

Climate Trends on the Highest Peak of the Northeast: Mount Washington, NH

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Abstract - Climate change in mountains can vary with elevation, but there is a paucity of long-term climatological datasets for examination of elevational patterns. In the Northeast, there are 2 robust datasets from the highest peak, Mount Washington Summit and Pinkham Notch, NH. We examined trends for temperature, snow, and other derived climate indicators for the period of 1930s through 2018. Results reveal changing climate conditions, consistent in direction of change, including warming temperatures, changing winters, and extended growing seasons. Differences occur with weaker winter warming on the summit, and snow-related indicators providing unclear results for wind-influenced upper elevations. Recommendations for distributed monitoring, particularly for snow metrics, are encouraged for an improved understanding of the complex climate-change response on the mountains in the Northeast.

Introduction

As humans increase greenhouse-gas concentrations in the atmosphere (IPCC 2014), the impacts on the planet's radiative balance, global climate, and meteorological processes are becoming progressively more apparent and in some cases severe (Dupigny-Giroux et al. 2018, IPCC 2014). The unfolding climate changes include increasing air and ocean temperatures, melting polar and land-based ice sheets, intensifying storms, and rising sea levels (Dupigny-Giroux et al. 2018). Globally, our planet warmed 1.0 °C (1.8 °F) over the period 1901–2016 (Wuebbles et al. 2017), and Arctic sea ice declined nearly 13% per decade since 1979 (NASA 2021). Organisms and ecosystems that adapted to past climates over centuries are now experiencing new extremes and shifts in baseline temperature and rainfall across the US (Weiskopf et al. 2020). Shifts in timing of leaf out and flowering, and displacement from disappearing habitats are examples of how life on our planet is already affected by climate change (Kimball et al. 2014, Monahan et al. 2016).

The northeastern US is warming faster than other regions in the conterminous US (Dupigny-Giroux et al. 2018), with some seasons more impacted than others. Changes in winter-climate indicators have been documented as 20 fewer “frost days” (minimum temperature <0 °C) and 19 fewer snow-cover days since 1917

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(Contosta et al. 2019). Extreme precipitation events are increasing in the Northeast, which has the second highest increase in extreme 1-day precipitation events (38%; 1901–2016) of all regions in the US (Dupigny-Giroux et al. 2018). Multiple rivers in the region, including ones in northern New Hampshire, saw a >10-day advance in snowmelt-related runoff in the springtime over the period 1960–2014 (Dudley et al. 2017, Dupigny-Giroux et al. 2018, Hodgkins et al. 2003). Not only is the Northeast warming faster than other regions of the US, but 80% of climate-model projections indicate that this region will cross the 2 °C warming threshold by 2040, a full 20 years ahead of the global temperature meeting this same marker (Karmalkar and Bradley 2017). Precipitation is also projected to increase in the Northeastern US both in the intensity of rainfall events and overall amounts in winter and spring (Lynch et al. 2016), including an increase in the proportion of precipitation falling as rain versus as snow (MCC STS 2020).

Mountain environments, with complex terrain, multifarious weather patterns, and variable air-mass exposure, may or may not reflect climate changes observed at nearby lower elevations (Ohuara 2012, Rangwala and Miller 2012, Seidel et al. 2009). In the Northeast, Wason et al. (2017) found that the monthly rate of minimum and maximum temperature changes on the summits of Mount Washington, NH (1917 m a.s.l.), and Mount Mansfield, VT (1340 m a.s.l.), were similar to the rates of change at lower-elevation sites across the Northeast for the period of 1960–2013 (Wason et al. 2017). However, an analysis of data for the Mount Washington, NH, summit (hereafter called the “Summit”) from 1935–2003, which also accounted for monitoring-site discontinuity over the period of record, showed the Summit warmed more slowly than an adjacent mid-elevation site at Pinkham Notch (612 m a.s.l.) (Seidel et al. 2009). Temperature data from Mount Mansfield’s summit has had equipment maintenance issues and its period of record is shorter; understanding these caveats, an analysis of this site suggest that proximate, lower-elevation Burlington, VT (100 m), is warming twice as fast as Mount Mansfield’s summit (Kelsey 2017–2018). Germane is the conclusion reached by Mountain Research Initiative EDW Working Group et al. (2015) that the paucity of quality, standardized, site-specific monitoring stations at higher elevations is problematic to our understanding of climate trends in mountains and needs to be remedied. Relying on nearby lower-elevation sites and estimates such as standard lapse rates to quantify spatial and temporal trends of climate change are insufficient and can be misleading in predicting the resilience or habitat shifts in these complex environments.

Furthermore, daytime (maximum) versus nighttime (minimum) temperatures are changing at different rates globally, with winter minimums warming the fastest (Davy et al. 2017, Gil-Alana 2018). Winter warming trends have been linked to planetary boundary layer (PBL) dynamics where stable and shallow PBLs form, especially at night (Davy et al. 2017). The PBL is the layer of the atmosphere that is closest to the Earth and is highly influenced by surface radiative dynamics. A shallower PBL with increased greenhouse gas concentrations and less volume of air to warm retains more of the Earth’s nighttime outgoing longwave radiation. Additionally, in the northeastern US, the diurnal variation in mountain PBL height

influences daily temperature differences between higher and lower elevations (Kelsey et al. 2018). In return, mountain surface-observation climate trends by elevation are influenced by PBL versus free tropospheric, the layer of air just above the PBL that is often disparate from surface-radiation exposure regimes. Differences between high- and mid-elevation warming in winter have been observed by Seidel et al. (2009), where winter minima at Pinkham Notch, for the period of 1935–2003, had the fastest rate of warming of all seasons at 0.18 °C per decade while the Summit showed a positive but insignificant warming trend for winter minimums at 0.08 °C per decade ($P = 0.45$). The free troposphere has experienced a weaker warming trend than the PBL at many locations globally (Pepin and Seidel 2005). Therefore, it follows that Mount Washington and other upper elevations in the region that are frequently exposed to free tropospheric air in winter could be expected to have lower warming rates relative to proximate lower elevations.

