**4.3** Searching for the Daily Mean Temperature

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## 1. INTRODUCTION

From the beginning of climatological study, there was an acceptance that the mean of twenty-four hourly temperature observations made during a calendar day was the true daily mean. The true daily mean was to be used to calculate the monthly and annual temperature means used by climatologists. The lack of the required hourly observations precluded such calculations for most climate stations. Numerous surrogate methods of approximating the true daily mean were used. This paper reports the results of an examination of twenty-five of those methods that compared the accuracy of each with the true daily mean.

### 1.1 Background

The National Climatic Data Center's Climate Database Modernization Program has scanned and indexed all nineteenth century weather observation forms from the United States that are held by the National Archives. Digitization of those records is underway and data from more than 280 stations have been keyed. One of the issues that arose is the variance in observation times. Another issue is the varied methods used to calculate the daily mean temperature.

The Army Surgeon General issued instructions in 1818 to his climate network to determine the daily mean by adding the temperature readings at 7 a.m., 2 p.m., and 9 p.m. and dividing the sum by three. That method was the one that had been used by the Meteorological Society in Mannheim, Germany beginning in 1781. The climate networks, that formed subsequently, prescribed formulas that were believed to approximate the true daily mean temperature. The degree of accuracy that was considered to be acceptable varied (Conner, 2008).

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The sum of the maximum and minimum temperatures divided by two produced a daily mean that has been in use since it was prescribed by the Weather Bureau beginning in 1925. That prescription was made more as a matter of convenience rather than of need at a time when it was possible for the Weather Bureau stations to make hourly observations. Since then, that method of approximating the true daily mean has persisted even as automated observations eliminated convenience as a factor.

There are at least two reasons for examining the methods of determining the daily mean. One is to identify the magnitude of bias induced by each formula used in calculating the daily mean. The second is to identify the magnitude of the bias that resulted in the monthly means.

## 2. DEFINITIONS

### 2.1 True Daily Mean Temperature

The American Meteorological Society's glossary of meteorology (Glickman, 2000) defines mean daily temperature: "Mean of the temperatures observed at 24 equidistant times in the course of a continuous 24-hour period (normally the mean solar day from midnight to midnight according to the zonal time of the station)." In this paper, that definition is used for the true daily mean.

### 2.2 True Monthly Mean Temperature

The American Meteorological Society's glossary of meteorology defines the true mean temperature: "As adopted by the International Meteorological Organization, a monthly or annual mean of air temperature based upon hourly observations at a given place, or on some combination of less frequent observations designed to represent this mean as nearly as possible." That definition is so broad that it encompasses all surrogate monthly means. Therefore, the term "True Monthly Mean Temperature" as used in this paper will refer to the monthly mean of the true daily means.

## 3. Methodology

The original observational records, related metadata, station histories, and supporting documents were examined to identify twenty-five surrogate formulas that had been used to approximate the true daily mean. Each of those formulas was applied to hourly data recorded for one twelve month period at one station of the Kentucky Mesonet. Hourly temperature data were recorded as the average of samples taken by three platinum resistance thermometers housed within an aspirated shield at three-second intervals for the previous five minutes ending at the top of each hour. Surrogate daily means, rounded to two decimal places were calculated in an S-Plus script using each formula and, from them, monthly means were derived. The resultant surrogate monthly means produced by each formula were compared to the true monthly mean derived from the hourly observations. The deviations were the basis for subsequent analyses.

## 4. RESULTS

As others found (McAdie, 1891 and Bigelow, 1909), there were significant differences in the means produced by surrogate formulas. Twenty-five of those formulas (F1 through F25) are evaluated here. The formulas used the hours of observation (h1 through h24) or the extreme maximum (xmax) and minimum (xmin) temperatures. For this study, they were divided into the following five groups to assess each one's accuracy in approximating the true daily mean.

### 4.1 True Monthly Mean Formula

Hourly data were the average of samples taken at three-second intervals for the previous five minutes ending at the top of each hour. The true daily mean was found by dividing those hourly values by 24. The true monthly mean was found by dividing the sum of the true daily means by the number of days in the month. The annual mean was the mean of those twelve values.

### 4.2. Paired Observations Formulas

One widely held belief during the nineteenth century was that the mean of homonymous observation times would produce an acceptable approximation of the true daily mean. The symmetry was appealing and the pairs offered convenient observation times.

