Effect of Observation Time on Mean Temperature Estimation[1]

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ABSTRACT

The increased interest and application of heating degree days (HDD) and growing degree days (GDD) prompted this study into the effect of different observation times upon the mean daily temperature. The study was based upon three years of hourly air temperatures measured at St. Paul. These data were used to calculate 1) a true daily mean, 2) a mean of the maximum and minimum between successive midnights as observed at first order stations, and 3) a mean of the maximum and minimum observed at all other hours of the day to simulate cooperative station means. Comparisons of the annual and monthly mean temperatures showed deviations can be of such magnitude as to discourage comparison of station temperatures and temperature-derived quantities such as HDD and GDD unless observation times are the same or corrections are applied.

1. Introduction

Recently the term heating degree days (HDD) has become familiar to almost everyone in temperate and northerly latitudes as a means of estimating fuel consumption. HDD also serve as a simple means of comparing one winter with another. HDD are defined as $\Sigma(T_b-\bar{T})$, where T_b ordinarily equals 65°F and $\bar{T}$ is the mean daily temperature. The summation of the positive daily values is made for either the heating season or the entire year from July through June.

In agricultural circles growing degree days (GDD) is now a common expression. For some time GDD have been used to estimate the harvest data of certain canning crops, and most recently GDD have been suggested as a means of rating the maturity of hybrid corn. Although there are several variations in the calculation of GDD, the basic equation is $\text{GDD}=\Sigma(\bar{T}-T_b)$. The base temperature T_b is usually set equal to 50°F for warm season crops, such as corn, and to 40°F for cool season crops such as small grains and potatoes. The summation of the positive values is for the crop growing season or portions of it.

In the rush to apply HDD and GDD the element that has been forgotten or overlooked is the time at which the temperature observation is made. This is not to imply that this topic has not been studied and analyzed in some detail (Bigelow, 1909; Rumbaugh, 1934; Mitchell, 1958; Weaver and Miller, 1970; and others). Rather surprisingly, at least at first glance, the time that the daily observation is taken does have an influence on the mean daily temperature. Since the error is systematic and cumulative, it does take on increasing importance when the temperatures are accumulated over one or more seasons as they are in the calculation of HDD and GDD.

One objective of this paper is to show how the mean daily temperature varies with the time of observation. Because of the broad engineering and agricultural applications of HDD and GDD, a second objective is to provide corrections applicable to the upper Midwest to these quantities so that the variation created by different observation times can be eliminated or at least minimized. Upon correction to a standard observation time the data from different stations then can be compared without the bias produced by varying times of observation.

2. Procedure

a. Observation day defined.

Ideally the mean temperature of a day would be obtained from either a mean of a continuous record of temperatures throughout the day or at least a mean obtained from 24 hourly temperatures. The latter method using hourly midnight to midnight values at a given place usually is taken as the "true daily mean" (Huschke, 1959). Neither method is ordinarily used, however, due to the time and effort required. Instead, the mean temperature for a day is accepted as the average of a maximum and minimum obtained within a 24 h period. The mean so derived is in fact a midrange of the extremes for the 24 h period that is used to represent the "true daily mean." At the full time

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(first-order) weather stations of the National Weather Service the 24 h day runs from midnight to midnight. At all cooperative stations the day is defined at the convenience of the observer. At most such stations the observation is usually taken either in the morning, often at 0700 or 0800 hours, or in the late afternoon.

The "day" at a station where the maximum and minimum thermometers are read at 0800 would then extend from 0800 of the previous day to 0800 of the current day. For an observation made at 1700 the maximum and minimum temperatures are observed and recorded 9 h later than the 0800 observation, yet both are recorded as the same calendar date. And some 7 h later at a first-order weather station (where personnel are on duty 24 h a day) an observer records the maximum and minimum observed from one midnight to the next. This too is recorded as the same date as the preceding two examples.

All three of the examples cited result in a calculated average temperature (more exactly a mid-range of the extremes) for the same calendar date that is derived from the maximum and minimum temperatures observed in three different 24 h periods. It is this lack of coincidence in the time period that produces the difference in the mean daily temperatures and thus the values derived from the means such as HDD and GDD.

b. Method of calculating mean daily temperatures.

A relatively unique set of data at a representative Minnesota station made it possible to determine the difference in mean daily temperatures that is created by varying the time of observation. Based upon these average differences correction factors were calculated for each observation hour that can be applied to seasonal HDD and GDD totals.

