Description of the Temperature Observation and Averaging Methods Used at the Blue Hill Meteorological Observatory

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The Blue Hill Meteorological Observatory (BHO) is unique due to its long history of private operation, its association with Harvard University during the middle 20th century, and its close affiliation with the National Weather Service (NWS) since the late 1950s (*Conover*, 1990). This history has prompted a need to maintain weather data that are internally self-consistent to ensure a long-term homogeneous climate record since 1885, while also generating statistics that are consistent with standard NWS practices for modern comparison with other locations. Accomplishing this goal requires the use of two different averaging methods for temperature, which provides an unusual opportunity to demonstrate the impact of each approach, and these methods are described here to clarify how each system is defined and applied at the Observatory.

At BHO, the manual (i.e. non-automated) temperature data are recorded with traditional equipment consisting of liquid-in-glass thermometers (for maximum and minimum temperature) and a daily hygro-thermograph chart recording for the measurement of hourly temperature. All of these are housed in a large, white, ventilated Hazen shelter, which has been on the same spot since the early 20th century, in the outdoor instrument enclosure. Hourly and daily extreme temperatures are recorded as whole integers, although the thermometers and thermograph are observed to the nearest tenth degree. The maximum temperature is measured with a mercury-in-glass thermometer that uses a restriction near the base of the mercury column to allow the mercury to remain close to its maximum value. The instrument is reset near the time of the morning low temperature by spinning it rapidly around its center point, which forces the mercury column down to the current temperature. Minimum temperature is measured with a thermometer containing colored alcohol with a blue index marker that floats inside the column. As the temperature drops, the marker is pushed downward by the shrinking alcohol column, and it remains at its lowest point after the temperature begins to rise. A separate psychrometer, which is a pair of mercury thermometers used to measure the dry and wet bulb temperatures, is used to record the temperature (also in the Hazen shelter) during the three manual observations taken each day at 7 AM, 10 AM and 1 PM EST. The combination of the maximum and minimum temperatures and the manual observations are used to derive corrections and temperatures at the intervening hours from the temperature trace on the hygro-thermograph chart. The resulting hourly and daily extreme values are rounded to the nearest integer and are recorded.

To determine the daily average, the current NWS practice is to generate a mean based on the average of the daily maximum and minimum. This method is used because these two values are the quantities that have been measured at the largest number of locations for the longest time. However, this type of mean is impacted by a number of biases. A positive bias results since the average of two integers has a remainder of either 0.0 or 0.5, and the latter is always rounded upward to the nearest integer while the former requires no rounding. This upward bias is minimized when generating a monthly average, since the current NWS method is to derive the monthly average as the mean of the average daily maximum and average daily minimum temperatures rather than the average of the daily mean temperatures. However, the highest and lowest temperatures each day or their average do no necessarily represent the actual distribution of temperature throughout a 24-hour period, and this introduces additional bias relative to the mean that would be derived from the average of 24 hourly values. A related bias is introduced by the period selected to define the maximum and minimum temperature, which is not necessarily the end of a calendar day and is known as the time of observation bias. A thorough analysis of these biases is beyond the scope of this report, though each can contribute discrepancies on the order of tenths of a degree or more (*Janis*, 2002; *Vose, et al.*, 2003). At the Observatory, for much of the earliest decades and into the 1950s, the time of observation for the purposes of recording extreme temperatures was either 7 PM or 8 PM EST. Since the late 1950s the time of observation has been 7 AM EST, though daily temperature extremes (taken from the continuous chart recording) and means (using the NWS method) are established for each calendar day ending at midnight EST.

For the purpose of deriving the most consistent and continuous monthly and annual mean temperature throughout the period of record, many of the biases listed above are avoided by utilizing a more accurate averaging method that uses hourly temperature data. In the mid-20th century, is was determined by BHO staff that the average of four temperatures per day (at 2 AM, 8 AM, 2 PM and 8 PM) provides a mean, known as the '2828' method, that is often very close to the mean that results from averaging all 24 hourly values over the course of an entire month or year. The 2828 average is what is reported by BHO as the 24-hour corrected (or adjusted) mean temperature, and averages using this method are the ones used internally for graphical and statistical analysis of monthly, seasonal, and annual mean temperature trends. Although 24 hourly temperatures are available for BHO each day back to the 1950s, these were not derived as a matter of course in earlier decades. However, manual observations for each day are available at or close to the hours needed to generate the 2828 mean. Monthly mean temperatures using the 2828 method were derived for the entire period of record (POR) in the mid-20th century to ensure long-term consistency in temperature averaging, and this method continues in use today.

