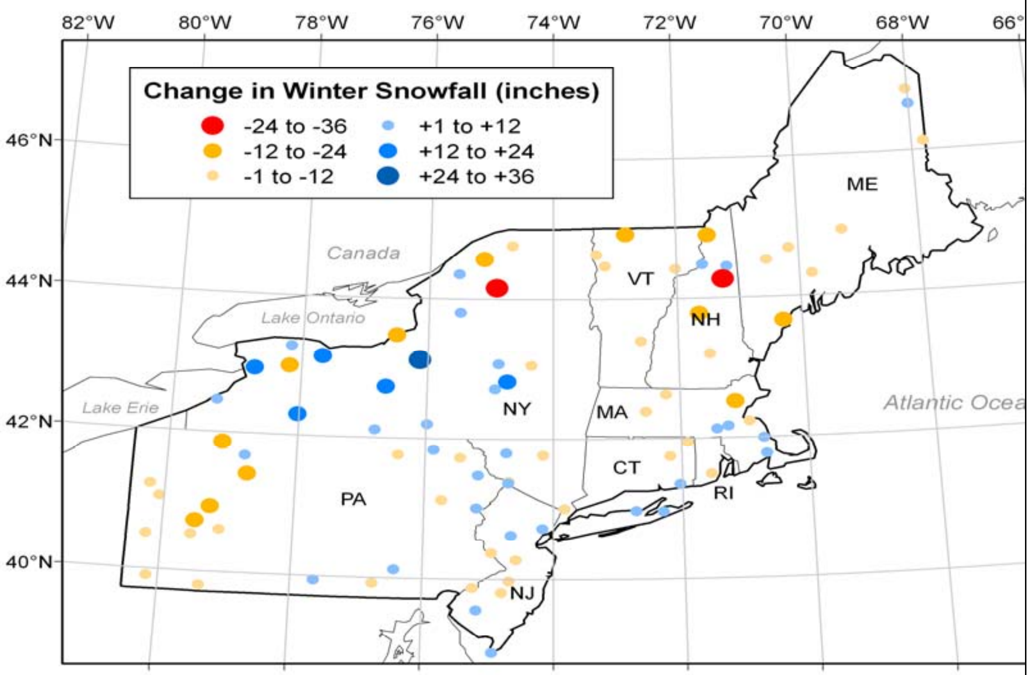

Figure 6. Spatial variability in total winter snowfall trends for the period 1965-2005. Trends are calculated from applying linear regression to 1965-2005 time series. Warm colors indicate decreasing trends; cool colors indicate increasing trends. The size and hue of the dot indicates the magnitude of the trend.

Snowfall

The detection of climate change signals in snowfall records is complex because snowfall is dependent on several factors. Moisture availability and the air temperature at various layers in the atmosphere determine whether precipitation comes in the form of rain, sleet, hail, or snow. Warmer air masses hold more moisture, which can lead to copious amounts of snowfall. Such was the case during the winter of 2007-2008, which set record seasonal snowfall totals at several locations across the northeast US despite warmer than average winter temperatures[8]. The measurement of snowfall can also introduce significant complications to data interpretation. Differences in measurement methods, and changes in station locations and time of observation can introduce non-climatic biases to snowfall records[9]. The stations used in this analysis have been screened for such factors[10], but there still exists significant variability in snowfall trends across the region (Figure 6).

Over the period 1965-2005, total winter snowfall has decreased by about 3.8 inches, averaged across the entire region. The majority of the total winter reduction in snowfall is occurring during the month of December, which has lost about 5.5 inches over the 41-year period (Table 1). The month of February (-2.8 inches) also experienced a modest decrease in snowfall. However, March (+2.1 inches) and January (+2.4 inches) snowfall records indicate slight increases in monthly total snowfall over the time period 1965-2005 (Table 1).

What Does This Mean for the Northeast US?

Over the past four decades, communities in the northeastern United States have witnessed significant changes in the character of their winters. Warmer temperatures, fewer days with snow cover, and decreased snowfall are all symptoms of a region being impacted by a warming globe. Our confidence in quantifying this warming signal comes primarily from the high-quality, reliable temperature records from over 138 meteorological stations located across the northeast. While this warming trend is likely the cause of region-wide decreases in snow cover duration, significant interannual variability remains in snowfall records, making this indicator less clear.