Long-term and robust meteorological measurements in Northeast mountains are sparse. Fortunately, the summit of Mount Washington has one of the longest (since 1932) high-quality montane meteorological data sets in the world. In Pinkham Notch, a mid-elevation site on the east side of the mountain, daily temperature and snow data have been collected since 1935. The Mount Washington Observatory is the only active meteorological station above 700 m in the mountainous regions of New York, Vermont, New Hampshire, and Maine that has both an extensive (>60 years) and continuous record. This paper moves beyond the work of Grant et al. (2005) and Seidel et al. (2009) by extending the record to examine the latest climate trends and provides additional insight by evaluating additional climate indicators at this Northeast high peak and proximate mid-elevation site from the 1930s through 2018. The comparison of these 2 sites provides a proxy for climate-change patterns across an elevational gradient in the northern Appalachian Mountains that lack adequate spatial coverage of long-term climate measurements.

Site Description

The study sites, Mount Washington summit (44°16'N, 71°18'W; 1917 m a.s.l.) and Pinkham Notch (44 °16'N, 71°15'W; 612 m a.s.l.), are located in the White Mountains of New Hampshire, part of the Appalachian Mountain chain (Fig. 1). Native American names for Mount Washington and the possible translations include Kawdahkwaj (“Hidden Mountain in the Clouds”), Agiocochook (“Home of the Great Spirit or Mother Goddess of the Storm”), and Waumbik (“White Rocks”). Our sites are within the land N’dakinna, which is the traditional ancestral homeland of the Abenaki, Pennacook, and Wabanaki peoples past and present (Indigenous New Hampshire Collaborative Collective 2021). We acknowledge and honor with gratitude the land and waterways and the alnobak (people) who have stewarded N’dakinna throughout the generations. The Summit is located within the largest contiguous alpine area in the Northeast, whose alpine–treeline ecotone boundary varies in elevation from 1114 to 1687 m on the mountain (Kimball and Weihrauch 2000). Downslope of the treeline, the landscape transitions to *Picea* (spruce)–*Abies* (fir) forests and then mixed conifer–hardwood forest where Pinkham Notch is located.

Methods

Mount Washington Observatory observers have measured and recorded daily and sub-daily meteorological variables, including temperature, snowfall, and snow depth, at the Summit since 1935. Daily minimum and maximum temperature

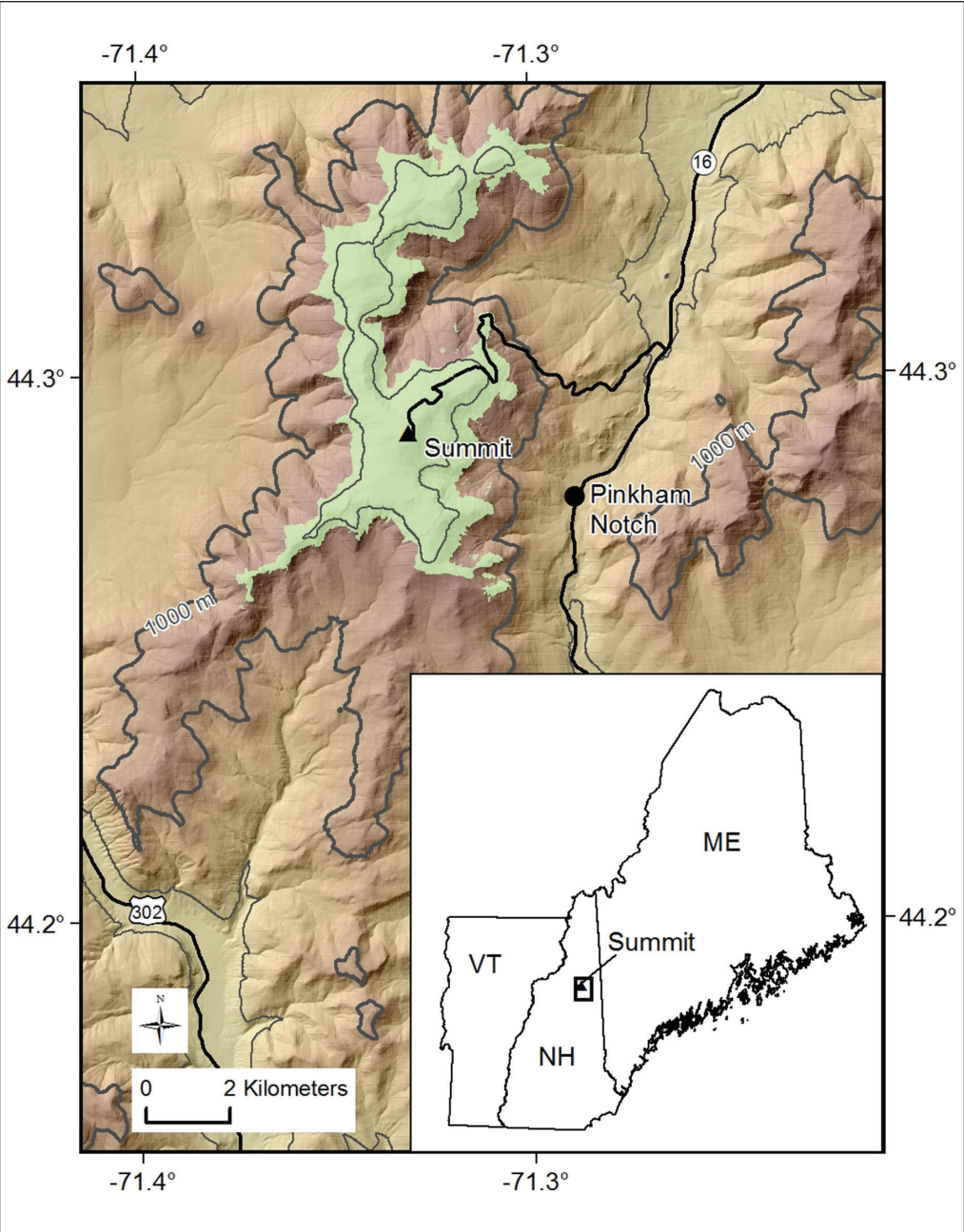


Figure 1. Location of Mount Washington summit and Pinkham Notch sites with topography and green shading designating alpine area.

