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CLIMATE VARIABILITY AS SEEN IN DAILY TEMPERATURE STRUCTURE

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ABSTRACT

Distinctive annual cycles of daily maximum and minimum temperature and temperature range are observed across the United States when averaging daily data for multiple decades. In some cases, abrupt changes in the range between daily maximum and minimum temperatures are observed within annual cycles. Such discontinuities, or steps, of 5°C may occur within a week, despite the fact that the daily data are averaged over several decades. Discontinuities are most pronounced in the fall and spring, and display differing characteristics of timing, rapidity, magnitude and direction of change across the nation. In northern and central portions of the eastern U.S., a winter minimum and summer maximum in temperature range is observed, while in the southern U.S. the opposite is found. Abrupt discontinuities are observed in early November in the Northeast and in late spring and early summer in the Southeast and Southwest.

Differences in mean daily temperature cycles between various portions of this century are a function of variations in maximum and minimum temperatures. The central U.S. had higher maximum and minimum temperatures during the 1930s than at other times this century, with little affect on daily temperature range. In the Northeast, the temperature range was lower in the 1930s, as a result of decreased maximum and increased minimum temperatures.

The dynamics responsible for changes within the annual cycle or between different periods have not yet been unequivocally identified. The location of the polar front jet stream and its associations with solar radiation, clouds, snow cover and other atmospheric and surface variables are certainly involved. For instance, a fall discontinuity appears to be associated with clouds in the Northeast U.S, and a spring snow melt signal is apparent in the extreme Northeast. Also, a monsoonal signal is suggested in the Southwest U.S.

While this is a preliminary study, it is important at this time to demonstrate that lengthy time series of daily temperature data identify important information regarding climate diagnostics and climate change detection that is lost when monthly or longer averages are employed. We believe that the identification of the climate system dynamics responsible for the structure of the annual cycle of daily temperature is a necessary first step in the study of

potential human-induced climate change.

INTRODUCTION:

In recent years a large body of research has been directed toward the detection of potential changes that may be taking place within the earth's climate system. More sensitive approaches to detection are being made possible by advancements in two key areas: progress in techniques related to modeling the earth's climate system, and the refinement of quality-controlled climatic data sets that allow intensive investigations of climate change issues. Many detection studies have been based on fingerprint methods (Madden and Ramanathan 1980; Barnett 1986). In this procedure, baseline model simulations are completed to provide a point of comparison for later model runs that include increased levels of CO_2 or other greenhouse gases. This allows the models to provide a suite of potential transformations from the present climate state to a new one that is in equilibrium with the changed atmospheric greenhouse-gas content. These templates, or fingerprints, can be used to guide researchers in searching for specific climate change signals within observed records that match the patterns found by the models. These and other hybrid methods of climate change detection (Barnett and Schlesinger 1987; Wigley and Barnett 1990) have been unable as yet to detect an unambiguous climate change signal.

One of the greatest weaknesses of detection methodologies in use today is their reliance on monthly or annual averages in conducting fingerprint comparisons. Although these low-frequency statistics are usually the simplest to employ, there is a considerable loss of information when daily data are averaged over longer periods. Specifically, information concerning changes in the shape of the annual cycle is obscured in these procedures.

The use of daily data in climate change studies has been limited in the past by the lack of quality controlled, homogeneous datasets that have a long period of record and dense station distributions over a large spatial domain. It is well know that temperature time series can be affected by a multitude of operational changes, including time of observation biases (Karl et al. 1986), station moves, instrument replacements, warming caused by urbanization (Karl et al.

1988; Karl and Jones 1989), or changes in the station's microclimatic environment. Thus, any daily data used in studies of climate change must undergo rigorous quality control procedures before being used.

The purpose of this paper is to demonstrate the utility of long time series of daily data in the understanding of climate change. We are interested in the low-frequency signal of climate change that is contained within the structure of long continuous time series (up to 100 years) of daily data. Data from the Historical Daily Climate Dataset (Robinson, 1993) are used to generate daily annual cycles of maximum and minimum temperatures at six stations in the eastern United States, three in the U.S. Great Plains and one in the southwest U.S. The annual cycle climatologies for these stations are then examined for a recent 30 year interval, and observed changes in the annual cycle of temperature during this century are investigated at three stations. Finally, we speculate as to the potential climate system dynamics at work within the annual cycle and between different periods. We believe that the identification of the climate system dynamics responsible for the shape of the annual cycle of temperature is a necessary first step in the study of potential human-induced climate change.

BACKGROUND

Investigations into temperature changes using the instrumental record have been conducted across the spectrum of spatial scales, from global studies to examinations at single locations. The study of planetary-scale variations of surface air temperatures is exemplified by those who have considered changes in areally averaged hemispheric temperatures (Jones et al. 1986; Hansen and Lebedeff 1987; Angell 1988; Spencer and Christy 1990). Others have examined changes in temperature and its variability at continental and hemispheric scales (Barnett 1978; Gutzler et al. 1988; Karl et al. 1991a), while regional temperature changes have been documented over diverse areas of the globe (Diaz 1986; Karl et al. 1991b; Michaels et al. 1988; Walsh and Chapman 1990; Kalkstein et al. 1990; Samson 1989). Even though temperature variations at a single location are difficult to interpret because of human-induced changes that can affect a given observing site, several studies have documented changes in the temperature regime at this level (e.g., Agee 1982; Skaggs and Baker 1989).

In these studies, which concentrate on mean temperatures, as well as in those which explore long term changes in diurnal temperature ranges (Karl et al. 1984; Karl et al. 1987; Robinson 1992), daily data are generally aggregated into monthly, seasonal or annual means. While these studies have increased our knowledge of climate dynamics, the aggregation of daily climate variables may result in the loss of valuable information. For example, using daily temperatures for a 74-station network in the eastern United States, Guttman and Plantico (1987) compared the published daily normals, interpolated from monthly averages for a 30-year period, to the calculated 30-year average daily temperatures. They found that the published normals were statistically different from the annual cycles created by using observed daily data, and that singularities seemed to exist in the average annual cycles of the observed data at several of the stations. In a follow up study, the same authors found no significant periodicities in the calculated daily annual cycles (Guttman and Plantico 1989). Most recently, Ruschy et al. (1991) have discussed large step changes in the annual cycle of the daily temperature range at several stations in Minnesota.

Few additional studies have examined long (>30 year) time series of observed daily data. Brinkman (1983) examined daily climate variability in Wisconsin with respect to seasonal temperature extremes, and Agee (1982) and Skaggs and Baker (1989) studied climate changes at singular locations. We know of no investigations of the annual cycle of daily temperature that have been completed using a spatially diverse station network possessing a long period of record.

