Effect of Changing Observation Time on Mean Temperature

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Abstract

Hourly temperature data for eight first-order stations in the United States have been used to determine the effect of observation time on mean temperature derived in the usual way from 24-hr maximum and minimum values. Results, presented in detail for exemplary stations and observation times, show that the greatest possible effect on temperature of arbitrary time changes varies with place and season between less than 1/2F and more than 3F at the stations investigated. A means of estimating both this maximum effect, and the effect of any specific time change, at an arbitrary location is presented. It is concluded that historical temperature data based on evening observations are apt to be more homogeneous than those based on morning observations. An example of the effect of typical observation time changes on a secular temperature series is presented, and stresses the value of thorough documentation of observation time by each cooperative observer.

1. Introduction

In the United States, mean temperatures are customarily derived from half the sum of the daily maximum and minimum temperatures occurring in the 24-hr period ending at observation time. In the case of first-order Weather Bureau stations, this observation time nearly coincides with midnight. In the case of the thousands of cooperative stations throughout the country, however, each voluntary observer is granted wide latitude in selecting an observation time compatible with his personal routine and with his own use of the climatological data. Most observers take their observations either in the early morning (near 0800), in the late afternoon (near 1700), or at the seasonally varying hour of sunset. Nearly all of them share an understandable reluctance to read their extreme thermometers at midnight.

That differences in observation time produce systematic biases in mean temperature derived from daily maxima and minima has occasionally been noted in the literature for many years. An oft quoted study, and perhaps the earliest, was that of Ellis [1], who compared mean temperatures based upon two standard observation times (0900 and 2100 GMT) with those based upon midnight observations, at Greenwich Observatory, England. Ellis found average discrepancies of about 0.2F, ranging from near zero in the winter season to a maximum of 0.4–0.5F in the spring and autumn, midnight readings being systematically lower. Other authors, in paralleling the work of Ellis for other isolated locations and similar selections of observation time, have verified the geographical prevalence of such temperature discrepancies, but mostly have turned up with larger average magnitude. Donnel [2], Hartzell [3], and Rumbaugh [4] each found that mean temperatures based upon late afternoon or evening observations at certain stations in the United States are typically about 1.0F higher than those based upon local midnight observations, and of the order of 2F higher in certain months of the year. On the basis of a worldwide selection of twelve stations (none in the United States), representing diverse climates, Hajósy [5] found maximum discrepancies comparable to those of Ellis [1] between similar observation times (0800, 2000, and midnight LST [1]). That author, however, concerned himself only with January and July, whereas the largest discrepancies are frequently to be found in other months. Other studies [6, 7], dealing with closely allied problems, have indirectly verified that highly significant temperature differences arise from changes in observation time.

It must be remarked that all these studies have involved either a very limited geographical area or a very small choice of observation times, or both. This fact rather precludes useful quantitative generalizations of the influence of observation

[1] Local Standard Time.

time on derived mean temperature. Moreover, it was the general intent of the foregoing authors either to evaluate the extent of incompatibility between the mean temperatures of different stations wrought by grossly dissimilar observation times at each, or to select an observation time which approximates the true 24-hr mean better than certain other times. The intent of the present writer, on the other hand, is primarily to evaluate the effect of arbitrarily small *changes* in observation time at a single station on the homogeneity of its climatological temperature records. This purpose, in turn, is not well served by the data of the foregoing studies.

Many specialized applications of cooperative station data in modern climatology require attention to problems of this kind. Among these applications is the study of climatic change in which a failure to take account of artificially disturbing influences in climatological time series can frequently lead to errors as large as the climatic variations themselves [8].

2. Problem

The typical long-record cooperative station has been manned during its history by a succession of observers, sometimes succeeding generations of a single family. Many changes of observer have coincided with changes in station location, but others evidently have not [9]. In the latter instances, as in the former, it is reasonable to expect a discontinuity of record, inasmuch as no two observers are likely to have identical observing schedules. There is also the possibility, of course, that an observer finds it necessary to vary his observation time at regular or irregular intervals, however slightly, and not be disposed to note the fact on his observation forms. The essential question to be answered is: what is the typical range of error introduced into climatological temperature records by these events? In certain (rare) cases where observation time changes are well documented, the answer may allow the records to be reduced confidently to a common observation time. In any case, observers can be made aware of the penalty if undocumented changes of observation time are not kept to a minimum in the future, and climatologists can be given a more realistic impression of the homogeneity of historical data.

