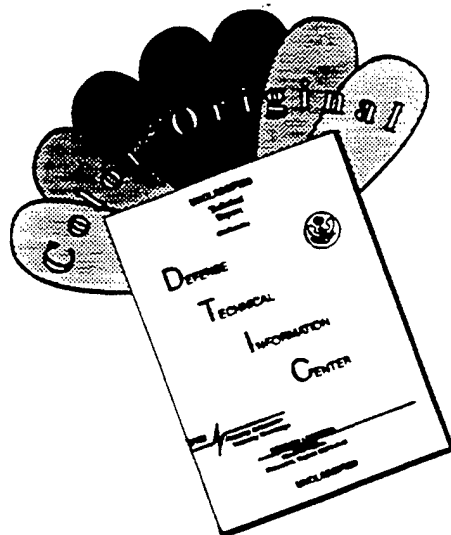


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THESIS

**TEMPERATURE DATA CONTINUITY WITH THE AUTOMATED SURFACE
OBSERVING SYSTEM**

Submitted by

Alison D. Schrumpf

Department of Atmospheric Science

In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 1996

Colorado State University

May 17, 1996

We hereby recommend that the thesis prepared under our supervision by Alison D. Schrupf entitled "Temperature Data Continuity with the Automated Surface Observing System" be accepted as fulfilling in part requirements for the degree of Master of Science.

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ABSTRACT OF THESIS

TEMPERATURE DATA CONTINUITY WITH THE AUTOMATED SURFACE OBSERVING SYSTEM

The National Weather Service has been installing Automated Surface Observing Systems (ASOS) at all first-order weather stations since 1991 as a part of their modernization program. The introduction of this new, automated method of observing the atmosphere has brought with it inherent differences in measuring surface meteorological conditions. One such affected variable is surface air temperature. When ASOS temperature readings at various weather stations were compared to simultaneous temperature readings reported by the Model HO83 instrument, which is used in conventional, man-made observations at those stations, discrepancies were often noted. These discrepancies lead to inevitable inhomogeneity in the temperature time series at stations where ASOS is installed. This investigation examines the sources contributing to these temperature differences for each of the 76 stations in this study.

Examination of temperature differences between conventional observations (using the Model HO83 and designated as CONV for this study) and pre-commissioned ASOS observations have shown conventional observations are warmer (for a large majority of stations) than the corresponding ASOS temperature measurements. Comparing all synoptic hours for all seasons, the average ASOS – CONV temperature differences ranged from -2.56°F (ATL) to +0.61°F (ORH), with a mean value of -0.79°F. Of the 76 stations

in this study, only 5 displayed an overall positive difference indicating ASOS was warmer than CONV. Major sources for the temperature differences between the two instruments were attributed to instrument bias, local effects, and solar effects.

Instrument biases, which resulted from the introduction of the ASOS temperature instrument, were calculated using nighttime observations when overcast skies were reported. Seasonal instrument biases were calculated for all of the 76 stations for every available season. Of the four seasons, summer had the fewest number of nighttime, overcast-sky observations for most stations. Despite this fact, all but five stations did have at least 30 sampled temperature comparisons from which to calculate the summer instrument bias. The seasonal instrument biases were predominantly negative indicating ASOS was cooler than CONV by an average of 0.53°F , and ranged from -2.17°F (ATL in the fall) to $+1.17^{\circ}\text{F}$ (ORH in the spring). Annual instrument biases were calculated using the seasonal values, and again these numbers were largely negative with a range of -1.96°F (ATL) to $+1.16^{\circ}\text{F}$ (ORH). Of the 76 stations, only 9 had positive annual instrument biases. Seasonal instrument biases did fluctuate slightly with the changing seasons, most likely due to electronic instabilities in the CONV instrument. For more than 67 percent of the stations, these fluctuations were $< 0.5^{\circ}\text{F}$, with at least 20 percent of the stations in each season having instrument biases in excess of -1.0°F .

Nighttime local effects were introduced as a contributing factor in the overall temperature differences since ASOS was most often installed at an entirely new location, rather than immediately next to the CONV instrument. Seasonal nighttime local effects, calculated by removing the seasonal instrument biases from the seasonal nighttime temperature differences, were fairly variable throughout the year with changes in both

magnitude and sign convention quite common. These seasonal values were predominantly negative with a range of -1.29°F (SAV in the spring) to $+0.91^{\circ}\text{F}$ (TLH in the summer). Annual contributions by these nocturnal effects were negative for 47 of the 76 stations, indicating that ASOS were most often placed in locations which were cooler at night than the CONV sites. Annual values ranged from -1.11°F (INW) to $+0.70^{\circ}\text{F}$ (TLH) with an average value of -0.16°F . As mentioned above, the seasonal nighttime local effects did fluctuate over the course of the year. Of the 31 four-season stations, 5 displayed evidence of an annual cycle in these nocturnal contributions with summer having the largest negative value and winter the least. In addition, 12 out of the 66 stations with at least three seasons of data displayed trends in temperature differences over the course of the year. Instead of displaying the sinusoidal fluctuations in local effects like many stations, these differences constantly became more negative, and in a few cases more positive, over time. The large remainder of stations showed considerably more moderate fluctuations over the four seasons, or had only one season which behaved quite differently than the other three.

The final contributions to the temperature differences between ASOS and CONV were the daytime local and solar effects. Seasonal values, calculated by removing the seasonal instrument biases from the seasonal daytime temperature differences, were largely negative and ranged from -2.26°F (JKL in the summer) to $+0.91^{\circ}\text{F}$ (DSM in the fall). Annually averaged contributions by daytime local and solar effects were overwhelmingly negative as 67 of the 76 stations had negative values ranging from -1.54°F (JKL) to $+0.61^{\circ}\text{F}$ (VTN), with a mean of -0.37°F . These findings support evidence that the HO83 hygrothermometer is subject to a solar heating problem not experienced by the ASOS

instruments, which is apparent in the daytime observations. Fluctuations in the seasonal daytime effects were also observed, with 33 percent of the four-season stations providing an indication of annual cycles in the daytime effects, with summer having the largest negative value.

Also noted in this investigation was a time dependence on temperature differences between ASOS and CONV readings. Seasonal diurnal cycles for 60 percent of the stations showed the largest, negative difference during the daylight hours, with a noticeable decrease in temperature difference at night, evidence again of the warm bias due to solar heating in the CONV instrument. At 21 percent of the stations, however, this diurnal cycle pattern was reversed due to strong, nocturnal, local influences. This particular nighttime phenomena is the direct result of ASOS quite often being installed at a new location which is cooler at night than the location of the CONV instrument.

Finally, regional similarities were noted during analysis of local and solar effects and temperature time series. Stations in high-sunshine climatic zones, such as TUS, LAS, and ABQ had the largest negative daytime local and solar effects, once more evidence in favor of an existing warm bias in the HO83 hygrothermometer. In addition, coastal sites displayed particularly stable temperature time series plots in contrast to inland, continental sites which showed considerably more variability over the course of this investigation.

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1.0 INTRODUCTION

A comparison of temperature measurements reported by conventional (CONV) observations at manned National Weather Service stations using the Model HO83 temperature instrument and pre-commissioned ASOS observations at those same stations has been conducted. The predominantly negative differences (ASOS – CONV) in ambient air temperature between the two instruments are indicative of the warm bias in the CONV measurements as compared to ASOS measurements. Sources contributing to these temperature differences have been categorized as being due to instrument bias, local effects, and solar effects, and were analyzed on both seasonal and annual scales. At the time of this writing, there has not been a great deal published on temperature comparisons between conventional and ASOS observations outside of the quarterly and annual progress reports for the *Climate Data Continuity with ASOS* project conducted by the Colorado Climate Center since 1991. Similar to those reports, this study investigates the sources of the temperature differences between ASOS and CONV measurements and illustrates how current weather, specifically winds and cloud cover, affect temperature differences between the two instruments.

1.1 Modernization

In keeping with an agreement reached in the late 1980s between the National Weather Service, Federal Aviation Administration, and the Department of the Navy, the

National Weather Service has been installing ASOS throughout the United States since 1991 (Nadolski, 1995). The installation of these automated systems is part of the National Weather Service's Modernization Program. According to the March 1996 *National Weather Service Modernization Update*, as of March 7, 1996 there were 699 ASOS installed throughout the United States, and of these 673 had been accepted and 245 of those were commissioned. Approximately 800 systems will be commissioned when the National Weather Service modernization effort is complete.

ASOS was designed to automate the weather observing process and allow weather station personnel more time to accomplish other tasks such as forecasting. In addition, automating the surface observing process is intended to reduce costs, expand areal coverage, provide data 24 hours each day and get rid of the subjectivity inherent in manual observations such as visibility and estimates of winds. A general introduction to ASOS is included in the *ASOS User's Guide* (National Weather Service, 1992). ASOS is a microprocessor-based system which uses an array of sensors with advanced algorithms to process not only synoptic weather data, but to disseminate a Surface Aviation Observation (SAO) for the station (Nadolski, 1995).

1.2 The Data Set

The data used for this investigation was obtained from the National Climate Data Center (NCDC) in Asheville, North Carolina. The data was transmitted electronically to the Colorado Climate Center (CCC) at Colorado State University for use in the *Climate Data Continuity with ASOS* project. The data set consists of hourly SAOs for both

conventional observations and pre-commissioned ASOS observations, when available, for 76 sites across the continental United States for the period of September 1, 1994 through August 31, 1995. Due to installation and commissioning dates, not all stations have complete ASOS data for the whole year of study. Temperature data are reported in whole degrees Fahrenheit.

This investigation took advantage of a brief National Weather Service moratorium on ASOS commissionings during the winter of 1994-1995. During this period no ASOS systems were commissioned as the official observing and reporting method for any stations, but they had been accepted and were transmitting observed weather data. This moratorium allows a unique comparison between pre-commissioned ASOS temperature observations and conventional hourly SAOs.

Overall, a total of 1,017,646 temperature observations were used during this study. Never before has there been such an extensive comparison between ASOS and conventional methods of temperature measurement. The hourly data allowed exploration of diurnal cycles in ASOS - CONV temperature differences, as well as enhancing daytime and nighttime effects.

One item to note is that there are no daily maximum and minimum temperature comparisons in this investigation since CONV observations were no longer required to report maximum and minimum temperatures as of January 1, 1995. Instead, this study compared the highest ($\Delta T_{\text{highest hourly}}$) and lowest ($\Delta T_{\text{lowest hourly}}$) hourly temperature values reported by both ASOS and CONV during each 24-hour period (midnight to midnight local standard time). It is also important to add that the hours of highest and lowest temperature for ASOS and CONV did not often coincide, such that the ASOS highest

hourly temperature for a certain day did not necessarily occur at the same hour as did the CONV highest hourly temperature, and the same was true for the lowest hourly temperatures.

1.3 The Purpose

At present, the National Weather Service is still a few years away from completing the installation of all ASOS systems in the United States. The moratorium on ASOS commissionings allowed a unique opportunity to compare temperature measurements made by conventional methods (HO83) and pre-commissioned ASOS systems at quite a number of stations, most of which were not previously considered for any comparisons.

The main goal of this investigation was to determine specific causes for relative temperature differences between ASOS and CONV temperature measurements. Factors affecting temperature differences were attributed to either instrument biases inherent in the manufacture of the instruments, local effects due to instrument separation, and solar heating effects due to exposure to the sun. Mean values for each of these factors at each station were determined both seasonally and annually in an attempt to provide a fairly accurate measure of the temperature differences throughout the year.

Other goals were to determine temporal variabilities in temperature differences between ASOS and CONV readings. Seasonal diurnal cycles were plotted for each station to see how temperature differences varied over the course of an average day within that season. Also, seasonal accumulated temperature differences were examined for changes in the temperature relationship between ASOS and CONV instruments. Time

series analysis of daily highest hourly and lowest hourly temperature differences plotted for the entire period record shifts between instruments and indicate annual cycles at a few sites. Of particular interest in isolating instrument biases were wind and sky cover conditions, since these meteorological variables have the most profound impact on temperature differences.

2.0 THE DATA

2.1 The Instruments

Physically the two instruments compared in this study are very similar in appearance and design. The main visual difference is the air deflection skirt located at the bottom of the aspirator cylinder on the ASOS instrument. Figure 2.1 shows a typical schematic representation of the Model HO83 and the ASOS hygrothermometers. Both instruments measure ambient air temperature using a platinum Resistive Temperature Device (RTD) enclosed in an aspirated, shielded cylinder. An important fact to note here is since the HO83 is an older instrument it is perhaps not quite as electronically stable as the newer ASOS hygrothermometer. Plus, the CONV instrument has been in the field for a number of years now, and in many cases the sensor housing has weathered, no longer retaining its original bright white and highly reflective surface.

2.1.1 HO83 Hygrothermometer

The Model HO83 Hygrothermometer System was manufactured by Technical Services Laboratory to be a climatic thermometer and dew/frost point indicator for the National Weather Service (Instruction Manual Hygrothermometer HO83, 1984). The system consists of three separate components: aspirator, transmitter, and a display unit as shown in Figure 2.2. Ideally the aspirator was placed outdoors in a location where it

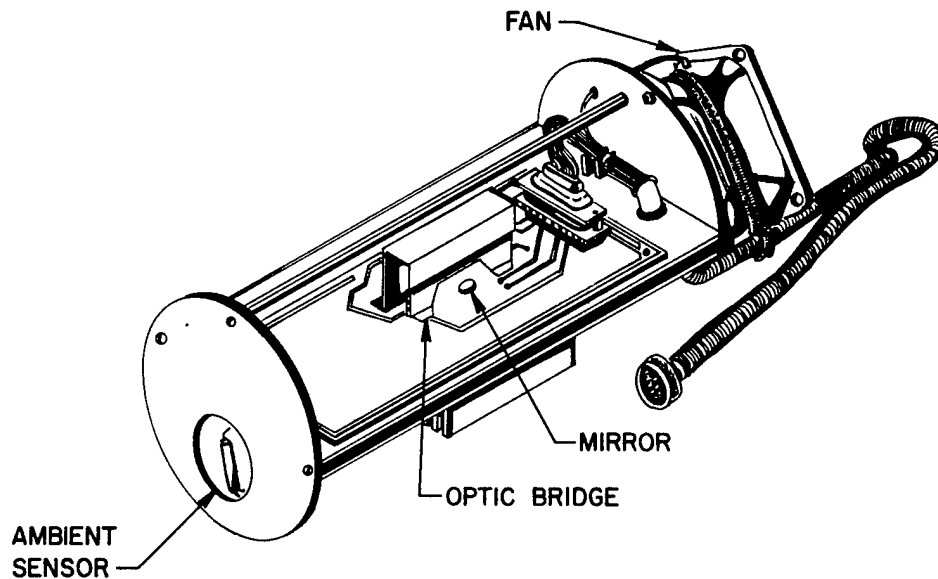
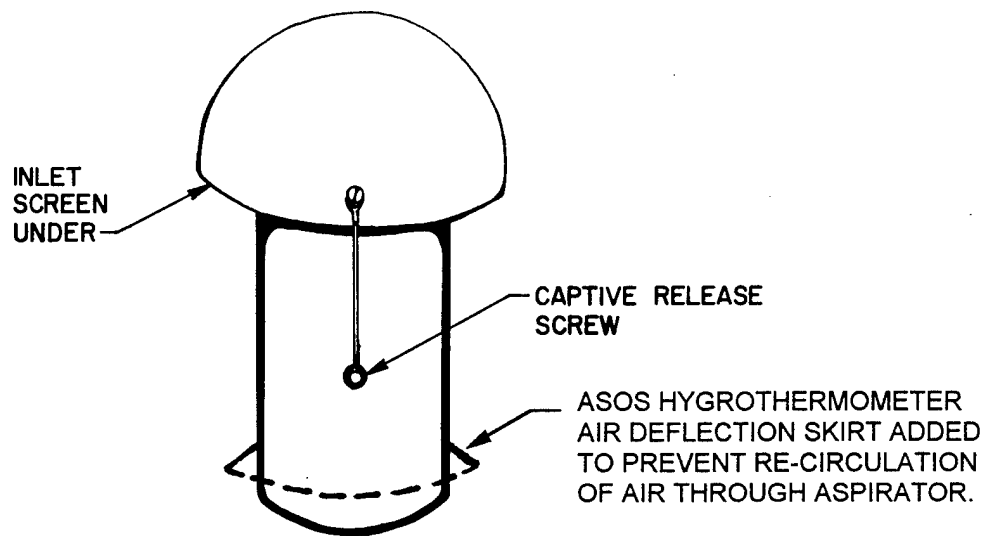


Fig. 2.1 Typical schematic of Model HO83 Hygrothermometer. The ASOS Hygrothermometer is very similar in appearance with the addition of the air deflection skirt pictured above. (Instruction Manual Hygrothermometer HO83, Vol 1, 1984.)

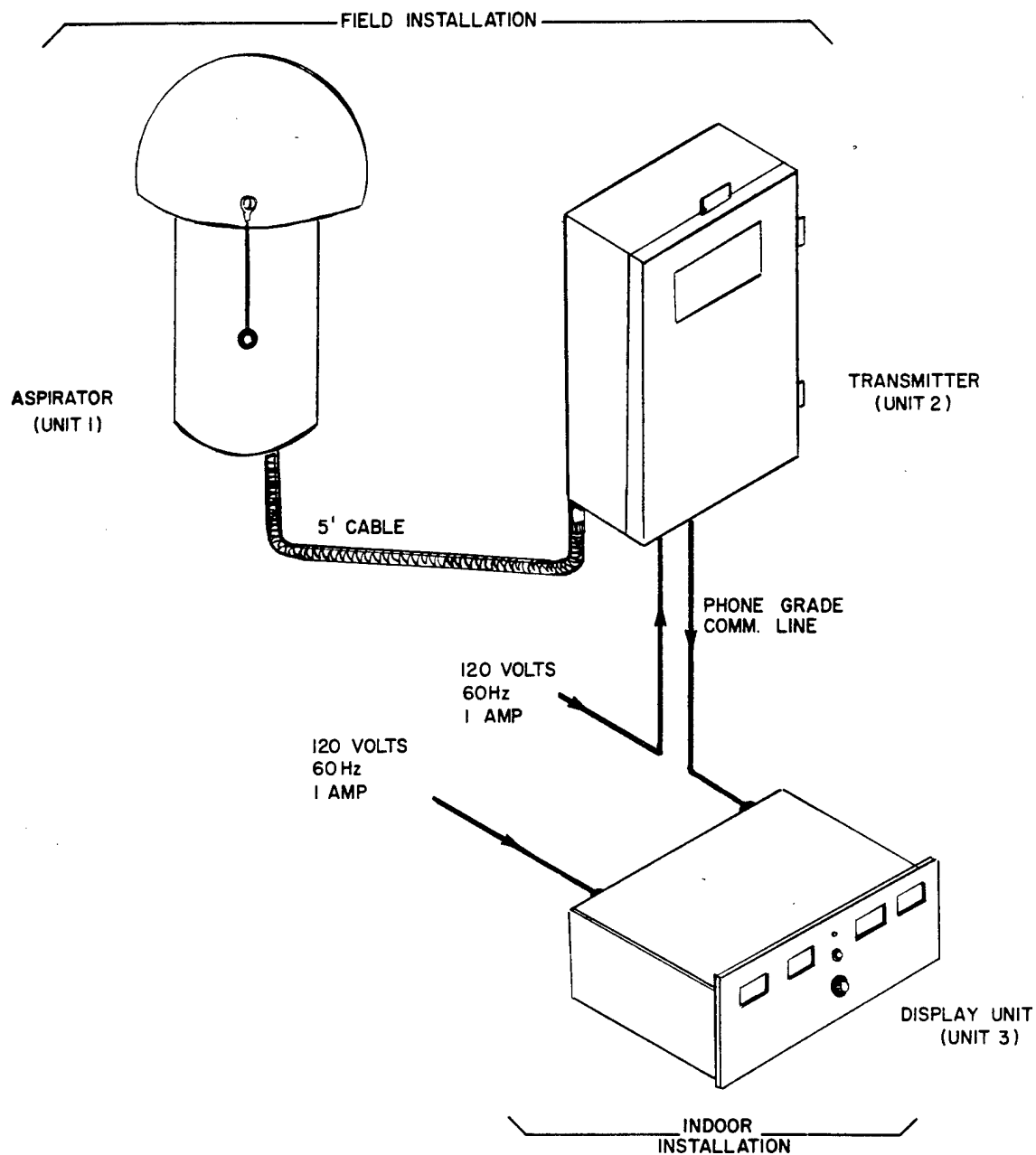


Fig. 2.2 Schematic representation of the three components of the Model HO83 Hygrothermometer. (Instruction Manual Hygrothermometer HO83, Vol 1, 1984).

could sample the surface atmosphere without contamination due to ground water, vegetation, and other distractive influences. Airflow is drawn into the top of the aspirator dome and directed downward through the cylinder casing where it is sampled by the ambient air temperature sensor before being expelled from the bottom of the cylinder housing. The transmitter is positioned close by the aspirator, usually within five feet, and is designed to be weatherproof. The final component, the remote display unit, is connected via telephone line to the transmitter and is located some distance away from the other two components in an indoor environment.

The HO83 as originally designed features a range of -76°F to $+140^{\circ}\text{F}$ with a resolution of 0.18°F and an accuracy of $\pm 0.9^{\circ}\text{F}$ (Instruction Manual Hygrothermometer HO83, 1984). The platinum-wire RTD is encased in a ceramic cylinder about $1/8$ inches in diameter and $3/4$ inches in length. At a temperature of $+32^{\circ}\text{F}$ (0°C), the RTD has an electrical resistance of exactly 100 ohms. The resistance varies linearly with temperature at a rate of 0.392 percent per degree Celsius. Both a maximum and minimum temperature display are available, but values for each are simply the highest and lowest temperature readings since the last system "reset," which is accomplished by manually depressing both the Max/Min Reset Switch and the Fahrenheit Display Switch located on the display panel at the same time. Data for this investigation from the Model HO83 instruments used the 5-minute average temperature output.

2.1.2 ASOS Hygrothermometer

The ASOS hygrothermometer has a design that is similar to the Model HO83 hygrothermometer, and operates in much the same way using a platinum RTD. The

current ASOS instrument, fielded in late 1993 and early 1994, incorporates several modifications to the original ASOS hygrothermometer. The aspiration rate was increased to allow more air flow past the sensor, and the aspirator fan was moved from the bottom to the top of the aspirator changing the direction of air flow to upward instead of downward through the instrument casing. Also, an air deflection skirt was placed around the lower portion of the aspirator body to prevent recirculating expunged air from the top of the shield. Next, the RTD element was changed from a 0.1% to a 0.03% basic accuracy. And finally, the electrical circuitry was improved with low temperature coefficient resistors (Crosby and Nadolski, 1993). Figure 2.3 shows a typical ASOS sensor array with the temperature/dewpoint sensor positioned second from the left end.

System specifications for the ASOS temperature sensor report range limits of -80°F to +130°F, with 0.1°F resolution. Accuracy for this sensor is $\pm 0.9^\circ\text{F}$ for readings between -58°F and 122°F, and $\pm 1.8^\circ\text{F}$ for readings between -80°F and -58°F and between 122°F and 130°F (ASOS User's Guide, 1992).

According to the ambient temperature algorithm, the sensor samples the atmosphere six times each minute to obtain a one-minute average ambient temperature value. If any consecutive one-minute readings differ by more than 6°F, then the current reading is marked as missing. Next, a 5-minute average temperature value is calculated using the last five one-minute readings. If four or more temperature values are valid in the last five minutes, ASOS performs a linear average to obtain the new 5-minute temperature reading. However, if less than four temperature readings are available for the previous five minutes, ASOS does not calculate a new 5-minute reading but uses the most current reading for the last 15 minutes. If there are no new temperature readings computed in the

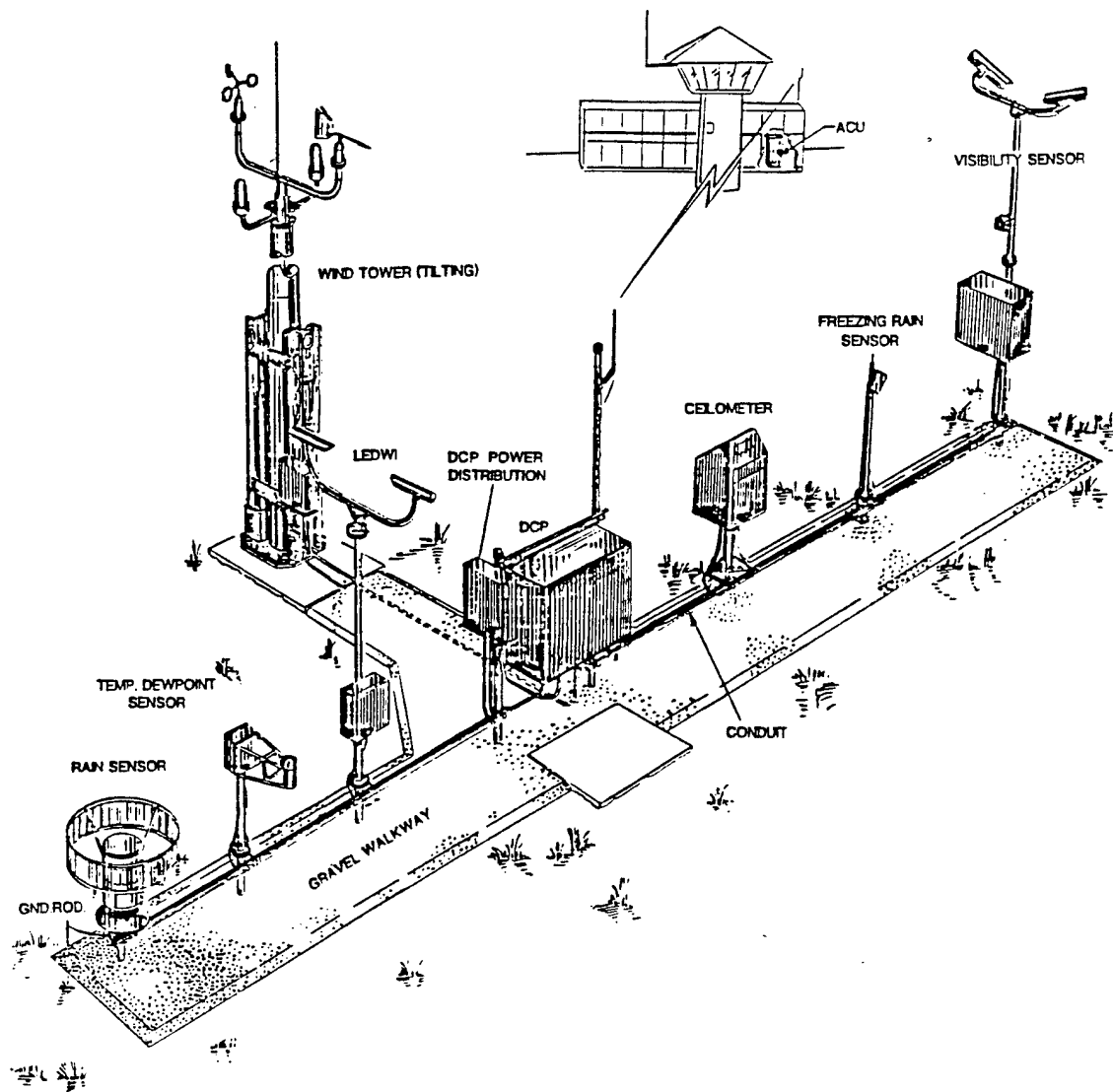


Fig. 2.3 Typical ASOS sensor array. (ASOS Level II System Manager Training Course Student Guide, 1992.)

last 15 minutes, then the output is marked as missing “-99” (Chu, 1994). The one-minute data can be stored for 12 hours before being written over by new data. And all the daily and monthly averages are calculated at midnight local standard time each night and on the first day of each month for the previous month, respectively. Data for this investigation used the ASOS 5-minute average temperature measurements.

As to the reliability and availability of the ASOS temperature sensor, the *Third ASOS Aviation Demonstration Industry Briefing* (National Weather Service, 1995) reported that the sensor was available on an average of 99.65% of the time with mean outages of 2.4 hours usually caused by sensor hardware, power failure, or on-site maintenance. Among all of the meteorological sensors in the ASOS array, the temperature sensor had the second highest number of outage times with an average of 639 hours between missing sensor events. Also, comparisons have been made to determine the performance characteristics of ASOS with respect to “true” ambient air temperature (McKee, et al., 1996). Direct comparisons between three modified ASOS hygrometers and a calibrated, National Weather Service secondary field standard (R. M. Young) in 1994 “found no systematic bias [of the ASOS instruments] relative to the National Weather Service secondary standard.” The tests indicated that ASOS has a range between instruments of approximately $\pm 0.3^{\circ}\text{F}$, with more of the instruments being cooler as opposed to warmer. Since there is no calibration against a field standard before each ASOS is commissioned, this range is presumably accurate for the current ASOS temperature instruments.

2.2 Site Locations and Classifications

The 76 stations chosen for this investigation were widely scattered across the continental United States (CONUS). Table 2.1 gives a complete listing of all the stations investigated in this study including station identifier (SID), station name, station location, and commissioning date when applicable.

Much of the data analysis involved stratifying the data into daytime and nighttime hours. In order to use the same set of hours for daytime and nighttime analysis, the stations were divided into groups based on their respective Local Standard Time Zone. Daytime was defined as the seven-hour period inclusive of 9:00am to 3:00pm LST, and night as the seven-hour period inclusive of 10:00pm to 4:00am LST. Table 2.1 also shows which time zone each of the stations is in, as well as the number of seasons each station had available for a complete analysis.

Each of the stations is classified based on the amount of data available for comparison at that station. The amount of data available is largely a function of installation dates, commissioning dates, and system outages. Since the ASOS systems used during the period of comparison with CONV temperature observations were not commissioned, it is likely that the pre-commissioned ASOS maintenance standards were different from those required for commissioned ASOS instruments. There are three categories of stations for analysis: four-season stations, three-season stations, and two-season stations. ACY is in the 4-season group, but was analyzed separately for the additional summer season because the ASOS instrument was relocated during this study. Each season consists of three consecutive months based on the following divisions:

Table 2.1 Stations used in Temperature Comparison Study

SID	Station Name and Location	LST Zone	# of seasons	Date Commissioned
ABE	Allentown, PA	Eastern	3	
ABQ	Albuquerque, NM	Mountain	3	
ACY ^M	Atlantic City, NJ	Eastern	4	
ALB	Albany, NY	Eastern	3	Commissioned Aug-95
ALO	Waterloo, IA	Central	3	
APN ^F	Alpena, MI	Eastern	3	
ATL	Atlanta, GA	Eastern	3	Commissioned Aug-95
AUS	Austin, TX	Central	3	Commissioned Jul-95
BFF	Scottsbluff, NE	Mountain	3	Commissioned Jun-95
BGM	Binghamton, NY	Eastern	4	
BIL	Billings, MT	Mountain	2	Commissioned May-95
BIS	Bismarck, ND	Central	4	
CAE	Columbia, SC	Eastern	4	
CAK	Akron, OH	Eastern	2	
CLE	Cleveland, OH	Eastern	4	
COU	Columbia, MO	Central	4	
CYS	Cheyenne, WY	Mountain	4	
DAB	Daytona Beach, FL	Eastern	3	Commissioned Jun-95
DAY	Dayton, OH	Eastern	3	
DRA	Mercury, NV	Pacific	2	
DSM	Des Moines, IA	Central	4	
DTW	Detroit, MI	Eastern	3	Commissioned Jul-95
ERI	Erie, PA	Eastern	4	
EUG	Eugene, OR	Pacific	3	
FAR	Fargo, ND	Central	4	
FNT	Flint, MI	Eastern	2	Commissioned Jun-95
FSD ^M	Sioux Falls, SD	Central	4	
FWA	Fort Wayne, IN	Eastern	3	
GEG	Spokane, WA	Pacific	2	
GJT	Grand Junction, CO	Mountain	3	
GRB	Green Bay, WI	Central	4	
HON	Huron, SD	Central	3	
INL	International Fall, MN	Central	3	
INW	Winslow, AZ	Mountain	3	Commissioned Jul-95
ISN	Williston, ND	Central	2	
JAX	Jacksonville, FL	Eastern	4	
JKL	Jackson, KY	Eastern	4	
LAN	Lansing, MI	Eastern	3	
LAS	Las Vegas, NV	Pacific	4	
LBB	Lubbock, TX	Central	3	
LBF ^M	North Platte, NE	Central	2	
LCH	Lake Charles, LA	Central	3	
LEX ^C	Lexington, KY	Eastern	4	
MCI	Kansas City, MO	Central	3	Commissioned Jul-95
MCO	Orlando, FL	Eastern	4	
MGM	Montgomery, AL	Central	3	Commissioned Jul-95
MHS	Mount Shasta, CA	Pacific	4	
MKE	Milwaukee, WI	Central	3	Commissioned Jul-95
MKG	Muskegon, MI	Eastern	3	
MLI	Moline, IL	Central	3	Commissioned Jul-95
MOB	Mobile, AL	Central	4	
MSN	Madison, WI	Central	2	
MSO	Missoula, MT	Mountain	3	
OFK	Norfolk, NE	Central	3	
ORH	Worcester, MA	Eastern	3	Commissioned Jul-95
PAH ^M	Paducah, KY	Central	3	Commissioned Aug-95
PDT	Pendleton, OR	Pacific	3	Commissioned Jun-95
PDX	Portland, OR	Pacific	3	
PIA	Peoria, IL	Central	3	
RAP	Rapid City, SD	Mountain	4	
RDD	Redding, CA	Pacific	4	
RFD	Rockford, IL	Central	3	Commissioned Jul-95
RSL	Russell, KS	Central	4	
RST	Rochester, MN	Central	3	
SAV	Savannah, GA	Eastern	4	
SBN	South Bend, IN	Eastern	4	
SGF ^M	Springfield, MO	Central	4	
SJT	San Angelo, TX	Central	2	
SLN	Salina, KS	Central	4	
SPI	Springfield, IL	Central	4	
SUX	Sioux City, IA	Central	3	Commissioned Jun-95
TLH	Tallahassee, FL	Eastern	4	
TRI	Bristol, TN	Eastern	2	
TUS	Tucson, AZ	Mountain	4	
VTN	Valentine, NE	Central	4	
YNG ^C	Youngstown, OH	Eastern	4	
^c	Collocated Station			
^M	Station moved			

Table 2.2 Seasonal Divisions

Season	From	To
Fall	September 1, 1994	November 30, 1994
Winter	December 1, 1994	February 28, 1995
Spring	March 1, 1995	May 31, 1995
Summer	June 1, 1995	August 31, 1995

A station is considered to have enough data for a full season's analysis if there are enough observations from both CONV and ASOS present to yield 2/3 of the possible number of temperature comparisons for that season (basically two out of three months worth of data must be present). Of the 76 stations, 31 comprise the four-season list, 35 are on the three-season list, and 10 qualified for the two-season list. Figures 2.4, 2.5, and 2.6 are geographical representations of the locations of the four-season, three-season, and two-season stations, respectively.

A few sites, APN, LEX, and YNG, were found to be collocated sites meaning the two temperature instruments were within several yards of each other. However at other sites, it was discovered that the two instruments were often positioned much farther from each other, in some cases distances greater than one mile were reported, which leads to our next discussion.

2.3 Location Effects

One of the most complicating factors in maintaining integrity in the temperature time series at any station is changing the location of the temperature measuring device. With the installation of ASOS came the decision to place the ASOS sensor array out in the airfield close to the touchdown zone of a primary runway. This new location was, in many

FOUR-SEASON STATIONS

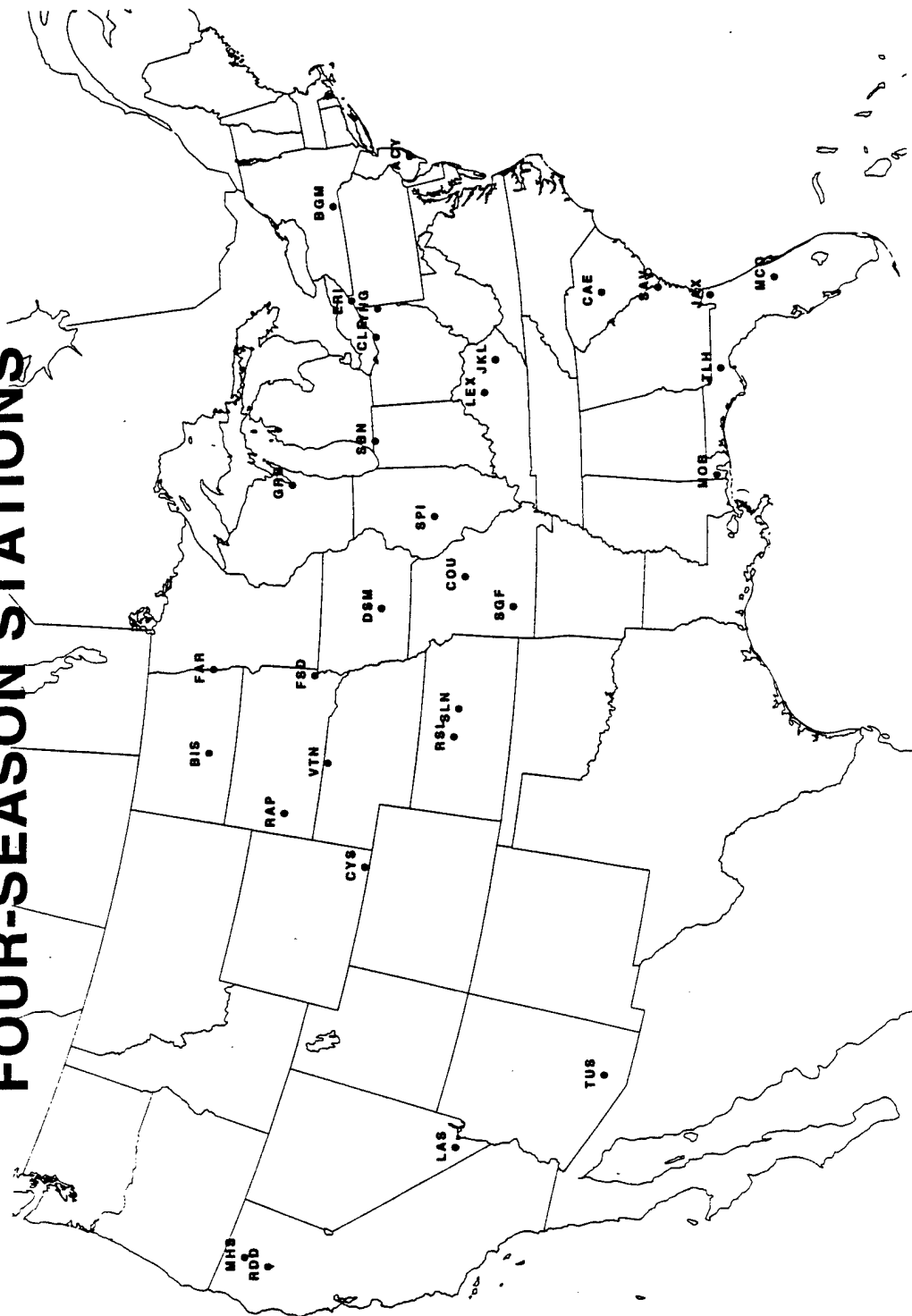


Fig. 2.4 Geographical locations of the four-season stations.

THREE-SEASON STATIONS

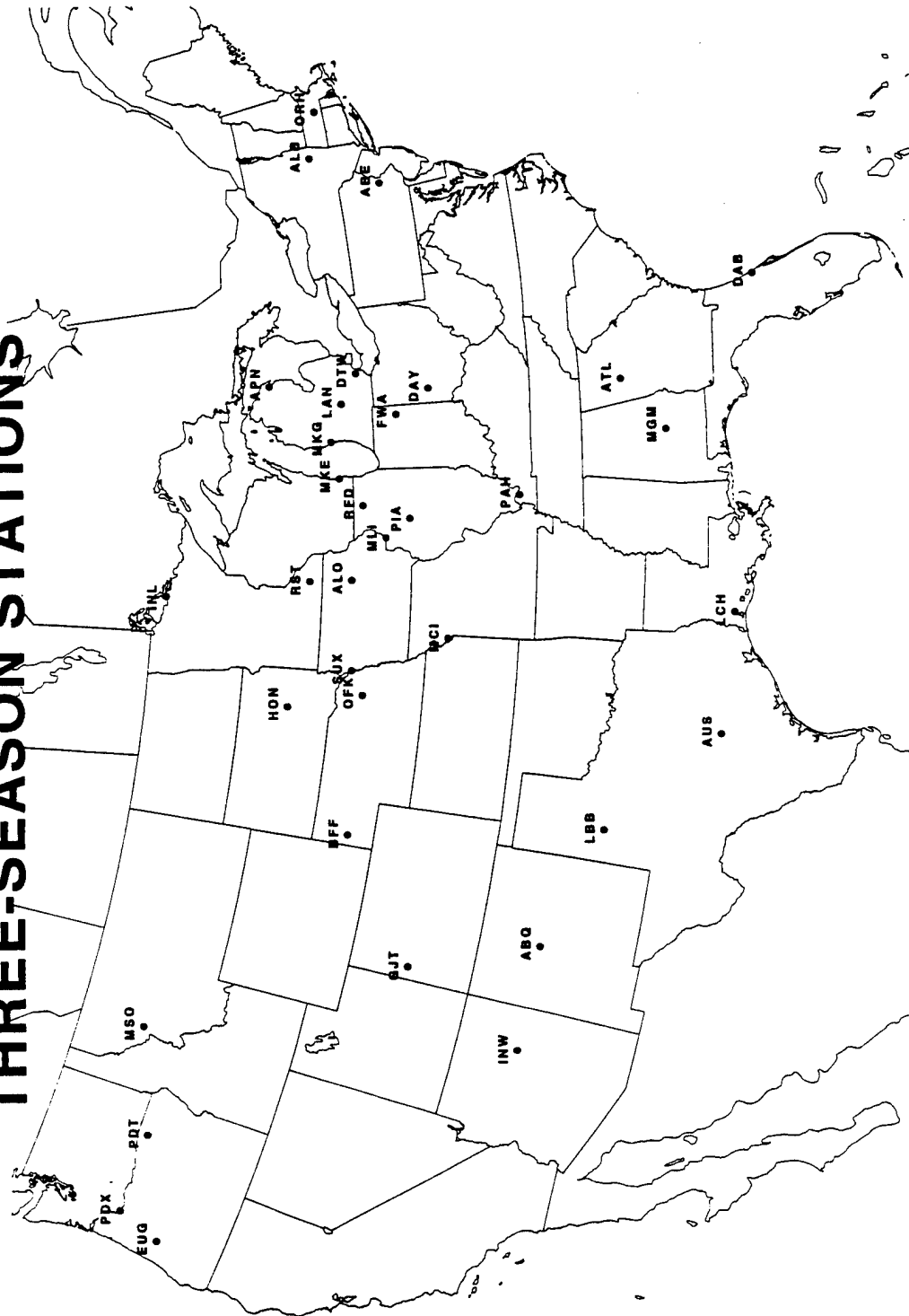


Fig. 2.5 Geographical locations of the three-season stations.

TWO-SEASON STATIONS

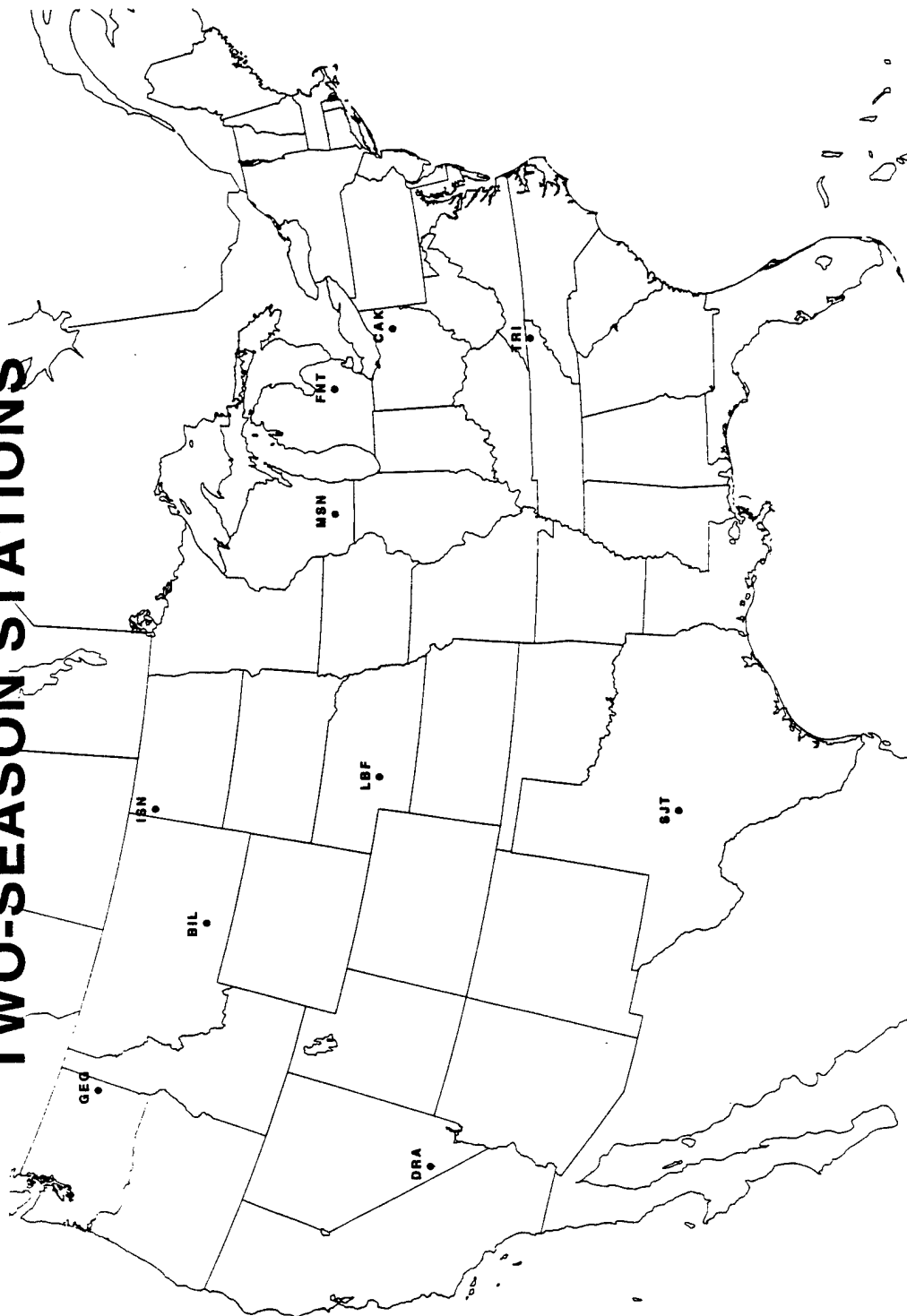


Fig. 2.6 Geographical locations of the two-season stations.

cases, quite different from where the CONV instrument was taking ambient air temperature measurements.

Site requirements for the HO83 aspirator called for mounting the unit approximately five feet above the ground in any location that could provide unobstructed air flow through the sensor assembly (Instruction Manual Hygrothermometer HO83, 1984). Consequently, these instruments were placed at various distances away from the weather station building, and preferably in locations as far away from standing water and dense vegetation as possible to minimize their effects, especially on the dew point.

Location changes of only a few hundred yards put ASOS further away from buildings and interference from other anthropogenic structures. Occasionally there were times when the ASOS location coincided with the HO83 installation site and the two instruments essentially wound up being collocated. The placement of ASOS in a new location could cause the instrument to be affected by a variety of local effects, which are much different from a site near a building, especially if ASOS is installed near the end of a runway as intended.

Obviously, altering exposure elements between the two sensors is going to cause differences in measured ambient air temperature. In the most extreme cases, when ASOS is installed up to miles away, these differences can be quite distinct. This investigation examines the effects on temperature difference between ASOS and CONV measurements due to these instrument relocations.

2.4 Observations

The data examined in this study consists of over 1,500,000 hourly SAOs from 76 weather stations across the continental United States for a one-year period. Each station had two data streams for comparison. One was the conventional data which included all official observations transmitted during the year of study, including hourly observations, special observations, and record special observations along with any corrections (CORs) to those observations; and the second was the unofficial, pre-commissioned ASOS observations for the same time period, when available, for the same stations. First, the CONV and ASOS hourly SAOs were separated from the rest of the observations. Next, ambient surface air temperature data, reported in whole degrees Fahrenheit, was extracted for each hour from each of the data streams for comparison. Needless to say, when one or both of the data streams were missing for any of the hours, no comparisons were made for those times.

An important note on observation timing should be included here. ASOS is a fully automated observing system and the temperature value which is sent as the current ambient value is the latest 5-minute average at 56 minutes past the hour. On the other hand, CONV SAOs are recorded for transmission sometime between 50 and 59 minutes after the hour. Since the temperature value must be physically read by the observer and entered into the computer for transmission, there is no guarantee that the ASOS and the CONV 5-minute average temperature values will even be for the same five minutes since the observer can read the HO83 Display Unit at any time within roughly a 15 minute

window. These timing differences may lead to even greater temperature differences between reported ASOS and CONV values, especially during periods when the temperature is changing rapidly. These effects cannot be isolated since it is not possible to know exactly when an observer recorded the HO83 ambient temperature, which could be several minutes prior to transmission time.

3.0 TEMPERATURE COMPARISONS

3.1 Concepts

The installation of ASOS marks a transition from CONV observations to automated observations with three important factors: a change of instruments, a change in location of instruments, and an expectation that solar heating effects will be larger for the conventional HO83 instrument (McKee, et al., 1996). Any contribution to temperature differences between ASOS and CONV will be due to a combination of these components.

For each station the hourly SAO temperature values, which are transmitted in whole degrees Fahrenheit, were compared using the difference technique where

$$\Delta T = T_{ASOS} - T_{CONV} \quad (3.1)$$

with the symbols being the ASOS temperature (T_{ASOS}), the CONV temperature (T_{CONV}), and the difference between them (ΔT). The resulting ΔT was expressed as a linear combination of its three contributions: instrument bias (inherent in the manufacture of the temperature sensor), local effects (due to instrument separation and determined by local climatic anomalies), and solar effects (due to exposure to solar radiation, a daytime phenomena only), such that

$$\Delta T = \Delta T_i + \Delta T_l + \Delta T_s \quad (3.2)$$

where the subscripts i = instrument bias, l = local effects, and s = solar effects (McKee, et al., 1996).

Ideally, the three components are separate and distinct contributions. However in reality, it is not possible to completely separate the components, especially the daytime local effects and solar effects. In addition, the temperature differences often fluctuate over time due to various causes discussed in the next section.

3.2 Data Problems

In addition to the data gaps caused by installation dates, commissioning dates, and systems outages previously mentioned, several other data problems affected this investigation. As a rule, temperature differences between ASOS and CONV measurements were ignored if the difference was greater than $+9^{\circ}\text{F}$ or less than -9°F . Differences beyond this range were considered to be outliers caused by some sort of instrument malfunction or data processing problem and were excluded from this analysis. Indeed in many instances, these outliers occurred just before an ASOS system outage.

Compounding the location effects caused by installing ASOS at some distance away from the HO83 was the decision by the National Weather Service to relocate an ASOS instrument sometime during the course of this investigation and after the initial installation. Included as an example, the ASOS at ACY was installed and transmitting weather observations at the beginning of this study. Then in late spring, the ASOS was moved to a site which clearly changed the observed temperature. Other stations like PAH underwent relocation which made continual analysis at those stations for the complete year impossible since CONV data was no longer available for the original site.

Close examination of the temperature differences between ASOS and CONV instruments at each station also revealed several unexplained irregularities in the data. For

example, why did ΔT suddenly change sign convention from negative to positive (ACY), now known to be the result of an instrument move, or positive to negative (VTN)? And why does ΔT have short excursions that don't seem to match long-term, temperature-difference patterns at certain stations (ERI, SGF)? In order to answer these and other questions, it was decided to examine the temperature differences between the two instruments at each station looking at the complete year's worth of data in a single snapshot. The resulting analysis was very helpful in discovering when the two stations exhibited a change in the normal temperature-difference pattern. First, seasonal accumulated temperature difference plots were generated for each station using all hours. These graphs were helpful in depicting significant fluctuations in temperature differences at each site. Any fluctuations indicate that something happened to one or both of the instruments at that site. Since there are two instruments at each location for comparison it is impossible to know which instrument changed without a third, control instrument. What is for certain is that something changed the temperature relationship between the two instruments. These changes could be the result of an instrument being moved, maintenance, replacement of a sensor, or electrical problems. To further investigate the shifts in temperature differences between the two instruments, $\Delta T_{\text{highest hourly}}$ and $\Delta T_{\text{lowest hourly}}$ time series plots were generated for each station for the whole year. These plots were very helpful in determining exactly when a shift occurred, how long it lasted, and whether it affected both the highest and lowest hourly temperatures values equally.

3.2.1 Accumulated ΔT Plots

If two sensors behave the same way all of the time, then a reasonable assumption would be that any temperature difference distinguished between the two should remain fairly constant with time. Graphically, there would be a linear relationship between the accumulated ΔT and time, with the slope of this line being proportional to the overall bias (McKee, et al., 1996). However, any changes in the slope of this line indicate that something changed the temperature relationship between the two instruments.

Figures 3.1(A) - (G) depict seasonal accumulated temperature difference plots for seven stations. Fall and winter comprise the first row while spring and summer are on the second row. Accumulated ΔT are the y-axis values, with days per season along the x-axis. For each season, all of the hourly temperature differences are plotted as a running total over time. Due to the large numbers of hourly observations, the beginning of each new season starts over with accumulated $\Delta T = 0$.

