Non-Climatic Trends in Divisional and State Mean Temperatures: A Case Study in Indiana[1]

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(Manuscript received 26 June 1978, in final form 2 February 1979)

ABSTRACT

Concern about climatic change and its effects on man has been increasing. Climatic changes affect the production of food and the allocation of energy resources. Proper interpretation of climatic change and the effect of weather on fuel use and crop production requires a homogeneous data base. A methodology is presented for removing non-climatic variability from monthly mean temperature records caused by changes in time of observation, station location, instrumentation and observer, using as an example climatological records for June, July and August from 1930 to 1976 in Indiana. Divisional and state mean temperature adjustments to the published figures were calculated. Divisional temperature corrections were usually negative, with an extreme correction of −1.5°F applied to the published Central Division temperatures in 1942–44 and 1950. State mean June, July and August corrections were negative every year, with an extreme correction value of −0.8°F in 1949. Even with the temperature corrections included, Indiana June, July and August mean temperatures showed a decrease of approximately 3°F from 1930 to 1976.

1. Introduction

Concern about recent weather fluctuations and climatic trends and their possible causes has been accelerating (Mitchell, 1961a; Budyko, 1969; Angell and Korshover, 1977). Also, increasing use has been made of climatic data to interpret the impact of weather and climate fluctuations on food production. Thompson (1975), Benci *et al.* (1975), Decker *et al.* (1976) and Newman *et al.* (1976) used *state averages* of *monthly mean temperatures* and total precipitation in weather-yield regression models to estimate the impact of climatic fluctuations on crop production. In these climatic impact studies, any changes in location of stations and time of observation were tacitly assumed to be random and to have little effect on *divisional* and *state* mean temperature records. Schaal and Dale (1977), however, showed that in Indiana a systematic change in the time that observations were taken at cooperative climatological stations—from evening to morning—contributed to the downward trend observed in divisional and state mean temperatures since 1940. Any other systematic changes in management of weather station networks, such as changes in instrumentation or not maintaining the same network configuration, may also bias divisional and state temperature means and thereby weather impact studies.

Mitchell (1961b) wrestled with the problems of heterogeneities in temperature series caused by station changes which confound microclimatic differences with climatic change. He discussed three approaches to the measurement of true climatic trend and derived the estimated error variances associated with each of the three methods: 1) reference-station index, 2) area-mean index and 3) tau index. A comparison of the error variances for the method described in this paper with those of Mitchell's tau and area-mean indexes are included as the Appendix to this paper. The method described here is similar to Mitchell's area-mean index, where the area is a division, except that the temperatures for each discontinuous station are corrected. Mitchell advocated the tau index method for its simplicity. Only the series of first-differences between the mean temperature at a station for a month (e.g., March, 1960) and that for the same month in the previous year (March, 1959) are used. Then, if a station were moved from a roof-top exposure to a ground exposure, the difference between mean temperatures over the period of the move would simply be omitted from the first-difference series. The average of the available first differences in a division provides a data series from which microclimatic changes have been removed from the true climatic change. With this method Mitchell obtained a "repre-

[1] Journal Paper No. 7195, Agricultural Experiment Station, Purdue University, West Lafayette, IN 47907. Partially supported by National Science Foundation, Atmospheric Science Section under Grant ATM 75-10001 A01.

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0021-8952/79/060750-11$06.75

sentative" climatic change without defining a "representative ambient temperature" for an area.

For weather impact studies, particularly for estimating crop growth and yield using physiologically based regression models, ambient temperature means representing the crop environment are necessary. Determining a "representative ambient mean temperature" is difficult especially in mountainous regions. We have assumed in this paper that the divisional mean temperatures estimated from the 1976 network configuration in Indiana is sufficiently representative for weather-crop yield studies, primarily because 1) we have more morning observation stations in 1976 than ever before (Schaal and Dale, 1977), and 2) the present network is believed to be relatively stable. Mitchell's series of tau indices could be applied to the 1976 divisional mean temperatures to estimate the "representative ambient temperatures," but the error variance for the divisional mean method described here is shown in the Appendix to be about one-third that of the simpler tau method.

Prior to October 1956, monthly mean temperatures and total precipitation were published in *Indiana Climatological Data* (1896–1956) for three divisions: Southern, Central and Northern. Divisional mean temperatures were based on the average of the monthly means from all temperature stations within the division for which the observational records were received before a specified cutoff date. Therefore, the divisional mean temperatures are not based on a constant network of stations. The state monthly mean temperatures were computed as an average of the three divisional means. Publication of state means was discontinued in January 1956, and the number of climatological divisions in Indiana was increased in October 1956 to the nine crop reporting districts used by the USDA Statistical Reporting Service. The same change occurred in most other states where climatological divisions and crop reporting districts were not identical. Since 1956, the state mean temperatures used in the referenced impact studies were weighted means, based on the ratios of the areas of the respective divisions to that of the state.

Since the work reported here was done in support of the development and testing of weather-crop yield models, the months selected for this pilot study were those for the major part of the growing season, June, July and August. The divisional monthly mean temperatures from 1930 to 1976 were corrected to the climatic divisions and network base of 1976 to form a "climatological series" (Thom, 1966), defined as a sample from a single population. If further work is done to assess the 1976 station base for climatic representativeness, any corrections required can be applied directly to those reported here to establish a more representative climatological series.