3. Data and procedure

In the present study, a selection of first-order airways stations was made according to the following criteria:

1. The stations were to be located in diverse climatic regions of the United States.
2. Hourly temperatures were to be available for each station in punched-card form since circa 1948.
3. Each station was to possess a ground thermometer exposure.

The eight stations selected are shown in tables 1–3 following. At each of these stations and in alternate *calendar months* (January, March, May, *etc.*), two years of record since 1948 were chosen on the basis of their having near-normal monthly mean temperature. That is, for each station and alternate calendar month, two nonconsecutive month-long series of hourly temperatures were obtained, each of which may be referred to as a *specific month* (January 1949, March 1952, *etc.*).

Then, in each of these specific months, the average of the highest and lowest hourly temperatures in the 24 hr ending with *each* hour was in effect compared with the average of the highest and lowest hourly temperatures in the 24 hr ending with (the previous) midnight. Midnight, in turn, was taken as the 2330 LST observation time. The temperature differences were then averaged over the month for each hour of the day, and summarized by station and calendar month. The procedure may be stated more concisely as follows.

For a particular day at a particular station, the difference in mean temperature as derived for observation time h and as derived for midnight h_0 can be written

$$\left.\begin{aligned} \Delta T_h &= \tfrac{1}{2}(M_h - M_{h_0} + m_h - m_{h_0}), \\ h &= 0030, 0130, \cdots, 2330 \text{ (hrs LST)}, \end{aligned}\right\}, \quad (1)$$

where the M's and m's are the daily maximum and minimum temperatures, respectively. We require the average value of ΔT_h for each observation time h and calendar month μ. This average is merely

$$\overline{\Delta T(\mu,h)} = \frac{1}{n(N-1)} \sum_{j=1}^{n} \sum_{i=1}^{N-1} (\Delta T_h)_{ij}, \quad (2)$$

where n is the number of specific months in calendar month μ, and N is the number of days in each month μ. In the present case, $\mu =$ January, March, *etc.*, and $n = 2$.

Inspection of the results (to be discussed presently) confirmed that use of (2) with truncated month-long time series of temperature can in many instances produce an extraneous drift in the values of $\overline{\Delta T_h}$ as h varies from 0030 to 2230 LST. The magnitude of this drift is essentially proportional to the difference in mean temperature between the first and last day of each specific month of data, and tends to be largest during the seasons of most rapid change in the annual temperature march. This error, however, can readily be eliminated from the final results by a correction which varies linearly through the range of h, and whose magnitude is established for each month and station by graphical alignment of the values of $\overline{\Delta T_h}$ before and after midnight. It has in fact been removed from the following results.

Each 24-hr period should be represented by 25 consecutive hourly temperatures; in the present computations, however, only 24 values were used in error. This fact has probably resulted in about a 10-percent underestimation of the maximum effect (D) of changing observation time on mean temperature (see below), but in a considerably lesser degree of underestimation of magnitude in all other results of this paper.[2]

The writer is further satisfied that, in the present context, use of the highest and lowest hourly temperatures in a 24-hr period, in lieu of the "true" maximum and minimum thermometer readings for the same period, is of trivial consequence. In support of this statement, reference is made to the data used in a pertinent study [10], subsequently extended, for Elmendorf Air Force Base, Alaska, where intrahourly temperature variability is not unlike that in the United States. Based on an analysis of eight months of thermogram traces, it was found that the extreme hourly temperatures agreed with the "true" extremes within 1F about 70 percent of the time, and within 2F about 95 percent of the time (the hourly temperatures always lying the closer to the daily mean). Use of hourly data had the effect of reducing the mean daily range by about 0.8F in all seasons,[3] but the times of extreme temperature, as fixed by the two systems of measurement, only rarely disagreed by more than 1/2-hr. Hence, one can conclude that the error introduced by the use of hourly temperatures is comparable to the error in the mean daily range: less than five-percent underestimation. It is additive to the error described in the foregoing paragraph.

4. Results

The hourly values of ΔT_h for each of the eight stations and alternate calendar months were obtained by use of the computing facilities of the National Weather Records Center in Asheville, N. C. These were then corrected for time series truncation as previously described.

In illustration of the general results, difference curves of mean temperature for three of the eight stations are shown in fig. 1. The curves for Tampa have been included because, among the eight stations investigated, Tampa showed the smallest variation of mean temperature due to varying time of observation. Similarly, Bismarck showed the largest variation among the selected stations in most months, and Philadelphia showed a rather typical magnitude of variation.