Beginning with a fairly well-behaved station in Figure 3.1(A), CYS exhibits a reasonably constant, linear relationship between accumulated ΔT and time. The slope of the line is such that -2000°F would be accumulated in 100 days in the fall. A total of 100 days with 24 observations per day with a -1°F difference each hour would lead to a total accumulated ΔT of -2400°F . Thus the hourly temperature difference for CYS in the fall is roughly -0.83°F each hour. All four seasons are quite smooth and have similar slopes, except for a slight shift during the summer season. The next Figure 3.1(B) strongly supports evidence of an ASOS instrument move at ACY sometime in late spring. Until that point, the overall pattern of the slope at ACY is negative; but after the instrument

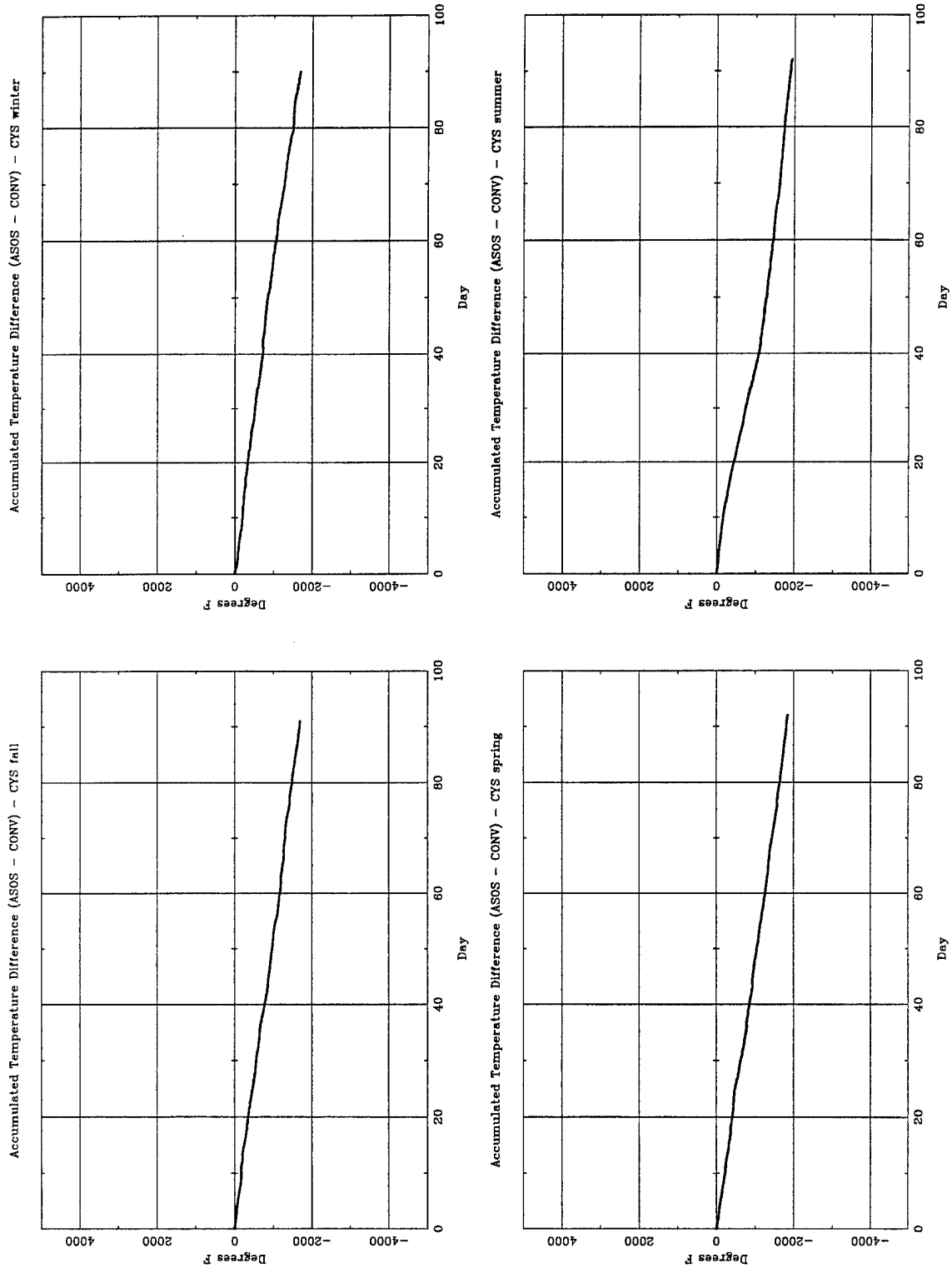


Fig. 3.1 (A) Seasonal accumulated temperature difference plots for Cheyenne, WY.

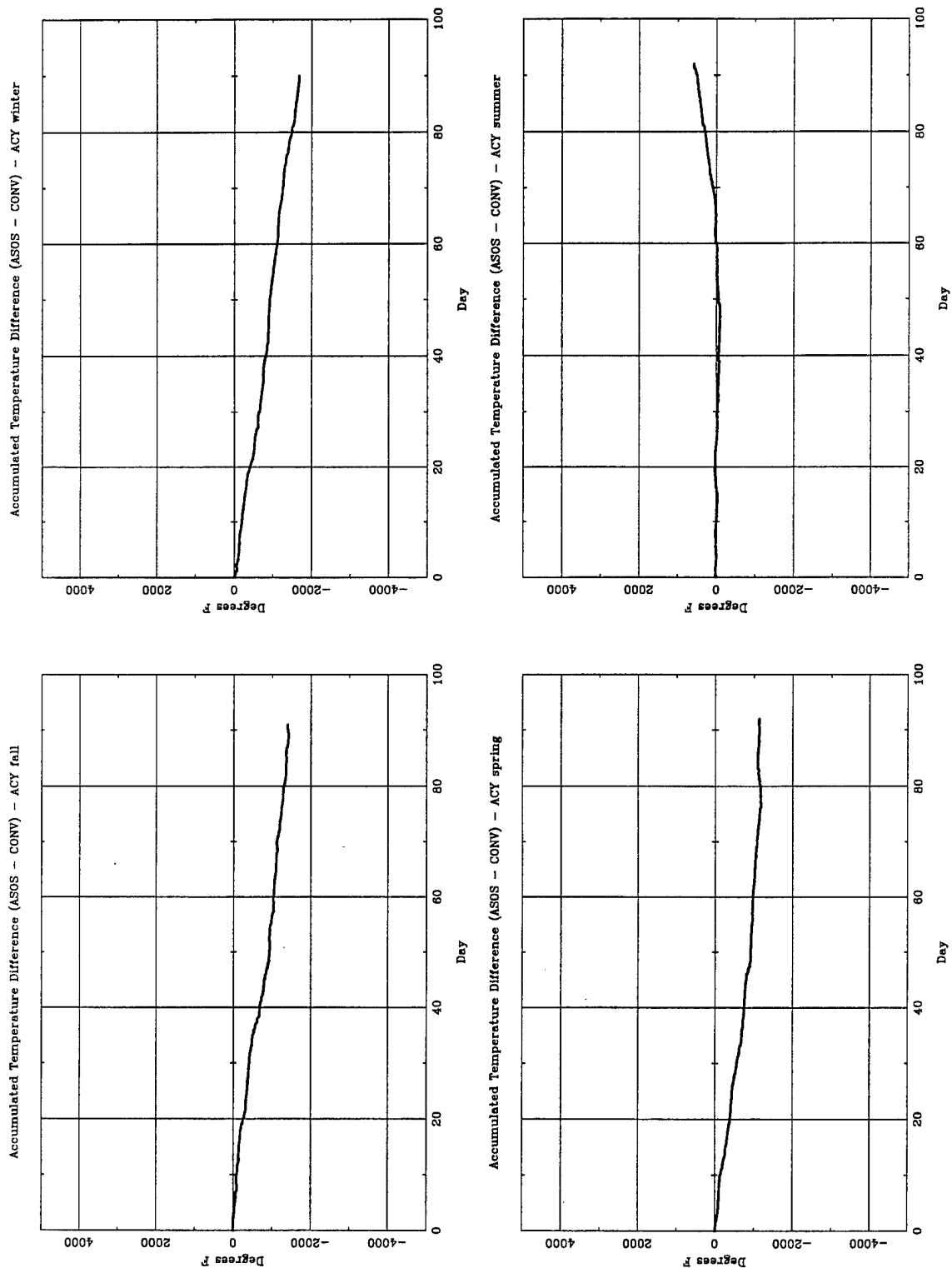


Fig. 3.1 (B) Seasonal accumulated temperature difference plots for Atlantic City, NJ.

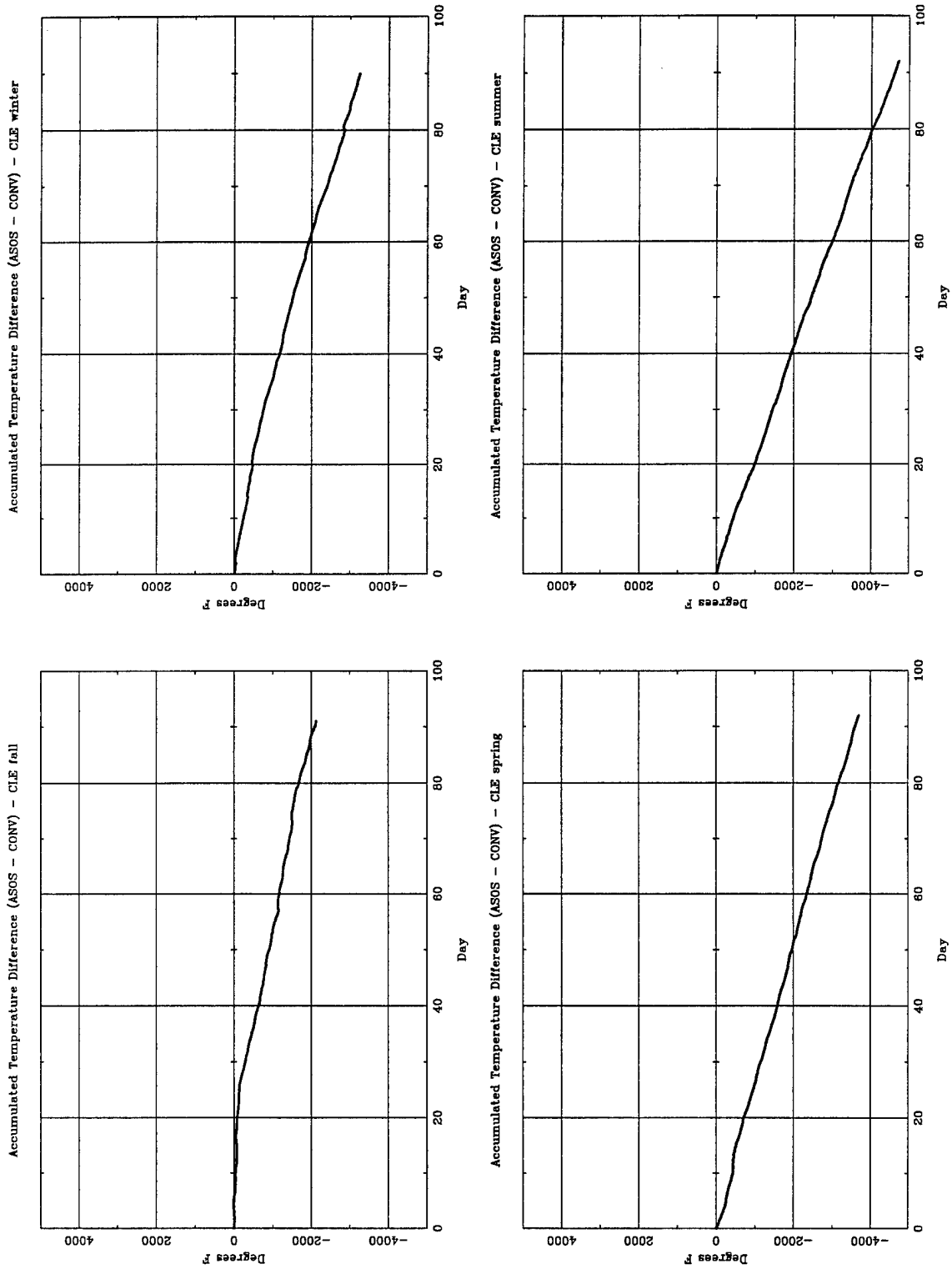


Fig. 3.1 (C) Seasonal accumulated temperature difference plots for Cleveland, OH.

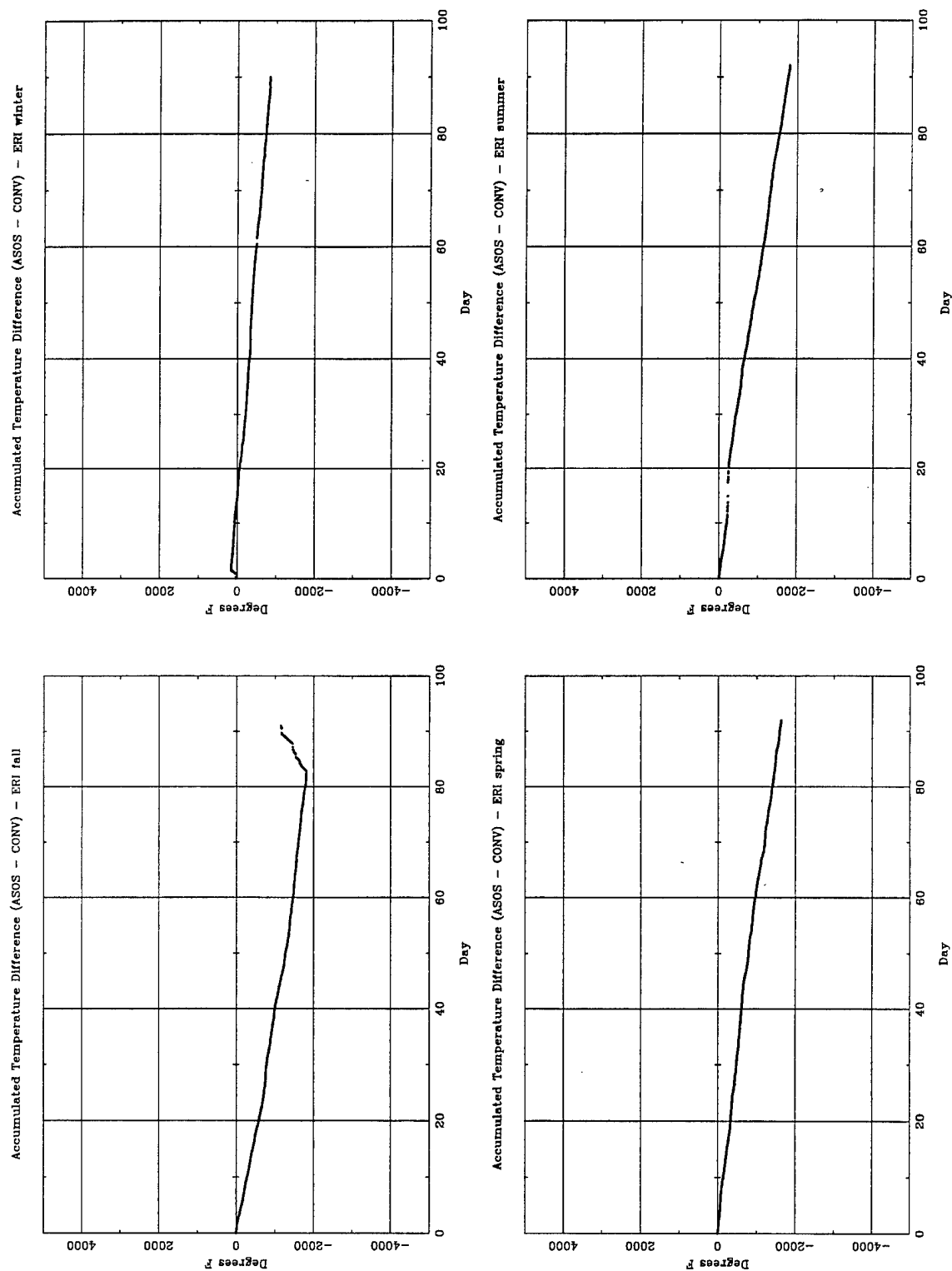


Fig. 3.1 (D) Seasonal accumulated temperature difference plots for Erie, PA.

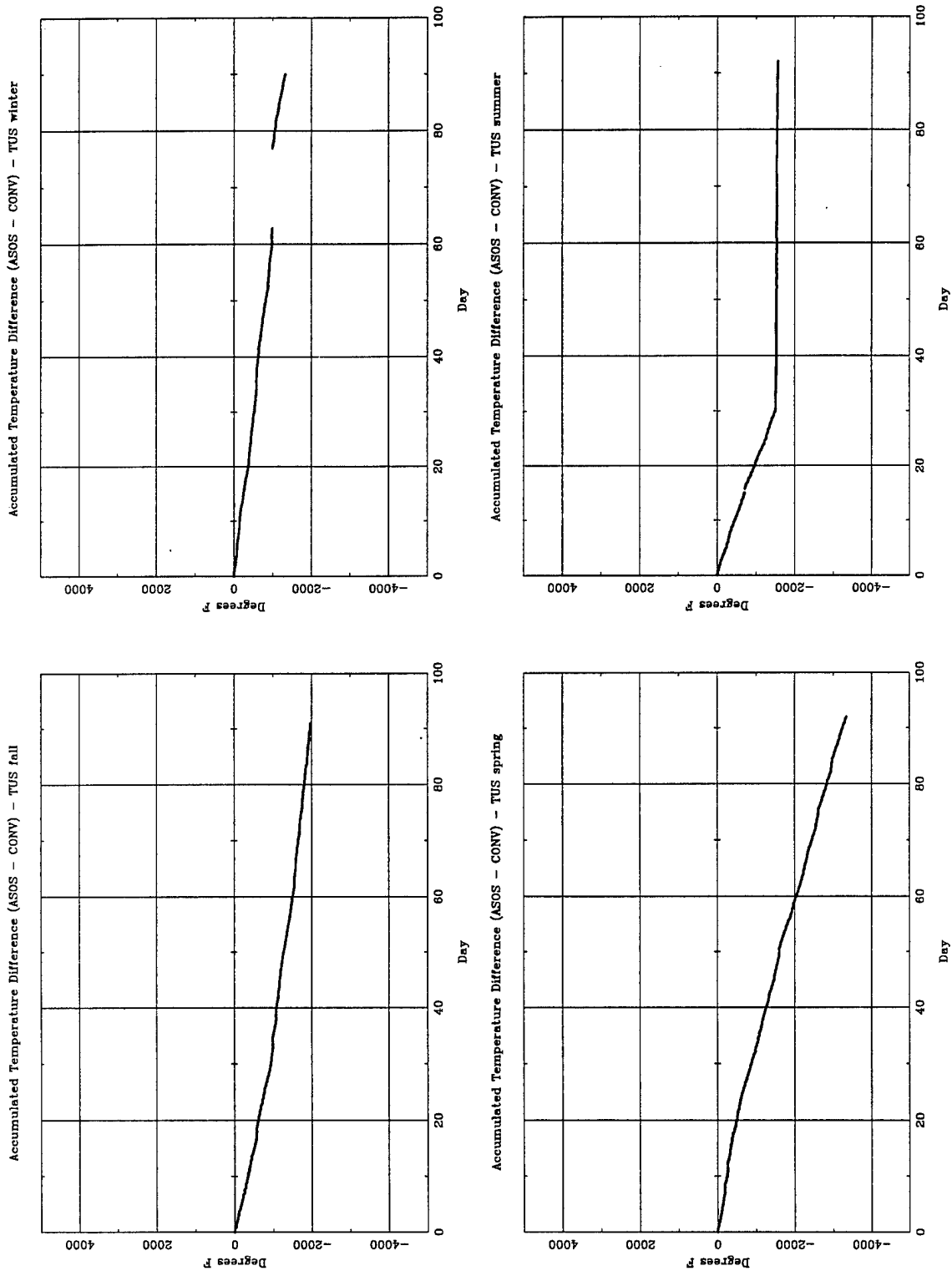


Fig. 3.1 (E) Seasonal accumulated temperature difference plots for Tucson, AZ.

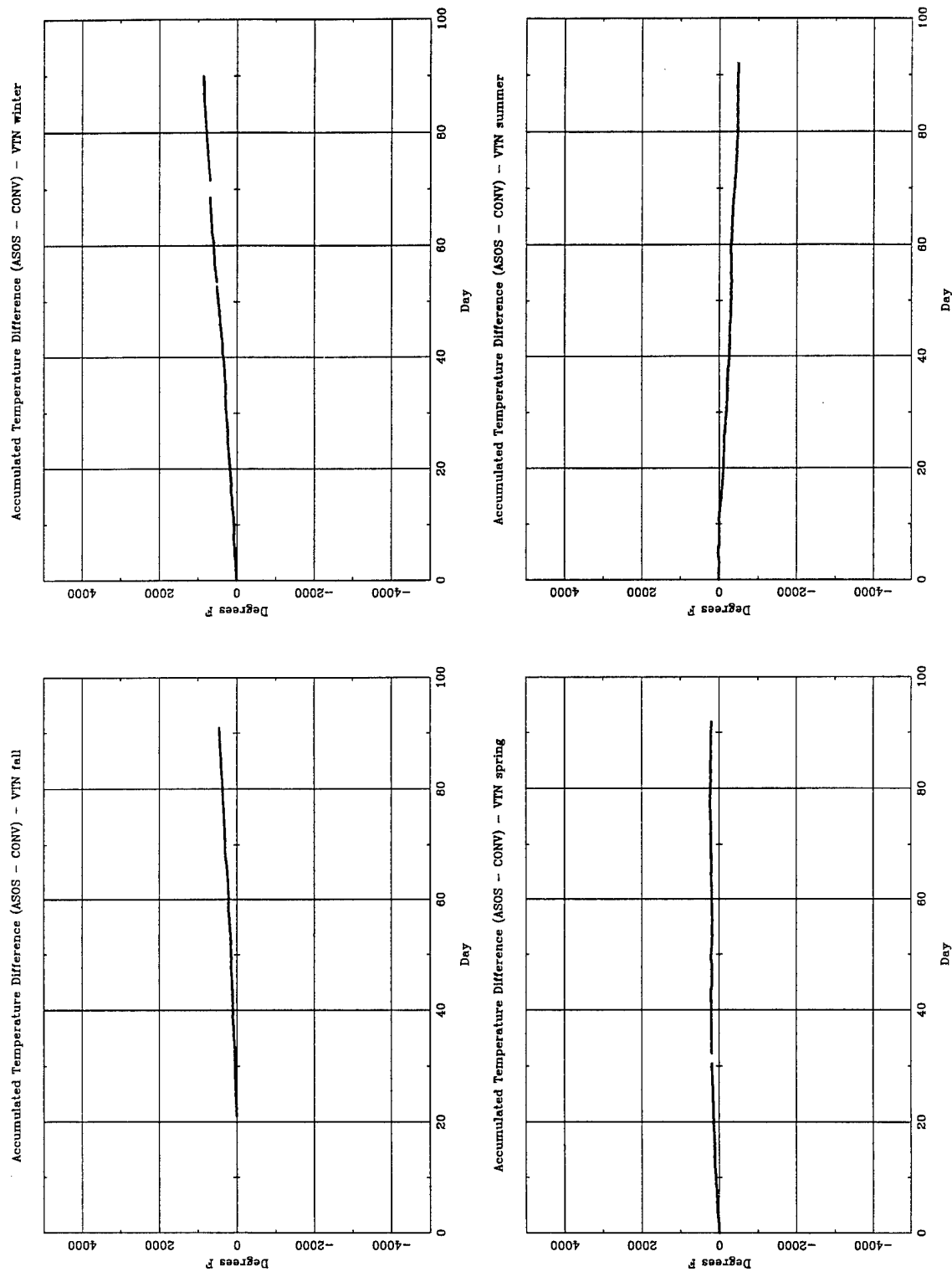


Fig. 3.1 (F) Seasonal accumulated temperature difference plots for Valentine, NE.

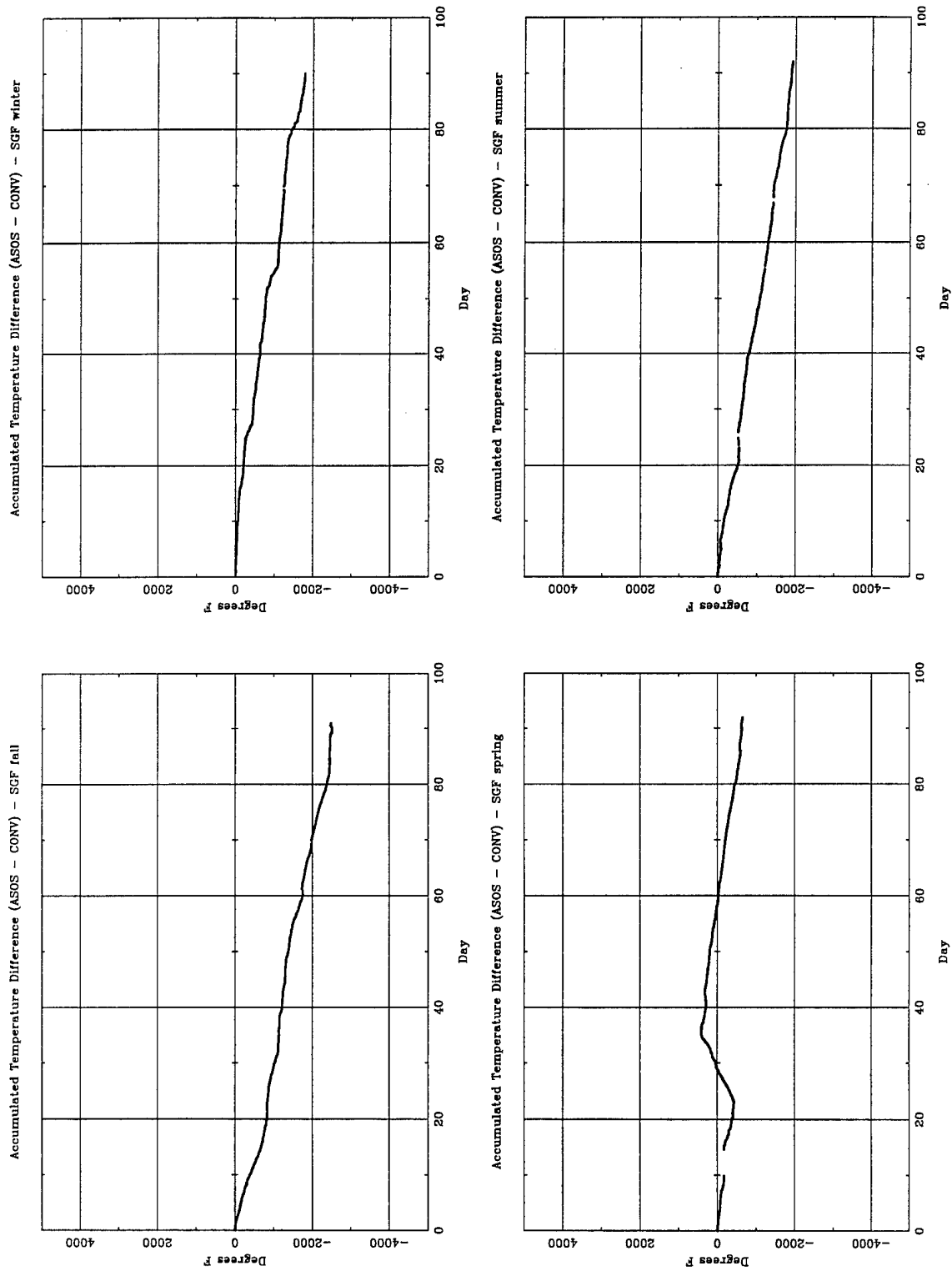


Fig. 3.1 (G) Seasonal accumulated temperature difference plots for Springfield, MO.

move, the relationship between the two instruments is dramatically different with an emerging positive slope toward the end of the summer season. Figure 3.1(C) is a nice example of a station which exhibits a trend over time. In other words, with each passing season, the accumulated ΔT between the two sensors at CLE is becoming larger resulting in a more negative slope over time. ERI in Figure 3.1(D) shows a quite dramatic, but only temporary, anomaly during late fall and early winter. The slope of the line changes considerably both in sign and value. The overall slope of the anomaly itself is positive over the course of its duration. Afterwards, ERI seems to return to its previous relationship between the two sensors. In Figure 3.1(E) TUS is moderately well-behaved in the first three seasons. The slope does change slightly quite often, and there is a brief period of missing data in the winter; but the overall behavior is fairly consistent. Then something happened in the summer! All of a sudden there is no longer a constant accumulation in the temperature difference between the two instruments. Upon examination of the raw data, it was discovered that the two instruments reported the exact same temperature value for most hours during the months of July and August. This likely means that one of the observations was edited. There is still a very slight, negatively sloped accumulation of temperature differences after June, but the relationship is significantly different. Next, one of the few stations with a positive bias, seen in Figure 3.1(F), VTN suffers a significant change in its slope sometime in the spring. The change is dramatic enough to completely alter the sign of the slope to a negative value by the summer season. In the last plot, Figure 3.1(G), SGF is plagued by problems. The accumulated ΔT plot meanders constantly with time. Despite an overall trend toward a

negatively sloped relationship, there are several periods of varying duration that display an obviously positive slope.

There could be many reasons for these changes in accumulated temperature differences over time. They include instrument moves, maintenance, sensor changes, electrical problems, weather events, and seasonal effects. Any of these could affect either the ASOS or CONV instrument.

3.2.2 Time Series Analysis

To further investigate shifts in temperature differences over the period of study, time series plots of temperature differences between the daily ASOS and CONV highest hourly and lowest hourly values were generated for each of the stations for the whole year (see Appendix A). Figures 3.2(A) - (C) are examples of these temperature time series analysis for $\Delta T_{\text{highest hourly}}$ and $\Delta T_{\text{lowest hourly}}$. Again, shifts in the now non-accumulated ΔT patterns indicate changes between the two instruments. Differences between the highest hourly values are plotted in the top graph, and differences between the lowest hourly values are on the bottom. Both graphs run sequentially from fall through summer, with daily legend values given in the upper right-hand corner of each plot.

In Figure 3.2(A), the instrument move in late spring is again quite noticeable for ACY, especially for $\Delta T_{\text{lowest hourly}}$ although not so obvious for $\Delta T_{\text{highest hourly}}$. The annual trend at CLE is notable in both temperature difference patterns in Figure 3.2 (B) as the mean of each plot becomes more negative with time. In Figure 3.2(C), the summer shift at TUS is significant in $\Delta T_{\text{highest hourly}}$, and quite perceptible in the $\Delta T_{\text{lowest hourly}}$. These plots

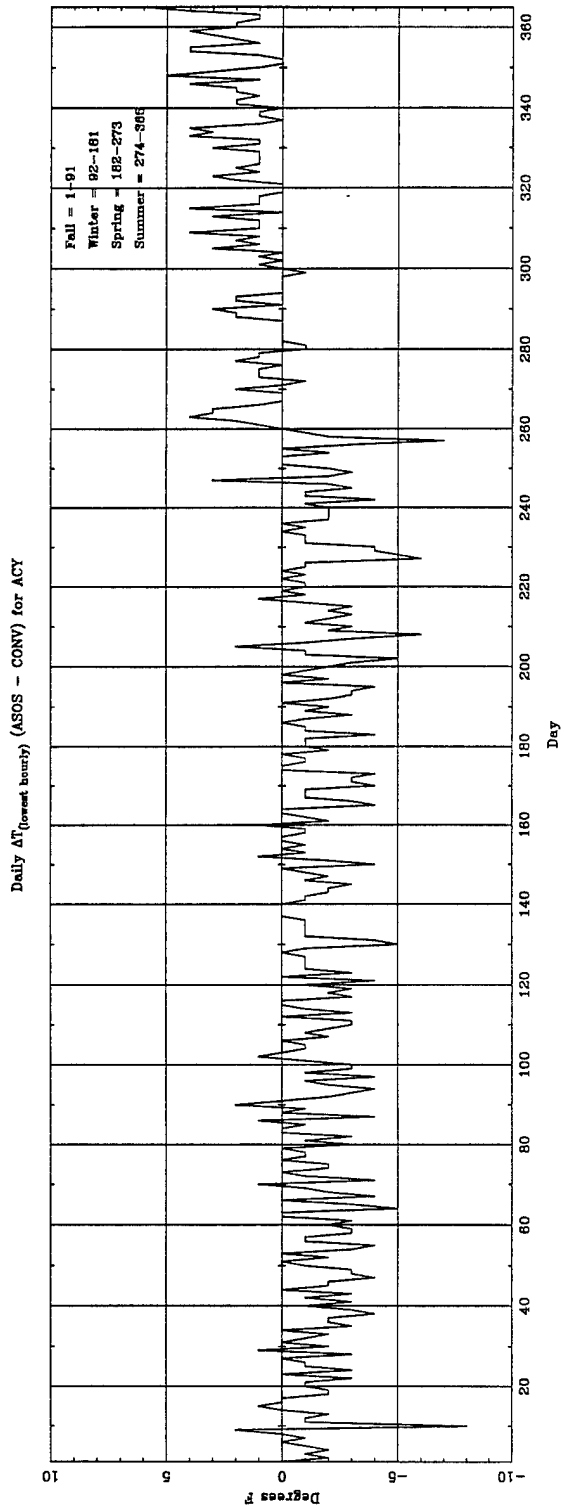
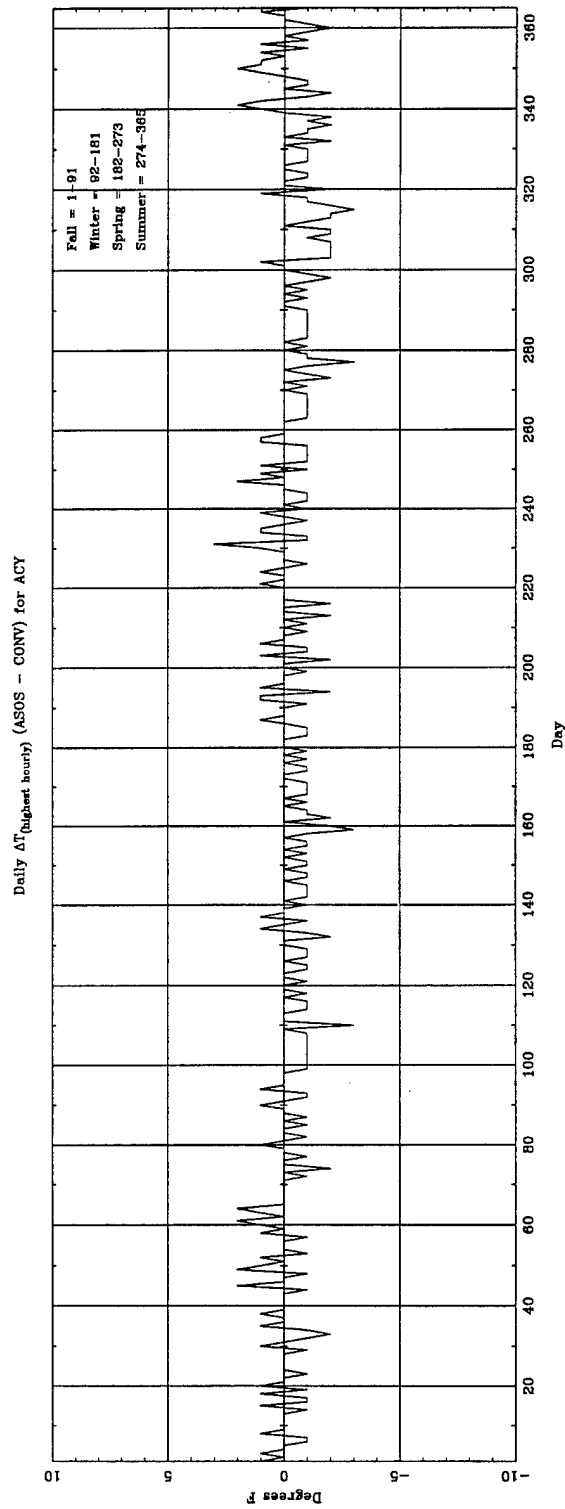


Fig. 3.2 (A) Temperature time series plots for Atlantic City, NJ.

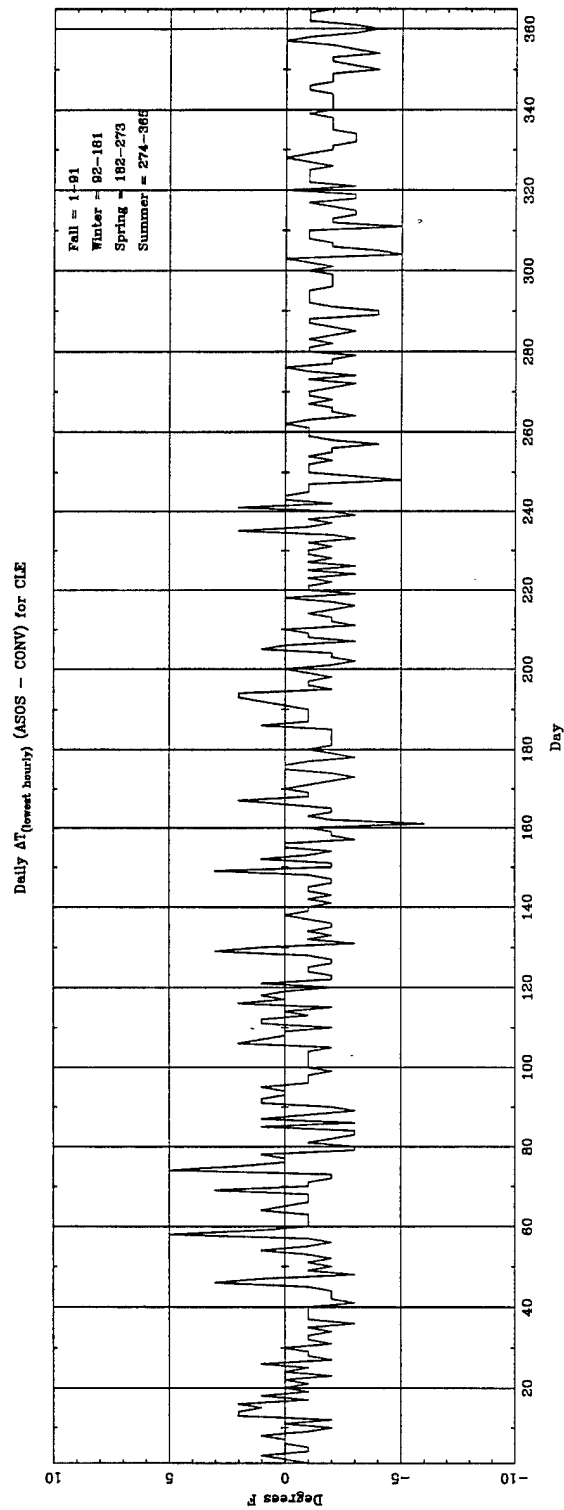
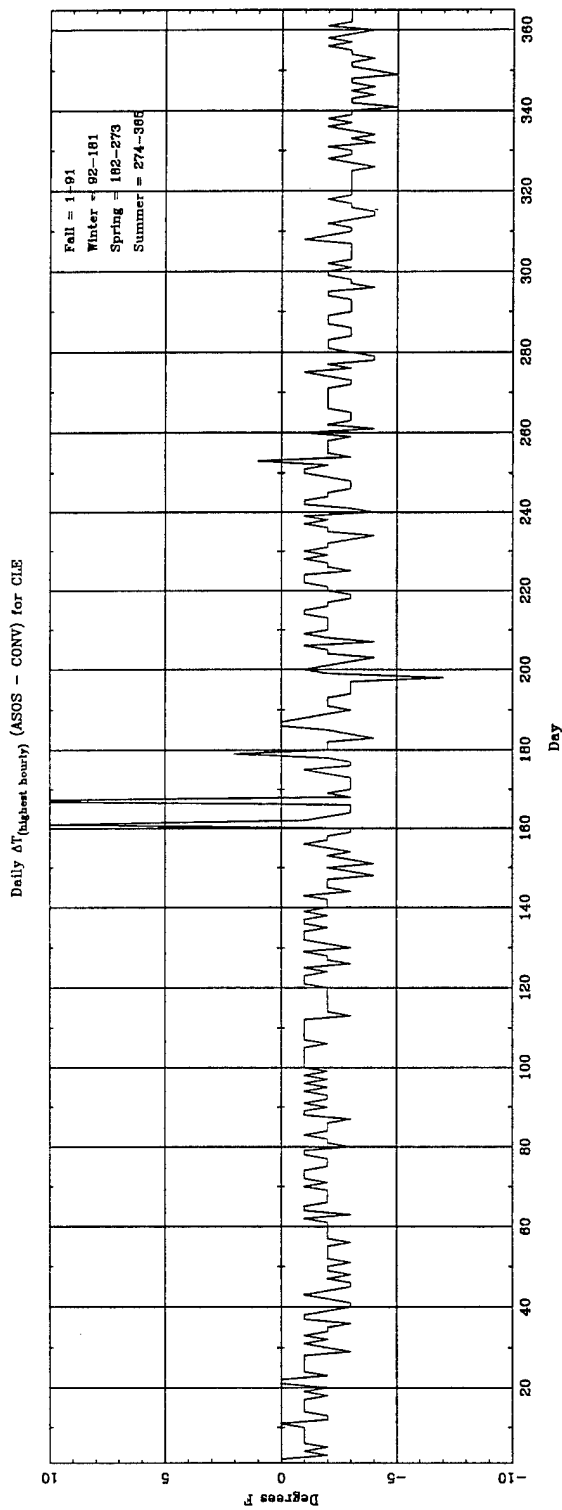


Fig. 3.2 (B) Temperature time series plots for Cleveland, OH.

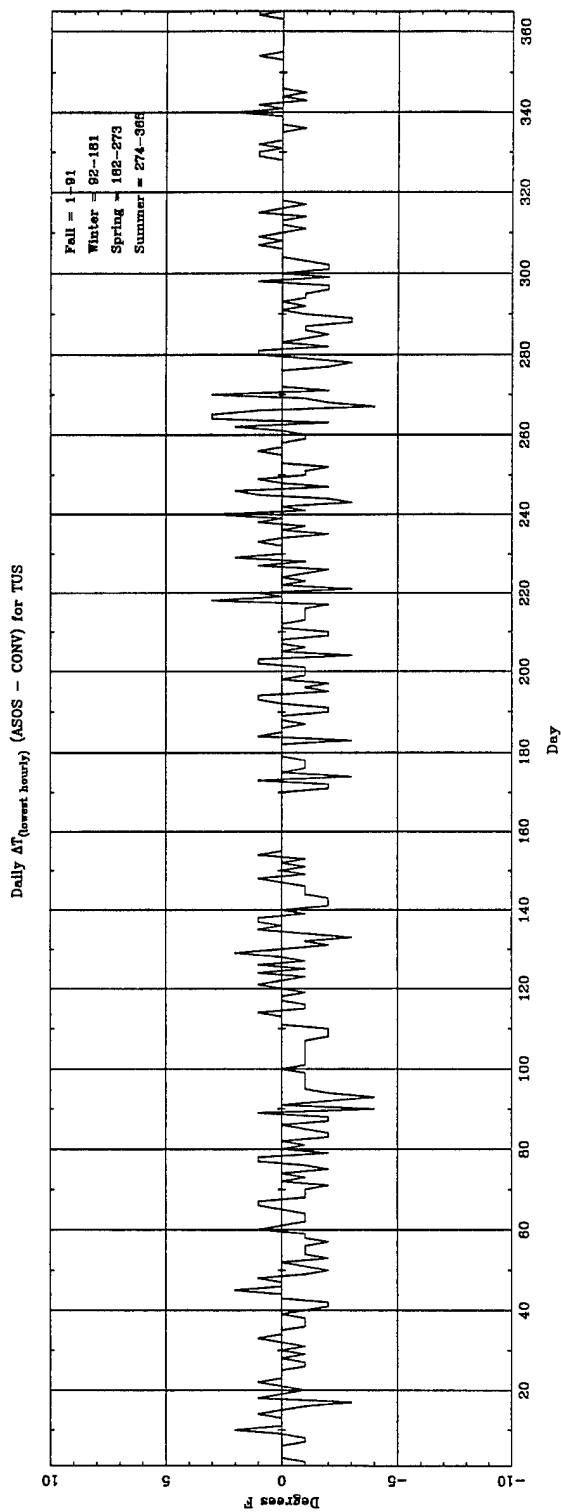
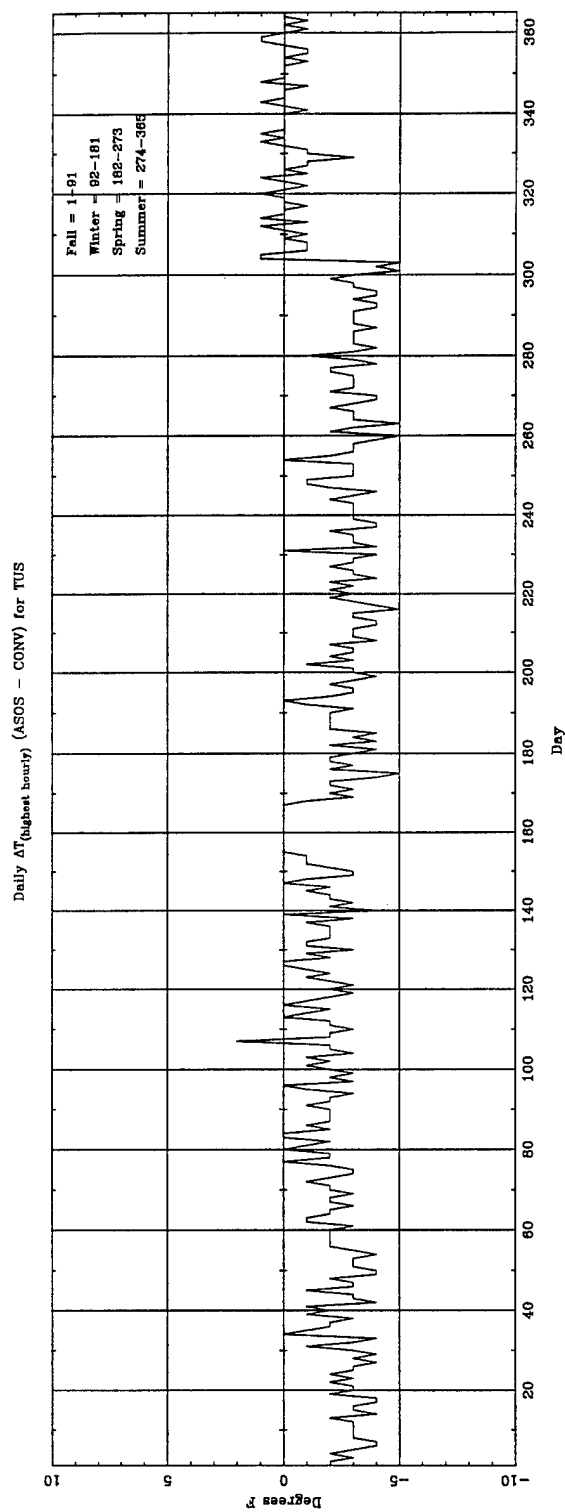


Fig. 3.2 (C) Temperature time series plots for Tucson, AZ.

confirm that ASOS is cooler than CONV measurements as evidenced by the negative averages of the time series plots. Most of these figures, the rest of which are located in Appendix A, do not present strong evidence supporting the existence of annual cycles in the temperature difference patterns, but more is discussed on this topic in section 3.7. After examining the irregularities in temperature difference patterns, the next focus was to isolate, as much as possible, the three contributions to the differences in temperature values between ASOS and CONV measurements.

3.3 The Instrument Bias, ΔT_i

Determining the temperature difference caused solely by the instrument bias required finding meteorological conditions which would reduce the other two effects. Eliminating the solar effect was quite easy by requiring nighttime analysis of the data. In order to eliminate local effects between the two instruments, conditions were selected which would minimize these local effects by homogenizing the surface boundary layer. The optimum conditions selected for this criteria were nighttime, high-wind analysis and nighttime, overcast-sky analysis such that $\Delta T = \Delta T_i$, since $\Delta T_i \sim 0$ and $\Delta T_s = 0$. Nighttime was defined as the seven-hour period inclusive of 10:00pm to 4:00am LST.

3.3.1 Nighttime, High-wind Analysis

Once the solar effect was eliminated, attention was turned to finding a relationship between ΔT and wind speed. With sufficient wind speeds at the surface, the boundary layer should be adequately mixed to eliminate local effects between the two instruments.

Homogenizing the boundary layer diminishes local temperature differences due to drainage currents, cold pools, radiational effects, and effects due to placement close to water. A consistent surface layer should be sampled by both instruments and reported as the same temperature unless there are differences in the two instruments inherent in their manufacture.

It was proposed that as wind speeds near the surface increased, the distribution of temperature differences between the two instruments would narrow to a range of only a few values which would include the instrument bias. In order to examine the population distribution of temperature differences within the range of $-9^{\circ}\text{F} \leq \Delta T \leq +9^{\circ}\text{F}$, tabular results for ΔT versus increasing wind speed were computed for each station for each season, both for all synoptic hours and all wind speeds (top table), and for nighttime hours with wind speeds ≥ 10 knots (bottom table) as seen in Tables 3.1(A) - (E). In each of the columns is recorded the number of comparisons having a temperature difference equal to ΔT along the first row with the corresponding wind speed category in the far left-hand column. All of the graphs display similar characteristics of having a broad temperature difference population distribution at lower wind speeds, and a narrowing of the distribution as wind speed increases. This narrowing of the ΔT distribution at higher wind speed is also evident in the nighttime, high-wind tables as well, though not quite as dramatic. Tables 3.1(A) & (B) are examples of stations with fairly even distributions at low wind speeds which taper to a range of only two to three values for ΔT at higher wind speeds. The other three tables depict the same overall pattern; but 3.1(C) & (D) have distributions which are skewed toward the negative ΔT values at low wind speeds, and 3.1(E) is skewed toward the more positive ΔT values at low wind speeds.

Table 3.1 (A) Tabulated temperature differences versus wind speeds for Cleveland, OH.

CLE fall, all hours, all wind speeds											ASOS - Conv										Sum	Mean	# top 3
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9				
0							4	16	26	16	10	4	2	2						80,	-0.47		
1																				0,	0.00		
2																				0,	0.00		
3					1	6	9	16	20	24	12	8	4							100,	-0.68		
4					4	8	11	35	43	41	15	14	3							174,	-0.84		
5						4	23	57	58	38	14	14	3	4	1					216,	-0.86		
6					2	6	4	24	55	71	42	12	16	6	4	1				243,	-0.94		
7			1	1	2	1	13	53	53	28	23	12	10	4	1					202,	-0.63		
8					2	2	14	69	97	47	9	10	1	2						253,	-1.01		
9						2	10	45	61	31	4	4	2	1						160,	-1.04		
10						1	12	51	79	36	8	3	1							191,	-1.07		
11						1	7	26	50	28	4	2								118,	-1.01		
12							10	37	44	32	2	2								127,	-1.12		
13							5	27	34	10	2									78,	-1.29		
14							7	16	18	14	1									56,	-1.25		
15							7	22	19	4										52,	-1.62		
16							4	14	19	4										41,	-1.44		
17							2	4	10											16,	-1.50		
18							2	16	6											24,	-1.83		
19						1	1	1	4											7,	-1.86		
20							3	7	3											13,	-2.00		
21								3	1											4,	-1.75		
22								4	3											7,	-1.57		
23								1	2											3,	-1.33		
24								2	1											3,	-1.67		
25									1											1,	-1.00		
26									1											1,	-1.00		
27								1	1											2,	-1.50		
28																				0,	0.00		
29																				0,	0.00		
30																				0,	0.00		
31																				0,	0.00		
32																				0,	0.00		
Total	0	0	1	3	15	30	168	578	725	395	116	89	32	17	3	0	0	0	0	2172,	-0.98	78.2%	

CLE fall, night, high winds											ASOS - Conv										Sum	Mean	# top 3
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9				
10						1	5	9	14	6	3	1								39,	-1.18		
11							4	12	9	1	1									27,	-0.63		
12							1	12	9	9	1	1								33,	-1.00		
13							1	7	7	2	1									18,	-1.28		
14							2	2	5	4										13,	-1.15		
15								4	4											8,	-1.50		
16								4	5	1										10,	-1.30		
17							1	2												3,	-1.67		
18							1	2	1											4,	-2.00		
19						1														1,	-4.00		
20							2	1	1											4,	-2.25		
21									1											1,	-1.00		
22																				0,	0.00		
23									2											2,	-1.00		
24								1	1											2,	-1.50		
25									1											1,	-1.00		
26																				0,	0.00		
27									1											1,	-1.00		
28																				0,	0.00		
29																				0,	0.00		
30																				0,	0.00		
31																				0,	0.00		
32																				0,	0.00		
Total	0	0	0	0	0	2	13	46	66	31	6	3	0	0	0	0	0	0	0	167,	-1.16	85.6%	

Table 3.1 (B) Tabulated temperature differences versus wind speeds for Tucson, AZ.

TUS winter, all hours, all wind speeds														ASOS - Conv						Sum	Mean	# top 3
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9			
0		1				3	18	31	56	86	36	20	2							253,	-0.43	
1																				0,	0.00	
2																				0,	0.00	
3						3	12	24	70	47	29	4	2							191,	-0.64	
4					3	1	16	34	98	65	22	8	3							250,	-0.74	
5					1	4	19	50	74	69	21	2	1					1		242,	-0.89	
6						2	16	39	60	49	21	5	1				1			194,	-0.79	
7				1	2		9	40	60	38	16	3								169,	-0.95	
8					1	2	16	23	45	28	11	7	1							134,	-0.93	
9					1	3	4	19	22	19	5	4	1							78,	-0.94	
10						1	4	15	17	12	7	3	1			1				61,	-0.67	
11							2	7	9	12	4	1								35,	-0.66	
12						2	3	7	8	6	5	1								32,	-1.00	
13									10	9	2									21,	-0.38	
14						1	1	5	8	2										17,	-0.47	
15						1	3	7	6	2										19,	-0.74	
16							4	9	3	1										17,	-0.94	
17								2	7	9										18,	-0.61	
18								2	2	6										10,	-0.60	
19								4	3	2										9,	-1.22	
20									1											1,	-1.00	
21									2											2,	-1.00	
22									1											1,	-1.00	
23									1	1										2,	-0.50	
24								1	2	1										4,	-1.00	
25								1		1										2,	-1.00	
26									1											1,	-1.00	
27																				0,	0.00	
28																				0,	0.00	
29																				0,	0.00	
30																				0,	0.00	
31																				0,	0.00	
32																				0,	0.00	
Total	0	1	0	1	8	21	121	307	570	477	184	58	12	0	0	1	1	1	0	1763,	-0.75	76.8%

TUS winter, night, high winds														ASOS - Conv						Sum	Mean	# top 3
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9			
10							2	2	2	5	5	1								17,	-0.29	
11									1	3	1									5,	0.00	
12									2	2	1	1								6,	0.17	
13									1	1	1									3,	0.00	
14									1	1	2									4,	0.25	
15									1		2									3,	0.33	
16									2		1									3,	-0.33	
17									1	3										4,	-0.25	
18									1	1										2,	-0.50	
19										1										1,	0.00	
20																				0,	0.00	
21																				0,	0.00	
22									1											1,	-1.00	
23																				0,	0.00	
24																				0,	0.00	
25																				0,	0.00	
26																				0,	0.00	
27																				0,	0.00	
28																				0,	0.00	
29																				0,	0.00	
30																				0,	0.00	
31																				0,	0.00	
32																				0,	0.00	
Total	0	0	0	0	0	0	2	2	13	17	13	2	0	0	0	0	0	0	0	49,	-0.12	87.8%

Table 3.1 (C) Tabulated temperature differences versus wind speeds for Atlantic City, NJ.