measurements are made using an alcohol-in-glass minimum thermometer and a mercury maximum thermometer, respectively, housed in a Stevenson shelter. See a detailed description of methods in Seidel et al. (2009) and Grant et al. (2005). There were changes in when the time-of-day observations were taken, as well as the number of times per day they were recorded, during the first decade of the record; however, similar to Grant et al. (2005) we did not attempt a “time of observation bias” correction. Snowfall is measured using the US National Weather Service (NWS) standards with a 20.32-cm-diameter precipitation can. Snow depth at the Summit is estimated by an observer based on a visual spatial average across a flat area between the Sherman Adams Building and the precipitation can along with knowledge of the previous snow depth observation (six hours prior) and weather conditions since this last observation. These visual estimates of snow depth are taken at the time of the synoptic observation, which includes a measure of snowfall, and reported in 1.27-cm intervals, including trace.

At Pinkham Notch, which is National Weather Service Cooperative Observer Program (COOP) site #276818, snow measurements began in 1930 and minimum and maximum temperature data collection began in 1935. Daily minimum and maximum temperatures were originally measured using standard liquid in glass (LIG) minimum and maximum thermometers in a Stevenson shelter until 1986/1987 when the site switched to a thermistor in a plastic shelter. Our analyses carry forward a correction to the Pinkham daily temperature data that was made by Seidel et al. (2009) after a homogeneity test and review of relocation of instruments was done indicating inhomogeneity. New snowfall and snow depth were measured daily, approximately at 07:00 am Local Standard Time with a stake marked at 2.54-cm intervals.

Metrics and indicators

We developed climate metrics and indicators from temperature and snow observations from each site based on Seidel et al. (2009) and Contosta et al. (2019). Temperature metrics include annual, seasonal, and monthly averages. Using daily minimum and maximum temperature observations, we calculated monthly averages, and then used monthly averages to calculate seasonal and annual averages for each year.

Snow metrics include snow season start and end, length of snow season, maximum snow depth in a snow season, and maximum 24-hour snowfall in a season. Snow metrics that relied on snow depth, rather than snowfall, are considered more reliable for the Summit because of the difficulty in collecting snowfall in the precipitation can at this site due to the frequent strong winds. We calculated annual summaries using a snow year of 1 July–30 June because the Summit site historically can see sporadic winter conditions as early as July (see Seidel et al. 2009). We excluded years if there were 10 or more days missing from the typical snow season of 1 November–31 May. This approach may be conservative for Pinkham Notch where gaps in the shoulder seasons, the start and end of the snow season, may occur as observers have not consistently recorded zero values throughout the period of record. Zero values are important to properly define the full snow season.

All climate indicators are summarized in Table 1. We used the same annual winter year used for the snow metrics described above, 1 July–30 June, for other climate indicators with the exception of snowmaking days before Christmas, mud days, and growing-season calculations. We calculated the growing season start and end using a killing frost threshold of -4.4°C (24°F). This threshold is generally used to reflect severe freeze when heavy damage to most plants is expected and the ground freezes solid. We note that the actual temperature exposure for low-stature alpine vegetation may differ slightly, since standardized NWS air temperatures are measured at 1.5–2.0 m above the ground.

We calculated the end of winter (or start of the vernal window) by adapting the method developed by Contosta et al. (2017) where the first day when smoothed air temperature crosses from below 0°C to above 0°C was identified using a Monte Carlo function. We name this climate metric “air temperature zero”. We did not

Table 1. Climate indicators definitions and data handling. See Contosta et al. (2019) and Seidel et al. (2009).

Indicator	Definition
Monthly averages for minimum, maximum, and average temperature	Average of daily values for average, minimum, or maximum temperature across month; months with fewer than 20 days of data were excluded from the analysis
Seasonal averages for minimum, maximum, and average temperature	Average of monthly values for average, minimum, or maximum temperature across the seasons as winter = December–February, spring = March–May, summer = June–August, fall = September–November; seasons containing a month with fewer than 20 days of data were excluded from analysis
Frost days	# of days with min temp below 0°C ; years missing 10 or more days of data were excluded from the analysis
Ice days	# of days with max temp below 0°C
Thaw days	# of days with max temp above 0°C
Extreme cold days: <i>Picea rubens</i> Sarg. (Red Spruce) damage threshold	# of days with min temperatures below -32°C
Snowmaking days before Christmas	# of days before Dec 25 with min daily temp below -5°C
Snow-covered ground days	# of days snow depth greater than 0 mm
Frozen-ground days in winter	# of days when ground was bare (snow depth = 0 mm) plus ice (max daily temp below 0°C)
Mud days	# of days with max temp above 0°C and snow = 0 mm limited to the months of November–May
End of winter: Air temp zero	First day when smoothed curve crossed from below 0°C to above 0°C
Growing season start and end	Dates of the last and first killing frost using the threshold -4.4°C (24°F)
Maximum snowfall in 24 hrs	Maximum recorded snowfall in 24 hours

attempt to calculate the length of the vernal window because of differences in our methods for start of the growing season and absence of long-term biological measurements such as leaf-out.

Statistics

All statistics were computed with R version 3.6.3 (R Core Team 2013) with the packages detailed in the code provided in Supplemental Materials A (see Supplemental File 1, available online at <http://www.eaglehill.us/NENAonline/suppl-files/n28-sp11-N1872d-Murray-s1>, and for BioOne subscribers at <https://dx.doi.org/10.1656/N1872d.s1>). We used a non-parametric Mann–Kendall test to evaluate the significance of the trends and considered P -values of ≤ 0.05 to be significant. We used Sen's slope, which requires fewer assumptions and is less sensitive to outliers than a least-square regression (Hamburg et al. 2013), to compute the magnitude of trends. We evaluated lag 1 autocorrelation for all indicators with significant P -values of ≤ 0.05 . If lag 1 autocorrelation was indicated, i.e., lag 1 was found to exceed the 95% confidence interval threshold, we applied an adjusted Mann–Kendall test following Hamed and Rao (1998) variance-correction approach as well as a modified Mann–Kendall using blocked boot-strapping (Önöz and Bayazit 2012), with 2000 iterations, both with 95% confidence intervals. The blocked boot-strapping test creates a distribution of 2000 possible z -values by randomly resampling the data. If the original Mann–Kendall z value is outside the bounds of lower and upper 95% confidence intervals reported from bootstrapping simulations, it is unlikely that that result was due to random chance and therefore indicates a trend in the underlying data. Number of years included for each metric, percent completeness (included years/possible years), and the range of possible years are reported in Supplemental Materials B (see Supplemental File 1).

