# The Recent Maximum Temperature Anomalies in Tucson: Are They Real or an Instrumental Problem?

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ABSTRACT

Since 1988, what appears to be an abnormal number of maximum temperature records has been set at the National Weather Service Office in Tucson, Arizona (TUS). We present several analyses that indicate that the current measurement system at TUS is indicating daytime temperatures that are 2 to 3 degrees too high. It appears that the instrument is not appropriately aspirated so that, during the day, temperature readings are significantly warmer than ambient air temperatures, while at night they are slightly cooler. The system at TUS is similar to one that has been installed at many National Weather Service sites around the country. We speculate on the impact this system may have on the climate record if the errors noted at Tucson are similar at the other sites.

## 1. Introduction

In recent years, weather records at the Tucson International Airport (TUS) indicate what appears to be an abnormal number of days on which daily maximum temperature records were set. For example, during 1986 and 1987 maximum temperature records were set on 21 days and 23 days, respectively. In 1988 this increased to 38 days, and to 59 in 1989. More recently, however, the rate at which maximum temperature records were being broken appears to have decreased somewhat, with "only" 24 set between 1 January and 15 October 1990. On the other hand, minimum temperature records have not shown any trends similar to those of the maximum temperature records. The number of minimum temperature records in 1986 through 1990 were 6, 17, 4, 3, and 8, respectively.

These temperature records could be interpreted to imply that abnormally warm conditions, even record warmth, occurred in Tucson during 1988 and 1989, while the more recent record suggests a slight cooling. All-time temperature records were set during the last week in June 1990 over most of Arizona; however, that appears to be an isolated event when compared to the rest of the year. An alternative possibility is that changes in the instrumentation for measuring temperature at the National Weather Service (NWS) office at TUS are responsible for these warming and cooling "trends." There is evidence to suggest that this is the case.

Temperature records have been kept at the Tucson airport for more than 50 years. Through 1987, the highest temperature recorded was 111°F, which was reached on six dates. In 1988 and 1989, that record was exceeded or tied on eight occasions with maxima of 114°F on 4 June 1988 and 4 July 1989. When all-time record temperatures are being recorded at a particular station, it is probable that other nearby stations would also be setting daily records, if not all-time records. With one exception, in 1988 and 1989 there were no other stations within 1000 miles of Tucson that set any kind of record on the dates when the temperature in Tucson was at or above the previous all-time record. This is shown in Fig. 1, which displays all the stations that set records on the eight days when Tucson was at or over 111°F in 1988 and 1989. On two days, 19 June 1989 and 1 July 1989, Tucson was the only station in the continental United States to set a maximum record of any sort. On 5 July 1989, a record was also set in Phoenix.

In 1990, 111°F was equaled or exceeded on 7 days; however, 6 of those records were set between 20 June and 1 July, when record temperatures were being recorded all over Arizona, with maxima of 117°F and 122°F in Tucson and Phoenix, respectively. The only other date in 1990 where the temperature exceeded 111°F was 4 June, when the high reached 112°F.

The fact that records set in Tucson in 1988 and 1989 were isolated suggests a problem with the temperature measurement, rather than a real anomaly in weather patterns. Examination of all-time records alone is, of course, not a convincing way to demonstrate problems

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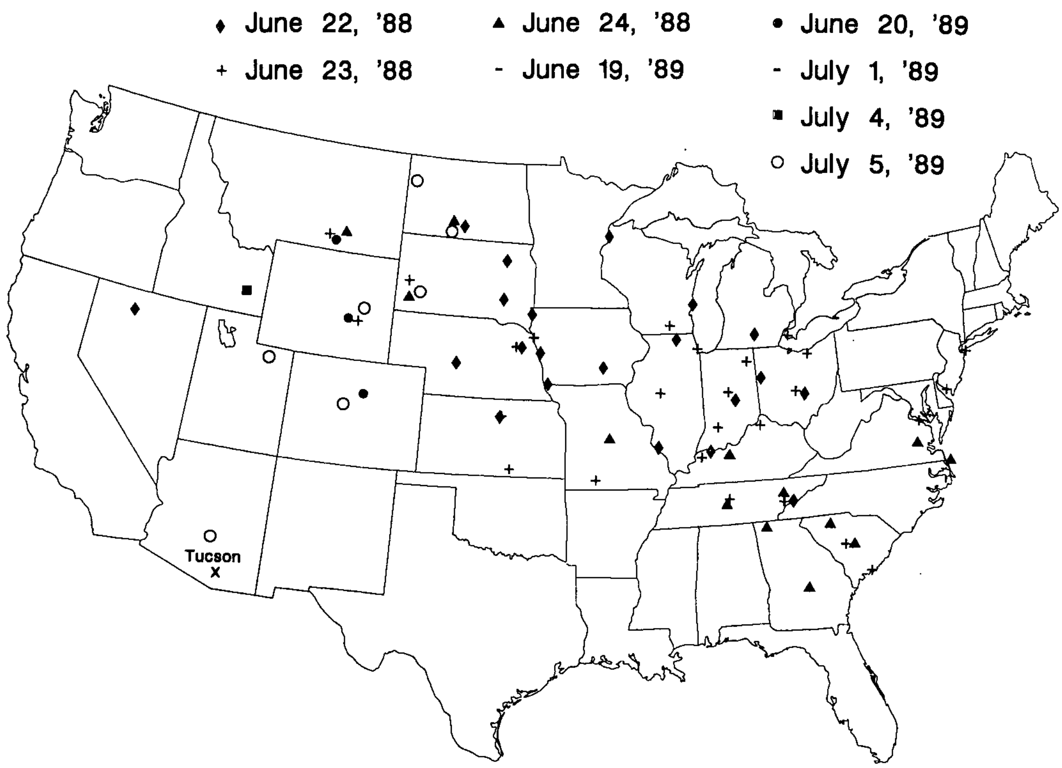


