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Evidence of Climate Change Declines with Elevation Based on Temperature and Snow Records from 1930s to 2006 on Mount Washington, New Hampshire, U.S.A.

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Abstract

Mount Washington, New Hampshire, has the longest northeastern U.S. mountain climatological record (1930s to present), both at the summit (1914 m) and at Pinkham Notch (612 m). Pinkham's homogenized daily temperature exhibits annual (mean = +0.07°C/decade, p = 0.07; min = +0.11°C/decade, p = 0.01), winter (min = +0.18°C/decade, p = 0.07), spring (max = +0.13°C/decade, p = 0.10), and summer (min = +0.11°C/decade, p = 0.01) warming trends. Though suggesting annual, winter, and spring warming (0.05 to 0.12°C/decade), mean summit temperature trends were not significant. Pinkham shows no significant change in date of first and last snow; however, the summit does but its period of record is shorter. Onset of continuous snow cover has not changed significantly at either site. Thawing degree days trended earlier at the summit (2.8 days/decade; p = 0.01) and Pinkham Notch (1.6 days/decade, $p < 0.01$), but end of continuous snow cover trended significantly earlier (1.6 days/decade; p = 0.02) only at Pinkham. Growing degree days showed no significant trends at either location. Pinkham exhibits more climatic change than the summit but less than regional lower elevations. Thermal inversions and high incidence of cloud fog commonly at or above the regional atmospheric boundary layer may explain the summit's resistance to climate warming. Caution is needed when extrapolating climate change trends from other mountains or proximate lower elevation climate data to upper elevations.

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Introduction

Evidence of climate warming and reductions in seasonal snow cover on global (IPCC, 2007), hemispheric (Dye, 2002), and regional scales (Hayhoe et al., 2007) are numerous. Paralleling reported temperature increases are indices pointing to an earlier start to the growing season over the northern hemisphere (Schwartz et al., 2006). Northern hemisphere snow cover extent has decreased by 7.5 ± 3.5% during March and April (Lemke et al., 2007), and snow pack is decreasing in the mountains of the western United States with implications for water supply as well as entire ecosystems (Mote et al., 2005). However, there is a growing body of evidence that suggests considerable variability in climatic trends among mountains ranges. For example, mountain glaciers in Glacier National Park, Montana, U.S.A., are shrinking (Hall and Fagre, 2003), while glaciers on Mount Shasta, California, U.S.A., are expanding, despite a regional warming over the past half century (Howat et al., 2007).

Temperature fluctuations during the last century at high elevation sites around the world also exhibit horizontal and vertical variability (Diaz and Bradley, 1997). Europe (particularly western Europe), and parts of Asia displayed the strongest high-altitude warming during the period of record due primarily to increases in daily minimum temperature. Within central Europe's mountains temperature patterns trend warmer, but again with spatial and altitudinal variations (Weber et al., 1997).

Long-term, instrumented climatological measurements of the mountainous regions of the world are not numerous, and in eastern North America are relatively scarce. Two recent papers from New England show a warming at the summit of Mount Washington, New Hampshire, U.S.A., from 1935 to 2003 (Grant et al., 2005), an overall decrease in mean dew point temperature from 1935 to 2004, and an increase in annual fog frequency (Seidel et al., 2007). Other regional montane studies have focused on shorter time scale microclimatic studies (e.g. Friedland et al., 1992, 2003) or used longer temperature data sets for other purposes (e.g. lapse rate calculation; Richardson et al., 2004). Regional assessments have shown New England to be heterogeneously warming (Keim et al., 2003; Trombulak and Wolfson, 2004; Hayhoe et al., 2007).

New England precipitation studies show changes in the winter and spring hydrological records at lower elevations: an increase in the rain/snow ratio (Huntington et al., 2004), earlier dates for center-of-volume flow in rivers affected by snowmelt (Hodgkins et al., 2003), amount and timing of ice-affected river flow (Hodgkins et al., 2005), a decrease in the number of days with snow on the ground (Burakowski et al., 2007), and earlier springs (5 days) by seasonal evapotranspiration (Czikowsky and Fitzjarrald, 2004). Changes in snow cover amount and duration have many impacts in the Northeast including changes in nutrient cycling, mammalian species composition shifts (Carroll, 2007), and human recreation (Hamilton et al., 2007).

Snow cover patterns can affect alpine plant community composition (Walker et al., 1999; Bjork and Molau, 2007), physiology (Starr et al., 2000), phenology (Inouye and McGuire, 1991; Kudo, 1991; Huelber et al., 2006), and population genetics (Hirao and Kudo, 2004) and are an important factor in plant community distribution on Mount Washington (Bliss, 1963;

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Sardinero, 2000). Temperature also impacts arctic and alpine plant communities. Warming can lead to a shrubbier composition in alpine (Cannone et al., 2007) and tundra vegetation (Arft et al., 1999; Walker et al., 1999), and warming trends have been linked to range restrictions in alpine species at lower elevations (Pauli et al., 2007) and latitudes (Lesica and McCune, 2004). Seasonal increases in temperature reduced snow cover depth and duration in the Swiss alps, increasing the length of the growing season and causing earlier flowering (Keller et al., 2005).

Future predictions of climatic change and impacts on mountain ecosystems are frequently based on the most proximate low elevation data or on extrapolations from other mountain regions. But using surrogate climatic data to describe potential responses by mountain biota can result in compromised conclusions. For example, *Picea rubens* tree-ring growth on Mount Washington correlates more closely with the Mount Washington mid-elevation and summit temperatures than temperatures from low-elevation stations within a 40 km radius (Kimball and Keifer, 1988). Richardson et al. (2004) demonstrated that though general elevation–mean annual temperature relationships held across their northeastern U.S. mountain study sites, there was significant variation in air temperature lapse rates up the sides of the mountains and the pattern of variation was not consistent among mountains.

Mount Washington has the most complete northeastern U.S. instrumented temperature and snow records for both mid and high elevations, ranging from the 1930s to the present. In this study we compare seasonal and annual temperature trends, growing and thawing degree-day trends, and trends in two indices of snow season length for the summit and for Pinkham Notch, a mid-elevation site on the eastern side of the Mount Washington. Our study modifies previous conclusions from this region by Grant et al. (2005), discusses New England mountain climatic trends in relation to alpine ecosystems, and compares our observed trends with other high elevation sites in the world.