The impacts of warmer winters are already being observed in the northeastern United States. Warmer winter temperatures have been associated with earlier river[11] and lake ice-out[12], which shortens the ice-fishing season. In addition, decreases in the snow to total precipitation ratio and snow density are linked to warmer than average winters and can be important to the timing and magnitude of spring runoff[13]. A shift to earlier and decreased spring runoff has been shown to impact the survival of salmon juveniles[14]. An observed decrease in the number of extreme cold temperature days[15] can lead to increases in tick populations, making vector-borne diseases like Lyme disease more widespread[1]. The lack of cold winter days also allows for the northward migration of hemlock woolly adelgid, an invasive insect that has decimated stands of eastern hemlock on the east coast of the United States[16]. Cold-temperature days are also important to cool-temperature crops such as apples, blueberries, cranberries and grapes, which require 200-2000 cumulative winter cooling hours (between 32^{o}F and 50^{o}F)[17]. If the cooling period requirement is not met, flower buds may die or blossoms may drop before they open, and those flowers that do develop may not set fruit, or the fruit may be undersized.

The impacts of decreased snow cover have been felt strongly in the multi-billion dollar winter tourism and recreation industry. During warm and slushy winters, the state of New Hampshire alone loses an estimated $13 million dollars in revenue from alpine and Nordic ski ticket sales, ice-fishing licenses, and snow-mobile registrations[18]. While large investments in snow-making technology will keep many alpine ski resorts in business during warmer than average winters[19], other winter tourism industries, like snowmobiling and Nordic skiing, have not been able to apply such adaptation strategies[20].

Snow cover also plays an important role in soil temperature and moisture properties. Reduced snow cover can have negative impacts on crops such as wild blueberries. In Maine, where ninety percent of the nation's wild blueberries are grown, blueberry crops in 2004 were down 43% from the previous year, partly due to frost damage brought on by inadequate snow cover and extreme cold temperatures[21].

Scientists use regional climate models to project temperature increases in response to higher and lower greenhouse gas emissions scenarios. Under lower emissions scenarios, winter temperatures can be expected to rise by an additional 5.8^{o}F relative to the 1960-1990 average by 2100[22] Under higher emissions scenarios, winter temperatures may rise by an additional 8^{o}F to 12^{o}F by the end of the century. In other words, the decision we make today and over the next decade concerning how we produce and how we use energy will determine how much warmer winter in the northeastern United States will be in the future. This warming will impact a wide range of sectors in our society, including marine resources, coastal infrastructure, winter recreation, agriculture, forests, and human health[22,23]. Regardless of the emissions scenario chosen, the average

What's the difference between weather and climate?

(Or: How can we have a snowy winter in New England if global climate is warming?)

Writer Robert Heinlein hit the nail on the head when he wrote "Climate is what we expect. Weather is what we get". The difference between weather and climate is a matter of time. Weather is the set of conditions of the atmosphere over a short period of time. *Weather* can change from minute-to-minute, hour to hour, day-to-day, and season-to-season. *Climate* is the average weather over time.

Weather is what is happening outside right now. Snow flurry, sunny day, thunderstorm and lightning, pelting rain, very hot summer day, Nor'easter, cold front, warm front, high pressure system sliding through the region . . . .

Climate is the longer-term averages of weather, often over time periods of decades or longer. To answer the question – is our climate changing? – scientists need to look at longer-term trends – many decades to centuries to millennia . These trends include standard measures of changes in mean annual temperature and precipitation, but can also include changes in extreme precipitation events that drop more than one inch of rain in one day, or the length of the growing season, or changes of the timing and amount of spring runoff, or ice-out dates on lakes and rivers, or sea-level rise. These can be measured at individual locations, but data from many locations is often averaged to provide a regional or sometimes global average.

