Time of Observation Temperature Bias and "Climatic Change"[1]

LAWRENCE A. SCHAAL AND ROBERT F. DALE

Department of Agronomy, Purdue University, West Lafayette, Ind. 47907

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ABSTRACT

Historical changes in time of once daily maximum and minimum temperature observations at cooperative climatological stations from 1905 to 1975 have introduced a systematic bias in mean temperatures. Unless corrected, this bias may be interpreted incorrectly as climatic "cooling" and may also affect the assessment of agricultural production potential and fossil fuel needs. Maximum and minimum temperature data for two years from the National Weather Service station at Indianapolis International Airport were used to evaluate the differences between mean temperature obtained by terminating the 24 h period at the midnight observation and the mean temperatures obtained by terminating the 24 h period at 0700 and 1900 hours, typical observation times for AM and PM observing stations. The greatest mean temperature bias occurs in March when a 1900 observation day yields a monthly mean temperature 1.3°F above a midnight observation, and a 0700 observational day gives a −1.3°F bias. Since the number of AM observing stations in Indiana have increased from 10% of the total number of temperature stations in 1925 to 55% in 1975, the March mean temperature shows a decrease of 1.2°F in the last 40 years, solely because of the change in substation observational times. Unless the time of observation bias is considered, the mixture of AM and PM observations complicates interpretation of areal temperature anomaly patterns. This bias is accumulated in monthly, seasonal or annual values of the mean temperature-derived variables—heating degree days, cooling degree days and growing degree days—and may provide misleading information for applications in industry and agriculture.

1. Introduction

Daily mean temperatures are the most common measure of climatic seasonality. Heating degree days and cooling degree days, calculated from daily mean temperatures, have been heavily used by the heating and air conditioning industry in design studies and long-range planning of fuel needs, as well as in day-to-day routing of fuel supplies. Growing degree days, also derived from daily mean temperatures, are finding increasing agricultural use in predicting crop development and selecting proper crop varieties for an area.

The true mean temperature for an area, however, may contain biases caused by temperature measuring instrumentation, its location and the time of observation. Usually, changes in instrumentation are documented and its effects on temperature measurements are evaluated. For example, aspirated hygrothermometers were installed at first-order National Weather Service and Federal Aviation Authority stations in the late 1950's and early 1960's. Temperatures from this instrumentation were sufficiently different from those which had been observed previously with liquid-in-glass thermometers in the Standard or Cotton Region Shelters that the date of instrument change was considered a significant break in the temperature record. Current temperature normals for these stations are based on hygrothermometer records only. A problem still exists in comparing temperature data from first order stations with those from surrounding cooperative climatological stations where liquid-in-glass thermometers are still used, but this bias problem is recognized. Similarly, the importance of a change in location of the instrumentation is usually recognized. In fact, location of stations forms the base for important mesoclimatological studies of urban-rural temperature differences.

The time of observation bias, however, frequently is either overlooked or ignored. Yet it may be a more important bias than those arising from changes in instrumentation or location. It depends upon the time of the daily observation and the climatic regime. At the least, these biases in estimating daily mean temperatures introduce additional variability into the climatological records. With systematic changes, such as an increasing percentage of operational AM reporting stations in the climatological network, these biases may cause spurious mean temperature spatial and temporal patterns with resulting application errors.

In this paper the biases in mean temperature and

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derived temperature variables arising from changes in time of observation have been discussed and evaluated, using Indianapolis International Airport six-hourly and midnight maximum and minimum temperature data for 1973 and 1974.

In this century, it has been customary in the United States to determine the mean temperature for the day by adding the daily maximum and minimum temperatures and dividing by 2. For any individual day the difference between the mean of the 24 hourly temperatures and the mean of the maximum and minimum temperature may be several degrees, depending on that day's hourly temperature departures from the normal diurnal temperature curve. Baker (1975), Mitchell (1958) and Bigelow (1909), however, have shown that period-mean temperatures based on daily mean temperatures calculated in this way correspond closely to period-mean temperatures computed from averages of hourly temperatures *if* the maximum and minimum temperatures are for the 24 h period ending at midnight, i.e., the maximum and minimum thermometers are read and set at midnight. If the observational day ends in midmorning or late afternoon, period-mean temperatures derived from the daily extremes may differ 2–3°F from means derived from hourly temperature observations.