ACY fall, all hours, all wind speeds														ASOS - Conv										Sum	Mean	# top 3
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9							
0	3	2	4	9	13	28	38	33	42	26	13	1	1		1					214,	-2.34					
1																				0,	0.00					
2																				0,	0.00					
3	1	2	3	4	6	10	23	25	49	47	5	8			1					184,	-1.53					
4			1	3	1	7	20	41	87	89	33	5	1		1					289,	-0.82					
5		1		2	4	4	14	31	104	113	44	15	2	1	1		2			338,	-0.48					
6				1		2	10	17	78	114	37	15	5	1	1					281,	-0.23					
7							3	15	55	92	36	3	1	1						206,	-0.22					
8							1	3	57	56	31	2	1	2						153,	-0.13					
9						1	2	4	37	62	18	2								126,	-0.26					
10							3	26	56	12	3									100,	-0.14					
11							1	2	20	36	6	1								66,	-0.29					
12								1	16	17	8	1								43,	-0.19					
13								1	15	22	7									45,	-0.22					
14									8	20	5	2								35,	0.03					
15									7	15	3									25,	-0.16					
16							1		1	12	3	1								18,	0.06					
17									5	9	2									16,	-0.19					
18									3	6										9,	-0.33					
19								1		1	1									3,	-0.33					
20									1	3										4,	-0.25					
21										2										2,	0.00					
22										1										1,	0.00					
23											3									3,	1.00					
24										1										1,	0.00					
25																				0,	0.00					
26																				0,	0.00					
27																				0,	0.00					
28																				0,	0.00					
29																				0,	0.00					
30																				0,	0.00					
31																				0,	0.00					
32																				0,	0.00					
Total	4	5	8	19	24	52	113	177	611	800	267	59	11	5	5	0	2	0	0	2162,	-0.65	77.6%				

ACY fall, night, high winds														ASOS - Conv										Sum	Mean	# top 3
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9							
10									6	13										19,	-0.32					
11									3	7										10,	-0.30					
12									5	1	2									8,	-0.38					
13								1	1	2										4,	-0.75					
14									1	2										3,	-0.33					
15									1	1										2,	-0.50					
16										3										3,	0.00					
17									1											1,	-1.00					
18										1										1,	0.00					
19																				0,	0.00					
20									1											1,	-1.00					
21										1										1,	0.00					
22																				0,	0.00					
23																				0,	0.00					
24																				0,	0.00					
25																				0,	0.00					
26																				0,	0.00					
27																				0,	0.00					
28																				0,	0.00					
29																				0,	0.00					
30																				0,	0.00					
31																				0,	0.00					
32																				0,	0.00					
Total	0	0	0	0	0	0	0	1	19	31	2	0	0	0	0	0	0	0	0	53,	-0.36	98.1%				

Table 3.1 (D) Tabulated temperature differences versus wind speeds for Sioux Falls, SD.

FSD spring, all hours, all wind speeds												ASOS - Conv								Sum	Mean	% top 3	
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9				
0		4	3	7	9	13	19	10	11	10	1										87,	-3.21	
1						1															1,	-4.00	
2					3	5	4	6	5	1											24,	-2.67	
3	1	1	1	6	6	5	8	14	9	8	2										61,	-2.77	
4			1	4	2	8	17	22	42	19	2		1								118,	-1.74	
5				2	4	9	16	24	55	21	5	1									137,	-1.55	
6	1				2	4	23	27	73	34	9	1									174,	-1.26	
7		1			1	2	16	17	65	35	6										145,	-1.21	
8			1	1	4	3	4	15	26	92	45	9	4								202,	-1.12	
9				1				6	19	65	42	3									136,	-0.91	
10					1	1	6	36	89	55	4	1									193,	-0.94	
11					1	1	8	19	72	35	10										146,	-0.91	
12						2	8	9	89	48	5	1									162,	-0.81	
13						1	2	5	52	43	5	1									109,	-0.60	
14					1	3	4	8	50	29	8										103,	-0.84	
15						2	4	12	54	31	5	3									111,	-0.78	
16							3	6	19	26	1										55,	-0.71	
17							1	12	29	18	3										63,	-0.84	
18							3	10	31	20	2	1									67,	-0.84	
19							1	3	11	7	2										24,	-0.75	
20							1		9	4	1										15,	-0.73	
21									3	4	1										8,	-0.25	
22								1	6	1	1										9,	-0.78	
23								3	5	2											10,	-1.10	
24								1	5												6,	-1.17	
25									5	1											6,	-0.83	
26								1		2											3,	-0.67	
27									2												2,	-1.00	
28										1											1,	0.00	
29																					0,	0.00	
30									1												1,	-1.00	
31									1												1,	-1.00	
32																					0,	0.00	
Total	2	6	6	25	33	61	165	291	950	542	85	13	1	0	0	0	0	0	0	0	2180,	-1.18	81.8%

FSD spring, night, high winds												ASOS - Conv								Sum	Mean	% top 3	
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9				
10								9	24	15	1	1									50,	-0.78	
11							1	5	19	5	4										34,	-0.82	
12								1	23	12	2										38,	-0.61	
13									12	10											22,	-0.55	
14								1	10	9											20,	-0.60	
15								1	18	8		1									28,	-0.64	
16								2	4	3											9,	-0.89	
17									8	4											12,	-0.67	
18									5	3											8,	-0.62	
19									2	3											5,	-0.40	
20									2												2,	-1.00	
21										1											1,	0.00	
22									3		1										4,	-0.50	
23									2												2,	-1.00	
24																					0,	0.00	
25									1	1											2,	-0.50	
26																					0,	0.00	
27																					0,	0.00	
28																					0,	0.00	
29																					0,	0.00	
30																					0,	0.00	
31																					0,	0.00	
32																					0,	0.00	
Total	0	0	0	0	0	0	1	19	133	74	8	2	0	0	0	0	0	0	0	0	237,	-0.68	95.4%

Table 3.1 (E) Tabulated temperature differences versus wind speeds for Tallahassee, FL.

TLH summer, all hours, all wind speeds														ASOS - Conv								
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	Sum	Mean	% top 3
0						2	14	32	73	151	136	60	15	3			1			487,	0.27	
1																				0,	0.00	
2																				0,	0.00	
3							7	32	71	70	48	21	9	3	3					264,	-0.05	
4						2	12	47	112	54	16	6	4	4	1					258,	-0.73	
5						2	11	56	112	29	9	11	1	1						232,	-0.98	
6							9	44	115	48	9	1	1			1				228,	-0.93	
7						2	2	23	109	24	1									161,	-1.04	
8					1		5	29	89	28	2	2								156,	-1.03	
9							8	15	58	19	1									101,	-1.10	
10								24	45	14	2									85,	-1.07	
11					1		1	11	42	13	2	1								71,	-0.96	
12							1	11	24	11	1									48,	-1.00	
13						1	1	1	18	6	1									28,	-0.93	
14							1	3	8	2		1								15,	-1.00	
15								2	7		1									10,	-1.00	
16						1		2		1										4,	-2.00	
17									7	1										8,	-0.88	
18						1	1	4	5											11,	-1.82	
19								1	5											6,	-1.17	
20							1		5	1										7,	-1.14	
21							1			2										3,	-1.00	
22	1								1											2,	-5.00	
23									1											1,	-1.00	
24																				0,	0.00	
25									1											1,	-1.00	
26																				0,	0.00	
27																				0,	0.00	
28																				0,	0.00	
29																				0,	0.00	
30																				0,	0.00	
31																				0,	0.00	
32																				0,	0.00	
Total	1	0	0	0	2	11	75	337	908	474	229	103	30	11	5	0	1	0	0	2187,	-0.58	78.6%

TLH summer, night, high winds														ASOS - Conv								
Wind Spd	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	Sum	Mean	% top 3
10								1	3											4,	-1.25	
11									5											5,	-1.00	
12									2	1										3,	-0.67	
13									3											3,	-1.00	
14									1											1,	-1.00	
15									1											1,	-1.00	
16																				0,	0.00	
17																				0,	0.00	
18								1												1,	-2.00	
19								1	1											2,	-1.50	
20									2											2,	-1.00	
21																				0,	0.00	
22																				0,	0.00	
23									1											1,	-1.00	
24																				0,	0.00	
25																				0,	0.00	
26																				0,	0.00	
27																				0,	0.00	
28																				0,	0.00	
29																				0,	0.00	
30																				0,	0.00	
31																				0,	0.00	
32																				0,	0.00	
Total	0	0	0	0	0	0	0	3	19	1	0	0	0	0	0	0	0	0	0	23,	-1.09	100.0%

Initially, wind speeds of 15 knots and greater were used in attempting to isolate the instrument bias. Observations were chosen for analysis when the ASOS winds were reported to be in excess of 14 knots, unless the ASOS winds were missing, in which case the CONV winds had to be in excess of 14 knots. However, compared to the total numbers of temperature comparisons available for each station, there were just too few nighttime observations with wind speeds greater than 14 knots to conclude that the instrument bias had been determined with any certainty. Lowering the wind speed requirement to 10 knots and greater did allow for more temperature comparisons, but the resulting biases were plagued by a few erratic numbers in the highest wind speed categories.

Graphical examples of these findings can be seen in Figures 3.3(A) - (D) which depict average temperature difference as a function of wind speed using every observation available during the course of the year. Nighttime observations are shown with a dotted line, daytime with a dashed line, and the average over all observations with a solid line. One item to note about these plots is the omission of reported wind speeds at 1 and 2 knots. Since wind speeds are reported as either calm (< 3 knots) or as 3 knots and above, the lowest wind speed categories (0 knots, 1 knot, and 2 knots) were all assigned the value computed for calm winds. It was initially suggested that ΔT would asymptotically approach some fixed value very near the instrument bias as wind speeds increased. And indeed the overall trend toward a fixed value in these plots reflects that potential. However, as seen in each of the figures, the temperature difference did not smoothly approach a fixed value for the instrument bias. At the highest wind speeds, all of the lines become more erratic and unstable as the numbers of observations decrease considerably.

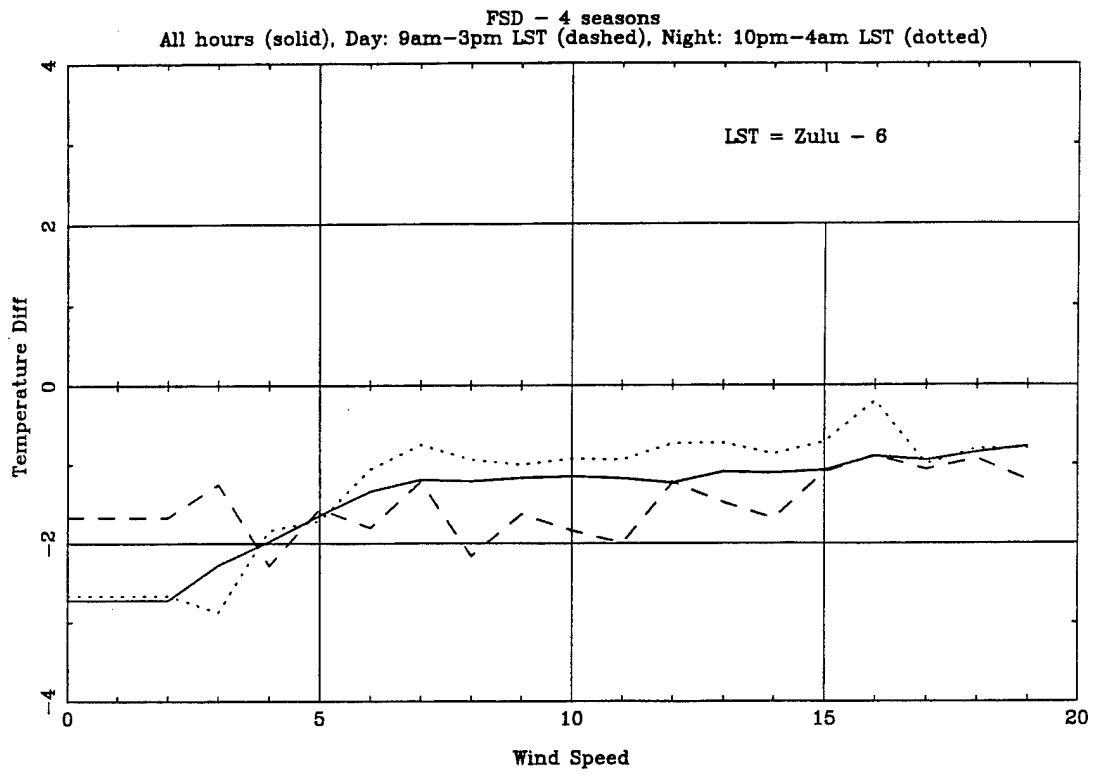


Fig. 3.3 (A) Wind speed versus temperature difference for Sioux Falls, SD.

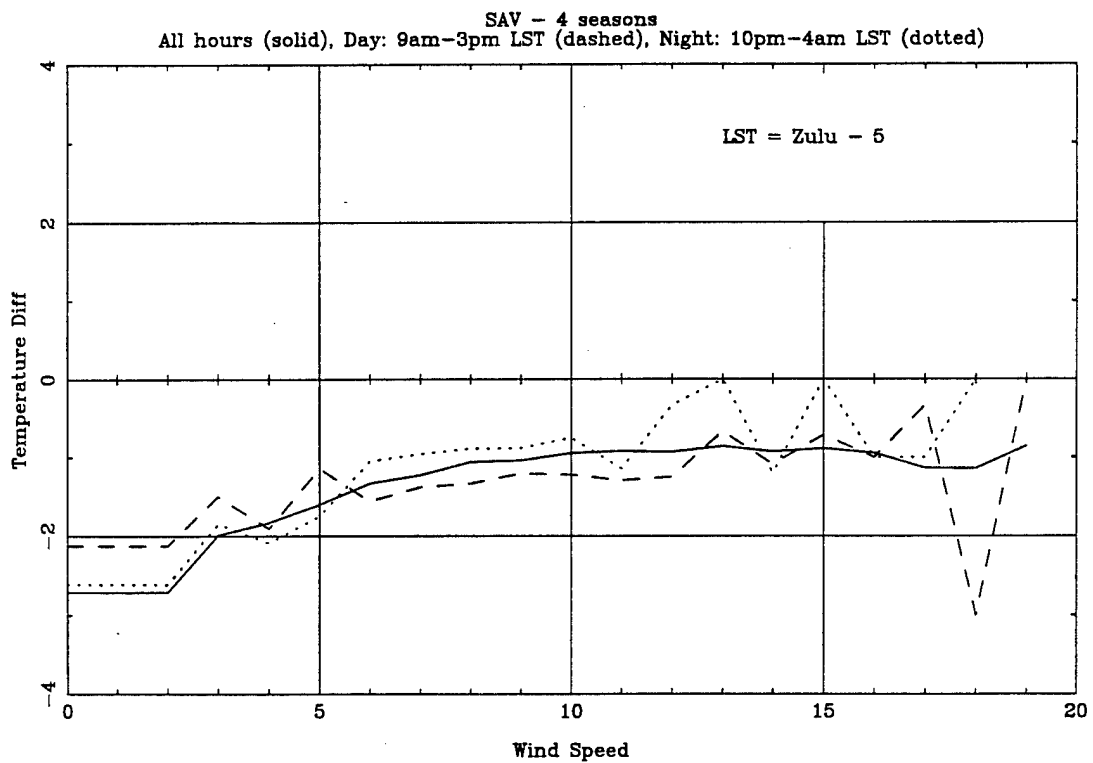


Fig. 3.3 (B) Wind speed versus temperature difference for Savannah, GA.

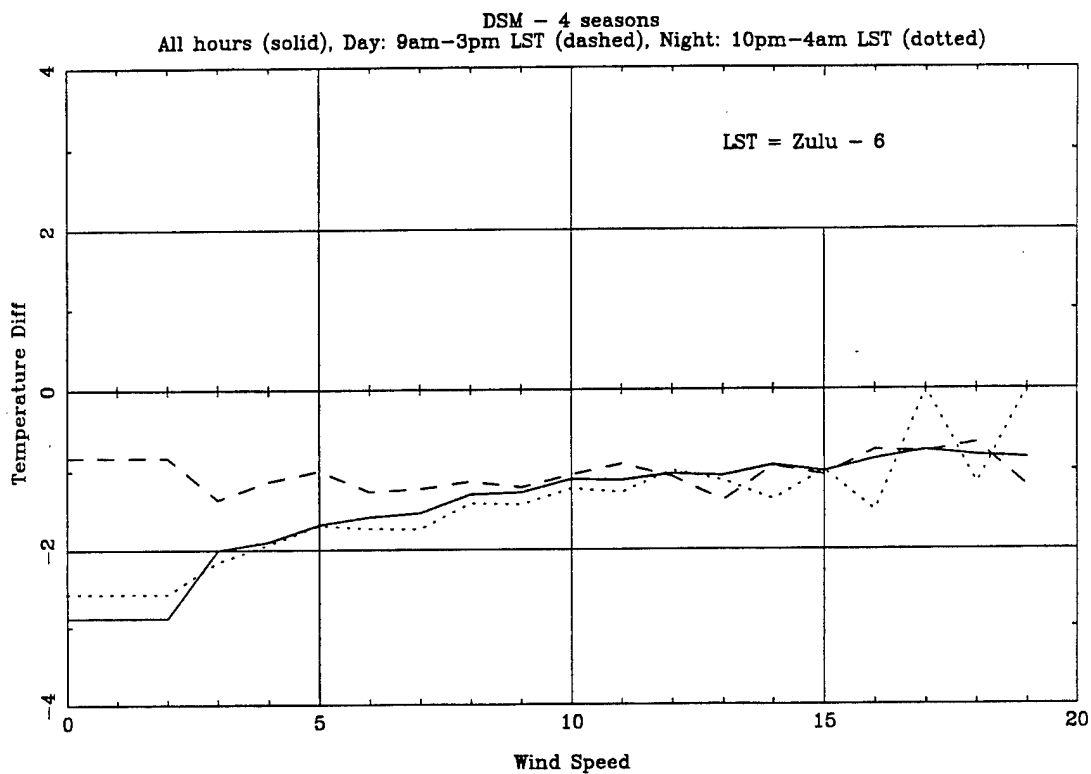


Fig. 3.3 (C) Wind speed versus temperature difference for Des Moines, IA.

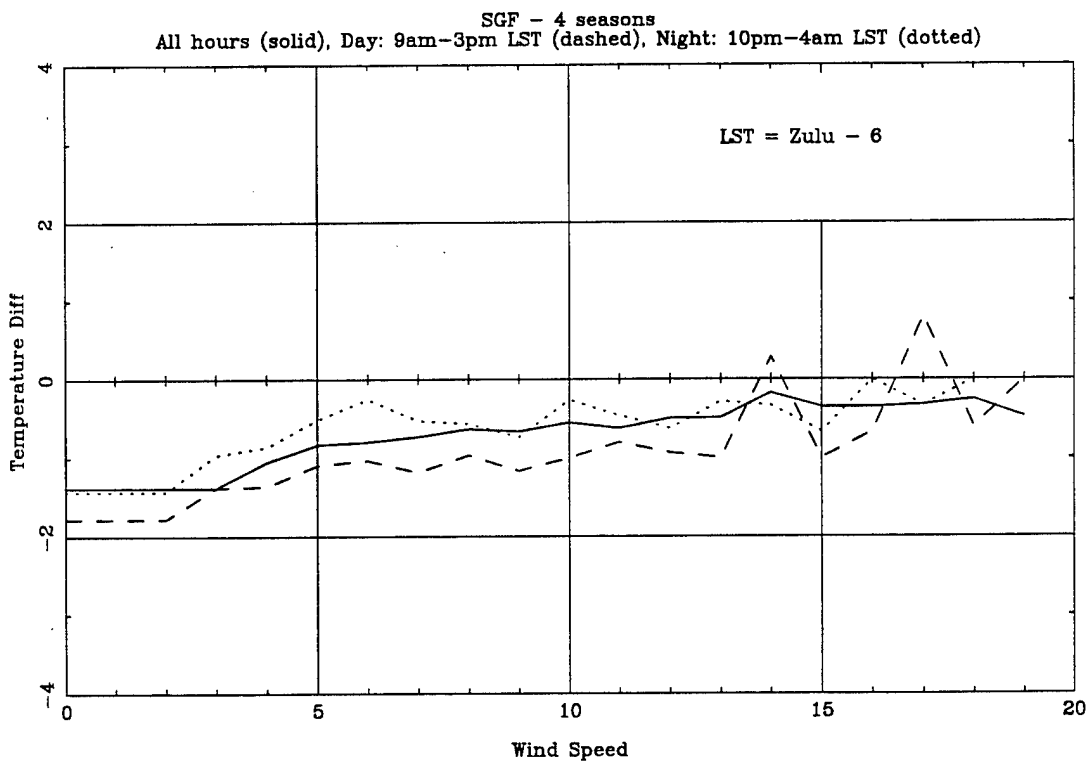


Fig. 3.3 (D) Wind speed versus temperature difference for Springfield, MO.

As a result of the low numbers problem associated with the nighttime, high-wind analysis, it was decided to use nighttime observations with overcast skies to determine instrument biases for each location.

3.3.2 Nighttime, Overcast-sky Analysis

The theory behind using overcast skies at night was to have enough cloud cover over an area to provide a downward infrared radiation source at the cloud base which would reduce horizontal temperature differences at the surface (McKee, et al., 1996). If the cloud cover is thick enough and covers an area somewhat larger than the distance between the ASOS and CONV instruments, and assuming that the cloud is radiating at a uniform temperature, then it would not take long for the downward infrared flux from the cloud to decrease temperature inhomogeneities in the surface layer below the clouds. This is accomplished through the net infrared radiation at the surface as the downward flux acts to diminish the magnitude of cold pools and warm spots at the surface.

Observations were selected for comparison when the highest sky cover category reported by ASOS was overcast, unless the ASOS sky cover field was missing, in which case, the temperature comparison was not done. The 12,000 feet limit of the ASOS ceilometer ensures low clouds were detected. There were many more nighttime observations reported with overcast skies than nighttime observations reported with high winds for an overwhelming number of stations. Population distributions of temperature differences versus cloud cover amount were calculated in Tables 3.2(A) - (C). For each station, the top table represents all observations from a particular season, while the bottom

table is only the nighttime hours for that same season. Each table shows a broad distribution of ΔT values for clear skies. But as the cloud cover amount increases to scattered, then to broken, and then to overcast, there is a significant narrowing of the distribution to a range of only a few values. In fact for all of the stations, as cloud cover increased to overcast, the distribution of the temperature differences narrowed such that over 90% of all the measured ΔT s were always within the top three numbers. Graphically, plots of ΔT versus cloud cover smoothly approach a fixed value for the instrument bias as seen in Figures 3.4(A) - (D). Although both nighttime, high-wind and overcast-sky analyses showed that ASOS was cooler than CONV at most stations, the nighttime, overcast-sky analysis was selected as the method for isolating the instrument biases.

Seasonal instrument biases were calculated for each station using the following technique:

$$\Delta T_i = \frac{\sum_{m=-9}^{+9} ((\Delta T_m)(\text{Number of Observations with } \Delta T_m))}{\sum (\text{Total Number of Observations})} \quad (3.3)$$

with m defined as the range of possible temperature difference values between -9°F and $+9^\circ\text{F}$. Annual values were calculated by adding up the seasonal instrument biases multiplied by the number of observations used to determine each seasonal bias, then dividing by the total number of nighttime overcast observations for the whole year. The resulting seasonal and annual instrument bias values, which are given in Tables 3.3(A) - (C), are predominantly negative. Seasonal contributions range from -2.17°F (ATL in the fall) to $+1.17^\circ\text{F}$ (ORH in the spring). Annual instrument biases ranged from -1.96°F

Table 3.2 (A) Tabulated temperature differences versus cloud cover for Savannah, GA.

SAV winter, all hours, all wind speeds												ASOS - Conv								Sum	Mean	% top 3
Sky Cover	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9			
CLR	2	6	8	12	31	66	108	160	414	219	32	7	1							1066,	-1.52	74.4%
SCT							9	16	52	24	2									103,	-1.06	89.3%
BKN						4		17	68	29	3									121,	-0.95	94.2%
OVC							4	53	450	211	4									722,	-0.78	98.9%
Total	2	6	8	12	31	70	121	246	984	483	41	7	1	0	0	0	0	0	0	2012,	-1.20	

SAV winter, night only												ASOS - Conv								Sum	Mean	% top 3
Sky Cover	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9			
CLR	1			4	18	49	52	49	104	52	7	4	1							341,	-1.93	61.0%
SCT							2	3	6	1										12,	-1.50	91.7%
BKN								7	17	4										28,	-1.11	100.0%
OVC								17	147	48										212,	-0.85	100.0%
Total	1	0	0	4	18	49	54	76	274	105	7	4	1	0	0	0	0	0	0	593,	-1.50	

Table 3.2 (B) Tabulated temperature differences versus cloud cover for Las Vegas, NV.

LAS spring, all hours, all wind speeds												ASOS - Conv								Sum	Mean	% top 3
Sky Cover	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9			
CLR					2	16	93	298	475	326	68	28	9							1315,	-0.97	83.6%
SCT						1	5	24	39	42	12	1	1							125,	-0.71	84.0%
BKN							3	7	47	44	8	1								110,	-0.55	90.0%
OVC								2	39	63	5									109,	-0.35	98.2%
Total	0	0	0	0	2	17	101	331	600	475	93	30	10	0	0	0	0	0	0	1659,	-0.88	

LAS spring, night only												ASOS - Conv								Sum	Mean	% top 3
Sky Cover	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9			
CLR					1	4	17	65	148	117	32	14	5							403,	-0.68	81.9%
SCT								1	5	9	3									18,	-0.22	94.4%
BKN									8	14	1	1								24,	-0.21	95.8%
OVC									17	22	2									41,	-0.37	100.0%
Total	0	0	0	0	1	4	17	66	178	162	38	15	5	0	0	0	0	0	0	486,	-0.62	

Table 3.2(C) Tabulated temperature differences versus cloud cover for Mount Shasta, CA

MHS summer, all hours, all wind speeds												ASOS - Conv								Sum	Mean	% top 3
Sky Cover	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9			
CLR				6	23	62	164	320	406	270	138	93	48	8	2					1540,	-0.93	64.7%
SCT					1	6	12	32	51	36	15	3		1						157,	-0.99	75.8%
BKN						3	11	21	48	36	10	5	1							135,	-0.83	77.8%
OVC			1			1	4	15	74	76	8	3	1			1				184,	-0.57	89.7%
Total	0	0	1	6	24	72	191	388	579	418	171	104	50	9	2	1	0	0	0	2016,	-0.89	

MHS summer, night only												ASOS - Conv								Sum	Mean	% top 3
Sky Cover	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9			
CLR				1	10	23	68	138	147	63	10									460,	-1.66	76.7%
SCT						2	4	14	23	8										51,	-1.39	88.2%
BKN							2	11	16	11										40,	-1.10	95.0%
OVC								4	30	26	1									61,	-0.61	98.4%
Total	0	0	0	1	10	25	74	167	216	108	11	0	0	0	0	0	0	0	0	612,	-1.50	

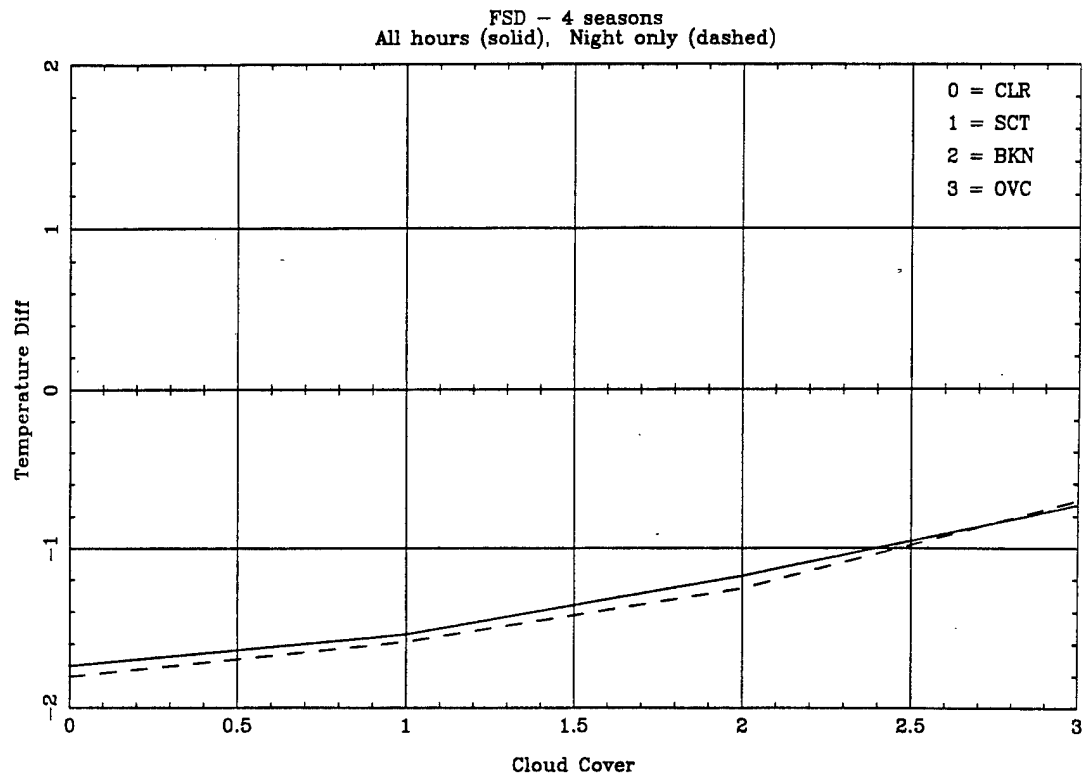


Fig. 3.4 (A) Cloud cover versus temperature difference for Sioux Falls, SD.

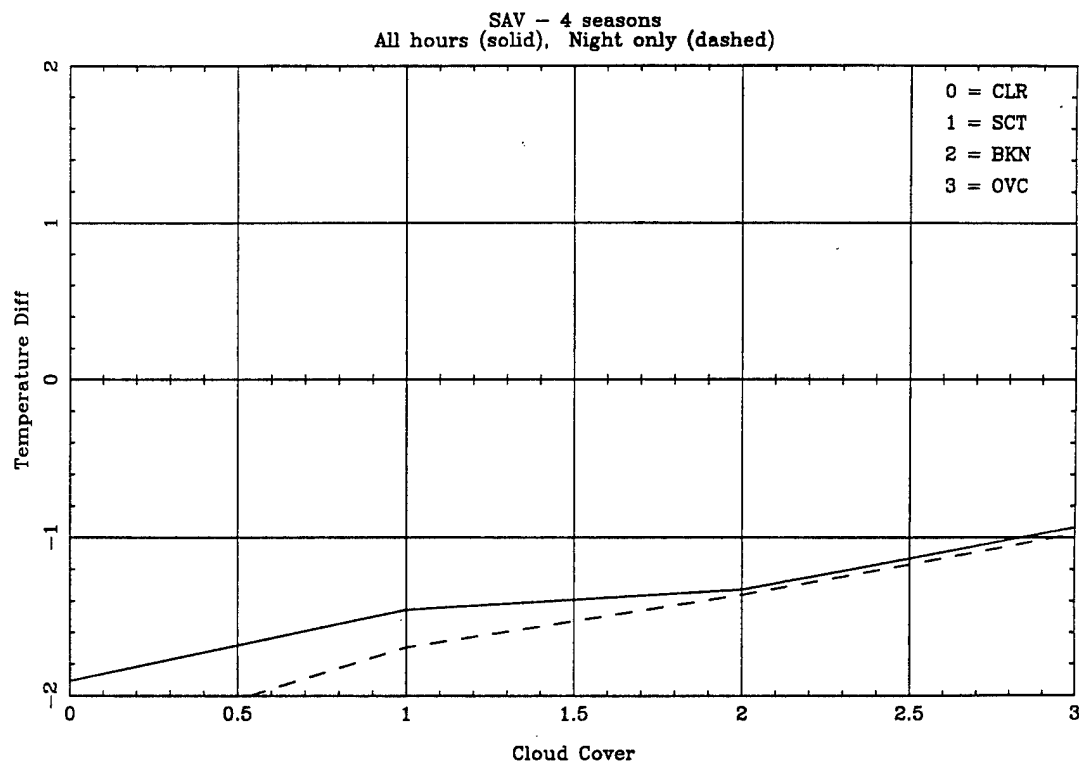


Fig. 3.4 (B) Cloud cover versus temperature difference for Savannah, GA.

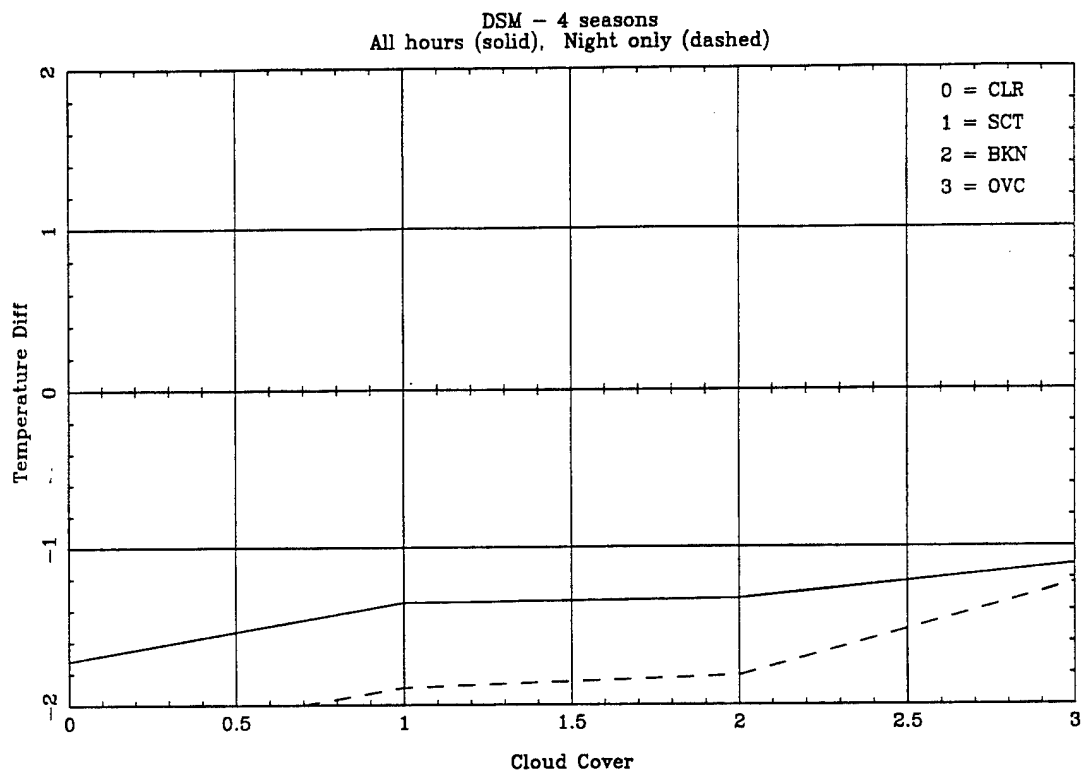


Fig. 3.4 (C) Cloud cover versus temperature difference for Des Moines, IA.

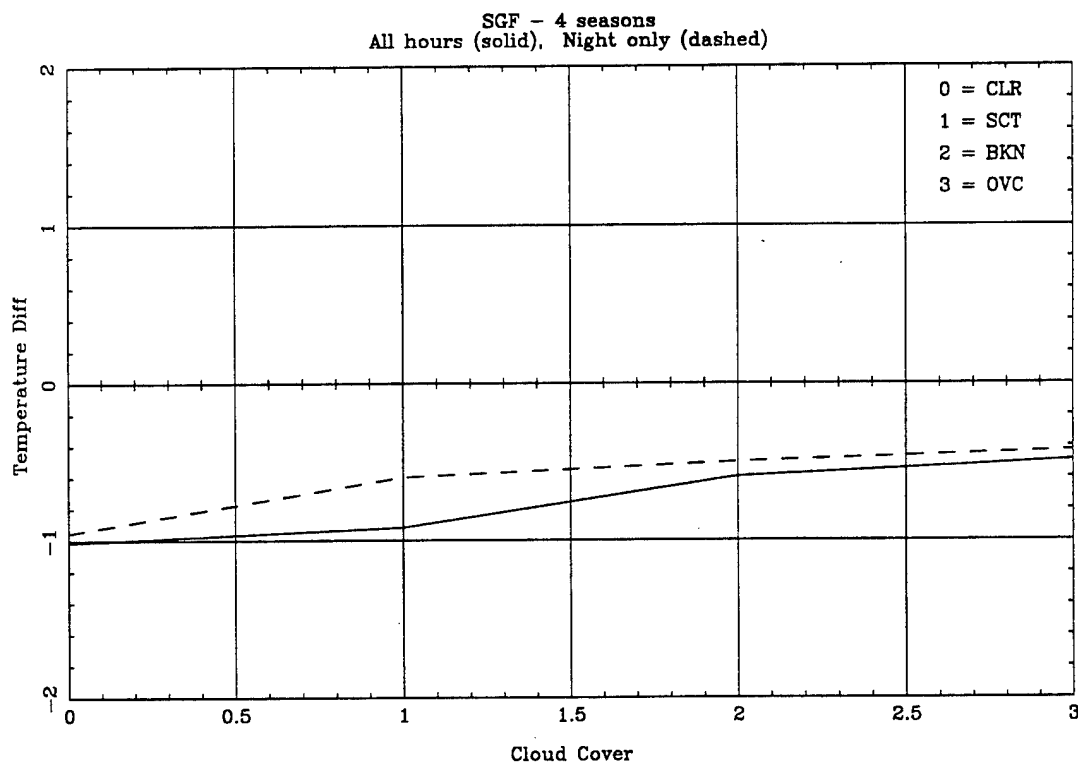


Fig. 3.4 (D) Cloud cover versus temperature difference for Springfield, MO.

Table 3.3 (A) Seasonal and Annual Instrument Biases for Four-season Stations and Average Temperature Difference over all Observations

Station	Fall Instrument Bias		Winter Instrument Bias		Spring Instrument Bias		Summer Instrument Bias		Annual Instrument Bias		All Possible Observations	
	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	Tot number of night ovc obs	ΔT	Number
ACY	-0.41	112	-0.58	230	-0.46	224	-0.16	103	-0.499	566	-0.649	6508
BGM	-0.49	247	-0.55	349	-0.82	227	-0.57	303	-0.597	1126	-0.680	7670
BIS	-0.43	207	-0.15	303	-0.32	279	0.09	107	-0.239	896	-0.387	8667
CAE	-0.51	162	-0.13	235	0.12	91	-0.07	94	-0.187	582	-0.218	8705
CLE	-1.31	167	-1.57	361	-1.71	242	-1.73	71	-1.572	841	-1.583	8716
COU	0.07	186	-0.08	267	-0.43	242	-0.79	70	-0.219	765	-0.408	8580
CYS	-0.72	125	-0.48	146	-0.7	278	-0.64	83	-0.645	632	-0.820	8674
DSM	-1.24	187	-1.13	272	-1.24	284	-1.46	87	-1.227	830	-1.470	8603
ERI	0.02	203	-0.32	409	-0.45	256	-0.47	91	-0.297	959	-0.651	8320
FAR	-0.82	147	-1.12	280	-1.01	276	-0.97	92	-1.009	795	-1.232	8027
FSD	-0.79	162	-0.47	275	-0.75	319	-1.09	86	-0.701	842	-1.350	8287
GRB	-1.68	206	-1.37	313	-1.4	181	-1.5	130	-1.474	830	-1.959	8132
JAX	-0.33	151	-0.43	195	-0.26	61	0.08	77	-0.296	484	-0.441	7877
JKL	0.39	141	0.31	328	-0.06	206	0.16	50	0.210	725	-0.274	8680
LAS	-0.23	28	-0.4	115	-0.37	41	-0.75	12	-0.393	194	-0.969	7958
LEX	-0.26	151	-0.12	314	-0.34	184	-0.2	54	-0.214	703	-0.354	8710
MCO	0.48	85	0.32	105	0.62	29	0.31	29	0.409	248	0.174	7025
MHS	-0.09	147	-0.09	322	-0.16	181	-0.61	61	-0.152	711	-0.420	7288
MOB	-0.35	164	-0.24	222	-0.32	187	-0.26	27	-0.286	600	-0.406	8709
RAP	-0.72	109	-0.45	165	-0.4	280	-0.86	102	-0.537	656	-0.537	7995
RDD	-0.42	113	-0.47	354	-0.46	197	-0.75	4	-0.460	668	-0.579	7837
RSL	-0.03	116	-0.39	163	-0.38	216	-0.38	60	-0.310	555	-0.559	8017
SAV	-1.03	202	-0.85	212	-1.1	77	-1.12	43	-0.976	534	-1.568	7617
SBN	-0.6	75	-0.28	406	-0.48	288	0.01	69	-0.353	838	-0.616	8548
SGF	-0.73	202	-0.52	263	-0.08	194	-0.02	46	-0.426	705	-0.833	8238
SLN	-0.29	127	-0.09	202	-0.1	223	0.1	59	-0.117	611	-0.436	7949
SPI	-1	201	-0.76	300	-0.88	310	-0.57	47	-0.849	858	-1.104	8398
TLH	-0.73	180	-0.84	208	-0.66	131	-0.78	54	-0.759	573	-0.545	8678
TUS	-0.81	37	-0.32	82	-0.92	25	-0.25	12	-0.527	156	-0.989	8299
VTN	0.24	124	0.52	183	0.15	287	-0.31	71	0.219	665	0.139	7570
YNG	-0.49	165	-1.25	361	-1.51	181	-1.38	72	-1.161	779	-1.257	7660
SUMS	-0.494	4627	-0.461	7940	-0.545	6197	-0.559	2163	-0.505	20927	-0.752	251942
MEANS												

Table 3.3 (B) Seasonal and Annual Instrument Biases for Three-season Stations and Average Temperature Difference over all Observations

Station	Fall Instrument Bias		Winter Instrument Bias		Spring Instrument Bias		Summer Instrument Bias		Annual Instrument Bias		All Possible Observations	
	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	Tot number of night ovc obs	ΔT	Number
ABE			-1.15	233	-0.97	217	-0.67	130	-0.975	580	-1.418	5932
ABQ			-0.94	112	-1.02	99	-0.48	56	-0.873	267	-1.410	6380
ALB	-0.41	205	-0.88	337	-0.65	267			-0.685	809	-0.783	6419
ALO	-0.65	156	-0.56	288	-0.72	265			-0.640	709	-0.689	5497
APN	-0.3	233	-0.4	401	-0.31	267			-0.347	901	-0.506	6084
ATL	-2.17	185	-1.78	264	-2.04	113			-1.961	582	-2.557	6449
AUS	-0.46	195	-0.4	254	-0.25	302			-0.355	751	-0.419	8491
BFF	-0.54	134	-0.24	157	-0.37	283			-0.374	574	-0.606	6455
DAB	0.01	140	0.1	172	-0.06	82			0.035	394	-0.165	6317
DAY			-0.29	287	-0.3	193	-0.13	61	-0.276	541	-0.455	5912
DTW	-0.7	174	-0.89	361	-0.68	239			-0.782	774	-0.946	6512
EUG			-1.08	313	-0.9	252	-0.53	161	-0.896	726	-1.148	5761
FWA	-1.03	159	-0.64	349	-0.6	215			-0.714	723	-1.053	6081
GJT	-0.68	119	-0.56	218	-0.51	164			-0.572	501	-0.888	7979
HON	-0.15	182			-0.24	279	0.12	72	-0.161	513	-0.223	6568
INL	-0.61	162	-0.53	322	-0.77	206			-0.620	690	-0.887	5233
INW	0.4	40	0.73	117	0.5	74			0.599	231	0.026	5565
LAN	0.3	152			0.18	201	0.75	109	0.354	462	0.160	5624
LBB			-0.61	140	-0.64	130	-0.67	43	-0.631	313	-0.920	6195
LOH	-1.24	176	-1.37	208	-1.4	212			-1.342	596	-1.367	5797
MCI	-0.22	174	-0.56	268	-0.7	249			-0.525	691	-0.449	6359
MGM	-1.3	173	-1.59	211	-1.72	102			-1.514	486	-1.644	5345
MKE	-1.66	166	-1.37	275	-1.62	264			-1.532	705	-2.035	6413
MKG	-0.23	202	-0.2	397	-0.29	259			-0.234	858	-0.287	6069
MLI	-0.44	198	-0.53	311	-0.43	218			-0.476	727	-0.353	6292
MSO	-0.36	139			-1.19	181	-0.53	104	-0.756	424	-1.143	5229
OFK			-0.58	256	-0.61	284	-0.76	68	-0.614	608	-1.061	6500
ORH	1.16	172	1.15	202	1.17	227			1.160	601	0.606	5668
PAH	-0.59	169	-0.54	239	-0.62	169			-0.578	577	-0.605	6063
PDT	-0.5	179	-0.25	342	-0.42	205			-0.360	726	-0.616	6320
PDX			0.16	331	0.16	255	0.12	209	0.149	795	-0.056	6371
PIA	-0.21	194	-0.33	288	-0.26	205			-0.275	687	-0.529	6115
REF	0.09	202	0.01	312	-0.27	260			-0.063	774	-0.191	6365
RST	-0.02	241	-0.2	247	-0.13	229			-0.117	717	-0.075	5973
SUX	-0.28	180	-0.59	250	-0.41	290			-0.440	720	-0.820	6502
SUMS		4781		8462		7457		1013		21713		216805
MEANS	-0.457		-0.528		-0.545		-0.278		-0.497		-0.729	

Table 3.3 (C) Seasonal and Annual Instrument Biases for Two-season Stations and Average Temperature Difference over all Observations

Station	Fall Instrument Bias		Winter Instrument Bias		Spring Instrument Bias		Summer Instrument Bias		Annual Instrument Bias		All Possible Observations	
	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	number of night ovc obs	ΔT_i	Tot number of night ovc obs	ΔT	Number
BIL	-1.29	147	-1.06	192	-0.92	213	-0.39	116	-1.160	339	-1.216	4286
CAK									-0.733	329	-0.785	4144
DRA	-1.33	43	-1.27	135					-1.284	178	-1.455	4300
FNT			0.22	353	0.3	246			0.253	599	-0.026	4314
GEG					-0.39	104			-0.372	165	-0.548	3579
ISN			-0.2	225	-0.39	233			-0.297	458	-0.642	3763
LBF			-0.04	158			-0.62	56	-0.192	214	-1.100	3925
MSN	-0.97	223	-1.02	310					-0.999	533	-1.311	4192
SJT			-0.6	223	-0.58	125			-0.593	348	-0.799	3757
TRI	-0.53	183					-0.47	110	-0.507	293	-0.887	3816
SUMS		596		1596		921		343		3456		40076
MEANS	-1.030		-0.567		-0.396		-0.455		-0.588		-0.877	

(ATL) to +1.16°F (ORH), with only 9 stations having a positive instrument bias. This data clearly shows that the CONV instrument is warmer on average than the ASOS instrument by 0.53°F. There were fluctuations in the seasonal instrument biases at each site, which were probably due to maintenance, changing of a sensor, or electrical problems in the sensor. For 2/3 of the stations, these fluctuations were < 0.5°F.

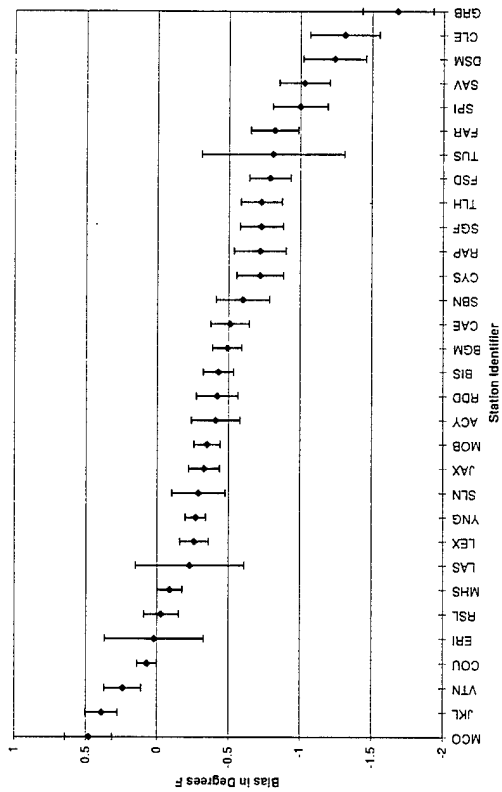
To establish the expected range in the instrument bias at each site, 95% confidence intervals were computed for the seasonal biases which were then plotted in order from most positive to most negative as seen in Figures 3.5(A) - (D). A majority of the confidence intervals (55%) were smaller in range than 0.16°F. Two observations are very apparent on each of these plots. First, most stations have negative instrument biases which translate to a warm biases in the CONV instrument as compared to ASOS. Second, there are a number of stations with instrument biases in excess of -1.0°F. In calculating the 95% confidence intervals, it was assumed that the data had normal population distributions of temperature differences with sample sizes well in excess of 30, and the Central Limit Theorem was applied in calculating the confidence intervals such that:

$$\left(\bar{x} - (1.96) \frac{\sigma_{\bar{x}}}{\sqrt{n}} < \mu < \bar{x} + (1.96) \frac{\sigma_{\bar{x}}}{\sqrt{n}} \right) \quad (3.4)$$

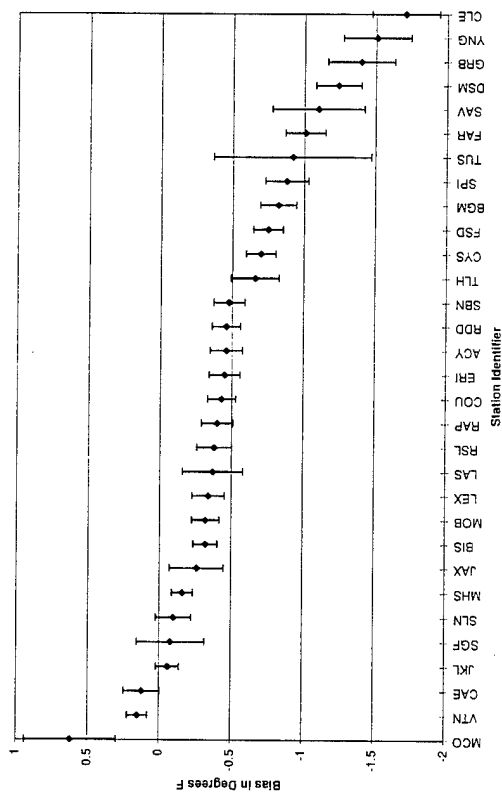
where $\bar{x}$ is the sample mean, n is the sample size, $\sigma_{\bar{x}}$ is the standard deviation of the sample, and μ is the population mean. For stations with seasonal sample sizes $n < 30$, a t -distribution with $n-1$ degrees of freedom was used to calculate the 95% confidence interval by:

$$\left(\bar{x} - (t_{0.025, n-1}) \frac{\sigma_{\bar{x}}}{\sqrt{n}} < \mu < \bar{x} + (t_{0.025, n-1}) \frac{\sigma_{\bar{x}}}{\sqrt{n}} \right) \quad (3.5)$$

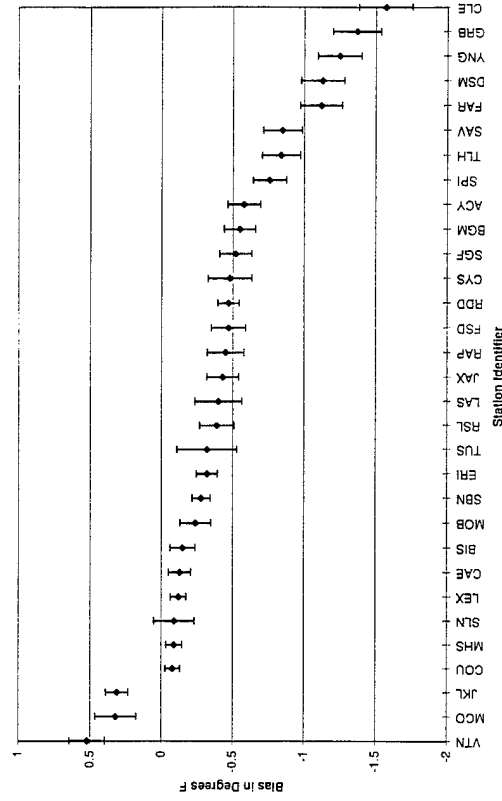
A. Instrument Bias for 4-season stations for Fall



C. Instrument Bias for 4-season stations for Spring



B. Instrument Bias for 4-season stations for Winter



D. Instrument Bias for 4-season stations for Summer

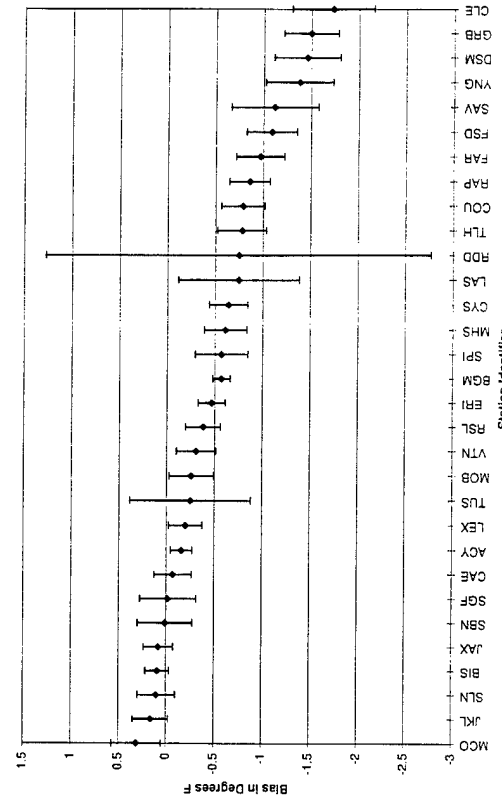


Fig. 3.5 Seasonal Instrument Biases for four-season stations plotted in order from most positive to most negative for the (A) fall, (B) winter, (C) spring, and (D) summer seasons.

where $t_{0.025}$ is the t value with 2.5% of the distribution above and below it (Devore, 1995).

Figure 3.5(D), which shows the instrument biases for the summer season, has a few stations with very large error bars due to the low number of nighttime overcast observations during that particular season. Redding, CA for example had sufficient numbers of nighttime, overcast skies for three months, but due to its climatic region, it reported only 4 observations with the required nocturnal cloud cover for the whole summer season.

To check the stability of the annual instrument bias, seasonal plots were overlaid on each other to see if they were relatively close to one another at each station. Figure 3.6 shows the mean bias for each season and the confidence interval for summer. The summer season was chosen because it had the widest range of confidence intervals for most stations. For 14 of the 31 four-season stations, all of the seasonal biases were within (or very close to) the 95% confidence interval from the summer season, so calculations of annual instrument biases for these stations are useful. There were still a number of stations, however, whose seasonal values did not always fall within the summer season's confidence intervals for the instrument bias. This is probably due to fluctuations in the ΔT field discussed previously and indicates that unexplained variations are present in the data.