FIG. 1. Dates of days when the maximum temperature in Tucson equaled or exceeded 111°F in 1988 and 1989. The location of stations around the United States that also equaled or set at least a daily maximum temperature record on those dates are indicated. Before 1988, the all-time record temperature in Tucson was 111°F. The location of Tucson is marked by an ×.

with a measurement system. In the discussion that follows, we will employ a series of more powerful methods to explore this question. We conclude there is indeed a significant difference between the temperature measurements made with the current thermometer system at the Tucson Weather Service office and the one previously in use, such that daytime temperatures are reported to be roughly 2° to 3°F warmer with the new system. These differences would, of course, produce record readings only if the temperatures already were well above normal. Thus, 1988 and 1989 were abnormally warm, though probably not of record warmth.

We present this analysis not because we are particularly concerned with the record temperatures at Tucson, but because the reason for the differences between the old and new temperature measurement systems at Tucson appears to be system related, such that the daytime temperatures read higher than they should. Since these systems are being installed at many sites around the country, it is possible that other locations may be experiencing a similar warm bias to their temperature readings, though perhaps not as large as those noted for Tucson. It is well known that record inhomogeneities can be caused by the introduction of new measurement systems. This problem is discussed by Karl et al. (1989).

The National Weather Service recordings of the various weather parameters are often the first that researchers turn to when studying climate changes such as global warming. Thus, it is important that biases in the data be identified and corrected before the record is hopelessly contaminated with errors and before small changes that are being searched for are lost.

## 2. Comparison of Tucson records with nearby stations

Figure 2 is a comparison of the daily maximum temperatures at the Tucson airport with the average of the daily maximum temperature at two of the cooperative climate stations in the Tucson area from 1948 to 1988. These two stations are the Campbell Avenue Experimental Farm (CAF) station and the Tucson Magnetic Observatory (TMO), operated by the University of Arizona (UA) and the U.S. Geological Survey (USGS), respectively. The temperature recordings from these latter sites are the standard maximum/minimum readings taken in a standard shelter. Since these thermometers are located within shelters and are not aspirated, their readings will be higher than an aspirated system at the same location during the time of maximum insolation. As far as we can determine, the

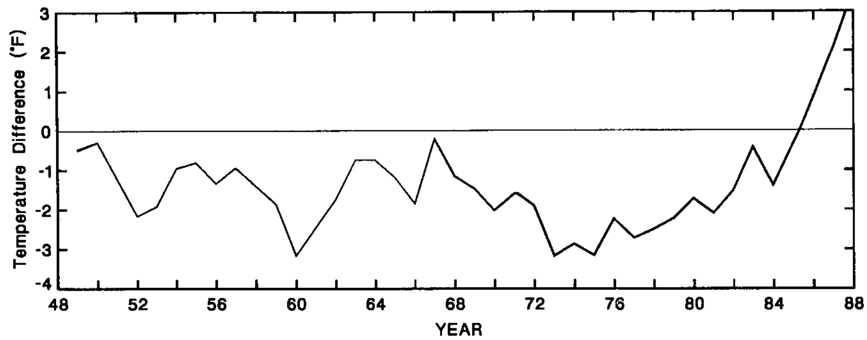


FIG. 2. The difference between the maximum June temperature at the Tucson Weather Service Office at the Tucson Airport (TUS) and the average of the maximum June temperatures at Tucson Magnetic Observatory and the Campbell Ave. Farms cooperative climate stations. Positive values mean that the temperature at the airport was higher than at the stations in town.

temperature readings at the airport site were made with aspirated systems throughout the period in Fig. 2.