Any variable derived from the temperature data is also affected by the time of observation bias. There are at least three derived temperature variables in common use today: heating degree days (HDD), cooling degree days (CDD) and growing degree days (GDD). Although many other variables besides temperature affect fuel consumption, the simple linear relation of fuel use on accumulated HDD has been sufficiently good that monthly and seasonal totals of HDD have been published in *Climatological Data* since 1943 and used by the heating industry before that. The assumption is that no heating is required on a day with a mean air temperature of 65°F or higher. The heating degree days for one day are defined as $HDD=65-(T_{max}+T_{min})/2$. Negative daily HDD are set equal to zero in accumulating HDD. Similarly, it is assumed that no artificial cooling is necessary on a day with a mean air temperature of 65°F or less. Cooling degree days for one day are defined as $CDD=(T_{max}+T_{min})/2-65$. Negative daily CDD are set equal to zero in accumulating CDD.

With increasing interest in estimating the progress of agricultural crops, there have been many ways suggested to compute GDD. In the method currently being used by NOAA in the *National Weekly Weather and Crop Bulletin* for *Zea mays* L. (corn) and warm climate crops, it is assumed that the base temperature for growth is 50°F, i.e., below 50°F there is no plant growth or development. Since there may be some plant growth on a day with maximum temperature above 50°F, even with the minimum temperature below 50°F, any minimum temperatures below 50°F are set equal to 50°F before computing the daily mean. Also, plant growth does not increase linearly with temperature, and may even decrease at very high temperatures. Therefore, all daily maximum temperatures above 86°F are set equal to 86°F. The GDD's for a day are then estimated as $GDD=(T_{max}+T_{min})/2-50$. Negative daily GDD are set equal to zero. The GDD are computed on a daily basis and accumulated for the desired growth period. Any time of observation bias in the daily temperature is accumulated in these derived temperature variables.

At first order National Weather Service (NWS) stations, daily mean temperatures consistently have been computed for the day ending at midnight. For cooperative climatological stations, the temperature observation is usually taken at a time between 1600 and 2000 LST. For operational stations (river, rainfall, agricultural weather), the observational time usually is between 0700 and 0800 LST. The situation is further confused when the observer changes his time of observation. At cooperative stations, the time of observation is selected as one mutually convenient to the observer and NWS. Understandably, not many cooperative observers read instruments at midnight. Even when the observer does not change the "clock time" of his observation, where Daylight Saving Time is observed during the warm season, biases from the two sun-time changes during the year are automatically incorporated in the records. Any mean temperature biases are mixed into the historical weather data and the temperature "normals"[2] themselves. Any induced instrumental or time of observation temperature heterogeneities complicate interpretations of climatic change and temperature applications to agriculture, business and industry.

Baker (1975) calculated for St. Paul, Minn., the 24 h mean daily temperatures for three years. He compared the mean monthly temperatures, computed from daily means of 24 hourly temperatures with those based on the averages of the daily high and low temperatures. The average of the hourly temperatures and the average of the daily extremes provided similar mean temperature estimates when the observational day ended at midnight. This is in agreement with the findings of Bigelow (1909). Mean monthly temperatures calculated by averaging the daily maximum and minimum temperatures for a midnight observational day station are considered to be a satisfactory base for comparing mean temperatures calculated from maximum and minimum temperatures taken at observational times other than midnight. The geographical pattern of mean temperature bias resulting

[2] By World Meteorological Organization agreement and definition, "normals" are defined as the averages for the preceding three decades. Temperature and precipitation normals presently in use are for 1941–70.

