A Model to Estimate the Time of Observation Bias Associated with Monthly Mean Maximum, Minimum and Mean Temperatures for the United States

THOMAS R. KARL, CLAUDE N. WILLIAMS, JR. AND PAMELA J. YOUNG
National Climatic Data Center, Asheville, NC 28801

WAYNE M. WENDLAND
Illinois State Water Survey, Champaign, IL 61801

(Manuscript received 4 April 1985, in final form 27 July 1985)

ABSTRACT

Hourly data for 79 stations in the United States are used to develop an empirical model which can be used to estimate the time of observation bias associated with different observation schedules. The model is developed for both maximum and minimum monthly average temperature as well as monthly mean temperature. The model was tested on 28 independent stations, and the results were very good. Using seven years of hourly data the standard errors of estimate using the model were only moderately higher than the standard errors of estimate of the true time of observation bias. The physical characteristics of the model directly include a measure of mean monthly interdiurnal temperature differences, analemma information, and the effects of the daily temperature range due to solar forcing. A self-contained computer program has been developed which allows a user to estimate the time of observation bias anywhere in the contiguous United States without the costly exercise of accessing 24-hourly observations at first-order stations.

1. Introduction

In the United States the importance of standardizing the method of calculating monthly mean temperatures was recognized as early as 1876 (Schott, 1876). The current practice of calculating monthly mean temperatures in the United States is to sum the daily maximum and minimum temperatures, divide by two, and find the average of these values over the month. At the first-order stations the daily maximum and minimum temperatures are derived from the 24-hour period corresponding to the standard calendar days, i.e., midnight to midnight. The vast majority of weather stations in the United States, however, are not first-order stations. Cooperative weather stations measuring temperature (approximately 5,000 in the United States) are staffed by volunteer weather observers, and as Mitchell (1958) points out, there is an understandable reluctance on the part of the observers to read their extreme thermometers at midnight. As a result the cooperative weather observers operate on a climatological day which does not necessarily correspond to the calendar day. When the ending time of the 24 hours of the climatological day varies from station to station or over a period of years at a given station, then a nonclimatic time of observation bias is introduced into the monthly means (and daily means). These biases have been thoroughly documented by Mitchell (1958), and more recent work has addressed the problem on a more local basis (Baker, 1975; Schaal and Dale, 1977; Winkler et al., 1981; Blackburn, 1983; Head, 1985).

In the United States there has been a systematic change in the preferred ending time of the climatological day. The instructions for cooperative weather observers measuring temperature (Weather Bureau, 1935, 1941, 1952; National Weather Service, 1972) recommend that maximum and minimum temperatures be recorded for the 24 hours ending near sunset (between 1700 and 2000 LST). About 75% (of a total of 3317) of the weather observers followed this schedule until the 1940s. Since that time many observers have changed their observation schedules to conform with the time precipitation measurements are needed (morning hours) for hydrological operational requirements (Schoun; personal communication, 1985), and now only about 45% (of a total of 5,392) record their previous 24-hour maximum and minimum temperature during the late afternoon hours (Table 1). Currently, one of the most frequent A.M. observation times is near 0700 LST and one of the most frequent P.M. observation times is near 1700 LST. Even a cursory investigation of the history of observation times at a handful of stations indicates that it is rare to find cooperative stations with uniform observing times throughout their history, and in many instances observers have changed their time of observation several times in a single decade.

Detailed spatial or temporal studies of climate in the

TABLE 1. Percent of A.M. (0100 to 1100 LST), P.M. (1200 to 2100 LST), and MD (2200 to 0000 LST) cooperative weather station in the United States.

Year	a.m. (%)	p.m. (%)	MD (%)
1931	14	79	7
1941	15	76	9
1951	19	65	16
1965	25	64	11
1975	34	55	11
1984	42	47	11

United States are frequently required to draw upon data from a denser network than the first-order stations and/or stations away from highly urbanized climates. This places added emphasis on the cooperative station network. The ever-present time of observation bias, however, presents difficulty in using these stations for detailed spatial analyses or in investigations of climate fluctuations or change. For these reasons we developed a procedure which requires a minimum of input from the user to estimate the time of observation bias for any ending hour of the climatological day for any location in the United States during any month of the year, applicable to the maximum, minimum and mean temperature.

2. Preliminary concepts

The term "time of observation bias" (TOB) in this article is defined as the difference between the monthly mean temperatures derived from a station which ends its climatological day at midnight (local standard time) and the same station which ends its climatological day at any other time. In Fig. 1 the time of observation bias for Bismarck, North Dakota is seen to vary substantially by hour, season, and even for the temperature element of interest. Bismarck is shown for illustration, although any station could have been used. We have defined two time of observation biases in Fig. 1, drift and drift-removed time of observation bias. The TOB with drift (hereafter referred to simply as TOB) includes the effects of month-end temperatures (i.e., hourly temperatures from the last day of the previous month incorporated into a 24-hour mean of the first day of the following month) on the mean temperature. The drift-removed curves have this effect removed. Blackburn (1983) discusses this problem. The bias due to drift is most pronounced during the transition seasons as evident in Fig. 1. The TOB during the fall and spring months around 0100 LST is substantially larger than that observed during the winter and summer (Fig. 1). This occurs because the observer who ends the climatological day at 0100 LST records the maximum, minimum, and mean temperature on the first of each month based on 23 hours of the previous calendar day and month, and only one hour of the current calendar day and month. This effectively forces the months during seasons when the mean monthly temperature is decreasing (i.e., the fall) to have a positive TOB around 0100 LST and the opposite effect during spring. This effect is mitigated with each succeeding hour after 0100 LST, and by 2400 LST it vanishes. The end-of-month temperature bias can be removed by using Eq. (1),

$$\mathrm{DCTOB}_i = \mathrm{TOB}_i - (T_{\mathrm{mo}} - T_{\mathrm{mo}-1})[(24 - i)/24] \quad (1)$$

where DCTOB_i is the drift corrected TOB for hour i, T_{mo} is the calendar day monthly mean temperature for month (mo), and $T_{\mathrm{mo}-1}$ is the calendar day monthly mean temperature for month (mo) with the last day of the month replaced with the last day of the previous month. Equation 1 has been used to obtain the drift-removed plots in Fig. 1. The TOB attributed to the end-of-month effect is of some importance, but it is not the primary cause of the total TOB bias.

There are two properties of a temperature series that are necessary to produce DCTOB. First, there must exist a nonzero mean monthly interdiurnal temperature difference (δ), and second, there must exist a diurnal temperature cycle (ρ) independent of δ. If either one of these two quantities is zero then the TOB is zero. Figure 2 demonstrates this principle. The six curves in Fig. 2 represent

a) A station without a diurnal cycle of temperature (whether such a station exists is not important for this argument), but with interdiurnal temperature difference $\delta = 10$.

b) A station with $\delta = 0$, but with a nonzero diurnal temperature cycle, $\rho = 20$.

c) A station with both a nonzero diurnal temperature cycle ($\rho = 20$) and nonzero interdiurnal temperature difference ($\delta = 10$). The time series for station C is equal to the sum of the temperatures at stations A and B. The value of $\rho = 2\delta$.

d) A station with nonzero δ and ρ, and $\delta = \rho = 10$.

e) A station with nonzero δ and ρ, and $\delta = 10$, $\rho = 4$.

f) A station with nonzero δ and ρ, and $\delta = 4$, $\rho = 10$.

Table 2 summarizes the daily maximum, minimum, and mean temperature for a midnight-to-midnight and a noon-to-noon observation schedule for a hypothetical month (February) using the six time series in Fig. 2.

Station C has nonzero δ and ρ, and as a result the TOB is 5°C, (cf. bottom row of station C in Table 2). At station D, δ is held constant with respect to station C, but ρ is reduced by 50% compared to station C. Despite this change in ρ the TOB[1] does not change indicating that δ was the limiting factor in determining the TOB at C. Station E has ρ reduced still further. Now ρ is only 40% of its value at station D, and it is

---

[1] In our example, the TOB and the DCTOB are identical. There is no drift in the daily mean temperature over the month of interest.