Results

Temperature metrics

Mean annual and seasonal temperature trends show all seasons are warming on Mount Washington with some variations in the rate of change by site and seasons (Fig. 2). The mean annual temperatures at Pinkham Notch and the Summit are warming by 0.14 and 0.10 °C per decade, respectively (Fig. 2a). Mean winter temperature is warming the fastest at Pinkham Notch (0.22 °C per decade $P < 0.01$) with the Summit also trending positive (0.14 °C per decade), but insignificantly ($P = 0.08$) (see Supplemental Material C in Supplemental File 1). Pinkham Notch also displays strong warming trends in spring and fall mean temperatures of 0.16 and 0.14 °C per decade, respectively, with summer warming overall, but more slowly at 0.11 °C per decade (Fig. 2b). All minimum and maximum temperature trends and P -values are provided in Supplementary Material C (see Supplemental File 1).

All monthly minimum and maximum temperature trends at the Summit and Pinkham Notch were positive, except Pinkham Notch October and Summit June maximum temperatures (Table 2). Overall, there were more significant warming

trends at Pinkham Notch than at the Summit site in individual months (Table 2). The transition months from winter to spring and summer to fall (April/May and

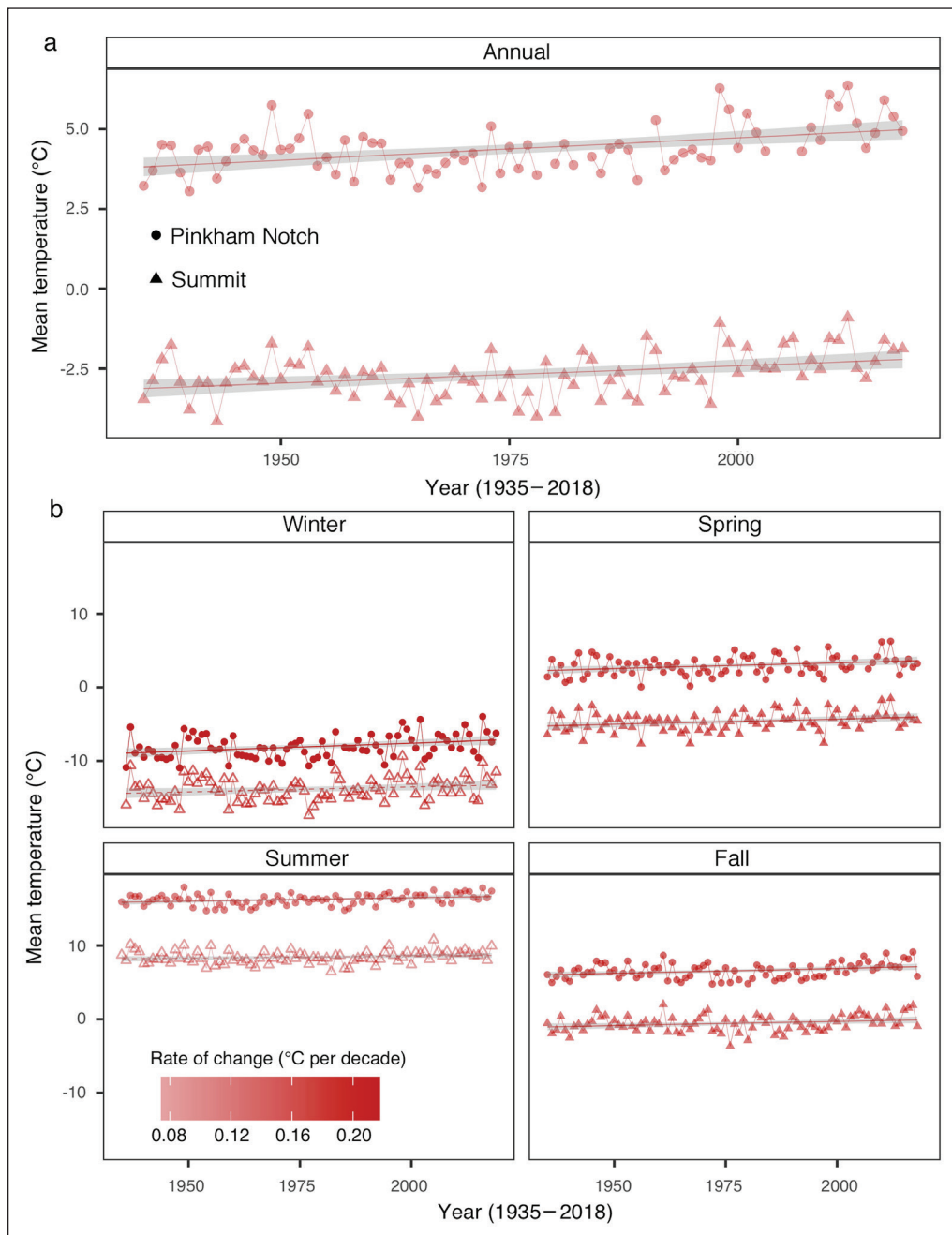


Figure 2. Mean temperatures (a) annually and (b) by season (winter = December–February, spring = March–May, summer = June–August, fall = September–November) for Pinkham Notch (circles) and Mount Washington summit (triangles). Open symbols denotes trends are not significant at $P < 0.05$. Red gradation bar is the rate of change in °C per decade.