The temperature difference curves rather closely resemble the curves of diurnal temperature change itself, and exhibit an especially rapid change in the two or three hours after sunrise. The greatest difference in derived mean temperature (for each month and station), defined as D, is seen to involve the hours near sunrise (the normal time of minimum temperature) and the middle of the afternoon (the normal time of maximum temperature). The magnitude of D varied in this study from 0.3F in July at Tampa to a maximum of 3.4F in January and November at Austin and in March at Columbus.

As it was stated previously, the aim of this study was not to select an observation time which allows the best approximation of the true 24-hr means, but rather to evaluate the extent to which changes in observation time threaten the homogeneity of a climatological temperature record. From the first viewpoint, fig. 1 lends justification for choosing an observation time near 0800 LST,

[2] This conclusion is based upon the following reasoning. In general, D would be affected when two conditions are concurrently met: a. the maximum temperature of the preceding day was higher than that of the current day, or the minimum of the preceding day was lower than that of the current day (these circumstances tend to be mutually exclusive); b. the time of extreme (maximum or minimum) temperature on the previous day was not later than the normal time of that extreme. Both conditions together are estimated to occur in about 30 percent of days during winter and summer and in about 40 percent of days during spring and fall. These percentage probabilities can be multiplied by the typical magnitude of difference between an extreme hourly temperature in a day and the temperature one hour later, determined from empirical and trigonometric reasoning seldom to exceed five percent of the daily range R. This product is a correction to D which may then be compared with the computed values of D below, and indicates that the latter are underestimated by about ten percent. Considering the sampling approach which forms the basis of the present study, this error is acceptably small though systematic.

[3] The monthly mean temperature, derived in the usual way, was affected less than 0.3F in all seasons, mostly being overestimated in the winter season by the use of hourly data.

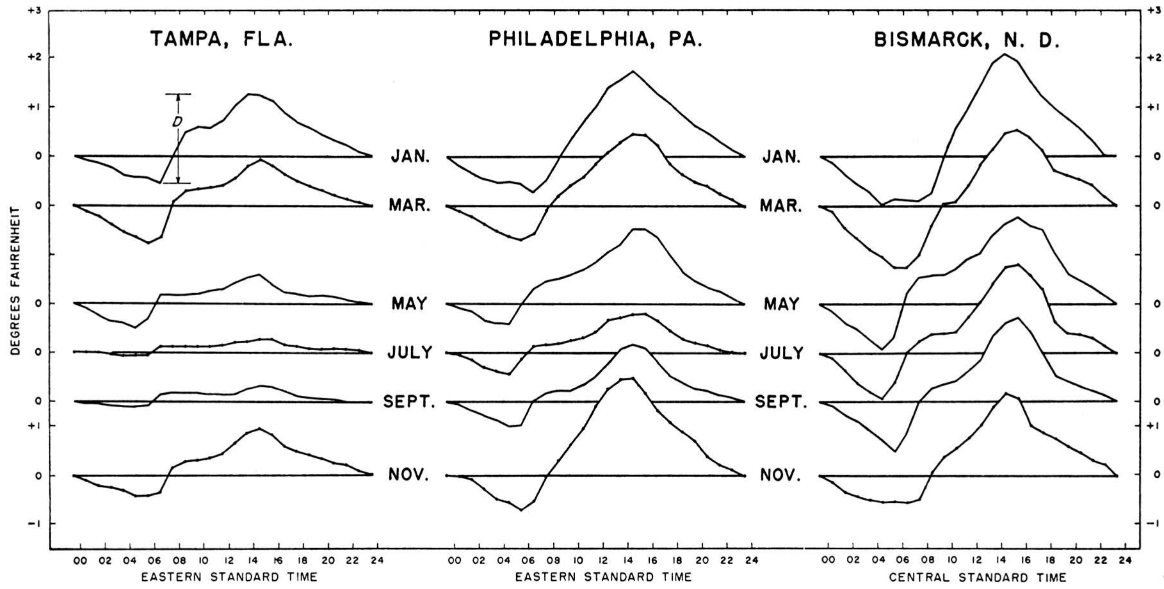

FIG. 1. Variation of derived mean temperature with observation time, relative to the mean temperature based on midnight (2330 LST) observations. Data effectively based on two years of hourly temperatures and corrected for time series truncation (see text). The greatest possible discrepancy in mean temperature resulting from changes in observation time at a given station and month is denoted by *D*.

as did Rumbaugh [4], as optimum for cooperative stations. From the second viewpoint, however, 0800 LST seems to be a very poor choice of observation time, and, especially in winter, evening observations are clearly to be preferred.