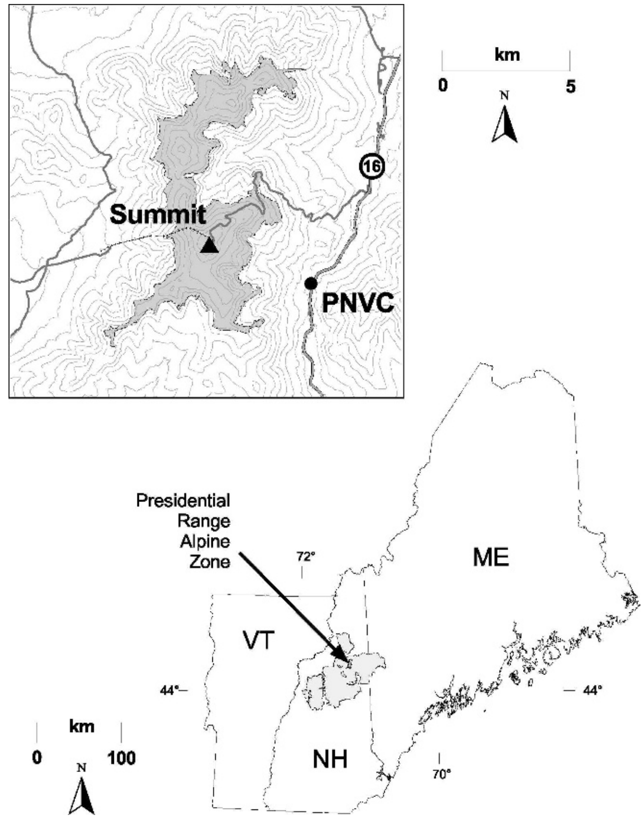

FIGURE 1. The White Mountain National Forest, outlined in black, in northern New Hampshire, U.S.A. The blowup shows the Presidential Range with contour intervals of 90 m, the alpine zone (gray shading), the summit of Mount Washington (triangle) and Pinkham Notch Visitor Center (circle) adjacent to NH route 16 (thick line). Additional landmarks are the Mount Washington Auto Road on the east side of the mountain and the Mount Washington Cog Railway on the west side of the mountain.

Site Location and Data Collection

BASIC DESCRIPTION OF REGION

Mount Washington (44°16′N, 71°18′W), the highest point (1914 m a.s.l.) in the northeastern United States, is part of the Presidential Range of the White Mountains of New Hampshire, a northern section of the Appalachian Mountains. The Presidential Range contains 2748 ha of contiguous alpine and subalpine vegetation surrounded by spruce and fir boreal forest with northern hardwood species at lower elevations. Treeline occurs at relatively low elevations and ranges from 1100 to 1700 m (Kimball and Weihrauch, 2000). The treeline-alpine ecotone is correlated with exposure to clouds and wind, slope, and aspect (Reiners and Lang, 1979; Kimball and Weihrauch, 2000).

The regional atmospheric mixing-layer typically is 1100–1500 m a.s.l. (Freedman et al., 2001), and on Mount Washington it exhibits diurnal and vertical migration that is influenced by daily solar heating, changing weather fronts, and the complex terrain of the surrounding mountain region. Above this mixing-layer is the "free atmosphere" where the winds approaching the Presidential Range are more geostrophic.

The climatological records are from the Mount Washington Observatory located on the rocky windswept summit of the mountain and from the Appalachian Mountain Club's (AMC) Pinkham Notch Visitor Center (612 m a.s.l.) in the upper extent of the northern hardwoods on the eastern side of the mountain (Fig. 1).

SUMMIT

The Mount Washington Observatory has maintained a staffed meteorological station atop the mountain since 1932. Consistent data records allow analysis of hourly temperature observations since 1935 and 6-hourly synoptic observations, including snow depth, since 1949. From 1932 through 1937 the observatory building occupied several locations on the summit, with additional moves in 1937 and 1980 (Grant et al., 2005). The area immediately surrounding the Observatory is felsenmeer.

Hourly temperature (T) observations are taken at the end of each hour using either a mercury thermometer mounted in a sling psychrometer or an alcohol-in-glass minimum thermometer. Daily minimum and maximum temperatures (min/max) are determined by reading the alcohol-in-glass minimum thermometer and the mercury maximum thermometer, respectively (Grant et al., 2005).

Snowfall and other hydrometeors are observed by trained and certified observers according to U.S. National Weather Service (NWS) standards. Snow depth is estimated by the observer based on a visual spatial average encompassing the summit at the time of the synoptic observation. Attempts are made to avoid overweighting due to drifts and wind-cleared zones. Snow depth is reported in 1.27 cm intervals, including trace.

Summit snow data from 1949 to 2004 were digitized as part of the same effort that produced the hourly and 6-hourly temperature and humidity data analyzed by Grant et al. (2005) and Seidel et al. (2007). For this study, Mount Washington Observatory staff updated the temperature and snow digital record to include 2005–2006. Due to the choice to define snow season criteria (see **Methods**) without using explicit snow depth, the snow data were not subjected to the time-intensive quality assurance checks for digitization errors.

PINKHAM

The Appalachian Mountain Club (AMC) has operated a NWS cooperative (COOP) station [COOP #276818, NCDC station ID 20018701, NWS Location ID HGMN3] at its Pinkham Notch Visitor Center (elevation 612 m a.s.l., 44°16′N, 71°15′W) in the White Mountain National Forest since 1930. The most recent National Climate Data Center (NCDC) station metadata (10 January 2008) describes the station thus: "Narrow north-south notch in mountainous and heavily wooded area."

