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AN ANALYSIS OF THE 1932-2004 AIR TEMPERATURE RECORD FROM THE SUMMIT OF MOUNT WASHINGTON, NEW HAMPSHIRE, USA

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1 INTRODUCTION

Analyses of weather observations at surface stations around the globe have indicated that surface temperature has risen by $\sim 0.6°C$ over the last century (IPCC 2001). Closer examination of these results has revealed that higher daily minimum temperatures account for the bulk of the warming trend, while daily maximum temperatures have not changed as much, leading to a decrease in the diurnal temperature range (DTR = maximum - minimum) (Karl et al. 1993). This paper will examine the continuous temperature record from the summit of Mount Washington, at 1914m ASL in the northern Appalachian mountains. Previously, only daily summary data had been available digitally; this paper will include results from daily summary data and original hourly temperature records which have recently been digitized.

Additionally, the data will be examined for evidence of a "weekend effect", which has been identified in temperature records from some regions of the US (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 properties have been hypothesized as the most likely cause of a weekend effect in regions where significant cycles in DTR have been identified (Forster and Solomon 2003).

The majority of surface weather observation stations are located at elevations which are not dissimilar to the surrounding topography. The Mount Washington Observatory, located at the summit of a somewhat isolated mountain, is at a significantly different elevation than all nearby stations, thus providing a unique dataset which may offer insight into processes in the upper boundary layer. The network of such summit observatories is sparse and shrinking (Diaz and Bradley 1997).

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2 DATA

2.1 Station history

Observations have been taken continuously at Mount Washington since late 1932; the Mount Washington Observatory has been designated as a National Weather Service "cooperative station" since 1 Jan 1937. In 1980, the station was moved approximately 91m north of and 6m higher in elevation than its original location. While this is a rather minor change in location, the new station is on the opposite side of the summit cone, which potentially has a different microclimate. Surrounding valley locations have not become significantly urbanized—since 1970, combined population in the three closest towns has increased from 13,000 to 17,000.

2.2 Datasets

Observations were taken irregularly (3 to 24 times per day, with many days missing) for the period 18 Nov 1932 to 31 Dec 1934, and daily summaries for this period are currently not available, thus this subset of data will not be considered in the current analysis. Since 1 Jan 1935, hourly temperatures have been recorded either from direct observation (i.e., sling psychrometer) or from thermograph recordings which have been referenced to the nearest direct observation (every three or six hours). In addition, daily maximum and minimum temperatures from self-registering thermometers are available from 1935 on. For the period of 1 Jan 1935 to 31 Dec 1939, the maximum and minimum thermometers were read twice a day at 0730 and 1930, thus the daily maxima and minima are subject to correction due to "time of observation bias" (Janis 2002), which has not yet been applied to the data discussed below. Since 1 Jan 1940, four daily observations were made of the maximum and minimum thermometers, at approximately 0100, 0700, 1300, and 1900 ($\pm$ 30 minutes), thus adequately representing the true local daily maximum and minimum (i.e., local midnight to midnight) (Janis 2002).

The two datasets examined here both cover the period of 1 Jan 1935 to 31 Dec 2003; the first is the hourly temperatures (called "hourly") and the second is the daily maximum and minimum from the self -registering thermometers (called "max-min"). The max-min record contains no missing data, while the hourly record is missing 85 complete days (days with more than three hours missing were discarded) and 45 other scattered individual observations. The max-min record was keyed in through a volunteer effort in the late 1990s and was manually checked for errors for this analysis. The hourly record was keyed in through a separate volunteer effort during winter 2003-2004, and was error checked through a combination of double keying and manual checking against the original paper records. Error rates are quantified at 0.03%, and all errors are less than $4°C$, based on a graphical means of triple checking the data. Daily maximum, minimum, mean and DTR were calculated from the hourly dataset, and annual maximum, minimum, mean and DTR were calculated from both the hourly and the max-min datasets.

3 RESULTS

3.1 Overall Trends

Annual averages of maximum, minimum, and daily average temperatures for the period 1935 to 2003 are plotted in Figure 1 along with results of linear regressions. Figure 2 shows annual averages of daily DTR over the same period. Maximum temperature has increased by $0.32°C$ for the hourly dataset and $0.24°C$ for the max-min dataset, while minimmum temperature has increased by $0.39°C$ for the hourly and $0.38°C$ for the max-min, leading to a change in DTR of $-0.16°C$ for the hourly and $-0.14°C$ for the max-min. Figure 3 shows a breakdown of maximum, minimum, and average temperatures by season. Annual and seasonal results for the full record (1935 to 2003) are given in Table 1.