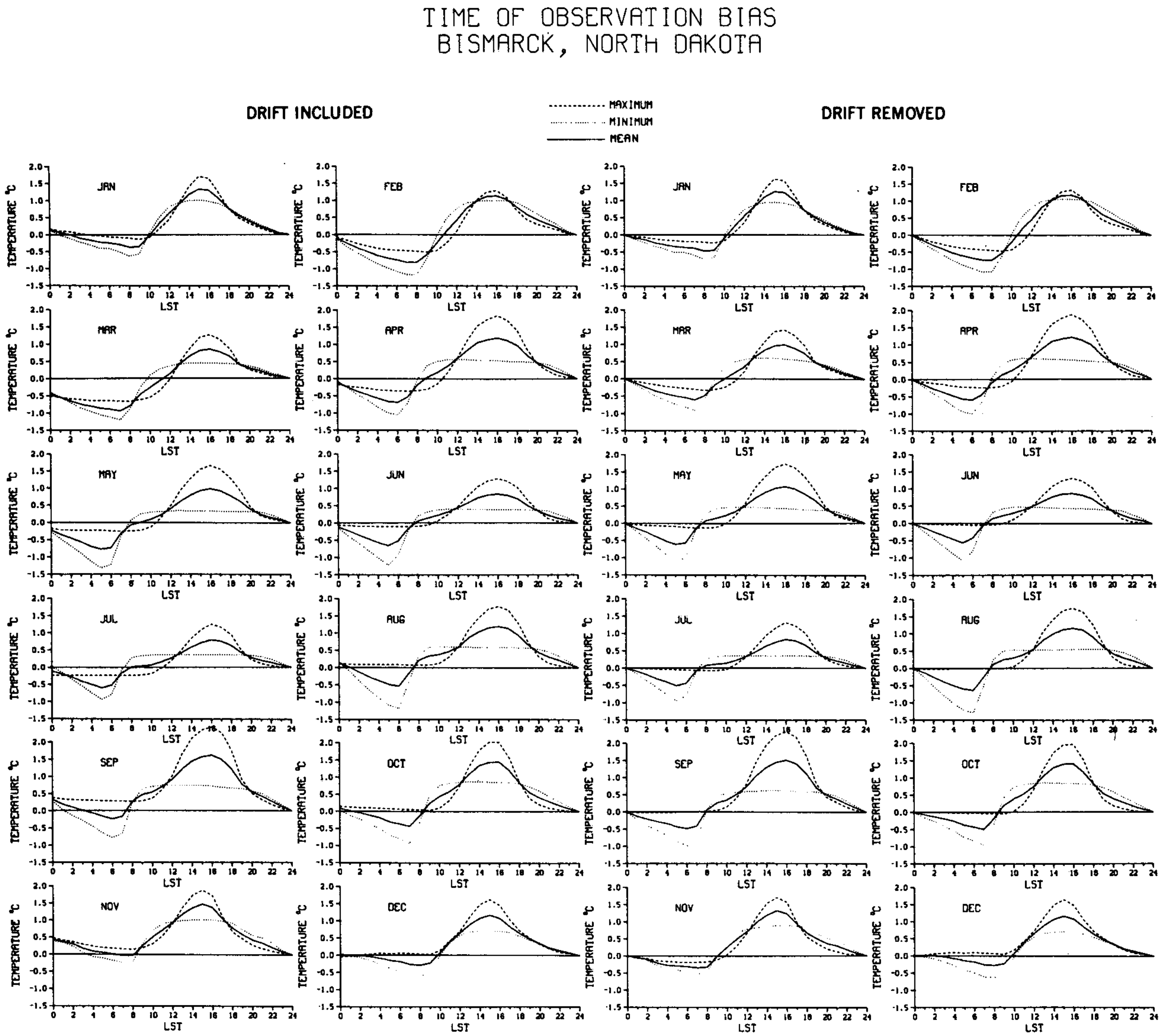

FIG. 1. Time of observation bias at Bismarck, ND for drift and drift-removed monthly mean temperature.

less than δ. At this station, ρ is the limiting factor of the magnitude of the TOB, and as a result the TOB = 2°C or 40% of its value at station D. For station F, δ is reduced by 40% of its value at station D, and now it becomes the decisive factor for the magnitude of the TOB. Again, similar to station E, the TOB is 40% of that calculated at station D. Of course, these examples are oversimplified, but they served us well in developing a strategy to predict the TOB at stations with varying δ and ρ.

Our choice of potential predictors in our model was guided by the examples in Fig. 2 and Table 2. A measure of δ and ρ are the two variables which will form the basis for any model to predict the TOB. The oversimplifications in our examples include the periodic behavior of the interdiurnal temperature difference averaged over 24 hours and an idealized diurnal temperature cycle. Often, much of the interdiurnal temperature difference is due to thermal advection. In practice, the diurnal temperature cycle due to solar forcings is altered, not only by thermal advection, but by changes in cloudiness, wind speeds, humidity, etc. This implies some days will have larger ρs than others, even after removing the effects of interdiurnal temperature differences. If a very small ρ is present (an overcast windy day) on a day with large δ, then ρ can be a limiting variable even if the monthly average of ρ is somewhat larger than δ. Additionally, the periodic behavior of δ in Fig. 2 leads to some unsettling properties, i.e., δ = 10°C for a midnight to midnight observer, but δ = 5°C as calculated from noon to noon (station A). We shall assume that the midnight-to-midnight value of δ is representative for all hours of the day. This turns out to be a very good assumption as

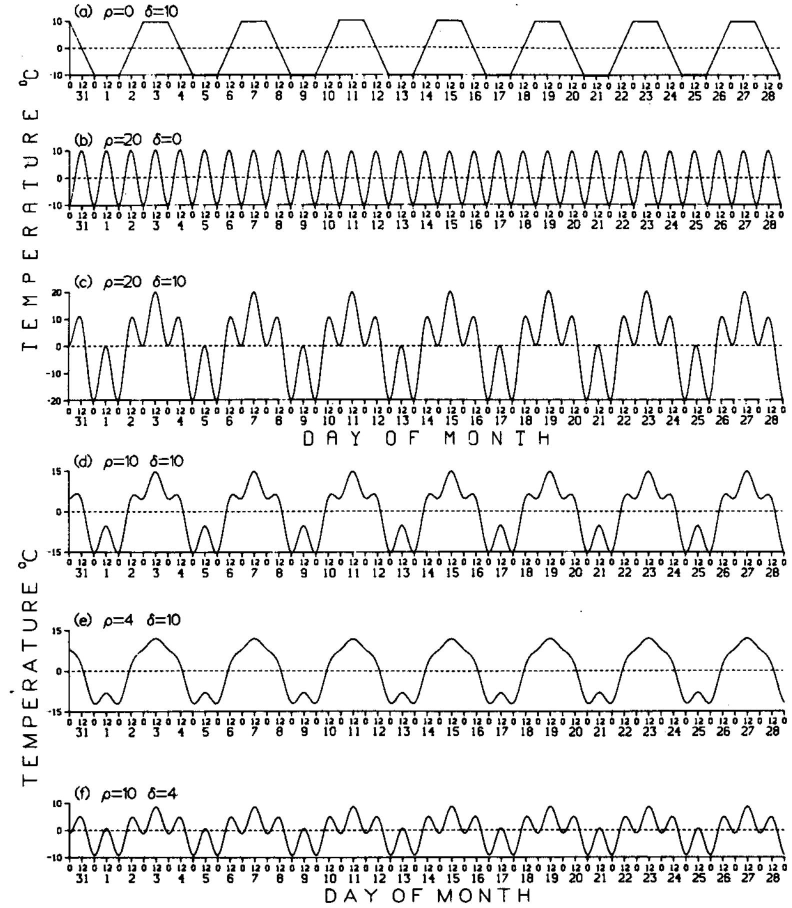

FIG. 2. Temperatures for a station with interdiurnal temperature variability only ($\delta = 10$), diurnal oscillation of temperature only ($\rho = 20$), and other stations with various combinations of δ and ρ.

there is very little evidence to indicate that thermal advection, a large contributor to δ, is dependent upon the time of day in any significant manner.

The importance of the TOB over the United States as derived from all 107 first-order stations in Fig. 3 (listed in the Appendix) is apparent in Fig. 4 by in-

TABLE 2. The maximum (Max), minimum (Min), and mean temperature for climatological days ending at noon and midnight (MD) based on the six hypothetical stations depicted in Fig. 2. The cycle of max, min and mean for days 1–4 repeat themselves 6 more times for days 5–28.

Day of	Noon-Noon			MD-MD			Noon-Noon			MD-MD			Noon-Noon			MD-MD		
month	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
	δ = 10 Station A ρ = 0						δ = 0 Station B ρ = 20						δ = 10 Station C ρ = 20					
1	0	−10	−5	−10	−10	−10	10	−10	0	10	−10	0	10	−20	−5	0	−20	−10
2	0	−10	−5	10	−10	0	10	−10	0	10	−10	0	10	−20	−5	10	−20	−5
3	10	0	5	10	10	10	10	−10	0	10	−10	0	20	0	10	20	0	10
4	10	0	5	10	−10	0	10	−10	0	10	−10	0	20	0	10	10	−20	−5
28	10	0	5	10	−10	0	10	−10	0	10	−10	0	20	0	10	10	−20	−5
Mean	5	−5	0	5	−5	0	10	−10	0	10	−10	0	15	−10	2.5	10	−15	−2.5
	δ = 10 Station D ρ = 10						δ = 10 Station E ρ = 4						δ = 4 Station F ρ = 10					
1	5	−15	−5	−5	−15	−10	2	−12	−5	−8	−12	−10	5	−9	−2	1	−9	−4
2	5	−15	−5	5	−15	−5	2	−12	−5	8	−12	−2	5	−9	−2	5	−9	−2
3	15	5	10	15	5	10	12	2	7	12	8	10	9	−1	4	9	−1	4
4	15	5	10	5	−15	−5	12	2	7	8	−12	−2	9	−1	4	5	−9	−2
28	15	5	10	5	−15	−5	12	2	7	8	−12	−2	9	−1	4	5	−9	−2
Mean	10	−5	2.5	5	−10	−2.5	7	−5	1	5	−7	−1	7	−5	1	5	−7	−1