Daily minimum and maximum temperatures were observed using standard liquid in glass (LIG) minimum and maximum thermometers in a cotton region shelter until switching to the maximum-minimum temperature system (MMTS), a thermistor in a plastic shelter (Quayle et al., 1991). The LIG instruments were moved due to construction in October 1966 and thermometer location changed again with the switch to the MMTS. Copies of NWS inspection reports give the installation date of the MMTS (number #4296) as 1 May 1986, while the NCDC Multi-network Metadata System gives the transition date as 1 October 1987. It is unknown when observers began to use the MMTS during this 17-month window.

The MMTS sensor is accurate to ±0.5°C, the temperature is displayed to the nearest 0.1 °F, recorded to the nearest whole degree Fahrenheit, and is calibrated annually against a specially maintained reference instrument (NCDC, 2006). The standard LIG-to-MMTS temperature adjustments (annual max −0.4°C, min +0.3°C, mean −0.1°C) were not applied to the LIG temperature data because the U.S. Historical Climatology Network (USHCN) data documentation (Quayle et al., 1991) and other studies do not recommend these adjustments for individual stations (Pielke et al., 2002; Hubbard et al., 2004). Pinkham inspection reports through 1990 (the latest stored on site) show positive scores for site location but occasional trouble with the LIG thermometers (e.g. 10/13/1976: "replaced min. therm.; was 2.54 different from max"). Due to the station changes described above the temperature data were subjected, as described below, to inhomogeneity tests for potential change points.

Temperature is nominally observed and recorded at 0700 Local Standard Time (LST); the only recorded change in schedule was from observations on the hour to 10 minutes past the hour. However, observations are often taken at 0600 LST (Michael Walsh, personal communication). Data have not been analyzed for a potential time of observation bias.

Both snowfall and snow depth are nominally measured at 0700 LST in a section of mature hardwoods in the center of the campus. New snowfall is measured once a day using a stake mounted to a 25.4 cm square piece of wood that is collected, measured, cleared and replaced. Snow depth is observed every morning using a wooden stake marked at 2.54 cm intervals and mounted in the ground prior to the first snowfall. In case of disturbance to this site, a backup stake is used.

Temperature and snow data for Pinkham from Data Set 3206 (DSI-3206): COOP Summary of the Day (January 1930–May 1948) and Data Set 3200 (DSI-3200): Surface Land Daily Cooperative Summary of the Day (June 1948–March 2007) were purchased from the NCDC (2003, 2006). The data were reformatted and selected for the following parameters: daily maximum temperature, daily minimum temperature, temperature at the time of observation, daily snowfall, and daily snow depth. NCDC quality control edits to the data were accepted as indicated by the Data Quality Flag (i.e. flag M = Switched TOBS with TMAX or TMIN). Data for only one flag, T (failed internal consistency check), were removed. As might be expected of a COOP station, there were more missing data from Pinkham than the summit's nearly complete record.

Methods

TEMPERATURE

Seasonal Averaging and Linear Trend Calculation

Daily maximum and minimum data were first used to calculate daily mean temperature [(max + min)/2]. The daily temperature data (max, min, mean) were then averaged into monthly values. Seasonal (Winter: December, January, February, etc.) and annual means were calculated from the monthly data. There had to be at least 20 days of data to compute monthly means. Seasonal and annual values were not computed if a month was missing from the respective interval. Pinkham temperature data for October and November 1979, December 1983, April 1990, June 2004, May 2005, and May 2006 did not have enough observations.

Linear regressions were fit to annual and seasonal mean data, and slopes are presented as decadal trends. The trend significance is indicated by the p-value from the linear fit. It should be noted that although summit annual and seasonal means are derived from the same data as that used by Grant et al. (2005), we do not calculate a value for winter 1935 (December 1934, January, February 1935) due to the missing-data criteria explained above. The significance values of the summit trends presented here are the p-values from the linear fit, not the Monte Carlo significance employed in the earlier study (Grant et al., 2005).

Homogenization of Data

Trends in climate data may exist due to actual climate change or to artifacts such as station relocations, instrument changes, or gradual alterations in the use of surrounding land; thus data should be subjected to a homogeneity test (Alexandersson and Moberg, 1997). Furthermore, to study climate trends derived from daily temperature data (e.g. number of days per year exceeding a maximum temperature, growing degree day accumulation) recent effort has been dedicated to homogenizing not only seasonal and annual averaged time series but daily data (e.g. Vincent et al., 2002; Brunet et al., 2006). This effort is made difficult due to the large daily variability of temperature.

The Standard Normal Homogeneity Test (SNHT; Alexandersson and Moberg, 1997) was applied to both Summit and Pinkham seasonal and annual mean temperature data. The summit temperature data were found to be homogeneous, similar to Grant et al. (2005), while Pinkham data were found to be inhomogeneous.

In order to homogenize Pinkham daily temperature data, the Spanish daily temperature homogenization method (Brunet et al., 2006), which is a hybrid of the SNHT (Alexandersson and Moberg, 1997) and a Canadian daily adjustment scheme (Vincent et al., 2002), was adopted and applied to the 1935–2003 Pinkham data. This time period was chosen because missing Pinkham data only allows annual mean values to be calculated through 2003. The regional comparison stations used for Pinkham consisted of the same 11 USHCN stations located within 1° latitude and 1° longitude of Mount Washington used previously to analyze the summit temperature (Grant et al., 2005). Monthly mean maximum and minimum data for these stations from 1930 to 2003 were obtained from the Department of Energy's Carbon Dioxide Information Analysis Center (available online http://cdiac.ornl.gov/epubs/ndp/ushcn/usa_monthly.html).

Only the point SNHT was used to identify inhomogeneities for Pinkham. Prior studies have shown the temperature trends on the summit to be less pronounced than regional trends (Grant et al., 2005); there was concern that Pinkham's potentially smaller trends would be overcorrected by the regional reference. Ideally a comparison test would be used with topographically similar stations; however Pinkham, similar to the summit, is unusual in New England due to its elevation and local topography. There was also concern that point inhomogeneities from Pinkham's station changes would be interpreted as trend inhomogeneities, given that the two known Pinkham station changes (1966 and 1986) occurred while the low-elevation stations in the region experienced localized cooling during the 1960s and warming trends since the late 1970s (Hayhoe et al., 2007).