Statistical significance was tested for via Monte Carlo simulations ($n = 10000$), as in Wilks (1995). For the 1935 to 2003 period, trends in the minimum and average were significant at the 1% level, while trends in the maximum and DTR were significant at the 5% level. The subset of data from 1939 to 1998 was also analyzed for comparison with Balling (www.greeningearthsociety.org/Articles/mtwash.htm); results are listed in Table 2. For

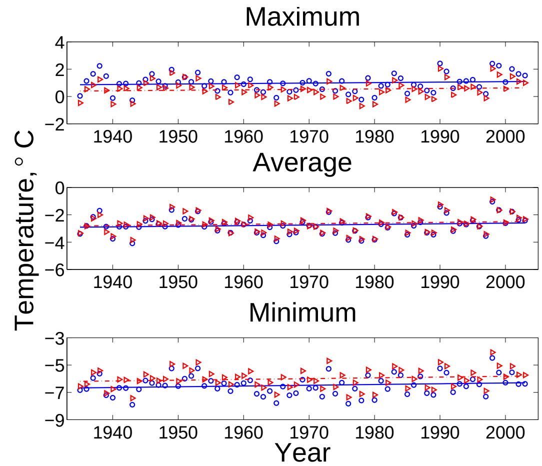

Figure 1: Temperatures and linear regressions for the 69 year record from max-min (circle with solid line) and hourly (triangle with dashed line) datasets.

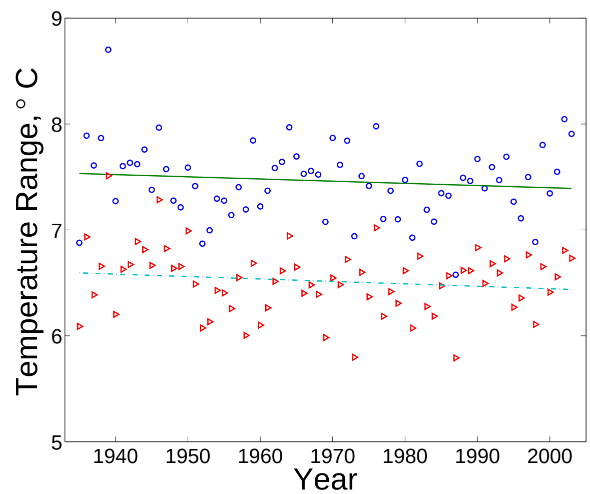

Figure 2: DTR and linear regression for the 69 year record from max-min (circle with solid line) and hourly (triangle with dashed line) datasets.

the 1939 to 1998 period, trends in the minimum and DTR were significant at the 5% level, while trends in the maximum and average were not significant. The trends for the subset of years considered by Balling differ from the trends indicated by the longer period. Data from 1935 to 1939 had a greater range than the early 1940s. As both the max-min and hourly datasets show this increased range, it cannot be attributed to a time of observation bias in the max-min dataset. Inclusion of these early data in analyses directly impacts overall results. It is not clear why Balling did not

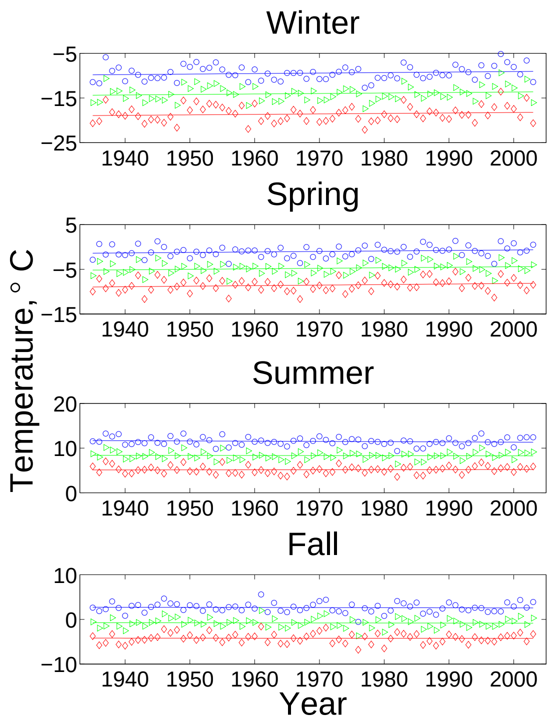

Figure 3: Maximum (circle), average (triangle), and minimum (diamond) temperatures by season for the 69 year record. Only max-min data are shown.

find a significant trend in the minimum temperature for the 1939 to 1998 period, while we did. Use of different statistical methods in one possibility; unfortunately Balling does not specify which method he used.