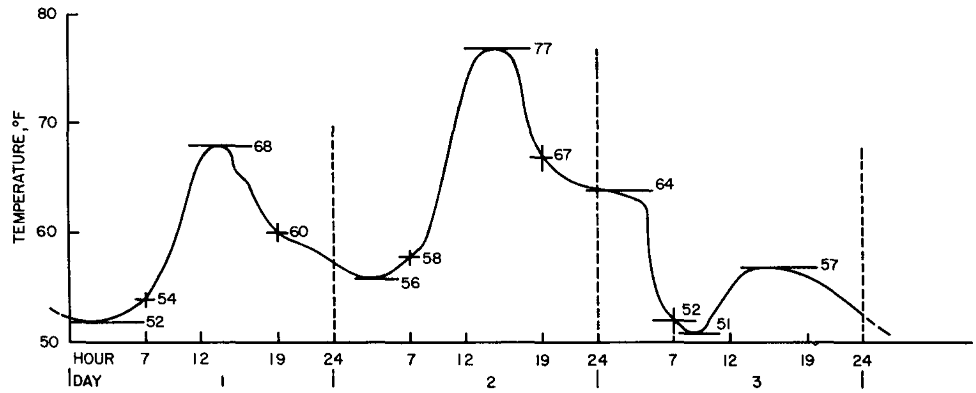


FIG. 1. Typical three-day continuous thermogram. Significant temperatures have been entered to demonstrate recording temperature extremes for different observational days shown in Table 1.

from daily observational times other than midnight can be deduced roughly from Fig. 1 in Mitchell (1958). He selected eight stations in the United States at both high and low latitudes to show the magnitude of the bias at different times of the year due to length of daylight, frontal passage frequency, and for any hour the observational day ended.

Another source of bias arises from observational and computational rounding errors. The temperature observations are read and recorded to the nearest whole degree. A day's mean temperature averages to a whole degree only about half the time. The other half of the means, ending with 0.5, are rounded upward to the next whole degree. If all daily mean temperatures are below 65°F, this results in an average negative bias of 15 HDD for a 30-day month. The conventional method of determining the monthly mean, however, is first to calculate the mean daily maximum and the mean daily minimum temperatures for the month, and then obtain the monthly mean from these two averages. This explains why accumulated daily HDD for a month are lower than the HDD monthly total calculated from the month's mean temperature, even when all temperatures are below the base being used.

2. Data and procedures

Extremes in temperature are recorded on Surface Weather Observation Form MFI-10B at Indianapolis Airport for the following segments of time (EST): midnight to 0100, 0100 to 0700, 0700 to 1300, 1300 to 1900, and 1900 to midnight. From these data for 1972 and 1973, daily accumulated monthly HDD, CDD and GDD totals were calculated for 24 h periods ending at midnight, 0700 and 1900. A variation of the 0700 observation was also made, using a 12 h minimum temperature instead of a 24 h minimum temperature at the 0700 terminus of the 24 h period. Since it is primarily "this morning's low," not the previous morning's low temperature, which is of interest, the 12 h minimum temperature is used in NWS operational programs and for public dissemination. With a warming trend, yesterday morning's low may have been the lowest in the previous 24 h, and a single morning minimum temperature may appear on two adjacent observational days. In such a situation, the 24 h minimum temperature, read at 0700, biases period-means downward, and the 12 h minimum at 0700 may correct this bias. The greatest biases occur in the cold months, and also depend on the severity and frequency of frontal passages.

The generation of the observational problem is well known by climatologists, but is reviewed briefly for those who may not have encountered these record difficulties. A hypothetical temperature curve is shown for 3 days in Fig. 1. If maximum and minimum thermometers were read and set at the four observation times discussed in this paper, the maximum and minimum temperature which would have been published in *Climatological Data* are shown in Table 1. Of course, the observational day maximum tempera-

TABLE 1. Maximum and minimum temperatures (°F) read from maximum and minimum thermometers at indicated observation times for typical temperature pattern shown in Fig. 1. Temperatures in table are those that would be published in *Climatological Data*.