In order to identify multiple change points in each series, the SNHT was applied to the entire series. If a change point was identified, the series was broken into two pieces, each of which was then subjected to the SNHT. This was repeated until either there were no significant change points or each section was smaller than 10 years. SNHT points were not identified within 5 years of the start or end of the series (Moberg and Alexandersson, 1997). Based on the Spanish daily adjustment method, 1966 and 1986 were picked as standard changepoints for Pinkham.

Adjustments for each monthly time series were calculated using the SNHT; starting from the end of each series data were adjusted to the most recent period to allow new data to be seamlessly added (Alexandersson and Moberg, 1997); i.e., 1967–1986 was adjusted to 1987–2003 and then 1935–1966 adjusted to 1967–2003. These monthly adjustments were then transformed into mid-month ''target'' values using a tri-diagonal 12×12 matrix (Sheng and Zwiers, 1998) and into daily adjustments by linear interpolation between the monthly targets (Vincent et al., 2002; Brunet et al., 2006).

The daily adjustments (Fig. 2) were applied to the Pinkham data, creating the Pinkham Daily Adjusted Temperature Series (PDATS). The calculated adjustments for the 1967–1986 period, which ended with the installation of the MMTS thermometer, matches the sign of the standard LIG to MMTS thermometer adjustments; namely, maximum temperatures were adjusted down and minimum temperatures were adjusted up.

DEVELOPMENT OF SNOW SEASON CRITERIA

The snow season was defined using the year associated with January (e.g. the season of 1 July 1968–30 June 1969 is winter 1969). Snow season criteria were mainly driven by the unique conditions atop Mount Washington. The high winds and complex terrain, including buildings, make it difficult to measure snowfall. Specific concerns are the ability to separate blowing snow from falling snow during times of high winds and to compare amounts measured during windy and calm conditions. The location and number of precipitation cans has also changed over the years. In short, it is difficult to place a confidence range on summit snowfall measurements, so we analyzed snow depth.

In order to avoid observer variability, snow depth observations were binned into two categories: (1) less than 2.54 cm, and (2) greater than or equal to 2.54 cm. This cutoff was chosen based on the protocol for determining snow cover disappearance in the International Tundra Experiment (ITEX) manual and other studies (Foster, 1989; Molau, 1996b). While methodology might vary over time and between individuals, we have high confidence that observers correctly identified what is essentially a snow/no snow cutoff. Choice of this criterion also avoids potential inhomogeneities in depth due to undocumented changes in method (Kunkel et al., 2007).

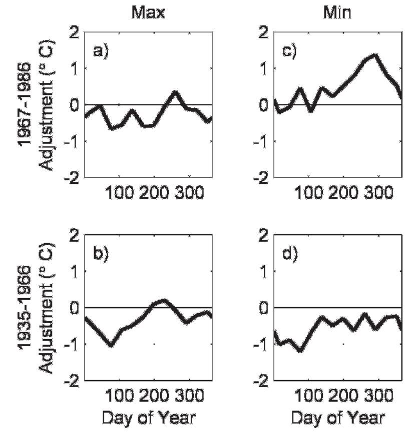

FIGURE 2. (a, b) Max and (c, d) Min daily adjustments applied to the 1967–1986 period and 1935–1966 period, respectively.

The binned data were used to calculate two separate length-of-season criteria. The first set of criteria, first and last snow (First/Last), are simply the first and last dates during a season that a snow depth, including trace amounts, was reported. The second criteria set, start and end of continuous snow cover (Start/End), are the dates after which and before which there was a continuous cover of at least 2.54 cm, allowing for ''thaw'' periods of no more than 4 days in length, with the end of cover most important to spring growth (Molau, 1996b). Continuous snow cover is generally used to calculate snow cover duration at higher elevations with persistent snow cover (e.g. Beniston et al., 2003). Allowing a short thaw period was necessitated by the summit data to extend the continuous snow cover season into spring. Otherwise a count-based calculation of snow cover duration (e.g. number of days with depth greater than a criterion per month) would be necessitated which would hinder the ability to identify the end of continuous snow cover, a biologically relevant event.

CALCULATION OF SNOW SEASON CRITERIA

Summit 6-hourly snow depth data were averaged to create a daily mean value. Pinkham daily snow depth is that reported at 0700 LST. Similar to temperature, the summit data were nearly complete while Pinkham was missing data. To have the most snow data possible, particularly at the tails of the season, missing Pinkham snow depth data were manually inspected and, if possible, missing depths were inferred.

After inspection, only 5 of 706 snow season criteria could not be used for Pinkham: first snow date for 1980 and snow cover start dates for 1980, 1983, 1990, and 1993. For the summit the end cover date in 1967 was not used because of suspected abnormal reporting practices: not once is total snow depth reported to be greater than 12.7 cm suggesting that observations were skewed low with reported conditions of less than 2.54 cm of snow artificially raised. In comparison, Pinkham does not show abnormally low snow depth during this winter.

TABLE 1

Annual and seasonal mean temperature with standard deviation and decadal trends with *p*-values for Pinkham (1935–2003) from PDATS data.

		Mean (°C)	Std. Dev. (°C)	Trend (°C dec.$^{-1}$)	Trend p
Annual	max	9.7	0.7	0.03	0.47
	min	−1.3	0.7	0.11	0.01
	mean	4.2	0.6	0.07	0.07
Winter	max	−2.8	1.6	0.11	0.24
	min	−13.8	1.6	0.18	0.07
	mean	−8.3	1.5	0.15	0.12
Spring	max	8.4	1.3	0.13	0.10
	min	−2.8	1.3	0.11	0.16
	mean	2.8	1.2	0.12	0.11
Summer	max	21.9	0.9	−0.02	0.76
	min	10.4	0.7	0.11	0.01
	mean	16.2	0.7	0.05	0.28
Autumn	max	11.6	1.1	−0.08	0.26
	min	1.1	1.0	0.08	0.19
	mean	6.3	0.9	0.00	0.99

TABLE 2

Annual and seasonal mean temperature with standard deviation and decadal trends with *p*-values for the summit, 1935–2003.