Analysis by season indicates that winter and spring have warmed by 0.7 to $0.8°C$ over 69 years in all parameters, significant at the 1% level for maximum, minimum, and average. Summer maximum temperatures have changed by $\sim -0.4°C$ over 69 years. Summer minima are increasing slightly, while all parameters for fall are decreasing, although these changes are not statistically significant.

3.2 Weekend Effect

An analysis was performed of the trends in DTR by day of week. Figure 4 shows changes in DTR averaged over "weekend" (Saturday, Sunday, and Monday) versus "weekday" (Wednesday, Thursday, Friday), after Forster and Solomon (2003). There is clearly no weekend effect in DTR. It is feasible that any weekly cycle might be phase shifted due to transport time, however, other clusterings did not reveal any trends, nor did seasonal clustering of the "weekend" versus "weekday" data. This is consistent with the findings of Forster and Solomon (2003) which found no significant weekend effect in the Northeastern U.S. These results are not surprising for Mount Washington, as the majority of aerosols implicated in the weekend effect are located within the boundary layer. The summit of Mount Washington, at 1914m, is usually near the top of the boundary layer and above the majority of the aerosol column.

Table 1: Change over 1935:2003, $°C$
Significance, based on Monte Carlo simulations with $n = 10000$, is indicated by: double underline (1%), single underline (5%)

	Max	Min	Avg	DTR
Annual (hourly)	0.32	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

Table 2: Change over 1939 to 1998, $°C$ reported by Balling (www.greeningearthsociety.org/Articles/mtwash.htm) and for the full period of the record (1935 to 2003).
Significance is indicated by: double underline (1%), single underline (5%)

	Max	Min	Avg	DTR
Hourly	-0.03	0.25	0.15	-0.28
Max-min	0.04	0.34	0.19	-0.30
Balling	0.04	0.27	0.16	-0.23
1935:2003 (hourly)	0.32	0.39	0.32	-0.16
1935:2003 (max-min)	0.24	0.38	0.31	-0.14

4 CONCLUSION

Significant trends were found in the 69 year temperature record of Mount Washington. Average temperature has increased by $0.3 \pm 0.08°C$ for the period 1935 to 2003 ($0.4°C$ per century), which is comparable to long term trends for interior northern New England (NERAG 2001). As with most stations, Mount

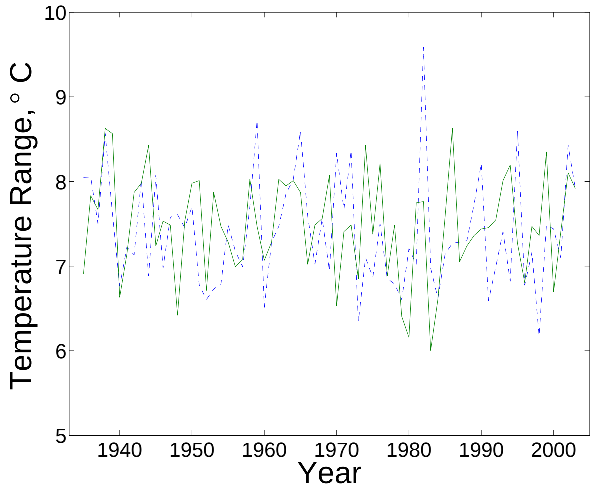

Figure 4: DTR grouped by "weekend" (Sat-Sun-Mon, solid line) vs. "weekday" (Wed-Thu-Fri, dashed line).

Washington experienced a sharper increase in minimum temperatures than in maximum, leading to an overall decrease in DTR of $-0.3 \pm 0.04°C$ for 69 years ($-0.4°C$ per century). The winter warming rate is over twice the annual warming rate, also consistent with trends in much of New England (NERAG 2001). No evidence of a weekend effect was found in the DTR records.

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