DATA

In recognition of the need for lengthy and accurate climatological observations for use in global change studies, a unique digital set of daily climatic data for approximately 1300 United States stations has been assembled (Robinson 1993). This set, known as the Historical Daily Climate Dataset (HDCD), contains observations of precipitation, snowfall, snow on the ground and maximum and minimum temperature. Records extend from 1988 back to the turn of the century for about 400 of the stations, and to the 1920s and 1930s for most others. Similar digital data are unavailable for almost all other U.S. stations before 1948. The quality of all data (each variable for each day of record) is examined, and flags representing the results of the query are incorporated into the set. Included in the set are station observations from every conterminous U.S. state, with the exception of Delaware. Most are cooperative stations or smaller first order sites, which are less likely to be influenced by urbanization than larger first order stations.

For the purposes of this introductory study, ten stations from the HDCD will be examined. These include Caribou, ME; Burlington, VT; Cooperstown, NY; Woodstock, MD; Winnsboro, SC; Belle Glade, FL; Grand Island, NE; Gothenburg, NE; Washington, IA; and Willcox, AZ (table 1). Daily temperature data for the periods of record discussed here are 99% or more complete, and of the available data, less than 0.2% are flagged as suspect at any station. For the purposes of this study, it was not necessary to fill in missing data, and all flagged data are excluded from the analyses.

DAILY ANNUAL CYCLES

a. Maximum and Minimum Temperatures

Daily annual cycles are derived here from maximum and minimum temperatures by calculating the long-term daily mean for each day of the year. The traditional method used to generate daily means is the application of a spline, fitted to 30-year monthly averages and evaluated for each day. This may suffice for many climate applications, but obscures potentially useful climate information. For example, at Cooperstown, NY (Fig. 1a), extended periods of alternating cold and warm intervals during January and February do not follow the spline fitted data. In Gothenburg, NE (Fig. 1b), the daily means show considerable fluctuations, with many one and two-day deviations from the spline data. In addition, deviations that last for extended periods are also common at Gothenburg, especially in the maximum temperature annual cycle.

b. Temperature Range

We have found that the daily temperature range exhibits rapid variations over the course of the mean annual cycle. Major discontinuities in temperature range are observed at many stations. Step changes may occur over periods as short as several days. For example, the mean daily temperature range at Burlington, VT falls from approximately 13°C to 8°C over a three day period in early November (figure 2b). There is also a step change from 10°C to 13°C over approximately two weeks in the middle of April. The step changes are quite large, despite the fact that the daily data are averaged over a 30-year period. These discontinuities are also found at other stations in Vermont.

An inspection of annual cycles of daily temperature range at stations along the east coast of the United States finds abrupt transitions of varying magnitude and length (figure 2). The daily range cycle at Caribou, ME (figure 2a) has the same general characteristics as Burlington, including a summer maximum and winter minimum. The autumn decrease in range is not as pronounced as in Vermont, occurring over the course of six weeks. Rather than a single step in spring, Caribou's range first decreases for one to two weeks in early April and then rises to summer levels by early May.

Overall, the daily temperature range is similar at Caribou and Burlington, and only about 2°C degrees less pronounced than at Cooperstown, NY (figure 2c), the next station examined in a southward progression along the interior East Coast. The shape of the New York station's annual cycle is quite similar to the Vermont station. This is most apparent in fall, when the discontinuity in range is coincident with that of Burlington. The spring increase in range at Cooperstown is more gradual than in Vermont. It is similar to that observed at Woodstock, MD (figure 2d), although at the Maryland station this rise is rather continuous from an early winter range minimum. The range decrease at Woodstock in autumn begins at about the same time as the more northern stations, but is more gradual. A fall maximum in temperature range, approaching that of late spring, is observed at Woodstock, but not further north. The magnitude of the daily temperature range is similar at Woodstock and Cooperstown.

While the magnitude of the annual cycle of daily temperature range is only about 1°C higher at Winnsboro, SC (figure 2e) than at Woodstock, a very different shape to the cycle is evident. A summer range minimum occurs in South Carolina, with range maxima in the transitional seasons. Winter daily ranges are slightly larger than in summer. No pronounced discontinuities are seen at Winnsboro, the decrease in range from spring to summer being quite gradual, with the fall increase occurring throughout October. It is interesting that the fall peak in South Carolina is coincident with the sharp downward discontinuity at the northern stations. Such a fall peak is not observed further south at Belle Glade, FL (figure 2f), rather a gradual increase in daily temperature range is observed from October to late January. At this time, the temperature range levels off until a rather pronounced step decrease of approximately 2°C occurs in April. The range varies little from June through September. While the annual cycle is less pronounced at Belle Glade than elsewhere in the eastern U.S., the magnitude of the daily temperature range is similar to that found elsewhere in the eastern U.S.

Distinctive annual cycles of daily temperature range are also observed in other areas of the United States. For example, at Grand Island, NE, the flow of the cycle during the year is smoother than in Eastern regions (figure 3a). The shape of the cycle is most similar to Woodstock, MD in the East. This is interesting, given that these stations are at about the same latitude. In the southwestern U.S., there is a pronounced decrease in the daily temperature range during early July (figure 3b). A gradual increase at Willcox, AZ follows, progressing to an early November maximum, much as is observed at Winnsboro, SC.

c. Interdecadal variations

Through time, change in the shape of the daily annual cycle of temperature variables may indicate changing climate system dynamics. Within a single month, large variations are observed in the mean daily differences that would not be distinguishable in monthly data. For instance, at Washington, IA, daily minimum temperatures during one 15 year period (1973-

88) were more than 3°C colder during the first half of January than during the 1952-67 period (figure 4). Opposite conditions were observed during the second half of the month. If one were to calculate the monthly difference, the two anomalies would nearly cancel, leading to the erroneous conclusion of no change. A similar situation can be observed in February, also, but not in March. Small changes in the timing of seasonal warming or cooling can create very large differences in temperature between two sub-monthly periods.

Examinations of the full annual cycle of daily temperatures show unique characteristics within certain decades. For example, mean daily maximum temperatures at Grand Island, NE were warmer in the 1930s compared to the entire 1900-88 period on approximately 90% of the days of the year (figure 5a). The warmth was most pronounced during summer. Daily minima showed similar tendencies, resulting in little change in daily temperature ranges over the course of the year (figure 5b).

The situation in the 1930s was different at Burlington, VT, where mean daily maximum temperatures showed only the slightest tendency towards being cooler than over the entire 1900-88 period (figure 5c). Minima showed some increase in the 1930s at Burlington, combining with the maxima to result in a stronger tendency towards a suppressed daily temperature range during this period (figure 5d).

DISCUSSION

The dynamics responsible for changes within the annual cycle or between different periods have not yet been unequivocally identified. Depending on the region, polar front positioning, the location of seasonal highs and lows, or monsoonal dynamics may be important in determining the abrupt transitions observed in the daily annual temperature cycles. These circulation features are associated with variations in atmospheric and surface moisture, clouds and snow cover, all of which influence the radiation balance, and, ultimately, surface air temperatures. The arrival of the polar front into the northeastern U.S., with an associated increase in cloudiness, may explain the abrupt reduction in daily temperature range in fall. This discontinuity precedes the establishment of a persistent snow cover by several weeks, thus snow can not be invoked as an explanation. At Caribou, ME, the timing of snow melt in spring is more in line with changes in the temperature range. Maxima may be held close to the freezing point until the snow disappears, potentially explaining the temporary pronounced decrease in the temperature range.