2. Data and procedures

Records for June, July and August mean temperatures from all temperature stations in Indiana were examined for the years 1930–76. The stations were subdivided into the present nine climatological divisions in Indiana. For convenience in handling current climatological applications, the year 1976 was chosen as the base year, and all calculations were performed to adjust the data series to the 1976 base year. The steps in the analysis of each division are listed as follows:

1) Mean monthly temperatures were listed by year and station within the appropriate month and division. A monthly divisional mean was calculated for each year and the departure of each station's mean temperature from the district average was recorded.

2) Histories were compiled for each of the stations, primarily using the *Indiana Climatological Data*, station index and annual listing of changes from 1950 to 1976 and the substation history (U.S. Dept. of Commerce, 1956) No. 1.1 from the station establishment through 1955. All changes in observational time, observer, location or instrumentation which could affect temperature records were noted.

3) In each district one or two stations were chosen for base or reference station(s) using several criteria: Each of these stations showed small fluctuation from year-to-year and month-to-month in the temperature departures from the divisional means (Step 1), although some trend could be accepted in the year-to-year departures. Usually these base stations had few changes in observers, were operated at one location continuously, and had no more than one change in observation time. One or two stations meeting these criteria were present in each division.

4) Since no stations were found with unchanged locations, observer or observation times from 1930 to 1976, base station temperature records first were adjusted, using another station with a homogeneous temperature record at least three years before and after the base station change. The difference method (Thom, 1966, pp. 7–9; Mitchell, 1961b, p. 6) was used to correct the station means prior to the station change, since all temperature records for base stations were corrected to the 1976 base.

5) Next, the temperatures for the remainder of the stations were corrected, using the values of the base station for computing correction factors. Whenever possible, comparisons were made for three years before and after a station change for each of the three months, thus giving nine comparisons both before and after each station change. For example, the average of the preadjusted departures (Step 1) for the three months, June, July and August, for each of the stations in the East Central Indiana Division (Division 6) are shown in Fig. 1. Dates of

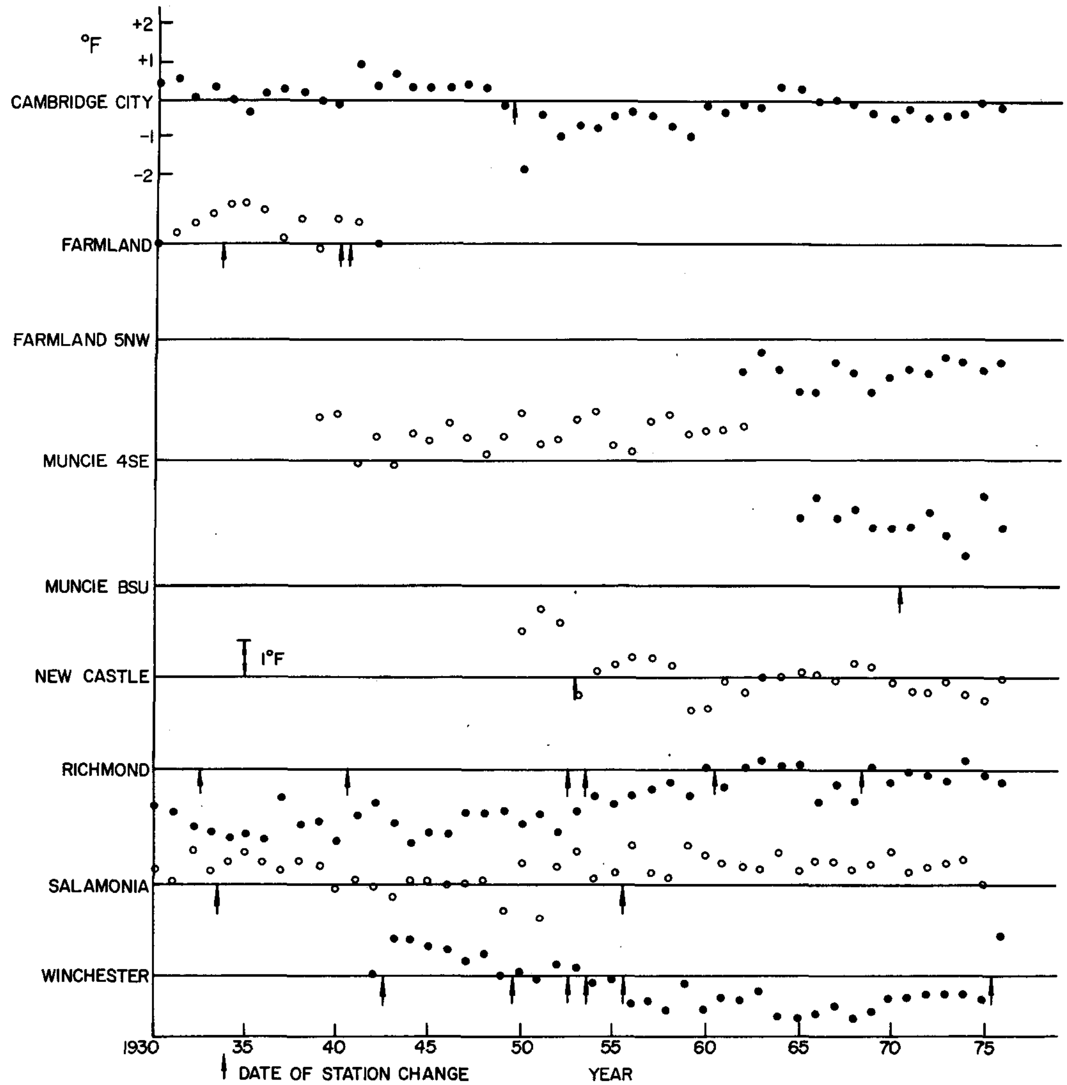

FIG. 1. Average mean temperature departures from divisional means, 1930–76, for indicated stations from June, July and August mean temperatures in East Central Division, Indiana, before corrections.