		Mean (°C)	Std. Dev. (°C)	Trend (°C dec.$^{-1}$)	Trend p
Annual	max	0.9	0.6	0.03	0.37
	min	−6.5	0.7	0.06	0.19
	mean	−2.8	0.6	0.05	0.25
Winter	max	−9.4	1.6	0.09	0.35
	min	−18.6	1.8	0.08	0.45
	mean	−14.0	1.6	0.09	0.39
Spring	max	−1.0	1.2	0.11	0.14
	min	−8.6	1.4	0.12	0.16
	mean	−4.8	1.3	0.12	0.14
Summer	max	11.5	0.9	−0.05	0.32
	min	5.1	0.8	0.01	0.79
	mean	8.3	0.8	−0.02	0.69
Autumn	max	2.6	1.0	−0.02	0.72
	min	−4.2	1.1	−0.01	0.89
	mean	−0.8	1.0	−0.02	0.80

For both First/Last and Start/End calculations the snow depth data were first divided into snow years (1 July–30 June) and indexed by day of winter (called DoW; 1–365 or 366 if a leap year). For each year First/Last data were calculated by finding all occurrences of snow depth greater than a cutoff criterion (C_{FL}), here 0 cm. The earliest occurrence (lowest DoW) of depth $> C_{FL}$ is the date of First snow depth and latest occurrence (largest DoW) of depth $> C_{FL}$ is the date of Last snow depth.

To determine Start/End dates for a snow year, all snow depth data greater than the Start/End depth cutoff criterion (C_{SE}), here 2.54 cm, were identified (snow subset) and the indices of these points stored (snow index). The first of the subset values was held as a potential Start date and the last as a potential End date. Next it was determined if a thaw period existed by taking the difference of adjacent snow index values. This difference index was transformed from days between snow to days of thaw by subtracting one. If these differences were less than the maximum number of continuous thaw days (d_{THAW}), here 4, then no thaw occurred and we used the above Start and End. If a thaw (or multiple thaws) occurred, the longest continuous period of the snow subset was selected and the first and last dates of this period were used as Start and End of snow cover.

CALCULATION OF THAWING DEGREE DAYS AND GROWING DEGREE DAYS

Thawing degree days (TDD, threshold T = 0°C) and growing degree days (GDD, threshold T = 5°C) were calculated for the PDATS data and summit data using ITEX formulae (Molau, 1996a). TDD and GDD are the sums of daily heat accumulation (H) greater than the respective threshold over a series of days, here starting 1 January. These formulae require either daily min/max temperature observations or 24 hourly observations per day.

For hourly T data, H is the sum of the day's hourly observations where T > threshold divided by 24. The summit's end of the hour observations were substituted for ITEX's recommended hourly averages. If hourly observations were missing they were replaced with an estimate, namely the mean value for that day and hour based on the full record.

For min/max data, H is defined as the daily mean T [(max + min)/2] if both min and max T are greater than the threshold or 0 if both min and max T are less than or equal to the threshold. For the third case, where the max is greater than the threshold but the min is lower, H is calculated by multiplying the daily T amplitude (max–min) by a scaling factor (Watanabe, 1978). Missing T values were estimated for periods up to 5 days using a mean based on the data preceding and following the missing data. If long stretches of data were missing, they were not estimated and that season's datum not used. The summit has no missing min/max data and Pinkham is only missing >5 continuous days a month three times during the critical winter and spring months: April 1990, May 2005, and May 2006. TDD for 1990, 2005, and 2006 were retained because the cumulative target value is reached prior to the period of missing data while GDD values were removed because the target value is reached after the missing data.

For each location the date at which TDD and GDD first reached an amount associated with the end of continuous snow cover and bloom of an early season plant, respectively, was identified. For the summit and Pinkham the approximate onset of bloom (15 May) for *Diapensia lapponica* and *Trillium undulatum*, respectively, was used (AMC, unpublished data). Specifics are described below. These values were plotted along with linear regressions with significance given by the associated *p*-values.

Results

TEMPERATURE TRENDS

The annual mean temperature at Pinkham from 1935 to 2003 using the PDATS data is 4.2°C, compared to the unadjusted value of 4.5°C. The most recent 30-year normal annual mean for Pinkham is 4.5°C (NCDC, 2004). PDATS seasonal means and standard deviations are presented in Table 1. The summit's annual mean temperature is −2.8°C; the seasonal means are shown in Table 2. At both stations the winter season is the most variable while the summer is the least variable.

Using the annual mean temperature from Pinkham and the summit, a lapse rate on the eastern slope of Mount Washington of 0.54°C/100 m was calculated. This value compares well with other annual mean lapse rates (range 0.5–0.70°C/100 m) on mountain ranges in the northeastern U.S.A., as tabulated by Richardson et al. (2004). The October 2001–September 2002 PDATS mean temperature, 5.9°C, is slightly cooler than extrapolated tempera-

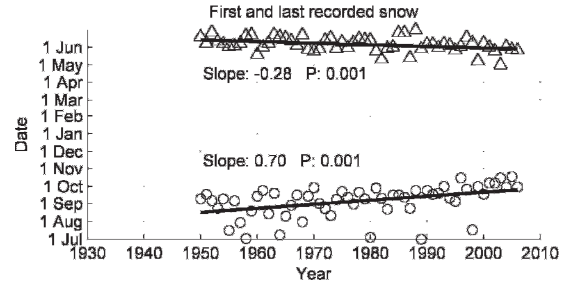

FIGURE 3. Summit day of first (circles) and last (triangles) snow with linear regressions for 1949–2006.

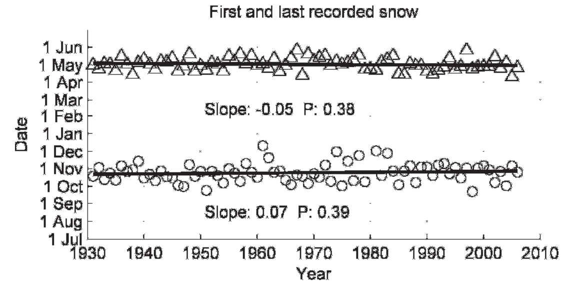

FIGURE 4. Pinkham day of first (circles) and last (triangles) snow with linear regressions for 1931–2006.

tures (~6.3°C) at similar elevations on Mount Moosilauke, New Hampshire, Whiteface Mountain, New York, and Mount Mansfield, Vermont, for the same time period (Richardson et al., 2004). Mean temperature at Pinkham from PDATS data (3.6°C) was colder than the estimated temperature at a similar elevation on the western slope of Camels Hump, Vermont (4.8°C) during a three-year period in the mid-1960s (Siccama, 1974).