Figure 2 shows that the differences between those temperatures taken at the airport and the average temperatures at CAF and TMO were fairly constant for over three decades. During most of the record shown in Fig. 2, the average temperatures at these two stations were approximately 2°F warmer than the airport temperatures. In 1986, a marked change occurred, so that by 1988 temperatures at the airport were actually warmer than at the other two stations by 2°F. Other than a slow urban buildup nearby, there were no significant changes at CAF or TMO between 1986 and 1988. Thus, this figure suggests that there was some sort of major change at the Tucson airport after 1986. It should be noted that since about October 1988, after the record included in Fig. 2, the readings for CAF appear to have dropped 2° to 3°F relative to those for TMO. We do not know the cause of this change, but it is the reason why we do not extend Fig. 2 beyond 1987.

There were apparently some minor changes in instrument locations at CAF and TMO during the record shown in Fig. 2, and it has been argued that these, rather than changes at TUS, caused the abrupt increase after 1986. Thus, to confirm that the abrupt change shown in Fig. 2 in 1986 is a result of something happening at the Tucson airport rather than at the comparison stations, we compared the Tucson readings with stations over a much wider area of southern Arizona. Many of these stations are somewhat removed from the Tucson area; thus, correlations between the temperatures at the various stations we used and Tucson are expected to be less than those used in Fig. 2. On the other hand, the advantage in using more stations is that changes at one or two of the surrounding stations will have minimal effects on the comparisons.

A network of 30 stations located within 200 miles of Tucson in southern and central Arizona was used in this comparison. Using temperature data for July from 1982 to 1989, a pair of regression equations was developed for each of the 30 stations to estimate the daily maximum and minimum temperatures at TUS. A weight was then assigned to the estimate derived for a given station, in proportion to the square of the $t$ statistic for that regression,

$$\text{weight} = t^2 = r^2(n-2)/(1-r^2),$$

where $r$ is the correlation coefficient between TUS and the interpolating station and $n$ is the number of days in the dataset on which the regression was based. An analysis of variance indicates that the sum of squares explained by our regression equations is approximately equal to the square of the correlation coefficient, suggesting that the weighting function used here is appropriate.

A weighted average using estimates of the TUS temperature from each station was then computed for a given day. We call this average the *expected temperature,* as contrasted to the temperature actually observed at TUS. This interpolation method is discussed briefly in Thiêbaux and Pedder (1987).

By examining changes over time in the differences between the expected and actual temperatures, discontinuities in the temperature time series at TUS may be identified. The period 1982–89 was chosen to provide data from four years prior to the anomaly indicated in Fig. 2 and four years subsequent to the anomaly. Since the expected temperatures are based on regression equations developed on data both prior to and subsequent to the anomaly, the expected temperatures should be higher than the actual temperatures prior to 1986 (actual minus predicted is negative) and lower than the actual temperatures subsequent to 1986 (actual minus predicted is positive). The procedure ensures that the average difference over the entire period be equal to zero, and hence it will not be possible to determine from this analysis whether the reported temperatures at TUS prior to 1986 were anomalously cold or whether the reported temperatures at TUS subsequent to 1986 were anomalously warm. On the other hand, abrupt changes in the difference between the actual and expected temperatures can be identified.

Table 1 shows the monthly average between the actual and estimated maximum and minimum temperatures for July from 1982 through 1989. The differences for the maximum temperatures were negative for the first four years, with an abrupt change to positive differences for 1986 and after. Thus, both Fig. 2 and Table 1 clearly indicate an abrupt increase in the maximum temperatures reported at TUS subsequent to 1986. The analysis presented in Table 1 strongly suggests this is a result of changes at TUS, since changes at any one of the interpolating stations would have only a very slight effect on the expected temperature and it is highly unlikely that a majority of the interpolating stations would exhibit changes of the same sign at the same time.

Standard $t$ tests were conducted to determine if the average difference between the actual and expected temperatures for the 1982–85 period and the 1986–89 period were statistically significant. The apparent difference between the 1982–86 average maximum temperature and the corresponding average for 1986–89 was 2.09°F. This is significantly different from zero with a $t$ statistic of 9.74 with six degrees of freedom (two-sample $t$ test with variances assumed equal). The probability that such a difference could occur by chance is roughly 0.001%. One can only conclude that the difference is real.

A similar comparison of the minimum temperatures for the periods 1982–85 and 1986–89 suggests an increase of 0.24°F. The test of significance for this difference being nonzero yielded a $t$ statistic of 0.77, which suggests roughly a 25% probability that this difference is due to chance. One cannot conclude that there has been a corresponding change in the minimum temperatures during this period. This, of course, is in agreement with the minimum temperature records, cited earlier, which showed no convincing trend over the 1986–90 period.