station changes are indicated by arrows in Fig. 1. Cambridge City was selected as the base station for Division 6 since among other reference station qualities, it has been operated by one observer since 1926. The station had only one change, that being the observation time in 1950. After correcting the Cambridge City record, all other station changes were corrected according to this base. New Castle is used as an example of the type of correction made. New Castle's observation time changed from afternoon to morning in April 1953. In Table 1 the mean temperatures for June, July and August are listed for the three years before and after this change. Also listed are the temperatures for Cambridge City, the base station, for each of these same months. The temperature difference, between New Castle and Cambridge City, ($\bar{T}_{NC}-\bar{T}_{CC}$), was calculated for each pair. Before the observation time change, the values ranged from 1.8 to 4.0°F. After the change, they ranged from −1.3 to 1.7°F. The average difference before the change was 2.8°F and after, 0.7°F. The average difference, 2.1°F, was subtracted from the New Castle temperature series for the period before the change in time of observation. Occasionally, such as at Winchester with changes in 1953, 1954 and 1955, three consecutive years without change were not available. For such cases corrections were less accurate and were made with whatever data were available. An additional problem occurred with stations at which observations were not made continuously through 1976. For example, at Farmland observations were taken only from 1930 to 1942. In each of these cases, the

TABLE 1. Mean monthly temperatures (°F) for New Castle and Cambridge City, Indiana, and differences ($\bar{T}_{NC}-\bar{T}_{CC}$) for June, July and August 1950–55.

Year	June New Castle	June Cambridge City	June Departure	July New Castle	July Cambridge City	July Departure	August New Castle	August Cambridge City	August Departure
1950	68.7	66.6	2.1	72.0	68.6	3.4	70.0	66.0	4.0
1951	71.0	68.7	2.3	75.6	72.0	3.6	73.2	71.2	2.0
1952	76.9	73.3	3.6	77.8	75.6	2.2	72.5	70.7	1.8
	Average difference = 2.8								
1953	73.7	72.2	1.5	73.5	72.9	0.6	71.2	72.5	−1.3
1954	73.4	71.7	1.7	74.8	73.8	1.0	71.7	71.3	0.4
1955	66.3	65.4	0.9	78.5	77.1	1.4	75.2	75.0	0.2
	Average difference = 0.7								

station values were corrected to the longest period of record. For Farmland, values were corrected to the 1934–40 period. At this point, mean monthly temperatures had been corrected within each station series.

6) The new divisional mean values for each year were computed from the corrected station temperatures. A computer program was written which handles Steps 6, 7 and 8. Since the temperature series were based on 1976 temperatures, mean values were first calculated for 1976 and then worked backward to 1930. This was necessary in order to account for the effect of stations entering and leaving the divisional mean calculations. Otherwise, unrepresentative "warm or cold stations" not active in 1976 may bias mean calculations.

7) If, in working backward from 1976, a station leaves the record, a correction must be made before calculating the mean. In this study, that station's departures from the division mean, calculated previously, for up to five years, three months each year, were summed and averaged. If fewer than five years were available, such as would happen if a station began operation in 1973, whatever data available were used. This average departure correction was then added in when calculating the monthly means for each of the years without the station. It corrected for the positive or negative bias associated with the particular station in prior years' calculations. Since several stations usually left the record in working backward to 1930, the calculated departure corrections were simply added algebraically and used with each year-month calculation.

As an example, we consider the case of Muncie BSU which from Fig. 1 averages about 2°F warmer than the division mean. In working backward in time from base year 1976, an accounting must be made for the temperature bias supplied by this station when it "leaves" the record in 1964. The Muncie BSU monthly station temperatures, the divisional mean, and the departure of the Muncie BSU temperatures from the district mean are listed in Table 2. The average of the 14 available departures, 2.2°F, is added into the correction for the district mean temperature for the period 1930–64.

Occasionally, a station was missing because of a broken thermometer or some other problem for only a month or two. In this case, the correction was calculated as described above, but that station's correction was removed when its records began again.

The other problem encountered when working backward in calculating the divisional means was the handling of a station which entered the record. In this case, the station was *not* used to calculate the district means for five years (June, July and August) after its entry. The district mean was calculated with

TABLE 2. Mean monthly temperatures (°F) for Muncie BSU and East Central Division, Indiana, and departures ($\bar{T}_{MBSU}-\bar{T}_{ECD}$) for June, July and August 1965–69.

Year	June Muncie BSU	June District	June Departure	July Muncie BSU	July District	July Departure	August Muncie BSU	August District	August Departure
1965	71.6	69.8	1.8	72.9	70.6	2.3	71.4	69.7	1.7
1966	72.1	69.8	2.3	78.5	75.4	3.1	72.7	70.0	2.7
1967	72.9	70.9	2.0	72.7	70.6	2.1	*	67.9	*
1968	72.9	70.3	2.6	75.4	73.2	2.2	74.6	72.5	2.1
1969	68.5	67.1	1.4	76.0	74.2	1.8	72.7	70.3	2.4

Average departure $(\overline{\bar{T}_{MBSU}-\bar{T}_{ECD}}) = 30.5/14 = 2.2$.

* Missing.