Summer range minima in the southeastern U.S. may be due to the onset of persistent maritime-tropical air masses. With them, atmospheric moisture increases, keeping daily minima higher, and afternoon cloudiness is enhanced, suppressing maxima. This situation is less common during the transitional seasons, leading to an increased range. Lower solar radiation and perhaps increased cloudiness associated with mid-latitude disturbances lower the winter range from the transition season maxima. This situation is more pronounced in the Southwest, with monsoonal clouds and precipitation affecting both maximum and minimum temperatures in summer.

A tendency towards greater continentality of the climate over the central United States in the 1930s, with associated drier atmospheric and surface conditions, explains increased maxima and minima at Grand Island, NE. These conditions were apparently not felt in the northeastern U.S., where a suppressed temperature range (a result of decreased maxima and increased minima) may have resulted from increased cloudiness. In the case of interdecadal comparisons in Washington, IA, the abrupt changes from colder to warmer relative conditions may be associated with changes in the location, intensity, and timing of the establishment of a longwave trough over the eastern U.S.

Work has commenced to increase the spatial coverage of the temporal analyses, as well as to diagnose the causes of variations in the daily temperature cycles. As mentioned previously, no other studies have explored daily temperature cycles at broad spatial dimensions. Only one local study has attempted to diagnose abrupt changes in the annual temperature cycle (Ruschy et al. 1991). Changes observed in Minnesota during the fall and spring were found to be related to solar radiation, cloudiness and snow cover. However, with none of these variables does the timing of changes during the year fit the abrupt changes in daily temperature range. The atmospheric circulation may play a key role in the timing of these temperature changes. Thus, temperatures may be influenced by a combination of these and other forcings, or, perhaps, thresholds are exceeded as these variables change, triggering the abrupt changes in temperature range.

SUMMARY AND CONCLUSIONS

Distinctive annual cycles of daily maximum and minimum temperature and temperature range are observed across the United States when averaging daily data for multiple decades. In all cases, distinct structures in the range between maximum and minimum temperatures are observed within the annual cycles. Range changes of 5°C may occur within a week, despite the fact that the daily data are averaged over many decades. Range changes are most pronounced in the fall and spring. Observed differences in mean daily temperature annual cycles between various portions of this century are found for submonthly periods. While the dynamical analysis of causes for these changes is ongoing, atmospheric and surface climate forcings are clearly implicated.

It is apparent that the use of lengthy time series of daily data identifies important information regarding climate diagnostics and climate change detection that is lost when monthly or longer averages are employed. We are continuing to expand the spatial coverage of the temperature analyses, and are beginning rigorous diagnoses of variations in the mean annual daily cycle climatologies as well as interdecadal variations in these cycles. We also plan to compare observed daily annual cycles with those derived from general circulation model output, for the purpose of detecting a greenhouse-gas induced climate change. If observed changes in annual cycles over the Twentieth Century correspond to differences in annual cycles between control and doubled-CO_2 model climates, a large step will have been taken toward confirming the cause of recent climate change.

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Table 1. Location and elevation of study stations.

Station	Latitude	Longitude	Elevation (m)
Belle Glade, FL	26° 39'	80° 38'	6
Burlington, VT	44° 28'	73° 09'	101
Caribou, ME	46° 52'	68° 01'	190
Cooperstown, NY	42° 42'	74° 55'	366
Gothenburg, NE	40° 56'	100° 10'	783
Grand Island, NE	40° 58'	98° 19'	566
Washington, IA	41° 17'	91° 41'	230
Willcox, AZ	32° 18'	109° 51'	1273
Winnsboro, SC	34° 23'	81° 06'	171
Woodstock, MD	39° 20'	76° 52'	140

Figure. 1a & b. Annual cycle of daily maximum and minimum temperatures at: a) Cooperstown, NY, and b) Gothenburg, NE. Based on a 30 year mean of daily values (1959-88) (thin line) and a spline fit applied to mean monthly temperatures during this period (thick line).