3.4 Nighttime Local Effects, ΔT_l

Once seasonal instrument biases were determined for each station, attention was turned to isolating the nocturnal local effects at each site. The temperature-difference

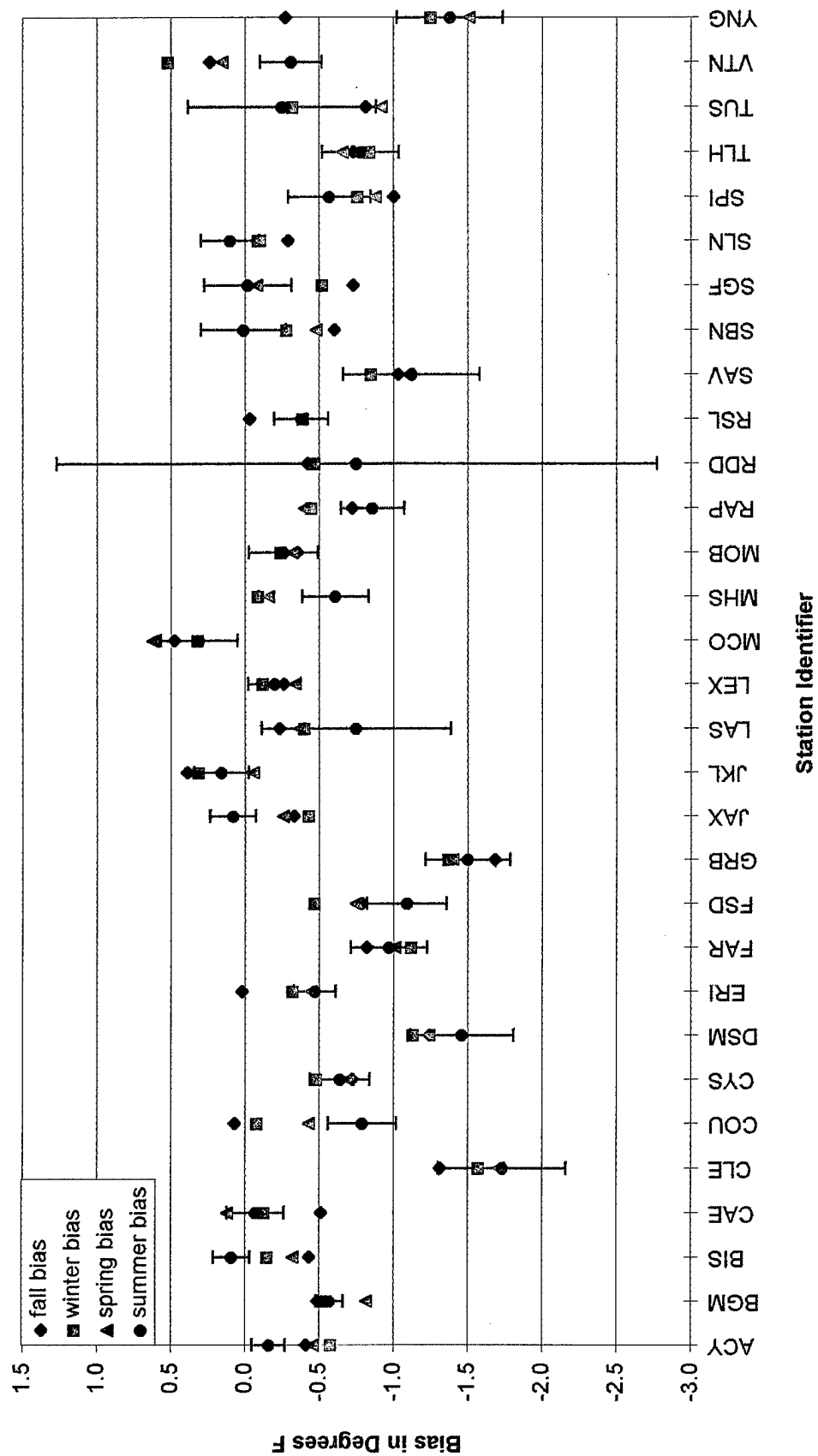


Fig. 3.6 Seasonal instrument biases for four-season stations plotted with summer season 95% confidence intervals.

equation at night now becomes $\Delta T = \Delta T_i + \Delta T_l$, with ΔT_i no longer unknown. To determine the seasonal, nocturnal local effect, the seasonal instrument bias was removed from the seasonal temperature difference for all nighttime observations, which included all wind speeds and all sky conditions. Once the instrument bias was removed, the remaining temperature difference was due to nighttime, local temperature inhomogeneities between the two sensors. Tables 3.4(A) - (C) give the seasonal and annual contributions to the temperature differences due to nocturnal local effects at all stations.

Seasonal nighttime local effects were quite variable over the course of the year at most stations, with changes in both magnitude and sign very common. Seasonal and annual nighttime local effects were calculated in an analogous manner to how seasonal and annual instrument biases were calculated. Some sites show large annual contributions by nighttime local effects. Remember at some locations the two instruments are quite a distance from each other. Seasonal values ranged from -1.29°F (SAV in the spring) to $+0.91^{\circ}\text{F}$ (TLH in the summer). Annual nocturnal local effects ranged from -1.11°F (INW) to $+0.70^{\circ}\text{F}$ (TLH), and showed that ASOS was cooler at night than CONV measurements on average by 0.16°F . The predominance of negative, annually averaged contributions by nocturnal local effects indicate ASOS systems were installed at locations which are predominantly cooler at night than the CONV site. On the other hand, collocated stations like APN, LEX, and YNG had negligible local effects since, by definition, collocated instruments are not far enough apart to be influenced by temperature inhomogeneities in the surface boundary layer. Indeed, all of these stations showed a marked decrease in contributions by nocturnal local effects with annual averages smaller than or close to 0.15°F .

Table 3.4 (B) Seasonal and Annual Nighttime Local Effects for Three-season Stations

Station	Fall ΔT_i	FALL (night only) ΔT_i	# of obs	Winter ΔT_i	WINTER (night only) ΔT_i	# of obs	Spring ΔT_i	SPRING (night only) ΔT_i	# of obs	Summer ΔT_i	SUMMER (night only) ΔT_i	# of obs	ANNUAL LOCAL EFFECTS
ABE				-1.15	-1.6	514	-0.97	-1.75	587	-0.67	-1.69	640	-0.771
ABQ				-0.94	-1.19	619	-1.02	-1.27	620	-0.48	-0.85	629	-0.290
ALB	-0.41	-0.54	636	-0.88	-0.84	627	-0.65	-0.64	615				-0.027
ALO	-0.65	-0.62	437	-0.56	-0.51	613	-0.72	-0.64	550				0.055
APN	-0.3	-0.16	637	-0.4	-0.35	623	-0.31	-0.35	539				0.055
ATL	-2.17	-3.03	626	-1.78	-1.95	617	-2.04	-2.68	644				-0.559
AUS	-0.46	-0.06	432	-0.4	-0.01	630	-0.25	-0.06	629				0.318
BFF	-0.54	-0.66	628	-0.24	-0.33	619	-0.37	-0.28	639				-0.039
DAB	0.01	-0.19	634	0.1	0.06	626	-0.06	0.00	585				-0.260
DAY				-0.29	-0.24	572	-0.3	-0.06	517	-0.13	0.06	640	0.159
DTW	-0.7	-0.83	636	-0.89	-0.89	623	-0.68	-0.73	637	-0.53	-1.33	636	-0.060
EUG				-1.08	-1.07	443	-0.9	-1.37	616				-0.468
FWA	-1.03	-1.57	624	-0.64	-0.51	602	-0.6	-0.69	548				-0.174
GJT	-0.68	-0.98	434	-0.56	-0.79	576	-0.51	-0.97	550				-0.329
HON	-0.15	-0.11	635				-0.24	-0.15	642	0.12	0.11	639	0.040
INL	-0.61	-0.86	447	-0.53	-0.74	597	-0.77	-1.1	468				-0.259
INW	0.4	-0.78	512	0.73	-0.37	608	0.5	-0.55	582				-1.107
LAN	0.3	0	582				0.18	0.05	431	0.75	0.52	639	-0.229
LBB				-0.61	-1.24	581	-0.64	-0.84	620	-0.67	-0.46	620	-0.198
LCH	-1.24	-1.31	586	-1.37	-1.4	520	-1.4	-1.52	570				-0.075
MCI	-0.22	-0.04	626	-0.56	-0.25	620	-0.7	-0.43	625				0.104
MGM	-1.3	-1.31	626	-1.59	-1.41	490	-1.72	-1.54	450				-0.155
MKE	-1.66	-1.88	636	-1.37	-1.45	584	-1.62	-1.78	644				0.041
MKG	-0.23	-0.18	627	-0.2	-0.15	599	-0.29	-0.27	558				0.413
MLI	-0.44	0.16	635	-0.53	-0.4	618	-0.43	0.08	581				-0.091
MSO	-0.36	-0.37	447				-1.19	-0.74	641	-0.53	-0.74	643	-0.154
OFK				-0.58	-0.67	617	-0.61	-0.74	633	-0.76	-1	633	-0.030
ORH	1.16	1.13	621	1.15	1.14	511	1.17	1.12	547				0.288
PAH	-0.59	-0.05	634	-0.54	-0.2	518	-0.62	-0.63	629				-0.352
PDT	-0.5	-1.05	633	-0.25	-0.5	595	-0.42	-0.67	626				0.008
PDX				0.16	0.32	617	0.16	0.51	622	0.12	0.33	639	0.117
PIA	-0.21	-0.25	636	-0.33	-0.3	620	-0.26	-0.22	638				0.191
RFD	0.09	0.21	601	0.01	0.1	621	-0.27	-0.13	541				-0.637
RST	-0.02	0.11	633	-0.2	-0.12	573	-0.13	0.25	640				
SUX	-0.28	-1.16	636	-0.59	-1.14	622	-0.41	-0.89					
SUMS			16477			18810							
MEANS	-0.457	-0.585	-0.128	-0.528	-0.594	-0.065	-0.545	-0.650	-0.105	-0.278	-0.505	-0.227	-0.114

Table 3.4 (C) Seasonal and Annual Nighttime Local Effects for Two-season Stations

Station	Fall			FALL (night only)			Winter			WINTER (night only)			Spring			SPRING (night only)			Summer			SUMMER (night only)			ANNUAL LOCAL		
	ΔT_i	ΔT	ΔT_i	ΔT_i	# of obs	ΔT_i	ΔT_i	ΔT	ΔT_i	ΔT_i	# of obs	ΔT_i	ΔT_i	ΔT	ΔT_i	ΔT_i	# of obs	ΔT_i	ΔT	ΔT_i	ΔT_i	ΔT	ΔT_i	# of obs	ΔT_i	ΔT	EFFECTS
BIL	-1.29	-1.31	-0.020	-0.020	634	-1.06	-1.08	-1.08	-0.020	-0.020	622	-0.92	-0.93	-0.93	-0.010	-0.010	589	-0.39	-0.53	-0.53	-0.140	-0.140	629	-0.077	-0.077	-0.077	-0.077
CAK	-1.33	-1.33	0.000	0.000	629	-1.27	-1.39	-1.39	-0.120	-0.120	628	0.3	0.08	0.08	-0.220	-0.220	643	-0.34	-0.61	-0.61	-0.270	-0.270	554	-0.142	-0.142	-0.142	-0.142
DRA						0.22	0.16	0.16	-0.060	-0.060	616	-0.39	-0.77	-0.77	-0.380	-0.380	484	-0.62	-1.54	-1.54	-0.920	-0.920	537	-0.205	-0.205	-0.205	-0.205
FNT						-0.2	-0.53	-0.53	-0.330	-0.330	611	-0.39	-0.44	-0.44	-0.050	-0.050	490	-0.47	-0.83	-0.83	-0.360	-0.360	487	-0.524	-0.524	-0.524	-0.524
GEG						-0.04	-1.31	-1.31	-1.270	-1.270	611	-0.58	-0.73	-0.73	-0.150	-0.150	500	-0.455	-0.878	-0.878	-0.423	-0.423	2207	-0.218	-0.218	-0.218	-0.218
ISN						-1.02	-0.86	-0.86	0.160	0.160	594																
LBF	-0.97	-0.49	0.480	0.480	629	-0.6	-0.56	-0.56	0.040	0.040	601																
MSN																											
SJT																											
TRI	-0.53	-1.18	-0.650	-0.650	632																						
SUMS					2524						4283						2706										
MEANS	-1.030	-1.076	-0.048	-0.048		-0.567	-0.796	-0.796	-0.220	-0.220		-0.396	-0.558	-0.558	-0.162	-0.162		-0.455	-0.878	-0.878	-0.423	-0.423					-0.218

3.5 Daytime Local and Solar Heating Effects, ΔT_s

The final contribution to the temperature differences observed between the ASOS and CONV observations was that of the daytime local plus solar effects. It is impossible to separate these two influences from each other, so the temperature difference equation becomes $\Delta T = \Delta T_i + \Delta T_l + \Delta T_s$, with ΔT_i no longer unknown. Isolating the combined effect of these two contributions was accomplished by removing the seasonal instrument bias from the seasonal temperature difference for all daytime observations. Tables 3.5 (A) - (C) show both seasonal and annual contributions to the temperature differences at each site due to daytime local and solar influences. Seasonal ranges for these daytime effects were from -2.26°F (JKL in the summer) to $+0.91^\circ\text{F}$ (DSM in the fall). The range of annual contributions from the daytime effects was from -1.54°F (JKL) to $+0.61^\circ\text{F}$ (VTN), with an overwhelming number on the negative side. The annually averaged contributions show that CONV instruments are warmer by 0.37°F during the daytime hours than ASOS instruments. Note that for about half of the stations the summer local and solar effects are more negative than these effects in the winter time. Indeed, the average over all stations in the four-season group of the seasonal biases is more negative in the summer (-0.50°F) than in the winter (-0.21°F). This supports evidence that the older HO83 hygrothermometer is subject to solar heating problems not experienced by the ASOS instrument. Indeed, it was proposed (Jones and Young, 1994) that the original version of the HO83 exhibits this warm bias due to "heating of the instrument housing by internal heat sources coupled with inadequate ventilation." Further evidence that the HO83 suffers more from solar heating effects is found in examining the daytime effects at

Table 3.5 (A) Seasonal and Annual Daytime Local and Solar Effects for Four-season Stations

Station	Fall	FALL (day only)	Winter	WINTER (day only)	Spring	SPRING (day only)	Summer	SUMMER (day only)	ANNUAL LOCAL & SOLAR EFFECTS
	ΔT_i	$\Delta T_i + \Delta T_o$	ΔT_i	$\Delta T_i + \Delta T_o$	ΔT_i	$\Delta T_i + \Delta T_o$	ΔT_i	$\Delta T_i + \Delta T_o$	ΔT_i
ACY	-0.41	0.01	-0.58	0.090	-0.46	0.250	-0.67	-0.76	0.253
BGM	-0.48	-0.61	-0.55	-0.270	-0.82	0.020	-0.57	-0.94	-0.190
BIS	-0.43	-0.200	-0.15	-0.78	-0.32	-0.460	0.09	-0.42	-0.449
CAE	-0.51	-1.47	-0.13	-0.60	0.12	-0.85	-0.07	-1.11	-0.865
CLE	-1.31	0.030	-1.57	-0.240	-1.71	-0.150	-1.73	-0.800	-0.292
COU	0.07	-0.350	-0.08	-0.070	-0.43	-0.180	-0.70	-0.810	-0.355
CYS	-0.72	-1.17	-0.48	-0.440	-0.7	-0.440	-0.64	-1.07	-0.563
DSM	-1.24	-0.33	-1.13	-0.360	-1.24	-0.78	-1.46	-0.660	0.420
ERI	0.02	-0.51	-0.32	-0.190	-0.45	-0.250	-0.47	-1.18	-0.414
FAR	-0.82	-0.91	-1.12	-0.420	-1.01	-0.270	-0.97	-1.22	-0.269
FSD	-0.78	-1.03	-0.47	-0.610	-0.75	-0.280	-1.09	-0.840	-0.503
GRB	-1.68	-1.32	-1.37	0.000	-1.4	-1.08	-1.5	-1.78	0.088
JAX	-0.33	-0.530	-0.43	-0.360	-0.26	-0.360	0.08	-1.230	-0.767
JKL	0.30	-1.3	0.31	-0.880	-0.06	-1.330	0.16	-2.260	-1.542
LAS	-0.23	-1.46	-0.4	-0.940	-0.37	-1.120	-0.75	-1.47	-0.901
LEX	-0.26	-0.6	-0.12	-0.32	-0.34	-0.78	-0.2	-0.8	-0.366
MCO	0.48	0.24	0.32	0.41	0.62	0.52	0.31	0.32	0.010
MHS	-0.09	-0.22	-0.09	0.000	-0.16	-0.210	-0.61	-0.13	0.480
MOB	-0.35	-0.62	-0.24	-0.66	-0.32	-0.57	-0.26	-0.86	-0.600
RAP	-0.72	-0.79	-0.45	-0.57	-0.4	-1.29	-0.86	-0.68	0.180
RDD	-0.42	-0.79	-0.47	-0.61	-0.46	-0.77	-0.75	-0.96	-0.237
RSL	-0.03	0.09	-0.39	-0.27	-0.38	-0.35	-0.38	-0.05	0.330
SAV	-1.03	-1.09	-0.85	-0.260	-1.1	-0.010	-1.12	-1.51	-0.390
SBN	0.6	-0.96	-0.28	-0.45	-0.48	-1	0.01	-0.75	-0.760
SGF	-0.73	-1.12	-0.52	-0.61	-0.08	-0.3	-0.02	-1.37	-1.350
SUN	-0.29	0.48	-0.09	0.340	-0.11	0.45	0.1	0.79	0.890
SPI	-1	-0.82	-0.76	-0.87	-0.88	-1	-0.57	-1.34	-0.770
TLH	-0.73	-1.09	-0.84	-1.1	-0.66	-1.19	-0.78	-1.31	-0.530
TUS	-0.81	-1.66	-0.32	-1.17	-0.92	-2.66	-0.25	-1.09	-0.840
VIN	0.24	1.03	0.52	0.530	0.15	0.42	-0.31	0.58	0.890
YNG	-0.49	-0.88	-1.25	-1.38	-1.51	-1.94	-1.38	-2.61	-1.230
SUMS									
MEANS	-0.494	-0.708	-0.461	-0.214	-0.545	-0.880	-0.563	-1.050	-0.310
									18390

Table 3.5 (B) Seasonal and Annual Daytime Local and Solar Effects for Three-season Stations

Station	Fall ΔT_i	FALL (day only) $\Delta T_i + \Delta T_o$	# of obs	Winter ΔT_i	WINTER (day only) $\Delta T_i + \Delta T_o$	# of obs	Spring ΔT_i	SPRING (day only) $\Delta T_i + \Delta T_o$	# of obs	Summer ΔT_i	SUMMER (day only) $\Delta T_i + \Delta T_o$	# of obs	ANNUAL LOCAL & SOLAR EFFECTS
ABE				-1.15	-1.51	513	-0.97	-1.32	574	-0.67	-0.76	641	-0.257
ABQ				-0.94	-1.77	613	-1.02	-1.79	610	-0.48	-2.07	620	-1.066
ALB	-0.41	-0.290	631	-0.88	-1.12	626	-0.65	-0.94	610				-0.273
ALO	-0.65	-0.080	444	-0.56	-1.05	609	-0.72	-0.77	549				-0.226
APN	-0.3	-0.450	633	-0.4	-0.78	625	-0.31	-0.93	446				-0.469
ATL	-2.17	-2.6	623	-1.78	-1.97	620	-2.04	-2.72	638				-0.436
AUS	-0.46	-0.550	429	-0.4	-0.86	623	-0.25	-0.76	630				-0.502
BFF	-0.54	-0.480	613	-0.24	-0.86	621	-0.37	-0.43	628				-0.385
DAB	0.01	-0.280	636	0.1	-0.06	627	-0.06	-0.31	581				-0.230
DAY				-0.29	-0.88	580	-0.3	-0.88	504	-0.13	-1.2	635	-0.764
DTW	-0.7	-0.520	632	-1.07	-1.37	627	-0.68	-1.12	642				-0.381
EUG				-1.08	-1.37	433	-0.9	-1.37	599	-0.53	-0.51	625	-0.238
FWA	-1.03	-0.030	624	-0.64	-1.17	587	-0.6	-1.22	544				-0.331
GJT	-0.68	-0.160	429	-0.56	-1.04	580	-0.51	-0.82	529				-0.332
HON	-0.15	-0.150	635				-0.24	-0.53	643	0.12	-0.31	642	-0.291
INL	-0.61	-0.190	454	-0.53	-0.92	601	-0.77	-0.99	478				-0.278
INW	0.4	0.090	517	0.73	0.97	595	0.5	1.2	577				0.504
LAN	0.3	-0.430	545				0.18	-0.16	437	0.75	0.49	641	-0.339
LBB				-0.61	-0.5	576	-0.64	-0.97	607	-0.67	-1.16	612	-0.243
LCH	-1.24	-0.010	588	-1.37	-1.13	624	-0.7	-1.36	577				-0.101
MCI	-0.22	-0.210	624	-0.56	-0.84	625	-0.7	-0.71	613				-0.437
MGM	-1.3	-0.520	616	-1.59	-1.89	485	-1.72	-2.19	442				-0.968
MKE	-1.66	-0.720	634	-1.37	-2.8	601	-1.62	-2.4	643				-0.128
MKG	-0.23	-0.090	622	-0.2	-0.29	578	-0.26	-0.5	551				-0.451
MLJ	-0.44	-0.360	637	-0.53	-1.05	623	-0.43	-1	583				-0.898
MSO	-0.36	-0.960	440				-1.19	-1.99	444	-0.53	-1.53	640	-0.860
OFK				-0.58	-1.27	620	-0.61	-1.19	642	-0.76	-1.53	638	-0.862
ORH	1.16	-0.820	613	1.15	0.27	550	1.17	0.28	591				-0.503
PAH	-0.59	-0.420	637	-0.54	-0.87	504	-0.62	-1.35	618				-0.047
PDT	-0.5	0.090	632	-0.25	-0.55	582	-0.42	-0.37	617				-0.852
PDX				0.16	-0.42	603	0.16	-0.68	623	0.12	-1	637	-0.712
PJA	-0.21	-0.790	627	-0.33	-0.99	624	-0.26	-0.84	530				-0.538
RFD	0.09	-0.500	595	0.01	-0.5	617	-0.27	-0.87	639				-0.145
RST	-0.02	-0.200	627	-0.2	-0.13	557	-0.13	-0.43	546				-0.113
SUX	-0.28	0.270	633	-0.59	-1.25	623	-0.41	-0.37	637				
SUMS			16370			18812							
MEANS	-0.457	-0.311		-0.528	-0.921		-0.545	-0.940		-0.278	-0.958	6331	-0.400

Table 3.5 (C) Seasonal and Annual Daytime Local and Solar Effects for Two-season Stations

Station	Fall		FALL (day only)		Winter		WINTER (day only)		Spring		SPRING (day only)		Summer		SUMMER (day only)		ANNUAL LOCAL & SOLAR EFFECTS
	ΔT_i	ΔT	$\Delta T_i + \Delta T_o$	# of obs	ΔT_i	ΔT	$\Delta T_i + \Delta T_o$	# of obs	ΔT_i	ΔT	$\Delta T_i + \Delta T_o$	# of obs	ΔT_i	ΔT	$\Delta T_i + \Delta T_o$	# of obs	
BIL	-1.29	-1.32	-0.030	626	-1.06	-1.11	-0.050	618	-0.82	-0.94	-0.020	581	-0.39	-0.7	-0.310	619	-0.040
CAK																	-0.170
DRA	-1.33	-1.54	-0.210	630	-1.27	-1.76	-0.490	617	0.3	-0.28	-0.590	643					-0.349
FNT					0.22	-0.19	-0.410	621	-0.39	-0.55	-0.160	497	-0.34	-0.36	-0.020	545	-0.406
GEG									-0.39	-0.87	-0.400	482					-0.087
ISN					-0.2	-0.89	-0.690	613					-0.62	-0.39	0.230	530	-0.588
LBF					-0.04	-0.6	-0.560	613									-0.194
MSN	-0.87	-2.71	-1.740	630	-1.02	-2.16	-1.140	592									-1.449
SJT					-0.6	-0.64	-0.340	590	-0.56	-0.86	-0.390	494					-0.358
TRI	-0.53	-0.87	-0.440	630									-0.47	-0.56	-0.090	479	-0.289
SUMS				2516				4284								2173	
MEANS	-1.030	-1.635	-0.805		-0.567	-1.093	-0.526		-0.396	-0.720	-0.324		-0.455	-0.503	-0.048		-0.403

stations located in high-sunshine climatic regions. Sites like LAS, TUS, and ABQ which are located in the southwestern United States have large annual contributions to temperature differences due to daytime effects of -1.0°F or more. Examination of the collocated sites, APN, LEX, and YNG, reveal daytime contributions to the temperature differences on average around -0.5°F .

3.6 Diurnal Cycles (ΔT versus Time of Day)

Having thoroughly examined the sources contributing to the temperature differences between ASOS and CONV measurements, seasonal diurnal cycles were generated to show how temperature differences varied with time of day. Figures 3.7 (A) - (F) show the average, hourly temperature differences versus time of day using all available observations for each station during each season. It is obvious that over 60% of the stations (see Appendix B) exhibit noticeable fluctuations to varying amounts over the course of an average 24-hour period. Figures 3.7 (A) - (D) provide evidence of the daytime warm bias of the HO83. During the daytime hours, ΔT is more negative because the CONV instrument is warmer than ASOS. At night these differences diminish; and in the case of JKL, it appears that ASOS is located in a spot which is warmer at night than that of the CONV site. Figures 3.7(E) - (F) are examples of pronounced but reversed diurnal cycles. For both GRB and SAV the daytime ΔT is still negative, but the nighttime local effects are quite significant being in excess of -0.8°F . These nocturnal influences are strong enough to reverse the diurnal-cycle patterns at these stations.

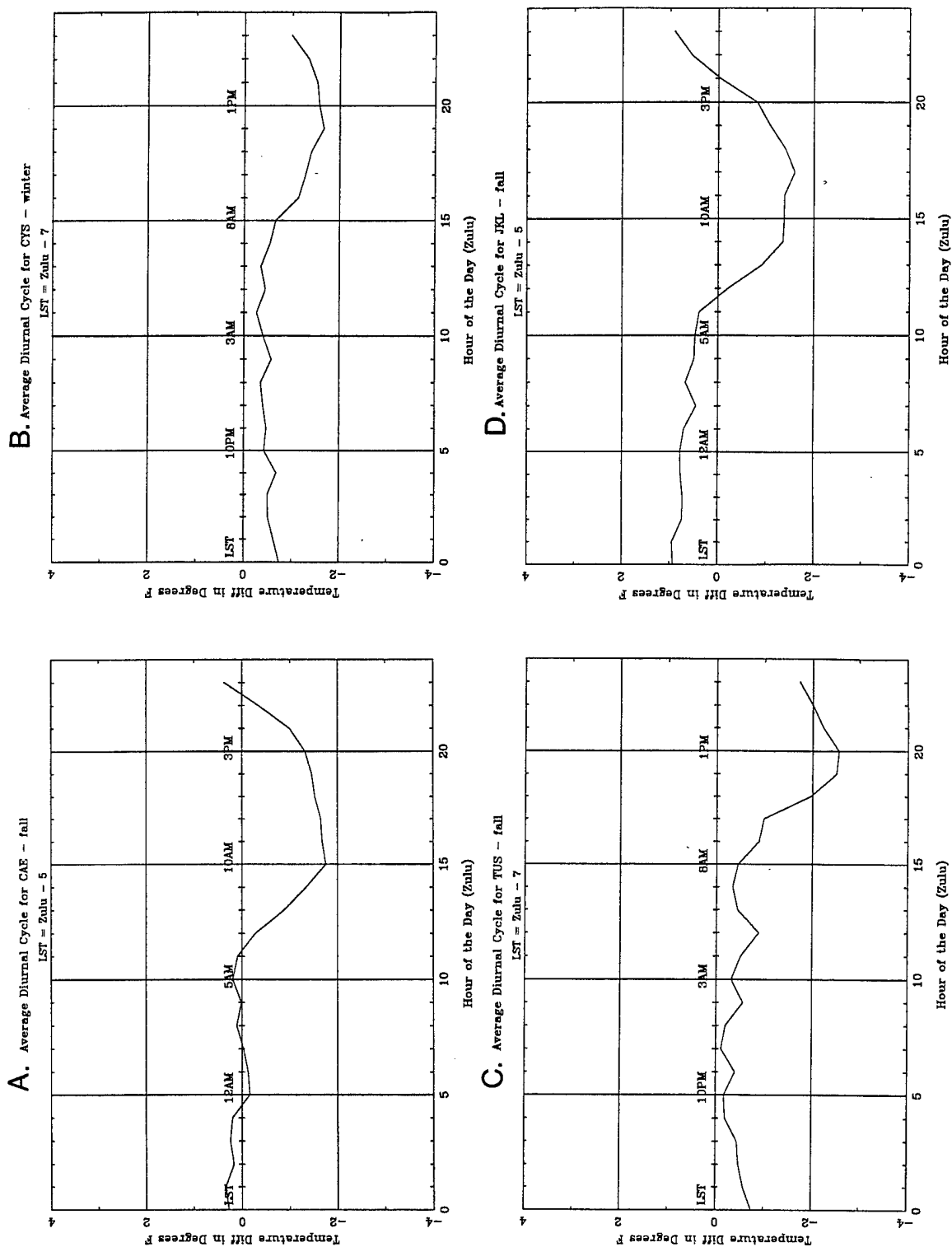


Fig. 3.7 (A) - (D) Seasonal diurnal temperature difference cycles showing daily pattern for majority of stations (daytime exhibits largest negative temperature differences.)

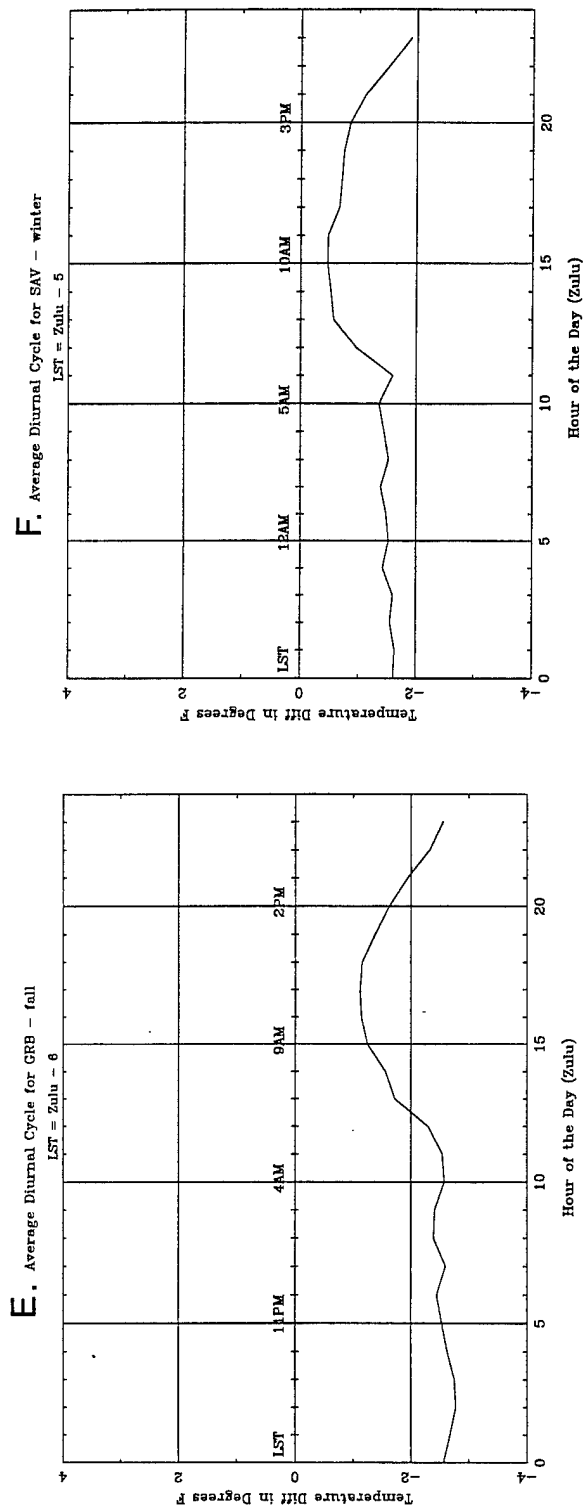


Fig. 3.7 (E) - (F) Seasonal diurnal temperature difference cycles showing reversed daily pattern depicted in 21 percent of stations (daytime still exhibits negative temperature differences, but nocturnal local effects are much more negative.)

3.7 Annual Cycles and Trends

In addition to daily temperature difference patterns, the nocturnal local effects and daytime local plus solar effects were examined for evidence of annual cycles and trends in the data. To help visually detect evidence of such patterns in the local and solar effects, bar graphs were generated for each station in the four-season and three-season lists using all available seasonal data shown in Figures 3.8(A) - (B). A seasonal cycle is identified by equitable values for the spring and fall seasons with winter and summer having opposite, more extreme values (DSM). In these cycles, it is the summer season which exhibits the largest negative value, while winter is the least negative. Of the 31 four-season stations, 5 exhibit evidence of an annual cycle in the nocturnal local effects. In addition, 12 out of 66 stations showed trends in their nocturnal seasonal effects. In other words, as time went by the contributions to seasonal temperature differences due to the nocturnal local effects became either more positive (ACY and SUX), or in most cases more negative (CLE, SBN, ABE, and EUG). These trends could be the result of seasonal weather phenomena, changing anthropogenic sources near the instruments, or simply changes in the instruments themselves.

Annual cycles and trends were also noted in similar bar graph plots of the seasonal daytime local and solar effects shown in Figures 3.9(A) - (B). Of the 31 four-season sites, 10 exhibit evidence of an annual cycle, with YNG, JKL, and SAV being the strongest examples. Of the 66 stations plotted, 26 had the most negative daytime bias during the summer season. Only 7 out of the 66 four-season and three-season stations exhibited trends in seasonal daytime local and solar effects.

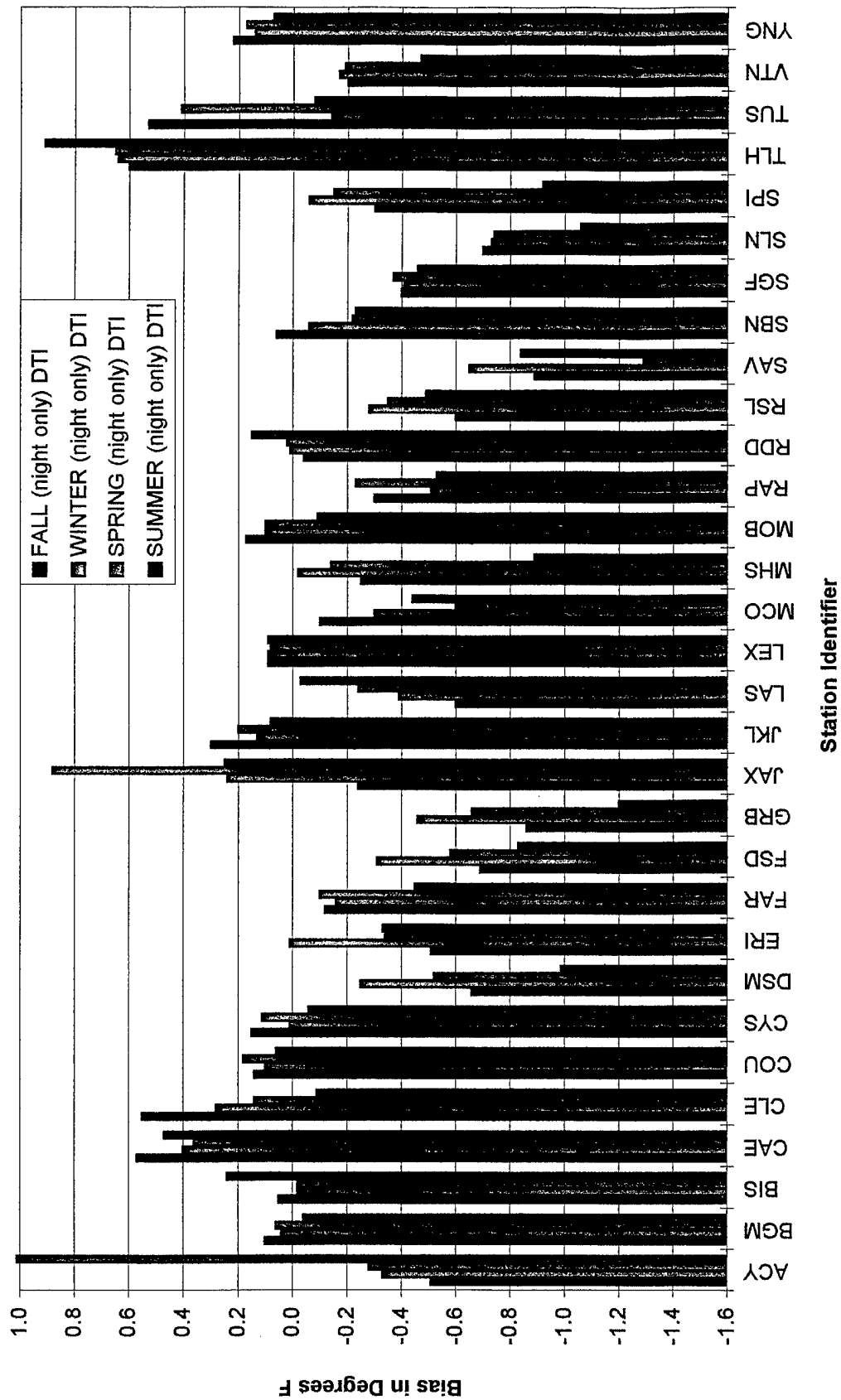


Fig. 3.8 (A) Seasonal distributions of nighttime local effects for four-season stations.

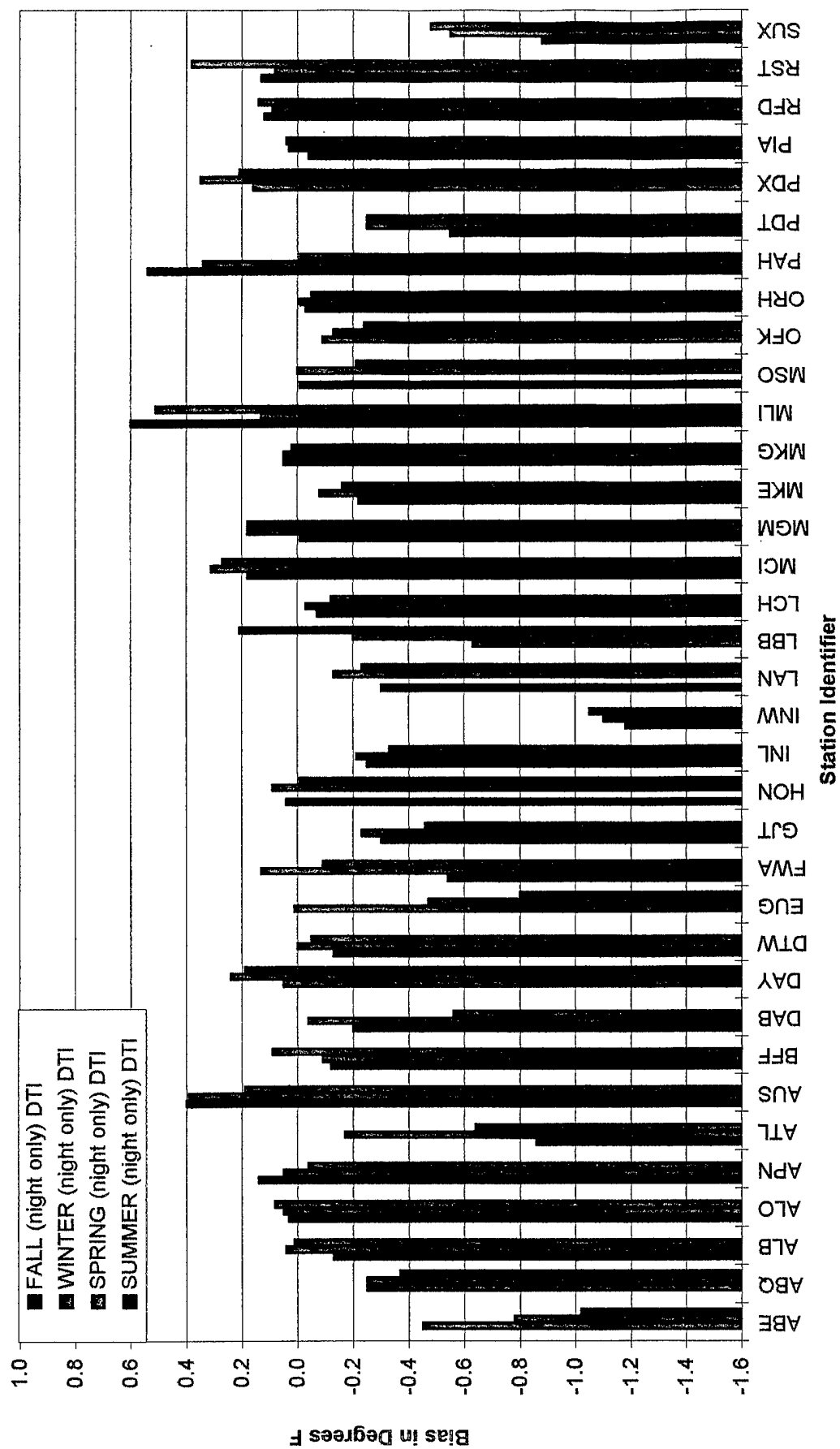


Fig. 3.8 (B) Seasonal distributions of nighttime local effects for three-season stations.

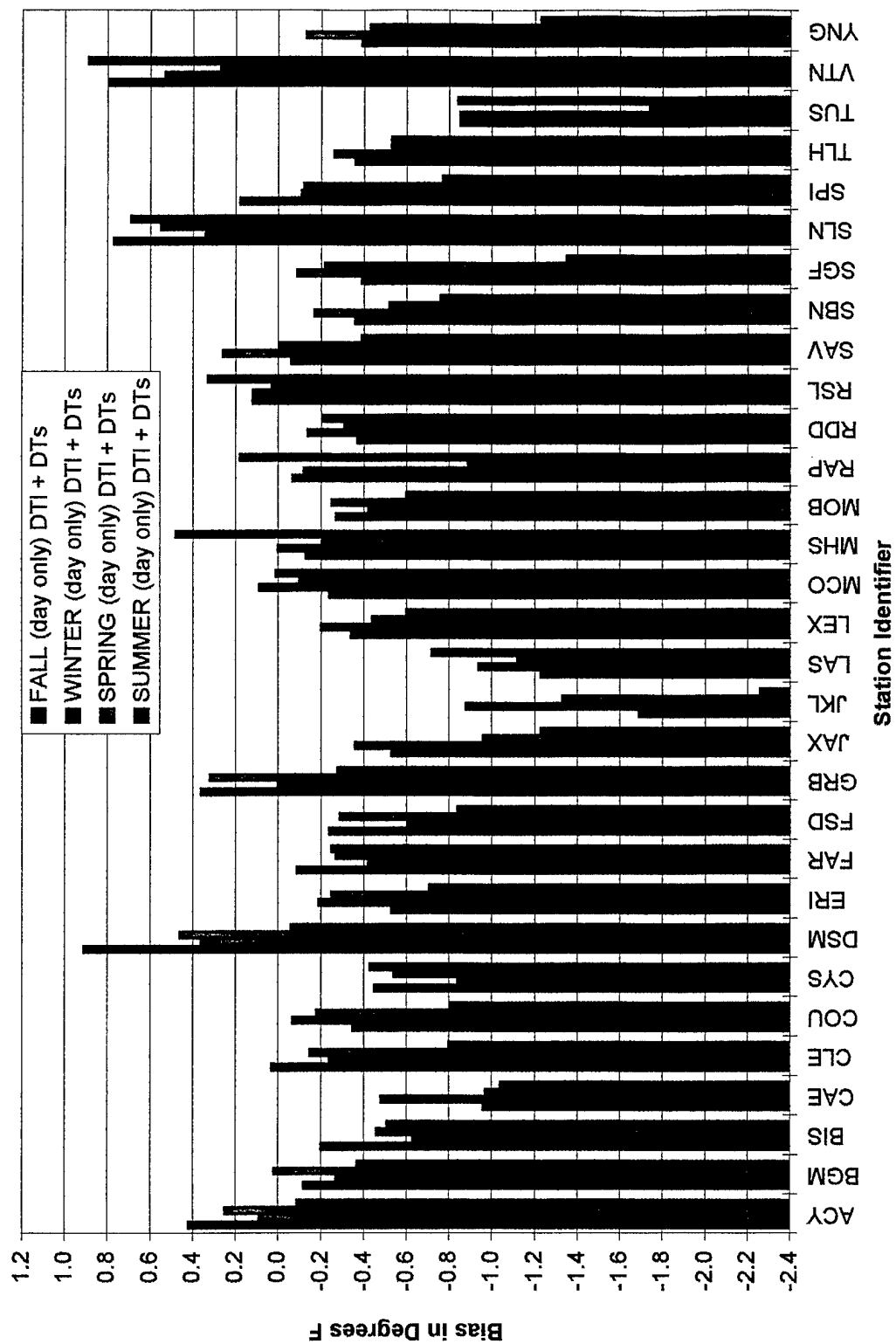


Fig. 3.9 (A) Seasonal distributions of daytime local and solar effects for four-season stations.

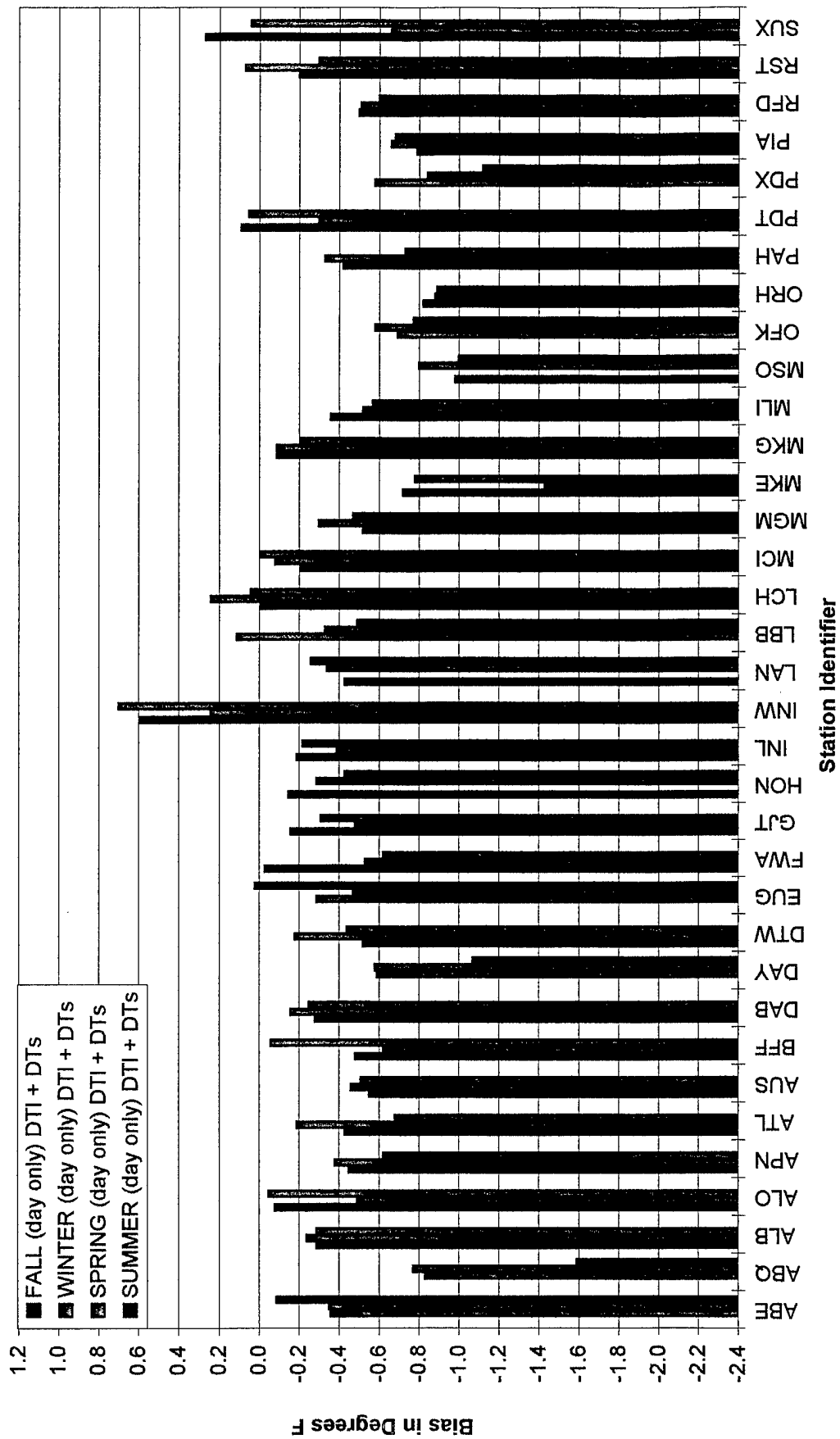


Fig. 3.9 (B) Seasonal distributions of daytime local and solar effects for three-season stations.

Returning to the temperature time series analyses, only a couple of stations exhibited signs of annual cycles in the temperature differences between $\Delta T_{\text{highest hourly}}$ and $\Delta T_{\text{lowest hourly}}$. JKL and CAE, shown in Figures 3.10 (A) - (B), were the best examples of well-behaved sites with fairly convincing evidence for the presence of an annual cycle in $\Delta T_{\text{highest hourly}}$. The mean temperature difference for these plots seems to fluctuate sinusoidally with the changing seasons. This could be due to an annual cycle in the temperature differences, or merely instabilities in the instruments. Again, it should be noted that most stations did not exhibit any evidence of having annual cycles in the time series data.

3.8 Regional Effects

Lastly, the data was examined to see if stations in like climatic zones exhibited similar temperature difference patterns. As mentioned earlier, several stations located in the sunny southwest such as LAS, TUS, and ABQ, had significant annual contributions due to daytime local and solar effects in excess of -1.0°F , supporting evidence of a warm bias in the HO83.

An interesting discovery in the temperature time series analysis showed that coastal sites had very stable and moderate temperature difference plots over the course of the year as seen in Figures 3.11(A) - (B) for DAB and LCH. The stability of these plots is most likely attributable to the moderating effects of coastal sea breezes and land breezes prevalent at these sites. In striking contrast to the coastal stations, inland-continental stations like FSD and SLN exhibit more erratic, fluctuating temperature difference time

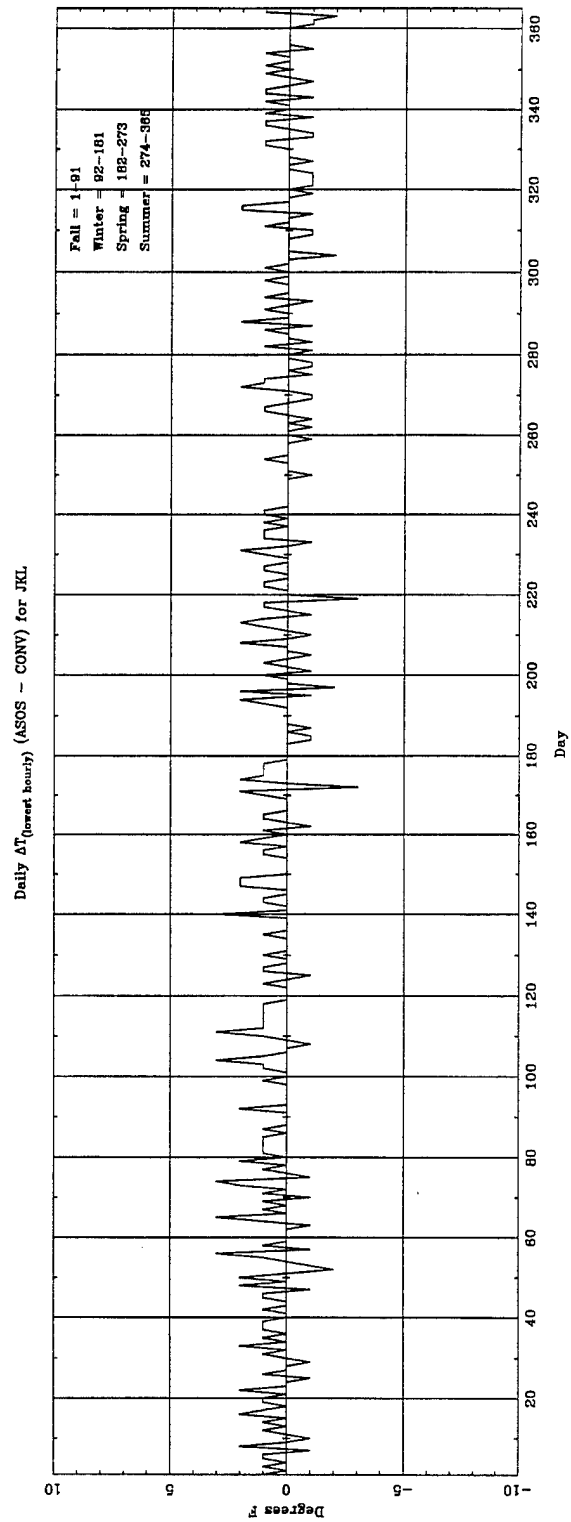
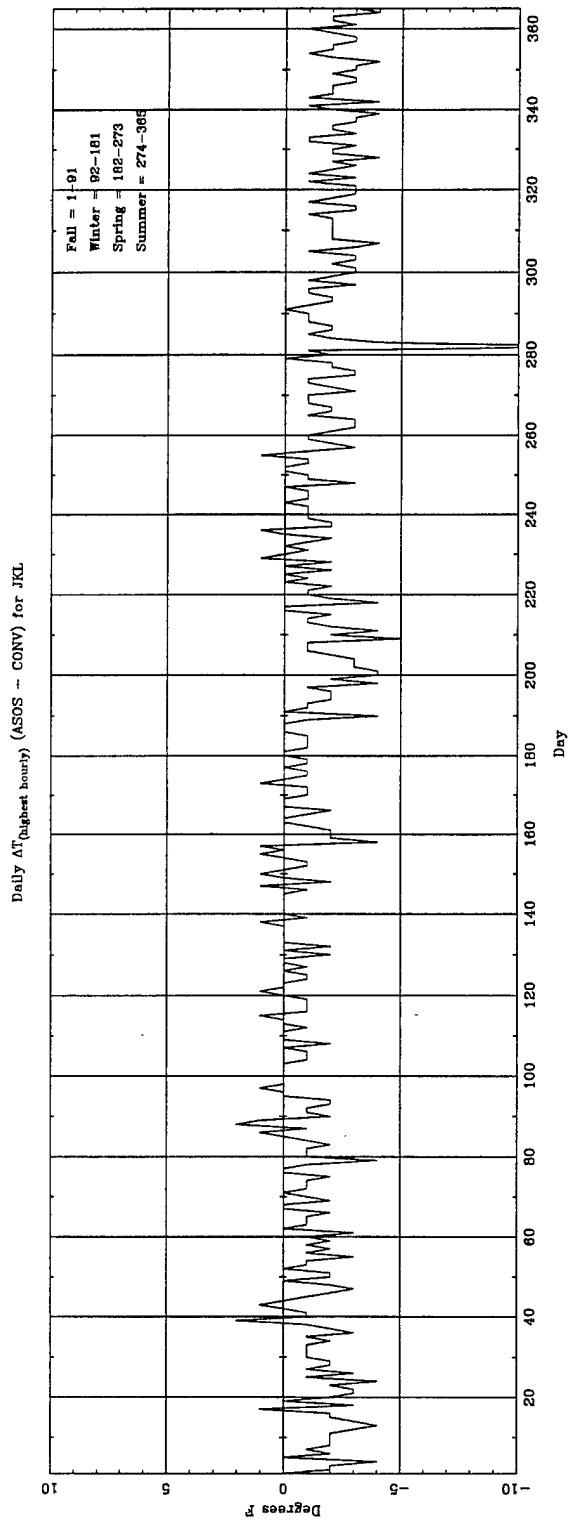


Fig. 3.10 (A) Temperature time series analysis for Jackson, KY.

