The 1935–2003 Air Temperature Record from the Summit of Mount Washington, New Hampshire

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ABSTRACT

Meteorological observations have been taken continuously at the summit of Mount Washington since 1932. Results of an analysis of the air temperature record over the 1935–2003 period show a statistically significant increase in mean temperature of ~0.3°C, while the diurnal temperature range has decreased by ~0.15°C. The decadal structure evident in the record reveals that, in contrast to North American trends, the summit experienced relatively cool temperatures in the 1940s. The late 1980s and early 1990s were relatively warm on the summit, in agreement with North American decadal trends. The times of daily maximum and minimum temperatures show that the summit climate is dominantly influenced by boundary layer processes 30% of the time and free air circulation 50% of the time. No evidence of a "weekend effect" was found.

1. Introduction

The Third Assessment Report of the Intergovernmental Panel on Climate Change reported that the global mean surface temperature has risen by approximately 0.6°C over the last century (Houghton et al. 2001). Further, the bulk of the rise in mean temperature is due to the increase in daily minimum temperature, leading to a decreased diurnal temperature range (DTR) of approximately 0.84°C century^{-1} (DTR = maximum − minimum) (Karl et al. 1993; Easterling et al. 1997). Surface temperature trends in the northeastern region of the United States show an overall increase of about half the globally averaged annual mean, with winter temperatures increasing nearly three times as fast as those in summer (NERAG 2001).

This paper examines the 1935–2003 temperature record from the summit of Mount Washington, the highest peak in the northeastern United States (1914 m MSL) in the northern Appalachian Mountains. This location is unique because it is subject to both boundary layer and free air processes (Holzworth 1967) and is one of a sparse global network of elevated stations, which had been shrinking until the late 1990s (Diaz and Bradley 1997). Recently there has been renewed interest in observing complex indicators of climate change in mountain regions, leading to a resurgence in elevated observatories (Diaz and Millar 2004; Becker and Bugmann 2001). Hourly and daily summary temperature data have recently been digitized as part of a broader effort to digitize all of the summit climatological data. The temperature record was examined for 1) decadal, annual, and seasonal trends in mean temperature; 2) annual and seasonal trends in DTR; and 3) time of daily extremes. Additionally, the data were examined for evidence of a 7-day cycle in temperature, the so-called weekend effect, which has been identified previously

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in temperature records from some regions of the United States (Forster and Solomon 2003).

2. Data

a. Site description and station history

Mount Washington (44°16′N, 71°18′W, 1914 m MSL) is part of the Presidential Range of the northern Appalachian Mountains. Neighboring peaks are at approximately 1600 m, and tree line for the range is at approximately 1400 m. Weather observations have been taken continuously on the summit of Mount Washington since late 1932, and the Mount Washington Observatory has been designated as a National Weather Service "cooperative station" since 1 January 1937. Figure 1 shows the location of Mount Washington in the northeastern United States along with neighboring U.S. Historical Climatology Network stations used in homogeneity tests. The area around the summit is primarily exposed rock with a thin layer of alpine vegetation. There is a fairly level "summit cone" approximately 150 m across on which several buildings have been built and demolished over the years. The land on the cone is a mixture of natural exposed rock, graded gravel, cement, and buildings. Approximately 75% of the cone has been modified from its natural state; however, this overall percentage has changed little over the 1935–2003 period. Figure 2 provides an overview of the changing land use, while Fig. 3 shows the summit in 1945 and 1985.

Under the auspices of the Mount Washington Icing Sensors Project (MWISP), Gillman et al. (2002) conducted a preliminary synoptic climatology for the Mount Washington region, covering the period from 1955 to 1999. Their results indicated that, during winter months, the summit is predominantly under the influence of northwesterly transport associated with either the eastern side of a surface anticyclone or the passing of a surface cold front through the region. A similar pattern applies to all seasons with the exception of summer when a southwesterly flow with characteristically warm temperatures and high humidity is also prevalent. The monthly mean temperature is below 0°C from October through April, and the mean annual wind speed is 15.3 m s^{-1}. In winter the sustained wind speed routinely reaches 50 m s^{-1} with gusts exceeding 70 m s^{-1}.

This dataset is valuable in confirming global surface temperature trends since it has undergone few moves since inception and the surrounding valleys have not become significantly urbanized (cf. Bücher and Dessens 1991). The most significant location change occurred in 1980 when the station was moved from the south to the northwest side of the summit cone, approximately 91 m north of and 6 m higher in elevation than its original location, as shown in Fig. 4. For the duration of the record, temperature was measured 2 m above the surface. The summit does not observe daylight savings time; local time is UTC − 5 year-round. An uninterrupted dataset extending back before 1948 is valuable in expanding the twentieth-century climate record (Brönnimann et al. 2005).