Station observation time	Temperature extremes	Date 1	2	3
Midnight	Max	68	77	64
	Min	52	56	51
1900	Max	68	77	67
	Min	52	56	51
0700	Max	—	68	77
	Min	52	54	52
0700*	Max	—	68	77
	Min	52	56	52

* 12 h minimum.

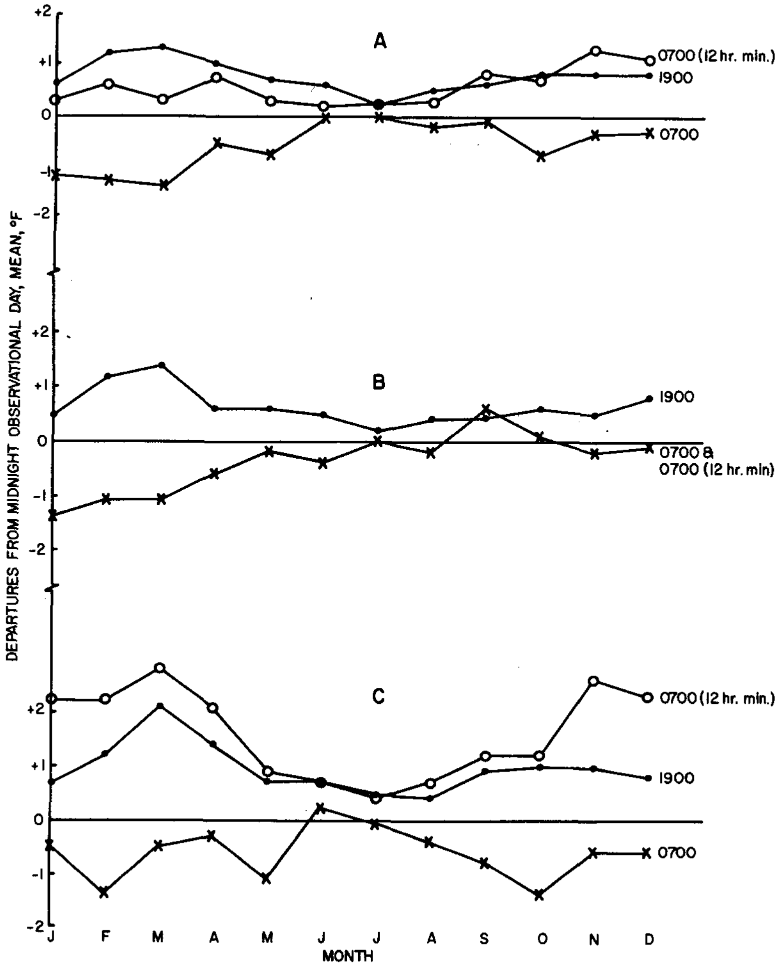


FIG. 2. Differences between mean monthly temperatures obtained with midnight observational day (0 line) and those obtained with 0700, 0700 (12 h minimum) and 1900 hour observational days, Indianapolis, Ind., 1973–74: (A) mean daily temperature, (B) mean daily maximum temperature and (C) mean daily minimum temperature.

tures are offset one day for an AM station, and those working with daily temperature means or period-means shorter than a month usually set the maximum temperature back to the previous day. But it is the difference in recorded temperatures which is important here. Note that the maximum temperature on day 1 for the 1900 observational day station is a "carryover" 67°F, 3°F higher than the maximum read at midnight. Conversely, on day 2 the minimum temperature for the 0700 observational day station is 54°F, 2°F lower than the "true" midnight minimum, but the 12 h minimum temperature at 0700 corrects the bias on this particular day.