TABLE 1. Average difference between reported and expected temperatures based on the 30-station regression for July; $t$ refers to the $t$ statistic as a measure of statistical significance of the average difference between 1982–85 and 1986–89.

| Period | Max $\Delta T$ | Min $\Delta T$ |
|---|---|---|
| 1982 | −1.76 | −1.08 |
| 1983 | −1.00 | +0.46 |
| 1984 | −1.03 | −0.69 |
| 1985 | −0.50 | +0.71 |
| 1986 | +0.44 | −0.16 |
| 1987 | +1.91 | −0.26 |
| 1988 | +0.61 | +0.16 |
| 1989 | +1.10 | +0.60 |
| 1982–85 | −1.07 | −0.15 |
| 1986–89 | +1.02 | +0.09 |
| | $t = 9.74$ | $t = 0.77$ |

## 3. Discussion

After the spurt of record-setting temperatures in 1989, we began an informal effort to understand what was happening. This included a number of visits to the National Weather Service at the Tucson airport, not only to look at the temperature recording equipment there, but also to determine the various changes in instrumentation that have occurred at that location in recent years. On one of our visits, 11 November 1989, we were supplied with a list of the equipment in place from 1958 on; this is given in Table 2. The various instruments are identified in the table with the usual National Weather Service model numbers. For descriptions of these instruments, the reader is directed to their operations manuals listed in the references. The HO-31 listed in Table 2 are standard unaspirated maximum/minimum liquid-in-glass thermometers exposed in a standard instrument shelter. The other instruments are aspirated electronic instruments that telemeter their readings into the WSO.

In 1980 there was a major site change from a location near the aircraft Operations Tower at the Tucson International Airport to near the present site, northwest of the weather service office, a distance of about 1/4 mile. There were major equipment changes in 1982, when the HO-50 was replaced by the HO-63, and again in 1986 when the HO-63 was replaced by the HO-83. Between 1982 and 1986 there were only minor instrument location changes.

In comparing Fig. 2 with Table 2, it is apparent that the only change that appeared to have a noticeable impact on the temperature record at Tucson was the change to the HO-83 in 1986. The major site change in 1980 and the change to the HO-63 in 1982 produced no noticeable persistent effects in Fig. 2. Figure 2 also indicates that the record was fairly consistent before 1958, indicating that any changes prior to that date also did not appreciably affect the record. Thus, our attention was drawn to the HO-83, whose installation appears to coincide with the abrupt increase in temperatures in 1986.

While we were at the weather service office in November of 1989, we examined the exposure of the sensing portion of the HO-83. The installation of the sensor agreed with the specifications outlined in the standards and procedures chapter of the Weather Service Instruction Manual (1982). It should be noted that the height of the temperature sensors has varied over the years, but within the 4 to 6 feet above ground level that is specified in the operations manual. It is apparent from Fig. 2 that the height changes that occurred when the HO-50 was replaced by the HO-63 are not echoed in the temperature record.

The HO-83 is located over the same type of surface

TABLE 2. List of model numbers and description of equipment in place from 1958 to present in the National Weather Service Office at Tucson International Airport.

| Instruments, model numbers, dates in service |
|---|
| 1. 15 Oct 58–4 June 80<br>WSO located in Tower and Operations Bldg.<br>* HO-31 located next to office (used as backup).<br>HO-50 located at center field.<br>* HO-31 is in a white instrument shelter. |
| 2. 4 Jun 80–21 Nov 82<br>WSO moved to present site 4 June 80.<br>HO-31 moved to 5 feet above dirt and rock surface, 40 feet NW of WSO, where it remains today. (It is still used as a backup.)<br>HO-50 moved to 5 feet above a dirt and rock surface, 79 feet NW of WSO. |
| 3. 21 Nov 82–20 Feb 86<br>HO-50 was replaced with an HO-63, which was located 6 feet above a dirt and rock surface, 79 feet NW of WSO. |
| 4. 20 Feb 86–present<br>HO-63 was replaced with an HO-83, which was located 4 feet above a dirt and rock surface 65 feet NW of WSO. |

as the earlier temperature sensors listed in Table 2. It is well away from the WSO building and is exposed to full sunlight most of the day. There are several hours in the early morning when it is in the shade of trees to the east. West of the thermometer site is a hangar area with extensive blacktop but that was in place well before 1986.

In order for an in situ temperature sensor to measure accurately the adjacent free air temperature, it must be adequately aspirated. In the HO-83, the sensor is contained in the upper portion of an uninsulated cylindrical housing topped with an insulated domed roof. The unit, which is coated with a reflective white paint, is aspirated by a muffin fan located at the bottom of the cylinder. It should also be noted that the HO-83 contains a Peltier cooled dewpoint system, which also emits heat within the cylinder containing the temperature sensor. Therefore, in addition to examining the exposure of the thermometer, we also measured the ventilation rate of its aspiration system at the entrance aperture of the housing, using a heated hot-wire anemometer. It was observed to be in the range 0.1 to 0.2 m $s^{-1}$, about a factor of 5 less than other temperature sensors with housings of similar design. Thus, it appeared to us that the problem with the instrument was with its aspiration system, not its location.