So, anybody who has lived in New England for more than a few years knows that the weather can change rapidly. As Mark Twain said: "Yes, one of the brightest gems in the New England weather is the dazzling uncertainty of it." But analysis of longer-term records is showing that our climate is changing as well. The overall trend towards warmer winters in the northeast does not mean we do not have any cold, snowy winters; it means we simply have fewer of them. And the odds of having a cold, snowy winter will continue to decrease if we continue on a business-as-usual energy pathway and continue to increase our collective emissions of heat-trapping gases.

- *Cameron Wake*

winter temperature in the northeast is projected to approach, or worse, rise above the freezing point by the end of the 21st century.

The warming trends identified in northeast U.S. meteorological station records are consistent with what scientists expect from a world being warmed by greenhouse gases. If emissions continue to rise, the average winter temperature in the northeast is likely to rise above the freezing point by the end of the 21st century, making snowfall and snow cover occur much less frequently. Even under lower emissions scenarios, we will continue to see changes in the character of our winters. The continuation of current rates of warming into the future most certainly will alter the character of winter in the northeastern United States.

APPENDIX I: Sensitivity Analysis for monthly and seasonal temperature trends.

Decadal trends are estimated from linear regression applied to twelve 30-year moving windows over the period 1965-2005. Trends in bold are statistically significant (*p-value* <0.10). An overwhelming majority of monthly temperature trends were found to be increasing trends, regardless of the 30-year window used. All trends for the months of January and February are increasing trends. Most importantly, seven of the twelve seasonal trends were found to be statistically significant increasing trends.

30-yr period	**Dec**		**Jan**		**Feb**		**Mar**		**Winter**	
	Trend (^oF/decad)	Sig. (p-value)	Trend (^oF/decade)	Sig. (p-value)	Trend (^oF/decade)	Sig. (p-value)	Trend (^oF/decade)	Sig. (p-value)	Trend (^oF/decade)	Sig. (p-value)
1965-1994	-0.06	0.94	+0.68	0.50	+0.85	0.33	+0.30	0.66	+0.44	0.27
1966-1995	+0.25	0.78	+1.00	0.33	+0.63	0.48	+0.35	0.60	+0.56	0.18
1967-1996	+0.16	0.86	+0.97	0.35	+0.70	0.43	+0.26	0.71	+0.52	0.21
1968-1997	+0.62	0.51	+1.43	0.15	+0.73	0.41	-0.05	0.95	+0.68	0.11
1969-1998	+0.85	0.36	+1.62	0.11	+0.95	0.30	+0.30	0.66	**+0.92**	**0.05**
1970-1999	+1.08	0.26	**+1.74**	**0.08**	+1.26	0.18	+0.13	0.84	**+1.05**	**0.03**
1971-2000	+1.10	0.25	+1.22	0.21	+1.38	0.14	+0.33	0.64	**+1.01**	**0.03**
1972-2001	+0.46	0.64	+0.94	0.32	+1.48	0.11	-0.10	0.89	+0.70	0.13
1973-2002	+1.04	0.31	+1.55	0.11	**+1.57**	**0.09**	-0.29	0.67	**+0.97**	**0.05**
1974-2003	+0.96	0.35	+1.42	0.16	+1.11	0.25	+0.07	0.91	**+0.88**	**0.08**
1975-2004	+1.22	0.23	+1.15	0.26	+0.90	0.35	+0.18	0.79	**+0.85**	**0.09**
1976-2005	+1.34	0.18	+1.40	0.17	+1.02	0.29	-0.25	0.70	**+0.86**	**0.09**
Average	+0.75 ±0.46	----	+1.26 ±0.32	----	+1.05 ±0.31	----	+0.10 ±0.23	----	+0.79 ±0.20	-----

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[4] National Weather Service Cooperative Observer Network data available for download at: http://cdo.ncdc.noaa.gov/pls/plclimprod/somdmain.somdwrapper

[5] The presence of snow cover influences temperature through a property known as *albedo*, or reflectivity. Surfaces with a high albedo reflect incoming solar radiation before it can be absorbed. Surfaces with a low albedo absorb incoming solar radiation and re-radiate it as long-wave radiation, or heat. A snow covered surface is therefore relatively cooler than bare ground, which has a lower albedo.

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