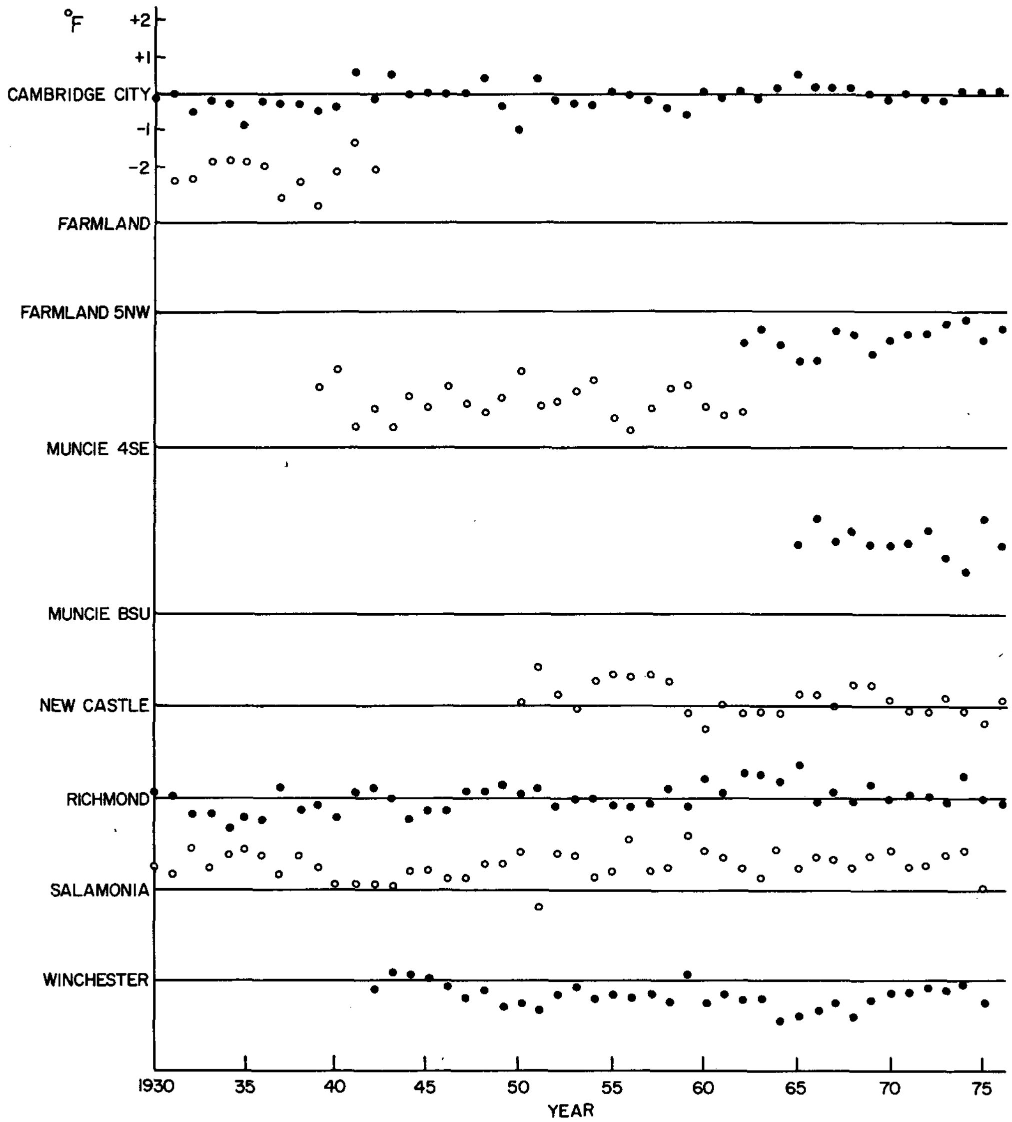

FIG. 2. As in Fig. 1 except after corrections to 1976 base.

mean temperatures of the other stations and the cumulative correction (from Step 7). A departure was calculated for this new station. For each of the 15 occurrences (five years, three months) the negative of its departure was added to the cumulative correction from Step 7. This new value, called the final departure correction, is the value which may have been added to that for *all* the stations for that month when calculating the mean. Theoretically, the divisional mean calculated by this method is exactly the same as that calculated previously without the new station(s). After five year's calculations, the 15 departures calculated for the new station were averaged. This average was subtracted from the cumulative value in Step 7. In other words, a warm bias is subtracted and a cold bias is added. After five years, this station was used directly in the subsequent mean temperature calculations, its bias correction having been included in the cumulative correction.

As an example, we consider the case of Muncie 4SE in Fig. 1. In working backward from 1976, the Muncie 4SE temperature series was first encountered in 1962, but these temperatures were not used in the calculation of the mean temperature for the first five-year period, 1958–62. The Muncie 4SE and district mean temperatures and departures are listed in Table 3 for this five-year period. The average departure was 1.2°F for the 15 cases. Muncie 4SE shows a positive temperature bias compared to the district mean. If the Muncie 4SE temperatures were used without any corrections in the district mean calculations, the district mean would be raised an average of 1.2°F divided

TABLE 3. Mean monthly temperature (°F) for Muncie 4SE and East Central Division, Indiana, and departures ($\bar{T}_{M4SE}-\bar{T}_{ECD}$) for June, July and August 1958–62.

Year	June: Muncie 4SE	June: District	June: Departure	July: Muncie 4SE	July: District	July: Departure	August: Muncie 4SE	August: District	August: Departure
1958	66.9	65.3	1.6	73.4	72.3	1.1	72.2	70.3	1.9
1959	72.1	70.0	2.1	74.0	72.7	1.3	77.1	75.5	1.6
1960	68.8	67.4	1.4	71.0	69.8	1.2	73.1	72.5	0.6
1961	68.4	67.3	1.1	73.0	72.4	0.6	71.7	70.6	1.1
1962	71.0	69.9	1.1	71.7	71.0	0.7	71.8	70.5	1.3

Average departure $(\overline{\bar{T}_{M4SE}-\bar{T}_{ECD}})=18.7/15=1.2.$

Incremental correction to be added to series $= -1.2$°F.

by the number of temperature stations reporting that month. To correct this problem, -1.2°F was added to the cumulative corrections from Step 7.