August/September) had the most consistent and significant warming across both sites. There were more significant winter minimum trends at Pinkham Notch. While no trends were significant for the Summit in the winter, the rate for the December maximum temperatures was the greatest (Table 2).

An analysis of individual monthly trends reveals similarities and differences (Table 2). Winter minimums drove winter trends at Pinkham Notch, with only December having both minimum and maximum temperatures significantly warming. Notably, the Summit December trends were similar in magnitude to those at Pinkham Notch, especially for maximum temperatures, but not significant. Daily maximums, but not minimums, consistently warmed in spring months (March, April, May) at Pinkham Notch. At the Summit, maximum temperature in these months also indicated warming, but only April was significant; minimum temperature also increased significantly in May for the Summit site. The month of September had significant warming trends in minimum temperatures at both sites, but as discussed below, maximum temperature trends were not significant due to autocorrelation.

Autocorrelation analysis found that some of the significant temperature trends had a lag 1 autocorrelation that exceeded the 95% confidence interval threshold: Mean annual temperature at Pinkham Notch and the Summit, Fall season temperature at Pinkham Notch, and minimum and maximum monthly mean temperature

Table 2. Trend and rate of change in monthly means of maximum, and minimum daily temperatures from 1935 to 2018. Statistical significance of trends is indicated as follows: * $P < 0.05$, ** $P < 0.01$, † failure to pass bootstrapped significance test

	Pinkham Notch		Mt. Washington summit	
	Maximum °C per decade	Minimum °C per decade	Maximum °C per decade	Minimum °C per decade
Jan.	+0.06	+0.24	+ 0.09	+0.06
Feb.	+0.15	+0.32**	+0.06	+0.12
Mar.	+0.22*	+0.09	+0.15	+0.13
Apr.	+0.31**	+0.09	+0.19*	+0.12
May	+0.22*	+0.09	+0.17	+0.20*
Jun.	+0.07	+0.05	- 0.03	+0.06
Jul.	+0.11	+0.09	+0.01	+0.11*
Aug.	+0.14*	+0.17**	+0.07	+0.12
Sept. ^A	+0.31	+0.22**	+0.22*†	+0.23**
Oct.	-0.01	+0.15*	+0.01	+0.05
Nov.	+0.05	+0.08	+0.11	+0.06
Dec.	+0.23*	+0.33**	+0.22	+0.18

^ASeptember maximum trends for both Pinkham Notch and the Summit were found to be autocorrelated and P -values were adjusted based on Hamed and Rao (1998). Further while the Summit P -value remains <0.05 , the block-bootstrapping results indicate that the trend was not significant at this level. See Supplemental materials D (in Supplemental File 1, available online at <http://www.eaglehill.us/NENOnline/suppl-files/n28-sp11-N1872d-Murray-s1>, and for BioOne subscribers at <https://dx.doi.org/10.1656/N1872d.s1>) for comparison of the different methods.

for the month of September at both Pinkham Notch and the Summit. However, after applying an adjusted Mann–Kendall and a block bootstrap procedure to determine whether significance was inflated due to autocorrelation, the significance of the trends did not change relative to the $P \leq 0.05$ threshold with the exception of Pinkham Notch and Summit September maximum temperatures. Supplementary Material D (See Supplemental File 1) provides the original z and P -values and the bootstrapped confidence intervals for the autocorrelation trends. It is unclear why September daytime maximum temperatures are autocorrelated.

Snow metrics

Total snowfall and maximum snow depth dramatically changed at Pinkham Notch over the period of record (Table 3, Fig. 3). The end of the continuous snow season is shorter by 1.7 days per decade, maximum snowpack depth declined 11.5 cm per decade, and total snowfall declined 20.7 cm per decade. The Summit did not show significant changes in snowfall or snowpack (Table 3); however, snow is often redistributed due to high winds, so accurate measurements are difficult to obtain. In fact, regular strong winds (hurricane-force winds are measured every other day, on average, from November through April) limit the amount of snow that stays on the Summit by redistribution, and if changes in total seasonal snowfall are occurring, it might not yet be enough to impact snow depth.

Seasonal conditions

Seasonal-condition metrics largely indicate a weakening winter season at both sites varying from 1.8 to 2.7 fewer frost and ice days per decade and 1.4 to 1.7 more thaw days per decade from the 1930s to 2018 (Table 4). Pinkham Notch frost days were indicated as potentially autocorrelated; however, adjusted Mann–Kendall analysis and bootstrapping found a stronger P -value than the basic Mann–Kendall (see Supplemental material D in Supplemental File 1). The Summit also is experiencing more mud days (days above zero when there is no snow on the ground), which could increase the number of soil freeze–thaw cycles. Pinkham Notch has 1.3 fewer snowmaking days before Christmas per decade. The growing season is also lengthening at both sites, with total gains of 3.9 and 1.8 days per

Table 3. Trend values for snow-metric indicators at Pinkham Notch and the summit of Mount Washington, NH. Trends are in days per decade or cm per decade for snow-depth metrics. ** $P < 0.01$, * $P < 0.05$.

Indicator	Definition	Trend and rate (days or cm per decade)	
		Pinkham Notch	Summit
Start of continuous snow	Start of continuous snow	+0.5	-1.8
End of continuous snow	End of continuous snow	-1.7**	+1.0
Maximum snowpack depth	Maximum recorded snow depth for the season	-11.5**	-5.5
Total snowfall	Sum of all snowfall throughout the season	-20.7**	+19.5
Maximum snowfall in 24 hours	Maximum snowfall recorded in 24 hours	-0.89	-0.38

decade at Pinkham Notch and the Summit, respectively (Fig. 4). At Pinkham Notch and the Summit, the “air temperature zero” date was 1.2 and 0.6 days per decade earlier, respectively (Fig. 5).