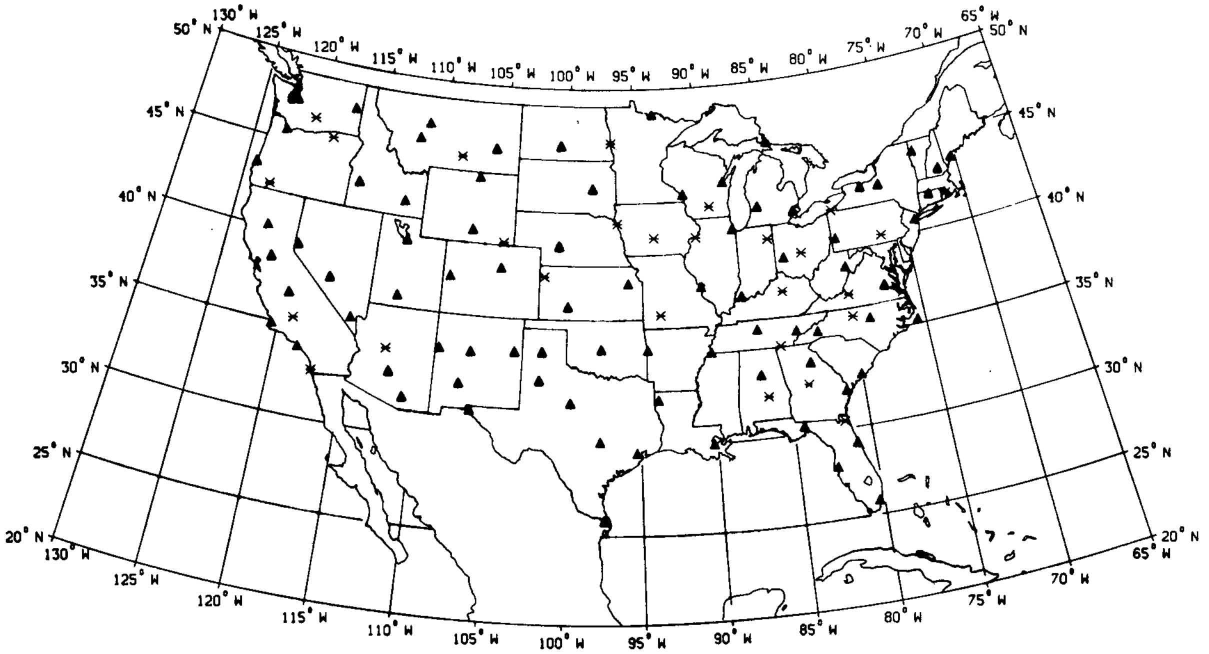

FIG. 3. Distribution of stations used in the development of the time of observation bias model (triangles), and stations used to test the model (asterisks).

spection of the difference field of mean monthly temperatures for two dissimilar climatological days. The differences are relatively large during the late fall, winter, and early spring compared to those during summer. The fact that there are pronounced seasonal and geographic differences is very important with respect to the potential predictability of the TOB. One word of caution is required regarding the interpretation of the patterns in Fig. 4. The isopleths suggest a continuous field, but discontinuities exist across changes in time zones. The steep gradient along the lee of the Rocky Mountains, for example, is considerably enhanced by the change of time zones from Central to Mountain time. For instance, if one station was situated 1 km east of the change in time zones in western Kansas and another 1 km west, the westernmost station's 0700 LST observation is comparable to that of 0800 LST of the eastern station, and likewise its 1700 LST observation is comparable to that of 1800 LST at the easternmost station. The TOBs at 0800 LST and 1800 LST in western Kansas are less than those at 0700 LST and 1700 LST. This effectively reduces the difference between the 0700 LST and the 1700 LST observation times at the westernmost station despite the fact that both locations would end their climatological day at the same local time. Similar effects occur along all the changes of time zones. The variability of true solar noon also affects the TOB within a time zone in a continuous manner from east to west or north to south, because of varying times of sunrise and sunset. The development of a physically realistic TOB predictive model must address these characteristics.

Despite the smooth appearance of the TOB in Fig. 1 there can be considerable variability of the TOB from year to year (Fig. 5). This year-to-year variability is attributed to the changes of δ and ρ from year to year due to differences in the timing of frontal passages, cloudiness, precipitation, etc. This variability has important implications for the development of predictive equations, and the use of such equations to calculate a TOB for a specific month of a given year. As indicated in Fig. 5 the TOB for any month and given year can be substantially different from the mean TOB. This suggests that estimates of TOB from a general model will be most appropriate when applied to a mean derived from a series of years. If the TOB for a specific year and month is important at a cooperative station then the hourly data for the year and month in question for a nearby first-order station can be used to give the best estimate of the TOB. The technique which we develop in this article is most appropriate when applied to means comprised of a series of years to estimate nonclimatic trends which are detrimental to spatial and temporal analyses of mean monthly maximum, minimum and mean temperature.

3. Data

Beginning in 1957 all United States first-order weather stations reported temperatures on the hour (actually read approximately 10–15 minutes before the hour). Prior to June of 1957 hourly temperatures were observed hourly, on the half-hour (U.S. Department of Commerce, 1970). Hourly temperatures (reported in whole °F) are available from the National Climatic Data Center (NCDC) for all first-order stations through

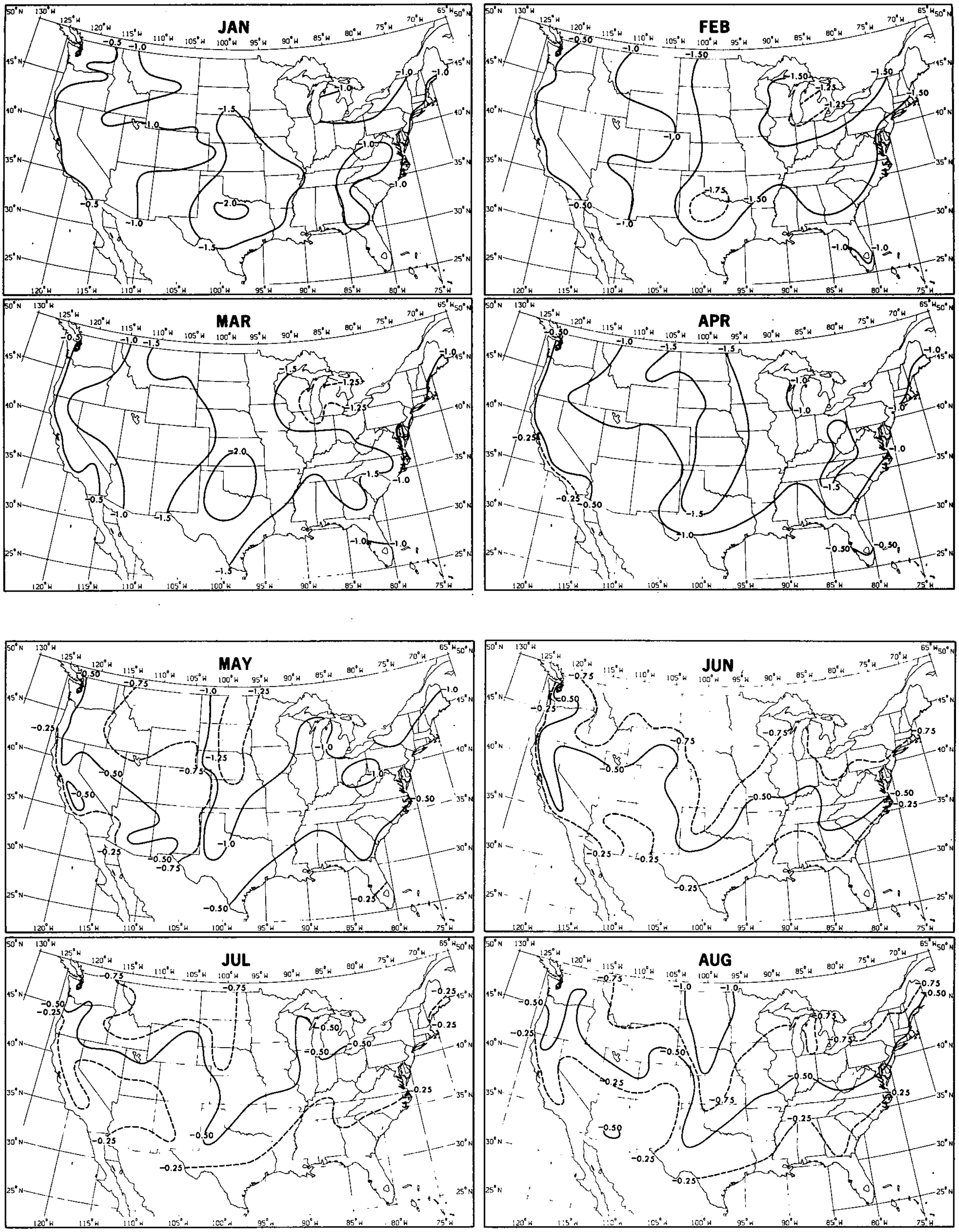

FIG. 4. Mean monthly temperature differences (°C) of a climatological day ending at 0700 LST minus 1700 LST.