An illustration of the impact of the 2828, 24-hour, and NWS averaging methods on January, July and annual mean temperatures over the last 15 years is shown in Table 1. For all three periods, the 24-hour and 2828 methods agree to within 0.2 degree F or less in any year and 0.1 degree F or less in the mean over all 15 years. In contrast, the difference between the NWS and 2828 methods is as much as +1.3 degree F in any year and +0.9 degree F in the mean over all 15 years. The bias in the NWS mean relative to the 2828 method is noticeably larger in July than in January, with an average difference of about +0.6 degree F in the annual mean. A possible explanation for the discrepancy in magnitude of this bias between the warm and cold months is that the stronger sun in summer is more likely than in winter to cause brief upward spikes in the extreme maximum temperature (and thus impact the NWS method), which are less representative of the diurnal temperature cycle captured by the other averaging methods.

BHO Temperature Average Comparison (degree F)									
	Jan	**Jan**	**Jan**	**Jul**	**Jul**	**Jul**	**Ann**	**Ann**	**Ann**
Year	**2828**	**24-hr**	**NWS**	**2828**	**24-hr**	**NWS**	**2828**	**24-hr**	**NWS**
2000	24.7	24.7	24.9	67.3	67.4	67.9	48.1	48.1	48.7
2001	27.1	27.1	27.3	67.6	67.5	68.3	50.2	50.2	50.8
2002	33.5	33.5	34.5	71.5	71.5	72.1	49.9	50.0	50.5
2003	20.6	20.6	20.6	71.7	71.6	72.7	47.6	47.6	48.2
2004	17.2	17.2	17.0	68.6	68.6	69.5	47.9	47.9	48.5
2005	23.8	23.8	24.0	71.0	71.1	71.8	48.9	48.9	49.5
2006	33.9	34.0	34.2	73.1	73.3	74.2	50.6	50.6	51.3
2007	30.3	30.3	30.3	70.6	70.5	71.9	49.0	49.0	49.7
2008	30.2	30.2	30.3	72.8	72.9	74.1	49.4	49.4	50.0
2009	21.8	22.0	21.9	67.6	67.6	68.5	48.4	48.4	48.8
2010	26.4	26.4	26.7	75.1	75.0	76.2	51.0	51.0	51.6
2011	24.4	24.4	24.5	74.0	74.0	74.2	50.4	50.4	50.9
2012	31.2	31.3	31.6	73.2	72.9	74.0	51.7	51.7	52.4
2013	29.5	29.5	29.3	74.1	74.0	75.1	49.5	49.4	50.0
2014	24.8	24.9	25.0	72.0	71.8	72.2	49.0	48.9	49.3
Mean	**26.6**	**26.7**	**26.8**	**71.3**	**71.3**	**72.2**	**49.4**	**49.4**	**50.0**

Table 1. January, July and annual mean temperatures derived using the three different averaging methods described in the text over the last 15 years.

The impact of the time of observation bias on BHO mean temperatures using the NWS method is illustrated in Table 2, which compares the mean temperatures for January and July for the last fifteen years using different observing intervals. In one case, monthly NWS means are derived from daily maximum and minimum temperatures recorded over a 24-hour period ending at midnight EST, and these data (in columns marked 'NWS 12A-12A') are the same as the columns for January and July marked 'NWS' in Table 1. In the other case, monthly NWS mean temperatures are derived from daily maxima and minima that were observed during a 24-hour period ending at 7 PM EST. The pattern that emerges is that the 7 PM time of observation results in a consistently warmer monthly mean than the 12 AM time of observation with a mean difference of about +0.9 degrees F in January and +0.3 degrees F in July. Due to the strong variability of winter weather, temperature extremes in January are much more likely to occur at times other than the typical times of day (i.e. early morning minimum and afternoon maximum), and this results in a greater time of observation impact in that month than in July.