F2 = (h10+h22)/2
F9 = (h06+h18)/2
F17= (h07+h19)/2
F19= (h08+h20)/2
F21= (h09+h21)/2

Of the five daily mean formulas that used paired times, four produced annual means that were from 0.30˚F (0.2˚C) to 1.50˚F (0.8˚C) colder than the true mean. The exception was the 10 a.m. - 10 p.m. pair (F2) advocated in England in 1831. That formula produced an annual mean that was 0.33˚F (0.2˚C) above the true mean.

The formula (F19) used by used by the Signal Service and the Weather Bureau for fifty-five years from 1870 through 1925 is of particular interest. It used the 8 a.m. and 8 p.m. pair and produced an annual mean that was 0.98˚F (0.54˚C) colder than the true mean in this study.

### 4.3 Triad Observations Formulas

Twelve different triad formulas used three observations each day to calculate the daily mean. Nine of the resultant annual means were from 0.07˚F (0.02˚C) to 2.57˚F (1.4˚C) warmer than the true mean; three were from 0.04˚F (0.02˚C) to 0.54˚ (0.3˚C) colder. Between 1818 and 1855, the Surgeon General used the Mannheim method to add the 7a.m., 2 p.m., and 9 p.m. observations and divide by three for the daily mean. That formula produced an annual mean 0.65˚F (0.4˚C) warmer than the true mean.

F5 = (h06+h12+h17)/3
F6 = (h06+h12+h19)/3
F7 = (h06+h14+h21)/3
F8 = (h06+h14+h22)/3
F10= (h07+h12+h18)/3
F11= (h07+h13+h21)/3
F12= (h07+h13+h22)/3
F14= (h07+h14+h20)/3
F15= (h07+h14+h21)/3
F16= (h07+h15+h23)/3
F18= (h08+h14+h20)/3
F20= (h09+h15+h21)/3

### 4.4. Combined Observations Formulas

Two of the four formulas for the daily mean, modified to more closely approximate the true mean, produced annual means that were only 0.01˚F (0.006˚C) warmer than the true mean. One of those was the Smithsonian Institution that used its formula (the sum of 7 a.m., 2 p.m., and two times the 9 p.m. reading, divided by four) from 1850 to 1870. The Surgeon General also used the Smithsonian formula from 1855 to 1888.

The Signal Service's use of six observations at an interval of four hours each day, added and divided by six, also produced an accurate approximation. However, the time demands on observers caused it to be abandoned after one year of use.

The other two formulas produced annual means that were warmer than the true mean. The one used by the New York Academies from 1825 to 1850 was 0.65˚F (0.4˚C) warmer and the other, used for one year by the Surgeon General, was 0.24˚F (0.2˚C) warmer.

F1 = (h07+h14+h14+h21+h21+h31)/6
F3 = (h03+h07+h11+h15+h19+h23)/6
F4 = (h03+h09+h15+h21)/4
F13= (h07+h14+h21+h21)/4

**4.5 Maximum-Minimum Formula**

Maximum and minimum thermometers were first used to capture the extremes of the day; recorded and reported but not used in daily mean calculations. A formula that allowed reading of those thermometers just once per day at a time chosen by the observer, offered an irresistible convenience to them. Just add the maximum and minimum and divide by two to approximate the daily mean. That formula (F22) was adopted by the Weather Bureau in 1926 and has been used since that time. In this study, it's annual mean was 0.15˚F (0.08˚C) colder than the true man.

Three other methods were proposed to modify that formula but none were more accurate and none found acceptance. All three also produced cooler annual means; from 0.22˚F (0.1˚C) to 1.37˚F (0.8˚C) cooler than the true mean.

F22= (xmin+xmax)/2
F23= (xmin+h15])/2
F24= (xmin+xmax+h08+h20)/4
F25= (xmin+xmax+h09+h21)/4

**5. DISCUSSION**

The most recent hourly data, June 2007 through May 2008, were used in this study. Data came from a twelve-month period that had an annual mean temperature of 58.7˚F (14.8˚C). Temperature records from the Bowling Green, Kentucky airport, located approximately 3.5 miles northeast of the Mesonet station, documented the study period as the 27th warmest of 110 years, with August 2007 establishing a record as the warmest of any month on record. However, all the comparisons made with all the formulas were made against the true daily mean, not against the normal temperature. Therefore, the data's departure from normal was not a factor in the results that are discussed below.

**5.1 Seasonal Deviations in Formulas' Results**

Each formula varied inconsistently from the true mean by month and by season, but some more than others.