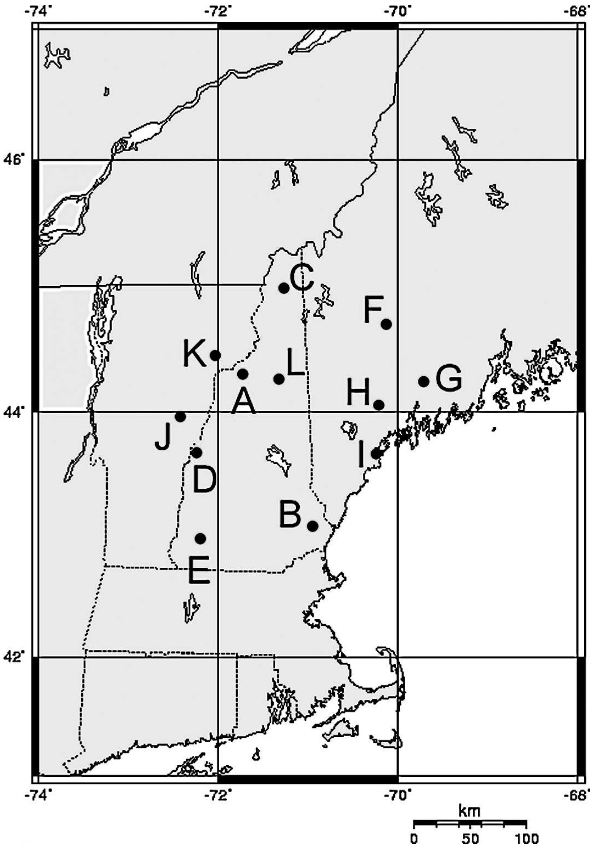

FIG. 1. Location of Mount Washington and neighboring U.S. Historical Climatology Network stations used in homogeneity tests: (A) Bethlehem; (B) Durham; (C) First Connecticut Lake; (D) Hanover; (E) Keene; (F) Farmington; (G) Gardiner; (H) Lewiston; (I) Portland; (J) Chelsea; (K) St. Johnsbury; (L) Mount Washington; the summit is at 44°16′N, 71°18′W, 1914 m MSL, and is 110 km from the Atlantic Ocean.

b. Datasets

Since 1937, temperature has been measured with equipment supplied by the U.S. National Weather Service and certified to their published specifications (Wright 1995). Routine operations began in 1932, but neither daily summary nor full hourly data are currently available for the period from 1932 to 1934. Therefore, the two temperature datasets examined here both cover the period from 1 January 1935 to 31 December 2003.