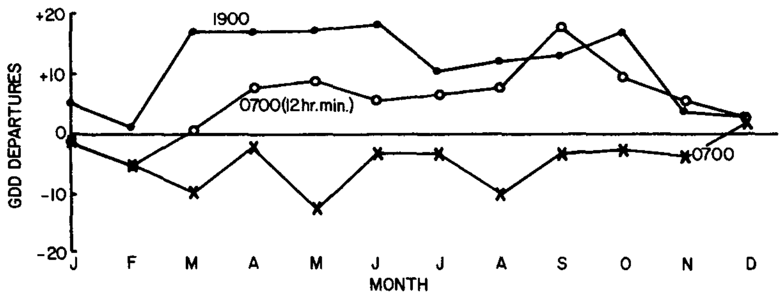
To examine the effect the individual station time of observation temperature bias might have on climatological division temperature normals, *Climatological Data, Indiana* was reviewed to ascertain the trend in observational times which have occurred from 1905 to 1975.

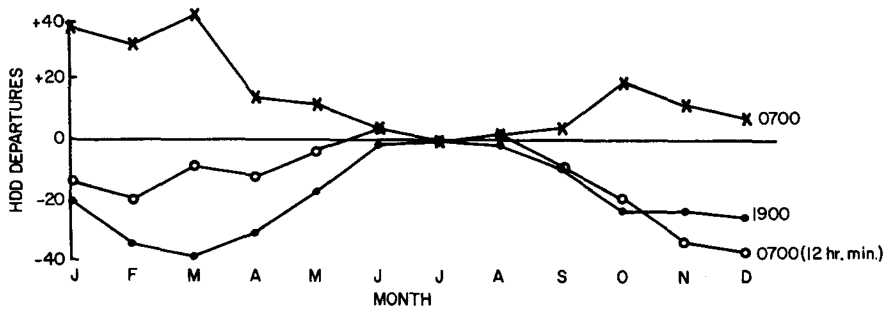
3. Results and discussion

The deviations of annual totals of HDD, CDD and GDD with observational times which differ from those obtained using midnight observational means are presented in Table 2. Assuming the diurnal temperature march from the aspirated hydrothermometer

TABLE 2. Differences between annual growing (GDD), heating (HDD) and cooling (CDD) degree days obtained with midnight observational day temperature means and those obtained with 0700, 0700 (12 h minimum) and 1900 hour observational day means, Indianapolis, Ind., 1973–74.

	Annual total (midnight)	Deviation from midnight annual total and percent change		
		1900	0700	0700 (12 h min)
GDD	3900	+134 (+3.4%)	− 50 (−1.3%)	+ 70 (+1.8%)
HDD	5080	−224 (−4.4%)	+183 (+3.6%)	−148 (−2.9%)
CDD	1006	+ 51 (+5.1%)	− 20 (−2.0%)	+ 62 (+6.2%)





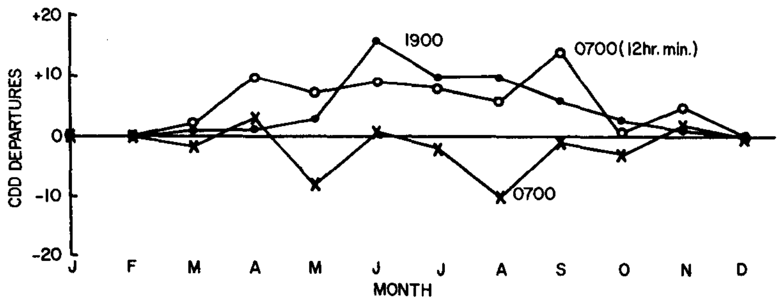


FIG. 3. Differences between growing degree days (GDD) calculated with midnight observational day mean temperature (0 GDD line) and those obtained with 0700, 0700 (12 h minimum) and 1900 hour observational days, Indianapolis, Ind., 1973–74.

FIG. 4. As in Fig. 3 except for heating degree days (HDD).

FIG. 5. As in Fig. 3 except for cooling degree days (CDD).

records at Indianapolis is representative of that at a climatological station, if the time of observation is changed from 1900 to 0700, the annual HDD total would be increased 407 HDD, an 8% increase with no change in climate!