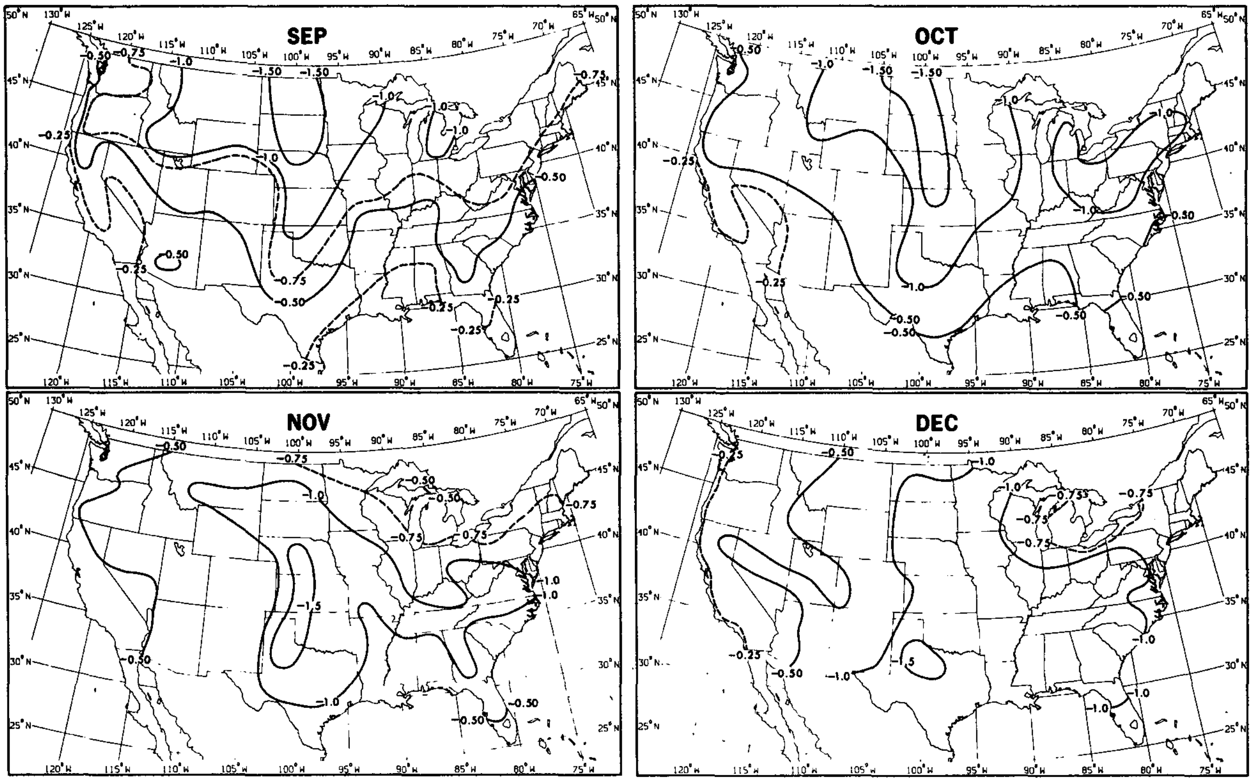

FIG. 4. (*Continued*)

1964. After 1964 only three-hourly data were routinely digitized onto magnetic tape. (Efforts are currently underway at NCDC to keypunch hourly data for many stations since 1965.) For these reasons seven years of hourly data (1958–64) were used at 107 first order stations in the United States to develop equations which can be used to predict the TOB (Fig. 4). Of these 107 stations, 79 were used to develop the equations, and 28 were reserved as an independent test sample.

The choice of stations was based on their spatial distribution and their station histories. Spatial station relocations were limited to less than 1500 m except for two stations—Asheville, North Carolina, and Tallahassee, Florida. These stations had relatively large station moves, 20 km and 5 km respectively, but they were retained because of their strategic location with respect to topography and major water bodies. At 72 of the 79 stations used to develop the TOB equations, temperature was recorded very close to 2 m above the surface. At the remaining seven stations, the instruments were repositioned from heights in excess of 5 m to those near 2 m sometime between 1958 and 1964. Changes in instrument heights from the 28 independent stations were more frequent: at nearly 50% of these stations the height of the instruments was reduced to 2 m above the ground from heights in excess of 5 m sometime in the same period.

The effects of changing instrument heights and station relocations, however, are probably less significant than the fact that hourly data were used to estimate the TOB rather than the actual highest (maximum) and lowest (minimum) temperatures during any 24-hour period (Mitchell, 1958). This latter effect was further investigated at four stations—Seattle, Washington; Bismarck, North Dakota; Tucson, Arizona; and Savannah, Georgia—by comparing the actual midnight-to-midnight maximum and minimum temperatures with those obtained from hourly data. The difference between the true 24-hour maximum as opposed to the highest of 25 hourly observations was nearly twice as great in summer as in winter, but less seasonal variation was noted for the minimum temperature (cf. Table 3). No systematic relationship between the magnitudes of the differences could be detected from the data of the four stations. Attempts were made to estimate the true maximum and minimum on a daily basis from the hourly data by using cubic splines, consideration of the random effects of rounding to the nearest whole Fahrenheit degree (about one-half Celsius degree), and hourly estimates of boundary layer stability based on the Pasquill stability categories (Doty et al., 1976). However, little success was achieved. We conclude, as do Collison and Tabony (1984) using data from England, that the failure of such methods suggests that

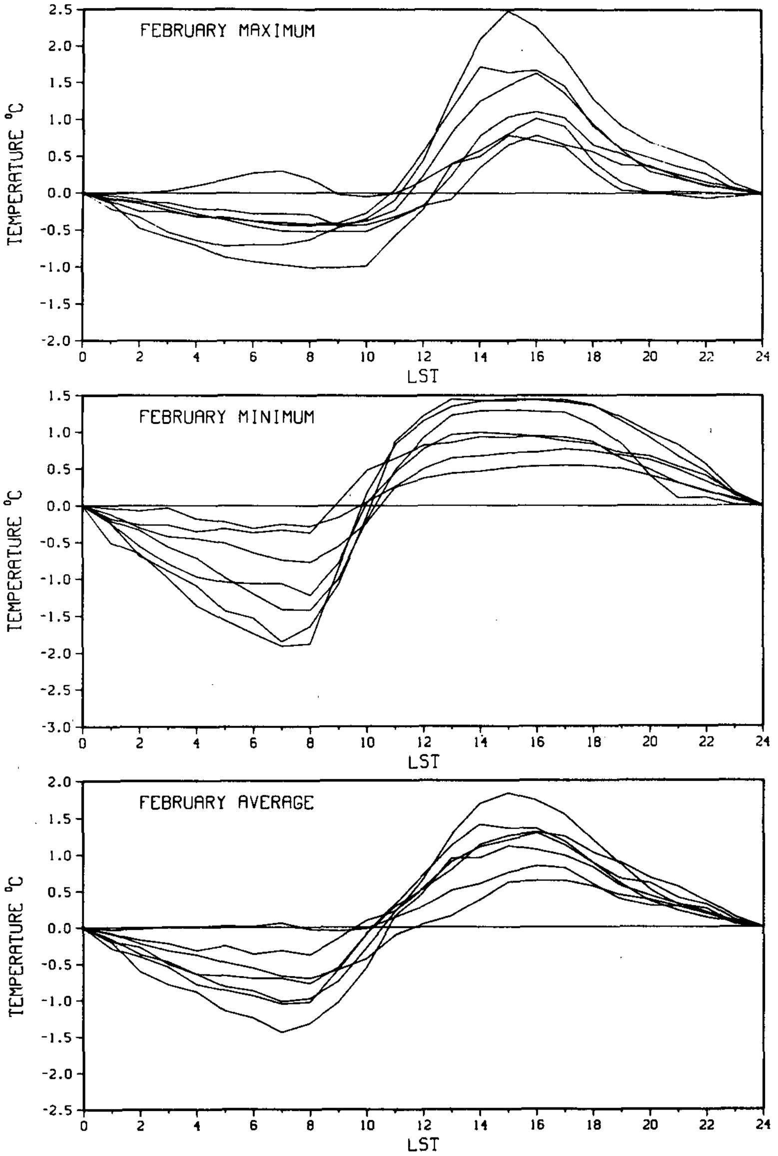

FIG. 5. Time of observation biases for each year 1958–64 for Bismarck, ND.

the actual daily maximum and minimum, relative to hourly readings, is the result of local site peculiarities and microscale processes, and is not well-related to synoptic-scale weather variations. For this reason we used site-specific average corrections to the hourly data to estimate the true daily maximum and minimum. For example, Table 3 depicts the average corrections to the hourly data for Bismarck to obtain the true daily maximum and minimum. These corrections were applied, and the TOB was calculated and compared to the TOB obtained without using the corrections. The differences were negligible, i.e., less than 0.03°C for all

TABLE 3. Mean difference of hourly maximum and minimum temperatures from the true 24-hour maximum and minimum temperature at Bismarck, ND.