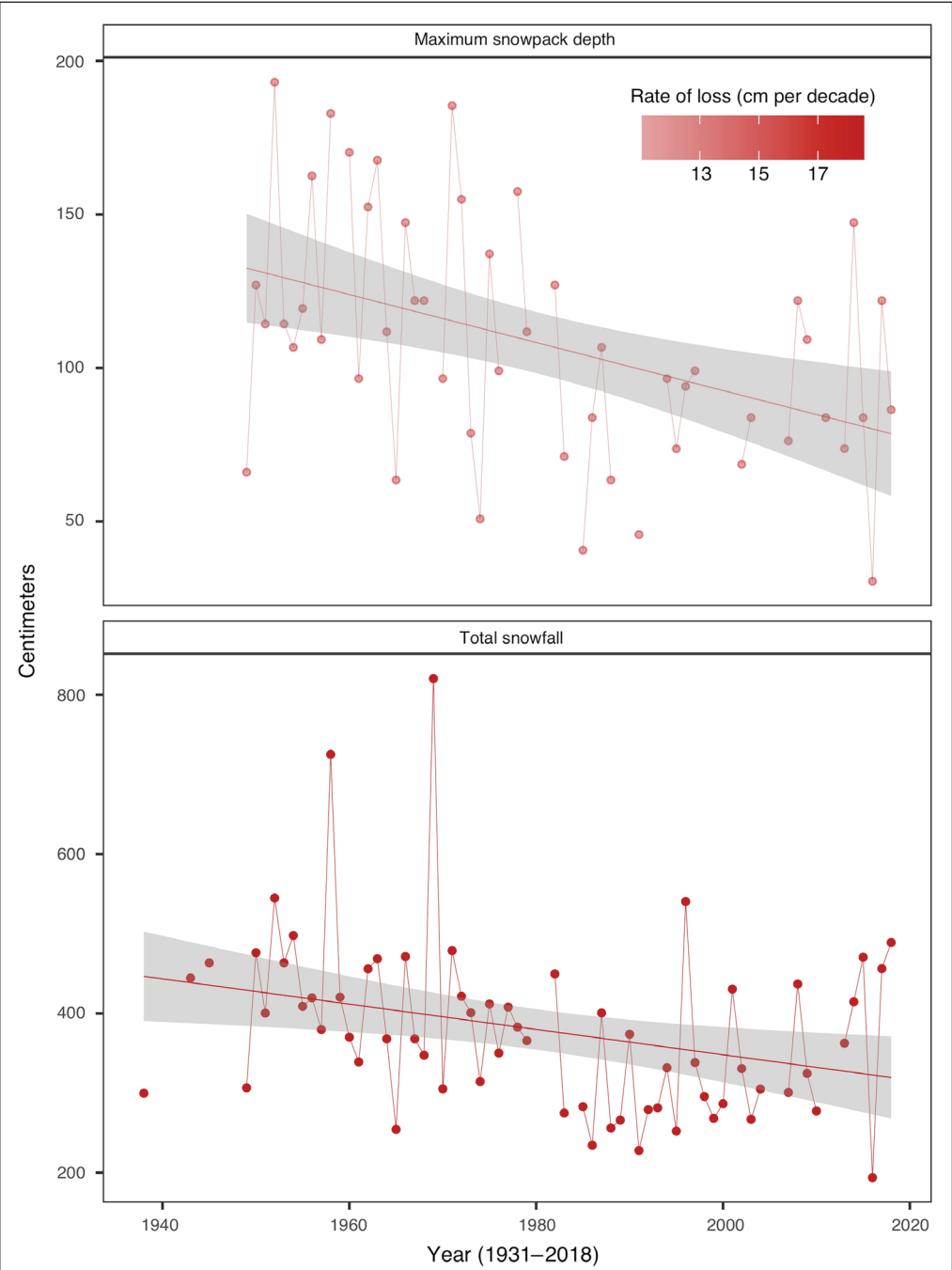


Figure 3. Maximum snowpack depth and total snowfall at Pinkham Notch, NH. Both trends are significant at $P < 0.05$. Red gradation bar is the rate of change in cm per decade.

Discussion

Examination of climate-change indicators at 2 proximate sites at different elevations on Mount Washington revealed that significant changes are detectable across multiple climate indicators including temperature, snow metrics, and length of growing season. Positive trends in temperature (warming) and negative trends in snow metrics (loss) are similar to those observed in other studies at broader scales (Brown et al. 2010, Contosta et al. 2019, Wilson et al. 2018). For example,

Table 4. Trend values for climate indicators at Pinkham Notch and the summit of Mount Washington, NH. ** $P < 0.01$, * $P < 0.05$.

Indicator	Definition	Trend and rate (days/decade)	
		Pinkham Notch	Summit
Frost day	Min daily temp below 0 °C	-2.2**	-1.8**
Ice day	Max daily temp below 0 °C	-2.7**	-1.8**
Thaw day	Max daily temp above 0 °C	+ 1.4*	+1.7**
Extreme cold day: Spruce damage	Min daily temp below -32 °C	0.0	0.0
Snow-making days before Christmas	Min daily temp below -5 °C before 25 December	-1.3**	-0.7
Snow-covered day	Snow depth greater than 0 mm	-0.7	-1.2
Frozen ground day	Bare ground plus ice: Max daily temp below freezing and snow depth = 0 mm	0.0	-1.6
Mud day	Bare ground plus thaw: Max daily temp above freezing and snow depth = 0 mm	+0.9	+1.4**
Length of growing season	Length of period between last hard freeze (min daily temp below -4.4 °C) in the spring and first hard freeze in the fall	+3.9**	+1.8**
Growing-season start	Last hard freeze in spring (min daily temp below -4.4 °C)	-1.9**	-1.7**
Growing-season end	First hard freeze in fall (min daily temp below -4.4 °C)	+2.5**	+1.0
Air temp zero	First date when smoothed temperature crosses from below 0 °C to above 0 °C	-1.2*	-0.6*

Table 5. Annual mean temperature rates of warming for the period of 1935–2018 at the 2 study sites (this study) and across regions (Regional source data: <https://www.ncdc.noaa.gov/cag/time-series/us/>).