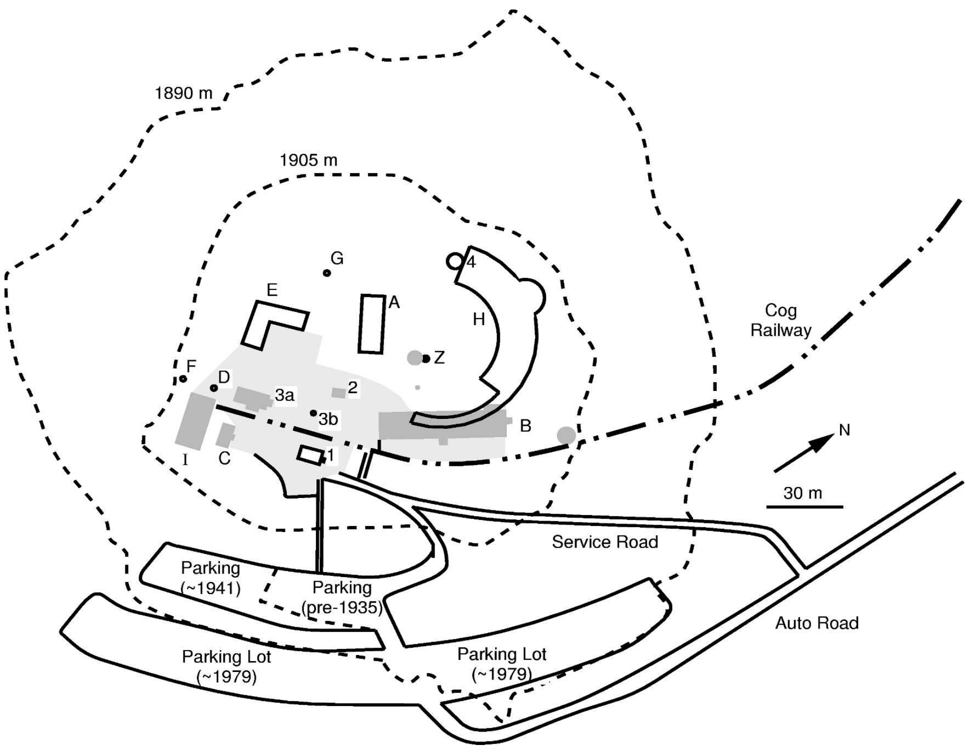

FIG. 2. Location chronology for max–min thermometer shelter (numbers) and large structures (letters) on the summit of Mount Washington. Structures still in existence are outlined in black; demolished structures are shown as gray shapes. 1) Beginning of record to 23 Jun 1936: outside of northwest side of the Stage Office entrance; 2) 23 Jun 1936–21 Oct 1937: outside of northwest wall of vestibule of Camden Cottage; 3a) 21 Oct 1937–1 Aug 1980 (except for periods noted in 3b): northwest wall of vestibule of "new" observatory building; 3b) Jun–Oct for the years 1937–40 and 22 Jul–21 Oct 1941: northeast face of 34-ft-tall observatory tower; 4) 1 Aug 1980–present: outside observation deck entrance on northeast side of observatory tower entrance to Sherman Adams building; (A) Tip Top House (1853–present); (B) Third Summit House (1915–1980); (C) Alford power (generator) house (1937–2003); (D) Alford antenna tower (1937–present); (E) Yankee Building (1941–present); (F) FM radio antenna tower (1952–present); (G) FM radio antenna tower (1988–present); (H) Sherman Adams building (1980–present); (I) WMTW transmitter building (1954–2003); (Z) Geographical summit at 1917 m. Gray discs near Z and to the right of B mark sites of demolished water storage tanks. Dashed lines are height contours for 1890 m (6200 ft) and 1905 m (6250 ft). Hatched area is approximate present-day extent of graded gravel.

The first is the hourly temperature, referred to as *hourly*, obtained from either direct observation (sling psychrometer) or continuous thermograph recordings referenced to the nearest direct observation (every 3 or 6 h). The second, called *max–min*, is the daily maximum and minimum temperatures from self-registering thermometers. From 1 January 1935 to 31 December 1939, these self-registering thermometers were read twice a day at 0730 and 1930 local time; thus, the daily maxima and minima are potentially subject to correction due to "time of observation bias" (Janis 2002). Time of observation bias is a statistical bias that may be introduced to a dataset when the daily period of measurement is different from the local calendar day, as minima or maxima can potentially be double counted. Since 1 January 1940, four daily observations were made of the maximum and minimum thermometers at approximately 0100, 0700, 1300, and 1900 local time, thus, adequately representing the true local daily extremes (Janis 2002). No correction was applied to the 1935–39 max–min data.

The max–min record contains no missing data, while the hourly record is missing 85 complete days (including days with more than 3 hours missing, which were discarded) and 45 other scattered individual observations. Daily maximum, minimum, mean, and DTR were calculated from the hourly dataset, and seasonal and annual maximum, minimum, mean, and DTR were calculated from both the hourly and the max–min datasets. Times of daily extremes were obtained from