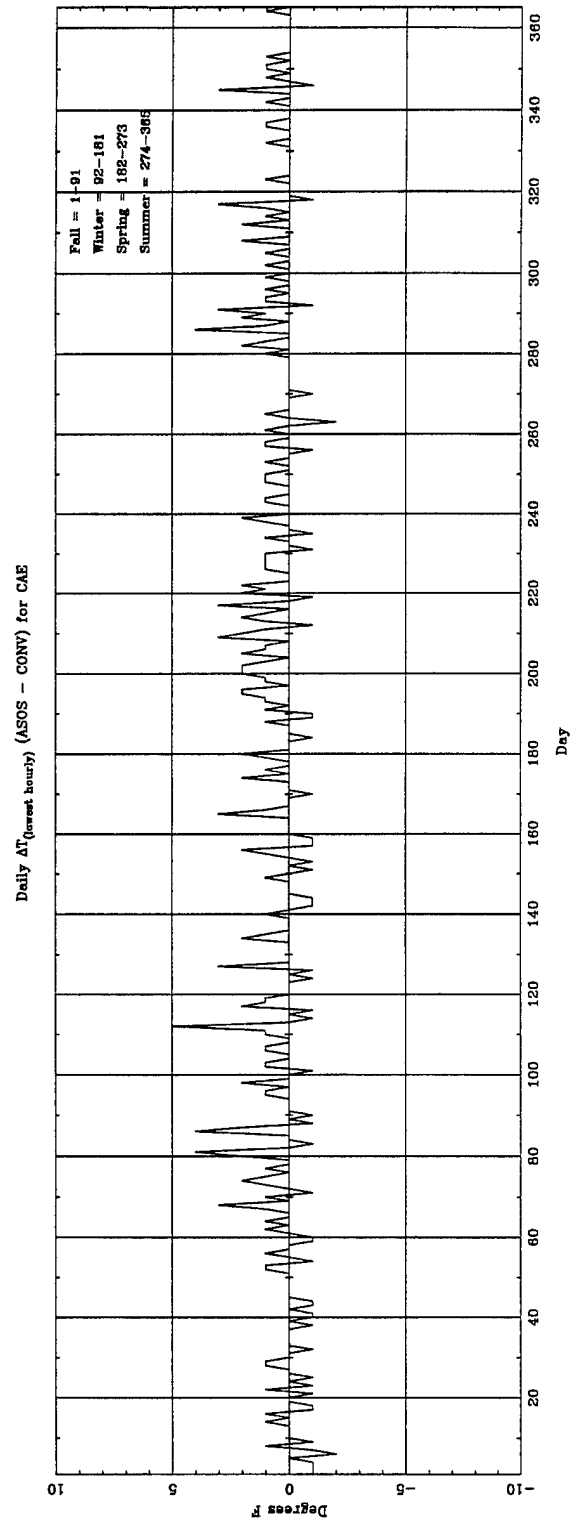
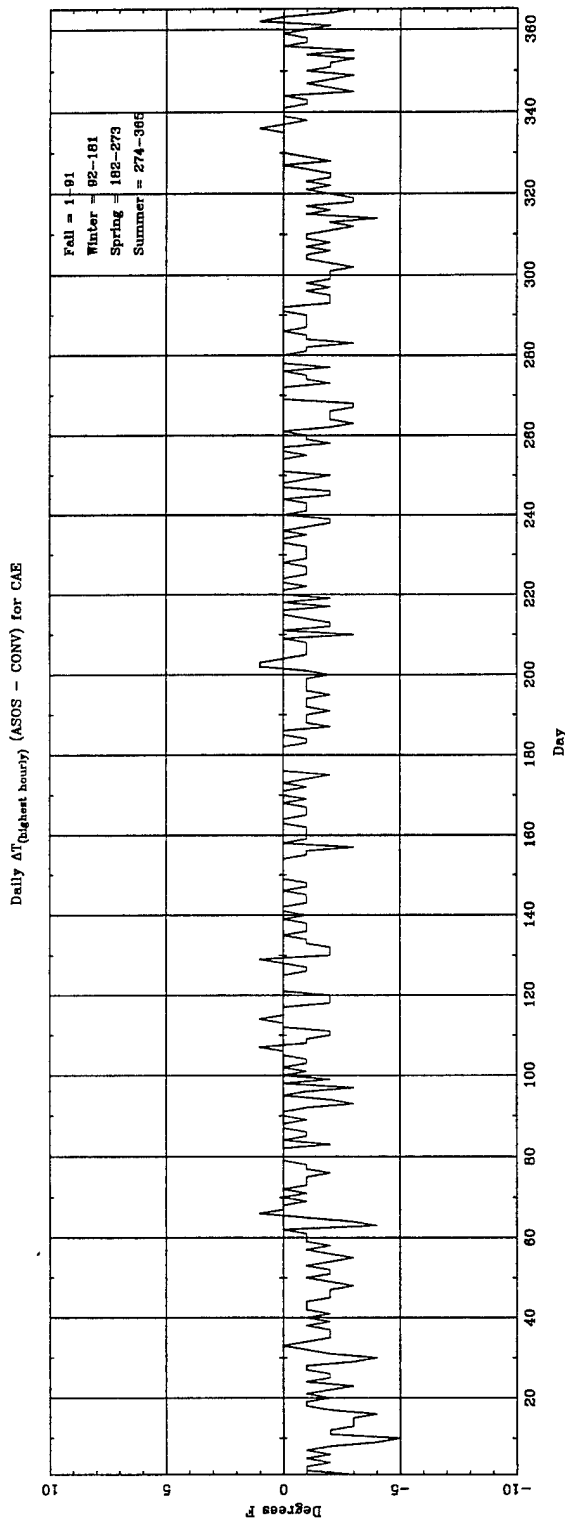


Fig. 3.10 (B) Temperature time series analysis for Columbia, SC.

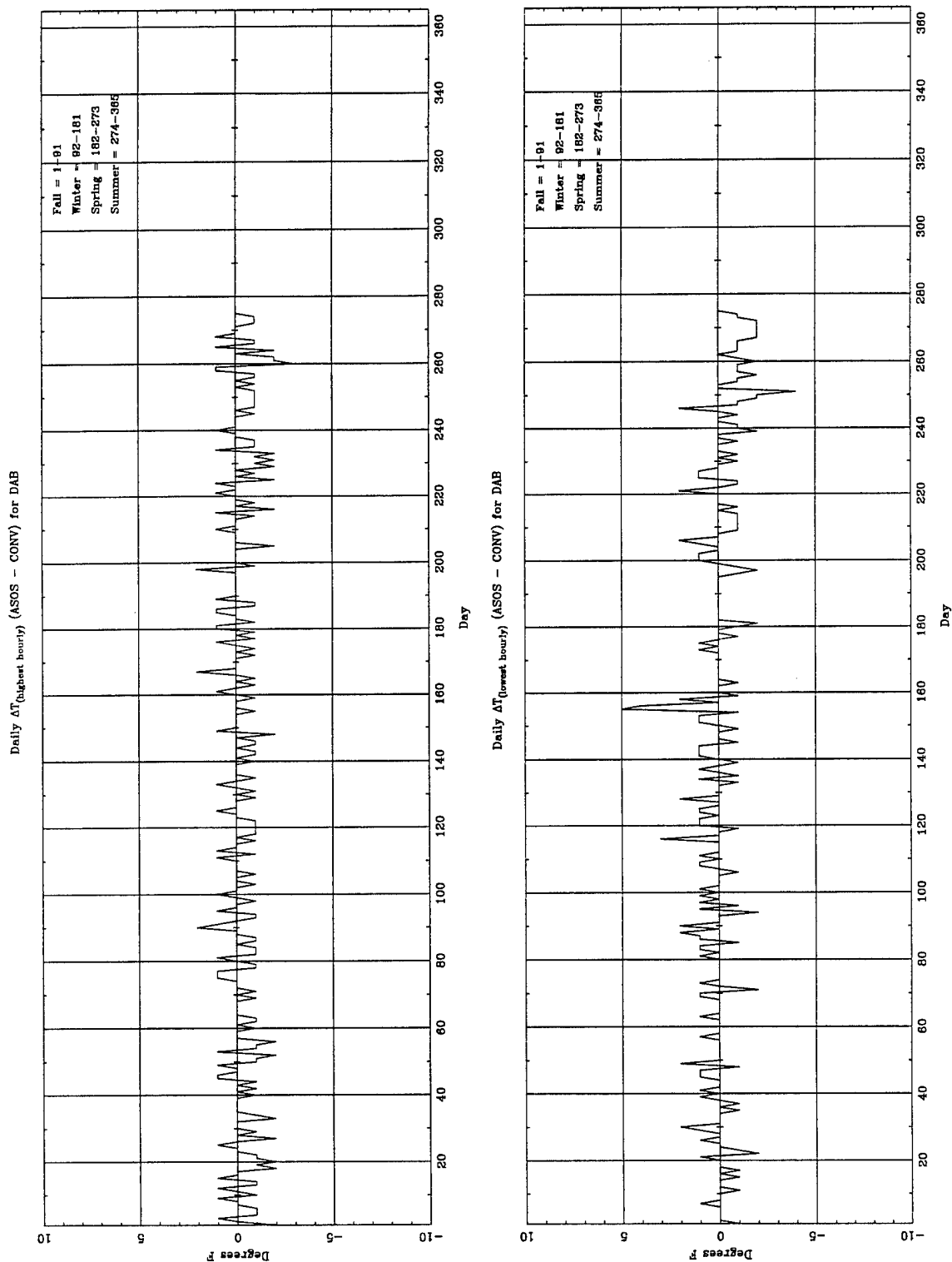


Fig. 3.11 (A) Temperature time series analysis for the coastal site of Daytona Beach, FL.

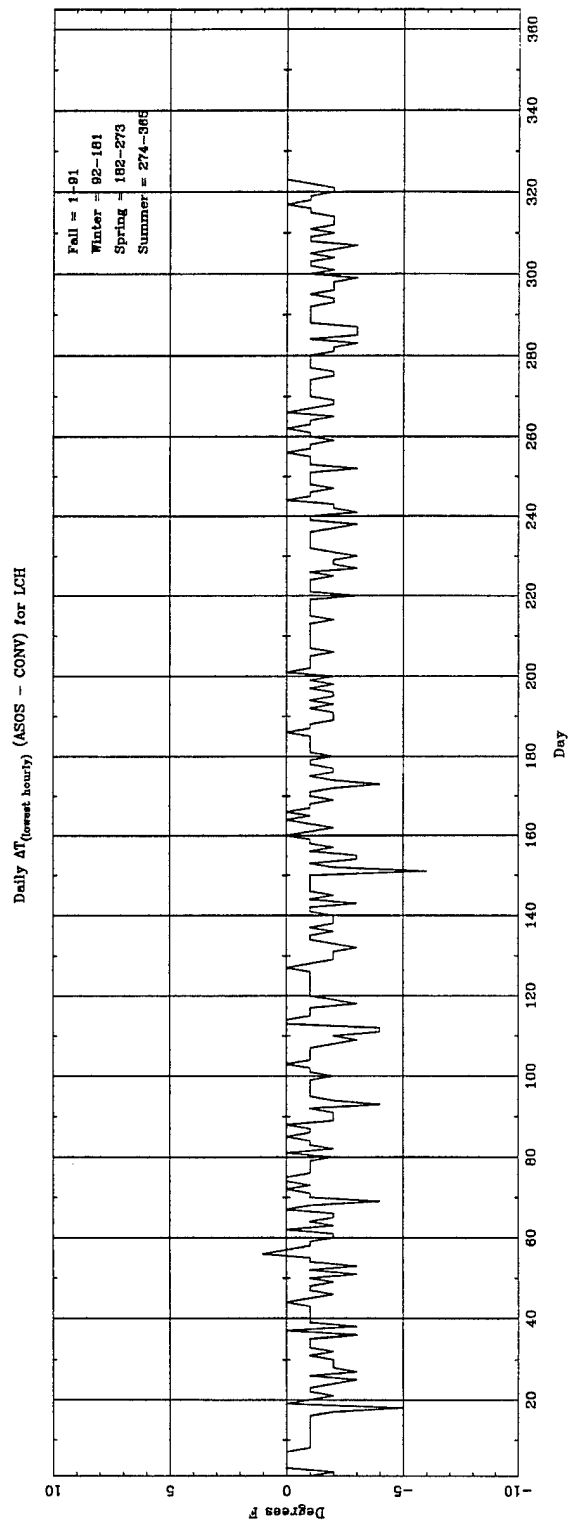
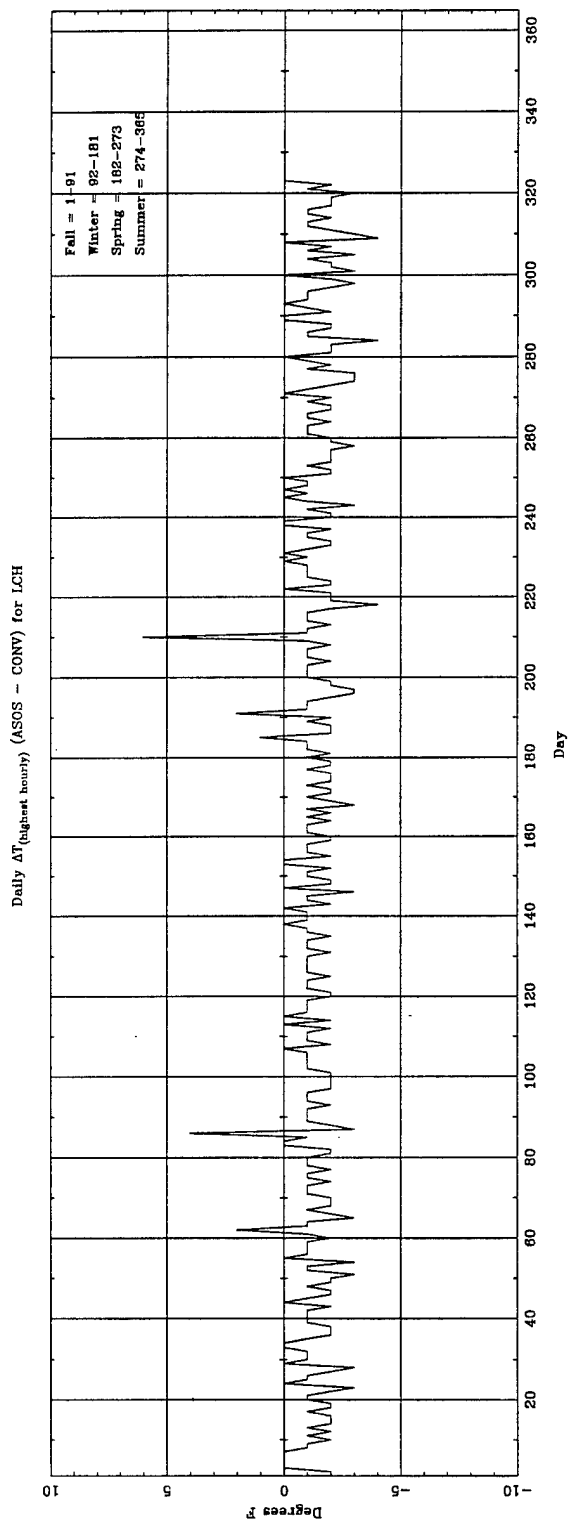


Fig. 3.11 (B) Temperature time series analysis for the coastal site of Lake Charles, LA.

series plots, as seen in Figures 3.11(C) - (D), probably in response to passing weather systems and large differentials in daytime heating and nighttime cooling patterns.

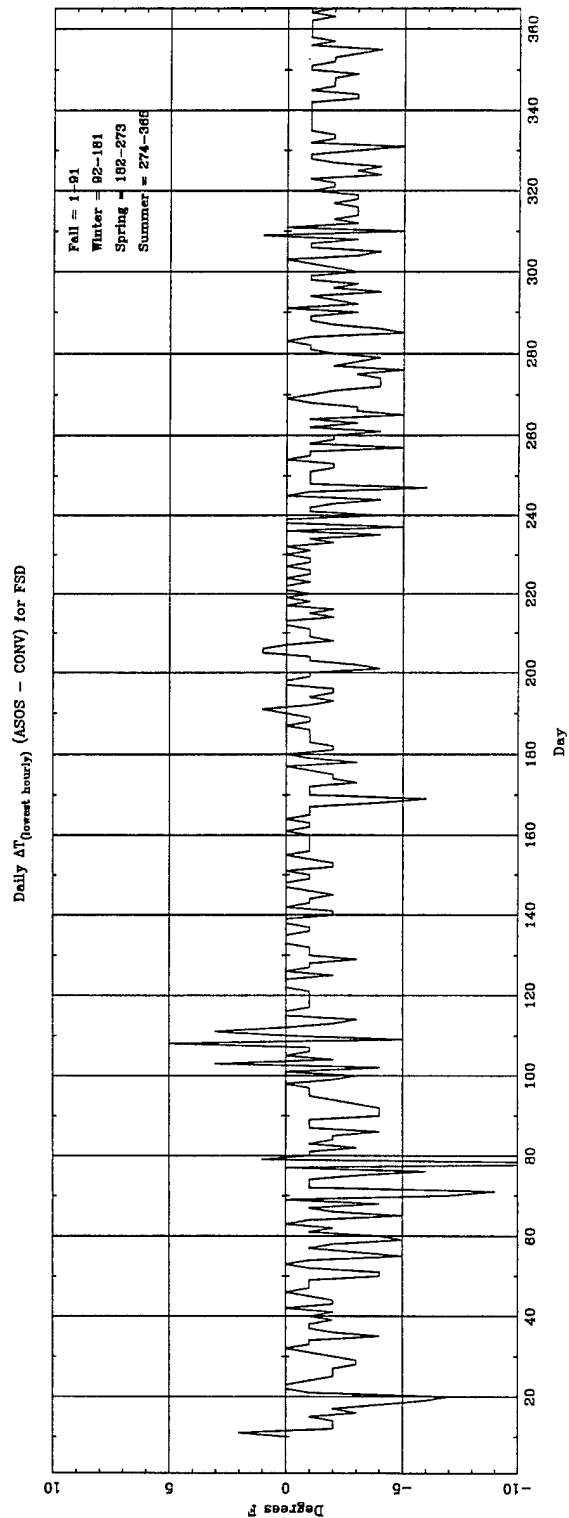
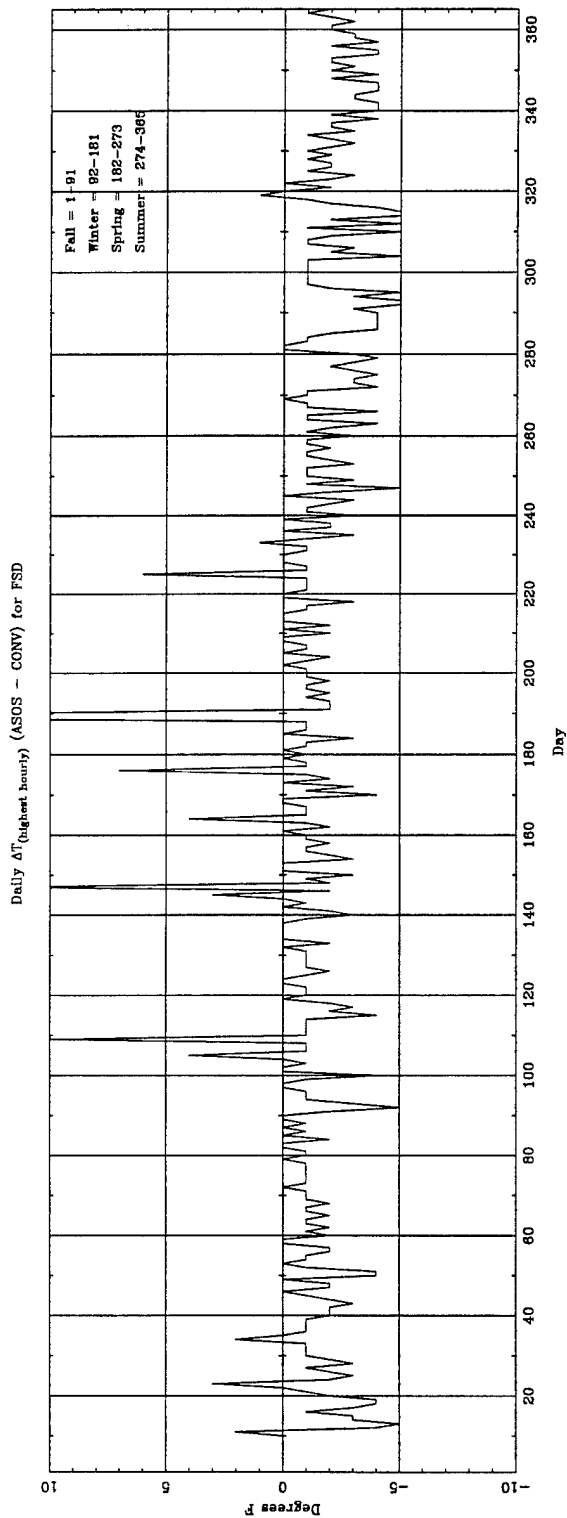


Fig. 3.11 (C) Temperature time series analysis for the continental site of Sioux Falls, SD.

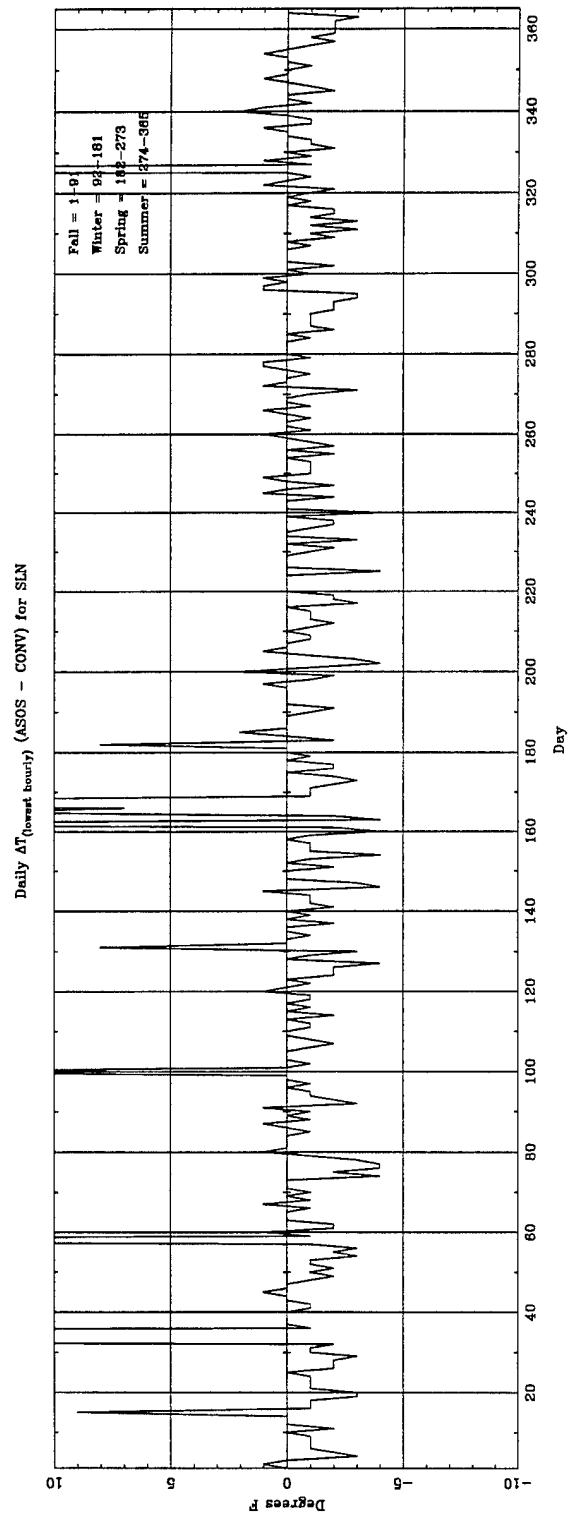
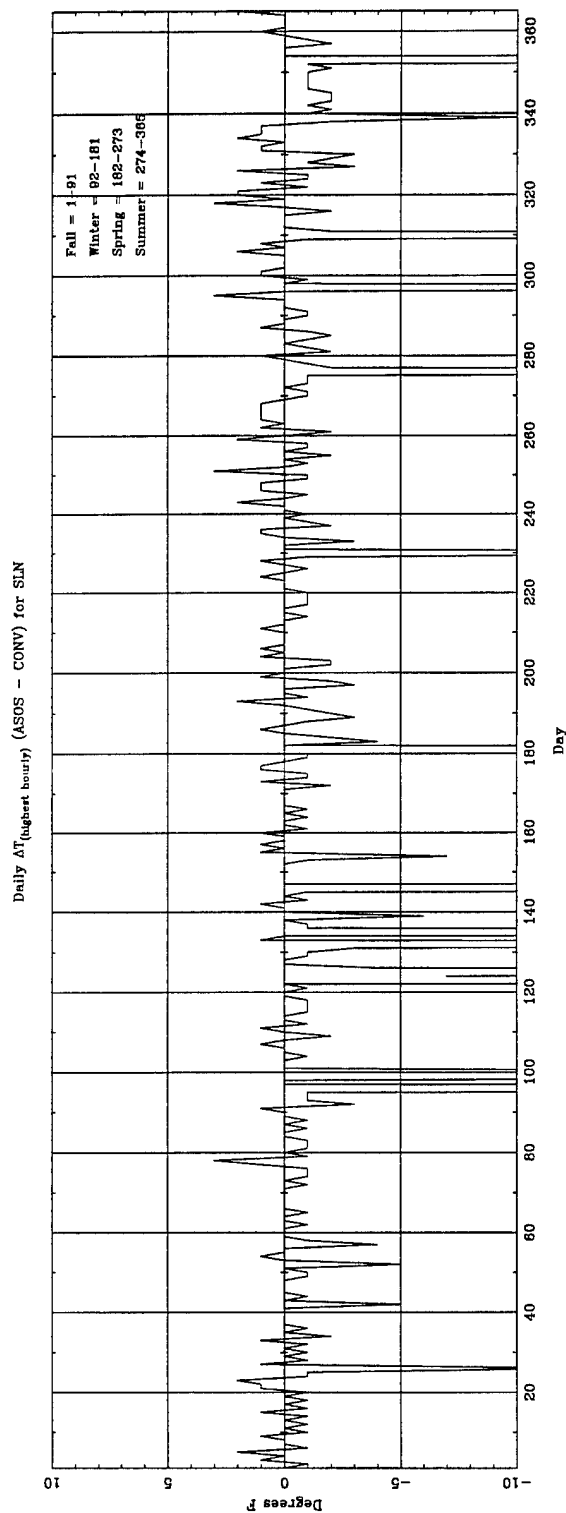


Fig. 3.11 (D) Temperature time series analysis for the continental site of Salina, KS.

4.0 CONCLUSIONS

The results of temperature comparisons between ASOS and CONV measurements examined in this investigation show that the CONV instrument, the Model HO83 hygrothermometer, is predominantly warmer compared to its ASOS replacement. The average temperature difference (ASOS - CONV) for all observations for all 76 sites is -0.79°F , with a considerable range of -2.56°F to $+0.61^{\circ}\text{F}$, resulting in a fair amount of variability among the CONV instruments.

ASOS has no systematic bias in measuring "true" ambient air temperature, although the ASOS hygrothermometers do vary by $\pm 0.3^{\circ}\text{F}$ in comparison to a calibrated field standard. Instrument biases, determined using nighttime overcast observations, between the ASOS and CONV hygrothermometers show that the ASOS instrument is most often cooler than the CONV instrument. On the average, the CONV instruments were 0.53°F warmer than the ASOS instruments with seasonal ranges of up to 2.17°F warmer and 1.17°F cooler than ASOS, with only 9 stations having a positive, annually-averaged instrument bias. It is both the variability and the prevailing warm bias among the HO83 hygrothermometers which indicate that ASOS is an improvement over CONV temperature measurements.

Installation of ASOS instruments at locations which were largely cooler at night than the CONV site resulted in negative, annually-averaged, nocturnal local effects at 47 of the 76 sites. These location effects do fluctuate considerably with the seasons both in

magnitude and sign convention with an annually averaged range of -1.11°F to $+0.70^{\circ}\text{F}$, and a mean of -0.16°F . In addition, the combined influences of the daytime local and solar effects are overwhelmingly negative adding to evidence of a solar heating problem in the CONV instrument. Seasonal ranges in the daytime effects showed CONV measurements were warmer than ASOS by as much as 2.26°F and could be cooler by as much as 0.91°F . Overall, 67 of the 76 stations had negative, annually-averaged contributions due to daytime local and solar effects, with a mean value of -0.37°F . Direct comparisons of the daytime bias at collocated sites showed typical solar heating effects of -0.5°F . Diurnal cycle plots also added considerable evidence of a warm bias in the CONV hygrothermometer with a majority of stations having the largest negative temperature differences during the daylight hours.

While there is some evidence of annual cycles and trends in the nocturnal local effects as well as the daytime local and solar effects at some stations, there is not enough evidence to support seasonal correction factors for manipulating all data reported by CONV and ASOS instruments. For the stations with probable annual cycles, the summer season most often has the largest negative values with winter usually having the least negative value of the four seasons. Again, these facts point to a solar heating problem experienced by the conventional HO83 hygrothermometer.

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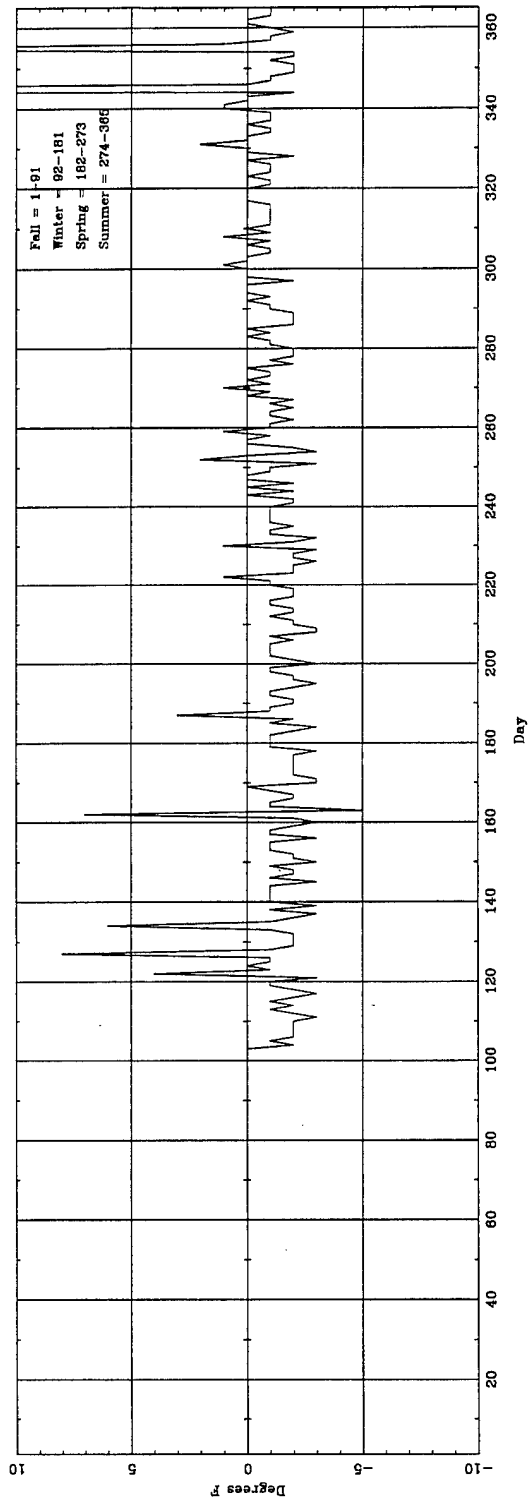
Systems Management Incorporated, 1992: Software User's Manual for the Automated Surface Observing System (ASOS). Report No. RSMI005-00019B Change 1, CDRL No. C04. Prepared for the U. S. Dept of Commerce, NOAA, National Weather Service, Silver Spring, MD, 567 pp.

APPENDICES

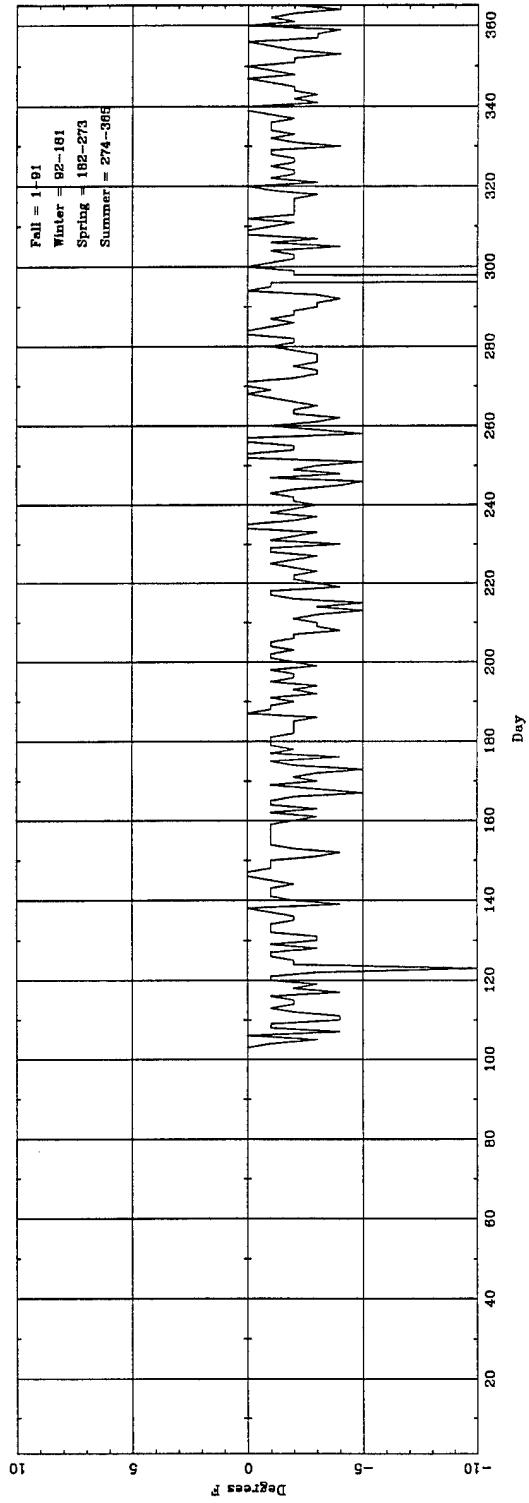
APPENDIX A: Temperature Time Series Plots

The following graphs depict the time series analysis of the temperature differences between ASOS and CONV SAOs with the highest hourly temperature and lowest hourly temperature for each 24-hour day (midnight to midnight LST). Beginning with September 1, 1994 as day 1, days run sequentially through the fall, winter, spring, and summer according to the legend in the upper right-hand corner of each graph. Temperature differences are plotted in whole degrees Fahrenheit with range of $-10^{\circ}\text{F} \leq \Delta T \leq +10^{\circ}\text{F}$ along the y-axis.

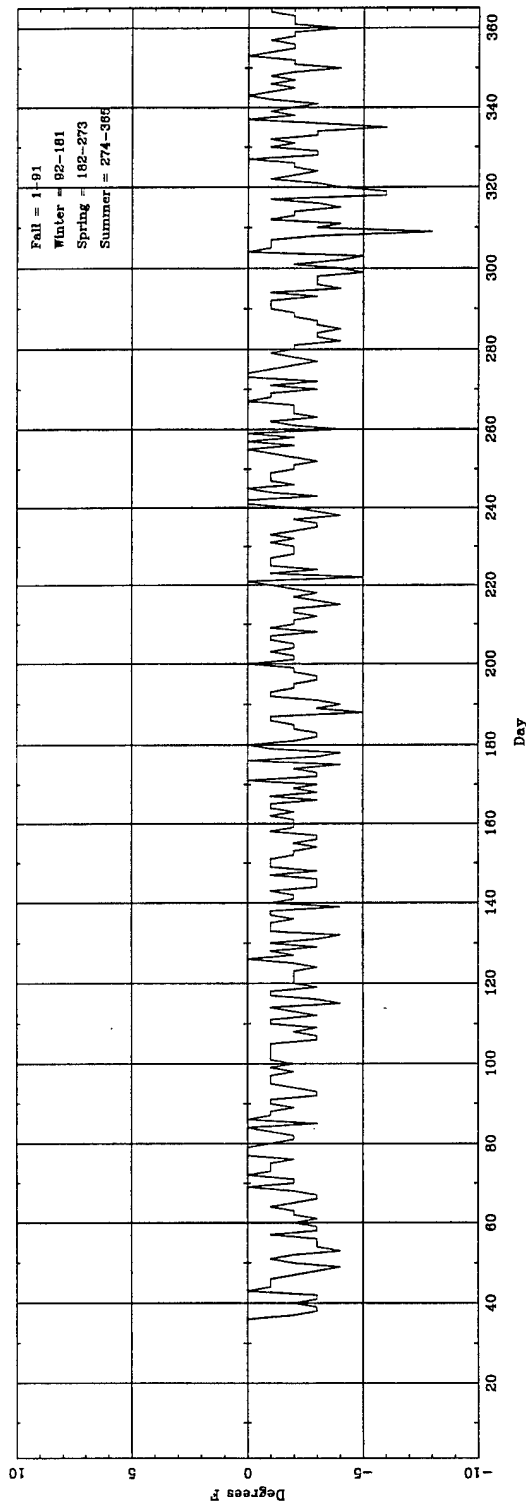
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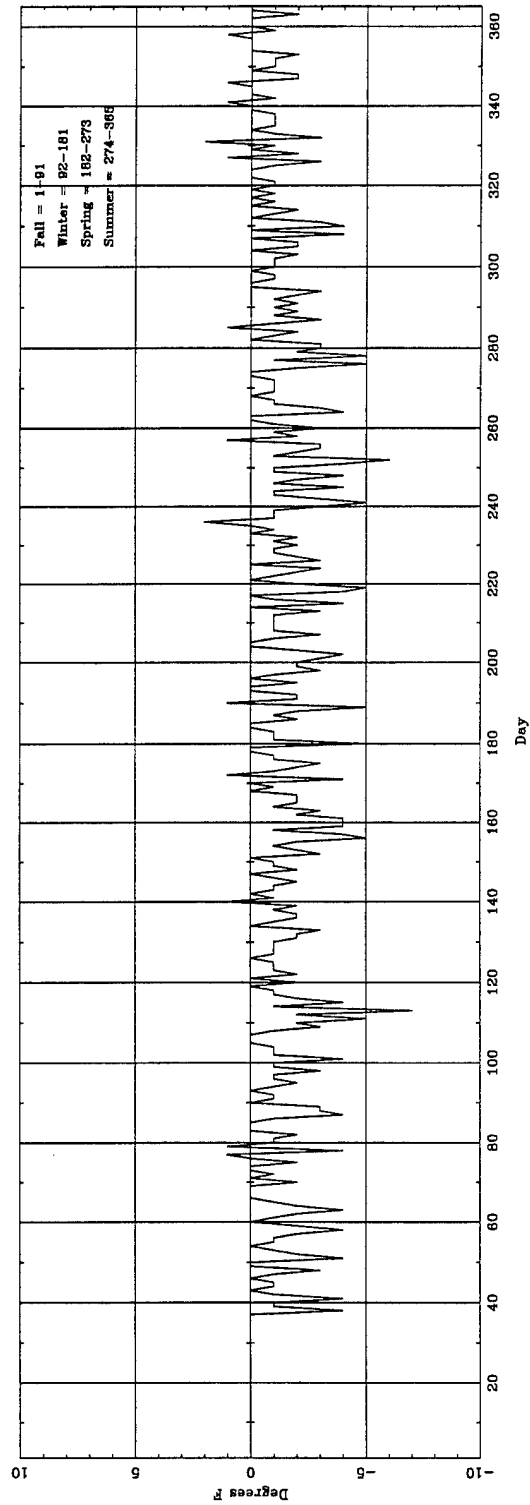
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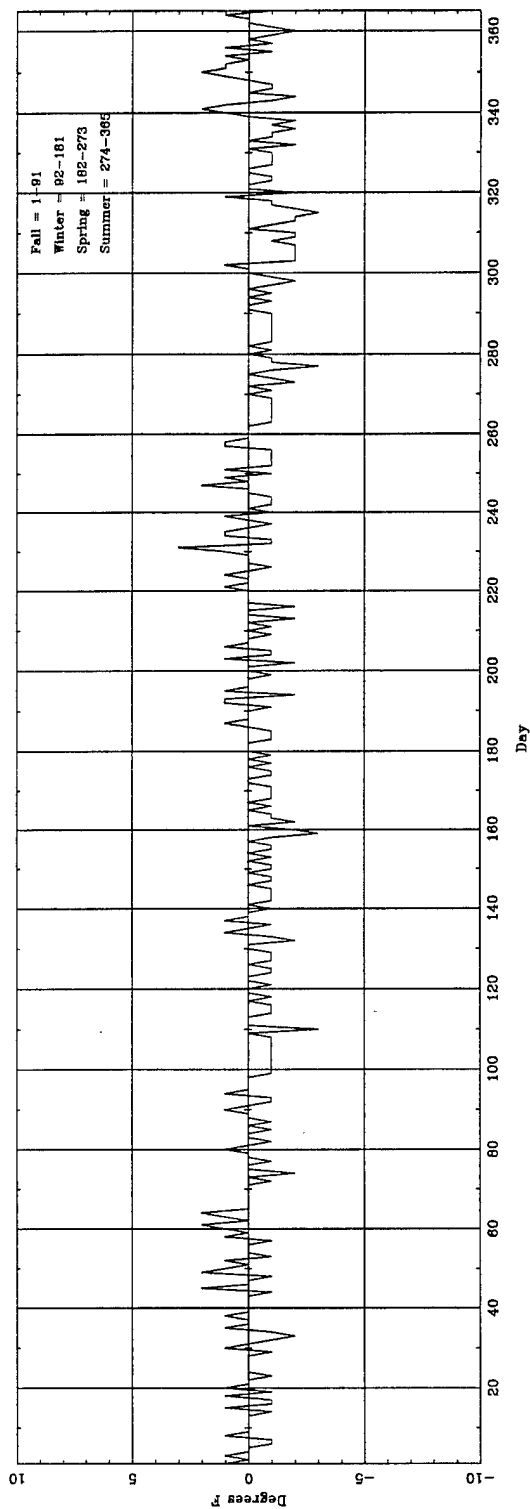
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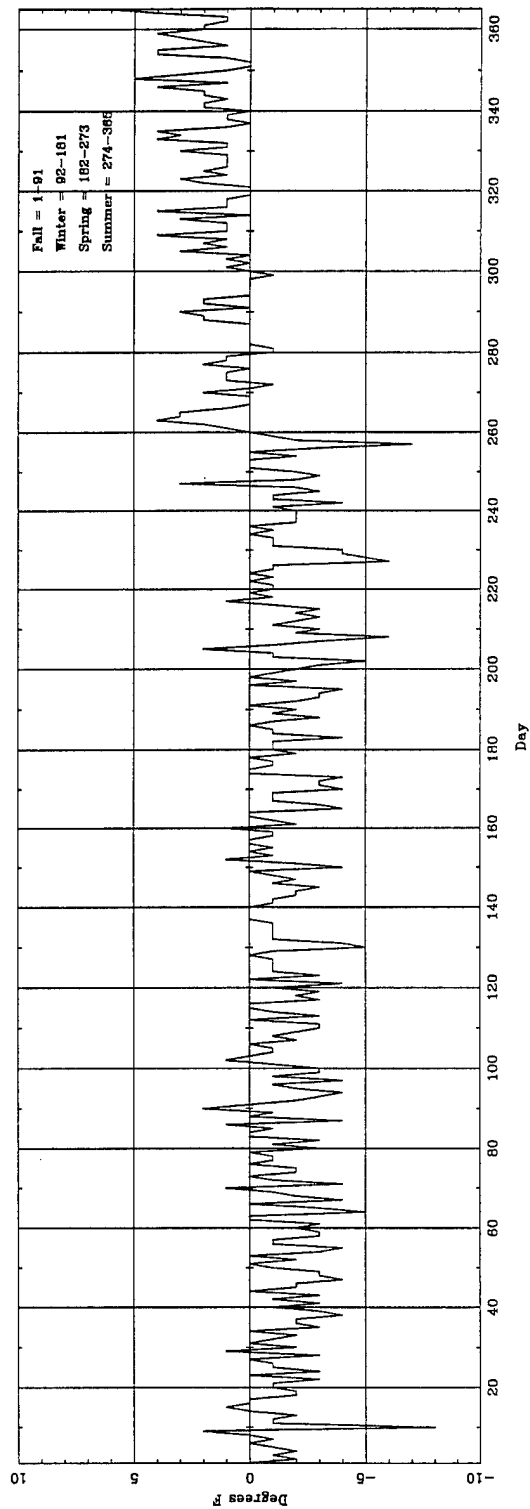
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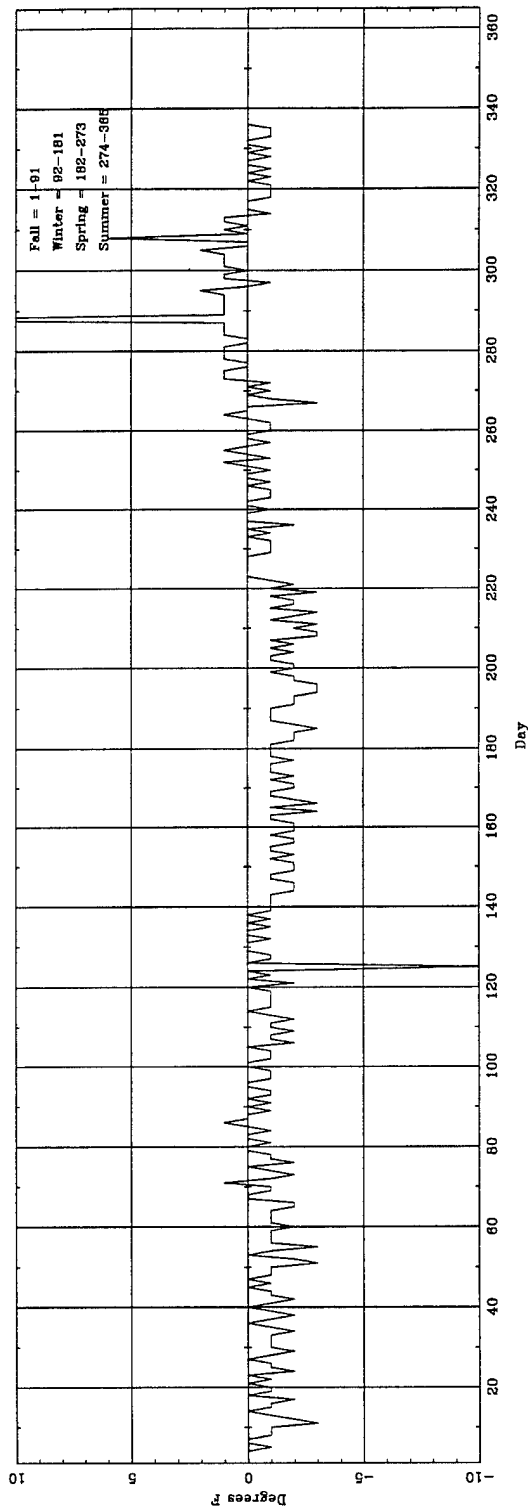
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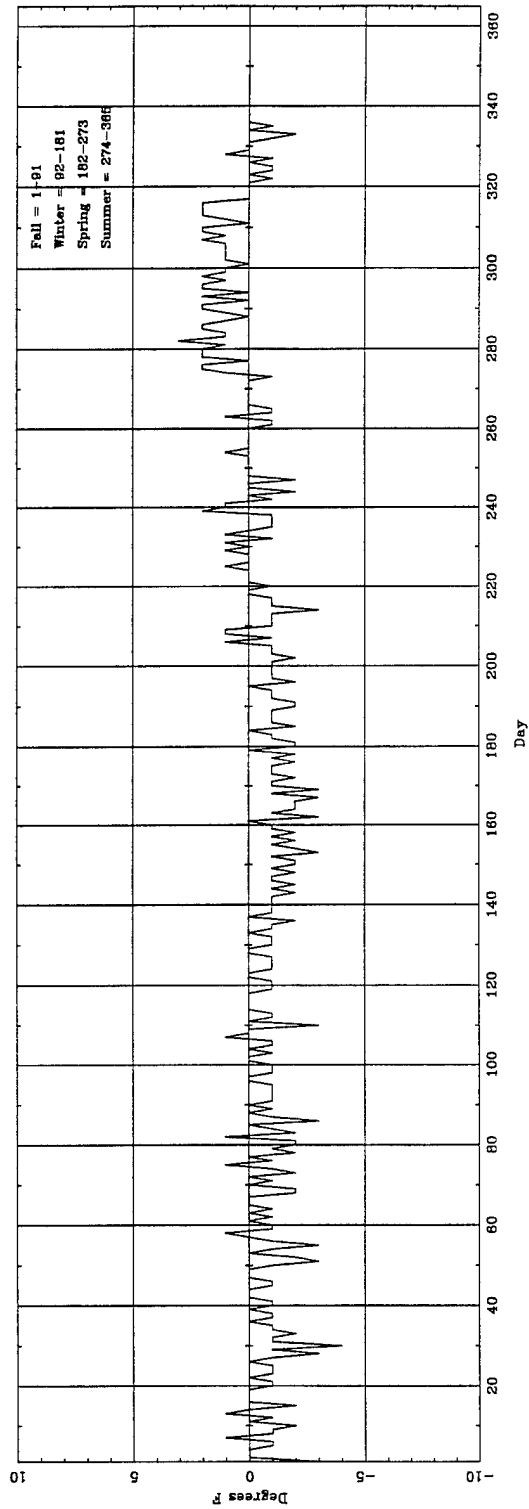
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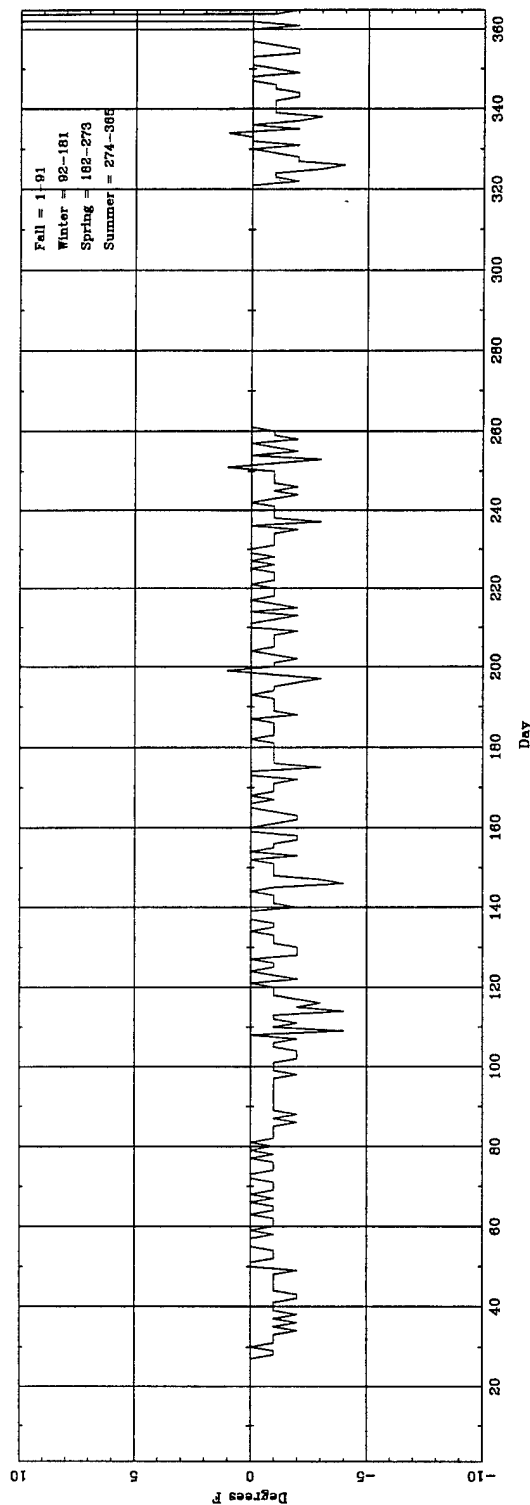
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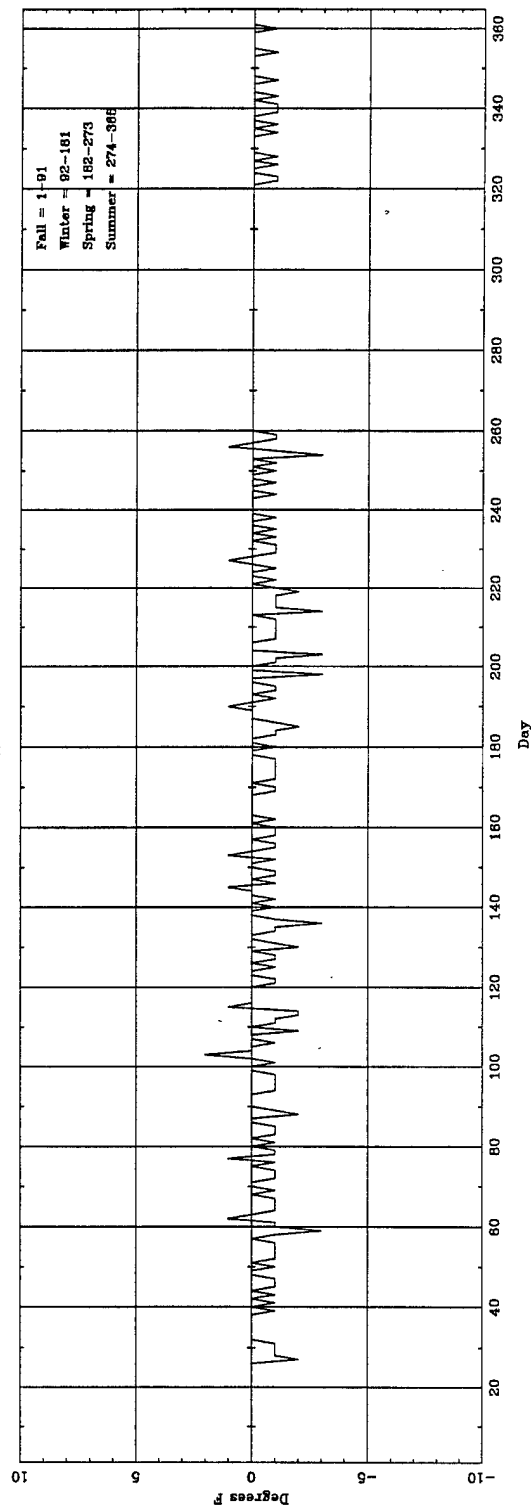
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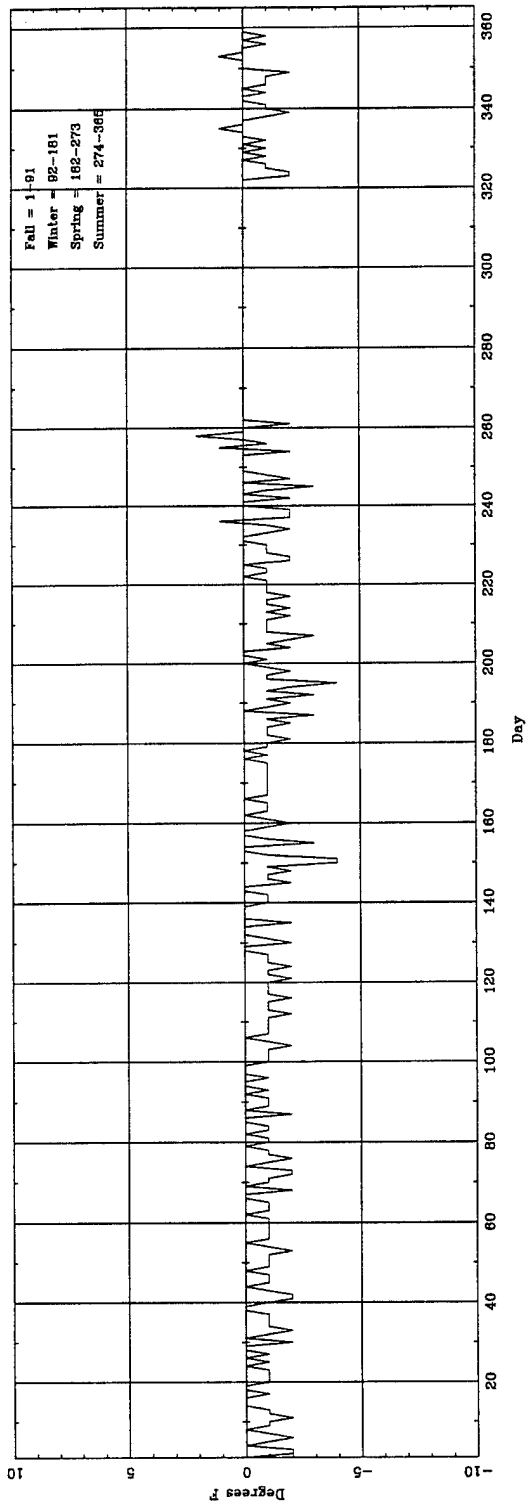
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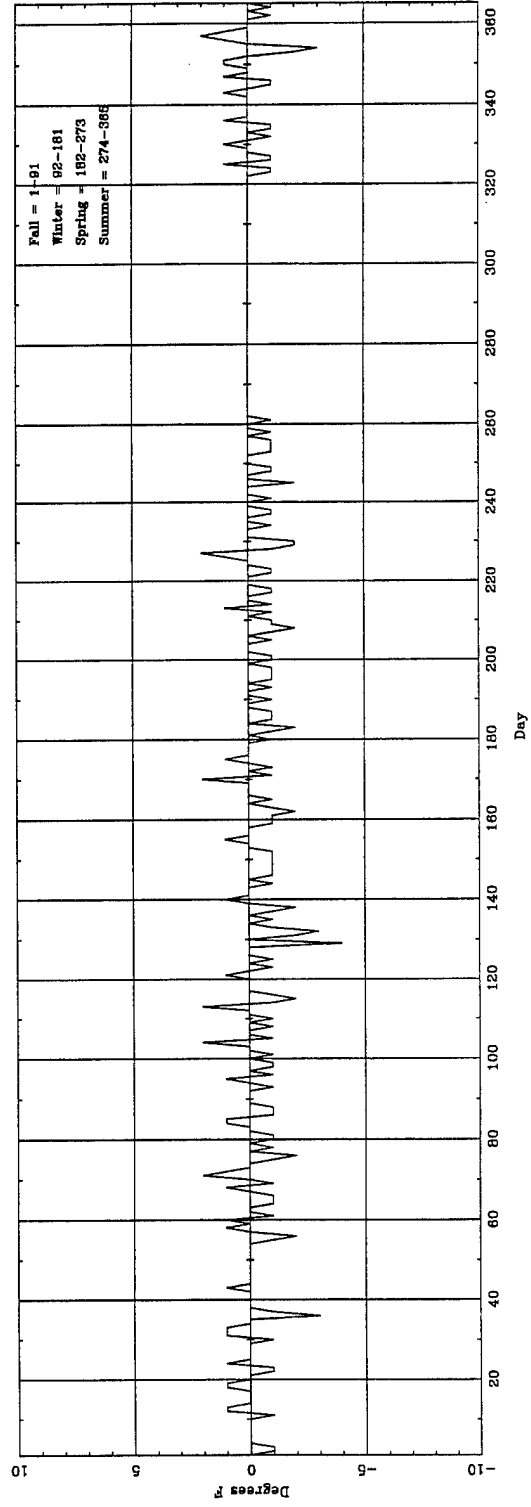
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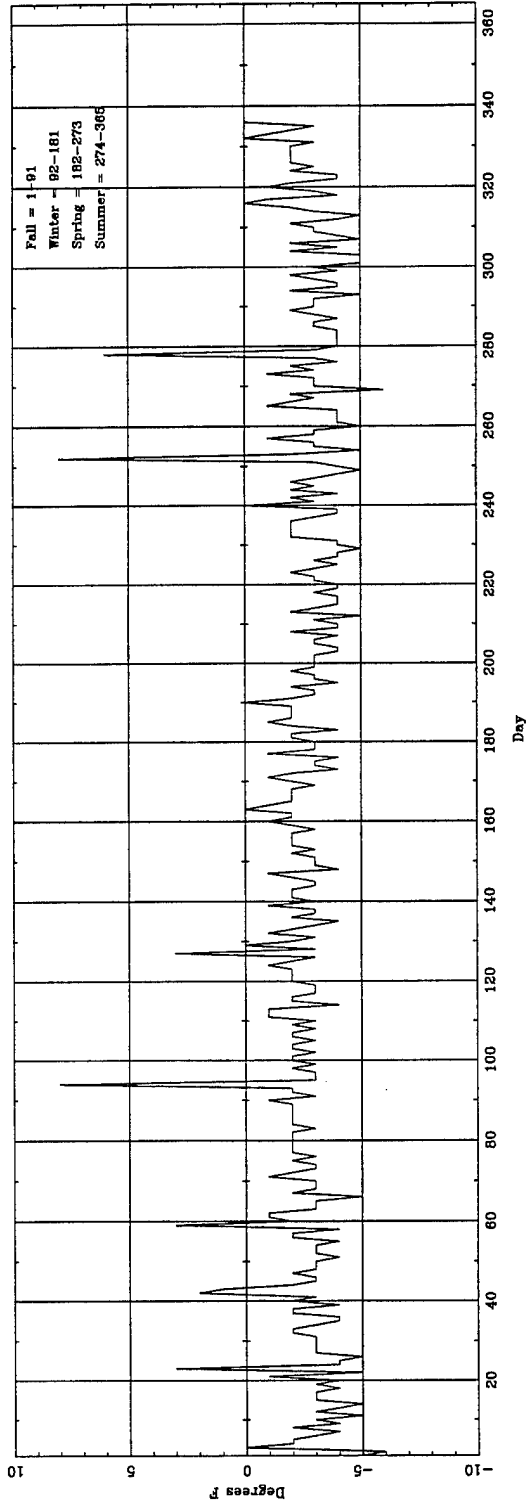
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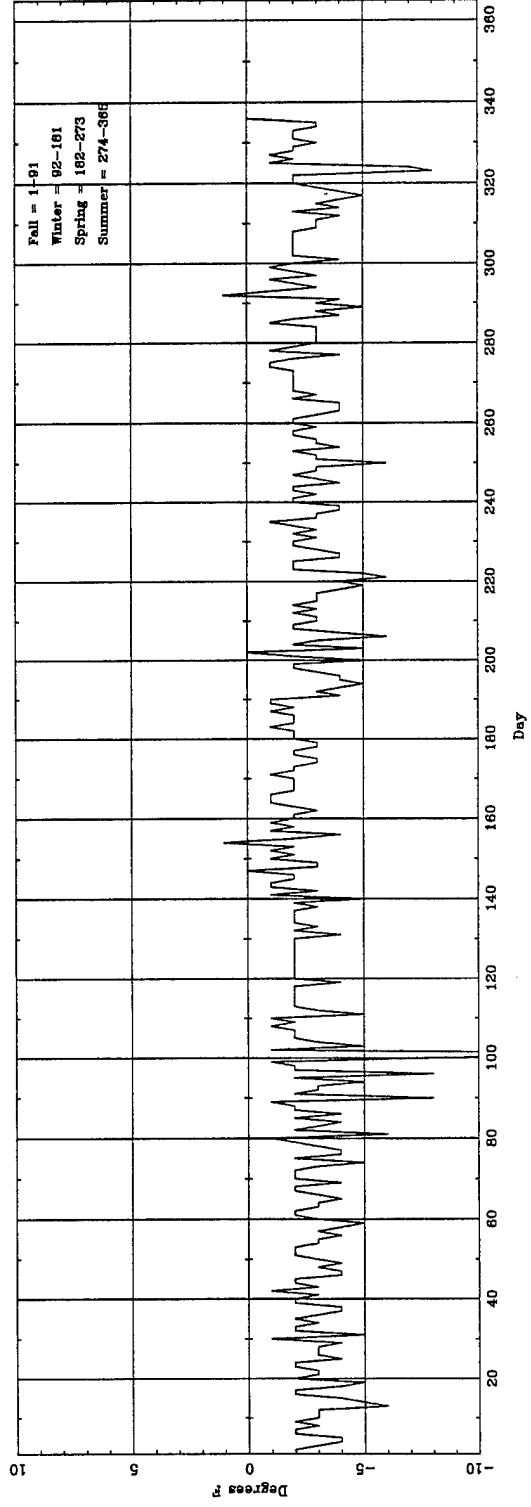
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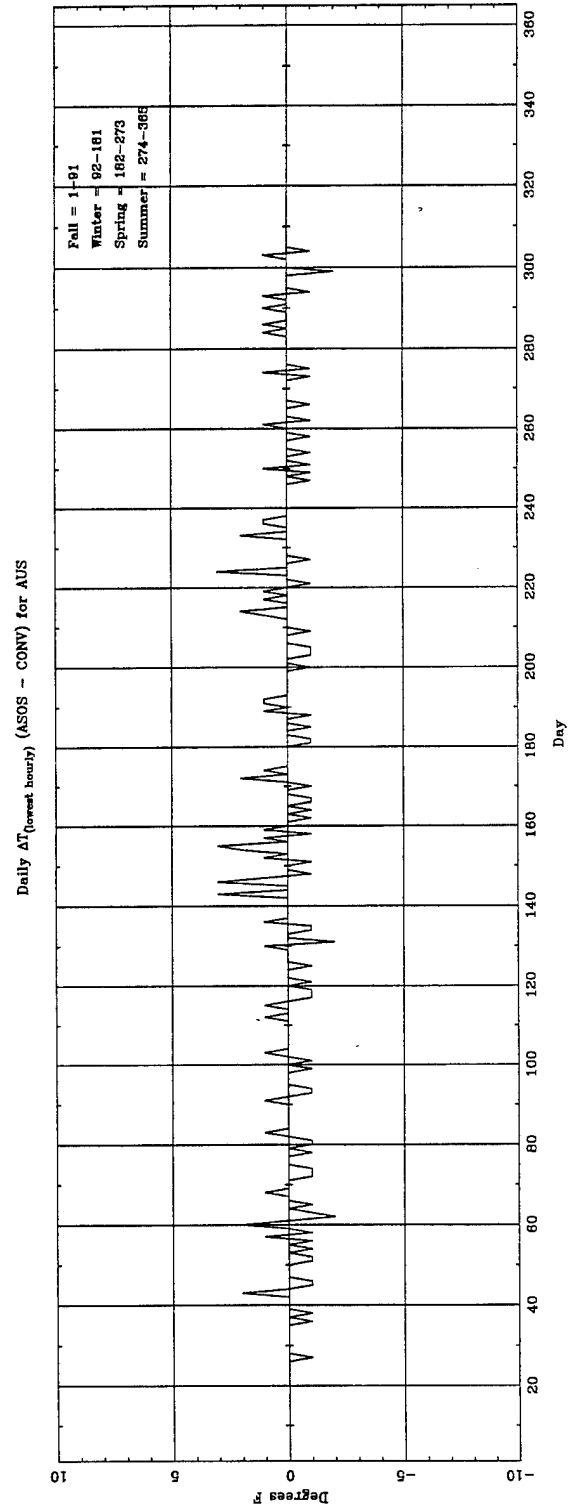
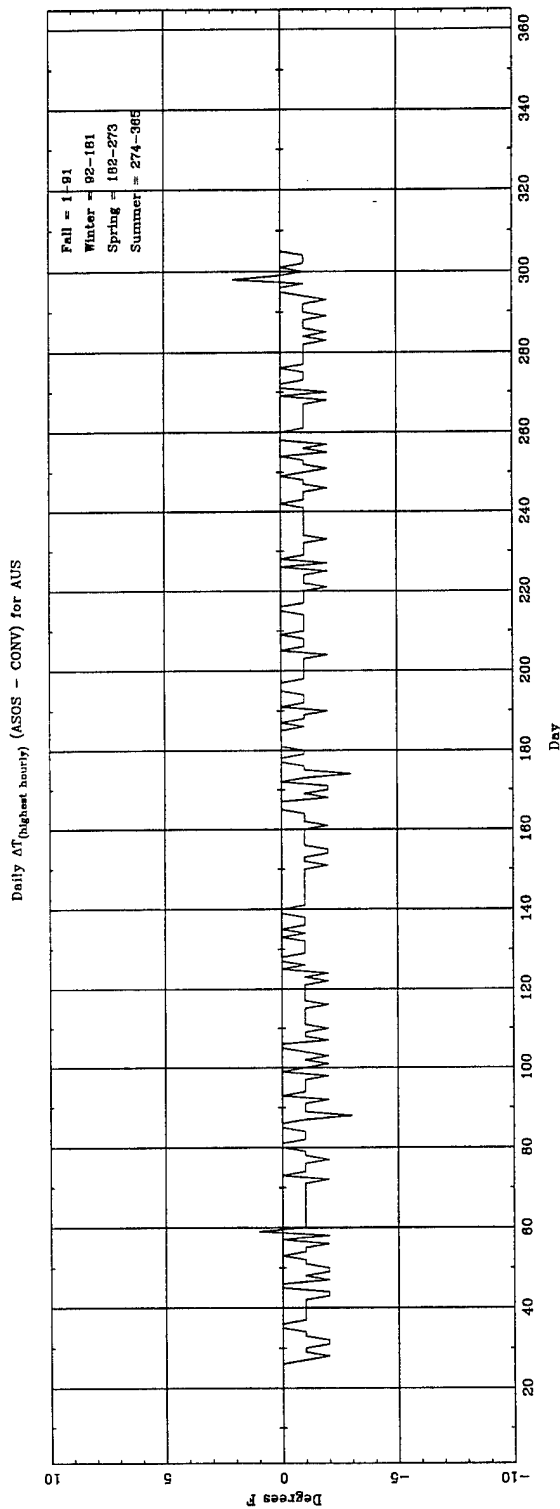