Tables 1, 2, and 3 illustrate the typical magnitude of slippage of temperature means resulting from certain shifts in observation time. A changeover from morning to evening observations (table 1) is seen to have a considerable influence on mean temperature. The injudicious statistical combination of a.m. and p.m. observations at one station is, therefore, hardly to be recommended as a general practice.

Tables 2 and 3 indicate that a minor change in observation time of one hour during the morning or the evening, respectively, can have a remarkably large effect on mean temperature in some regions and seasons. The largest effects occur in the first few hours after sunrise.

TABLE 1. Effect of change from morning to afternoon observation. Shift of derived mean temperature due to change of observation time from 0730 to 1830 LST.*

Station	Month					
	Jan.	March	May	July	Sep.	Nov.
Austin, Tex.	2.2	1.3	0.1	0.1	0.2	1.3
Bismarck, N. Dak.	1.9	1.6	0.5	0.4	0.6	1.3
Columbus, Ohio	2.2	2.1	0.7	0.2	0.3	1.0
Denver, Colo.	0.8	0.5	0.3	0.2	0.4	0.7
Fresno, Calif.	0.3	0.2	0.1	0.0	0.1	0.0
Philadelphia, Pa.	1.3	0.7	0.2	0.1	0.2	0.9
Spokane, Wash.	0.5	0.4	0.0	0.2	−0.1	0.2
Tampa, Fla.	0.6	0.3	0.0	0.0	−0.1	0.2

* Based effectively on two years of data since 1948.

TABLE 2. Effect of one-hour change in time of morning observation. Shift of derived mean temperature due to change of observation time from 0630 to 0730 LST.*

Station	Month					
	Jan.	March	May	July	Sep.	Nov.
Austin, Tex.	0.1	0.7	0.3	0.0	0.1	1.0
Bismarck, N. Dak.	0.0	0.3	0.3	0.3	0.6	0.0
Columbus, Ohio	−0.1	0.6	0.4	0.2	0.7	0.3
Denver, Colo.	0.3	0.4	0.1	0.0	0.2	0.5
Fresno, Calif.	0.4	0.2	0.0	0.0	0.0	0.5
Philadelphia, Pa.	0.2	0.5	0.1	0.0	0.1	0.5
Spokane, Wash.	0.0	0.2	0.0	0.0	0.1	0.2
Tampa, Fla.	0.5	0.7	0.0	0.0	0.0	0.5

* Linear interpolation for intervening months is not recommended where observation time is near time of sunrise. Period of data as in table 1.

Table 3. Effect of one-hour change in time of afternoon observation. Shift of derived mean temperature due to change of observation time from 1730 to 1830 LST.*

Station	Month					
	Jan.	Mar.	May	July	Sep.	Nov.
Austin, Tex.	−0.4	−0.5	−0.1	−0.1	−0.1	−0.3
Bismarck, N. Dak.	−0.2	−0.4	−0.5	−0.6	−0.5	−0.2
Columbus, Ohio	−0.1	−0.3	−0.2	−0.1	−0.2	−0.1
Denver, Colo.	−0.2	−0.4	−0.3	−0.1	−0.2	−0.2
Fresno, Calif.	0.0	−0.1	−0.2	−0.1	−0.1	0.0
Philadelphia, Pa.	−0.2	−0.2	−0.3	−0.2	−0.2	−0.2
Spokane, Wash.	−0.1	−0.2	−0.4	−0.4	−0.2	−0.1
Tampa, Fla.	−0.1	−0.1	0.0	0.0	0.0	−0.1

* Period of data as in table 1.

5. Generalization of results

It was hoped that a means could be found to apply the foregoing results to the estimation of the effect of variable observation time at arbitrary stations in the United States. The eight stations used in this study are obviously inadequate to define the effect at all other stations by geographical interpolation. The greatest temperature difference D at each station and month, however, was found to be highly correlated with the mean daily temperature range R, with the mean cloudiness C, and with the mean interdiurnal temperature change I, for each station and month. As might be expected, the elements C and I are good indicators of the magnitude of day-to-day variability of the diurnal march of temperature, on which D essentially depends. These correlations allowed the use of graphical methods to yield an estimate for D,

$$D' = 0.05\,R\,(C + 0.30\,I), \qquad (3)$$

where R and I are in degrees F and C is on a scale from 0 to 1. Fig. 2 shows how the estimated D compares with the "measured" D for the dependent data. This correlation should be checked against independent data when these might become available.