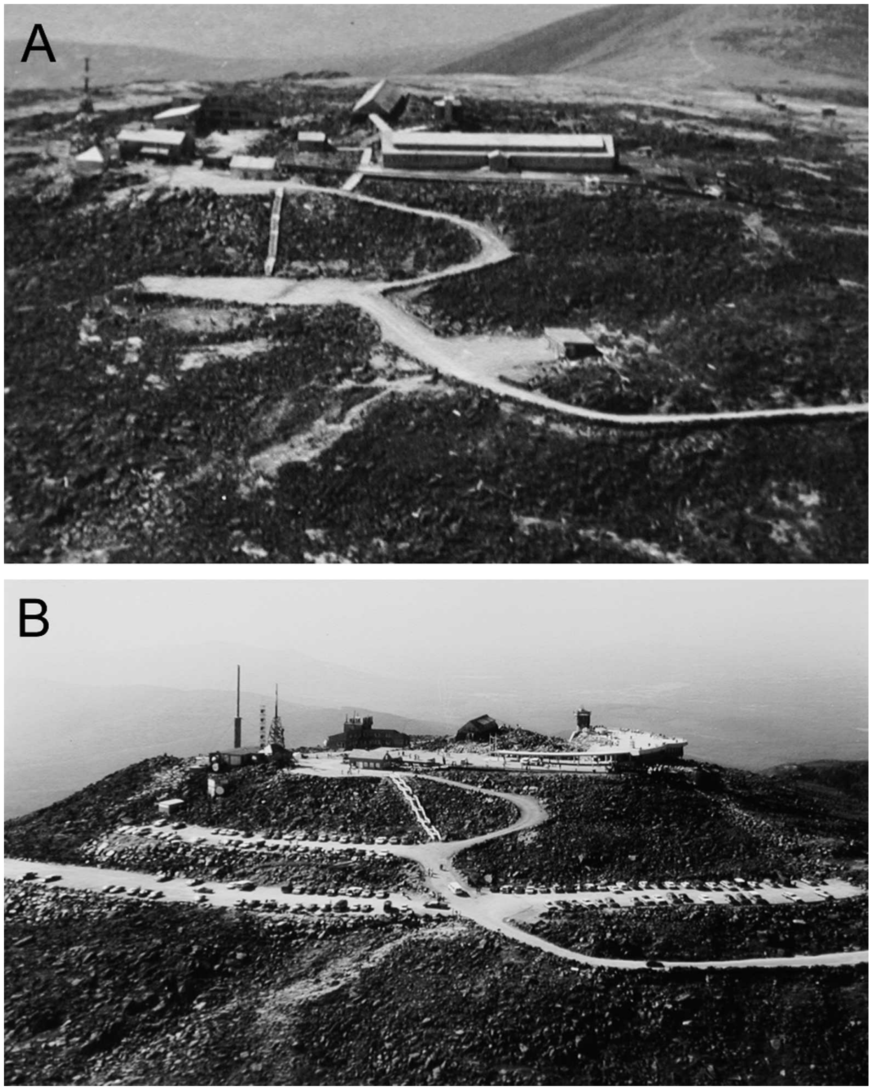

FIG. 3. Aerial views of the summit cone in (a) 1945 and (b) 1985. Several buildings have changed, but the overall percentage of modified land area has remained approximately 75%.

the hourly record. In the case of duplicate extreme temperatures in one day, the first hour encountered was used.

Ideally, a test for homogeneity of the data would be performed by comparing to similar, neighboring stations. However, there are no other year-round, long-term elevated stations in the northeastern United States. The Historical Climate Network contains 11 surface stations, shown in Fig. 1, within 1° latitude and 1° longitude of Mount Washington with quality controlled data available through 1994 (Easterling et al. 1996): 1) Bethlehem, New Hampshire (No. 270703; 44°17′N, 71°41′W, 421 m MSL); 2) Durham, New Hampshire (No. 272174; 43°9′N, 70°57′W, 24 m MSL); 3) First Connecticut Lake, New Hampshire (No. 272999; 45°5′N, 71°17′W, 506 m MSL); 4) Hanover, New Hampshire (No. 273850; 43°42′N, 72°17′W, 184 m MSL); 5) Keene, New Hampshire (No. 274399; 42°57′N, 72°19′W, 155 m MSL); 6) Farmington, Maine (No. 172765; 44°41′N, 70°9′W, 128 m MSL); 7) Gardiner, Maine (No. 173046; 44°13′N, 69°47′W, 43 m MSL); 8) Lewiston, Maine (No. 174566; 44°6′N, 70°13′W, 55 m MSL); 9) Portland, Maine (No. 176905; 43°39′N, 70°18′W, 14 m MSL); 10) Chelsea, Vermont (No. 431360; 43°59′N, 72°27′W, 244 m MSL); and 11) St. Johnsbury, Vermont (No. 437054; 44°25′N, 72°1′W, 213 m MSL). The mean monthly maximum, minimum, and average temperatures from these 11 stations were compared to the monthly values for Mount Washington for the 1935–94 period. The standard normal homoge-

FIG. 4. Summit cone of Mount Washington: Original station location is at A and current station is at B; the two are approximately 90 m apart. Prevailing wind direction (W to NW) comes directly out of the page.

neity test (Alexandersson and Moberg 1997) was applied and revealed no significant single point shifts or trends in the Mount Washington record relative to the neighboring stations.

3. Results and discussion

a. Overall trends

Annual mean temperature and DTR are plotted in Fig. 5 along with results of linear regressions. Both hourly and max–min datasets are shown. The temperature trends and their statistical significances (for the full period as well as subperiods defined in section 3b) are summarized in Table 1. Mean temperature calculated from the max–min (hourly) dataset has increased 0.31°C (0.32°C) over 69 years. This is consistent with changes seen in the northeastern United States, which has, on average, increased 0.4°C from 1895 to 2000, with considerable spatial variation (NERAG 2001). Maximum temperature at Mount Washington has increased 0.24°C (0.23°C), while minimum temperature has increased 0.38°C (0.39°C) over the 1935–2003 period. Diurnal temperature range has decreased 0.14°C (0.16°C) over the same period.