Air temperatures measured by a thermocouple in a standard temperature shelter have been recorded automatically each hour by means of a potentiometric strip chart recorder for a number of years at the University of Minnesota St. Paul Campus weather station. The thermocouple was provided with a mass similar to that of liquid-in-glass maximum and minimum thermometers so that extraneous and minute temperature fluctuations would be eliminated. Standard liquid-in-glass maximum and minimum thermometers were also housed within the same temperature shelter, and their record provided a daily check against the thermocouple values. In addition, the potentiometric recorder was periodically serviced by the manufacturer's personnel.

Hourly temperature data for the three-year period 1962–64 were selected for study. Inspection of the records indicates that these years are satisfactory representatives of the St. Paul station's temperature record. For example, the 1961–73 average annual temperature is 44.7°F and the annual averages for 1962, 1963 and 1964 are 43.8, 45.4 and 46.5°F, respectively. Interruptions in the record were very slight and few of the hourly observations had to be substituted in order to provide a complete record. The major source of the substituted data was the record of the hygrothermograph housed in the same temperature shelter. When this record was unavailable data were substituted from the Minneapolis-St. Paul National Weather Service airport station located less than 8 mi distant. In all cases where substitution was required the data were compared with the thermocouple record both before and after the missing portion so they could be adjusted if necessary to agree with the thermocouple-derived data.

The mean daily temperature was obtained in two different ways. The first way was to find the mean of 24 values from one midnight to the next. Twenty-three of the 24 values were the hourly temperatures from 0100 to 2300. The 24th value was the mean of the two midnight values. In this way equal weight was given to each hourly value even though two midnight values were used. The daily means thus obtained for the three years were defined as the true daily mean.

The second method of calculating a mean daily temperature was to search the 25 hourly temperatures for the highest and lowest value that occurred from one midnight to the next. The daily mean of these two values for each of the three years constituted what will be termed the first-order mean daily temperature. This method is like that used at the first-order National Weather Service stations. A minor difference in the temperature extremes between the maximum-minimum temperature record and the hourly temperature record may arise when the maximum and minimum temperatures do not coincide with and are not equal to the hourly recorded temperatures. These differences would affect the temperature range but the mean would hardly be affected.

Next a set of the other 23 daily mean temperatures was obtained in a manner similar to that just described by searching for the maximum and minimum temperatures within each 24 h period extending from 0100 to 0100, 0200 to 0200, and so on to the last one from 2300 to 2300. The mean temperatures thus obtained are comparable to those measured by the cooperative observers whose observation is seldom made at midnight as is done at the first-order stations. These will be termed the cooperative means.

Two different comparisons were then made. The first comparison was to see how closely the true daily mean was estimated by the first-order and the cooperative means. The second comparison was between the first-order and the cooperative means.

3. Variation with observation time

a. Mean temperature

Fig. 1 shows that on an annual average basis the least difference from the true mean (that is, the first-

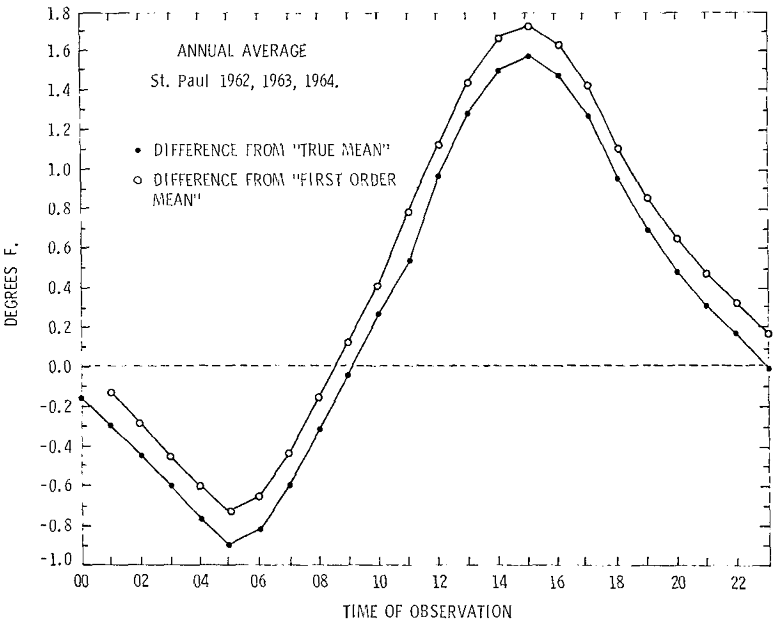

Fig. 1. The average annual variation of mean daily temperatures obtained at different hours of the day about the true daily mean and the first-order mean temperatures (first-order or cooperative means minus true mean, and the cooperative mean minus the first-order mean).