Based on PDATS data, Pinkham shows significant ($p \leq 0.01$) warming trends for annual and summer minimum temperature (Table 1). Pinkham annual mean, winter minimum, and spring maximum temperature evidenced increases with a lower significance level ($p \leq 0.1$). Although not all are significant, warming trends in winter and spring at Pinkham are larger than summer and fall.

The summit shows annual, winter, and spring warming trends in maximum, minimum, and mean temperature although none are statistically significant (Table 2). Summer and autumn show cooling trends, which may correspond to the increased fog frequency (Seidel et al., 2007).

Similar to the summit, the Pinkham minimum trends (except for spring) are larger than the maximum trends. The Pinkham annual minimum trend is roughly twice as large as that observed on the summit. The Pinkham annual mean trend is slightly larger than that at the summit while the maximum trend observed at Pinkham matches that observed at the summit. Pinkham's annual mean trend (0.07°C/decade) is similar to that of the region (0.08°C/decade) over the last century (Hayhoe et al., 2007) and slightly smaller than the regional trend (0.10°C/decade) from 1931 to 2000 (Keim et al., 2003). Pinkham's annual mean trend is approximately halfway between the 1931–2000 trends for the southern (0.11°C/decade) and northern (0.0°C/decade) NOAA climate divisions of New Hampshire (Keim et al., 2003). Pinkham's annual mean warming is similar to that in NOAA climate divisions encompassing the mountains of Maine and to a lesser degree the mountains of Vermont (Keim et al., 2003), although these data are generally low-elevation stations.

SNOW SEASON LENGTH

The trends in the dates of first and last observed snow depth on the summit are significant, with first snow occurring 7.0 days/decade later in autumn and last snow occurring 2.8 days/decade earlier in the spring (Fig. 3, Table 3). The trend in date of first snow (0.73 days/decade later) and last snow (0.50 days/decade earlier) at Pinkham are similar in sign but smaller in magnitude and not significant (Fig. 4, Table 3).

In contrast to the First/Last snow results, the summit shows no significant trends in the start (0.44 days/decade earlier) and end (0.18 days/decade later) of continuous snow cover (Fig. 5, Table 3). Pinkham (Fig. 6, Table 3) shows an earlier melt with a significant trend of 1.6 days/decade earlier. The trend in start of continuous snow cover at Pinkham is 0.50 days/decade later in autumn. Earlier end of continuous snow cover at Pinkham is consistent with the decreasing trend in snow depth based on independent Pinkham Notch samples taken in a 15-day window around 1 March for the Maine Cooperative Snow Survey (Hodgkins and Dudley, 2006). The much longer period of record for snow measurements at Pinkham (1931–2006) compared to the summit (1949–2006), with the 1960s being a regionally recognized cooler period (Zielinski and Keim, 2003) may explain the greater decadal rate of change and significance of the summit's first and last snow results.

DEGREE-DAY VALUES

Degree-day calculations are used to convert temperature data to a more biologically relevant metric; in montane environments cumulative degree days are strongly tied to phenological events and snowmelt. GDD with a 5°C threshold has often been used in relation to alpine plant development, while TDD with its threshold at freezing is related to snowmelt timing. In order to establish target TDD values for trend analysis, at each location the mean of the TDD values (based on min/max data) on the mean

TABLE 3

Mean, standard deviation, decadal trends, and *p*-values of the day of the year of the First/Last snowfall and Start/End of snow cover.

Station			Snow		Snow cover	
			First	Last	Start	End
Summit 1949–2006	mean	(day)	6 Aug (218)	6 June (157)	24 Nov (328)	29 Apr (119)
	std. dev.	(days)	27	13	28	22
	trend	(days dec^{-1})	7.0	−2.8	−0.44	0.16
	p-value		<0.01	<0.01	0.86	0.89
Pinkham 1931–2006	mean	(day)	26 Oct (299)	2 May (122)	2 Dec (336)	19 April (109)
	std. dev.	(days)	19	11	20	13
	trend	(days dec^{-1})	0.73	−0.5	0.5	−1.6
	p-value		0.39	0.38	0.64	0.02

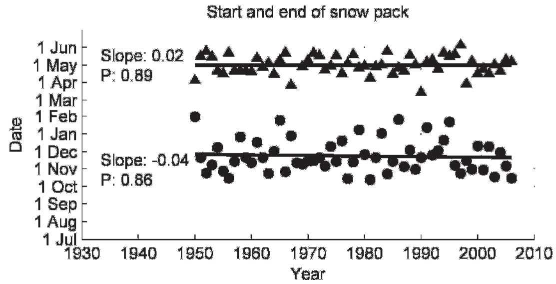

FIGURE 5. Summit day of start (circles) and end (triangles) of continuous snow cover with linear regressions for 1949–2006.

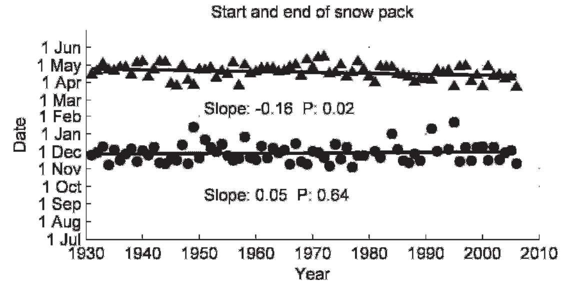

FIGURE 6. Pinkham Notch day of start (circles) and end (triangles) of continuous snow cover with linear regressions for 1931–2006.

date of the end of continuous snow cover, shown in Table 3, was calculated. This gave a target TDD value of 26 and 111 for the summit and Pinkham, respectively. Using a similar method, target GDD values of 15 and 137 for the summit and Pinkham, respectively, were derived from the approximate bloom date (15 May) of a species monitored by the AMC's phenology program at each location, namely *Diapensia lapponica* above treeline and *Trillium undulatum* at Pinkham.