Temperature difference	Month												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Maximum (°C)	−0.23	−0.31	−0.38	−0.43	−0.47	−0.53	−0.50	−0.50	−0.47	−0.35	−0.31	−0.25	−0.39
Minimum (°C)	0.54	0.50	0.46	0.47	0.44	0.44	0.41	0.43	0.44	0.44	0.53	0.58	0.47

months and hours for the four stations tested. In hindsight, this is not a surprising result because the effect of underestimating the maximum, and overestimating the minimum is only important on days with a carry-over (i.e., usually just prior or subsequent to a period when there is a significant change in the daily mean temperature) of the maximum or minimum temperature of the previous day. This carry-over is often much larger than the average difference between the true maximum (minimum) and the hourly maximum (minimum) (Fig. 2).

4. Development of the TOB model

a. The basic form of the model

The development of the TOB model is based on the concepts set forth in section 2. The goal of the model is to predict the TOB by using readily available climate information, and not resorting to hourly data at nearby first order stations. The approach taken was to use multilinear regression equations, i.e., the coefficients of equations are linear, but the equations themselves involve products or quotients of dissimilar variables. (In the traditional terminology of linear regression these terms are often referred to as the "interaction effects.") The form of the multilinear regression equation is given by Law et al. (1984). As related to our problem it can be defined by

$$\mathrm{DCTOB}_{\mathrm{mo},i} = a(\delta_{\mathrm{mo}}\rho_{\mathrm{mo}}B_{\mathrm{smo},i}) \qquad (2)$$

where the subscript i represents an hour of a specific month (mo) and smo represents the local solar month; a is a coefficient to be determined by a least-squares procedure, and B is the base curve for the maximum, minimum or mean temperature. The base curve B, is the time series of TOB_i averaged from all 79 dependent stations (triangles in Fig. 3) for each local solar month and hour, where the hours are averaged with respect to hours before or after sunrise. We have defined a local solar month by the maximum elevation of the sun above the horizon for the fifteenth of that month, for a given station location. Table 4 contains the class limits of the sun's elevation above the horizon for each of 12 solar months used in this study. We have arbitrarily chosen to divide the maximum solar elevation above the horizon into 12 categories across the United States. In practice this means that we actually average the base curve across the standard calendar months, but this prevents us from averaging across large latitudinal cross section of the country, i.e., from Florida to Maine. In this regard the general shape of the diurnal cycle of the DCTOB is more consistent than it would have been by averaging over the standard calendar months. An approximate form of Eq. (1) is used to obtain the TOB_i once the DCTOB_i has been estimated:

$$\mathrm{TOB}_i = \mathrm{DCTOB}_i + [(T_{\mathrm{ma}} - T_{\mathrm{mb}})/60][(i - 24)/24], \qquad (3)$$

where the subscript mb represents the month before mo, and ma represents the month after mo.

TABLE 4. The limits of the maximum solar elevation (degrees) above the horizon for each of the 12 solar months.

Solar month	Range of maximum solar elevation
1	$X < 22.5$
2	$22.5 \leqslant X < 28.5$
3	$28.5 \leqslant X < 34.5$
4	$34.5 \leqslant X < 40.5$
5	$40.5 \leqslant X < 46.5$
6	$46.5 \leqslant X < 52.5$
7	$52.5 \leqslant X < 58.5$
8	$58.5 \leqslant X < 64.5$
9	$64.5 \leqslant X < 70.5$
10	$70.5 \leqslant X < 76.5$
11	$76.5 \leqslant X < 82.5$
12	$X \geqslant 82.5$

TABLE 5. Percent of the total variance of the DCTOB explained by the base *B*.

Month	Maximum (%)	Minimum (%)	Mean (%)
Jan	81	89	88
Feb	85	86	88
Mar	85	89	90
Apr	87	88	91
May	83	83	84
Jun	77	73	78
Jul	76	74	78
Aug	79	72	80
Sep	78	76	81
Oct	84	82	86
Nov	83	88	89
Dec	80	85	86
Mean	81.5	82.1	84.9

b. The base curve (B)

The role of B in Eq. (2) can be regarded as an initial estimate of the DCTOB. Since B is categorized with respect to the time of sunrise and maximum solar elevation, its configuration is a good estimate of the DCTOB. By averaging with respect to maximum solar elevation we avoid combining locations like Bismarck, North Dakota, and Tallahassee, Florida, during the same calendar month; and by averaging with respect to hours before and after sunrise we mitigate the problems associated with east–west changes in sunrise within the various time zones (section 2; Fig. 4). The amplitude of B is greater for low compared to higher sun elevations.

The significance of B can be evaluated by simplifying Eq. (2) to

$$\mathrm{DCTOB}_{\mathrm{mo},i} = b(B_{\mathrm{smo},i}) \qquad (4)$$

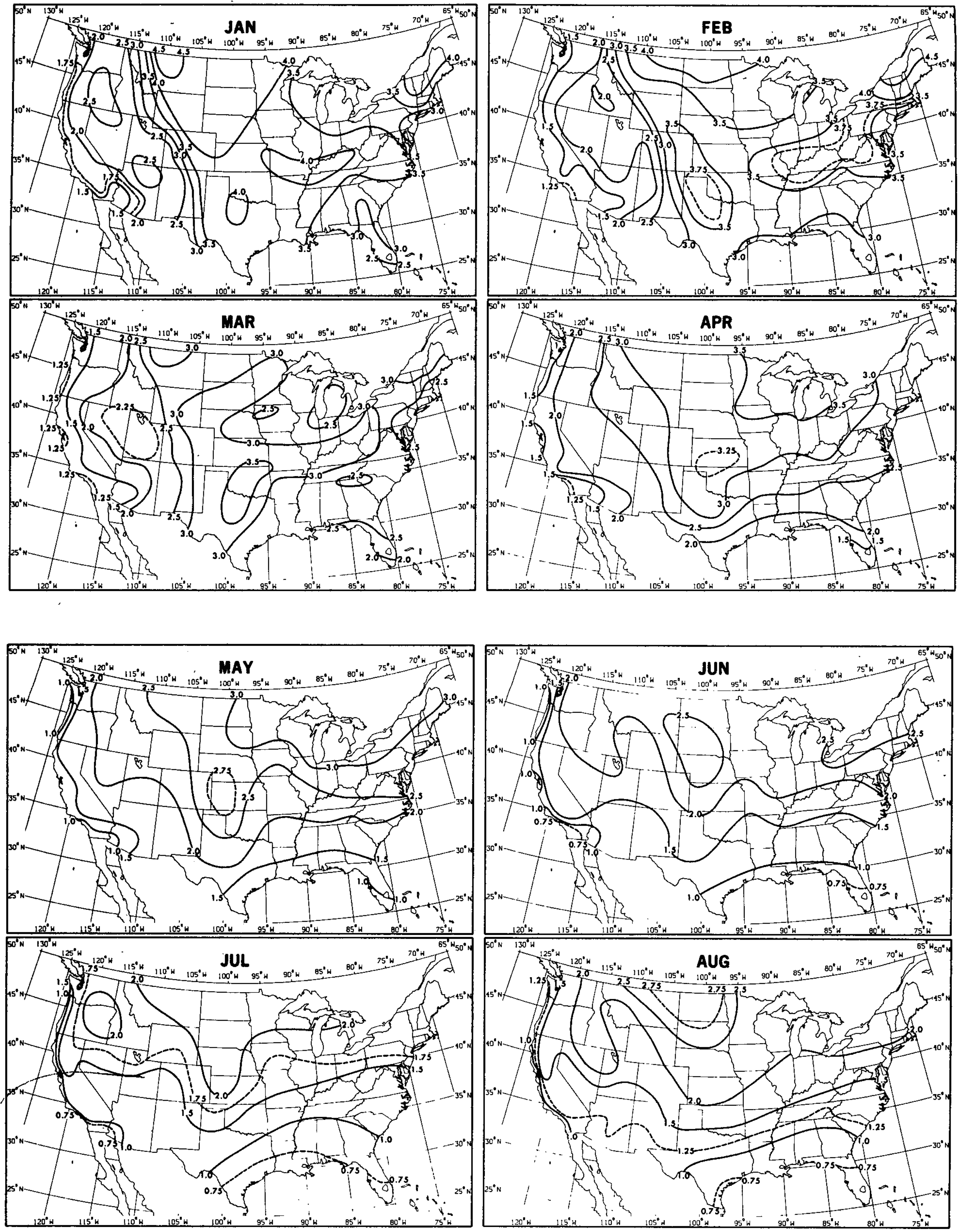

FIG. 6. Spatial patterns of interdiurnal mean temperature (°C) differences (δ).