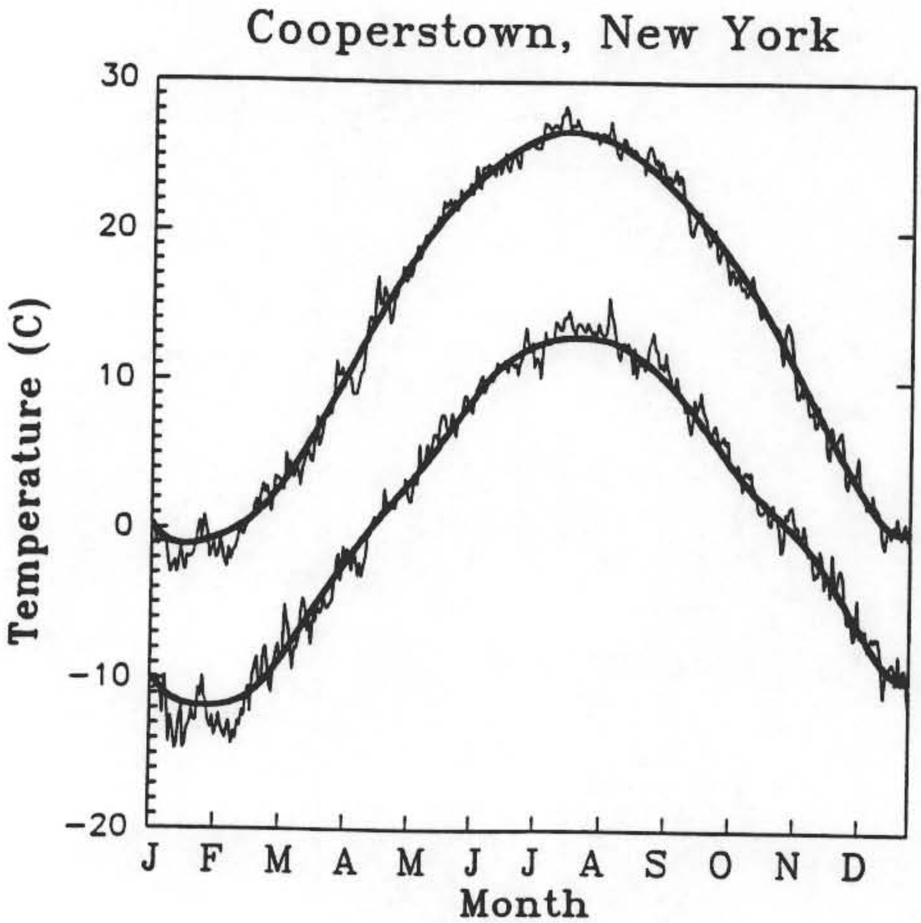


Fig. 1a

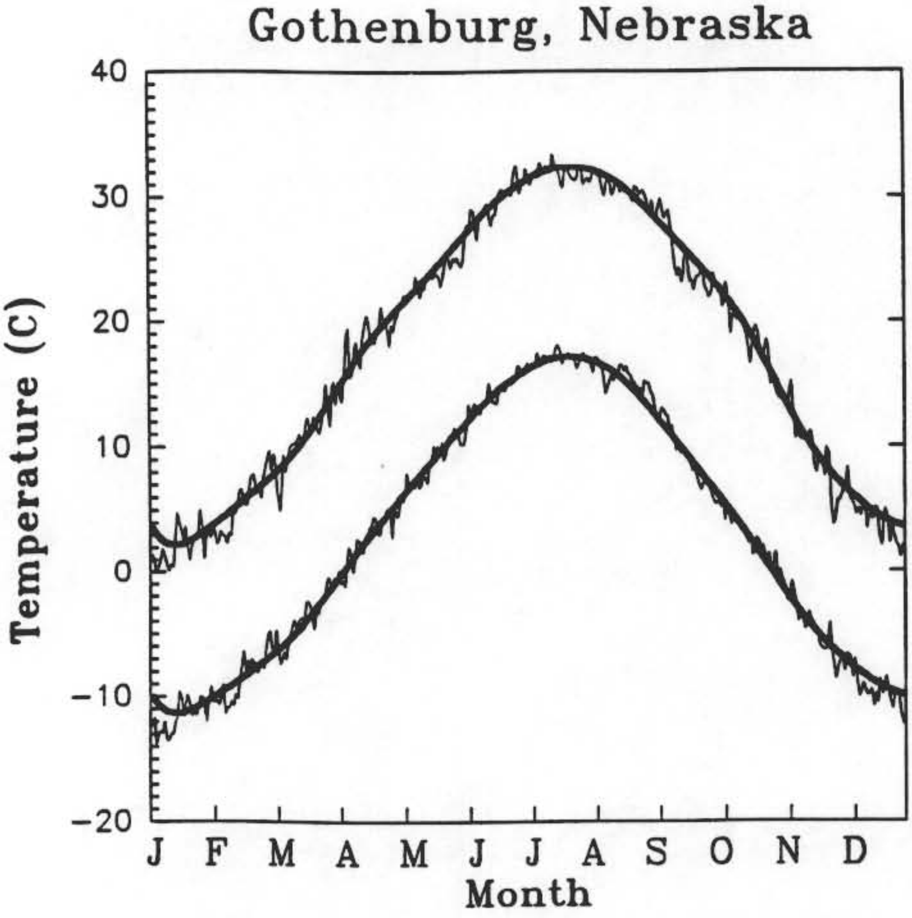

Gothenburg, Nebraska
40
30
20
10
0
−10
−20
Temperature (C)
J F M A M J J A S O N D
Month

Fig. 1b

Figure 2. Mean daily annual cycles of temperature range (maximum minus minimum) for six stations in the eastern United States.