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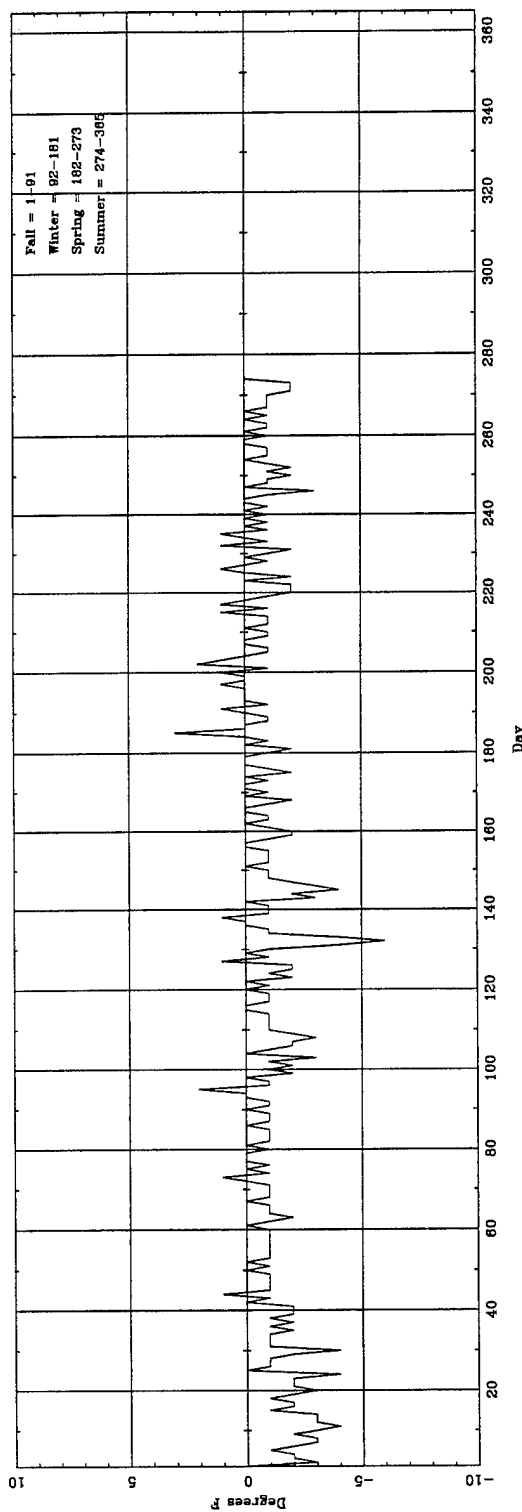


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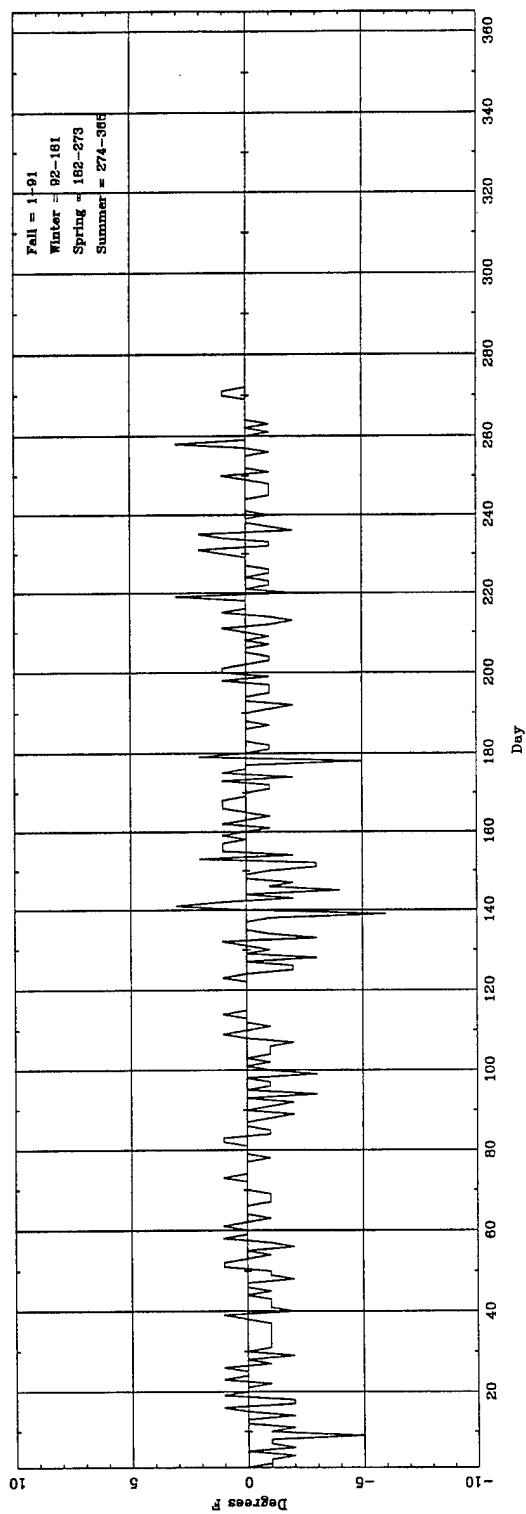