order mean or cooperative mean minus the true daily mean; and the cooperative mean minus the first-order mean) occurred with the 2300 observation. The next most favorable time was with the 0900 observation and then the midnight observation. Fig. 1 also shows that the mean daily temperatures calculated from observations made between 0000–0900 were lower than the true daily mean by as much as 0.9°F on an annual basis. It is evident that late forenoon, afternoon and evening observations result in mean daily temperatures greater than the true daily mean. It is also apparent from Fig. 1 that the poorest estimation of the true daily mean occurred with the 1500 observation, which resulted in a mean that on an annual basis averaged 1.6°F higher than the true daily mean.

The magnitude and sign of the departure from the true daily mean are functions of what point in time the observation is taken with respect to the daily heating cycle. For example, an afternoon observation made on a warm day followed by a cool day results in two high maxima, one recorded on the warm day and one recorded on the next day. One cool night would result in just one low minimum being recorded. In contrast, with an early morning observation the occurrence of one cool morning would result in two low minima being recorded, one on the cool day and one on the following day. One warm day followed by a cool one would produce only one high maximum with an early morning observation. Since midnight observations show relatively little departure from the true daily mean (Fig. 1), the above-described relationship will also be true for the departures of the cooperative means from the first-order means.

Fig. 1 also shows that similar variations were found between the cooperative means of observations made at any hour of the day and the midnight or first-order observation mean which they hopefully duplicate. It may be seen that on an annual basis a first-order station's midnight observation will be most nearly duplicated by the 0100 and the 0900 observations. As in the comparison with the true daily mean the 1500 observation gave the greatest annual difference, averaging more than 1.7°F higher than the first-order mean.

Once a specific observation time has been selected and a temperature record established, a change in observation time is to be avoided. It is apparent from Fig. 1 that a time change will have a considerable influence upon the mean temperature. The greatest difference on an annual basis would occur if a 0500 observation is changed to 1500. This would result in a change of about 2.5°F from either the true daily mean or the first-order mean. Other observation time changes, although not as radical in result, would serve to decrease the stability of the record as noted by Mitchell (1958).

Fig. 2 shows in detail how the mean daily temperature obtained at the 23 different observation hours varies from the first-order mean during each month. The variation from the true daily mean is very similar and therefore not shown. The variations shown in Fig. 2

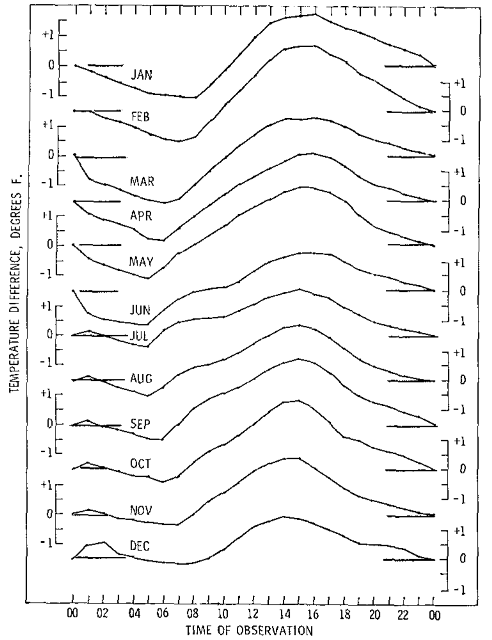

FIG. 2. The average monthly variation of mean daily temperatures obtained at different hours of the day about the first-order mean temperatures (cooperative means minus first-order means).

parallel rather closely the daily heating cycle. The occurrence of the largest negative deviations follow more or less the hour of sunrise, as shown in Table 1, while the largest monthly positive deviations only vary from the 1400 to the 1600 observation. The range between the positive and negative average hourly deviations from the first-order mean was greatest in February at 3.2°F. The smallest, in December, equalled 1.6°F.