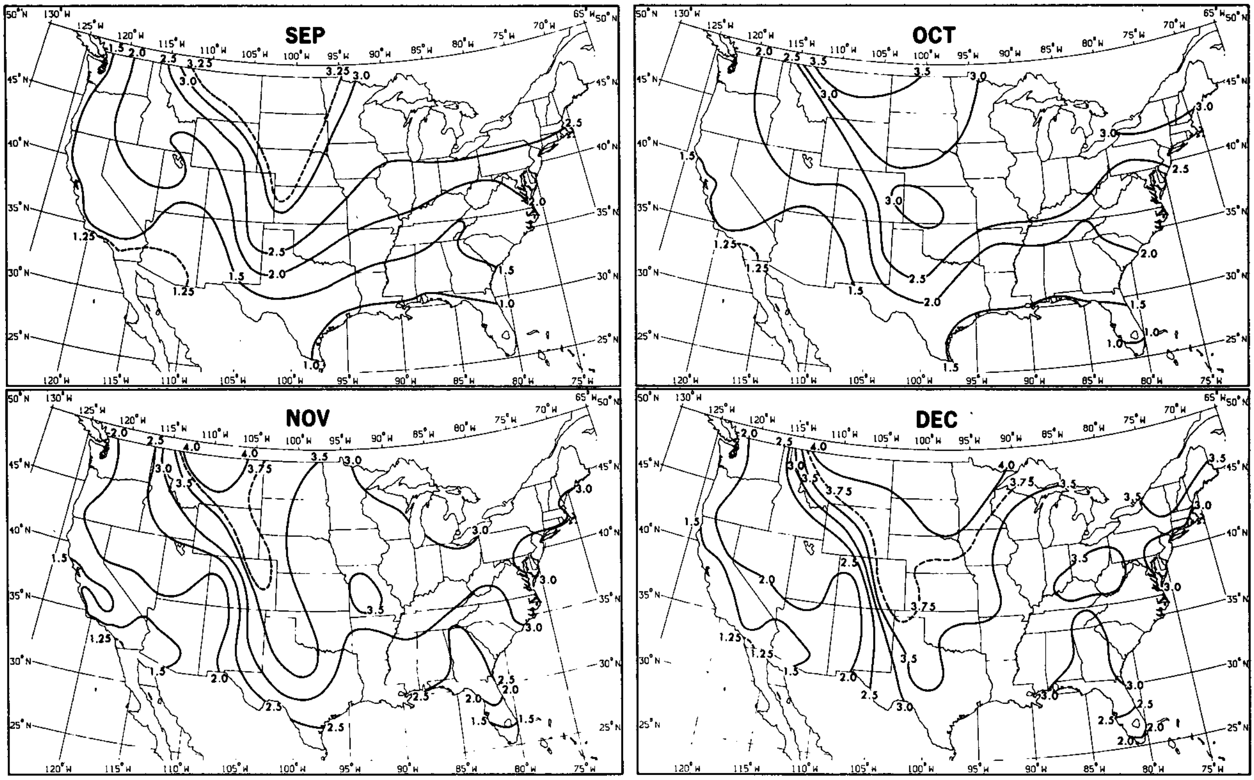

FIG. 6. (*Continued*)

The variance explained by B in Eq. (4) using data from all 79 dependent stations for each calendar month (Table 5) indicates that B is a very good initial estimate of the DCTOB. Of course, there is no possibility of obtaining any east–west gradients of the TOB using Eq. (4). From Fig. 4. we know that Eq. (4) is not an acceptable model.

c. Interdiurnal temperature differences (δ)

The 24-hour mean daily temperature was calculated for each station. Using this quantity the mean monthly absolute value of the day-to-day differences of the daily means (δ) was calculated for all stations. The spatial patterns of δ for each month are depicted in Fig. 6. The patterns indicate that this parameter is spatially coherent, and not subject to large spatial gradients except along the West Coast. This is a very desirable feature since it suggests that point values can be adequately estimated by simple interpolation from Fig. 6.

The values of δ at each of the 79 dependent stations were used to derive the coefficient c in the following bilinear equation:

$$\mathrm{DCTOB}_{\mathrm{mo},i} = c(\delta_{\mathrm{mo}} B_{\mathrm{smo},i}). \tag{5}$$

The effectiveness of such an equation is indicated in Table 6. The variance (R^2) of the TOB explained by Eq. (5) is extremely high during all months for the average temperature, somewhat lower (but still quite high) for the maximum temperature, and lower still for the minimum temperature. A comparison of Tables 5 and 6 indicates that the introduction of δ has improved estimates of the DCTOB for all months and all elements.

d. Diurnal temperature range less interdiurnal variability (ρ)

The diurnal temperature range attributed to the diurnal temperature cycle was calculated for each sta-

TABLE 6. Percent of the total variance of the DCTOB explained by B and δ.

	Maximum (%)	Minimum (%)	Mean (%)
Jan	93	91	93
Feb	94	91	94
Mar	91	92	95
Apr	93	90	95
May	93	89	94
Jun	90	84	91
Jul	88	82	89
Aug	90	81	91
Sep	91	85	94
Oct	93	89	95
Nov	90	92	95
Dec	85	89	91
Mean	90.9	87.9	93.1

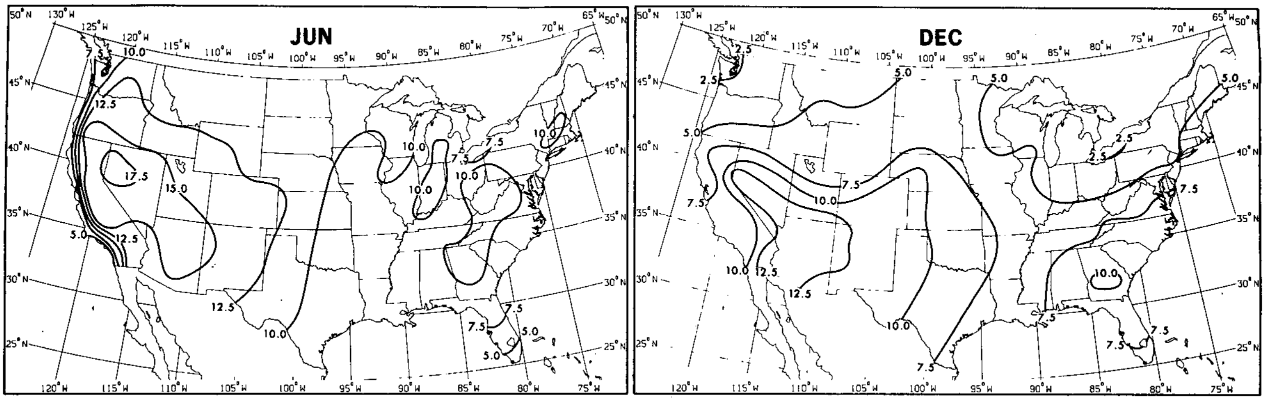

FIG. 7. Spatial patterns of ρ, the diurnal temperature (°C) range, after removing the effects of interdiurnal temperature variability.

tion by implicitly removing the effects of δ. This procedure involves the calculation of the hourly mean temperature for each month using all seven years of data. The difference between the highest and lowest hourly mean temperature is a measure of the diurnal temperature range (ρ) without the effects of the interdiurnal variability (δ), assuming that δ is independent of the time of day. The other procedure whereby the temperature range is calculated each day and averaged across each month and year, implicitly contains some effects of interdiurnal temperature differences, δ. The magnitude and the spatial patterns of ρ are depicted for the two solstice months in Fig. 7. There is considerable spatial variation of ρ within a month and between these two months as well. The north–south gradient of ρ is relatively large during December, at least partially due to the relatively low solar insolation at the higher latitudes, and relatively little cloud cover in the Southwest. During summer the gradient of ρ has virtually vanished in the eastern United States. The most important aspect of Fig. 7 however, is the magnitude of ρ with respect to that of δ (Fig. 6). We see that ρ is usually much larger than δ. Only during December at the northern stations do we find values of ρ nearly equal to δ. Based on our examples in Fig. 2 and Table 2 this indicates that ρ may be superfluous to the TOB model during many months.

The variance explained by the use of ρ, δ, and B [Eq. (2)] for each element indicates the addition of ρ actually reduces the total variance explained by the model (Table 7). When the variation of ρ is reduced by scaling to the 0.5 power before introducing it into Eq. (2), the variance explained by Eq. (2) increases (Table 7), but with respect to Table 6 not enough to warrant the general inclusion of ρ into the model. December is the only month when ρ enhances the value of Eq. (2) with respect to that of Eq. (5). An F-test indicates that the increase in variance explained with the addition of ρ is significant at the 0.01 level for both the maximum and mean temperature. This is attributed to the magnitude of δ and ρ at the northerly locations during this time of the year. In fact, a significant portion of the increase of variance in Eq. (5) is due to better estimates of the TOB at the most northerly locations. In December the use of Eq. (2) tends to overpredict the TOB at the most northerly stations for all three elements considered: maximum, minimum, and the mean. Since Eq. (5) explains a few percent more than the total variance of the DCTOB explained by Eq. (2), and it is simpler than Eq. (2), we prefer Eq. (5) for all months except December; in December we use Eq. (2). We do not expect the DCTOB determined from Eq. (5) to apply to stations on isolated mountain peaks where ρ may be substantially less than δ. Even during December however, we do not expect very good results at these remote locations from Eq. (2), unless one has a reasonable estimate of ρ. On the other hand, no systematic error with respect to elevation was evident when Eqs. (2) and (5) were applied to our data set.

5. Independent tests using the TOB model

Equations (2), (3) and (5) were used to calculate the TOB at 28 independent stations for maximum, min-

TABLE 7. Percent of the total variance of the DCTOB explained by the B curve, δ, and ρ. Numbers in parentheses reflect the total variance for the same variables except the square root of ρ is used instead of actual values.