BHO Time of Observation Impact on Average Temperature						
	Jan	**Jan**	**Jan**	**Jul**	**Jul**	**Jul**
Year	**NWS 7P-7P**	**NWS 12A-12A**	**Difference**	**NWS 7P-7P**	**NWS 12A-12A**	**Difference**
2000	26.3	24.9	+1.4	68.2	67.9	+0.3
2001	28.0	27.3	+0.7	68.9	68.3	+0.6
2002	34.7	34.5	+0.2	72.7	72.2	+0.5
2003	21.3	20.6	+0.7	72.9	72.7	+0.2
2004	18.6	17.0	+1.6	69.7	69.5	+0.2
2005	24.8	24.0	+0.8	72.5	71.8	+0.7
2006	35.0	34.2	+0.8	74.5	74.2	+0.3
2007	31.5	30.3	+1.2	72.3	71.9	+0.4
2008	31.2	30.3	+0.9	74.3	74.1	+0.2
2009	22.6	21.9	+0.7	68.7	68.5	+0.2
2010	27.5	26.7	+0.8	76.4	76.2	+0.2
2011	25.4	24.6	+0.8	74.4	74.2	+0.2
2012	32.2	31.6	+0.6	74.4	74.0	+0.4
2013	30.1	29.3	+0.8	75.5	75.1	+0.4
2014	25.8	25.0	+0.8	72.6	72.2	+0.4
Mean	**27.7**	**26.8**	**+0.9**	**72.5**	**72.2**	**+0.3**

Table 2. January and July mean temperatures derived using the NWS averaging method for an observing day ending at 7 PM EST and ending at 12 AM EST over the last 15 years.