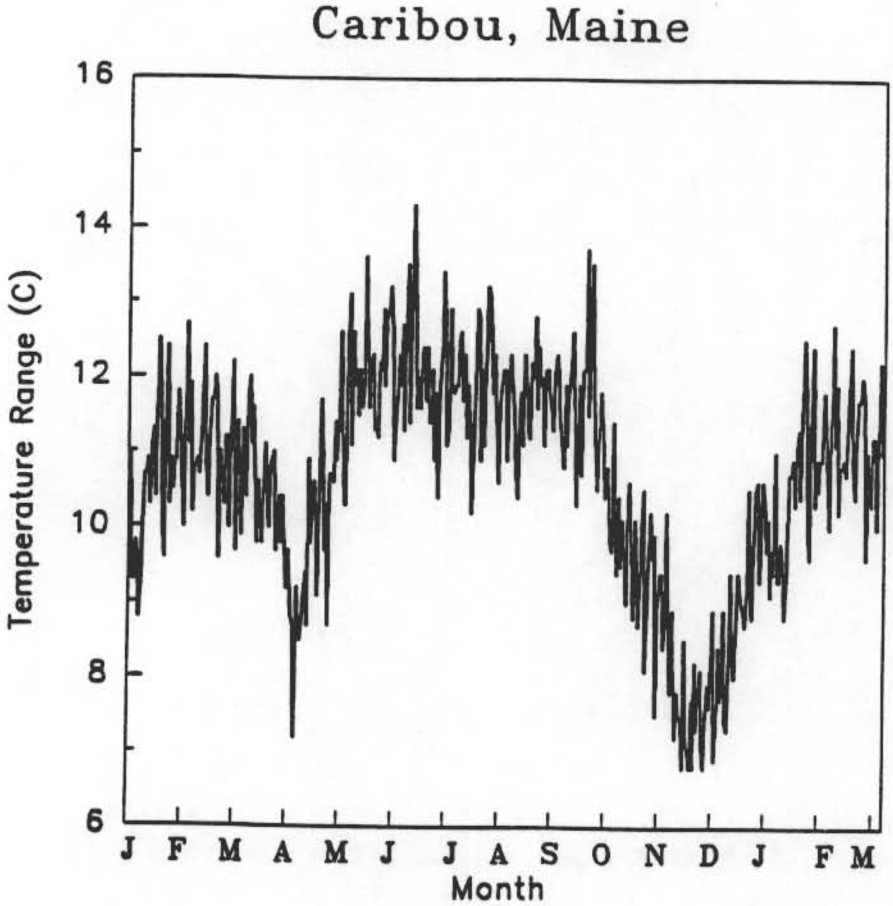


Fig. 2a

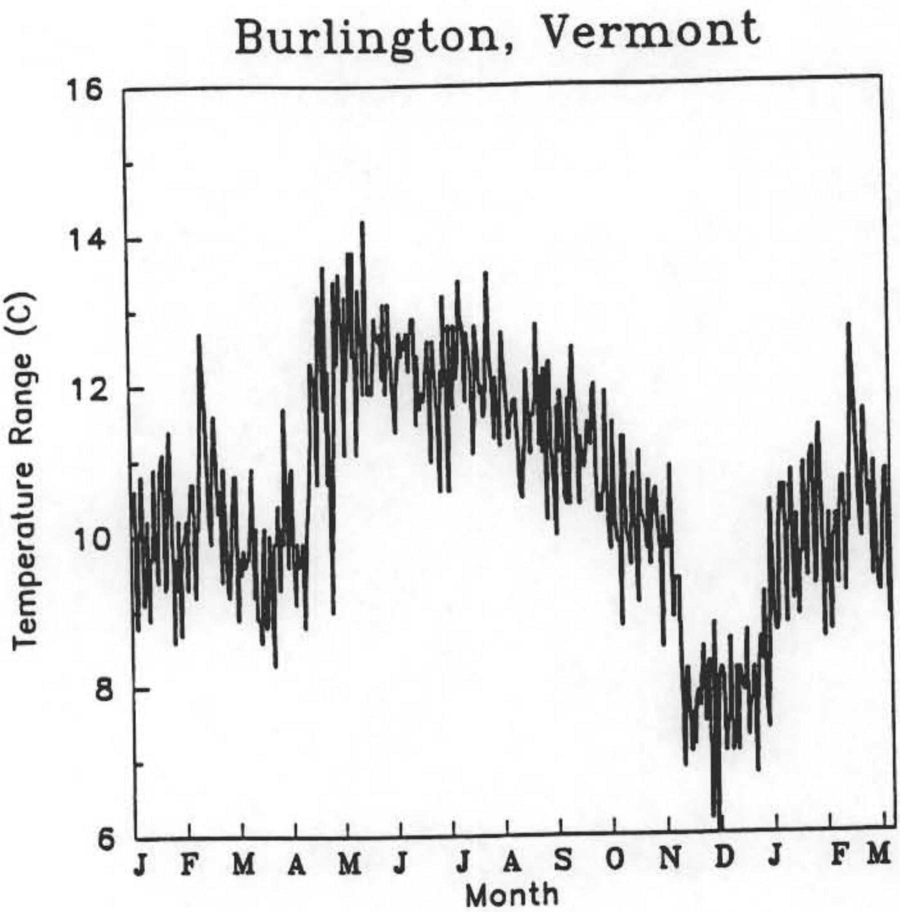

Burlington, Vermont
16
14
12
10
8
6
Temperature Range (C)
J F M A M J J A S O N D J F M
Month

Fig. 2b

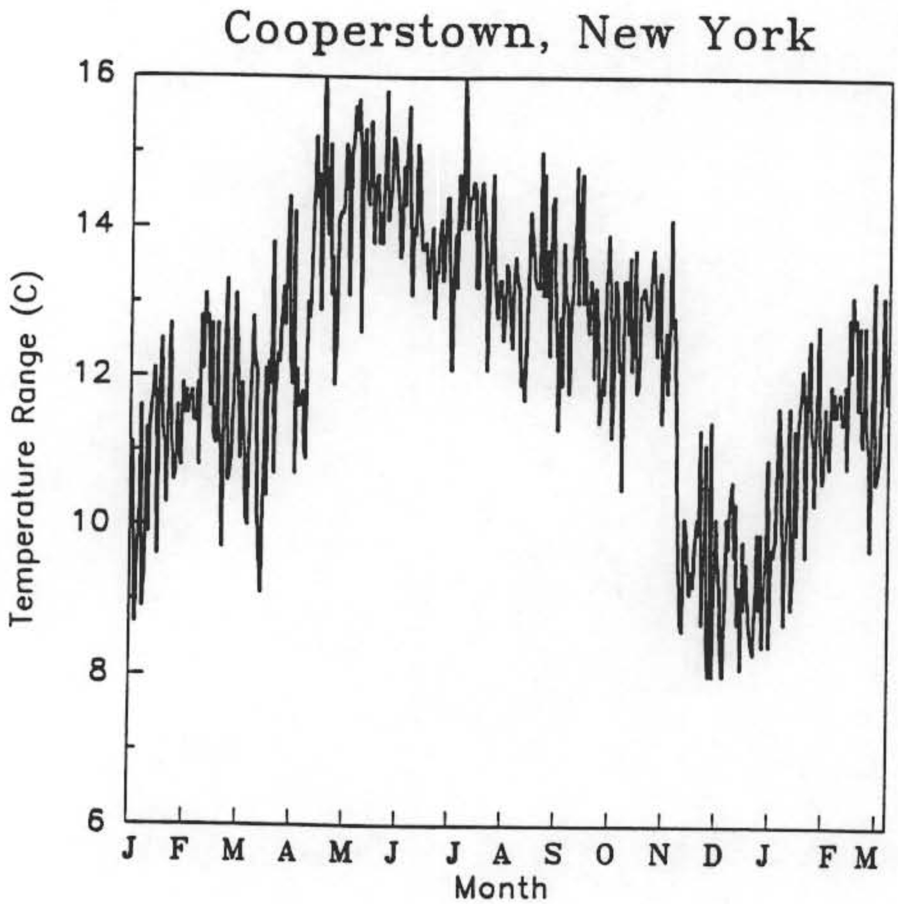
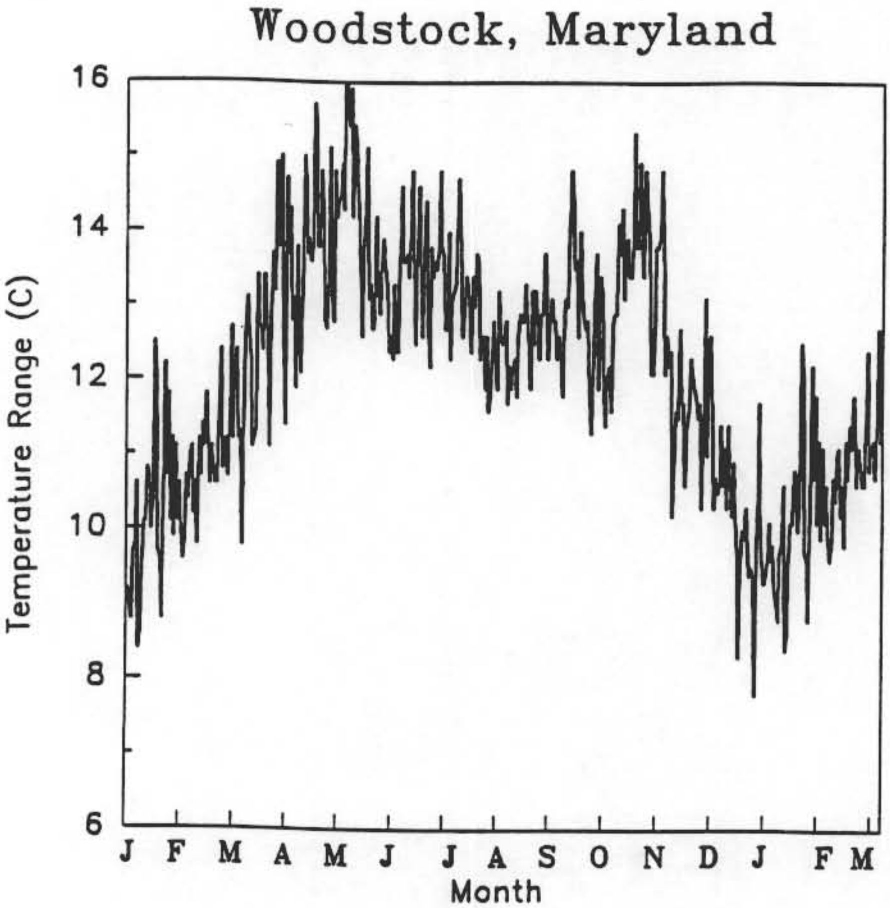

Cooperstown, New York
16
14
12
10
8
6
Temperature Range (C)
J F M A M J J A S O N D J F M
Month

Fig.