The deviations of the mean daily maximum, minimum and mean temperatures from the midnight observational day means are shown for each month in Fig. 2. The daily mean temperature (Fig. 2a) for March with a 1900 observational day averaged 1.3°F higher than those for a midnight observational day. The 0700 observational day mean for March averaged 1.3°F lower than the midnight mean. Thus, in March, a station with a 0700 observation time will average 2.6°F cooler than a station with a 1900 observation. Since all daily mean temperatures are below 65°F in March in Indiana, this 2.6°F difference equates to 81 HDD (31×2.6) or about 10% of the "normal HDD" for March. This disparity, caused simply by different times of observation, complicates interpretation of both areal and temporal climatic anomaly patterns. The mean for the modified 0700 observation, using 12 h minima, was closer to the midnight observation mean, but was still higher than the midnight readings.

For the 1900 observational day the mean daily minimum temperature (Fig. 2c) for March averaged 2.1°F higher than that for a midnight observation while the March mean daily maximum temperature (Fig. 2b) for the 1900 observation was 1.4°F higher. As can be seen in Fig. 1, however, the "carryover" maximum becomes the major source of bias when the time of observation is moved from 1900 to 0700,

TABLE 3. Number and ratio (in parentheses) of AM, PM and midnight observational stations to total number of stations for which temperature data were published in July *Climatological Data*, Indiana.

Year	Total number	Observation time Midnight	AM	PM
1905	61	2 (0.03)	13 (0.21)	46 (0.75)
1915	66	4 (0.06)	16 (0.24)	46 (0.70)
1925	70	8 (0.11)	7 (0.10)	55 (0.79)
1935	72	6 (0.08)	8 (0.11)	58 (0.81)
1945	81	7 (0.09)	22 (0.27)	52 (0.64)
1955	86	8 (0.09)	38 (0.44)	40 (0.46)
1965	96	12 (0.12)	43 (0.45)	41 (0.43)
1975	93	13 (0.14)	51 (0.55)	29 (0.31)

a more common time of observation for cooperative stations. The 1900 observational day averages, whether minimum or maximum, continue higher than the midnight average for all months of the year.

The modified 0700 observation, using a 12 h minimum temperature, provides the greatest mean daily minimum temperature bias of +2.8°F. The low 0700 mean daily maximum temperature (−1.1°F) tends to offset this bias when they are combined for the daily average.

The deviations of the monthly GDD are shown in Fig. 3. For the spring months the 1900 observation gave a bias of +17 GDD. For the year (Table 2) the bias accumulated to +134 GDD or 3.4% over those computed with a midnight observation. These are annual totals and include GDD contributions for days before the last spring freeze and after the last fall freeze. The 0700 observation introduced a negative bias for the year, −50 GDD or −1.3%. The 0700 modified observation had a bias of +70 GDD for the year.

The monthly HDD biases are shown in Fig. 4. March showed the greatest observational time bias. The 0700 observation HDD monthly total was 41 HDD above those calculated from the midnight observation. The 0700 modified observation showed only a −8 HDD bias. The 1900 observational day yielded a March total 38 HDD less than that of the midnight observation. For the year (Table 2), the bias accumulated to −244 GDD or −4.4% for the 1900 observational day, and −148 HDD or −2.9% for the 0700 modified observation.

Monthly CDD biases plotted in Fig. 5 showed the June 1900 CDD were 16 greater than those for the midnight observation. The greatest monthly bias observed for the 0700 observational day was a −10 CDD departure in August. The 0700 observational day out-performed the other two observational days.

A substation that has been changed from 1900 to 0700 in time of observation can increase the seasonal HDD total for the station by 8%, i.e., from −4.4 to +3.6% (Table 2). If the summary data were being used to monitor and plan fuel use, this simple change in observational time would overestimate the fuel needs by 8%, using the linear fuel-HDD relation developed over the past record. As weather data are used more quantitatively than now in day-to-day industrial and agricultural operation and long-range planning, these discrepancies will become more troublesome.