Since many observations, perhaps the majority, are taken anywhere from 0600 to 0900, or even at local sunrise, particular attention should be paid to the variation of the means taken at these times. This is shown in Fig. 2 but in greater detail in Figs. 3 and 4. The early morning observations show a distinct trend of decreasing negative values that extend from about March into September and October. The afternoon observation times give values consistently greater than either the true daily mean (Fig. 3) or the first-order mean (Fig. 4), but show no trend as do the forenoon observation derived means.

TABLE 1. Largest positive and negative mean monthly deviations from the first-order mean and the observation hour in which they occurred.

Month	Negative deviation (°F)	Observation hour	Positive deviation (°F)	Observation hour	Range (°F)
January	1.1	0800	1.7	1500	2.8
February	1.0	0700	2.2	1500	3.2
March	1.6	0600	1.3	1600	2.9
April	1.3	0600	1.6	1600	2.9
May	1.1	0500	1.9	1500	3.0
June	1.1	0500	1.3	1600	2.4
July	0.4	0500	1.5	1500	1.9
August	0.5	0500	1.8	1500	2.3
September	0.5	0600	2.2	1500	2.7
October	0.5	0600	2.3	1400	2.8
November	0.4	0600	1.8	1400	2.2
December	0.2	0700	1.4	1400	1.6

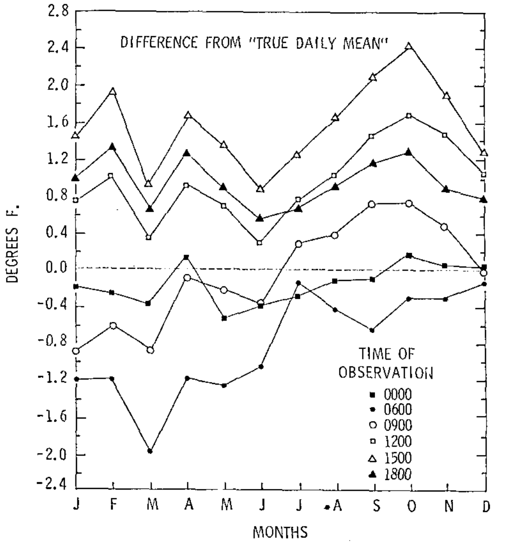

FIG. 3. Average montly difference between mean daily temperatures obtained at the indicated observation times and the true daily mean.

In Fig. 3 a marked minimum in the means obtained from the observations is shown to have occurred in March and a marked maximum in October. The October afternoon observation maxima may be explained by the fact that temperatures are generally

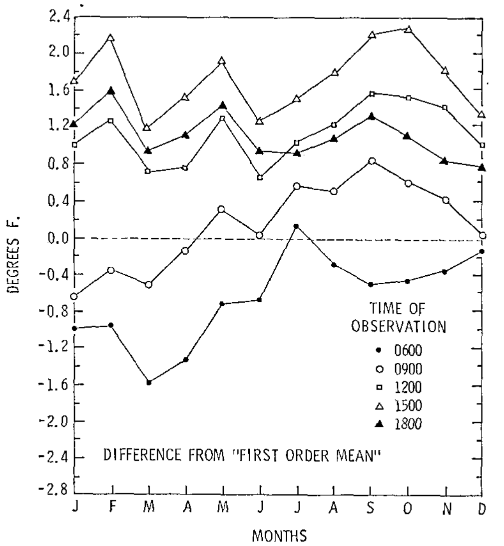

FIG. 4. Average monthly difference between mean daily temperatures obtained at the indicated observation times and the first-order mean.

declining most rapidly throughout this month. Thus when the thermometers are reset after the observation the current reading is frequently the maximum for the next day. By the same token the low March values occurred because at this time of year temperatures are generally increasing at the maximum rate for the year and the minimum reading is often the temperature at which the minimum thermometer was set at the observation of the previous day.

b. Heating degree days and growing degree days.