Woodstock, Maryland
16
14
12
10
8
6
Temperature Range (C)
J F M A M J J A S O N D J F M
Month

Fig. 2d

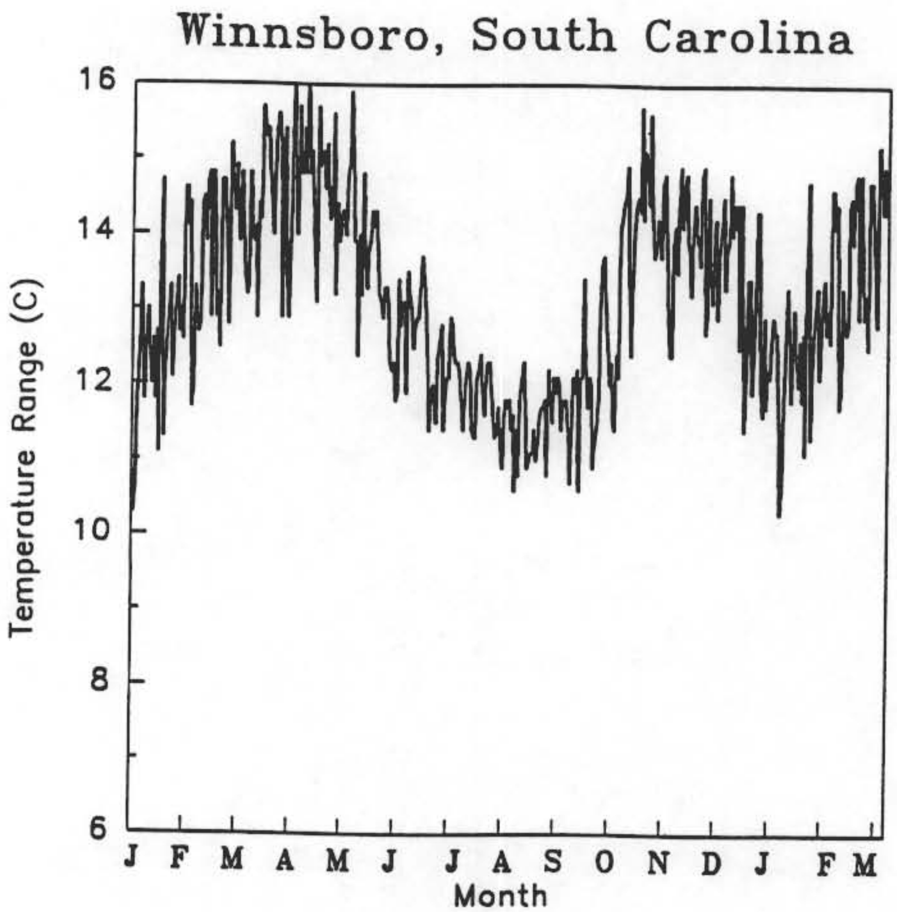

Winnsboro, South Carolina
16
14
12
10
8
6
Temperature Range (C)
J F M A M J J A S O N D J F M
Month

Fig. 2e

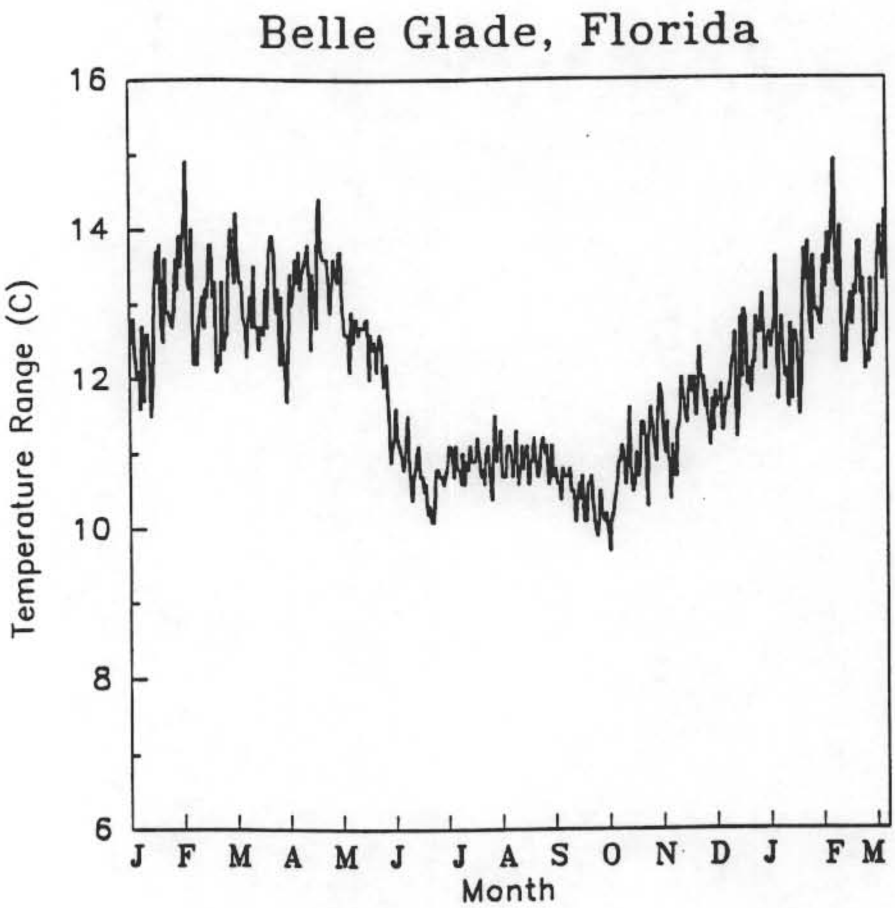

Belle Glade, Florida
16
14
12
10
8
6
Temperature Range (C)
J F M A M J J A S O N D J F M
Month

Fig. 2

Figure 3. Mean daily annual cycles of temperature range for Grand Island, NE and Willcox, AZ. Note the vertical scale for 3b has been altered to accommodate the data.