If the HO-83 is not aspirated sufficiently, we would expect that the measured temperatures would be higher than a well-ventilated temperature during daylight hours. The maximum difference between the indicated and well-ventilated temperatures should coincide with the maximum insolation, generally around noon, with positive differences between sunrise and sunset. At night, since the instrument is exposed to the sky and therefore will cool by radiation to the sky, we might expect it to read colder than the ambient temperatures.

To demonstrate that the problem may be related to inadequate aspiration, we need to examine the behavior of the instrument throughout the day, rather than just at the time of the maximum temperature. Ideally this should be done by comparing the readings from the HO-83 with a carefully selected accepted standard. Finding such an acceptable standard instrument was difficult; thus, we chose to compare the performance of the HO-83 with that of the HO-63 which, from Fig. 2, appeared to provide readings similar to the earlier systems. We make no claims that the HO-63 should be considered a standard, but we can at least compare the two systems.

## 4. Comparison of the HO-83 with the HO-63

As far as we know, there never was an hour-by-hour comparison of these two systems when the HO-83 was installed in Tucson. Since the HO-63 is no longer available at the WSO in Tucson, it is impossible to make a side-by-side direct comparison of them. However, it is possible to compare them indirectly.

We did this by first finding a nearby station where we were reasonably sure that there have been no changes of any kind since 1985. These include instrument changes, site changes, and any changes near the site that might influence temperatures (such as construction of any sort). With such a nearby site, we can form differences hour by hour between that site and Tucson and then average these differences for each hour over a period of, for example, a month. This process will then provide a comparison of the two sites throughout the day. Nonzero differences will then be due to differences in instrumentation between the sites, exposure differences, and natural and urban differences. Such a comparison in itself is interesting but leads to debate as to which site is the "correct" one.

For our purposes, we can construct differences between years of the hourly average differences of temperature between Tucson and the nearby site. This year-to-year difference will contain within it any differences due to instrumentation and site changes. Not contained within this difference will be the natural variations of temperature between the years, since the day-by-day difference between the nearby stations removes most of the natural variation and we assume the variations to be uniform over the Tucson area.

If the nearby site is also one where changes near that site and changes in instrumentation are negligible, then difference between the years will be due only to changes to the site at Tucson or the instrumentation there. Finally, as we have noted above, we believe site changes and differences in instrument location at Tucson have themselves been negligible; thus, the differences between years should basically show changes due to instrument changes or drift of a particular instrument.

### *a. Selection of the nearby site*

Since our goal is to examine changes after the HO-83 was installed in 1986, we need a nearby site that has not changed since 1985. We chose the station at Davis–Monthan Air Force Base (DMA), located about 3 miles east of the Tucson airport in very similar terrain. Both sites are essentially in the center of the Tucson Valley and are on the southern edge of Tucson. The thermometer at DMA is located on the south side of the major northwest–southeast-oriented concrete runway on the base, about a quarter of a mile from the runway. This is on the opposite side of the runway from the base itself and is in mostly undisturbed desert. There are no buildings within almost a mile of the site.

The thermometer at DMA is similar to the HO-83, in that it consists of a temperature sensor housed inside a metal case to shield it from the sun and a fan provides a flow of air to aspirate the element. It is, however, much older than the HO-83. We could find no one on the base who could remember when it was installed, but most felt that it dated from the 1950s. The mechanical and electrical mechanisms in the instrument are examined weekly, and a calibration check is done each month.

The instrument at DMA clearly did not change in the years since 1985, and the site also has undergone very little change in that period. Since we could find no evidence of any slow trends in the readings from the DMA thermometer—it is serviced regularly—and since it is relatively close to the Tucson airport, we decided to use the records from DMA for the comparison just described.

The temperature records from TUS and DMA were obtained directly from the surface observations record filled in hourly at each site by the observers on duty. At both stations these records were available back to 1985.

### *b. The comparison*

In the analysis that follows, we will discuss the average differences as a function of time of day between the temperatures recorded at the WSO at the Tucson airport (TUS) and those from Davis-Monthan Air Base (DMA) in June and September 1989, 1987, and 1985. The HO-63 was used to record the temperatures at TUS in 1985, and the HO-83 was used in 1987 and 1989. Differencing between 1989 and 1985 or 1987 and 1985 compares the HO-83 to the HO-63. Both 1987 and 1989 are used to determine if there are any trends in the HO-83 itself. We will concentrate on the temperatures of June and September since we feel that the problems associated with the HO-83 are related to inadequate aspiration, and so the related errors should be most pronounced when the solar insolation is greatest during the summer. We chose not to use July and August because of the extensive cloudiness usually present in those months.

In Figure 3, differences between TUS and DMA for June 1989 are shown, where positive values mean the reported TUS temperature was higher than the DMA temperature. Thus, right after sunset, TUS read about a degree higher than DMA until the early morning hours when, for a short period, TUS was cooler than DMA. After sunrise, there was an increase in the differences until around local noon, when the differences exceeded 3°F. The peak is more or less symmetric about local noon and falls off rapidly near sunset.