Trends may appear in data due both to real change in climate or to gradual or abrupt artifacts such as station relocations, instrument changes, and gradual alterations in the use and modification of surrounding land (Lanzante 1996; Alexandersson and Moberg 1997). The failure to detect any single shift or trend change-points in this record suggests that artifacts do not significantly contribute to the trends discussed in this section. Fur-

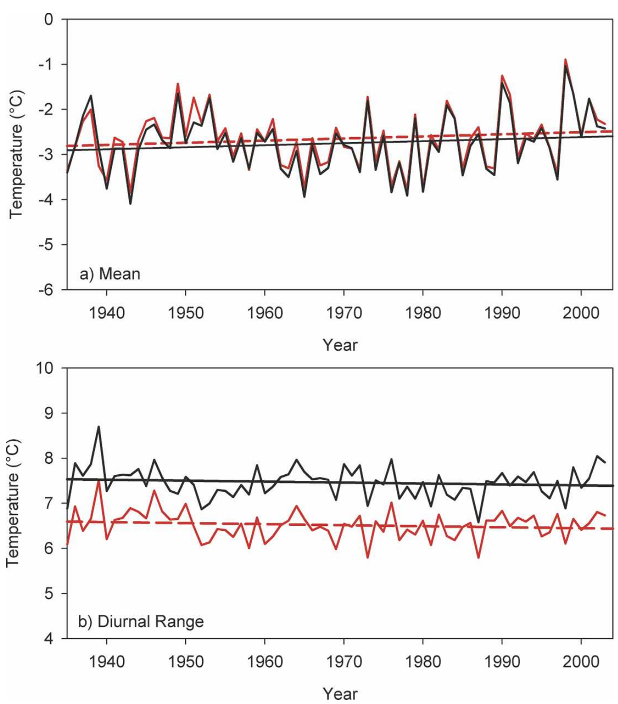

FIG. 5. (a) Mean temperature and (b) diurnal temperature range, with linear regressions, for the 69-yr record from max–min (black) and hourly (red) datasets. Max–min (hourly) mean temperature has increased by 0.31°C (0.32°C); diurnal range has decreased by 0.14°C (0.16°C).

TABLE 1. Change (in °C) over the 1935–2003 period unless otherwise noted. Significance, based on Monte Carlo simulations with n = 10 000, is indicated as 1% (bold font) and 5% (italic font).

Dataset	Max	Min	Avg	DTR
Annual (hourly)	*0.23*	**0.39**	**0.32**	*−0.16*
Annual (max–min)	*0.24*	**0.38**	**0.31**	*−0.14*
Winter (max–min)	**0.77**	**0.65**	**0.71**	*0.12*
Spring (max–min)	**0.76**	**0.84**	**0.80**	−0.08
Summer (max–min)	**−0.37**	0.09	−0.14	**−0.46**
Fall (max–min)	−0.16	−0.07	−0.11	−0.09
Hildebrandt	−0.12	0.06	0.00	−0.18
Balling	0.04	0.27	0.16	−0.23
Max–min (1939–98)	0.04	**0.34**	0.19	**−0.30**

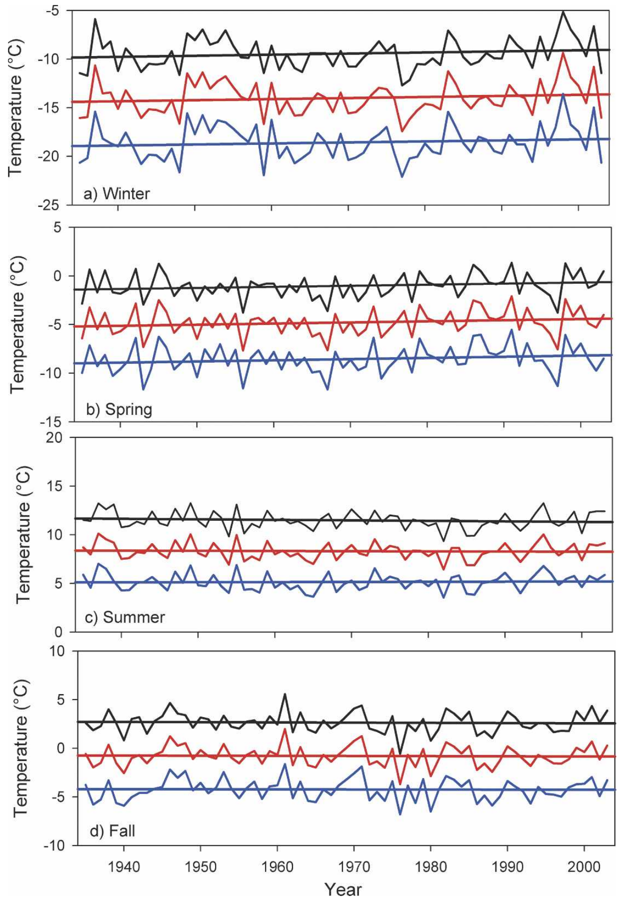

FIG. 6. Seasonal trends in temperature, with linear regressions, for (a) winter (Dec–Feb), (b) spring (Mar–May), (c) summer (Jun–Aug), and (d) fall (Sep–Nov). Max–min data are shown: maximum (black), mean (red), and minimum (blue) temperatures for the 69-yr record. Note: all panels have the same scale.

thermore, the null hypothesis test for determining significance of a slope is problematic, and physically real trends may still be present when the hypothesis is not rejected (Nicholls 2000). Therefore, significance for the linear regressions was determined by generating 10 000 sample datasets via Monte Carlo simulations, as described in Wilks (1995). Changes in the minimum and mean temperature were significant at the 1% level, while trends in maximum and DTR were significant at the 5% level.