The changes that have taken place in time of observation for each decade from 1905 to 1975 are shown in Table 3. The increased percentage of stations taking morning observations is shown in Fig. 6. In 1905 21% of all Indiana stations took their observations in the morning. This increased to 44% in 1955 and 55% in 1975. Therefore, the biases described for a single station have been incorporated into the climatological division monthly mean temperatures as well as the 30-year "normals." Whether one uses individual station HDD totals to examine patterns of fuel use over an area, GDD departures from normal, or divisional mean temperatures for an increasing number of weather and crop yield prediction studies, the observational time bias component *has to be considered.* This is especially important in evaluation of climatic change.

If all the PM stations were assumed to take observations at 1900 and all AM stations at 0700, and the 2-year Indianapolis temperature record is representative of other Indiana stations, the bias estimates from Fig. 2a can be used to predict the bias in a divisional or state mean temperature caused by the systematic change toward AM reporting stations. The progressive bias "cooling" in the Indiana climate for March has been estimated in Table 4. For example, in 1975 there were 31% PM stations, 55% AM stations and 14% midnight observing stations with respective biases (°F) of +1.3, −1.3 and 0. The time of observation daily mean temperature bias for March

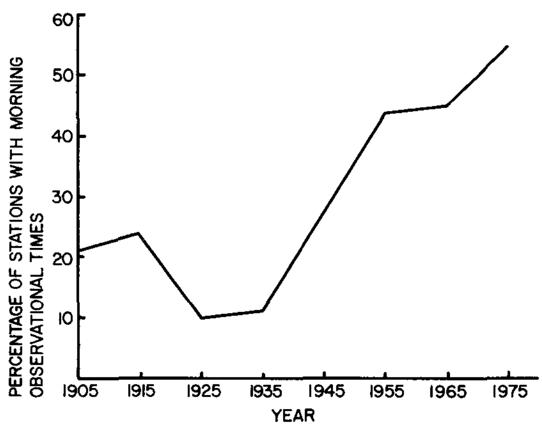


FIG. 6. Percentage of number of published temperature observing stations with morning observational times in July. *Climatological Data*, Indiana, for indicated year.

1975 divisional or state means is then estimated as

$$\text{bias} = (0.31)(+1.3) + (0.55)(-1.3) + (0.14)(0) = -0.31°\text{F}.$$

Although this is not great, the "climatic cooling" is apparent from the bias estimates for the other years in Table 4. The climate has "cooled" 1.2°F in the last 40 years, solely because of change in time of observations.

There has been increasing use of the component mean daily minimum and mean daily maximum temperatures in weather and crop yield studies and in other applications where the range in temperature is important. The bias estimated for the mean daily minimum temperature for March is given in Table 4. The mean Indiana daily minimum bias decreased from +1.6°F in 1935 to +0.4°F in 1975, a 1.2°F "temperature drop" in the last 40 years.

The time of observation bias also creates distorted areal patterns. For example, the corrections to station mean temperatures for March 1976 required to offset the biases in the Central Division, Indiana are plotted in Fig. 7. They range from −0.3 to +1.3°F. Biases for observational days ending at other times than 0700 and 1900 were taken from Mitchell (1958). The distribution of corrections arbitrarily adds 1.3°F to most stations in the northern half of the Division with little correction in the south. Without such corrections the study of urban-rural temperature differences may be misleading, the time of observation biases being of the same order of magnitude as city heat island effects. The corrections also raise the "true" divisional mean 0.5°F.

A fraction of a degree bias accumulates when summing daily mean temperatures into HDD, CDD, GDD or any other derived indices over a season. The March HDD biases are also estimated in Table 4.