Also shown in the figure are the approximate times of the diurnal changes in wind direction at TUS. There is a strong diurnal variation in wind direction in the Tucson Valley with northwest winds in the afternoon and southeast winds at night and in the morning. At one time, we wondered if the warm afternoon temperatures at TUS were a result of flow off the blacktop areas just northwest of the thermometer site. However, the change to very large positive values in Fig. 3 occurs before the wind shifts, and the transition back to lower values also occurs before the wind shifts to southeast. Thus, Fig. 3 suggests that the large differences at TUS and DMA are not due to this wind shift and the hot air coming off the blacktop. Perhaps this should not be a surprise since, during a June afternoon in Tucson,

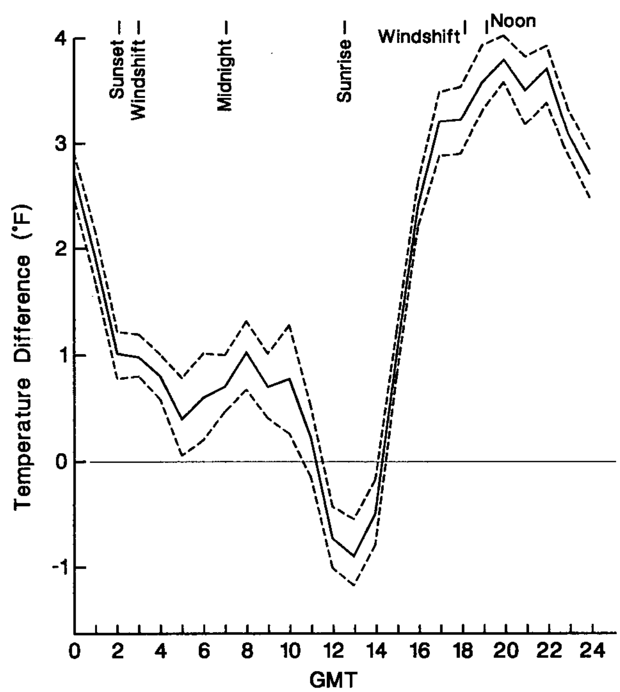


FIG. 3. Average difference between temperatures at TUS and DMA in June 1989 as a function of the time of day. Solid line denotes the average difference, and the dashed lines denote one standard deviation from this average. Also shown are the approximate times of the diurnal shift in the wind direction. Winds are generally from the northwest in the afternoon and early evening and from the southeast during the night and morning. Positive values mean the TUS is warmer than DMA. Times indicated are UTC.

lapse rates in the first several kilometers above the ground are adiabatic to superadiabatic, and large horizontal temperature gradients would be very transient.

The curve in Fig. 3 clearly shows that there are differences between DMA and TUS. Some are related to differences in the site. A visit to both sites would quickly suggest to even the casual observer that TUS is a warmer site during most of the day than is DMA. There are more buildings nearby, and, of course, there is the blacktop to the northwest. The positive differences, after sunset and into the morning hours, probably are a result of this. On the other hand, TUS is located in a relatively low area, while DMA is on a low broad ridge. These topographic features are very subtle but are likely to be significant during nocturnal cooling, when cool air collects even in broad low-lying regions. Thus, the negative differences just before sunrise may be due to cool air pooling around the airport.

As we will show in the next figure, much of the large positive difference during the day is probably due to the HO-83 and its poor aspiration rather than site differences, although some of the positive values during the day in Fig. 3 are a result of the fact that TUS is a warmer site than DMA. Note here, though, that the peak in Fig. 3 is roughly symmetric about local noon. Also, the onset of the transition to high values occurs about two hours after sunrise (recall that trees shade the site in the early morning), and the transition back to modest positive values occurs at sunset.

Figure 4 shows the difference between 1989 and 1985 and the difference between 1987 and 1985 of the average TUS, DMA temperature difference. As with Fig. 3, variations during the day are shown. In 1985 and 1987, we averaged the TUS, DMA differences over June and September. In 1989, we used only June, since there was a dramatic change in the reported temperatures from TUS during the last half of September, which we will describe in the next section.

Figure 4 implicitly compares the HO-83 and the HO-63. We emphasize again that we feel that the only reason for nonzero differences in Fig. 4 is the difference between HO-83 and HO-63. Positive values indicate that the HO-83 consistently reports temperatures warmer than the HO-63 at a particular time. Error bars for two standard deviations of the data are shown, and they indicate that, over much of the record, the differences are significant at the 95% confidence level.