Analysis of the max–min data by season, shown in Fig. 6 and Table 1, indicates that winter (December–February) and spring (March–May) have experienced the largest changes in temperature, with the winter mean having increased by 0.71°C and the spring mean having increased by 0.80°C, both significant at the 1% level. Summer (June–August) mean temperature has decreased 0.14°C and fall (September–November) mean temperature has decreased 0.11°C, although these are not statistically significant changes. Previous work has shown that winters in the northeastern United States have, on average, warmed at three times the rate of summers (1°C in winter and 0.3°C in summer), with a large spatial variability in these trends (NERAG 2001). The dramatic increase in Mount Washington winter temperatures is consistent with the regional findings.

Decadal trends in mean temperature for the Northern Hemisphere, as discussed in Parker et al. (1994), showed 1990 to have been the warmest year to that time, referenced to the 1951–80 normal, and culminated a dramatic 5-yr warming trend. The 1935–45 period was also relatively warm. Annual anomalies for Mount Washington, relative to the 1951–80 normal (−2.93°C), are shown in Fig. 7, along with a 5-yr running mean. The warmest year on the summit, and globally (Houghton et al. 2001), was 1998, with the mean 1.9°C above the 1951–80 normal. The mean for the 1990–2003 period is 0.6°C above the 1951–80 normal. The 1935–39 and the 1950s mean were also 0.3°C above 1951–80, although the 1940s were only 0.1°C above 1951–80, which is in contrast to the findings of Parker et al. (1994) that the 1936–45 period was unusually warm.

b. Trend sensitivity

Hildebrandt and Balling (1998) analyzed monthly summary data from Mount Washington obtained from the National Climatic Data Center (NCDC). These data (hereafter referred to as Hildebrandt) are derived from the max–min data in monthly reports submitted to the NCDC, and was digitally available only for the period 1939–97. A follow-up analysis (see information online at http://www.greeningearthsociety.org/Articles/mtwash.htm) added 1998 to the dataset (hereafter referred to as Balling); trends from both analyses are shown in Table 1. Linear regressions were performed on both datasets and the resulting slopes were different from each other as well as from those from the 1935 to 2003 period. An exploration of the sensitivity of the trend to window size and position was conducted. Linear regressions were calculated on max–min data for window sizes from 50 to 69 yr for all combinations of contiguous data (e.g., for a window size of 60 yr, trends were calculated for 1935:1994, 1936:1995, . . . , 1944:2003). For the mean temperature, slopes ranged from -8×10^{-3} to 15×10^{-3}; for the maximum, slopes ranged from -11×10^{-3} to 16×10^{-3}; and for the minimum slopes ranged from -4×10^{-3} to 15×10^{-3}. In nearly all cases, the negative slopes were found when the window included the earlier years, while the largest positive slopes were found when the 2000s were included. These trends in the trends reflect that the sum-

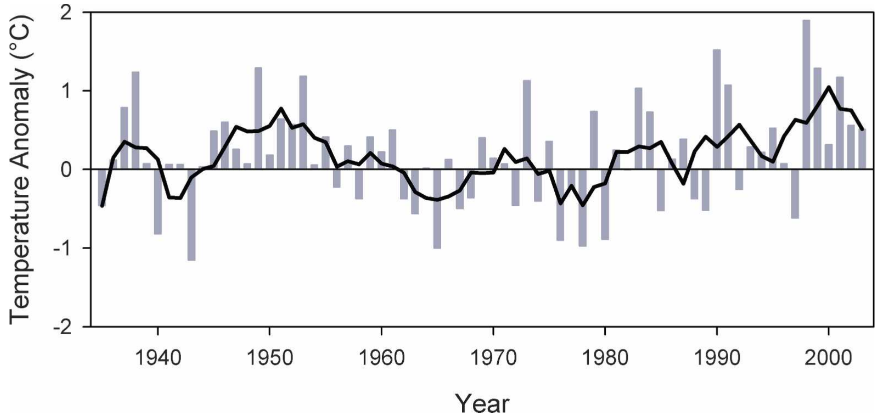

FIG. 7. Annual mean temperature anomaly from the max–min dataset, referenced to the 1951–80 normal (−2.93°C). Five-year running mean is also shown.

mit experienced relatively cooler temperatures in the 1960s and 1970s (generally below the 1951–80 normal) and warmer temperatures from the 1980s to the early 2000s.