After correcting all monthly station means to the 1976 base back through 1930, an overall year-month correction factor was calculated for each division. This value, added to the original uncorrected division mean temperature, gives the new division mean temperature value based on the 1976 station configuration in the division. This value for each month was the sum of the corrections computed in Steps 4 and 5, the cumulative correction from Step 7, and the negative value of any departures from average for stations just entering the record from Step 8. The sum was divided by the total number of stations for that month to give the overall average correction.

3. Results and discussion

The corrected series of station temperature departures from divisional means averaged for June, July and August were graphed in Fig. 2 for each year in

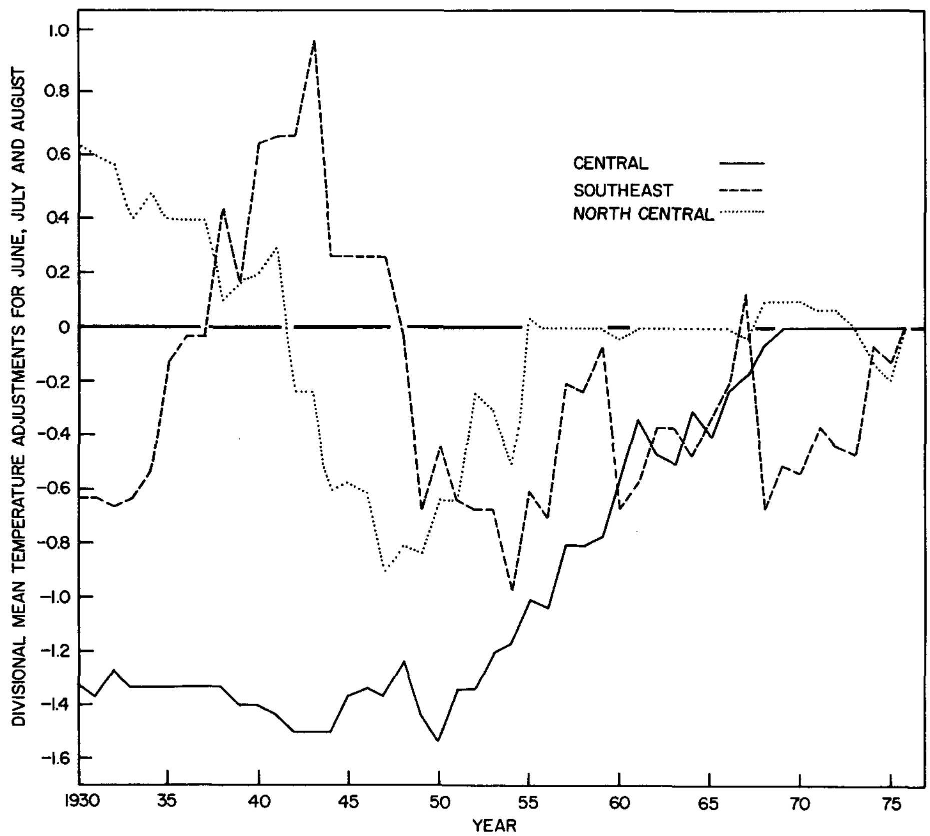

FIG. 3. Divisional corrections, 1930–76, to published mean temperatures for the Central, Southeast, and North Central divisions in Indiana, with 1976 base.

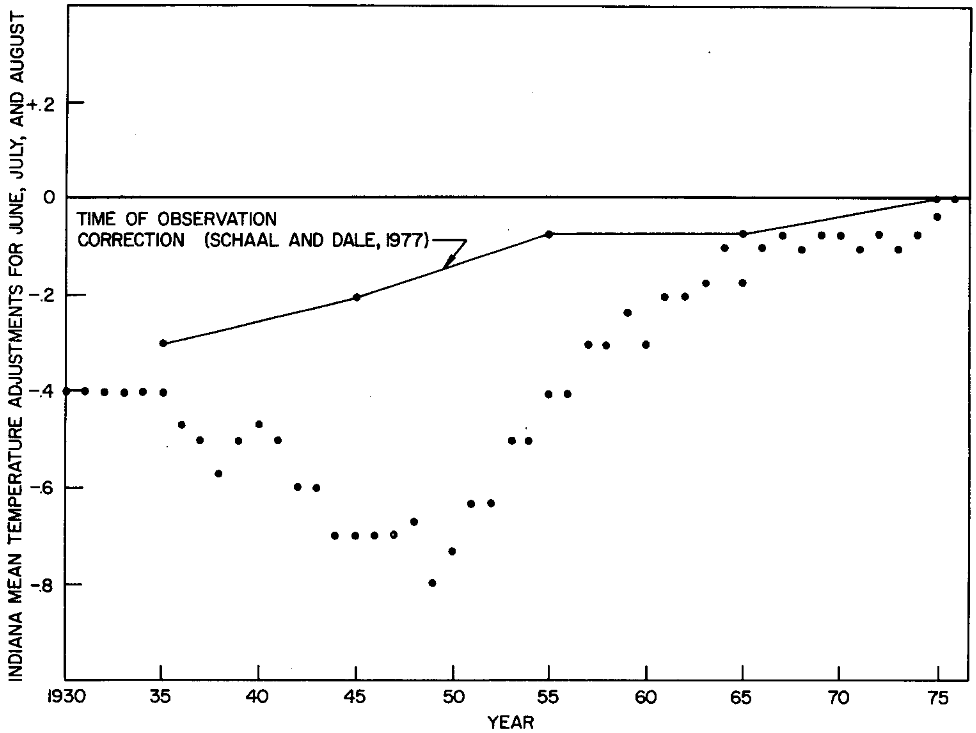

FIG. 4. Adjustments for calculating a corrected series of mean June, July and August temperatures in Indiana with a 1976 base.