In using (3), it should be kept in mind that D is the *greatest possible* average temperature difference which can result from arbitrarily varying the observation time, and not the difference arising from a time change of a given number of hours. In the preceding section, however, it was noted that $\overline{\Delta T_h}$ is algebraically least near sunrise (about one hour before) and greatest in the mid-

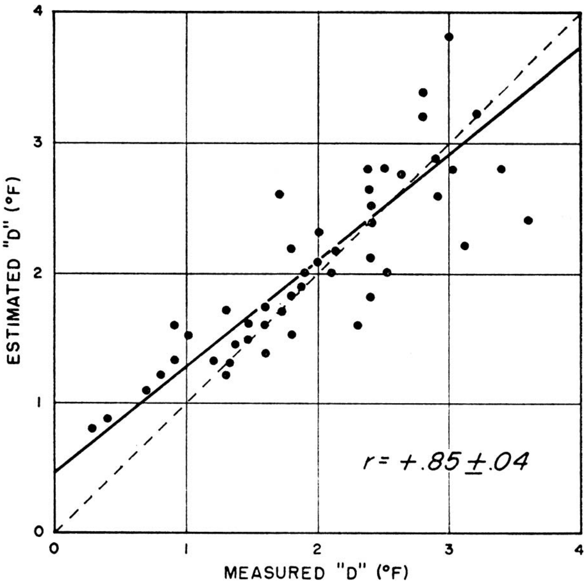

Fig. 2. Correlation between computed values of D, and estimated values of D based on (3) in text, where D is the maximum possible discrepancy in mean temperature resulting from observation time changes. Solid line is best fit, and dashed line is the equivalence assumed by use of (3).

afternoon (near 1400 LST). Hence, a crude estimate of the influence d of any specified shift Δh of observation time can be obtained by setting

$$d = D\,\Delta h/(15 - h_s) \qquad (4a)$$

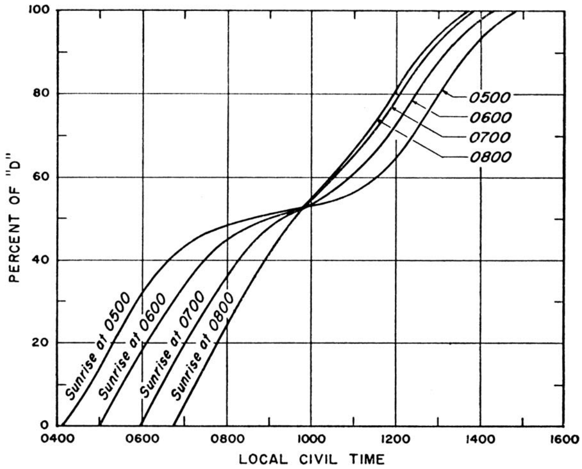

Fig. 3. Increase of derived mean temperature with increasingly later observation time, expressed as a percentage of D, for various times of sunrise. Once D is obtained, this graph can be used to estimate the effect of a change between any two a.m. observation times. Curves should be considered very approximate.

when the observation times lie between one hour before sunrise and 1400 LST, or

$$d = D\,\Delta h/(9 + h_s) \qquad (4b)$$

when the observations are between 1400 LST and one hour before sunrise. In these equations, h_s is the time of sunrise in hours after midnight LST, and Δh is likewise expressed in hours or decimal fractions thereof. The assumption of a uniform temperature change $\Delta(\overline{\Delta T_h})/\Delta t$, $t =$ time, from sunrise to midafternoon implied in (4a) is not very realistic for $\Delta h \leqslant 3$ hr, although the assumption of a uniform change in the period from mid-afternoon to sunrise, as in (4b), is rather more acceptable. A better estimate of d in the morning hours may be obtained by use of fig. 3, where the variation of $\overline{\Delta T_h}$ with time h, expressed as a fraction of D, is shown for various local times of sunrise.