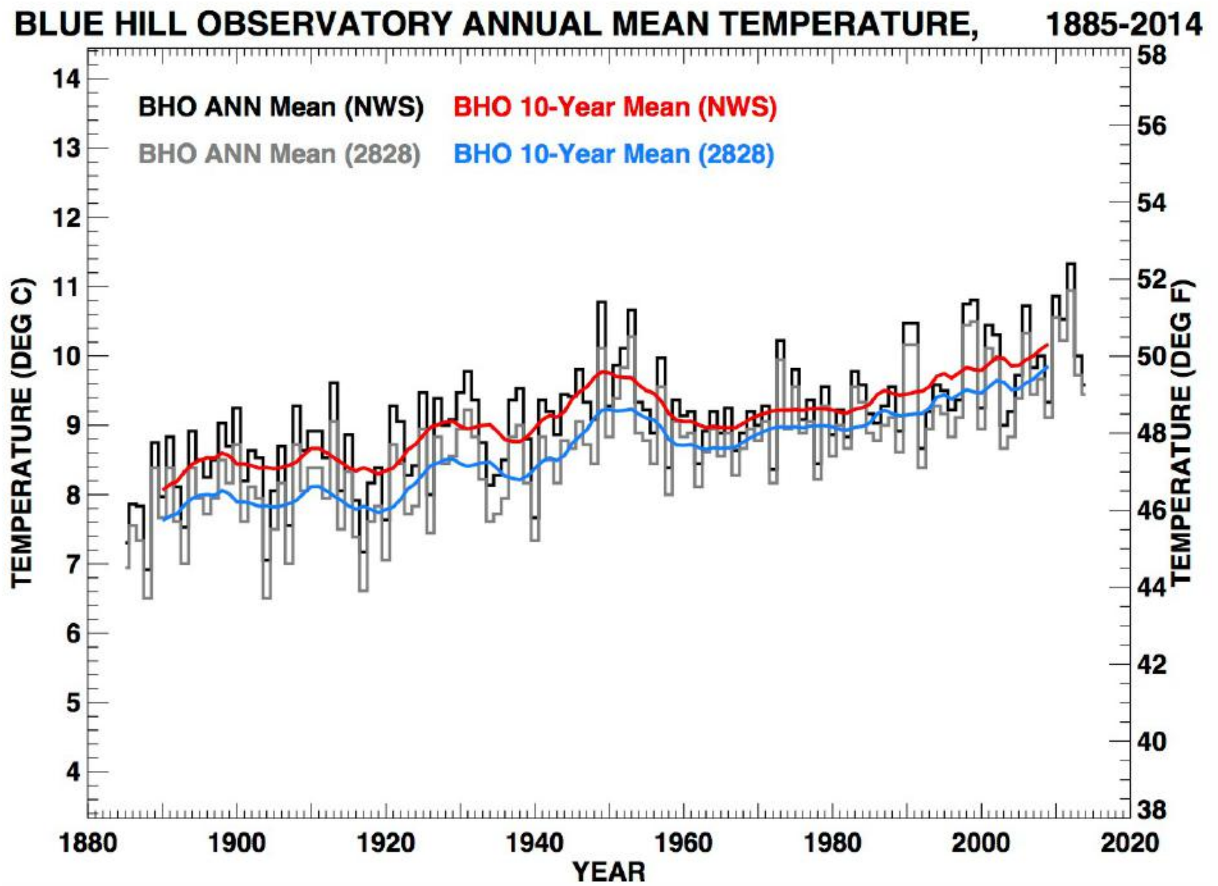

Figure 1. BHO annual mean temperatures derived with the 2828 (gray) and NWS (black) averaging methods described in the text over the full period of record, and the 10-year running annual mean temperatures derived with the 2828 (blue) and NWS (red) methods.

The impact of the difference between the 2828 and NWS averaging methods on the long-term annual mean temperature at BHO is shown in Figure 1. Average temperatures for each calendar year derived by dividing the sum of the annual mean maximum and annual mean minimum temperatures by two (the NWS method) are plotted in black in Figure 1, while the mean for each year derived by averaging the monthly mean temperatures calculated using the 2828 method are plotted in gray. The 10-year running means are also shown for the NWS method (in red) and for the 2828 method (in blue). It is immediately apparent that the NWS averaging method provides a higher annual mean temperature throughout the period of record. There is also a suggestion of a slight difference in the upward trend since the late 19th century, with a larger difference between the methods in the first half of the POR than in the second half. This is a consequence of the sensitivity of the NWS averaging method (but not the 2828 method) to the bias caused by the time of observation and the fact that at BHO this changed from 7 PM or 8 PM prior to the late 1950s to the midnight to midnight calendar day starting in 1959.