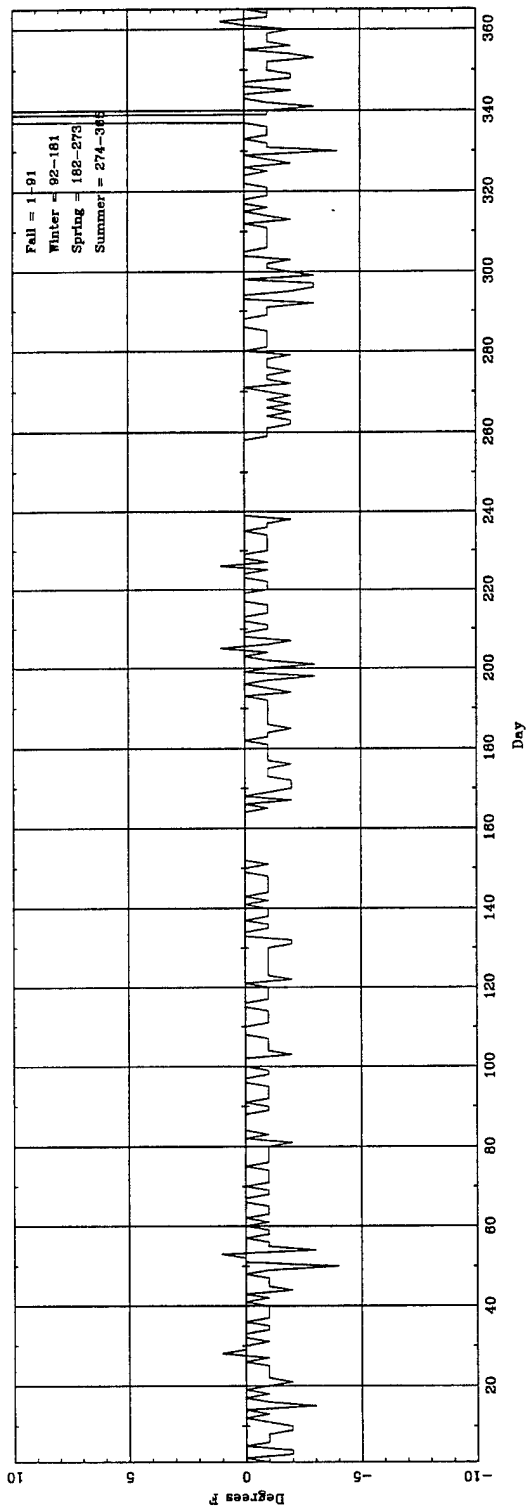
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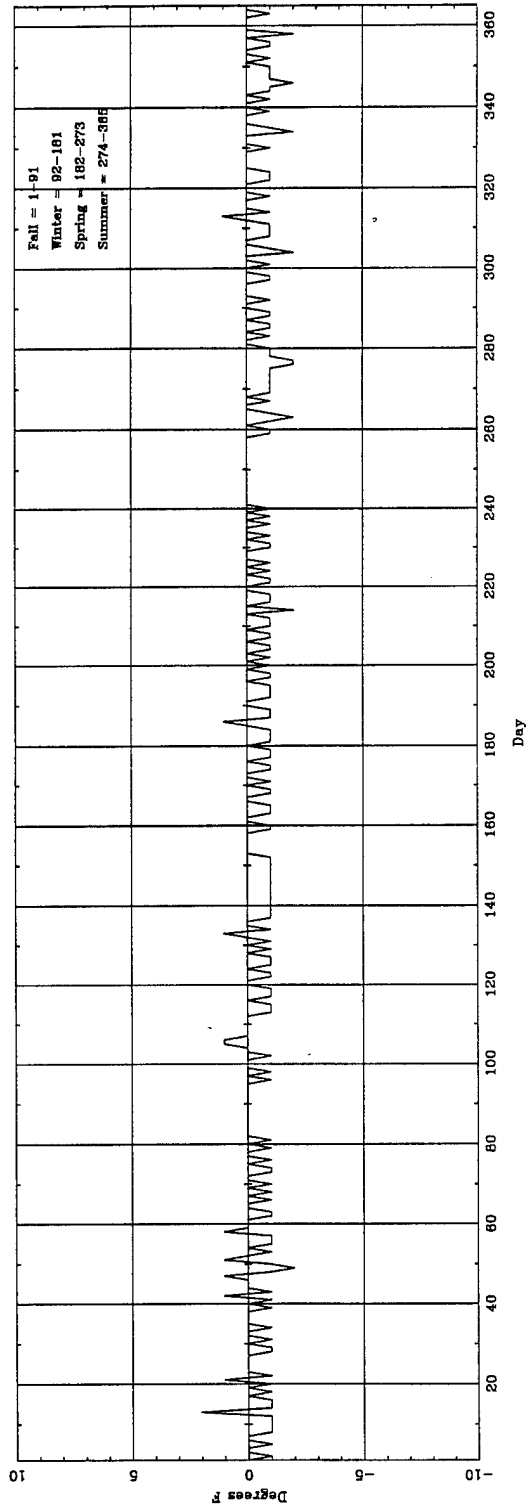
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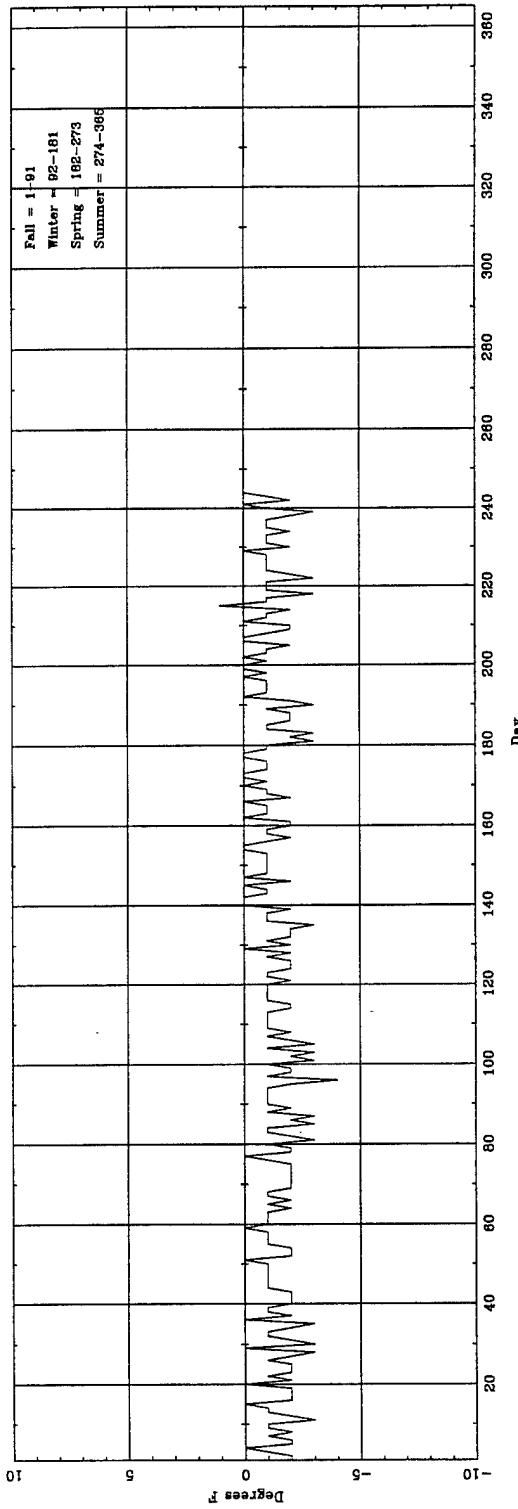
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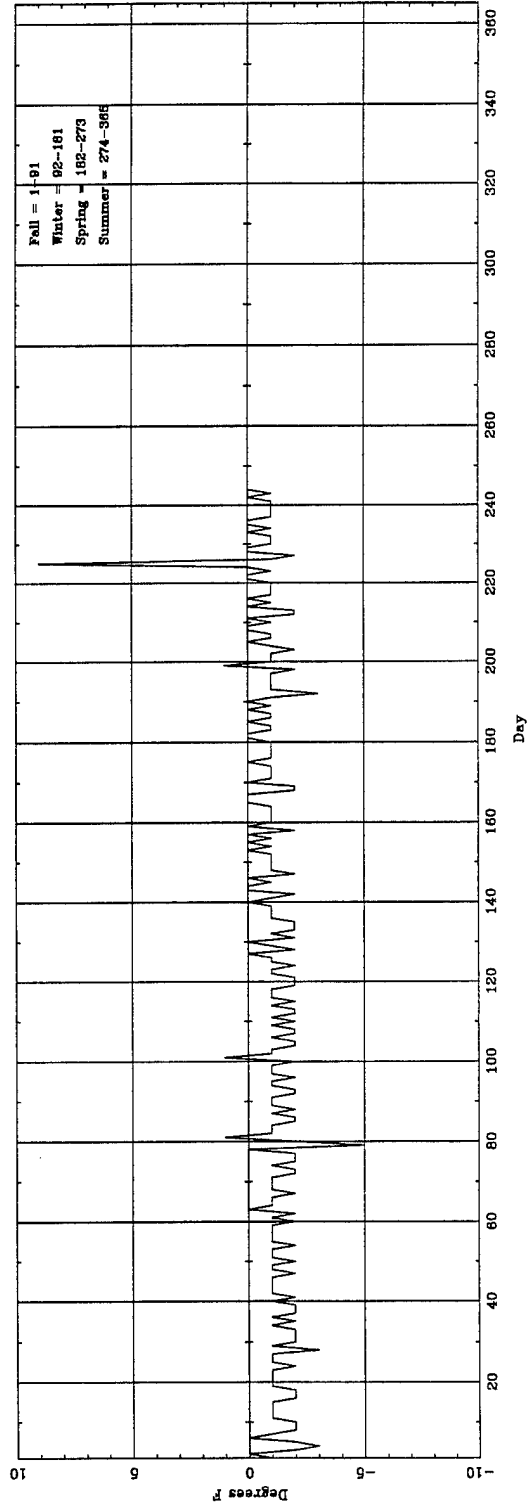
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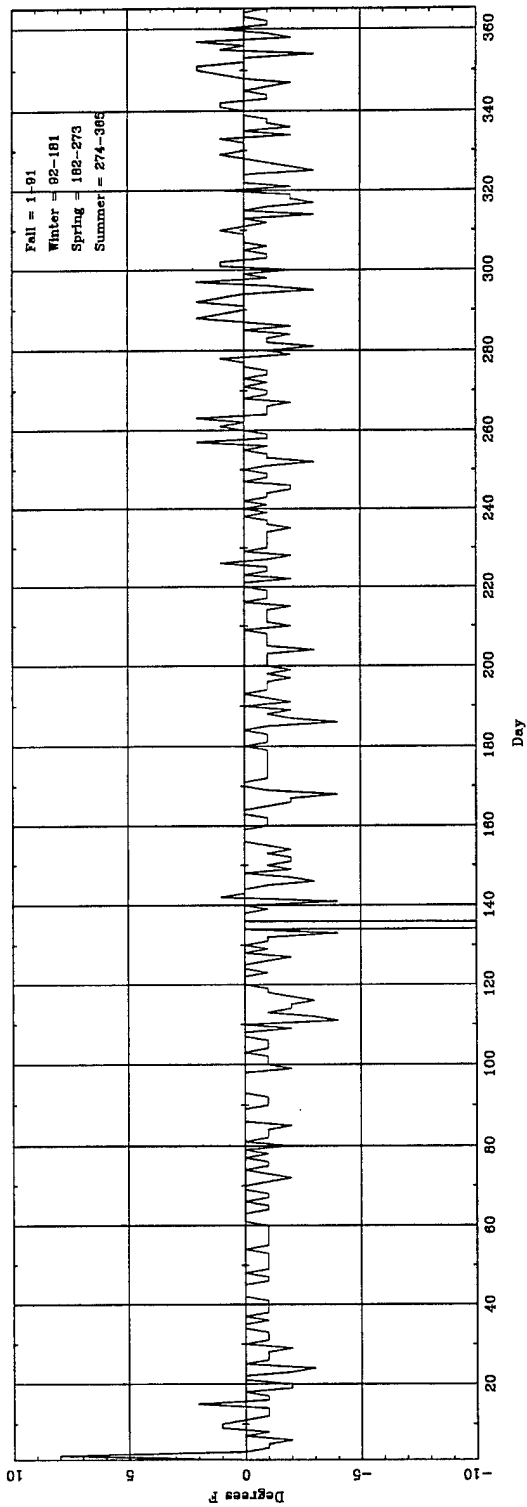
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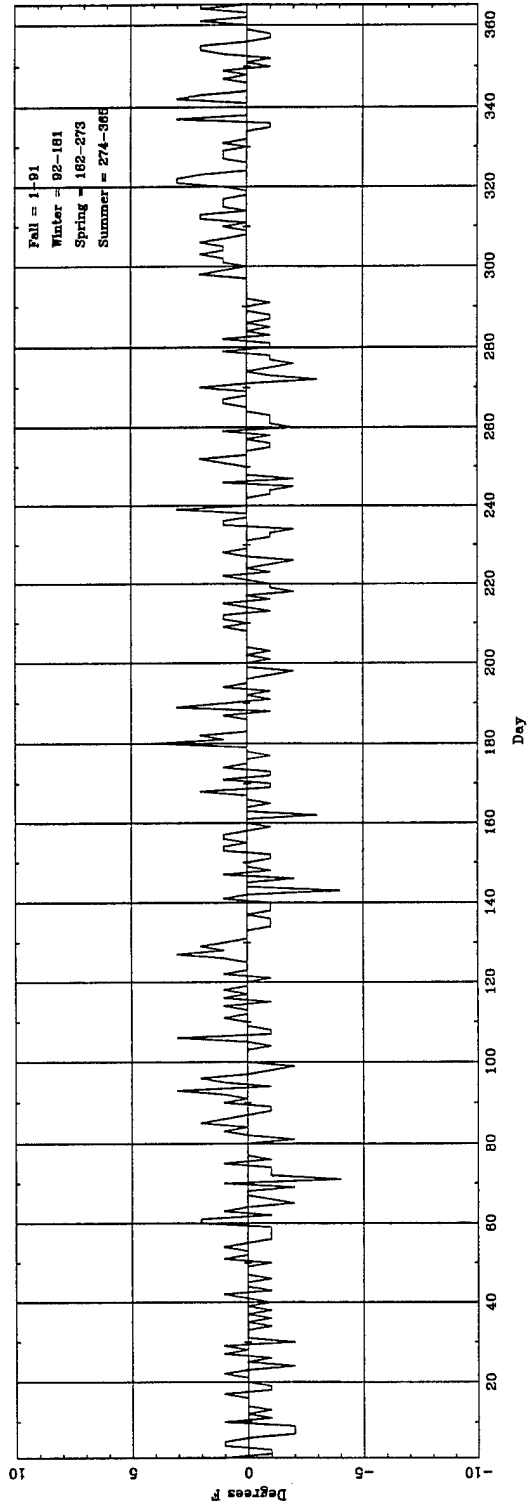
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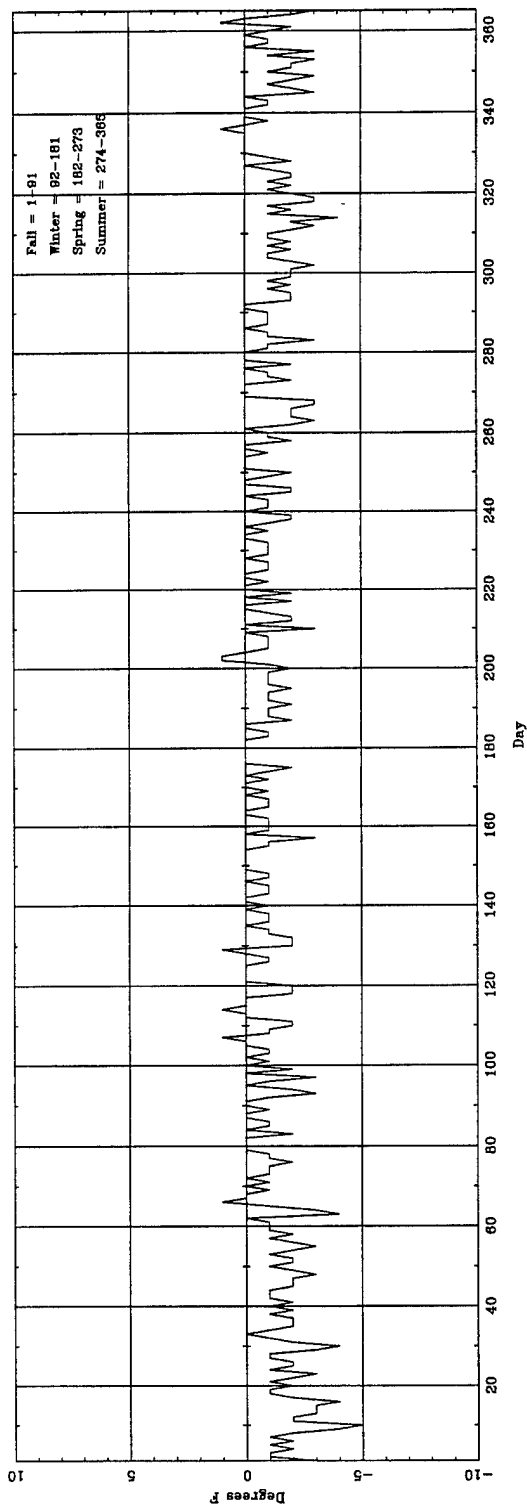
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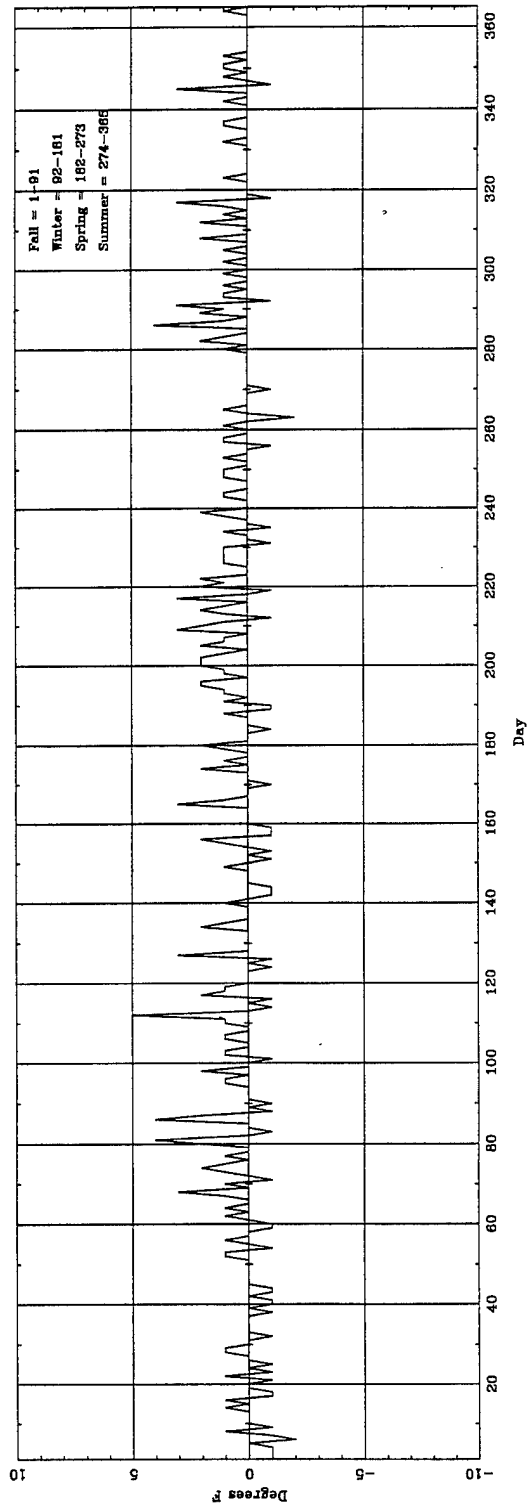
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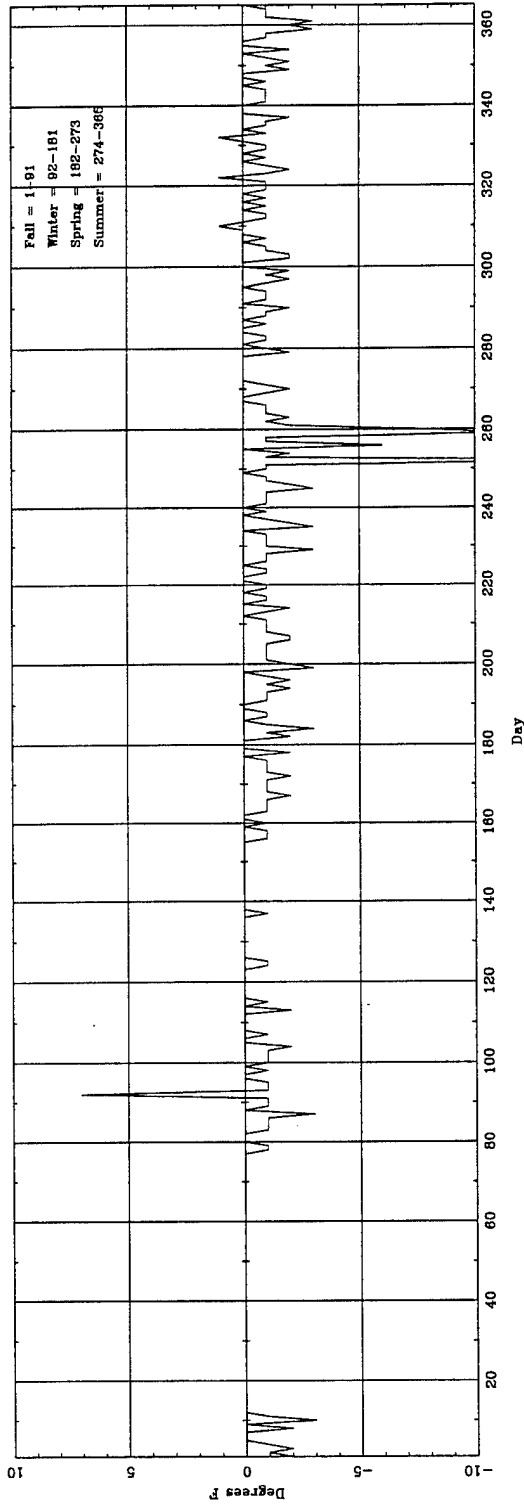
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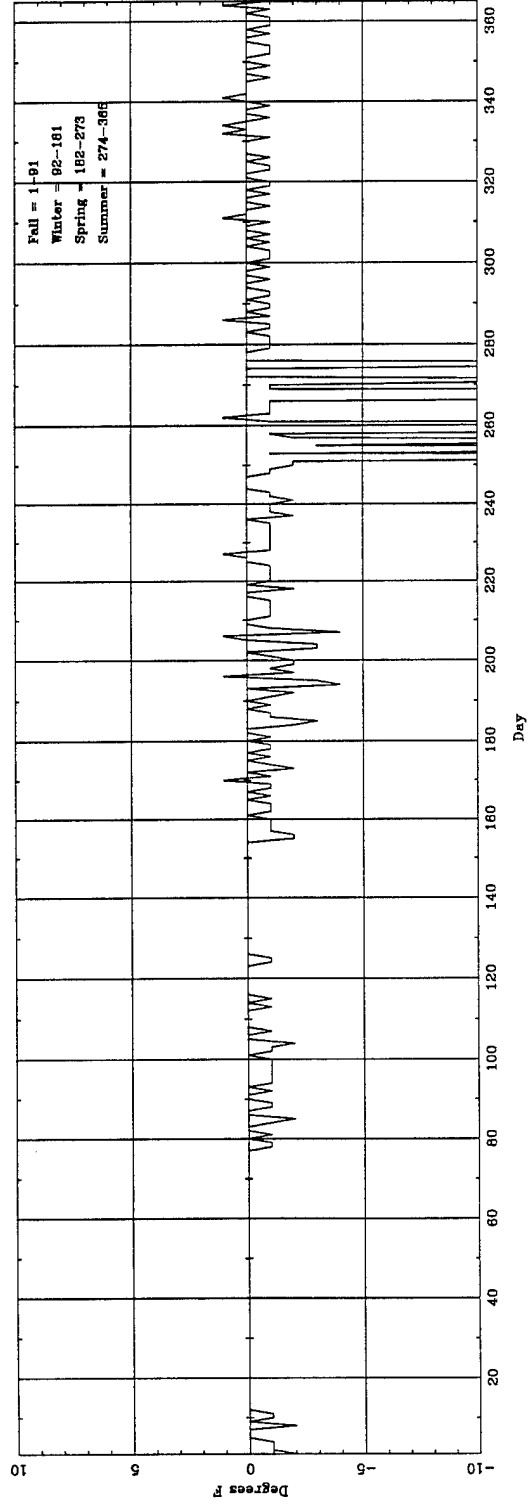
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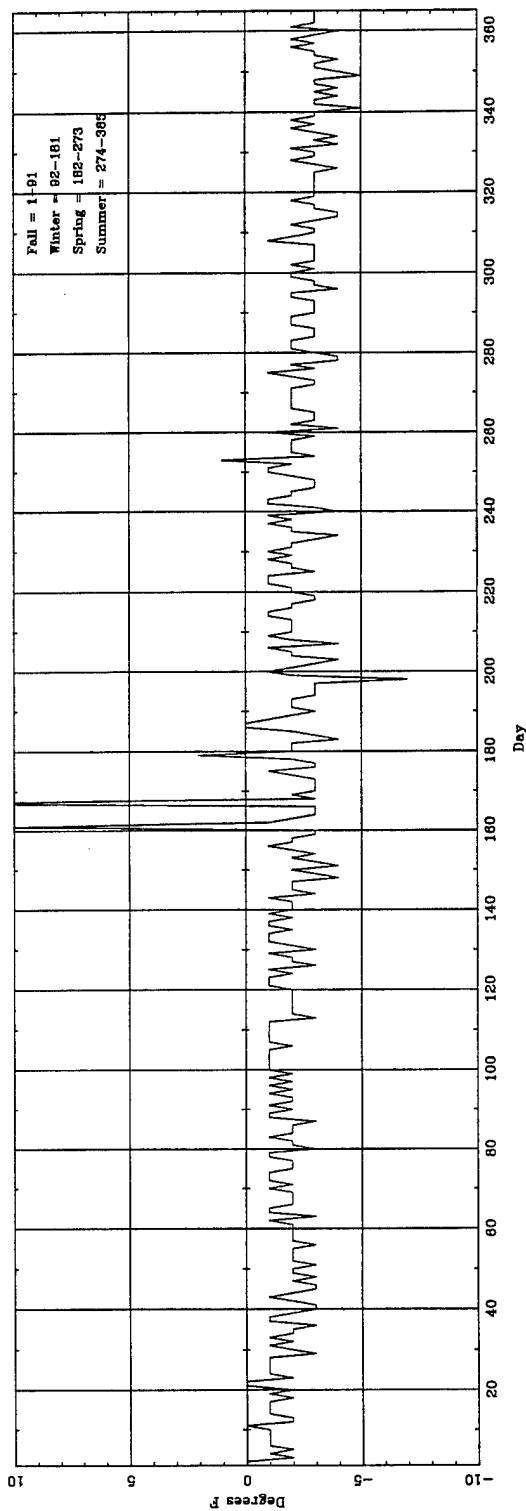
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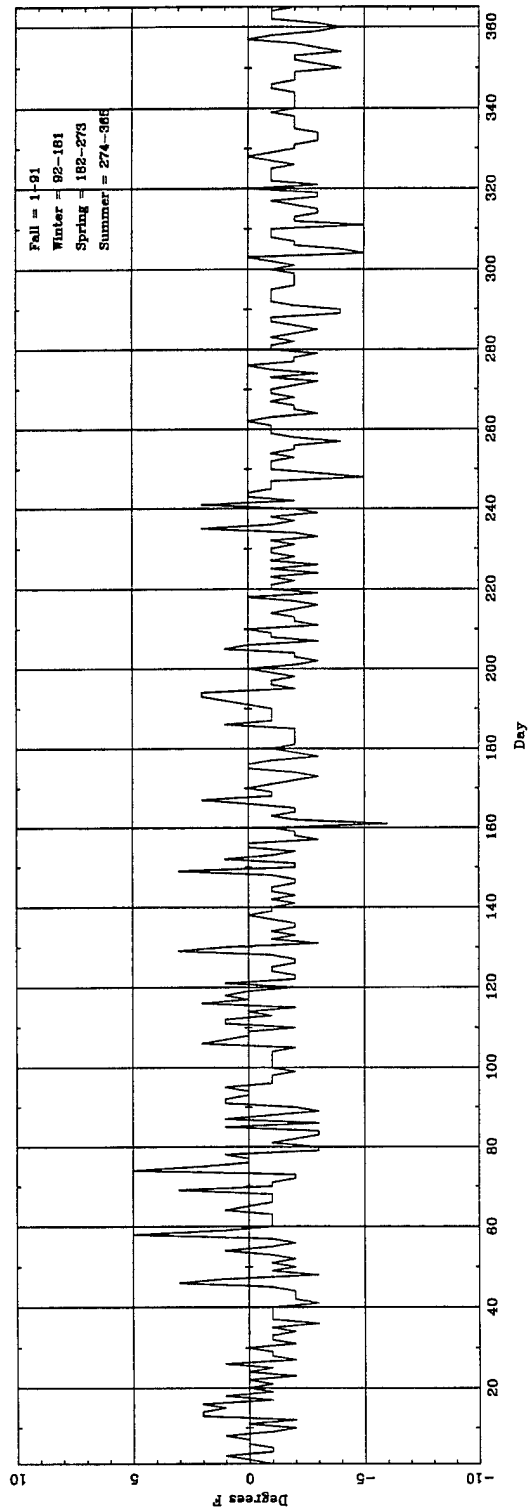
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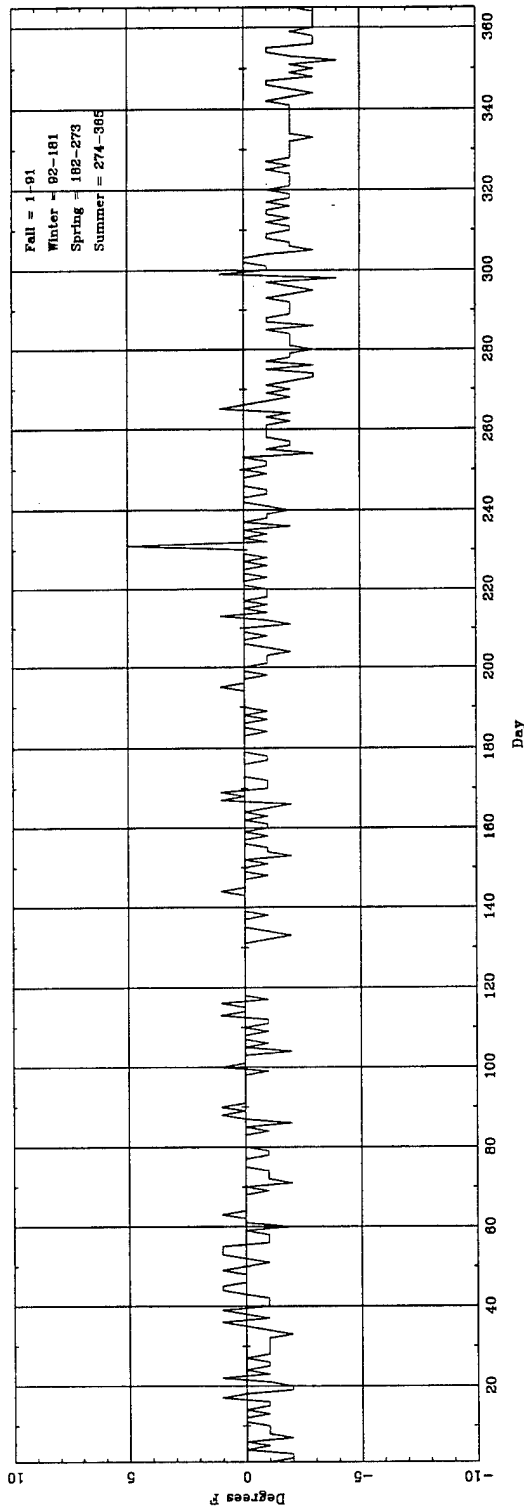
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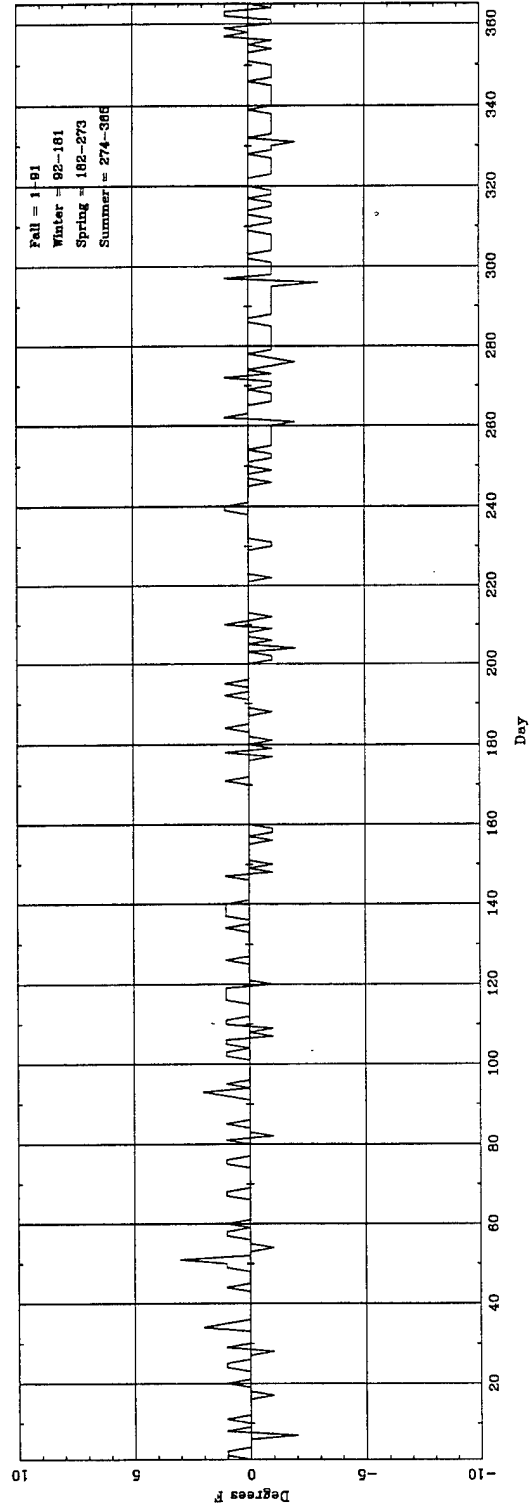
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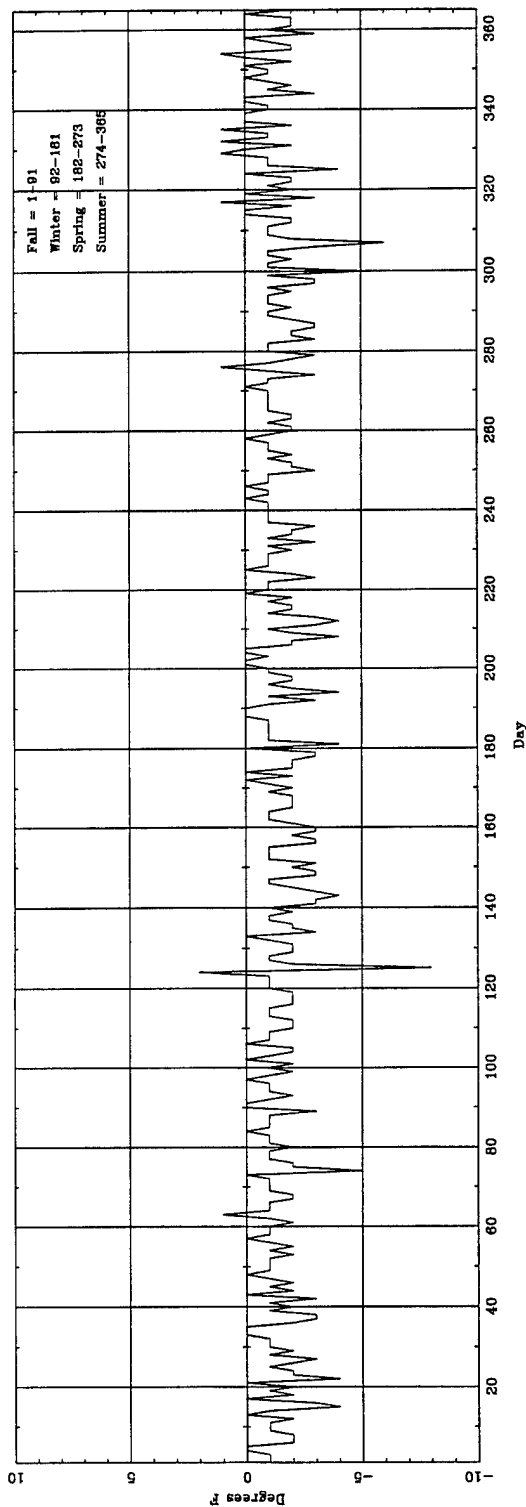
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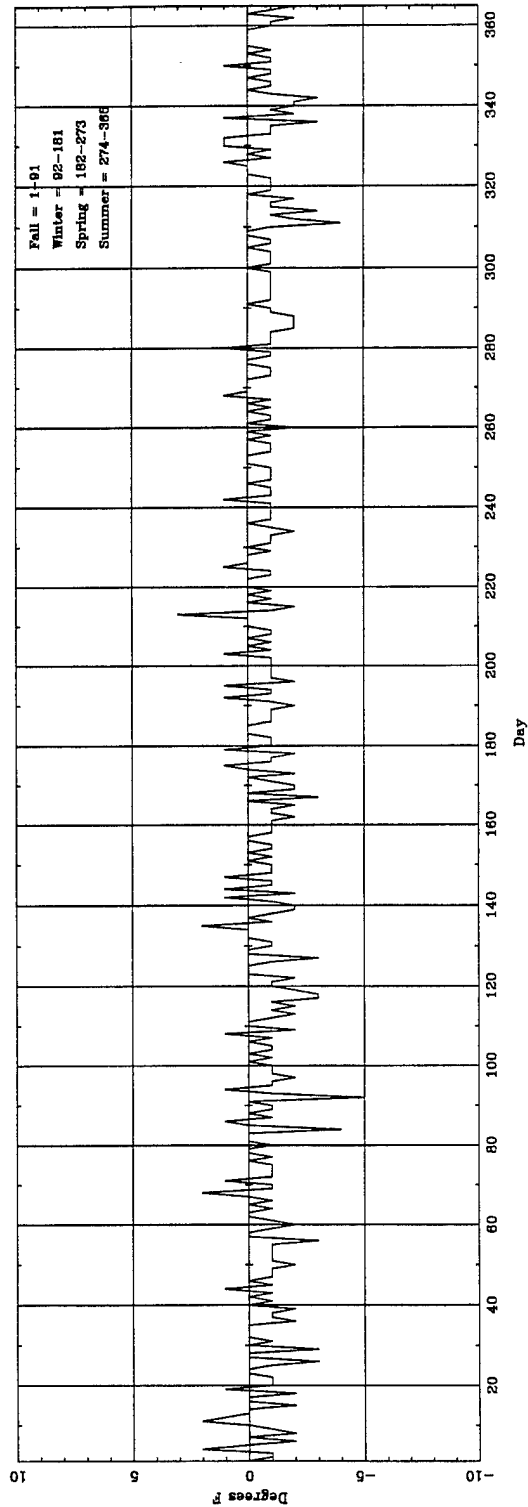
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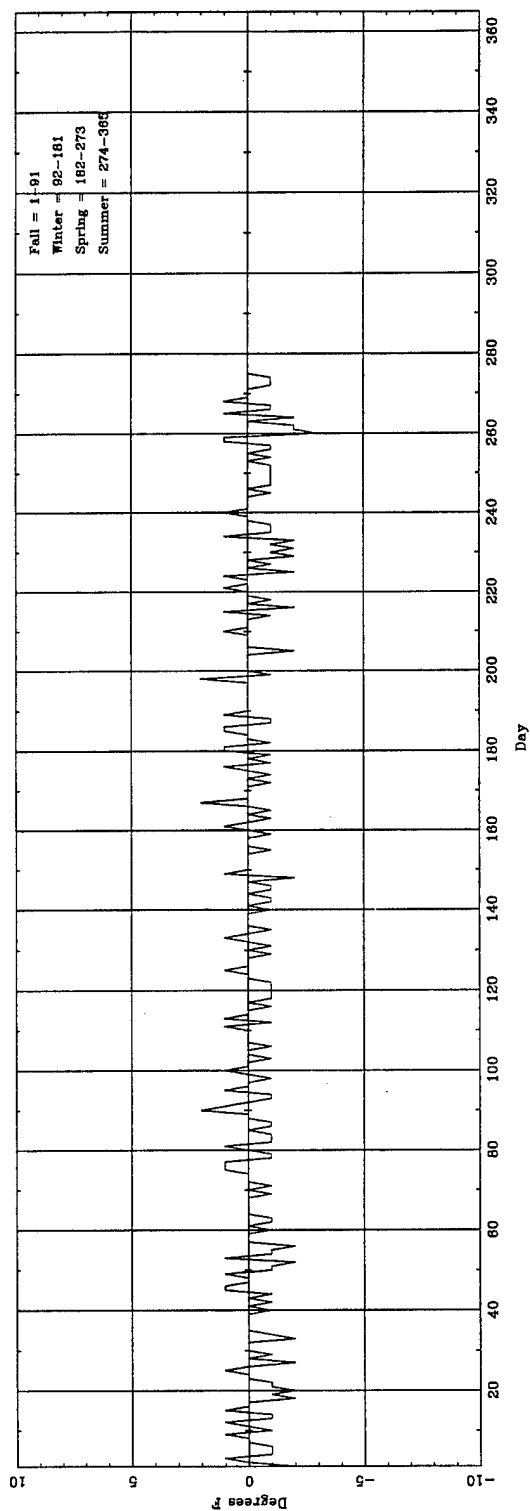
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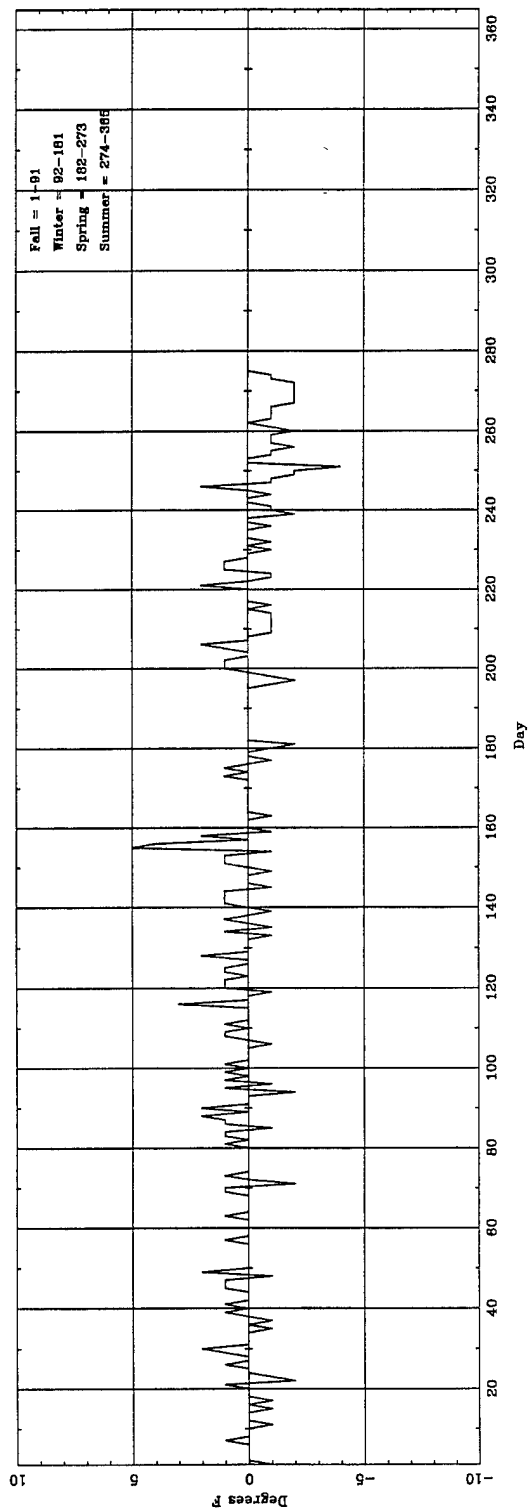
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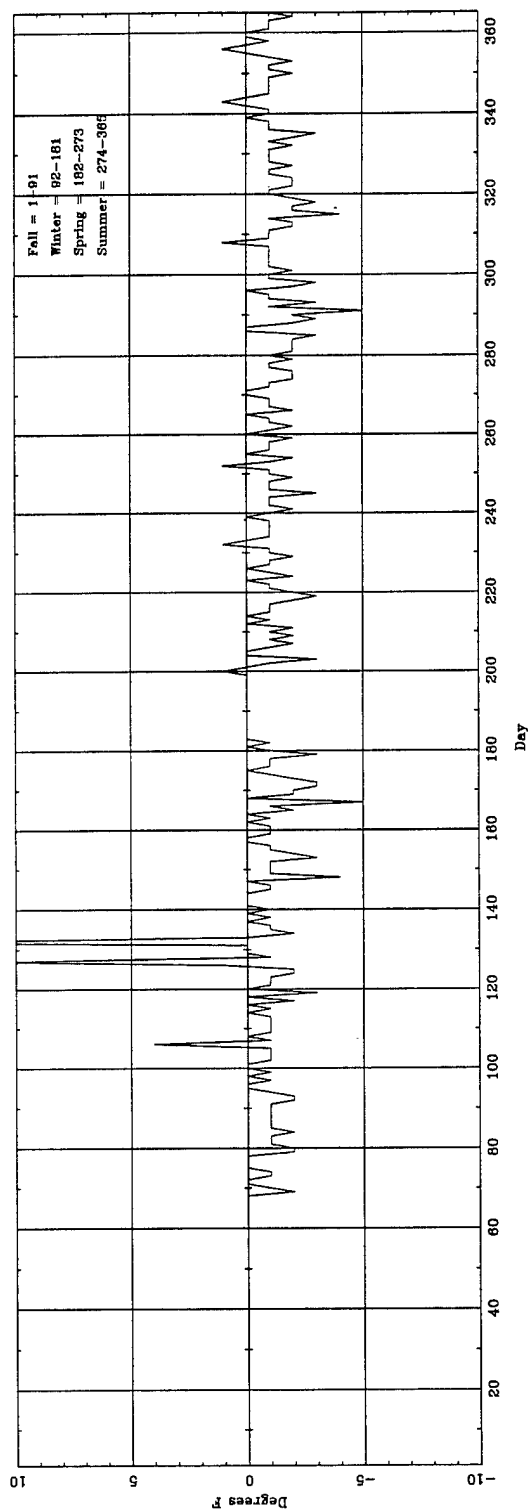
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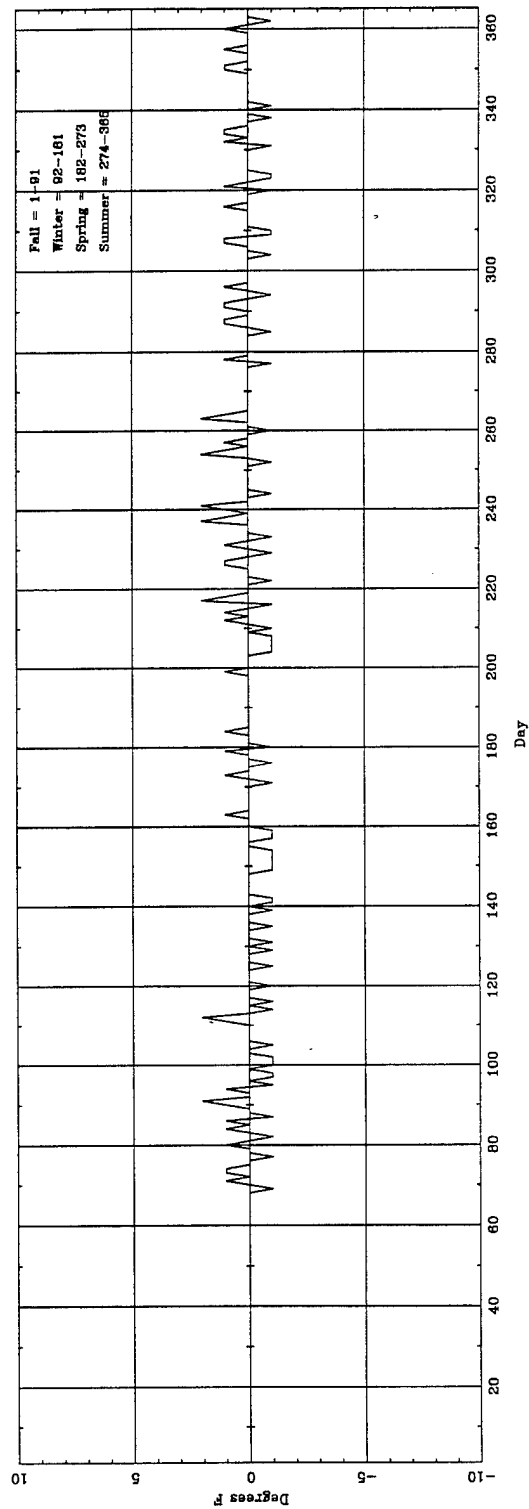
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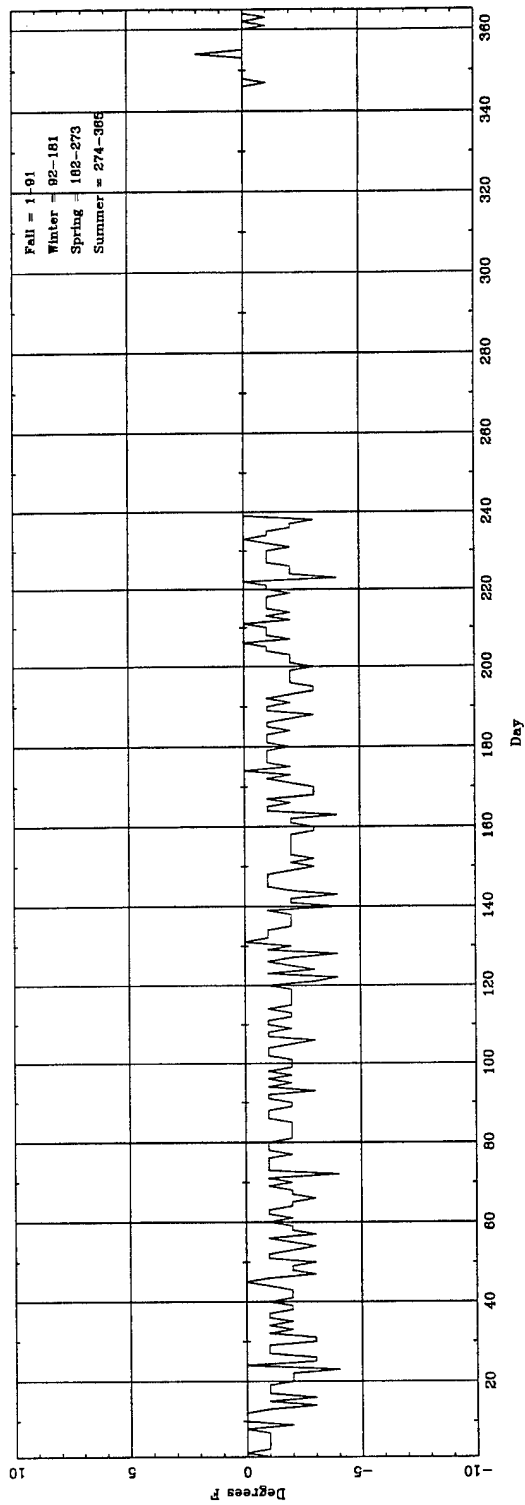
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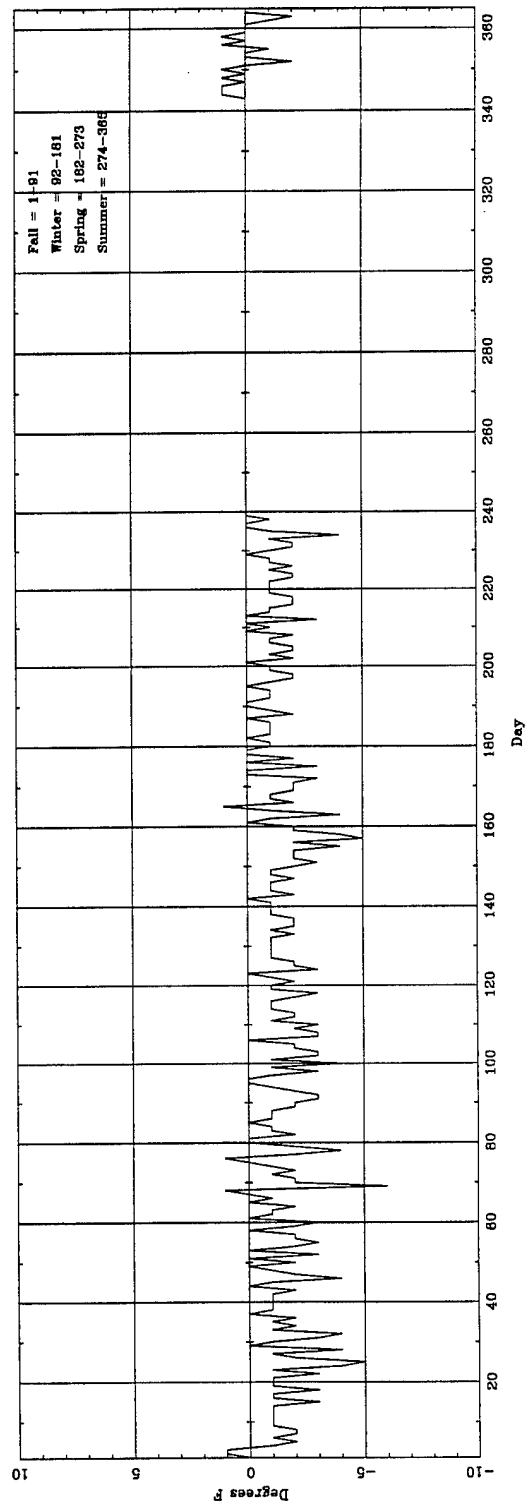
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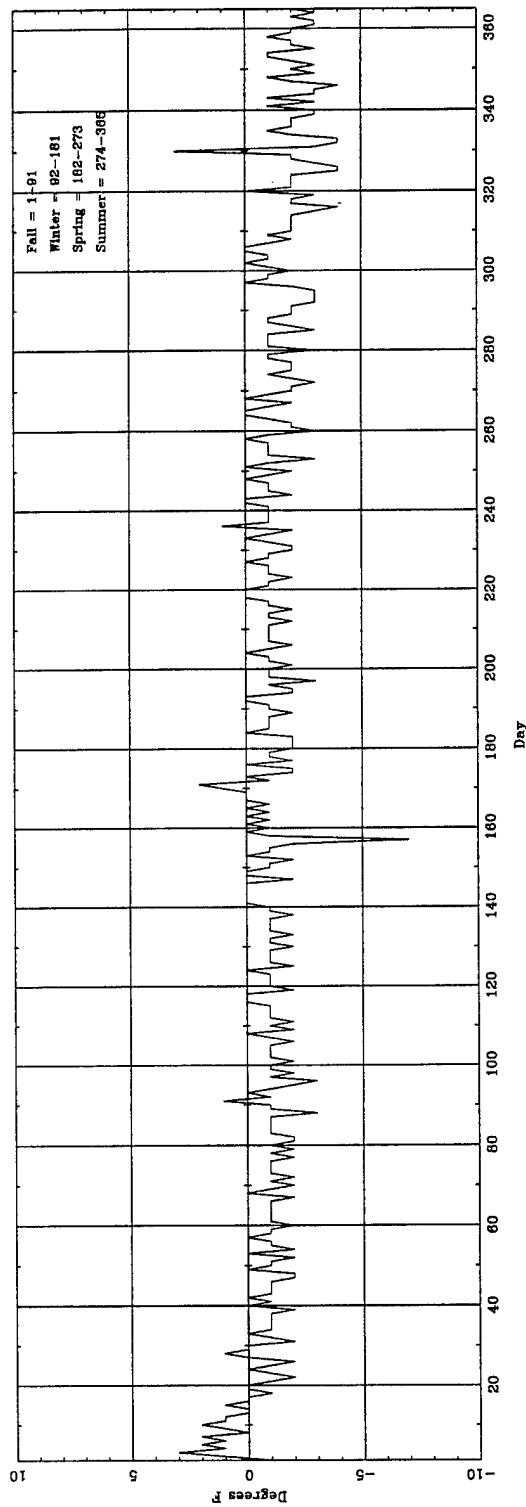
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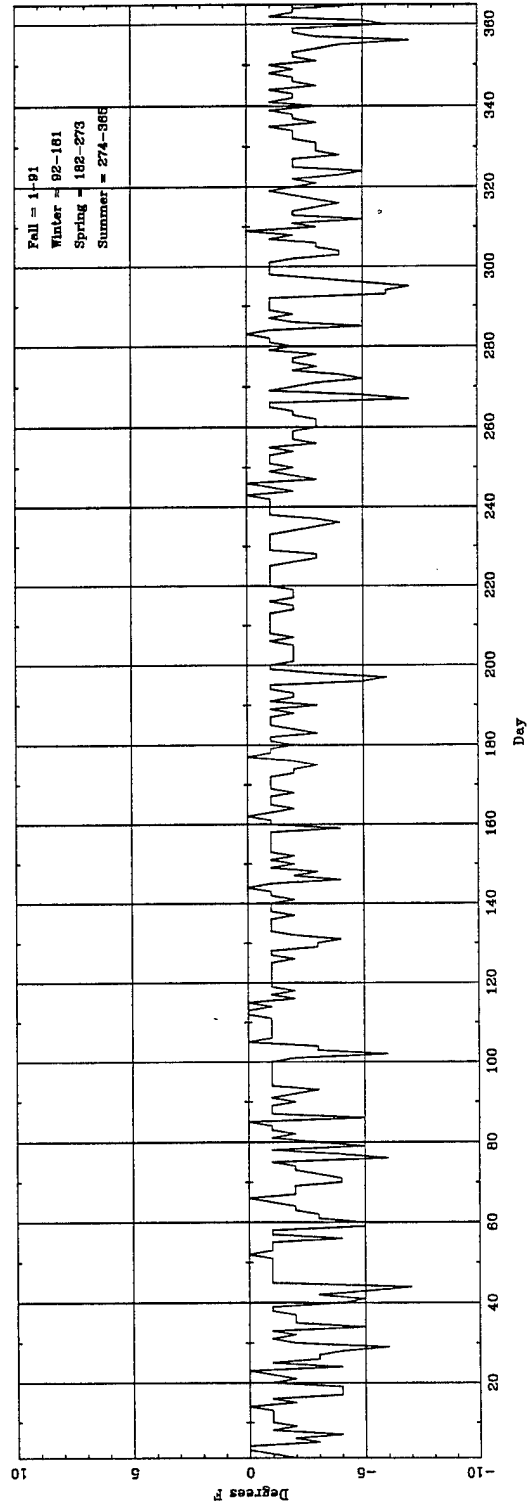
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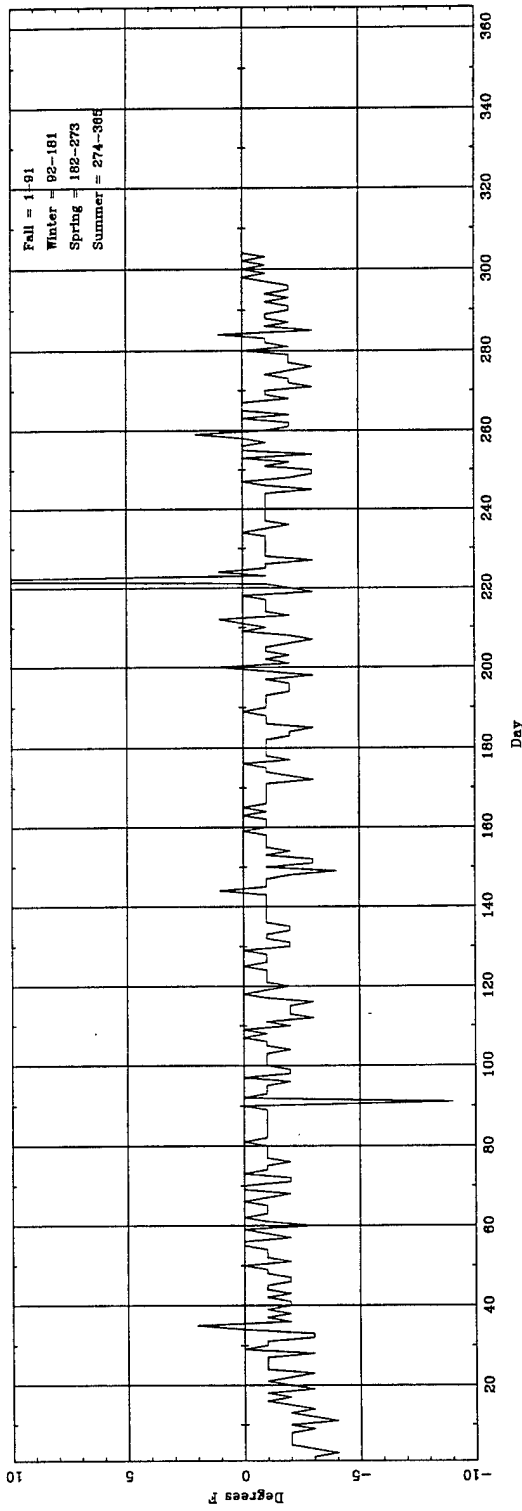
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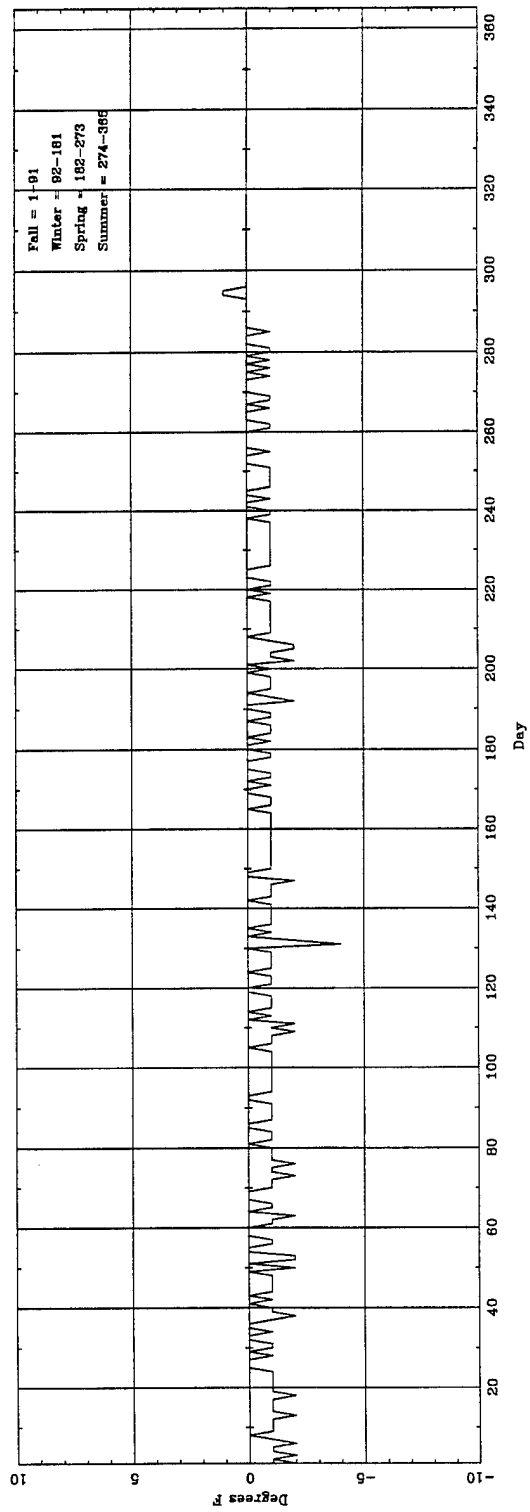
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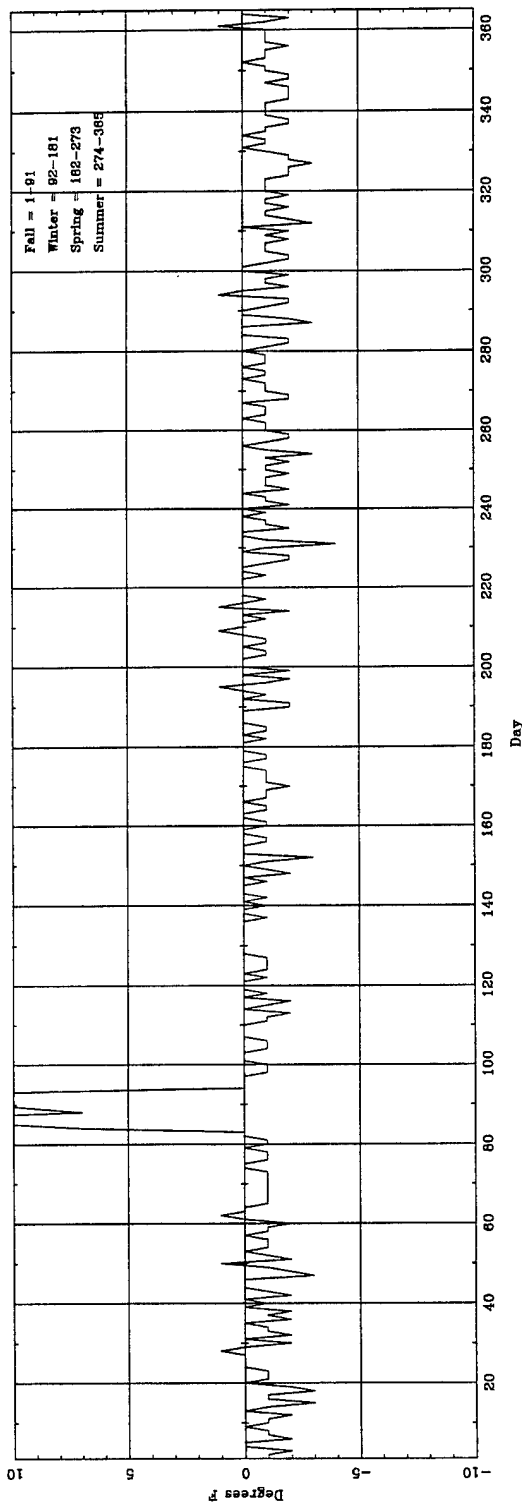
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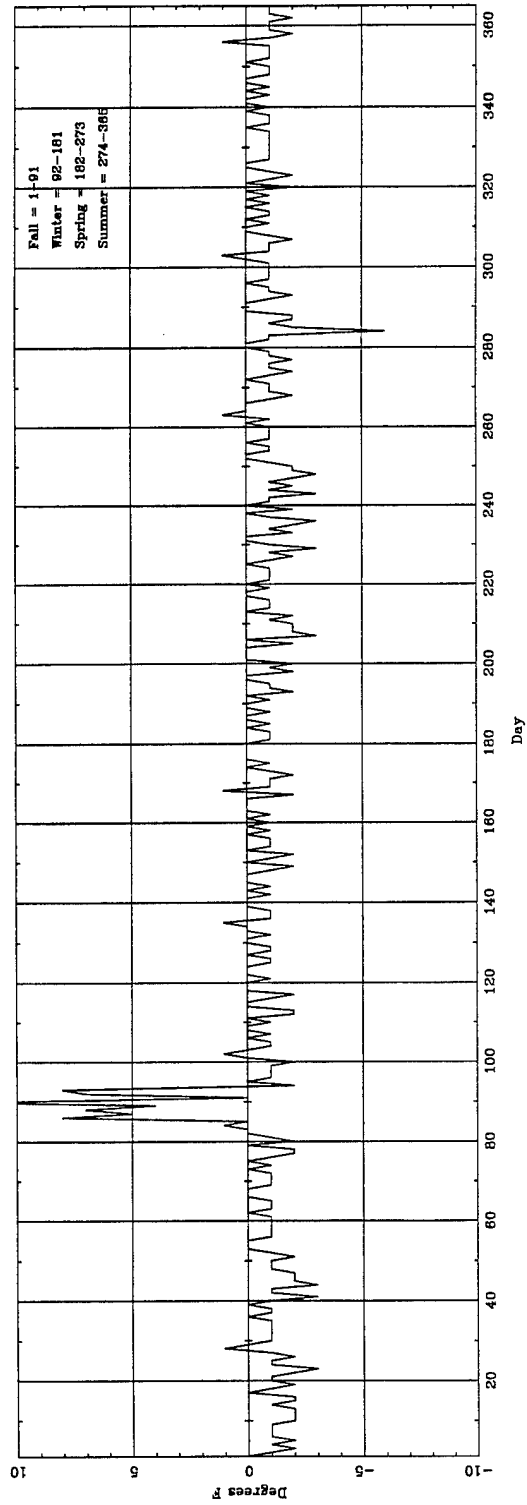
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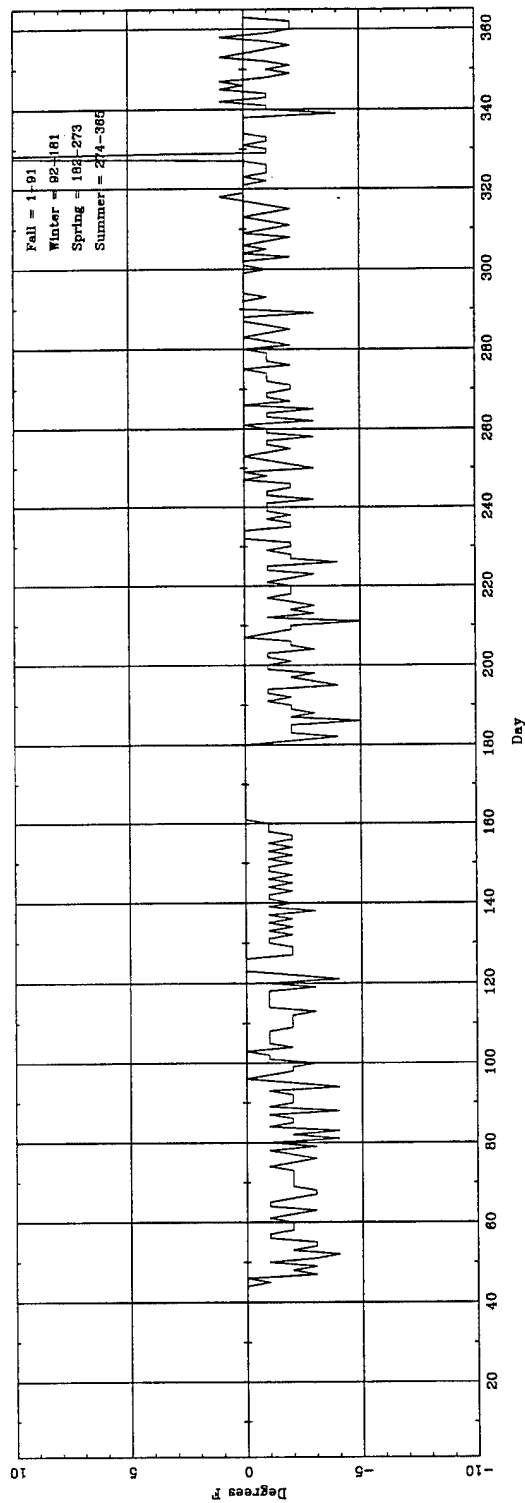
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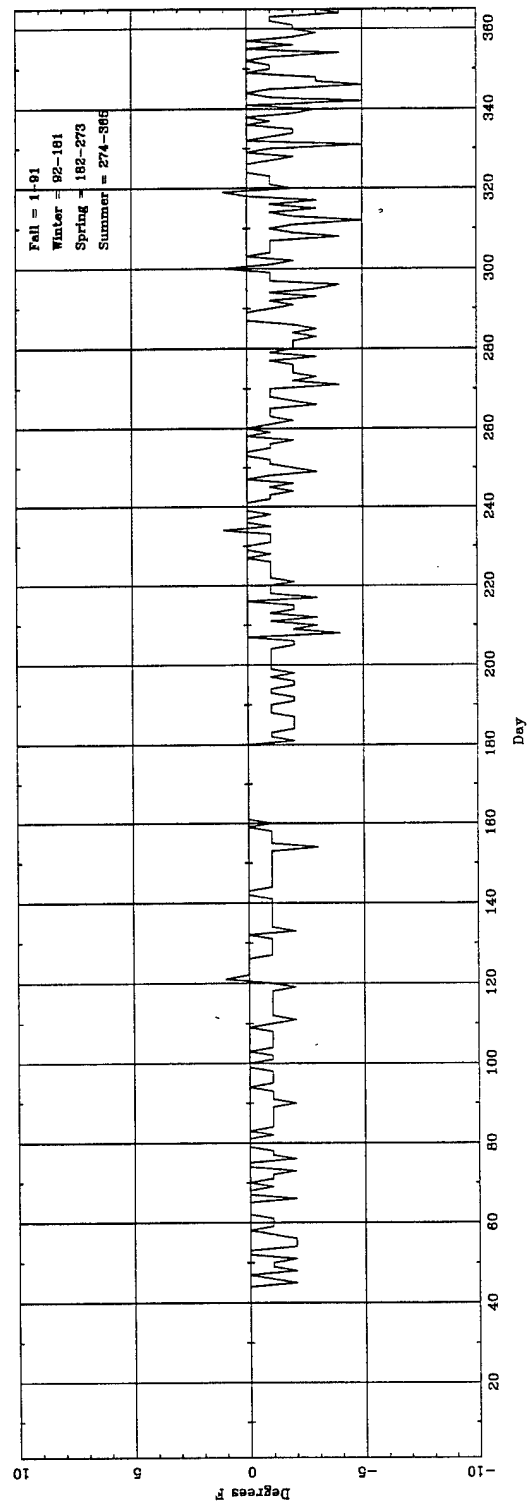
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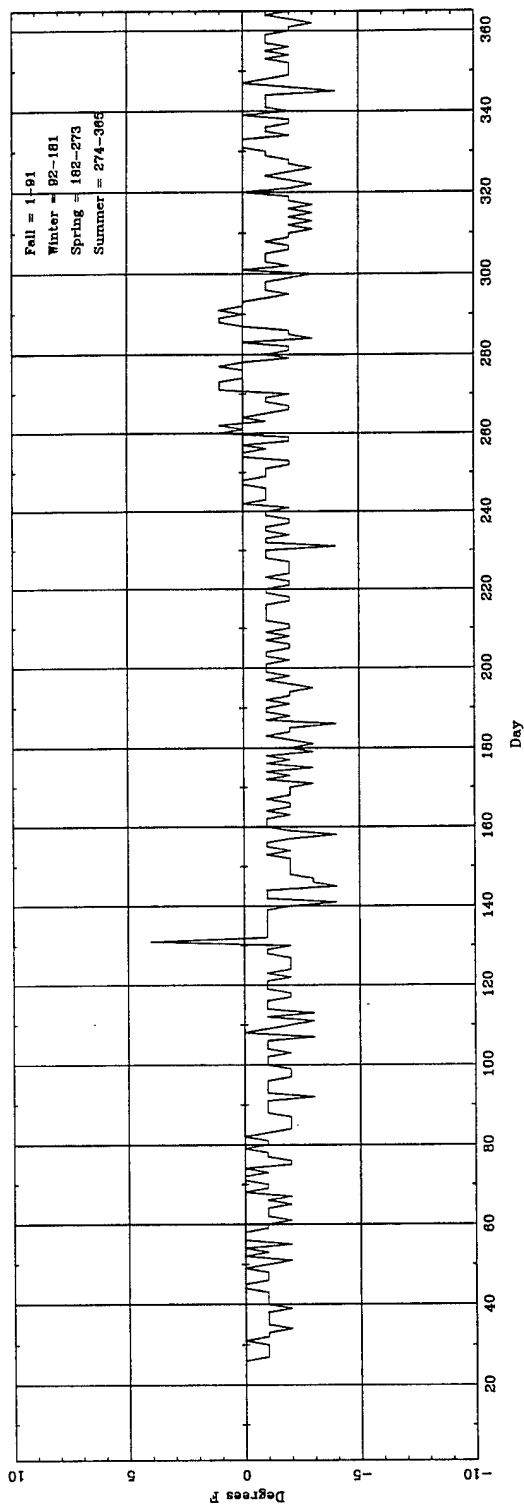
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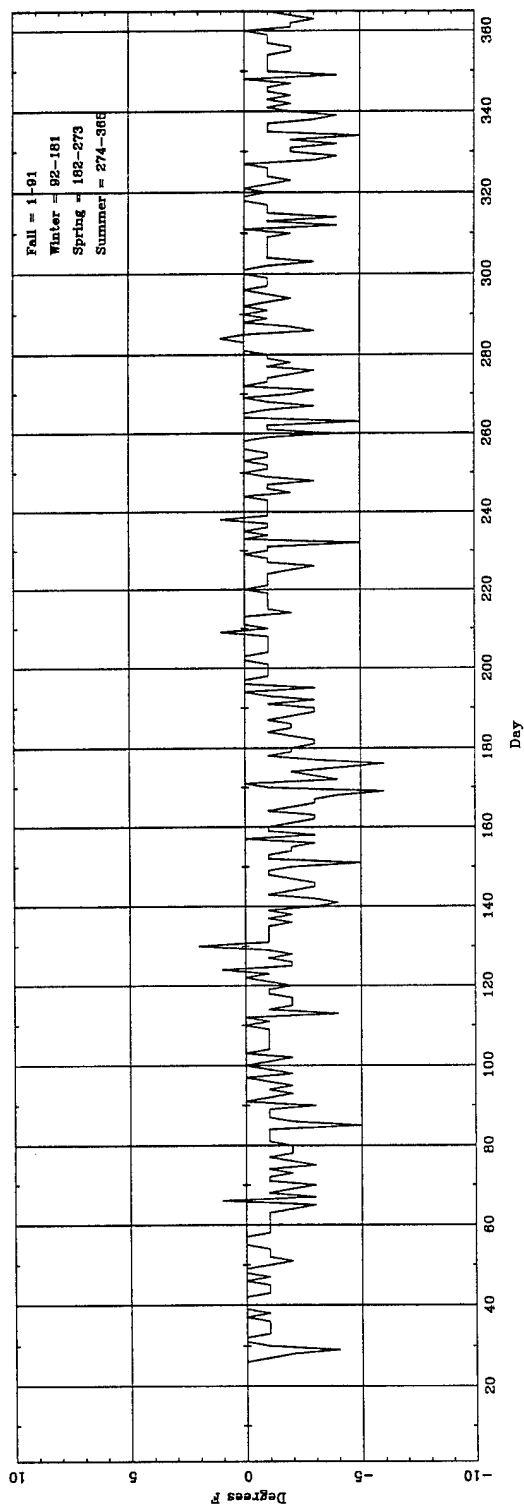
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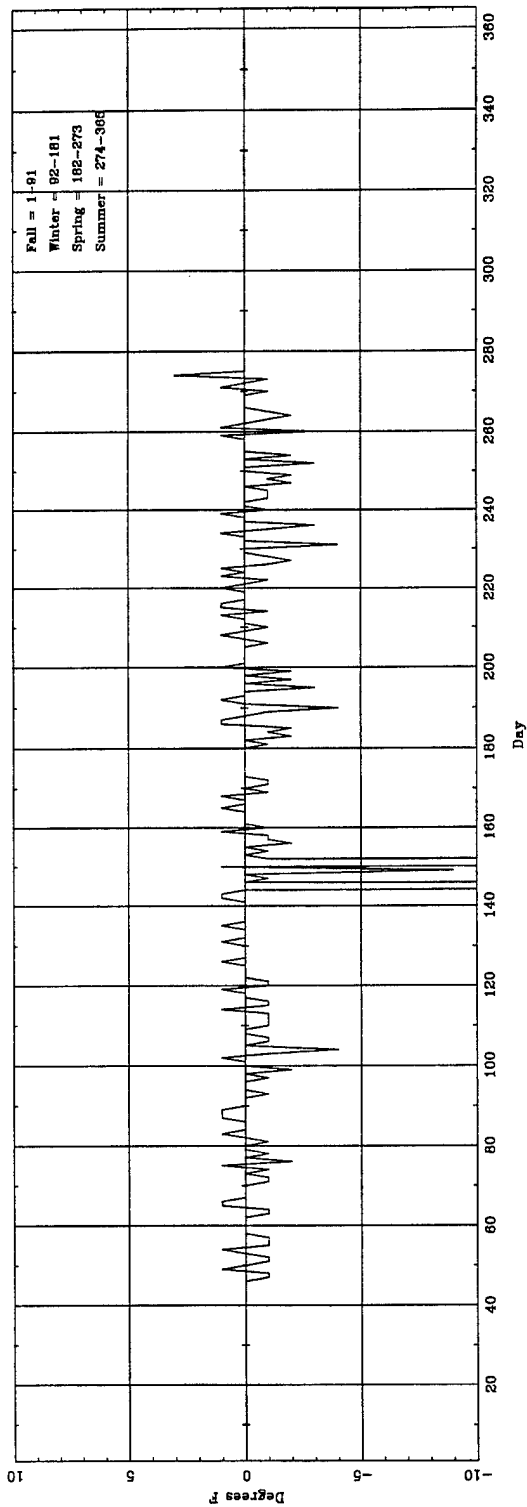
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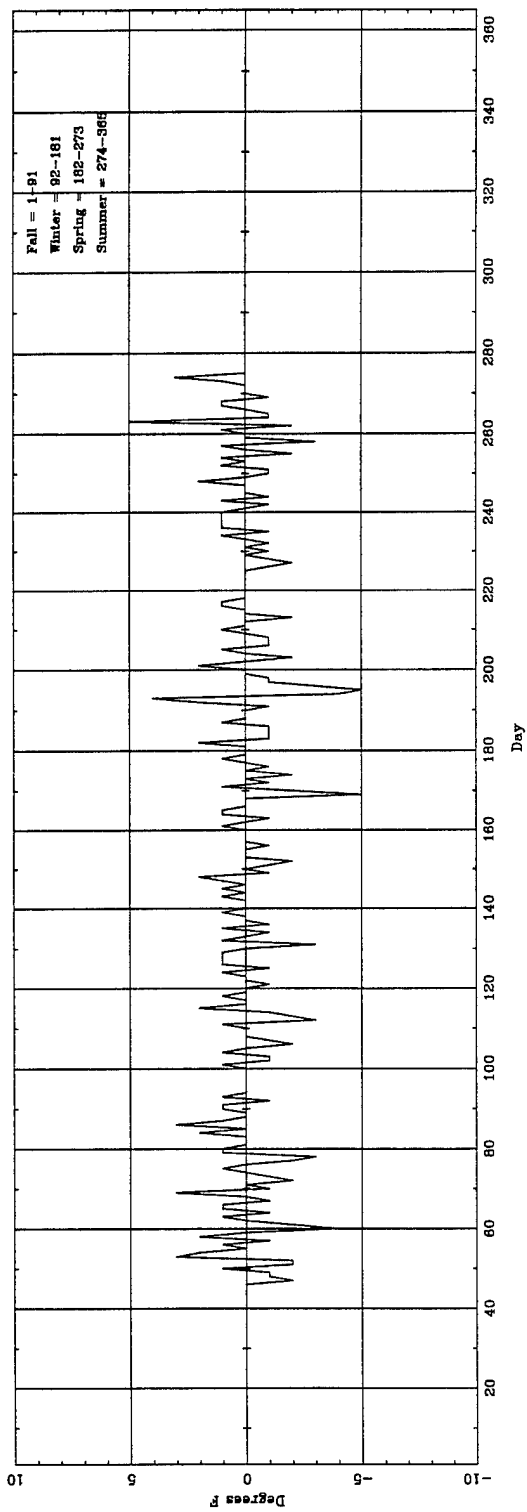
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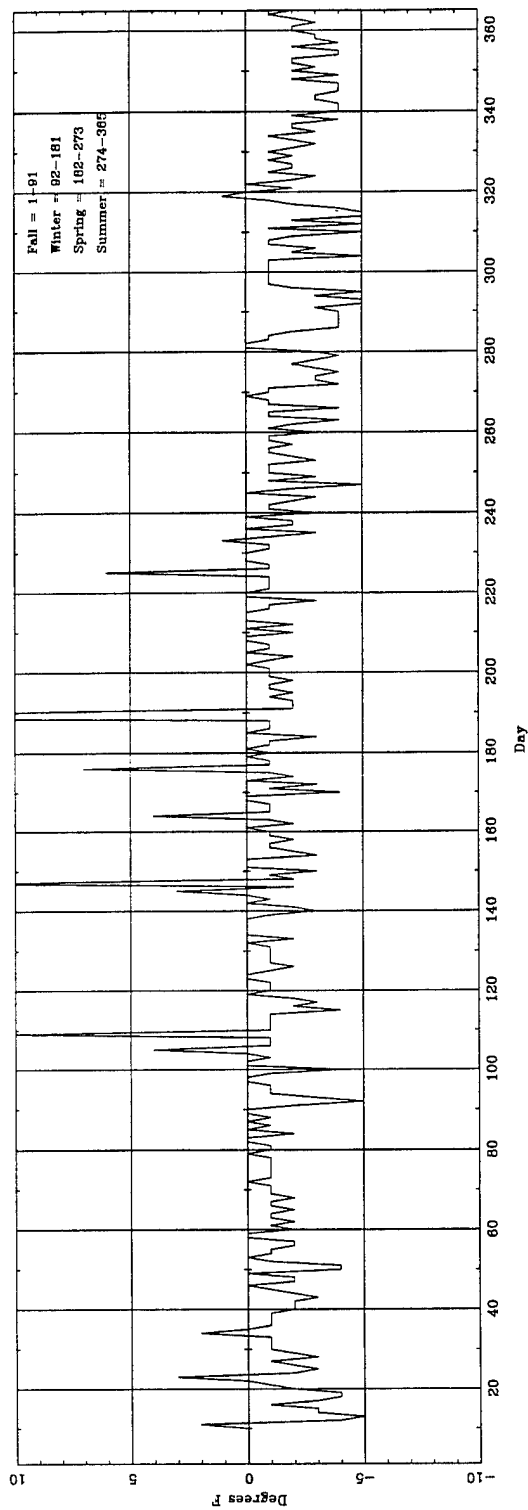
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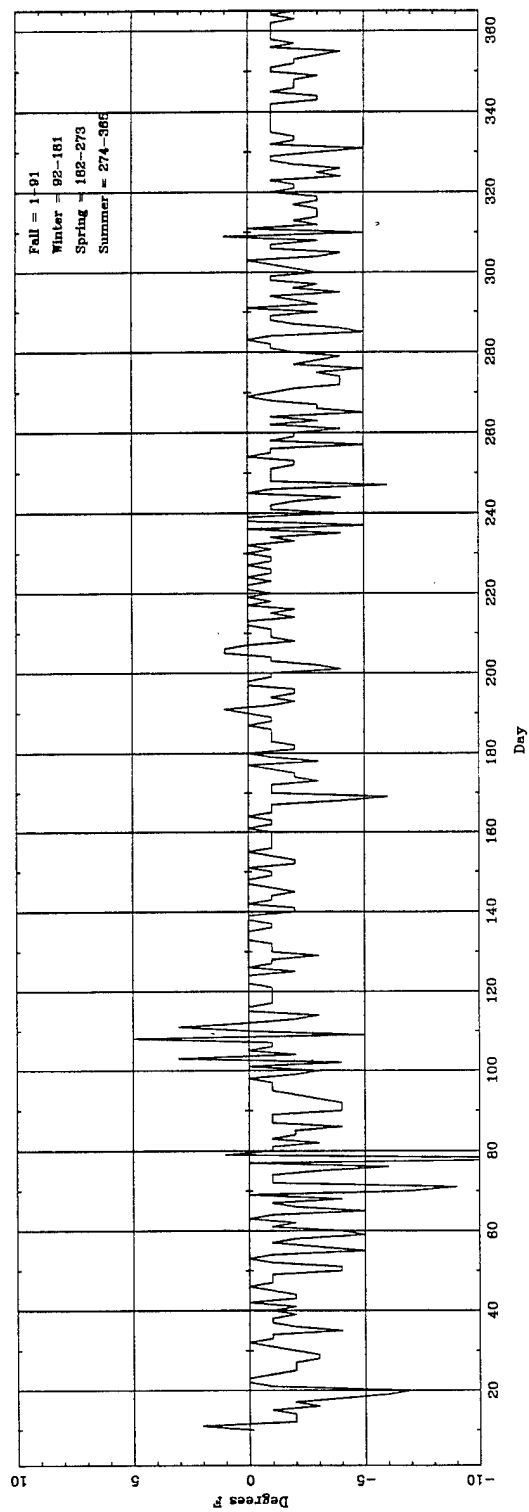
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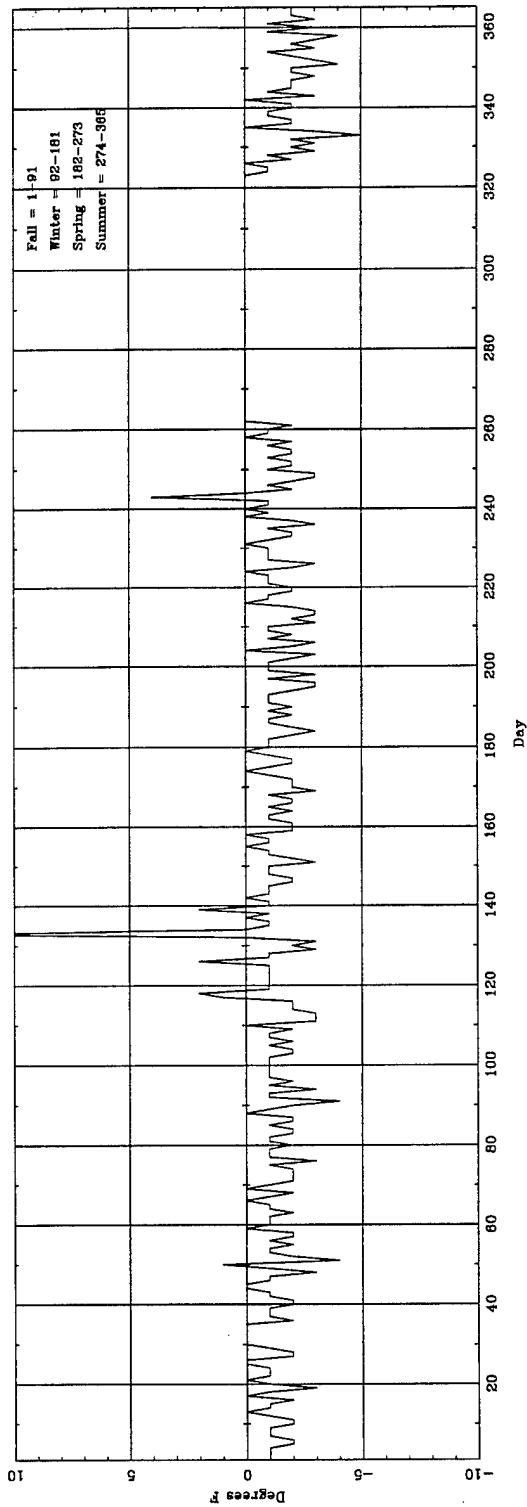
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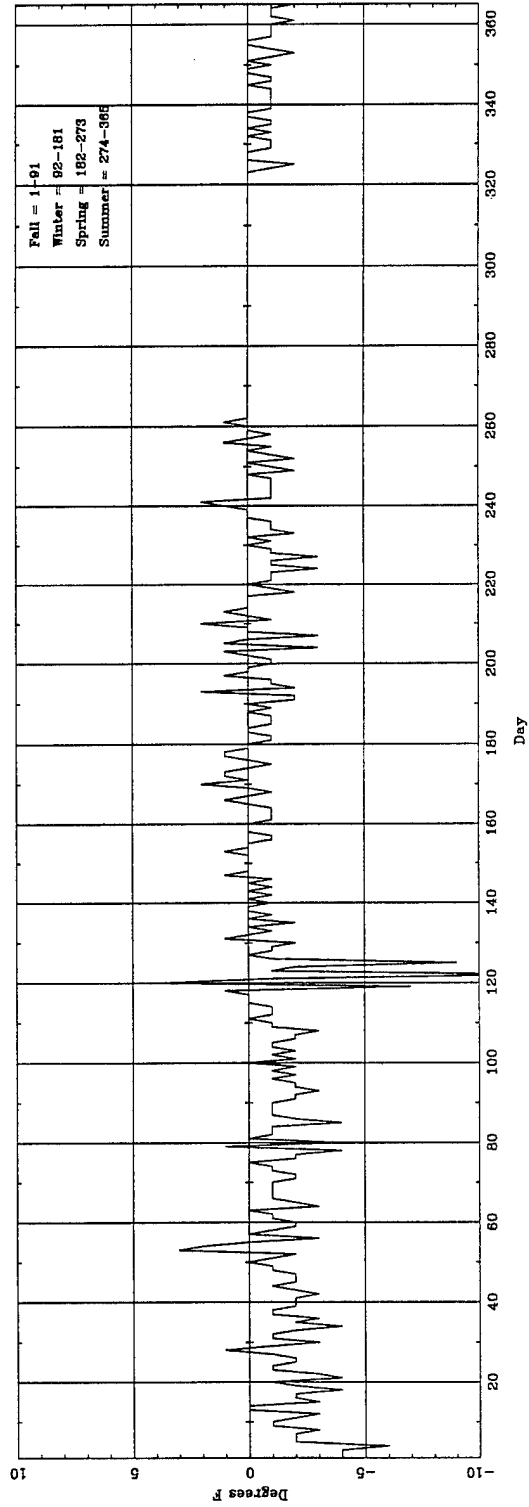
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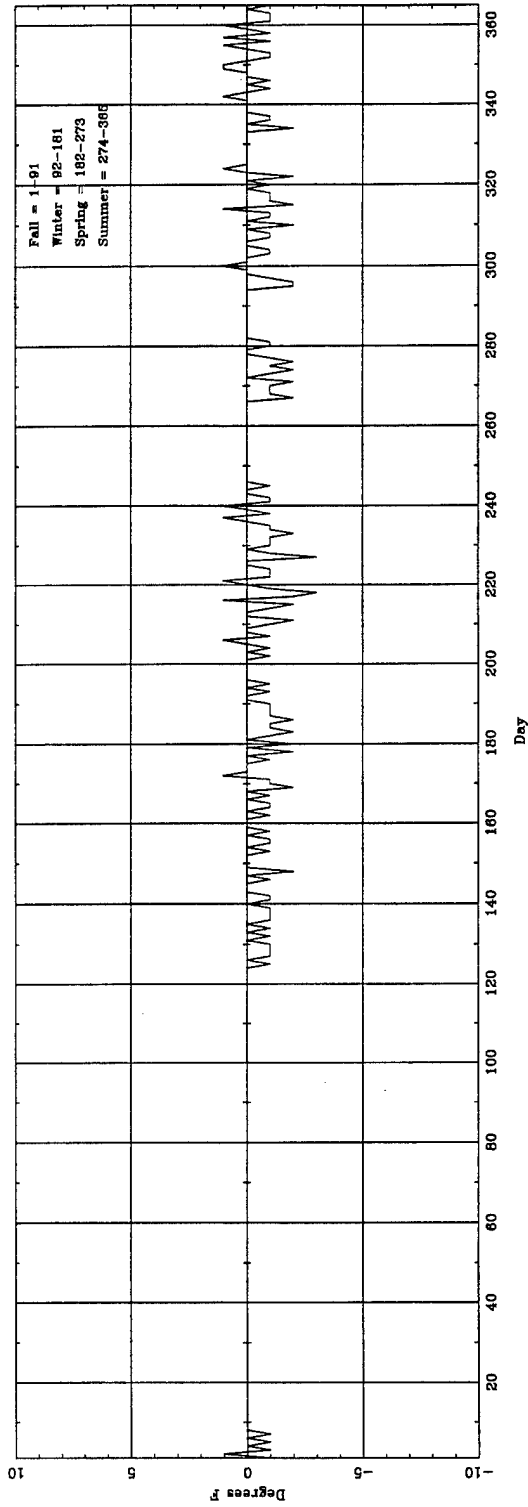
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for FWA