Month	Maximum (%)	Minimum (%)	Mean (%)
Jan	88 (89)	85 (90)	90 (94)
Feb	91 (92)	87 (91)	92 (95)
Mar	90 (92)	87 (91)	91 (95)
Apr	91 (93)	87 (89)	92 (94)
May	90 (92)	86 (88)	90 (93)
Jun	85 (89)	78 (82)	80 (89)
Jul	80 (85)	75 (79)	83 (85)
Aug	86 (89)	73 (78)	89 (88)
Sep	90 (92)	79 (83)	90 (92)
Oct	91 (94)	84 (88)	95 (94)
Nov	90 (92)	85 (90)	91 (95)
Dec	88 (89)	83 (89)	89 (93)
Mean	88.3 (90.7)	82.4 (86.5)	88.4 (92.3)

imum, and mean temperatures for all 12 months. The TOBs were predicted using a computer program which required as input the following quantities: month of interest, latitude, longitude, mean temperature of previous month, and mean temperature of the subsequent month. The values of δ and ρ for the 79 dependent stations and an additional 23 points along areas of sharp gradients, i.e., mainly West Coast locations, provided a grid of values for δ and ρ. In order to obtain δ and ρ between grid points a quadrant scan was made to detect the nearest grid point within each quadrant. A simple linear interpolation scheme was then applied to obtain the appropriate value for the specific location. The only restriction included the following distance check: if a station was more than 750 km from the interpolated position it could not be used. This is potentially important for stations located along borders of the United States so that stations in Florida are not used in interpolations in Texas, etc. Figure 8 summarizes these results for all 28 stations. The 16 and 84% confidence limits reflect the average uncertainty of the observed TOB at any single station. This is defined by using the sample standard deviation s of the hourly estimates of the true TOB for each month (cf. Fig. 5) to obtain the uncertainty s_u associated with the estimate of the true TOB at each station. The result is $s_u = s/\sqrt{n}$, where n is the number of years of data. The values of s_u are pooled from all 28 stations to obtain the 16 and 84% (one sigma) confidence limits in Fig. 8 (the "I's"). The two thick curves represent the standard deviation of the observed TOB minus the predicted TOB from all 28 stations. The thin curve represents the average TOB predicted by the model, and it is used to detect bias, i.e., the tendency to consistently over- or under-predict.

The only indication of bias for the maximum temperature appears during the early morning hours in January and October, but even during these hours the model average is just barely outside the confidence interval of the observed TOB (e.g., the thin line beyond the confidence limits). The standard error of prediction varies from approximately 0.10 to 0.20°C near sunrise which is nearly as large as the actual TOB, but during the afternoon hours the standard error of prediction is usually between 0.15 and 0.30°C which is approximately one-fourth of the TOB.

The standard error of prediction for the minimum temperature at sunrise is 0.2–0.3°C at a time when the actual TOB is about three times as large. During the afternoon the standard error of prediction is reduced to 0.10–0.15°C or about one-third of the actual TOB bias. Figure 8 indicates a tendency to overestimate the TOB during the early morning hours in April, but to

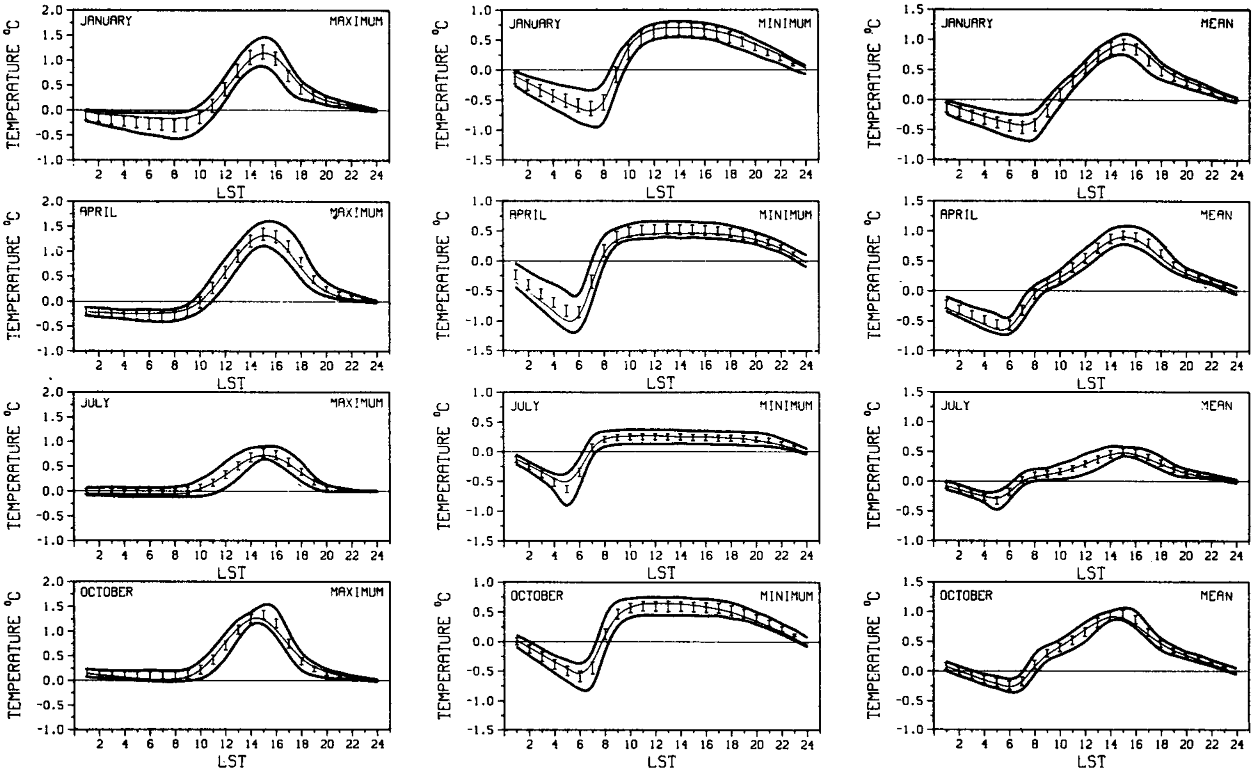

FIG. 8. Standard error of prediction of the model estimates of the TOB (two bold curves), the mean estimate of the TOB derived from the TOB model (thin curve), and the 16 and the 84% confidence limits of the mean observed TOB (capital "I") for all 28 independent stations. Cubic splines were used to smooth each curve.

underestimate during July. This may have arisen largely by chance since the months on either side of these two months have considerably less bias, and actually change sign for two of the four adjacent months.

The standard error of prediction for the mean temperature varies from approximately 0.15–0.20°C around sunrise to approximately 0.10–0.20°C during the afternoon. This is only moderately larger than the corresponding confidence limits for the estimate of the true TOB, and is about two to three times smaller than the observed TOB around sunrise, and about five times smaller than those during the afternoon. The average of the TOB predicted by the model (thin line Fig. 8) does not depict any serious over- or under-prediction, as the model predictions usually fall within the confidence limits during all hours of each month.

Similar to the results in the developmental data set the TOB model equations perform slightly better for the mean temperature compared to the maximum or minimum separately. This is not surprising since the influence of δ and ρ is spread over a greater time span, i.e., two values (maximum and minimum temperature) usually separated by several hours. The TOB model is least effective during the early morning hours for the maximum temperature because for this element this is a time when the TOB is relatively small.

6. Conclusion

We have shown that the TOB in the United States can be quite large—as much as 2°C—and that the difference in biases, e.g., when the observation time changes from the late afternoon to near sunrise, is even greater. We find a significant increase of "A.M." observers with the demise of "P.M." observers. This often means that spatial or temporal analyses of climate, especially climate change, based on cooperative weather stations must adjust the observations for the TOB.

We have developed a TOB model which can be used to estimate the TOB with reasonable accuracy at any location in the contiguous United States. The model is based on physically realistic principles. It should be generally applicable except for locations where the monthly mean diurnal temperature range (less interdiurnal variability) is less than the monthly mean interdaily temperature difference. Only small areas of the United States are exclusive to this method such as might be found on high mountain peaks. The main advantage of this model is that it eliminates the cumbersome task of obtaining hourly data at first-order stations, and then calculating and interpolating the TOB to the location of interest.

An ANSI (American National Standards Institute) FORTRAN-77 computer program is available from the authors at cost which includes the TOB model presented and tested herein. In this program we use data from 109 stations to fix δ and ρ, as well as the 23 additional points located in areas of sharp gradients. The program is written as a subroutine and requires the following specification: latitude of station, longitude of station, month of interest, hour of interest, estimate of the mean temperature of the subsequent month, and an estimate of the mean temperature of the previous month. Users can override the program's estimate of δ and ρ by entering their own values. The subroutine returns the TOB with respect to daily readings taken at midnight.

Acknowledgments. Thanks are due Mr. Ron Baldwin and Ms. Phala Franks for their assistance with the computer processing, and to the Information Management Section of the National Climatic Data Center (NCDC) for the typing of the manuscript. Much of this work was funded by the NCDC, but additional funds were provided by the Department of Energy, Carbon Dioxide Research Division under Grant DE-AC02-83ER60162, and by the National Climate Program Office through Grant COMMNA81AAD00112.