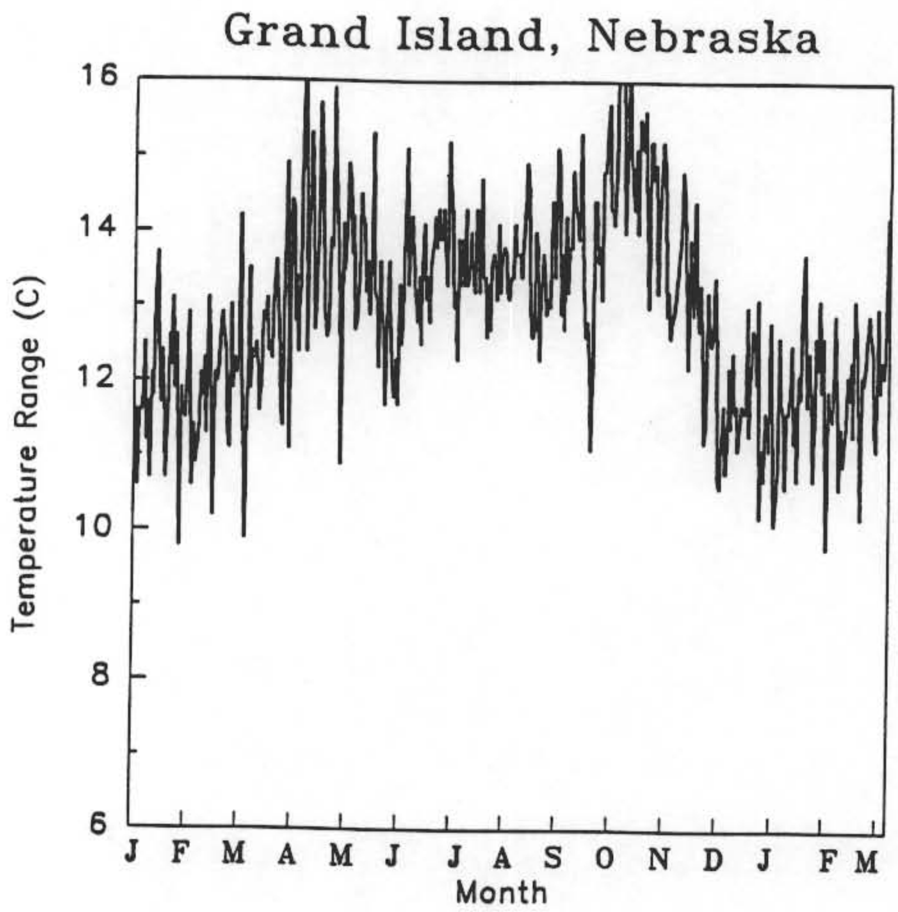


Fig. 3a

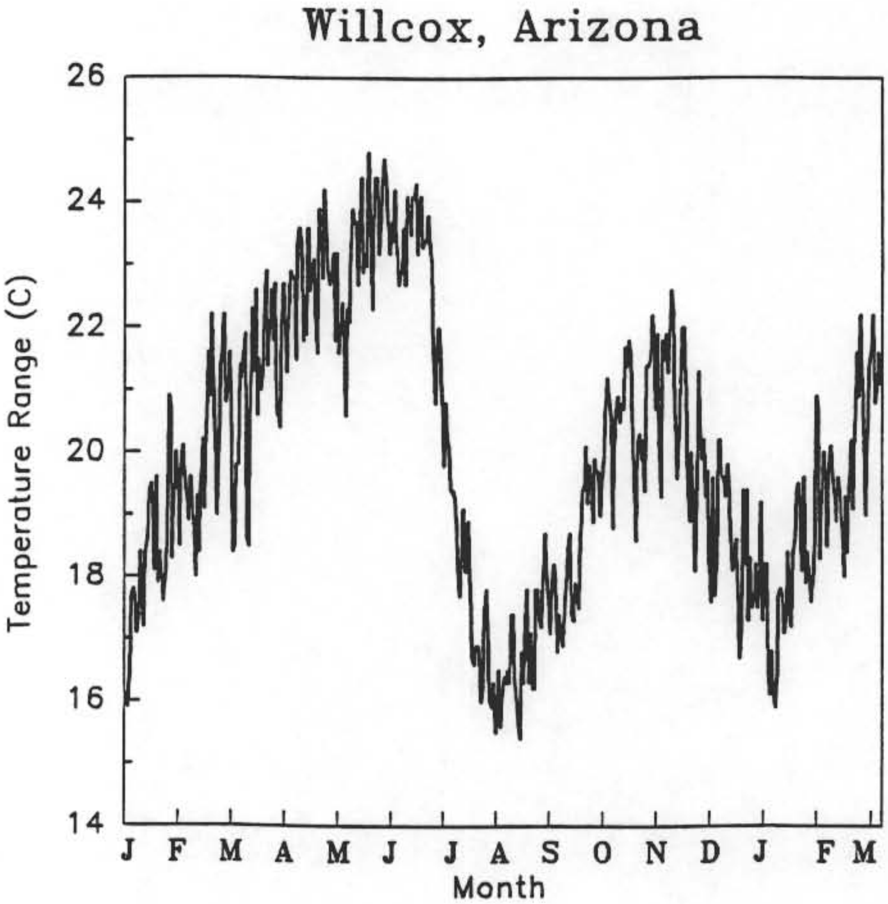

Willcox, Arizona
26
24
22
20
18
16
14
Temperature Range (C)
J F M A M J J A S O N D J F M
Month

Fig. 3

Figure 4. Differences in mean daily annual cycles of minimum temperature in January through March between 1952-67 and 1973-88 (difference equals 73-88 minus 52-67).