The trend in summit GDD calculated from hourly data is advanced 9 days compared to GDD calculated from summit min/max data (Table 4). This suggests the min/max calculation of GDD estimates heat accumulation for the summit differently than hourly data. This can possibly be explained by an assumption in the calculation of min/max GDD, namely that a typical solar-driven diurnal heating pattern (radiative) with daily maximum in the afternoon and daily minimum shortly before sunrise is modeled using a sine-like relationship. The summit often does not follow this pattern; on 50% of days the summit experiences advective forcing and/or cloud immersion, which results in daily temperature extremes being recorded near midnight (Grant et al., 2005). During winter months only 23% of days can be classified as radiative increasing to 37% during summer (the remaining days are unclassified). This suggests that while both GDD calculations could be used to develop relationships between temperature and plant growth, the hourly calculation might more completely represent the actual accumulation of heat. Both min/max and hourly data sets give similar results when calculating TDD.

The date at which thawing degree days at the summit first reaches 26 advanced significantly ($p = 0.01$) using both min/max and hourly data sets (Fig. 7, Table 4). Pinkham showed a significant ($p < 0.01$) TDD advance (Fig. 8, Table 4) of about half the magnitude of that found at the summit. Growing degree-day trends are not significant for the summit or Pinkham (Figs. 7 and 8, Table 4) although all suggest earlier onset of spring warming. Although the observed negative trend in summit TDD would suggest earlier snowmelt, the end of the summit's snow cover shows no significant trend. However, at Pinkham the significant trend of an earlier end to the continuous snow cover of -1.6 days/decade matches the earlier accumulation of TDD (-1.6 days/decade).

INTERACTION OF SNOW AND TEMPERATURE

To explore the relationship between temperature and snow cover, a series of linear regressions was performed. Each of the many regressions used the end of snow cover date paired with an individual month's average max, min, or mean temperature (e.g. average April max vs. snow cover) or combinations of adjacent spring and winter months (e.g.. average April + March max vs. snow cover). The strongest relationship for the summit was that between end of snow cover and average April max temperature ($r^2 = 0.18$, $p = 0.001$). A similar analysis for Pinkham showed the strongest relationship between end of snow cover and average April + March max temperature ($r^2 = 0.51$, $p < 0.001$; PDATS data). There is both a difference in the timing of warmth important to snowmelt between the summit and Pinkham and the importance of that warmth; it appears just over half of the variability in timing of snowmelt below treeline can be attributed to temperature, while only 18% of the variability in melt timing on the rocky, windswept summit is due to temperature.

Snow cover also plays a role in protecting alpine plants from damaging frosts. Taschler and Neuner (2004) determined frost resistance for various species and concluded that protection by snow cover and other frost avoidance strategies influences the impact of low temperatures during the nascent growing season. In order to further explore the relationship between end of continuous snow cover and harmful late frosts on the summit, the number of days below minimum temperature thresholds within 60 days of the end of continuous snow cover was calculated. Two threshold temperatures were chosen, using Taschler and Neuner (2004) for guidance, to represent potential alpine plant frost damage: -2°C for floral damage and -5.5°C for vegetative damage. The summit experiences respective medians of 16 and 7 days below floral and vegetative thresholds post end of snow cover. There is large inter-annual variability (floral range of 2–55 days and vegetative 0–50 days) with early end of snow cover years having many days below the threshold temperatures. Using linear fits, neither measurement of frost risk shows evidence of significant trends (*p*-values of 0.63 and 0.87). As it might take several seasons of cold post-snow temperatures to exhaust a plant's energy reserves, decadal averages were analyzed; these also showed no trend. These results suggest that, for the alpine flora on Mount Washington that initiate growth soon after snowmelt, the balance between the risk of early growing season frost damage versus the gains of a longer growing season has not changed significantly during the period of record.

Discussion

Post-glacial climatic warming trends are frequently generalized as being horizontally and vertically synchronous across the landscape, along with the assumption that alpine ecosystems may be at great risk. Our results parallel those of Diaz and Bradley's (1997) that spatially, montane climate warming is complex. For different mid-latitude mountain regions in the world, the magnitude of climatic change is likely to vary considerably and be influenced by different factors. Mount Washington's summit temperatures over the last 70+ years, though trending towards warming, do not exhibit a statistically significant change ($p <$

TABLE 4

Mean, standard deviation, decadal trends, and *p*-values for day of the year when thawing degree days and growing degree days reach targets described in text.

	TDD				GDD			
	Mean (day)	Std. dev. (days)	Trend (days dec^{-1})	*p*	Mean (day)	Std. dev. (days)	Trend (days $dec.^{-1}$)	*p*
Summit								
min/max	30 April (120)	18	−2.8	0.01	17 May (137)	14	−0.4	0.64
hourly	30 April (120)	18	−2.7	0.01	8 May (128)	15	−1.1	0.20
Pinkham								
min/max	20 April (110)	9	−1.6	<0.01	16 May (136)	8	−0.5	0.27

0.05). Although our trends match those presented earlier for Mount Washington by Grant et al. (2005), the significance values differ. This earlier study did not account for temporal autocorrelation in their Monte Carlo simulations, has since been revised, and now concludes there were no significant temperature trends (Grant et al., 2008).

At our mid-elevation site there is a statistically significant warming in both annual and summer temperatures, with greater warming than that observed on the summit and less than that reported for lower elevations in the region. Pinkham mean temperatures show mixed results when compared to prior short-term studies in the White, Green (Vermont), and Adirondack (New York) Mountains. Nearby (48 km SW) and of similar elevation (222–1015 m a.s.l.), the U.S. Forest Service Hubbard Brook Experimental Forest experienced a significant warming trend from 1955 to present. Pinkham's end of snow cover, similar to the U.S. Forest Service's Hubbard Brook Experimental Forest's snow duration (Campbell et al., 2007), is happening earlier.