APPENDIX

Development and Test Station List

Development Stations				Test Stations			
Station, State	Lat (N)	Long (W)	Elevation (m)	Station, State	Lat (N)	Long (W)	Elevation (m)
Miami, FL	25°49′	80°17′	2	Jacksonville, FL	30°25′	81°39′	7
Brownsville/Rio Grand, TX	25°54′	97°26′	5	Montgomery, AL	32°18′	86°24′	60
Tampa, FL	27°58′	82°32′	7	Macon, GA	32°42′	83°39′	109
Daytona, FL	29°11′	81°03′	9	San Diego, GA	32°44′	117°10′	6
Houston/Hobby, TX	29°39′	95°17′	15	Prescott, AZ	34°39′	112°26′	1529
New Orleans/Moisant, LA	29°59′	90°15′	1	Chattanooga, TN	35°02′	85°12′	205
Austin, TX	30°18′	97°42′	187	Bakersfield, CA	35°25′	119°03′	149
Tallahassee, FL	30°26′	84°19′	20	Greensboro, NC	36°05′	79°57′	272
El Paso, TX	31°48′	106°24′	1195	Norfolk, VA	36°53′	76°12′	8
Tucson, AZ	32°07′	110°56′	788	Springfield, MO	37°14′	93°23′	386
Savannah/Travis, GA	32°08′	81°12′	12	Roanoke, VA	37°19′	79°58′	363
Abilene, TX	32°26′	99°41′	534	Lexington, KY	38°02′	84°36′	298
Shreveport, LA	32°33′	93°46′	53	Goodland, KS	39°22′	101°42′	1113
Charleston, SC	32°54′	80°02′	12	Columbus, OH	40°00′	82°53′	248
				Harrisburg, PA	40°13′	76°51′	102
				Fort Wayne, IN	41°00′	85°13′	244

APPENDIX (*Continued*)

Development Stations				Test Stations			
Station, State	Lat (N)	Long (W)	Elevation (m)	Station, State	Lat (N)	Long (W)	Elevation (m)
Truth or Consequences, NM	33°14′	107°16′	1469	Cheyenne, WY	41°09′	104°49′	1871
Phoenix, AZ	33°26′	112°02′	338	Moline, IL	41°27′	90°31′	180
Birmingham, AL	33°34′	86°45′	186	Des Moines, IA	41°32′	93°39′	29
Lubbock, TX	33°39′	101°50′	988	Providence, RI	41°44′	71°26′	17
Los Angeles, CA	33°56′	118°23′	30	Erie, PA	42°05′	80°11′	223
Athens/Ben Epps, GA	33°57′	83°19′	243	Medford, OR	42°22′	122°52′	401
Santa Maria, CA	34°54′	120°27′	73	Sioux City, IA	42°23′	96°22′	333
Albuquerque, NM	35°03′	106°37′	1618	Madison, WI	43°08′	89°20′	262
Memphis, TN	35°03′	89°59′	80	Pendleton, OR	45°41′	118°51′	454
Zuni, NM	35°06′	108°48′	1963	Billings, MT	45°48′	108°32′	1088
Tucumcari, NM	35°11′	103°36′	1234	Yakima, WA	46°34′	120°32′	322
Amarillo, TX	35°14′	101°42′	1094	Fargo, ND	46°54′	96°48′	273
Cape Hatteras, NC	35°16′	75°33′	2				
Fort Smith, AR	35°20′	94°23′	140				
Oklahoma City, OK	35°24′	97°36′	390				
Asheville, NC	35°36′	82°32′	671				
Knoxville, TN	35°49′	83°59′	290				
Raleigh/Durham, NC	35°52′	78°47′	134				
Las Vegas/McCarran, NV	36°05′	115°10′	659				
Nashville, TN	36°07′	86°41′	178				
Fresno, CA	36°47′	119°42′	101				
Richmond, VA	37°30′	77°20′	48				
Bryce Canyon, UT	37°42′	112°09′	2315				
Dodge City, KS	37°46′	99°58′	791				
Evansville, IN	38°02′	87°32′	117				
Tonopah, NV	38°04′	117°05′	1654				
Sacramento/Executive, CA	38°31′	121°30′	5				
St Louis, MO	38°45′	90°23′	168				
Elkins, WV	38°53′	79°51′	600				
Topeka, KS	39°04′	95°38′	268				
Grand Junction, CO	39°07′	108°32′	1478				
Reno, NV	39°30′	119°47′	1340				
Denver/Stapleton, CO	39°46′	104°53′	1613				
Dayton, OH	39°54′	84°12′	305				
Red Bluff, CA	40°09′	122°15′	104				
Pittsburgh, PA	40°30′	80°13′	351				
Newark, NJ	40°42′	74°10′	3				
Salt Lake City, UT	40°47′	111°58′	1287				
North Platte, NE	41°08′	100°42′	848				
Chicago/Midway, IL	41°47′	87°45′	186				
Rawlins, WY	41°48′	107°12′	2053				
Hartford, CT	41°56′	72°41′	52				
Detroit City, MI	42°25′	83°01′	189				
Grand Rapids, MI	42°54′	85°40′	208				
Pocatello, ID	42°55′	112°32′	1360				
Syracuse, NY	43°04′	76°16′	122				
Rochester, NY	43°07′	77°40′	166				
Concord, NH	43°12′	71°31′	103				
North Bend, OR	43°25′	124°15′	3				
Boise, ID	43°34′	116°13′	866				
Portland, ME	43°39′	70°19′	19				
La Crosse, WI	43°56′	91°17′	202				
Huron, SD	44°23′	98°13′	391				
Burlington, VT	44°28′	73°09′	101				
Green Bay, WI	44°29′	88°08′	210				
Sheridan, WY	44°46′	106°58′	1202				
Portland, OR	45°36′	122°36′	6				
Miles City, MT	46°26′	105°52′	801				
Sault Ste Marie, MI	46°28′	84°22′	220				
Helena, MT	46°36′	112°00′	1187				
Bismarck, ND	46°46′	100°45′	503				
Seattle/Tacoma, WA	47°26′	122°18′	116				
Great Falls, MT	47°29′	111°22′	1117				
Spokane, WA	47°37′	117°31′	718				
International Falls, MN	48°34′	93°23′	359				

REFERENCES

Baker, D. G., 1975: Effect of observation time on mean temperature estimation. *J. Appl. Meteor.*, **14**, 471–476.

Blackburn, T., 1983: A practical method of correcting monthly average temperature biases resulting from differing times of observation. *J. Climate Appl. Meteor.*, **22**, 328–330.

Collison, P., and R. C. Tabony, 1984: A comparison of daily maximum and minimum temperatures with the highest and lowest of 24 hourly observations. *Meteor. Mag.*, **113**, 337–341.

Doty, S. R., B. L. Wallace and G. C. Holzworth, 1976: A climatological analysis of Pasquill stability categories based on 'STAR' Summaries. National Climatic Center, Asheville, NC, 51 pp.

Head, D. E., 1985: Mean temperature biases as a function of the time of observation. 105 pp. [Available from North Central Regional Climate Center, Illinois State Water Survey, Champaign, IL 61820, NRCC Paper No. 6.]

Law, H. G., C. W. Snyder, Jr., J. A. Hattie and R. P. McDonald (Eds.), 1984: *Research Methods for Multimode Data Analysis.* Praeger Scientific, 36–40.

Mitchell, J. M. Jr., 1958: Effects of changing observation time on mean temperature. *Bull. Amer. Meteor. Soc.*, **39**, 83–89.

Schaal, L. A., and R. F. Dale, 1977: Time of observation temperature bias and "climate change." *J. Appl. Meteor.*, **16**, 215–222.

Schott, C. A., 1876: Tables, distribution, and variations of the atmospheric temperature in the United States and some adjacent parts of America. Smithsonian Contributions to Knowledge 277, Smithsonian Institution, XI–XV. pp. XI–XV. [Available from National Oceanic & Atmospheric Administration, Library & Information Services Division, 6009 Executive Blvd., Rockville, MD 20852.]

U.S. Department of Commerce, 1970: TD-1440 Surface airways reference manual. p. 1. [Available from National Climatic Data Center, Federal Building, Asheville, N.C. 28801.]

U.S. Weather Bureau, 1935: Instructions for cooperative observers. Circular B-C, 8th ed., p. 18. [Available from National Oceanic and Atmospheric Administration, Library & Information Services Divisions, 6009 Executive Blvd., Rockville, MD 20852.]

——, 1941: Instructions for cooperative observers. Circular B-C, 9th ed., p. 20. [Available from National Oceanic and Atmospheric Administration, Library & Information Services Divisions, 6009 Executive Blvd., Rockville, MD 20852.]

——, 1952: Instructions for Cooperative Observers. Circular B-C, 10th ed., p. 4. [Available from National Oceanic and Atmospheric Administration, Library & Information Services Divisions, 6009 Executive Blvd., Rockville, MD 20852.]

U.S. National Weather Service, 1972: National Weather Service Observing Handbook, No. 2, Revised December, 1972. p. 4. [Available from National Oceanic and Atmospheric Administration, Library & Information Services Divisions, 6009 Executive Blvd., Rockville, MD 20852.]

Winkler, J. A., R. H. Skaggs and D. G. Baker, 1981: Effects of temperature adjustments on the Minneapolis-St. Paul urban heat-island. *J. Appl. Meteor.*, 1295–1300.