During the night, the HO-83 apparently reports temperatures that are perhaps a half of a degree cooler than those that would be reported by the HO-63. This was noted for both 1987 and 1989. After sunrise, the differences become positive, and in 1989 they exceeded 2°F. These positive differences are more or less symmetric about local noon and quickly drop back to zero near sunset. Comparing 1987 and 1989 shows that the differences between the HO-83 and HO-63 during the day increased between those years.

Figure 4 can be easily explained if we assume that

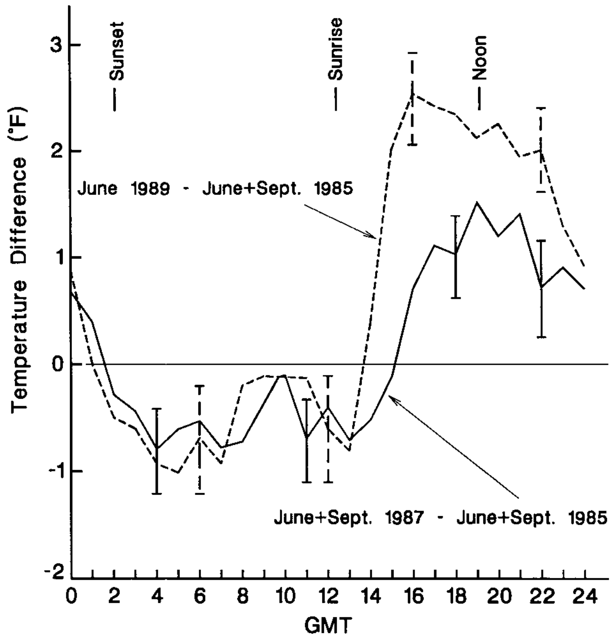


FIG. 4. Average difference between the years listed of the difference between the temperatures at TUS and DMA as a function of the time of day. As described in the text, this figure is essentially a comparison of the HO-83 with the HO-63 at TUS. In 1985 and 1987, June and September data were averaged before differencing between the years. In 1989, only June data were used, as explained in the text. Representative error bars for two standard deviations are indicated. Positive values signify that the more recent temperatures are warmer. Times shown are UTC. The indicated sunrise and sunset times are approximate, since the averages contain both June and September data.

the HO-63 was appropriately aspirated and therefore reported consistent temperatures, while the HO-83 suffered from poor aspiration. With poor aspiration, solar insolation during the day would heat the shield above ambient temperatures, and this heat would not be carried away by the airflow. Thus, the temperatures would read high. They would be most in error near local noon, and this error would be a minimum at sunrise and sunset. At night radiational cooling of the shield would occur, and therefore we might expect the poorly aspirated system would read cool, though this cooling would be less significant than the warming of the intense daytime solar insolation. Furthermore, after the instrument has been exposed to the elements for some time, the surface of the shield ought to darken somewhat. It is painted white, but the paint may oxidize or it may simply become dirty. Thus, we might expect that temperatures reported by a poorly aspirated system during the day would slowly warm with time. Figure 4 suggests that this is happening with the HO-83.

### c. Recent changes at TUS

In the section above, we suggested that there was a significant change in the temperatures reported from

TUS in late September 1989. This can be seen by first comparing the daily variation of the differences between TUS and DMA, averaged over the first two weeks of September 1989, with similar averages for October 1989 (Fig. 5). Note that the curve for September is very similar to the one for June shown in Fig. 3. The curve for October is similar to both in shape, except that it is shifted down about 2°F. This suggests that there was some change in the operation of the HO-83 in late September that was equivalent to a recalibration of the instrument down 2°F.

We can show the date on which this "calibration" occurred by plotting the daily average difference between TUS and DMA during September 1989. This is shown in Fig. 6. The curve clearly drops about 2°F between 20 and 21 September. We asked the weather service about this, and they emphasize that there was no recalibration on this date. It is possible that the shift is a result of a malfunction elsewhere in the system. A calculation of a curve for June 1990, similar to the ones in Fig. 5, shows that it was similar to October 1989. Thus, whatever happened on 20 or 21 September 1989 remains. In a sense this is good because the thermometer is no longer reading exceptionally high, and the records that were set in 1990 are probably reasonable. On the other hand, the low temperature readings might now be in error.