Differences in the mean temperature can assume major importance when viewed over several months as is the case when applied to HDD and GDD. Fig. 5 shows suggested corrections that can be applied to the HDD and GDD calculated from temperatures obtained at various observation times during the day. The HDD and GDD calculations upon which Fig. 5 is based were made from the formulas described in the Introduction to this paper and not upon the procedure used by the National Weather Service. The T_b used is 65°F and 50°F for the HDD and GDD, respectively. In Fig. 5 reference is made only to the first-order mean since no regularly reporting stations use the true daily mean in recording mean temperatures. In general, since an observation made before 0900 results in a mean temperature lower than the first-order mean, fewer HDD are obtained. Thus a correction must be added to the HDD total to bring it into agreement with the number calculated using the first-order mean. For example, about 170 HDD should be added to the annual HDD total obtained using 0700 observation data. In contrast, since higher mean temperatures are obtained in a late forenoon, afternoon or evening observation than with the first-order mean midnight observation, then a negative correction is required. As an example a 1700 observation requires a reduction of almost 400 HDD from the annual total to agree with that obtained by using the midnight observation. Almost 500 HDD should be subtracted from the HDD calculated from a 1500 observation.

In the case of GDD appreciable differences also occur between the seasonal totals calculated from daily means based upon different observation hours. These differences in GDD totals more than equal some of the proposed hybrid corn varietal differences in GDD required to reach maturity. For example, a seasonal (May–September) total difference of more than 300 GDD could result between two sites simply because of different observation times. This is equivalent to more than 13% of the May–September 50°F base temperature and about 7% of the 40°F base temperature GDD seasons in the upper Midwest.

Similarly in the case of a heating season total of HDD a difference of 700 HDD could result if a station recording temperatures at 0600 was compared with one recording at 1500. This difference amounts to more than 8% of the annual normal HDD for Minneapolis-St. Paul.

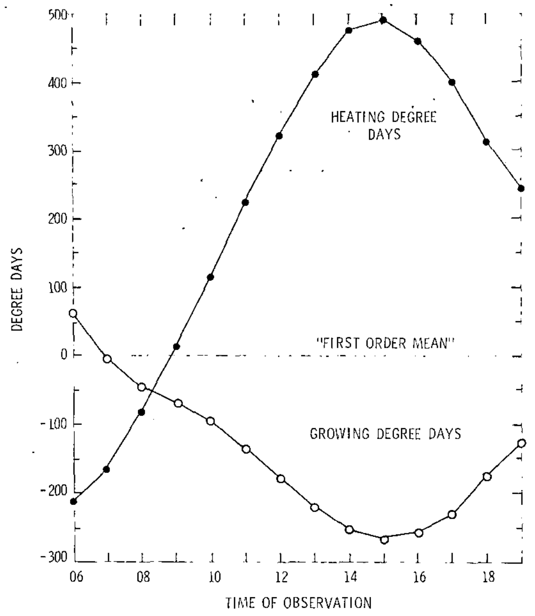

FIG. 5. Suggested corrections for total heating season Heating Degree Days (T_b=65°F) and May–September Growing Degree Days (T_b= 50°F) derived from mean daily temperatures obtained from 0600–1900 hour observations.

The variations about the first-order mean cited here hold for a good share of the upper Midwest based upon results from similar types of studies (Mitchell, 1958; Weaver and Miller, 1970). The diurnal and seasonal variation of temperature, i.e., the degree of continentality of the climate, governs the amount of variation that is found.

4. Conclusions

In a continental climate such as experienced at St. Paul, the time that the daily temperature observation is taken is of considerable importance with respect to comparability of the data. It was found that mean daily temperatures may vary as much as 1.7°F on an annual basis from the first-order station's midnight observation. In October the deviation may be as much as 2.3°F from the first-order mean. On an annual basis early morning observations show a negative deviation from the first-order mean while observations made in late forenoon, afternoon and evening result in mean daily temperatures that deviate positively.

A change in observation time from 0600 to 1500, for example, can result in an artificial deviation in the St. Paul station's mean annual temperature by 2.3°F from the first-order station's mean. In the month of February this same change would result in a 3.2°F deviation of the daily mean. In July a deviation of only about 1.6°F would result.

Such changes in the mean daily temperature as just cited have serious consequences upon temperature-derived quantities such as HDD and GDD. Since these two quantities are accumulated over at least five months of the year in many parts of the country, the effect is magnified. For example, the heating season at St. Paul, approximately September through May, can differ by 700 HDD simply by shifting the observation time from 0600 to 1500. Further, the 1500 observation time results in a deviation of nearly 500 HDD from the station's seasonal total. Variations of a greater proportional magnitude can occur to the GDD totals with consequences of equal concern.

Based upon results of this study it is suggested that care be taken in the application of the recently issued 1941-70 normals (NOAA, 1973) of temperature and HDD for both first-order and cooperative stations which have not been corrected for the observation time bias.

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