East Central Indiana, Division 4. The average station departures in Fig. 2 visibly are more uniform and of lower variability than those for the same station, before correction, shown in Fig. 1. For example, in Fig. 1, Richmond exhibits a readily apparent long-term warming trend, which might be improperly interpreted as climatic change. In Fig. 2 this trend is essentially removed. Similarly, for Winchester the temperature corrections have eliminated the positive temperature bias shown in Fig. 1 from 1942–53. After corrections, most departures were slightly negative at Winchester. Even the base station, Cambridge City, showed improvement, although it was fairly uniform before corrections were made. Almost all of Cambridge City's corrected departures (Fig. 2) were within 0.2 or 0.3 of a degree from the divisional means.

The average of the June, July and August mean temperature corrections, for three of the nine districts, Central, Southeast and North-Central from 1930 to 1976 are shown in Fig. 3. Most district mean temperature values published in Climatological Data for June, July and August during the 1930's, 1940's and 1950's were higher than those which would have been predicted with the 1976 station network. Since most of the corrections were negative, this indicates that at least some of the recent climatic cooling is a result of changes in the station network. Also, strong "non-climatic gradients" exist between divisions. For example, in 1943 the temperature bias corrections of −1.5°F in the Central Division and +0.9°F in the Southeast Division caused a "non-climatic" temperature gradient of 2.4°F between these two adjacent Divisions.

A weighted average of all the district curves, based on the area of each district, is shown in Fig. 4. This Indiana state mean temperature correction for each year may be compared to a curve, after Schaal and Dale (1977), which shows their estimated average June, July and August temperature correction based solely on changes in observation time. Both curves predict similar values in the 1930's and after 1960, but the composite adjustment calls for much larger corrections in the 1940's and 1950's than shown by the Schaal and Dale curve. Several stations had, or acquired, roof top exposures in the 1930's and 1940's. These stations during summer were usually 2 or 3°F warmer than a station located on the ground. These warmer roof-top locations were phased out during the late 1940's. Quite often, they were replaced by a colder station relative to the division mean. Many new stations were located at sewage treatment facilities, usually at the lowest point in the vicinity. Thus, a systematic station location change has added to the temperature bias caused by the systematic change in time of observation. An examination and comparison of the curves in Fig. 3 with the weighted curve in Fig. 4 shows that the state correction curve cannot be used to estimate district values.

State average mean temperatures for June, July and August using the corrected divisional means and

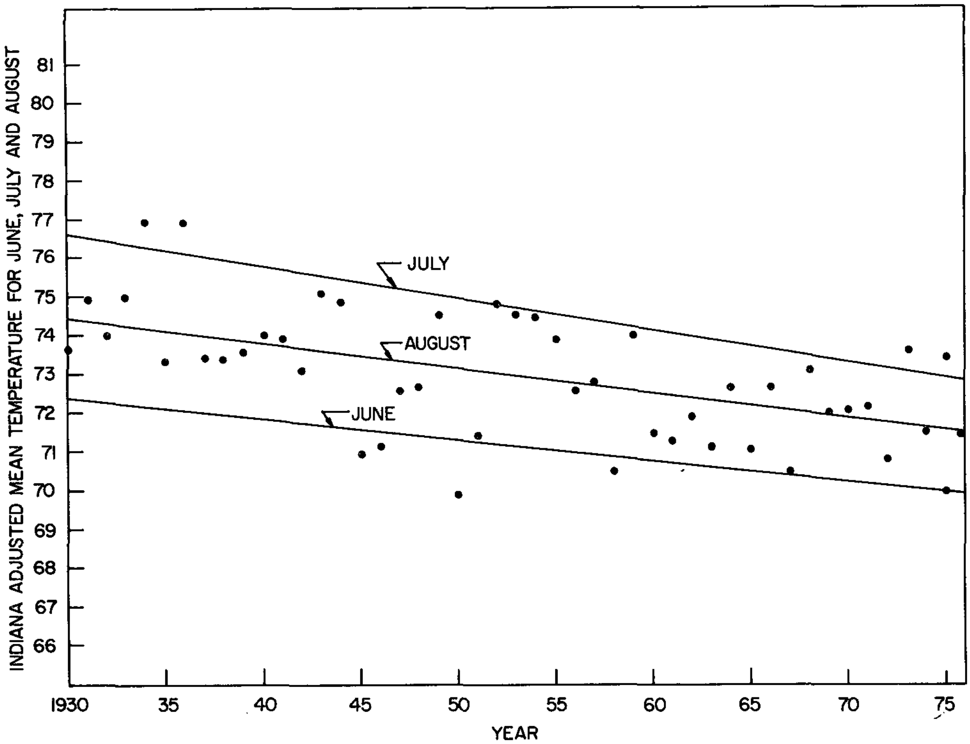

FIG. 5. Indiana average mean temperatures for June, July and August, 1930–76, calculated for a 1976 base. Lines represent separate regressions of indicated monthly mean temperature on year. The August line is approximately the same as that for the average summer temperature.

appropriate area weights were calculated. An average of June, July and August temperatures for each year was also calculated and graphed in Fig. 5. The lines marked June, July and August on Fig. 5 represent the simple linear regression of the respective month's corrected mean temperature on year. The regression line for the three-month mean temperature on year was almost exactly the same as that shown for August. Even after the temperature adjustment there has been considerable cooling in the summer. The regression estimate for the mean summer temperature, shown by that for August, provides a value of 74.5°F for 1930 and 71.5°F for 1976, a temperature trend of −3.0°F in the 47-year period.