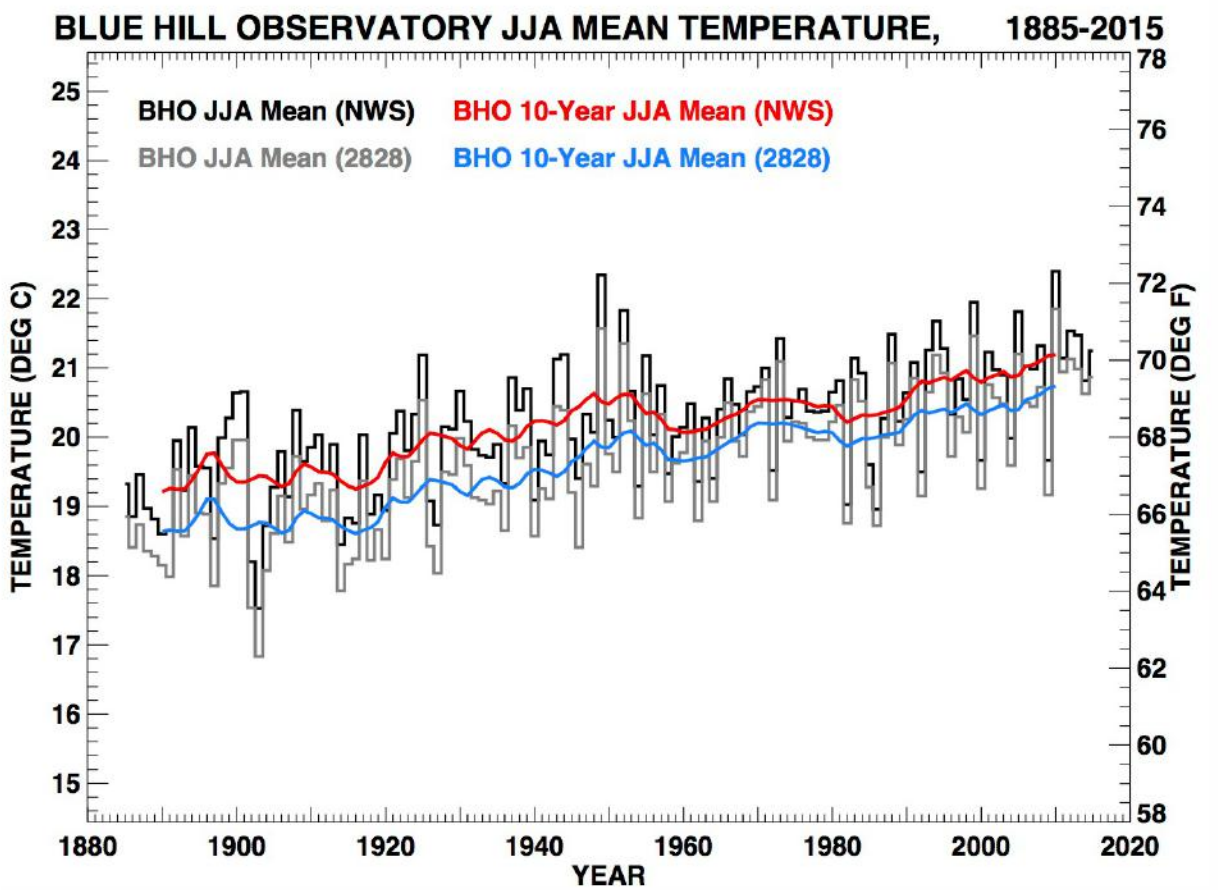

Figure 2. BHO June, July, August mean temperatures derived with the 2828 (gray) and NWS (black) averaging methods described in the text over the full period of record, and the 10-year running JJA mean temperatures derived with the 2828 (blue) and NWS (red) methods.

Figure 2 shows the impact of the difference between the 2828 and NWS averaging methods on the long-term June, July and August (JJA) summer mean temperature at BHO. The summer temperature data are plotted identically to the annual data in Figure 1, including the use of a vertical scale of the same magnitude, though with a different range, to highlight the relative differences between annual and summer means. The difference between the two averaging methods, which is most noticeable in the separation between the red and blue 10-year mean curves, is slightly larger in JJA than in the annual means. This observation is consistent with the mean temperatures listed in Table 1 for recent years, which show the greatest disparity between the averaging methods in July. Figure 2 is evidence that this pattern has been persistent throughout the period of record at BHO. The shift to closer agreement between the two methods in the mid-20th century is also apparent, due at least in part to the time of observation change. The amount of the shift in the NWS mean in the late 1950s is on the order of 0.5 degree F, which is consistent with the impact of the time of observation bias at this location listed in Table 2.