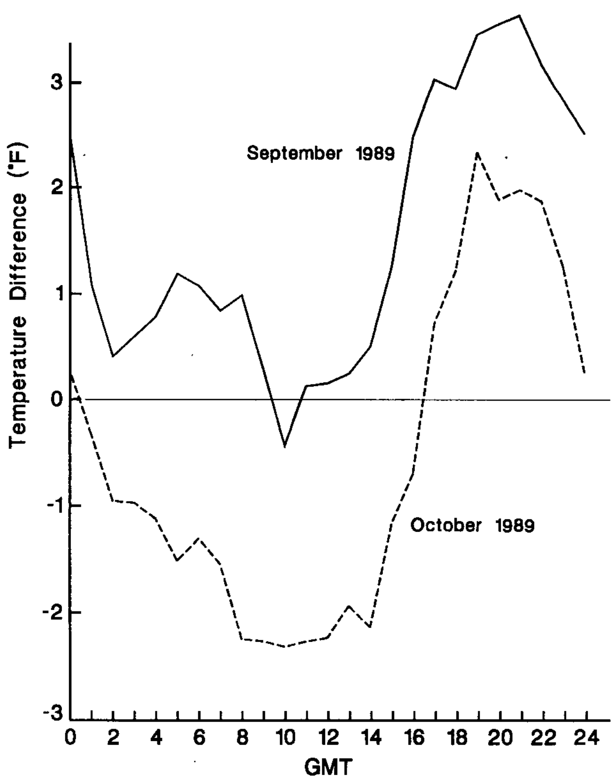


FIG. 5. Same as Fig. 3 but for September 1989 and October 1989. In September 1989, only data from the first two weeks of the month were used, as explained in the text.

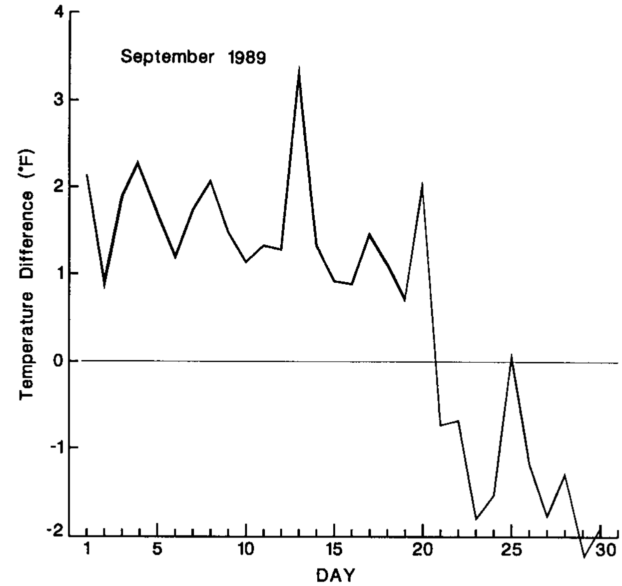


FIG. 6. Difference between TUS and DMA averaged over the day in September 1989. Positive values mean that TUS was warmer than DMA.

## 5. Conclusions

Because of the consistency of the differences between TUS and the stations shown in Fig. 2 from the beginning of the record to 1986, we feel that the HO-63 was providing temperatures that were at least consistent with the earlier systems. It is unlikely that the systems that preceded the HO-63 had errors similar to the HO-63 and that these errors would have remained undetected for 40 years. Thus, we choose to believe that those systems, including the HO-63, were all providing reasonable records. Therefore, the comparison between the HO-63 and the HO-83 shown in Fig. 4 indicates that there are significant problems with the current instrument at TUS, the HO-83. In particular, the problem appears to be related to insufficient aspiration of the temperature element inside the shield. There is no reason to believe that this problem should be limited to the summer months, even though this was the season we studied.

It is not known by us whether the apparent insufficient aspiration of the HO-83 is a design problem with the instrument or whether it is unique to the one at TUS. If it is a design problem, then it is serious because these instruments have been installed at all first-order sites around the country, and all of these could be providing erroneous readings. On the other hand, if it is unique to the TUS instrument, then it is a problem only for Tucson, which can be corrected simply by replacing that particular HO-83.

A consideration of Fig. 4 leads to an additional conclusion. If calibration checks are done in the morning, a thermometer that performs like the HO-83 in Tucson would never show any major discrepancies, since the error is a minimum at that time. If checks are done at noon, for example, a recalibration can be done which will bring the instrument into specifications then, but it will be off at other times.

When we started this study, there was some speculation that similar problems have occurred at other stations where the HO-83 was installed. This is indeed possible if the apparently insufficient aspiration in the Tucson instrument is a design flaw. However, two factors suggest that only a handful of other stations would experience easily noticed effects. In the first place, insufficient aspiration will produce the greatest error in areas where solar insolation is very high. Thus, in Tucson we may be seeing the problem at its worst. Even at its worst, the error may be slightly more than 2°F, so areas with less solar radiation than Tucson may have significantly less error. Elsewhere the error would not be noticeable on a day-to-day basis as it was in Tucson, although it would be producing a detectable error in the climate record for the station.

In the second place, the error at Tucson appeared to slowly increase with time, up to the abrupt change in September 1989. Even in Tucson, this error was not particularly apparent when the instrument was first installed in 1986. If other HO-83 systems are behaving similarly to the one in Tucson, there simply may not have been enough time for the error to have become apparent at other stations, and only a very careful analysis would reveal it. All this makes us wonder about the future of temperature measurements made by the National Weather Service using the HO-83 and the impact such measurements may have on the climate record.

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