Site or region	Warming rate (°C per decade)
Mount Washington summit, NH	0.10
Pinkham Notch, NH	0.14
New Hampshire	0.17
Northeast	0.11
Contiguous US	0.12

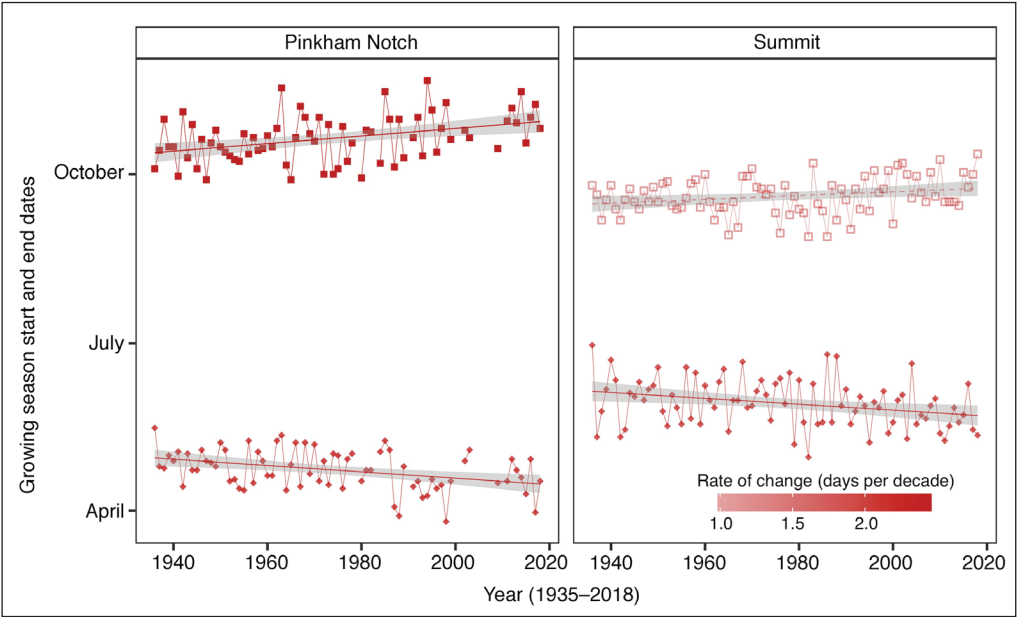


Figure 4. Start (diamonds) and end (squares) of growing season using a -4.4°C severe freezing for Pinkham Notch (left) and the summit of Mount Washington (right). Open symbols denotes trends are not significant at $P < 0.05$. Red gradation bar is the rate of change in days per decade.

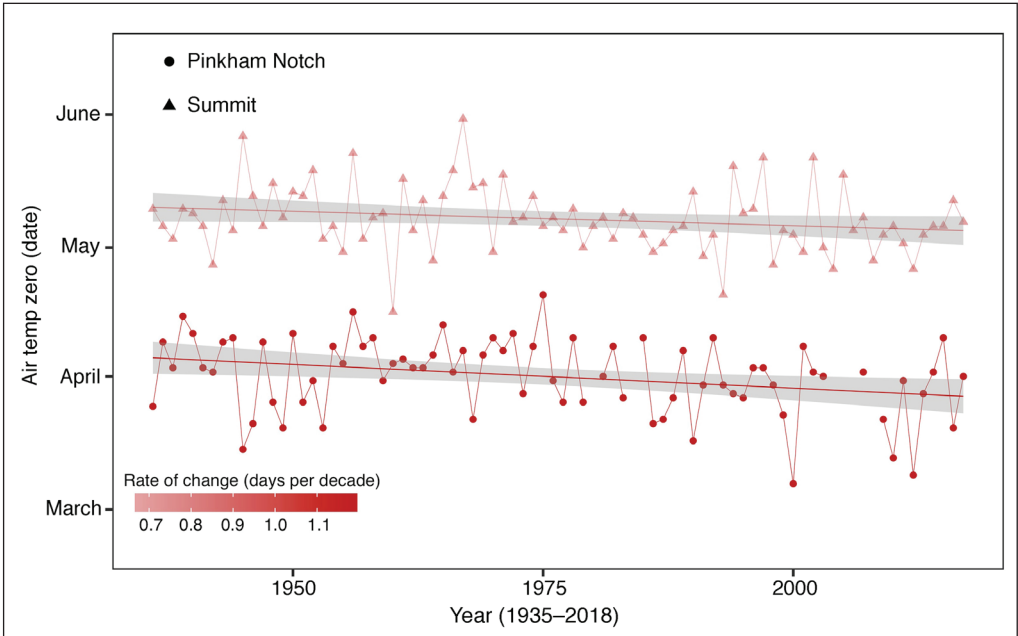


Figure 5. Yearly air temp zero date (start of vernal window; see table 4) for Pinkham Notch (circles) and summit of Mount Wahsington (triangles).

comparing the annual mean warming trends to the state of New Hampshire (NH), the Northeast, and the contiguous US (Table 5), using the same period 1935–2018, Pinkham Notch warmed at slightly lower rate than NH but at a greater rate than the broader Northeast or contiguous US. However, the Summit site warmed more slowly than has been observed at any of the other sites or geographic scales.

Warming rates and significance at both Pinkham Notch and the Summit site increased with the additional 15 years added to the record since the previous analysis by Seidel et al. (2009). Summit annual temperatures are now increasing at a statistically significant rate, although still at a slower rate than Pinkham Notch. The most recent 15 years have been the warmest period on record globally. This accelerated rate of warming regionally and in our study is consistent with the continued rise of greenhouse-gas emissions and positive-feedback mechanisms that are accelerating global warming (IPCC 2014).