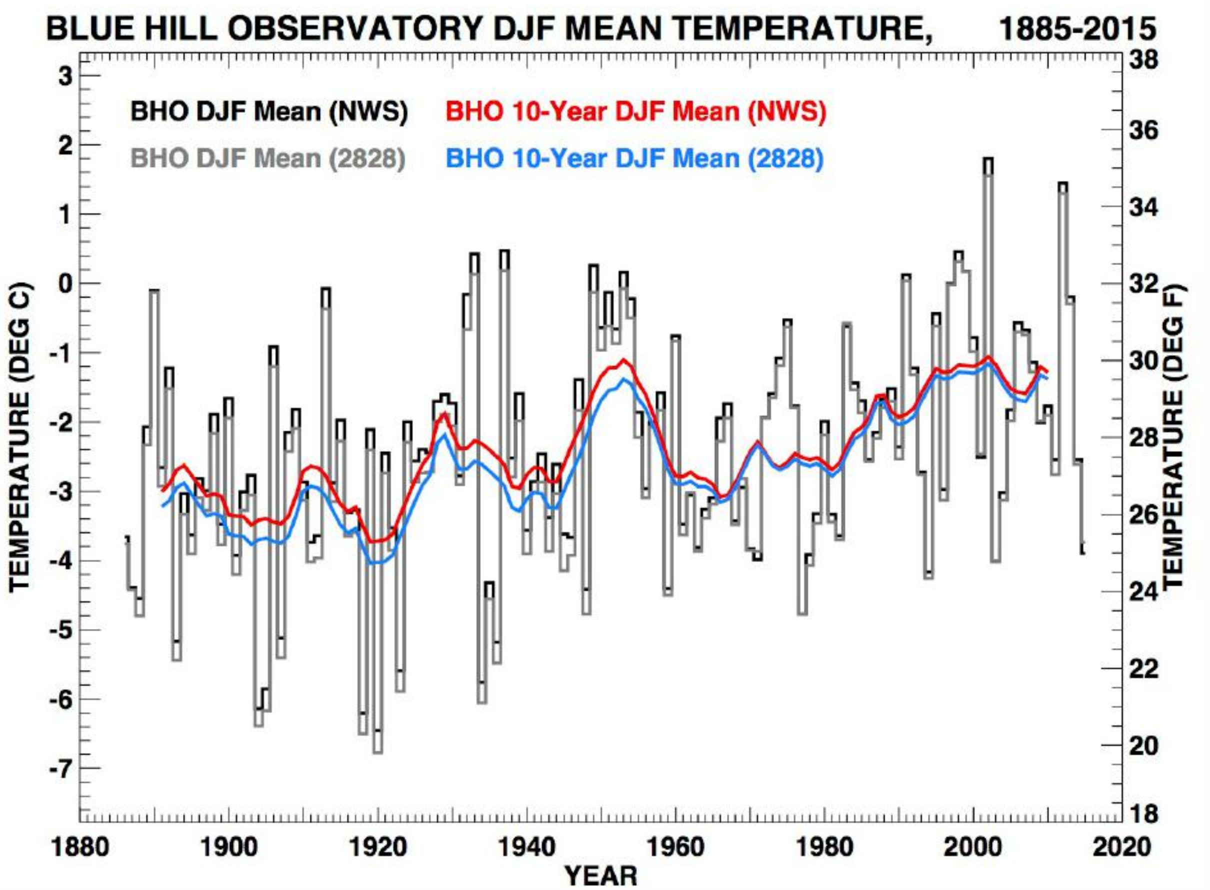

Figure 3. BHO December, January, February mean temperatures derived with the 2828 (gray) and NWS (black) averaging methods described in the text over the full period of record, and the 10-year running DJF mean temperatures derived with the 2828 (blue) and NWS (red) methods.

Finally, Figure 3 shows the impact of the difference between the 2828 and NWS averaging methods on the long-term December, January and February (DJF) winter mean temperature at BHO. The winter temperature data are plotted identically to the annual and summer data in the preceding figures to highlight the relative differences among the winter, summer and annual means. There are also noticeable decadal swings in winter that are either muted or missing in summer. The smaller difference between the averaging methods in January seen in Table 1 is also apparent in Figure 3 for the full winter season over the entire period of record, and this closer agreement has persisted throughout the record. This effect is evidence that the maximum and minimum temperatures are more representative of the diurnal temperature cycle in the cold season than they are in the warm season, especially for an observing day ending at midnight. In addition, although an upward trend in winter temperature at BHO is apparent, especially in the latter half of the 20^{th} century, it is modulated by a much larger inter-decadal variations than seen in the warm months. The causes of this decadal variability have not been investigated, though they are likely due to a combination of local, regional and global factors.

Summary

The procedures for measuring temperature and the two methods that are used to derive average temperature at the Blue Hill Observatory have been described and compared for the full period of record since 1885. The '2828' method for deriving daily, monthly and annual mean temperature uses four measurements at six hour intervals per day to provide the most effective and consistent way of comparing temperatures over the entire period of record in all seasons. This approach also avoids some of the biases associated with the NWS averaging method, which is defined as the mean of the daily maximum and minimum temperatures, such as numerical rounding, the inconsistency caused by using daily extremes to represent a full diurnal cycle, and the bias introduced by the time of observation. It was shown that the difference between the two methods is larger in the summer months that in the winter season. In addition, the change in the time of observation of daily temperature extremes from evening to midnight at BHO in the late 1950s produces a noticeable shift of about 0.5 degree F in the annual mean temperatures derived using the NWS method relative to the more self-consistent 2828 averaging method. The NWS method also produces annual and seasonal average temperatures that are typically higher than means derived with the 2828 method, though this effect is generally more noticeable in summer than in winter. The application of the 2828 averaging method at BHO since the late 19th century and the continued observation of hourly temperatures will ensure both the continuity of annual mean temperatures at the Observatory and the consistent and effective analysis of temperature changes into the future.

References

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