Work is underway to compare yield predictions made with weather-crop yield models using corrected divisional and state means with those using the divisional and state means in the published *Climatological Data,* as done by Nelson and Dale (1978) for Tippecanoe County. The results of this study may also have application in correcting historic district and state growing and heating degree days.

APPENDIX

Comparison of Error Variances of Corrected Means with Those of Mitchell's Tau and Area-Mean Indices

Mitchell (1961b) discussed in depth three methods for homogenizing temperature series for use in studying climatic change:

1) *Reference-station index.* This is a time series of monthly mean temperatures from a single "reference station" selected for its homogeneity.

2) *Area-mean index.* A time series of monthly mean temperatures based on all stations within an area, e.g., a climatological division.

3) *Tau index.* In this method a difference in monthly mean temperatures is calculated for each station between year y and $y-1$, and the differences d_{ky} are averaged for all stations $k=1$ to n within the area (division). No individual d_{ky} values are used which bracket a known discontinuous station change. Therefore, the determination of change in temperature caused by a station relocation or change in time of observation is unnecessary. The cumulative sums of the average temperature differences form a climatic change series without defining the ambient temperatures.

As a method of comparing the desirability of using any of these methods, Mitchell developed the error variance equation associated with each method. Ratios of the error variances for each method to those for other methods were calculated for typical values of the parameters and various numbers of years. A smaller error variance would be preferred. Mitchell gave the following conclusions:

1) Unless the reference station has a homogeneous series of temperatures at least 50 years in length, both the area-mean and the tau index methods may be expected to have a smaller error variance than that for the reference station method.

2) The area-mean index method had an expected error variance less than that for the tau method for monthly mean temperatures after only ten years, and about two-thirds of the error variance for a series of 40 years of mean monthly temperatures.

3) For seasonal temperature means, however, the tau method's error variance was approximately 70% of that for the area-mean index error variance for all lengths of records.

Because the error terms for the tau method were more normally distributed than those for the area-mean method, Mitchell recommended the tau method for monthly and seasonal means when the error for the tau method does not exceed that for the area-mean index by more than 20%. However, when monthly parameters were used in Mitchell's models, the 20% discrimination value was reached after only 10 years. Thus, the area-mean index, as computed by Mitchell, should be preferred for longer periods where changes in monthly mean temperatures are desired.

The reader is referred to Mitchell for the complete development of the error variances, but his final error variances for the area-mean and tau indices are given below:

Area-mean index

$$v(F_y)=\frac{2\gamma v(C)+\gamma' y v(\Delta)+v(\epsilon)}{N(1-\gamma)}. \quad (1)$$

Tau index

$$v(E_y)=\frac{1+(y-1)(2\Gamma-\gamma)}{N(1-2\Gamma)}v(\epsilon). \quad (2)$$

For both (1) and (2), from Mitchell:

- γ average relative frequency of missing values in the mean temperature series
- γ' average relative frequency of years in which discontinuous exposure changes occur at the stations in the network, limited to categories of exposure change for which the variance of their temperature effects exceed a certain critical magnitude
- Γ $[=\gamma+\gamma'/2\alpha]$
- α ratio of the number of all discontinuous exposure changes to the number of those which are not bracketed by missing reported mean temperatures, averaged for all stations in a region
- N total number of stations in a region that report mean temperatures, with or without interruption, in an interval of years
- y year identifier, usually counted backward from the most recent year
- $v(\epsilon)$ variance of ϵ, usually averaged over all stations in climatological division and, if not subscripted, over full length of record
- $v(C)$ variance of normal temperatures at the stations in a region around the areally averaged normal, in a given month (or season)
- $v(\Delta)$ additional variance of temperature effects (i.e., of magnitudes of inhomogeneities) caused by all discontinuous exposure changes greater than a certain magnitude
- $v(E_y)$ tau-index error variance
- $v(F_y)$ area-mean index error variance.

In this study, a modified area-mean index method was applied to the divisional mean temperatures. Instead of using the divisional mean temperatures as published, as Mitchell does for his area-mean approach, each temperature series from each station was edited for station changes. A homogeneous series of temperatures was developed for each station after the method of Thom (1966) and Mitchell (1961b, p. 6), and used to compute a new series of divisional means, as described in this paper.

Mitchell's component of error caused by discontinuities is represented by $v(\Delta)$ in $v(F_y)$ or Eq. (1). This error variance term must be replaced by one reflecting the error associated with adjustments to the temperature record.

Following the logic of Mitchell (1961b, Appendix B) we define

$$\delta_{ky}=T_{ky}-\tau_{ky}, \quad \delta_{jy}=T_{jy}-\tau_{jy},$$

where

- T_{ky} recorded temperature at station k in year y
- τ_{ky} true temperature at station k in year y
- δ_{ky} error in estimating the true temperature, and similar arguments for (j).