Elevational variability

The differences in the rate of warming at these adjacent sites have persisted even with the addition of more-recent data since Seidel et al. (2009). While this work did not investigate the mechanisms for variation in warming with elevation directly, previous work indicates that driving factors include regional PBL height, cloud cover, local topographic interactions, and seasonal vegetation cycles (Córdova et al. 2016, Daly et al. 2009, Dobrowski et al. 2009, Gallagher et al. 2011, Kelsey et al. 2018). The difference between high- and low-elevation warming at this mountain location in the Northeast is particularly evident in winter temperature minima. Mount Washington is more frequently exposed to free tropospheric air in winter which could explain the slower warming rates relative to lower elevations during this season. The free troposphere has experienced a weaker warming trend than the PBL at many locations globally (Pepin and Seidel 2005). Importantly, warming trends are more consistent at both elevations during spring through early fall—the seasons when sensible heating grows the convective PBL past the Summit elevation most days. The month of September appears to show consistent day and nighttime warming at both sites, with Pinkham Notch warming the fastest during the day. Recent observational data and theory indicate that the mean position of the polar jet stream is shifting northward (Francis and Skific 2015, Francis and Vavrus 2015). These changes in natural modes of variability (Dai et al. 2019, Liu et al. 2020) may partially explain this distinct warming in early fall (and spring) when the climatological polar jet stream location is relatively close to Mount Washington and small changes northward can have pronounced impacts on temperature.

Seasonal variability

The dramatic warming in winter temperatures at Pinkham Notch is consistent with observations at Hubbard Brook Experimental Research Forest in Thornton, NH, and across the Northeast (Campbell et al. 2010, Fernandez et al. 2020, Rustad et al. 2014). While the Summit winter months do not reflect these strong warming rates, we observed a positive trend; specifically, the rate of increase in December maximum was on par with the highest rates in any month at 0.22 °C per decade ($P =$

0.06). Our region will continue to warm (Grogan et al. 2020), and therefore it is likely these warming rates will continue. It is still unclear whether the higher elevations will overcome the lag in winter warming relative to the stronger regional pattern.

The lack of significant changes detectable in the snow metrics at the Summit are inconsistent with most trends found at Pinkham Notch and regionally. Contosta et al. (2019) found 21 fewer snow-covered days over 100 years (1917–2016) across the Northeast US, while both the Mount Washington sites had no significant change in the number of snow-covered days for the period 1935–2018. These contrasting findings may be a result of the different time periods examined, but for Pinkham Notch it is more likely due to the exclusion of years based on our missing data criterion of no more than 10 days missing per snow season (n years = 49). If we adjust that criterion to 20 days, Pinkham Notch is losing 2.6 days per decade of snow-covered days ($P < 0.05$; $n = 66$ years), which aligns with the other snow metric result that does show changes, i.e., end of continuous snow season. In contrast to the negligible trend in snow-cover days found on the Summit, increases in the duration and magnitude when the dewpoint exceeds 0 °C in winter-thaw events on the Summit have been observed between 1940–2020, indicative of increases in potential snow-depth loss (Kelsey and Cinquino, in press). Condensation melt—when water vapor condenses on the snowpack and releases latent heat—is more efficient at ripening and melting a snowpack than by sensible heating from warm, dry ($T_d < 0$ °C) air alone (e.g., Light 1941). Our findings of snow loss at Pinkham Notch and uncertainty of snow conditions at the Summit (e.g., this study and that of Kelsey and Cinquino [in press]), underscore the need for an elevation-distributed snow-measurement approach to help understand drivers of snowpack variability in mountainous terrain.

The trends for frost, ice, and thaw days, as well as snowmaking days before Christmas, are similar in direction and rate of change as reported in Contosta et al. (2019). For example, Contosta et al. (2019) found 18 fewer frost days across Northeastern US and Atlantic Canada over the past 100 years (i.e., 1.8 fewer days per decade). Our study found 2.2 and 1.8 fewer frost days per decade at Pinkham Notch and the Summit site, respectively. So, while the strength of winter-warming trends varies with elevation, other climate metrics that characterize winter conditions indicate that changes are occurring across montane landscapes. This is one of just a few winter-climate metrics that is changing at a similar rate across elevations and the greater Northeast US/Atlantic Canada region (Contosta et al. 2019).

The growing season is lengthening at both Pinkham Notch and the Summit. This metric in combination with the strong temperature trends in the spring and fall transitional months has implications for the biota inhabiting mountains in the Northeast. However, earlier warming does not always translate to the same magnitude of earlier plant activity. Recent evidence of an expanding vernal window has been documented in the Northeast, where earlier snowmelt is advancing faster (-1.7 days per decade) than budburst (-1.0 days per decade) for the period 1980–2005 (Grogan et al. 2020). Another alpine study found spring flowering dates are occurring 1–2 days earlier over a 77-year period for alpine plants in the Presidential

range, NH, and this weak phenological sensitivity could be in part due to inadequate chilling requirements in the fall and winter, as suggested by Kimball et al. (2014). As discussed earlier, September is strongly warming at upper elevations, and that is the time of year when the vegetation in this alpine environment typically completes senescence and hardens for winter.

Conclusion

This work brings together temperature and snow metrics and other climate indicators collected during 9 decades at Mount Washington, NH, to provide a more detailed and updated assessment of climate change at this mountain location. The forested mid-elevation site continues to warm faster than the Summit; and like the broader New England region, has the greatest change in winter primarily due to elevated minimum temperatures. The addition of 15 years of data—representing the warmest period in this record’s history—to the last Mount Washington analysis (Seidel et al. 2009) shows annual warming rates on the summit for the period of 1935–2018 are now statistically significant. Snow trends in the alpine zone remain obscure since this high-wind environment complicates accurate measurements.

The paucity of quality, long-term data at different elevations at other northeastern mountains remains problematic. Additional monitoring sites are needed to better understand the complexity of transitioning climates and snow season in the region’s mountains, where exposure to seasonal planetary boundary-layer effects by elevation can also vary. Studies to better understand and quantify the mechanisms behind the seasonal and elevational variations found in this work would greatly benefit the understanding of what is most at risk and improve our ability to more precisely predict resilience of cold-dependent mountain ecosystems.

Acknowledgments

We thank the Mount Washington Observatory and its staff, seasonal employees, and volunteers who observe, collect, and maintain data. We are grateful to current and past AMC Staff who have collected data at the NWS COOP station over the years. We thank the White Mountain National Forest, where the AMC operates the Pinkham Notch Visitor Center, and the National Weather Service Gray, ME, staff for their support of the Pinkham Notch COOP station.

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