c. *Times of extremes*

Boundary layer thickness in New England ranges from 1 to 2 km in summer (Holzworth 1967); thus, weather at Mount Washington is subject to influences from both the boundary layer and the free troposphere. The times at which daily maximum and minimum temperatures occur allow each day to be broadly classified as dominated by one of these two processes. Days when the summit is affected by the boundary layer tend to have the traditional solar-radiation-driven temperature cycle with minimum temperature before sunrise and maximum temperature in the afternoon. Days that are dominated by advection tend to have maximum temperature at the beginning of the day and minimum temperature at the end of day, or vice versa, with the day defined as local midnight to midnight. Ten years after the Mount Washington Observatory began operations, Conrad (1941) conducted a preliminary analysis of the temperature record. Briefly summarizing, data from 1935 to 1937 were examined for the time of daily maximum and minimum temperature in order to determine the type of weather prevailing on the summit. Data were clustered in 2-h blocks (i.e., 0000–0200, 0200–0400 local time, etc.) for easier comparison with the results in Conrad (1941). A day was coded as 1) radiative if the minimum occurred between 0400 and 0800 and the maximum between 1200 and 1800 or 2) advective if the maximum occurred between 0000 and 0200 and the minimum between 2200 and 2400, or vice versa.

This analysis shows that advective weather primarily influences station temperature on 50% of the days while radiative processes are the primary influence on 30% of the days, which is consistent with the results based on the 1935–37 data, where 50% of the days were advective and 24% were radiative, while the rest were mixed or showed no clear pattern (Conrad 1941). Figure 8 shows a histogram of the daily extreme times. The percentage of advective days does not vary seasonally (50 ± 1%). However, the percentage of clearly radiative days increases dramatically in the summer (37%, versus 23% for winter), reflecting the higher temperatures and lower wind speeds characteristic of summer, which allow the sun to better heat the summit cone and surrounding slopes.

d. *Weekend effect*

The data were examined for evidence of a "weekend effect," which has been identified in temperature records from some regions of the United States (Forster and Solomon 2003). As there are no known natural cycles with a period of seven days, any trends in meteorological variables with a weekly period must be linked to human activity. Changes in cloud cover and cloud properties have been hypothesized as the most likely cause of a weekend effect in regions where significant cycles in DTR have been identified in the United States (Forster and Solomon 2003). Other studies have correlated local pollution and heat generation resulting from traffic patterns to weekly cycles in temperature (Simmonds and Keay 1997), but local effects are not expected to be important at a relatively isolated station such as Mount Washington.

An analysis was performed of the trends in DTR by grouping the data into "weekend" (Saturday, Sunday, and Monday) versus "weekday" (Wednesday, Thurs-

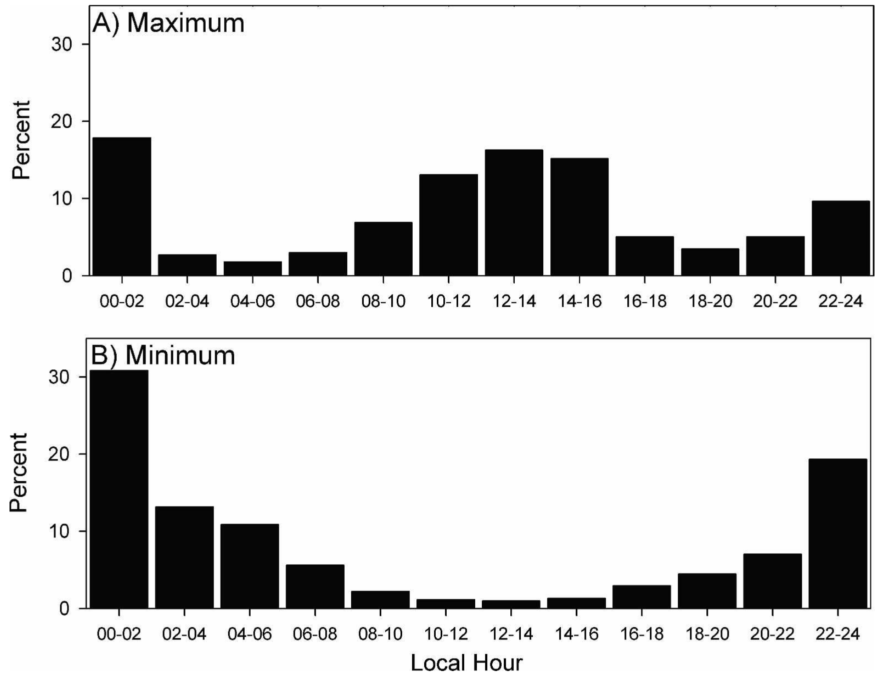

FIG. 8. Frequency of occurrence for time of (a) maximum and (b) minimum extreme temperatures. Note the high occurrence of maxima and minima occurring at midnight (0000–0200 or 2200–2400), which is characteristic of advective weather and rarely occurs at a low-elevation surface station.