Then if

$$D_{k-j,y}=\tau_{ky}-\tau_{jy}, \quad d_{k-j,y}=T_{ky}-T_{jy},$$

the error ϵ in estimating the difference between two stations may be expressed as

$$\begin{aligned}\epsilon_{k-j,y}&=d_{k-j,y}-D_{k-j,y}\\&=(T_{ky}-T_{jy})-(\tau_{ky}-\tau_{jy})\\&=(T_{ky}-\tau_{ky})-(T_{jy}-\tau_{jy})\\ \epsilon_{k-j,y}&=\delta_{ky}-\delta_{jy}.\end{aligned}$$

The variance may be expressed as

$$v(\epsilon_{k-j,y})=v(\delta_{ky})+v(\delta_{jy})-2c(\delta_{ky}\delta_{jy}).$$

The δ_{ky} and δ_{jy} can be assumed to be uncorrelated, and the covariance c term vanishes. Also, the variance of δ_{ky} or δ_{jy} is independent of station k or j. The relation may be simplified to

$$v(\epsilon_y)=2v(\delta_y). \quad (3)$$

It then follows that the variance of the mean difference either before or after the known station change may be calculated by

$$v(\Delta\bar{T})=v(\delta_y)\left(\frac{1}{n_1}+\frac{1}{n_2}\right).$$

For these calculations, $n_1=n_2=n$ and for most cases $n=9$, as described in procedures (three years with three months before and after the change).

Therefore,

$$v(\Delta\bar{T})=2v(\delta_y)/9.$$

However, the value sought is the difference

$$D=\Delta\bar{T}_{\mathrm{B}}-\Delta\bar{T}_{\mathrm{A}},$$

where B and A refer to before and after, respectively. This difference has variance $v(D)=2(v\Delta\bar{T})=(4/9)v(\delta_y)$, and from (3), $v(D)=2v(\epsilon_y)/9$. This represents the error associated with one correction for discontinuity in the area-mean ratio method. The frequency of this error is exactly equal to that of $v(\Delta)$ already in Eq. (1). Since the error is assumed independent of year, this error term may now be expressed as

$$\frac{\gamma' y(2/9)v(\epsilon)}{N(1-\gamma)}.$$

In this area-mean approach the effect of stations entering or leaving the record permanently is considered by computing the positive or negative bias each station supplies to the district mean. One of these deviations may be expressed as

$$d_{k-\cdot,y}=T_{k,y}-\bar{T}_{\cdot y},$$

where $T_{k,y}$ has error variance $v(\delta_{ky})$, $\bar{T}_{\cdot y}$ has error variance $v(\delta_{ky})/n_y$, and n_y is the number of stations in year y used to calculate the mean. The variance is

$$v(d_{k-\cdot,y})=v(\delta_{ky})+\frac{1}{n_y}v(\delta_{ky})-\frac{2\rho}{\sqrt{n_y}}c(\delta_{ky}\delta_{ky}),$$

where the correlation coefficient, $\rho=1$, $c(\delta_{ky}\delta_{ky})=v(\delta_{ky})$ and

$$v(d_{k-\cdot,y})=v(\delta_{ky})+\frac{1}{n_y}v(\delta_{ky})-\frac{2}{\sqrt{n_y}}v(\delta_{ky}).$$

Using (3) and assuming previous arguments, this simplifies to

$$v(d_{k-\cdot,y})=\tfrac{1}{2}v(\epsilon)\left(1-\frac{1}{\sqrt{n_y}}\right)^2.$$

But, since an average $d_{k-\cdot,y}$ was calculated on the basis of 15 cases (five years times three months) immediately before and after a station leaves the record,

$$v(\bar{d})=\frac{1}{15}\left[\tfrac{1}{2}v(\epsilon)\left(1-\frac{1}{\sqrt{N}}\right)^2\right],$$

where N has been substituted for n_y.

Since this discontinuity is also quite infrequent, usually with either 0 or 1 case each year, its frequency of occurrence may be expressed by the same formula as was $v(\Delta)$ in Mitchell's original area-mean index variance formula (1),

$$\frac{\gamma' y\left(1-\frac{1}{\sqrt{N}}\right)^2 v(\epsilon)}{N(1-\gamma)30}.$$

Thus, the area-mean index error E_w variance for this study may be expressed as

$$V(E_w)=\frac{2\gamma v(C)+(2/9)\gamma' yv(\epsilon)+\left(\frac{1}{30}\right)\left(1-\frac{1}{\sqrt{N}}\right)^2\gamma' yv(\epsilon)+v(\epsilon)}{N(1-\gamma)},$$

and the ratio of Mitchell's tau index to our area-mean index may be calculated as

$$K^2=\frac{V(E_y)}{V(E_w)}=\frac{(1-\gamma)}{(1-2\Gamma)}\cdot\frac{1+(y-1)(2\Gamma-\gamma)}{2\gamma R^2+(2/9)\gamma' y+\left(\frac{1}{30}\right)\left(1-\frac{1}{\sqrt{N}}\right)^2\gamma' y+1},$$

where $R^2=v(C)/v(\epsilon)$. Using Mitchell's seasonal indices of

$$\gamma=0.05 \qquad \Gamma=0.076$$
$$\gamma'=0.06 \qquad R^2=4$$

and using the 47-year period and the average of 10 stations per district, the calculated ratio is $K^2=3.05$. This states that the error variance for the tau method is likely to be three times greater for seasonal values than the modified area-mean method utilized in this study.

As a test of the parameter values supplied by Mitchell, the parameters were calculated with a random sample of data from the East Central Climatological Division in Indiana. The estimated values of γ, γ' and R^2 for this district were similar to those supplied by Mitchell. We believe that the increased accuracy of the modified area-mean index method justifies the extra work involved.

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