Use of (3) in deriving D depends, of course, on the availability of monthly mean data for the daily range R, the cloudiness C, and the interdiurnal temperature change I. Suitable values of R and C for first-order stations may be obtained from [11] and [12] respectively, whence values for other stations may be satisfactorily interpolated. No monthly values of I, however, are known to the writer, published or otherwise, for more than a few stations and a few years of record in the United States. In most cases, it is possible to obtain a good estimate of I from charts of the standard deviation of monthly mean temperature [13], denoted as S_m, together with a reasonable assumption as to the 1-day lag autocorrelation coefficient of surface temperature, ρ_1. These quantities are related by the quasi-exact expression

$$I = [4n/3(1+\rho_1)]^{\frac{1}{2}}(1-\rho_1)S_m, \qquad (5)$$

where n is the number of days in the month. With good approximation, (5) may be simplified to

$$I = 4.7(1-\rho_1)S_m. \qquad (6)$$

Furthermore, in the United States, it is permissible to assign $\rho_1 = 0.70$ universally, although values near 0.85 would be better in the extreme northwestern United States in winter. Hence, we may use (3) in the modified form

$$D' = 0.05\,R(C + 0.35\,S_m) \qquad (7)$$

for routine computations, where each independent variable may be interpolated from existing published data. The effect of a specific change in observation time may then be estimated by use of (4a) or fig. 2, and/or (4b).

6. Hypothetical example

By way of conclusion, a practical example is given of the effect of variable observation time on a secular record. For this purpose, Philadelphia temperatures for January and July since 1904 were extracted from *Bulletin W* and *Local Climatological Data* publications of the United States Weather Bureau, and were *assumed* to represent homogeneous temperature series for a hypothetical cooperative station in that area, based upon observations taken at 0800 EST throughout the 52-yr period. It is true, of course, that the Philadelphia record is actually very inhomogeneous, and that observations were not commonly made at 0800 but these circumstances are, for our purpose, beside the point. Next, a hypothetical station history was drawn up for the Philadelphia "cooperative station," in which the observation time was allowed to vary occasionally in a manner typical of many cooperative stations, but in which no other kinds of inhomogeneity (station moves, instrumental defects, *etc.*) were considered. This station history is given in table 4. Then, by use of the appropriate curves in fig. 1, Philadelphia temperature series for January and July were adjusted to reflect the influence of variable observation time. Finally, in order to emphasize the consequences to long-period trends, ten-year moving averages of temperature were derived from the original series and the adjusted series in both calendar months. These, in turn, are shown in fig. 4 for comparison. One can see by this example how a secular trend or other long-period anomaly can be introduced into a temperature record by changing observation time, which is not climatically real.

TABLE 4. Hypothetical station history for Philadelphia (treated as a cooperative station), listing changes in time of temperature observation.

Inclusive dates	Time of observation	Effect of time change (° F) Jan.	Effect of time change (° F) Jul.	Reason for change
1904–15	0800 EST			
1916–18	0600 EST	−0.4	−0.1	Observer took new job.
1919–34	0700 EST	+0.1	+0.1	Observer at former job, but new schedule.
1935–40	1800 EST	+1.5	+0.2	Observer's son took over station, found evening observation more convenient.
1941–45	1800 EWT	+0.2	+0.2	War Time prevailed.
1946–date	1800 EST EDT	−0.2	0	Observer used Daylight Time in summer season, Standard Time otherwise.

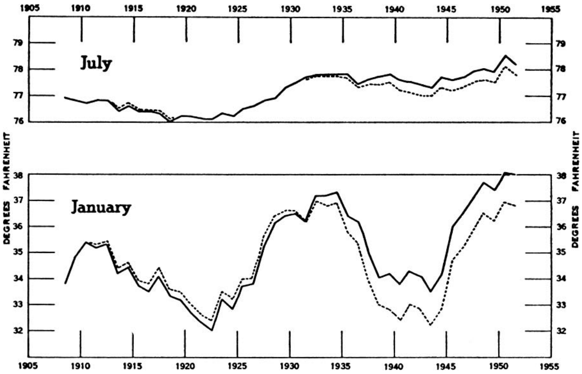

FIG. 4. Ten-year moving averages of temperature at a hypothetical cooperative station in Philadelphia, Pa., for January and July. Solid curves show secular variations of temperature corresponding to the station history given in table 4. Broken curves represent "homogeneous" series reduced to 0800 EST observation time. Data are based on observed Philadelphia temperatures which are *not* intrinsically homogeneous; the climatic trends themselves are therefore inaccurate.

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