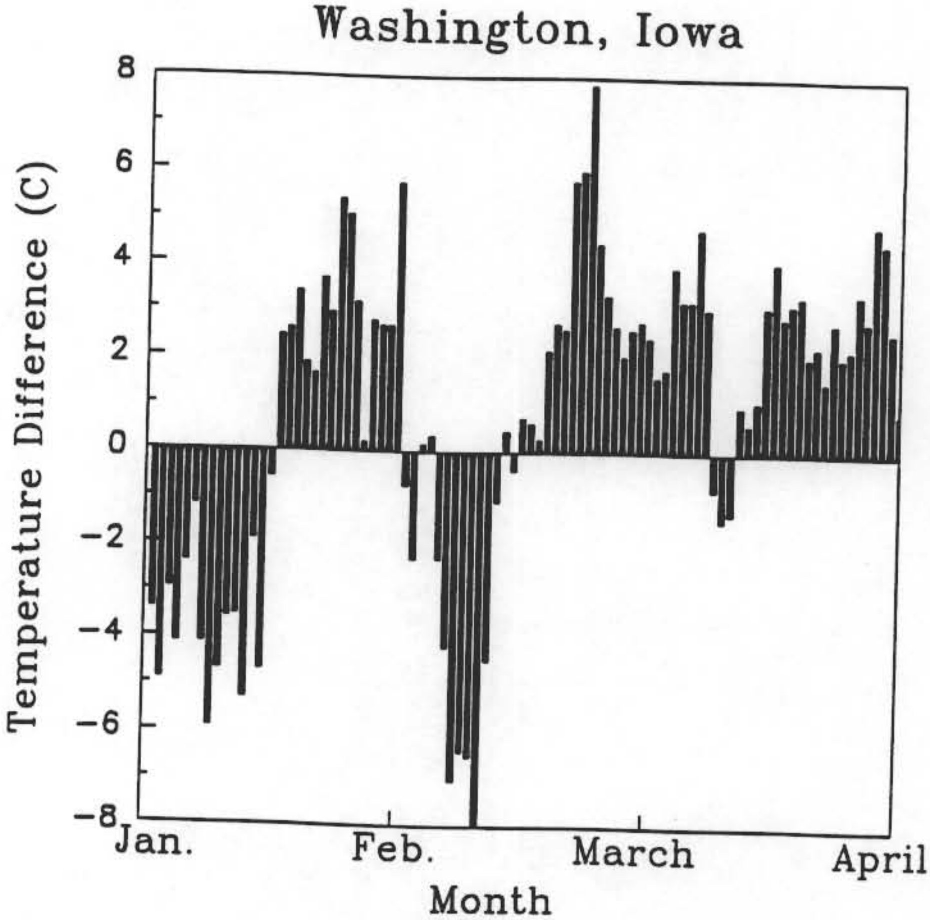


Figure 5. Differences in mean daily annual cycles of maximum temperature at Grand Island, NE between 1900-88 and 1930-39 (difference equals 30-39 minus 00-88).

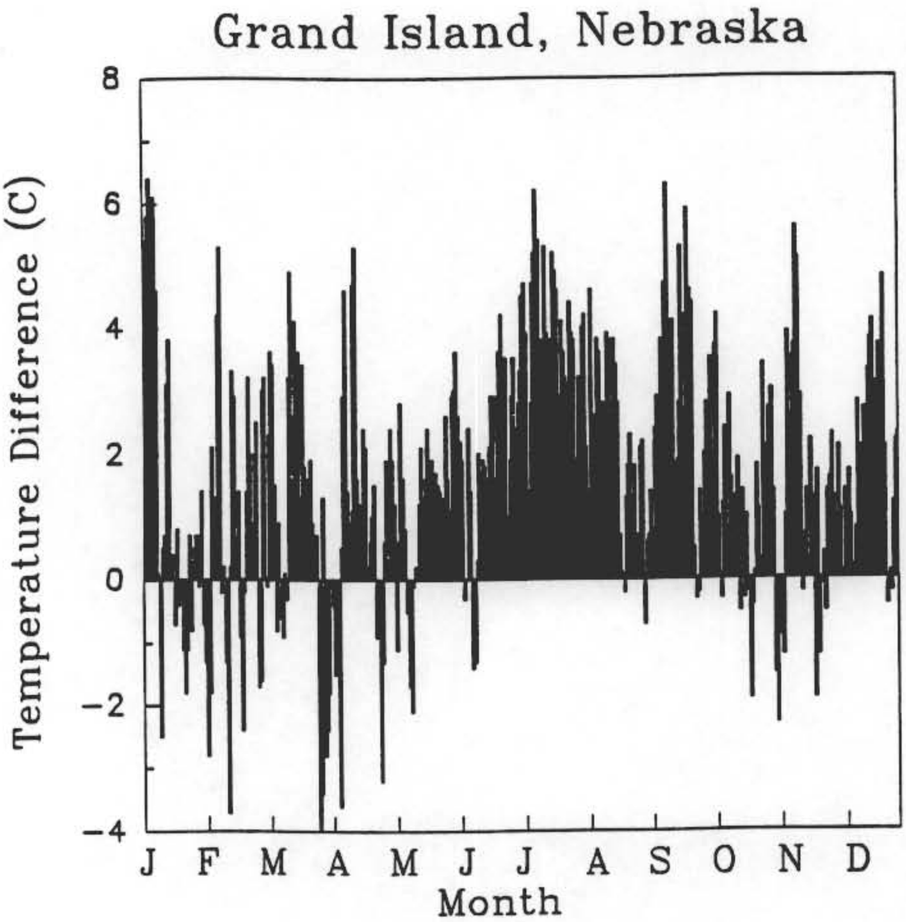


Fig. 5a

Figure 5d. Same as 5a, except for temperature range at Burlington, VT.

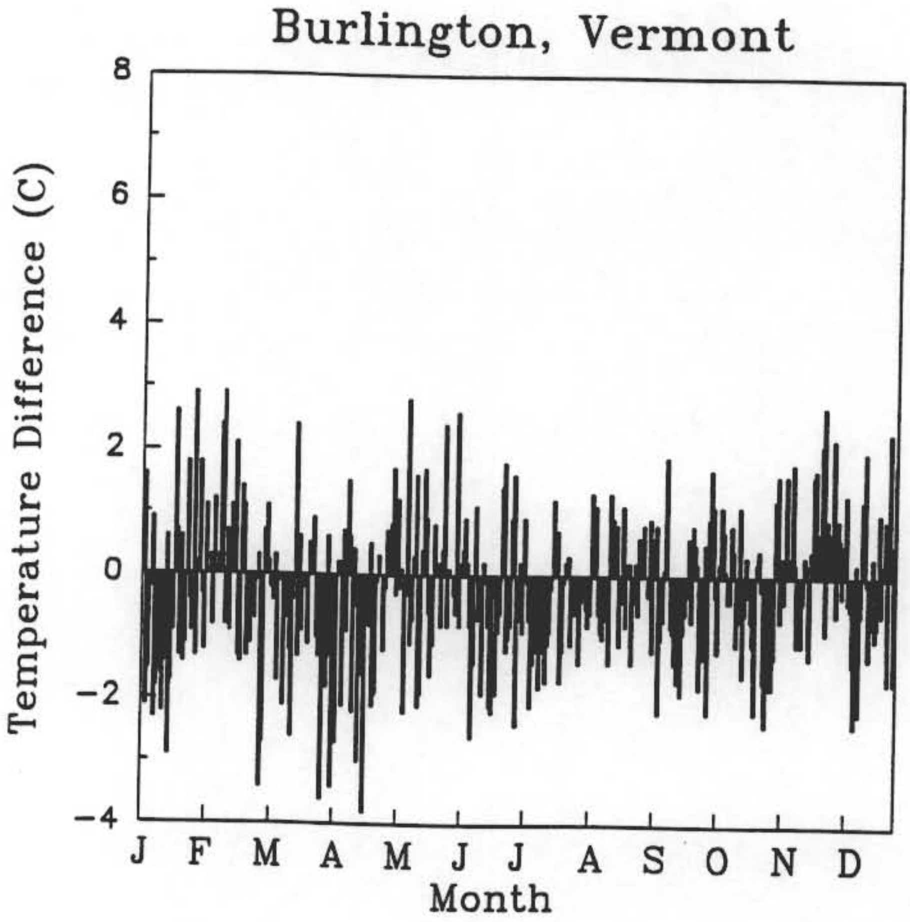


Fig. 5d