The estimated effects of changes in time of observation on the division and state mean temperatures are conservative primarily because the usual time for the PM observation is between 1600 and 1800. The closer the observational times approach the maximum temperature of the day (the daily maximum usually

TABLE 4. Divisional or state mean temperature estimated bias (°F) for March.

	Daily mean	Daily minimum	HDD
1905	+0.7	+1.5	−29
1915	+0.6	+1.4	−27
1925	+0.9	+1.6	−33
1935	+0.9	+1.6	−33
1945	+0.5	+1.2	−26
1955	0	+0.7	+ 1
1965	0	+0.7	+ 2
1975	−0.3	+0.4	+11

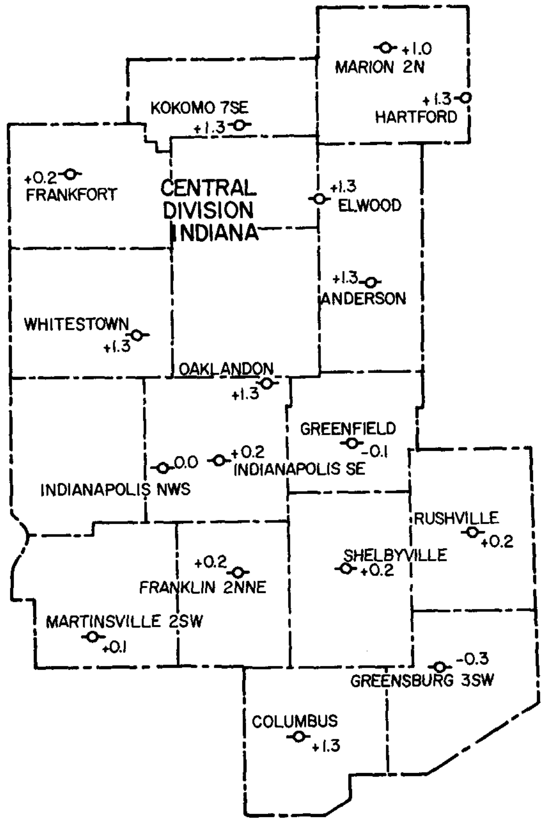


FIG. 7. Mean temperature corrections estimated as needed for indicated stations in Central Division, Indiana, to convert March 1976 mean temperature to midnight base.

occurs between 1300 and 1600 h), the greater the positive bias in the maximum temperature.

This problem has long been realized, and in the NOAA Environmental Data Service (EDS) quality control operations, AM and PM stations have always been separated when preparing daily maximum and minimum temperature arrays. Since a PM observational day station provides maximum and minimum temperatures which usually are published in *Climatological Data* on the proper calendar day, the PM time of observation has been favored for climatological convenience. For current weather reporting and forecasting services, however, AM observational times have been preferred. Maximum temperatures published for AM stations in *Climatological Data* usually are for the previous day. Since the operational services of NOAA have and will continue to push for AM observations, and the temperature observational biases are slightly less than those for PM stations, it is suggested that as opportunities arise, cooperative observers be encouraged to change to morning observations for more homogeneous areal climatological patterns.

The biases from other sources, such as station moves, city encroachment and change of equipment, have not been considered here, and may be the main cause for heterogeneity in a single station record. The time of observation bias, however, is a more insidious and consistent bias which has to be taken into account in any historical study of environmental change. As weather-dependent operation studies reveal more consistent quantitative relations, the economic importance of the time of observation bias in estimates of fuel use and food supply will become evident.

Although Mitchell (1958) concluded that PM observations tend to result in more homogeneous mean temperature time series than those taken in the morning, weather forecasting service preference and trend toward AM observing and reporting stations provides real reason for speeding this observation time transition at as many stations as possible for more homogeneous mean temperature patterns. This same problem distorts the daily areal patterns and complicates data quality control and summary for other weather variables measured once daily, such as evaporation and precipitation. The North Central Regional Technical Committee (NC-94) on Weather Information for Agriculture has written the Director, NWS, supporting an accelerated change toward AM observations at climatological stations whenever possible.

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