day, and Friday) after Forster and Solomon (2003) and then comparing the averages of these two groups in a time series. No significant difference between the two groupings was found. It is feasible that any weekly cycle might be phase shifted owing to transport time; however, other clusterings (e.g., Thurday–Friday–Saturday versus Sunday–Monday–Tuesday, and so forth) did not reveal any trends nor did seasonal breakouts of the above groups. A fast Fourier transform analysis of the raw hourly data and daily DTR series also revealed no weekly peak. This is consistent with the findings in Forster and Solomon (2003), which showed no significant weekend effect in the northeastern United States. These results were not surprising, as the majority of aerosols that may affect cloud properties, implicated in the weekend effect, are located within the boundary layer, whereas the summit is usually near the top of (or entirely above) the boundary layer with the exception of the warmest summer days (Fischer et al. 2004).

4. Conclusions

Significant trends were found in the 69-yr temperature record of Mount Washington. Mean annual temperature has increased by $0.3 \pm 0.08°C$ for the period 1935–2003 ($0.4°C$ century^{-1}), comparable to long-term trends for interior northern New England (NERAG 2001). As with most stations, Mount Washington experienced a sharper increase in minimum temperatures than in the maximum, leading to an overall change in DTR of $-0.15 \pm 0.04°C$ for 69 years ($-0.2°C$ per century). The winter warming rate is over twice the annual warming rate, also consistent with trends in much of New England (NERAG 2001). Time of daily extreme temperatures reveals that 50% of the time the summit weather is dominated by advective processes, 30% of the time by radiative processes, and the rest are mixed or demonstrate no clear pattern. No evidence of a weekend effect was found in the DTR records.

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The authors of Grant et al. (2005) have noted an error in the published version of their paper. Because of the use of an incorrect statistical model, the statistical significances shown in Table 1 of Grant et al. (2005) are overestimates of the true significance of the trends. Grant et al. (2005) used Monte Carlo (MC) simulation to create 10 000 artificial datasets mimicking the 1935–2003 annual temperature series. Each Monte Carlo dataset was created by applying a statistical model of daily maximum and minimum temperature to create a 69-yr dataset. Maxima for each day of the year were modeled by multiplying the standard deviation (calculated using all the observed data for that day of the year) by a normally distributed pseudorandom number and then adding that day's mean value of maximum temperature (again based on the full dataset for that day of the year). A year's worth of minimum data was modeled in the same fashion. This was repeated 69 times to produce 69-yr-long MC time series. The entire procedure was then repeated 10 000 times.

Daily, seasonal, and annual means with linear fits were then calculated from the modeled daily maximum and minimum temperatures for each of the 10 000 MC datasets. The 10 000 MC results were ranked and the value of the trend in the 250th and 9750th place found. If the observed warming trends were less than or greater than these values, they were found to be "significant at 0.05 level." An analogous procedure was used to calculate the 0.01 significance level.

We believe this method overestimates the significance of the trends because the model is based on daily values and does not account for daily autocorrelation in temperature. The tables below (Tables 1–3)

TABLE 1. Original and new significance (sig) values for the max–min dataset, 1935–2003. DTR = diurnal temperature range.

		Slope (°C yr^{-1})	Original sig	p value sig
Annual	Max	0.0035	0.05	0.38
	Min	0.0055	0.01	0.19
	Avg	0.0045	0.01	0.25
	DTR	−0.0021	0.05	0.33
Winter	Max	0.0112	0.01	0.24
	Min	0.0092	0.01	0.33
	Avg	0.0102	0.01	0.27
	DTR	0.002	0.05	0.87
Spring	Max	0.011	0.01	0.14
	Min	0.0121	0.01	0.16
	Avg	0.0116	0.01	0.14
	DTR	−0.0011	–	0.75
Summer	Max	−0.0054	0.01	0.32
	Min	0.0014	–	0.79
	Avg	−0.002	–	0.69
	DTR	−0.0067	0.01	0.02
Fall	Max	−0.0024	–	0.72
	Min	−0.0011	–	0.89
	Avg	−0.0017	–	0.80
	DTR	−0.0014	–	0.69

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TABLE 2. Original and new significance values for the max–min dataset, 1939–98.

	Slope (°C yr^{-1})	Original sig	p value sig
Annual max	0.0007	–	0.88
Annual min	0.0056	0.01	0.29
Annual avg	0.0032	–	0.51
Annual DTR	−0.005	0.01	0.03

TABLE 3. Original and new significance values for the hourly dataset, 1935–2003.

	Slope (°C yr^{-1})	Original sig	p value sig
Annual max	0.0034	0.05	0.38
Annual min	0.0057	0.01	0.18
Annual avg	0.0047	0.01	0.23
Annual DTR	−0.0023	0.05	0.23

present significance levels from the Grant et al. (2005) paper along with the updated levels using p values for linear regressions of the $n = 69$ seasonal or annual averages.

REFERENCES

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