Four of the Paired Formulas means were colder than the true mean in all seasons. The fifth (F2) formula, the 10 a.m.- 10 p.m. pair, was warmer in all seasons except for the winter when it was colder during each of those three months. Even then, it was from 0.33˚ (0.2˚C) to 0.80˚F (0.4˚C) warmer than the other paired formulas, perhaps the reason that none of the climate networks adopted it.

Of the twelve triad formulas, eight were warmer in all months and in all seasons. Two were colder in all but winter. Both of them used 6 a.m. for the morning reading and either 9 p.m. or 10 p.m. for the evening reading. The longer time before the morning minimum and after the afternoon maximum may be the explanation. The other two were colder in all but spring and summer. Both made evening observations at either 10 p.m. or 11 p.m., well after the nightfall.

The four combination formulas had less seasonal variation than the other formula groups. The formula used by the Smithsonian ((7 a.m. + 2 p.m. + 2 times 9 p.m.)/4) ranged from an average of just 0.20˚F (0.1˚C) warmer in summer to 0.24˚F (0.1˚C) colder in the fall.

The formula employed since 1925 (sum of the maximum and minimum divided by two) produced means that varied from 0.73˚F (0.4˚C) colder in April to 0.36˚F (0.2˚C) warmer in August.

**5.2 Annual Deviations in Formulas' Results**

Four of the five paired formulas produced annual means that were from 0.30˚F (0.2˚C) to 1.53˚F (0.9˚C) colder than the true annual mean while the fifth (used by the Signal Service and Weather Bureau from 1870 to 1925) was 0.59˚F (0.3˚C) warmer that it was.

The annual means derived from the triad formulas had nine that were from 0.07˚F (0.04˚C) to 2.57˚F (1.4˚C) warmer than the true annual mean. The one that was used by the Surgeon General was 0.65˚F (0.4˚C) warmer. Of the other three results, the variance was from 0.04˚F (0.02˚C) to 0.54˚F (0.3˚C) colder than the true mean.

The combination formula used by the Smithsonian produced an annual mean that varied from the true annual mean by just 0.01˚F (0.01˚C) warmer, the best of the 25 formulas examined. The range of variation among the combination formulas was from 2.57˚F (1.4˚C) warmer from the formula proposed by Drew (1860) to 1.53˚F (0.9˚C) colder from the formula proposed by Buijs-Ballot (1872), the two extremes among all 25 formulas examined in this study.

Four formulas used the maximum and minimum temperatures. All were up to 0.58˚F (0.3˚C) colder than the true annual mean. In our evaluation, the formula used by the Weather Bureau and the National Weather Service since 1925 produced an annual mean that was just 0.15F (0.09˚C) colder than the true mean. Previous contemporaneous studies in the nineteenth century had found that its formula (sum of maximum and minimum divided by two) would produce annual means about 0.50˚F (0.3˚C) warmer than the true mean (Hazen, 1890). Our result is likely due to the larger positive bias in daily maximum temperatures measured in a Cotton Region Shelter than in an aspirate shield. (Hubbard and Lin, 2002)

## 6. CONCLUSIONS

Climate networks prescribed times for their observers to make temperature measurements. Those times were accompanied by a formula for calculating the daily mean. Times and formulas combined to produce an approximation of the true daily mean.

The digital data now being accumulated through the Climate Database Modernization Program will offer the first opportunity for climatologists to understand nineteenth century climate using actual observations. To avoid misunderstanding, each station's data should be evaluated considering the times of observation and the formula it used at that location.

Clearly, the times of observation and the formula used will require that adjustments to some stations' data be made to compensate for the variations identified in this study. The technique used herein should be applied to other stations that have or had hourly temperature data for comparison with their ancestor stations that have nineteenth century temperature data.

A follow-on study is being planned for such stations that are suitably distributed geographically and have suitable periods of record. It will determine if there are consistent results from the formulas, relative to the true mean, when used at stations in different locations, exposures, and climatic regions. The objective is to determine what adjustments to the data could to be made to more closely estimate the daily mean at a nineteenth century stations.

Meanwhile, the preliminary results shown in this paper indicate that the times and formulas used by the Surgeon General's and Smithsonian Institute's stations in most years may be an acceptable approximation of the true daily mean. The maximum-minimum formula used by the Weather Bureau and National Weather Service after 1925 may be acceptable too, although not as close.

In any case, the times and formulas should be considered when nineteenth century data are used.

## 7. REFERENCES


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