For biologically relevant temperature indices such as TDD and GGD, only TDD was statistically significant at both elevations in our study. However, only at our mid-elevation site did this manifest itself with a statistically earlier end of continuous snow cover. The summit's dates of first (autumn) and last (spring) measurable snow are significantly later and earlier, respectively,

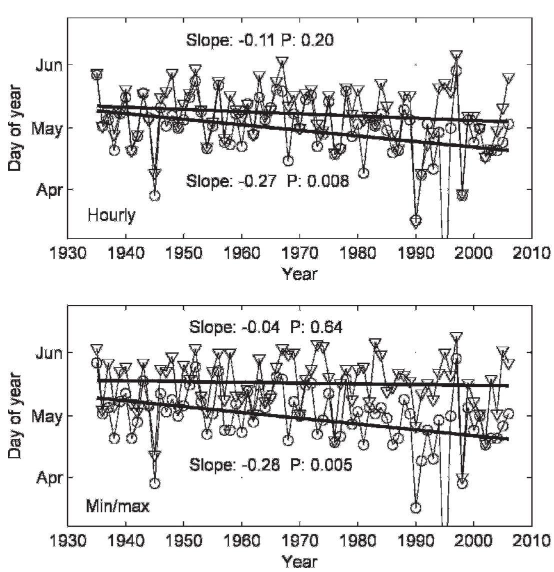

FIGURE 7. Day of year on which growing degree days (triangles) and thawing degree days (circles) first sum to target values (GDD = 15, TDD = 26), with linear regressions for the summit. The top panel show results based on hourly data and the bottom panel from min/max data.

but the period of record is much shorter than for Pinkham; summit trends in onset and termination of continuous snow cover are not significant. Temporal trends of growing degree days were not significant at either site although they suggest earlier thawing and onset of the growing season.

Grant et al. (2005) estimated the summit of Mount Washington experiences free-atmosphere (troposphere) conditions on 50% of days in both summer and winter. This may explain why the summit exhibits a weak but not statistically significant warming trend, because during these conditions the summit would not necessarily be coupled with events observed from the surrounding regional lower elevation trends. Alpine areas in Europe, Asia, and other locations are experiencing warming trends, usually most significant in daily minima temperatures, and often greater in magnitude at higher elevations (Beniston et al., 1994; Diaz and Bradley, 1997). However, other alpine areas demonstrate less typical patterns, such as the Front Range, Colorado, U.S.A., where long-term trends indicate warming at mid-elevations, but a cooling trend within the alpine zone (Pepin, 2000).

There is evidence that resistance to climate warming at the higher elevations on Mount Washington has considerable tenure. Spear (1989), using pollen and plant macrofossil records from Mount Washington and surroundings, concluded that since 5000 yr BP, the subalpine forest and treeline-alpine ecotone boundary on Mount Washington has not exhibited demonstrable shifts. In contrast, mid and lower elevation tree species showed responses to climatic shifts in temperature. He concluded that alpine treeline is a poor temperature indicator for the region and hypothesized that wind and moisture determine the mountain's treeline position. Harding (2005) pointed out that alpine treeline in Scotland demonstrated a similar record of historical resistance. In his study of seed bank dynamics, seed dispersal, and colonization, he found no evidence for upward shifts in alpine vegetation under future warming scenarios, and suggested that models that do not

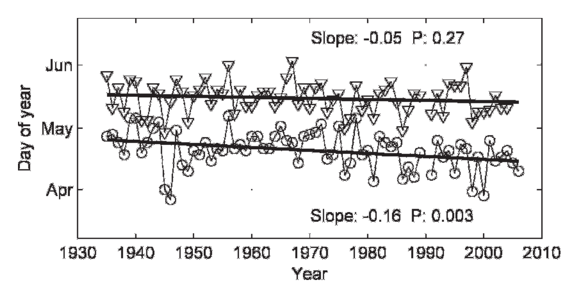

FIGURE 8. Day of year on which growing degree days (triangles) and thawing degree days (circles) first sum to target values (GDD = 137, TDD = 111), with linear regressions for Pinkham.

incorporate factors beyond temperature are likely to be poor predictors of future plant distributions.

Mount Washington's resistance to warming due to the frequency of being in the free atmosphere could also help explain why northeastern U.S. alpine ecosystems, which are remnant biogeographic islands from the last glacial period, are some of the lowest elevation alpine ecosystems at similar or more northern latitudes anywhere in the world. In addition, increasing frequency of fog events on Mount Washington (Seidel et al., 2007) could result in increased fog and rime ice deposition. Siccama (1974), Reiners and Lang (1979), Richardson et al. (2004), like Spear (1989), hypothesized that the transition from deciduous hardwood forest to coniferous spruce-fir forest to the alpine ecotone boundary on the mountains in this region is related in part to the cool, moist climate derived from frequent exposure to clouds. On northern New England mountains, Ryerson (1990) measured icing rates to increase exponentially above 800 m, with micro-topographic relief exposure a secondary control. He concluded that the dependence of icing rate upon elevation is largely a function of New England wind and cloud regimes and differs from other mountainous locations. However, evidence of an increasing cloud ceiling elevation at northeastern U.S. airports (Richardson et al., 2003) may have implications for the current cloud regime and mountain ecosystems, especially at mid-elevations. Research should be expanded to determine the applicability of increasing cloud ceiling elevation observations from airports to the region's mountains, where orographic effects are important.

The thermal structure of the lowest 2–3 km of the troposphere, the "planetary boundary layer," is complicated and includes inversions where temperature increases rather than decreases with height. Inversions are particularly common during winter over some middle and high latitude land regions. Inversions act to decouple surface temperatures from tropospheric temperatures on daily or even weekly time scales (Karl et al., 2006).

Our results support the conclusion that some mountains may only weakly follow regional low elevation surface climatic trends and may exhibit resistance to climatic warming with elevation. Factors may include temperature inversions, being in the free atmosphere at least a portion of the time, and sufficient atmospheric moisture availability to result in frequent cloud or fog exposure on the upper slopes. What regional climatic temperature increases would be sufficient to alter these dynamics is unknown.

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