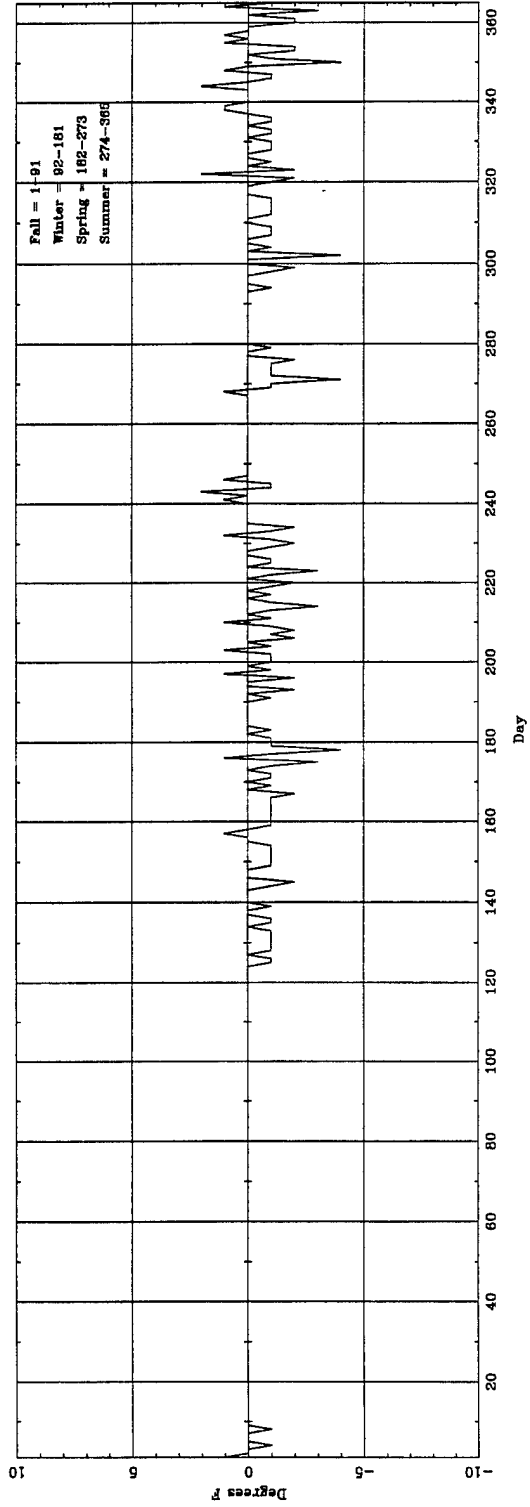
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for FWA



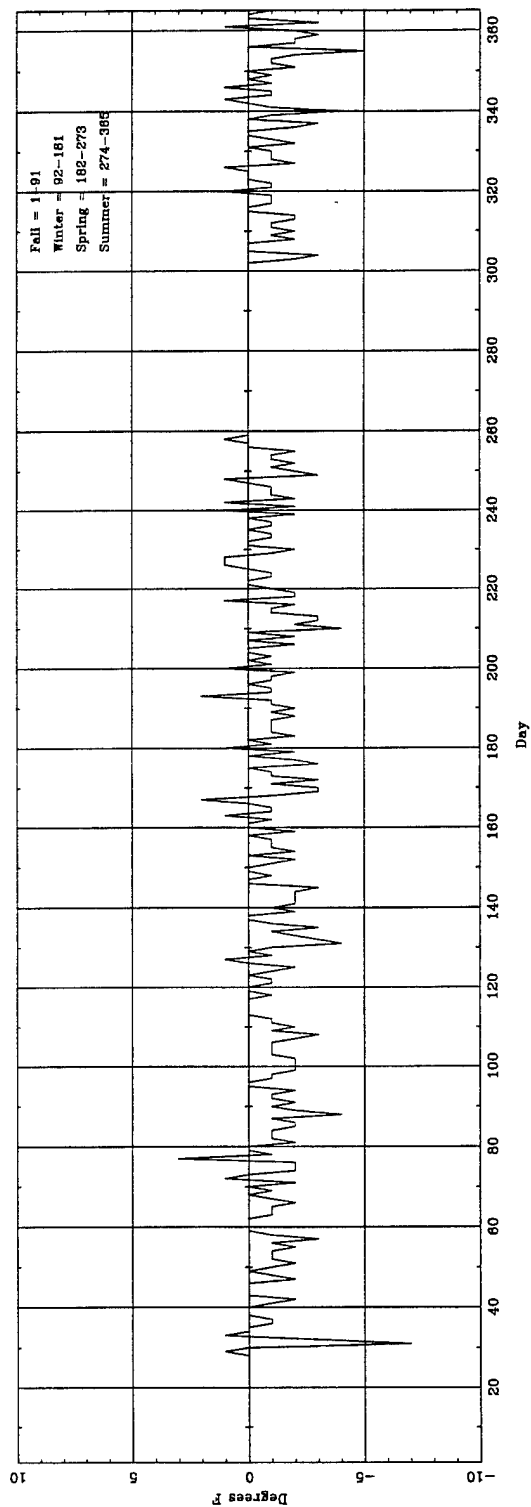
Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONV) for GEG



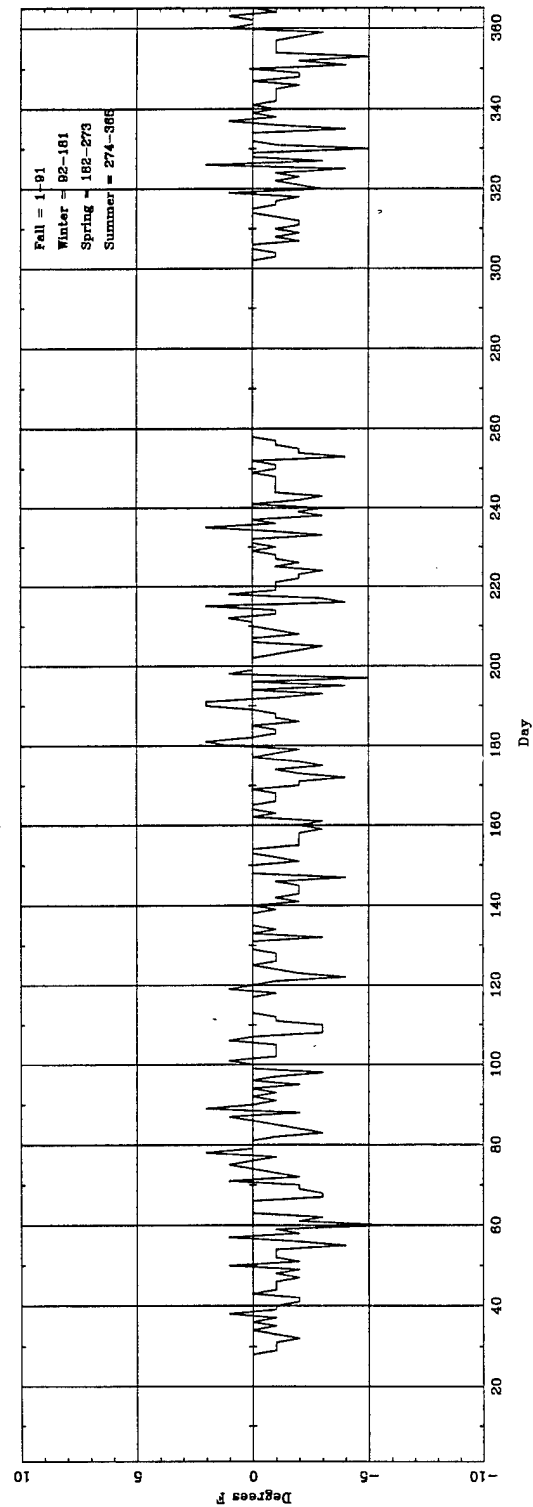
Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for GEG



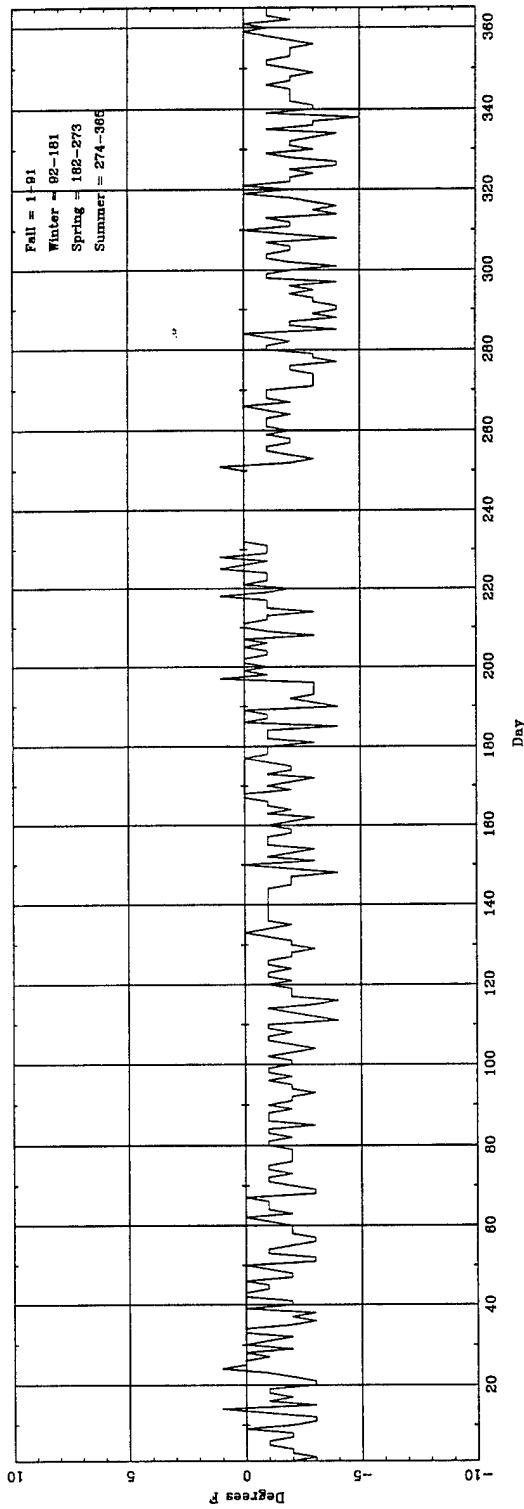
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for GJT



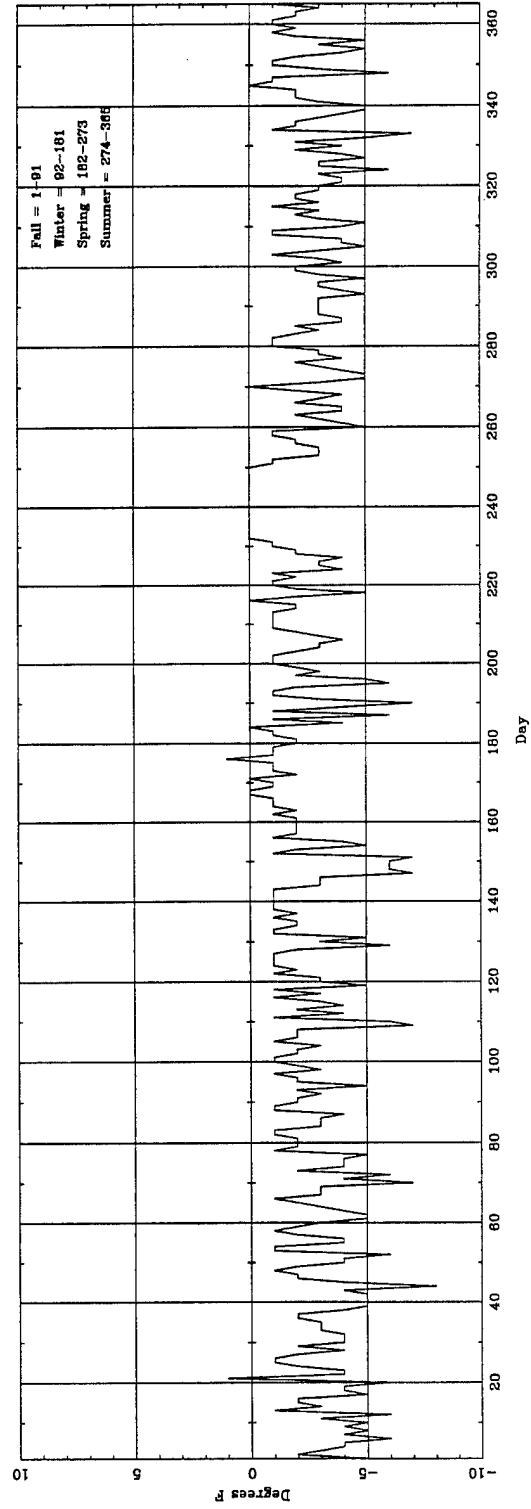
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for GJT



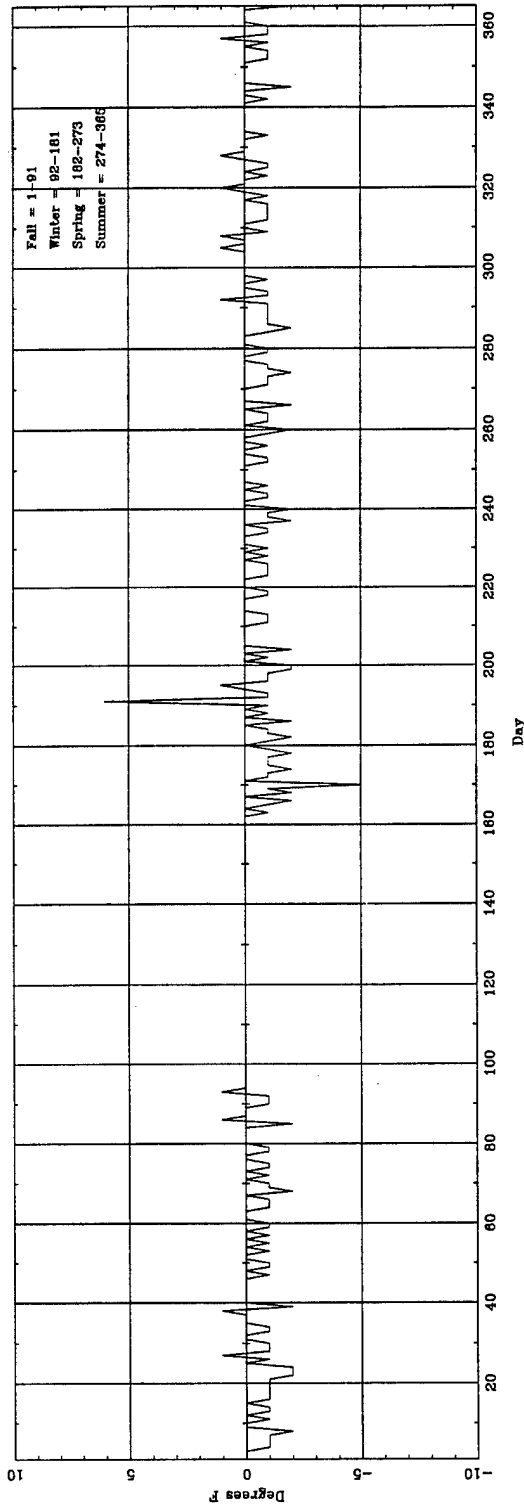
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for GRB



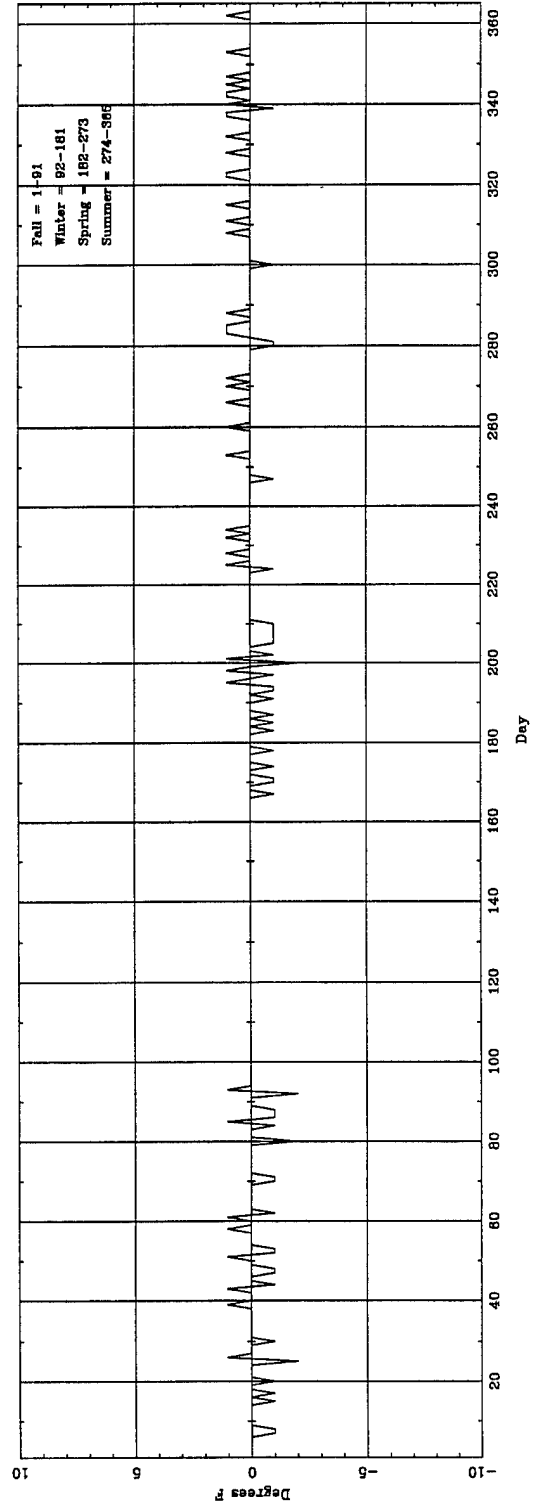
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for GRB



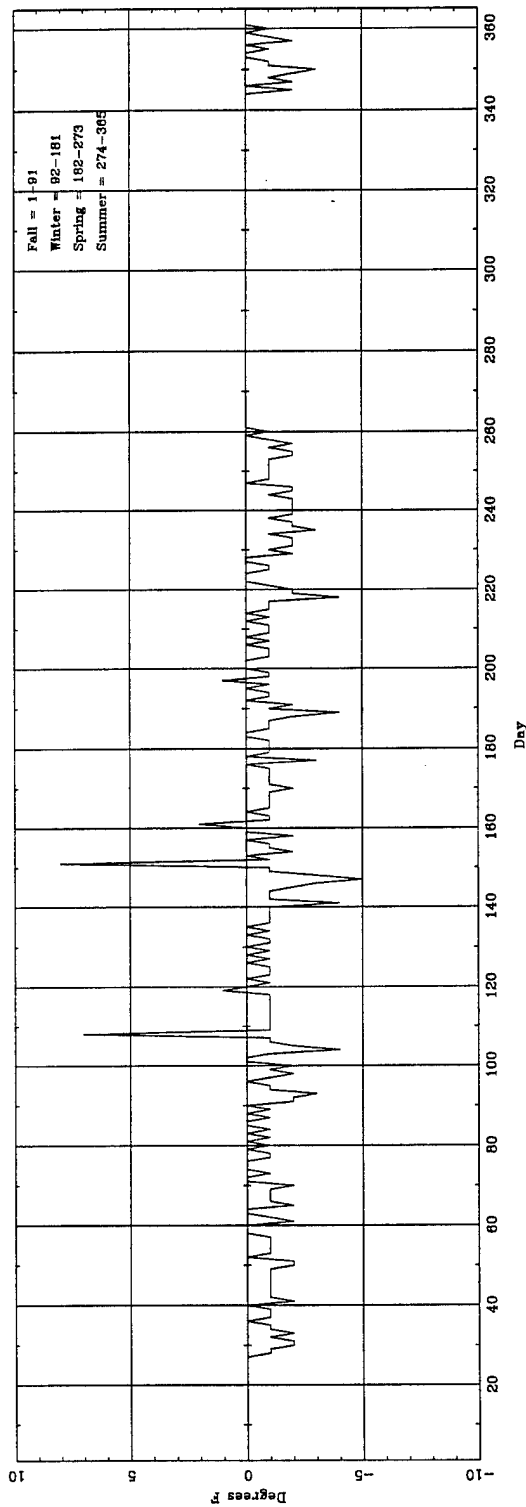
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for HON



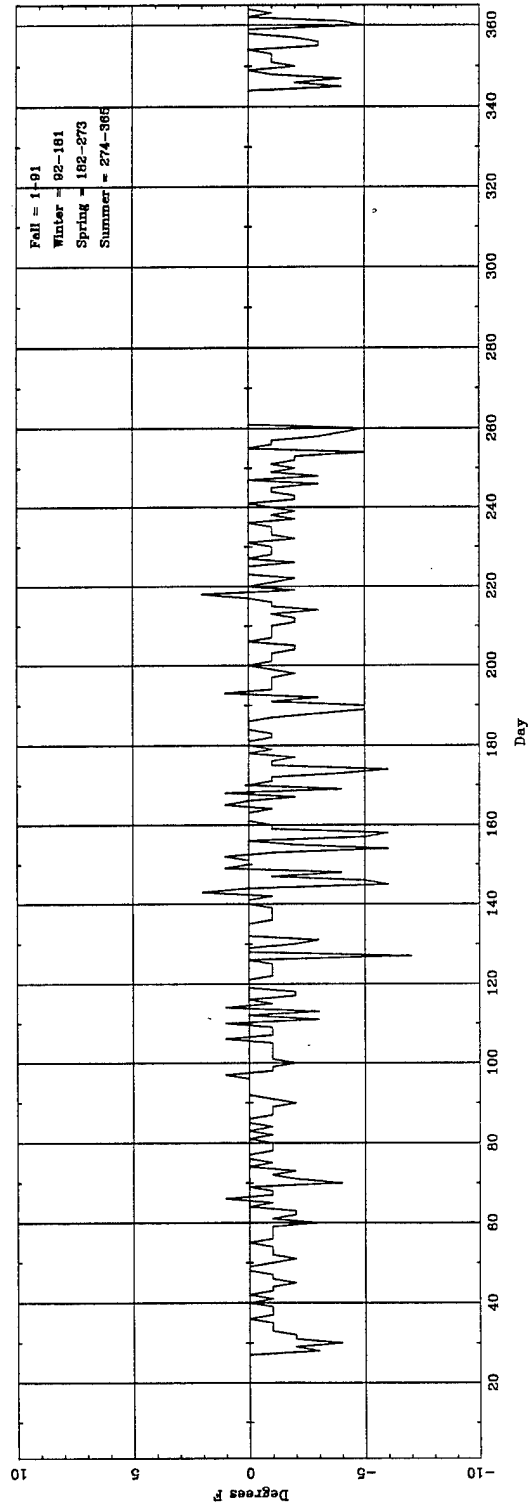
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for HON



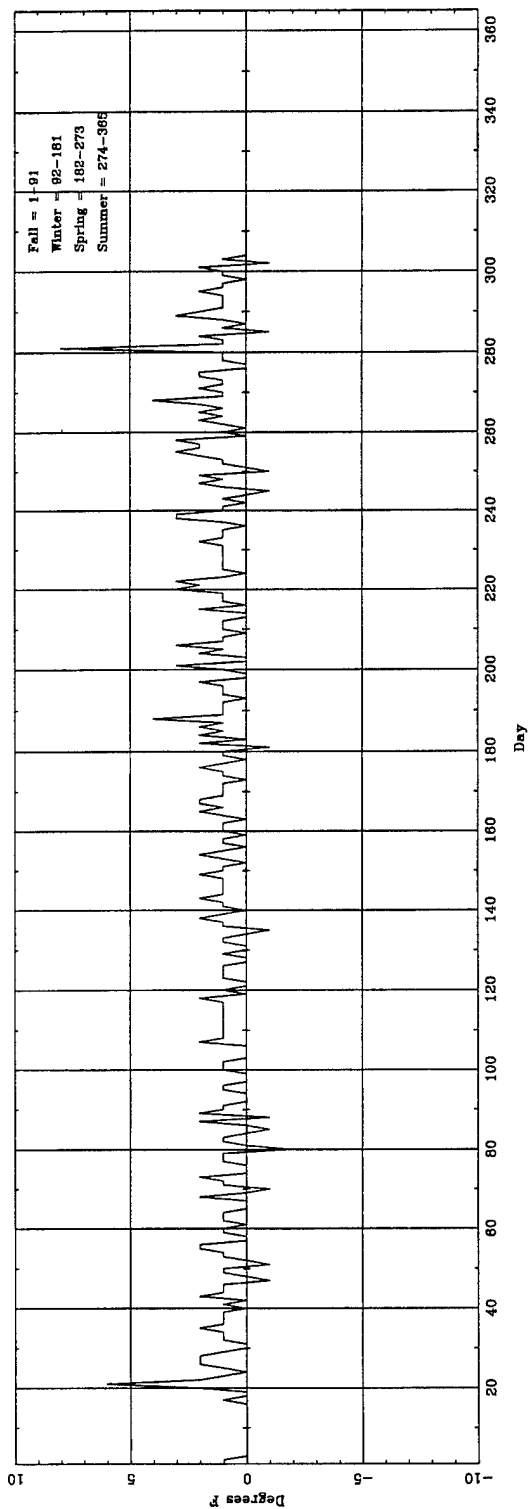
Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONV) for INL



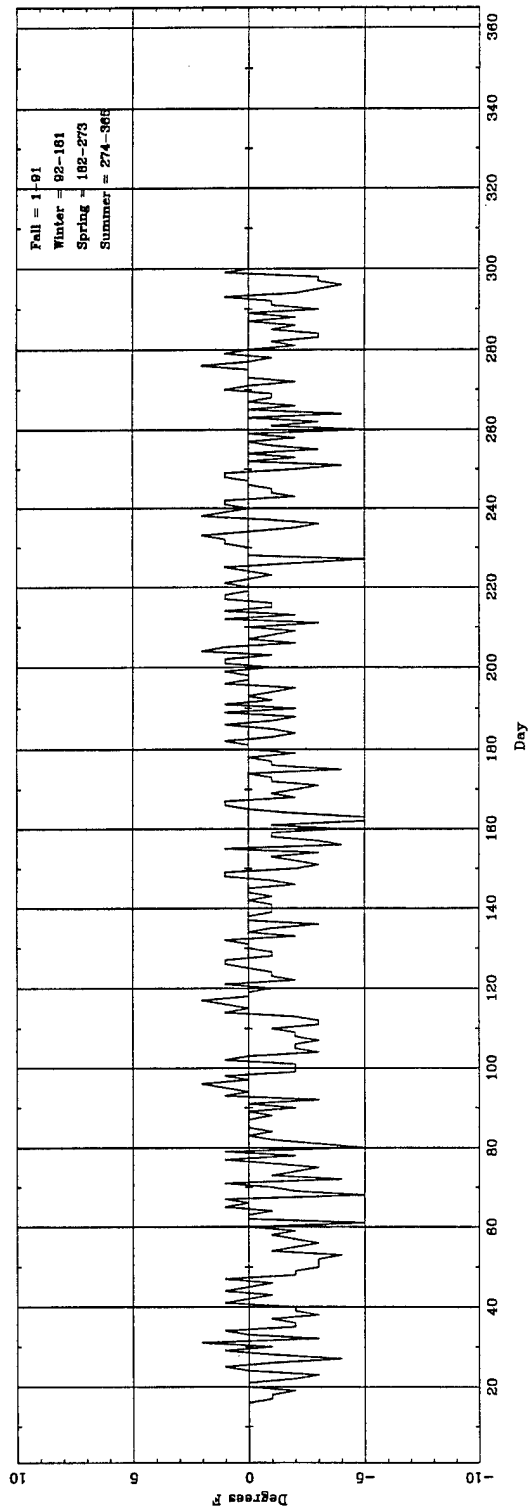
Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for INL



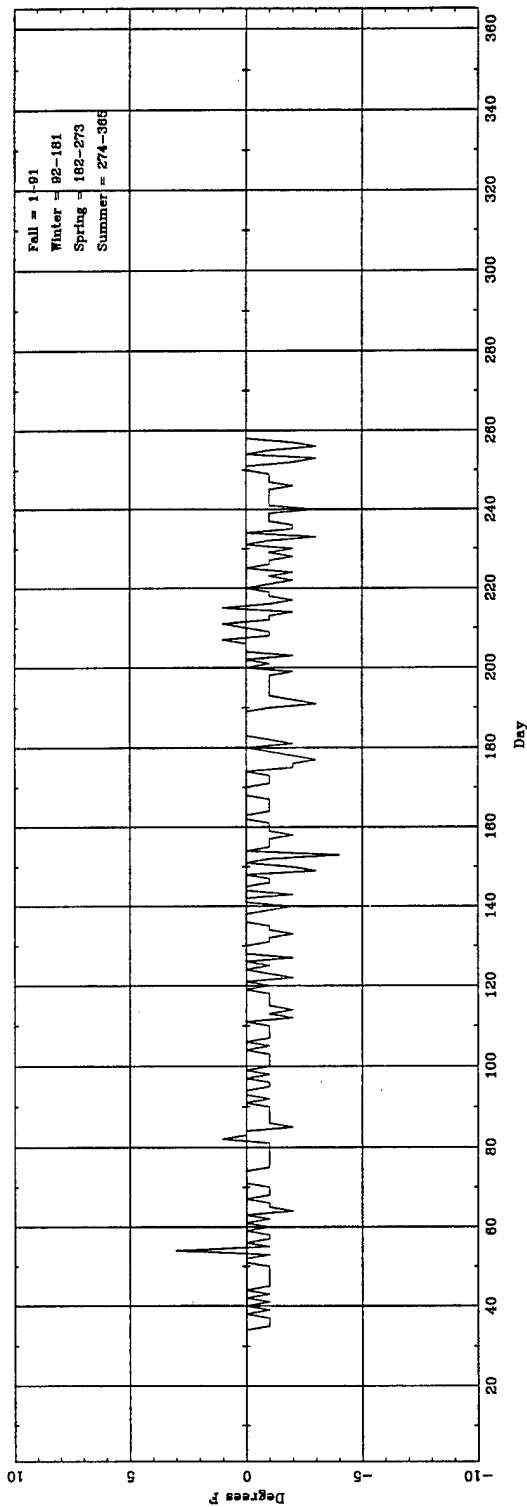
Daily $\Delta T_{\text{lagged hourly}}$ (ASOS - CONV) for INW



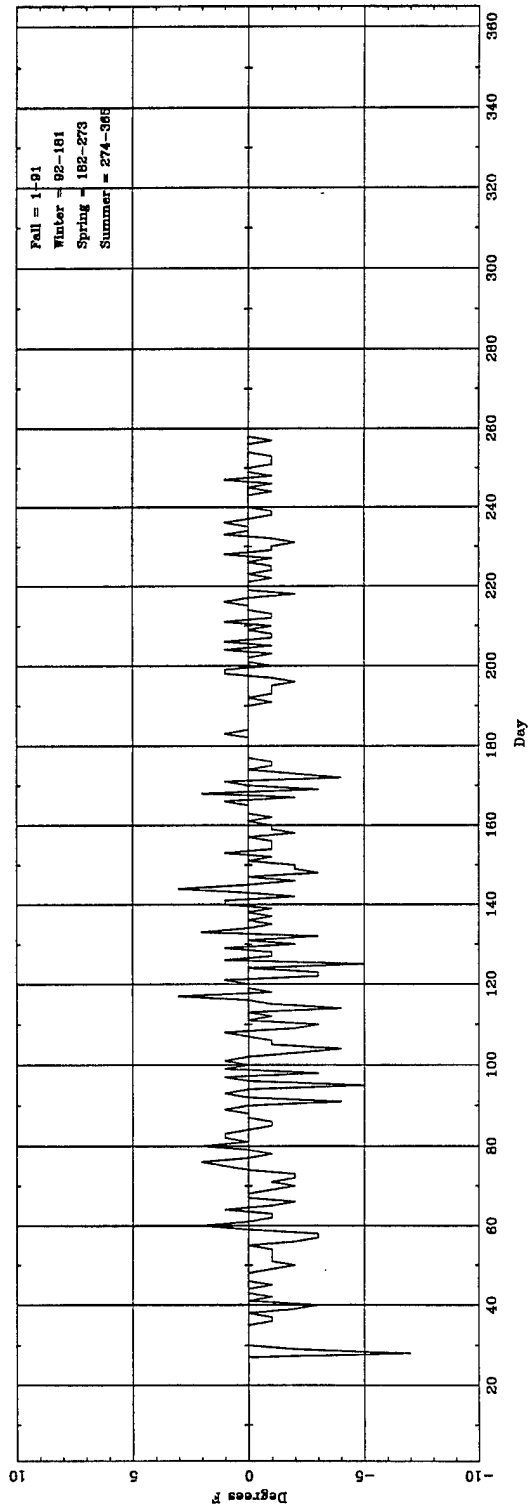
Daily $\Delta T_{\text{lagged hourly}}$ (ASOS - CONV) for INW



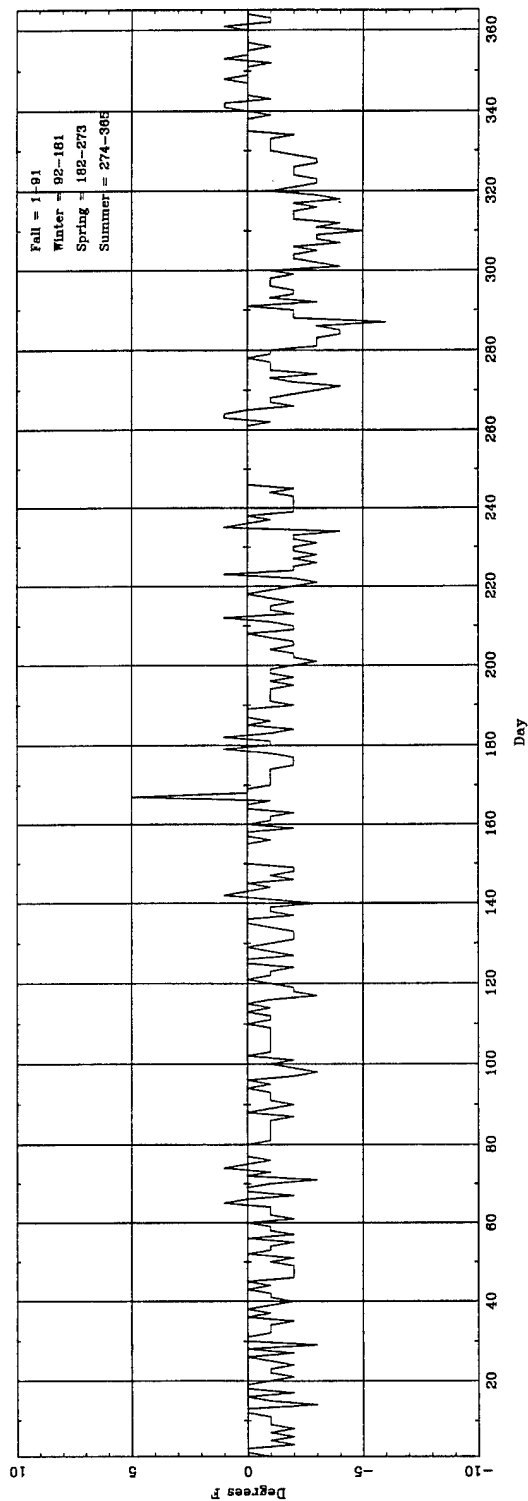
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for ISN



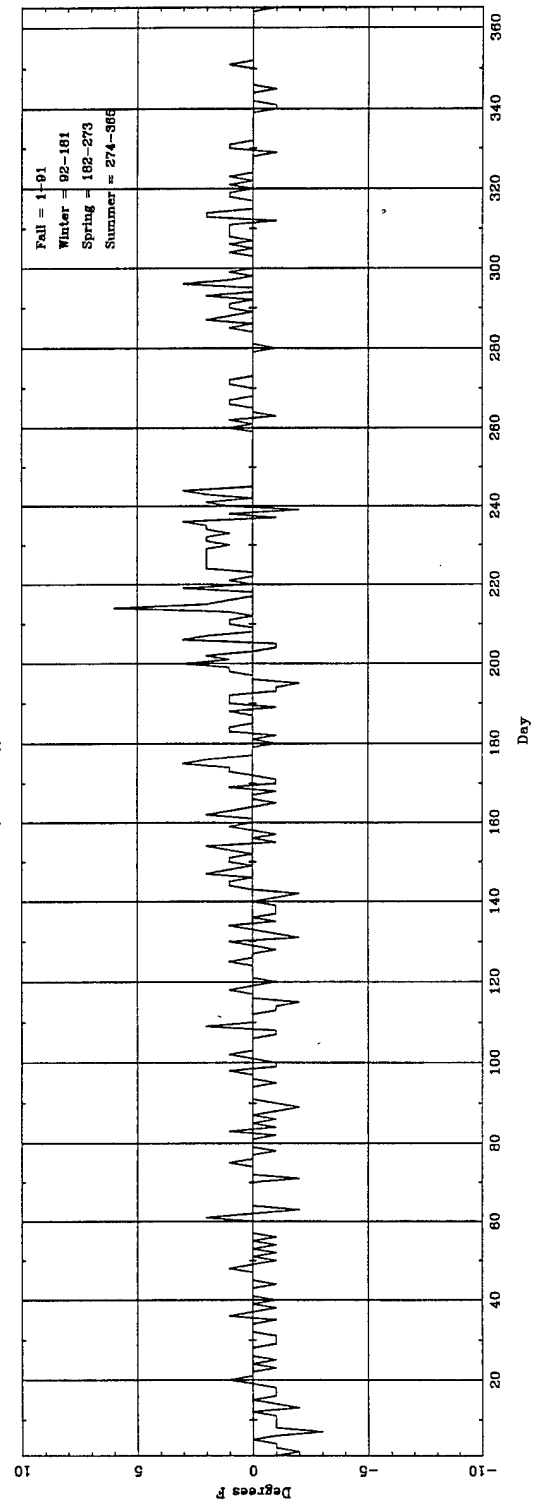
Daily $\Delta T_{\text{(great hourly)}}$ (ASOS - CONV) for ISN



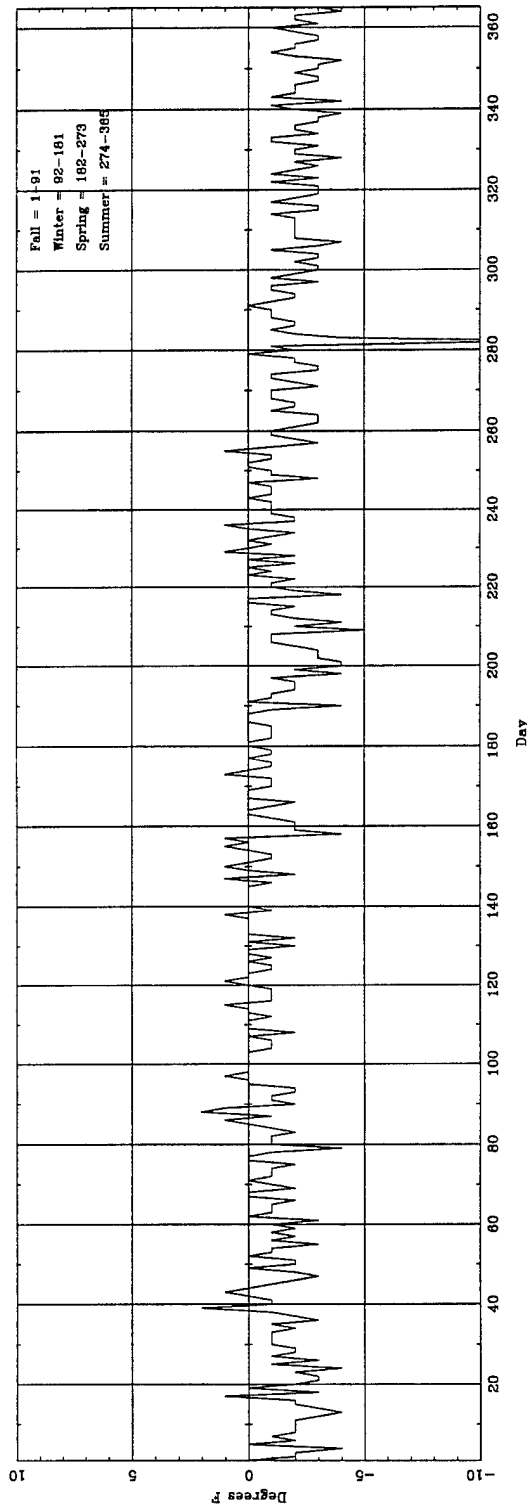
Daily $\Delta T_{\text{night}}^{\text{hourly}}$ (ASOS - CONV) for JAX



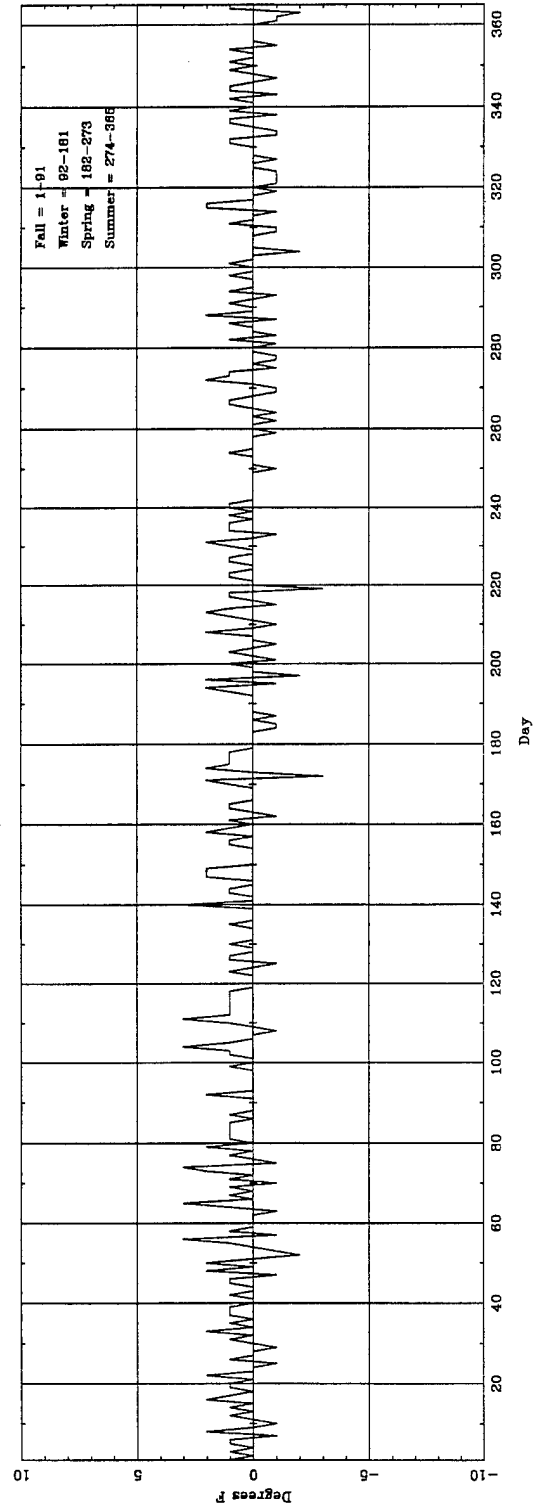
Daily $\Delta T_{\text{dawn}}^{\text{hourly}}$ (ASOS - CONV) for JAX

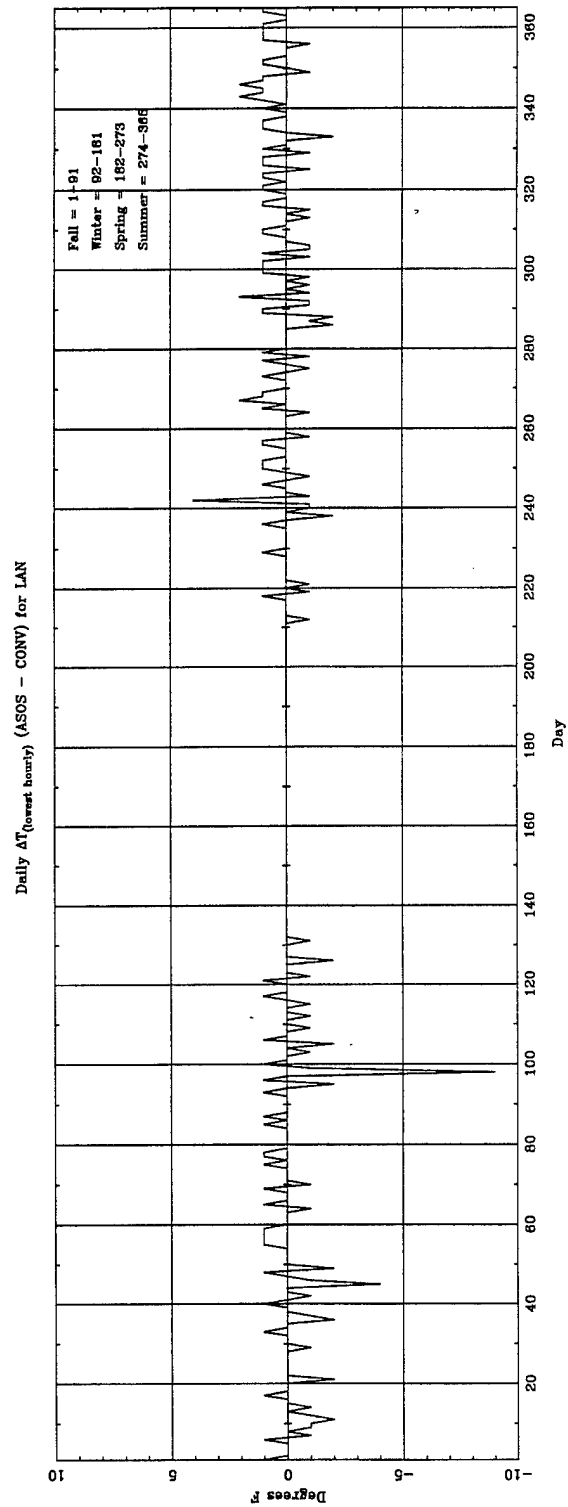
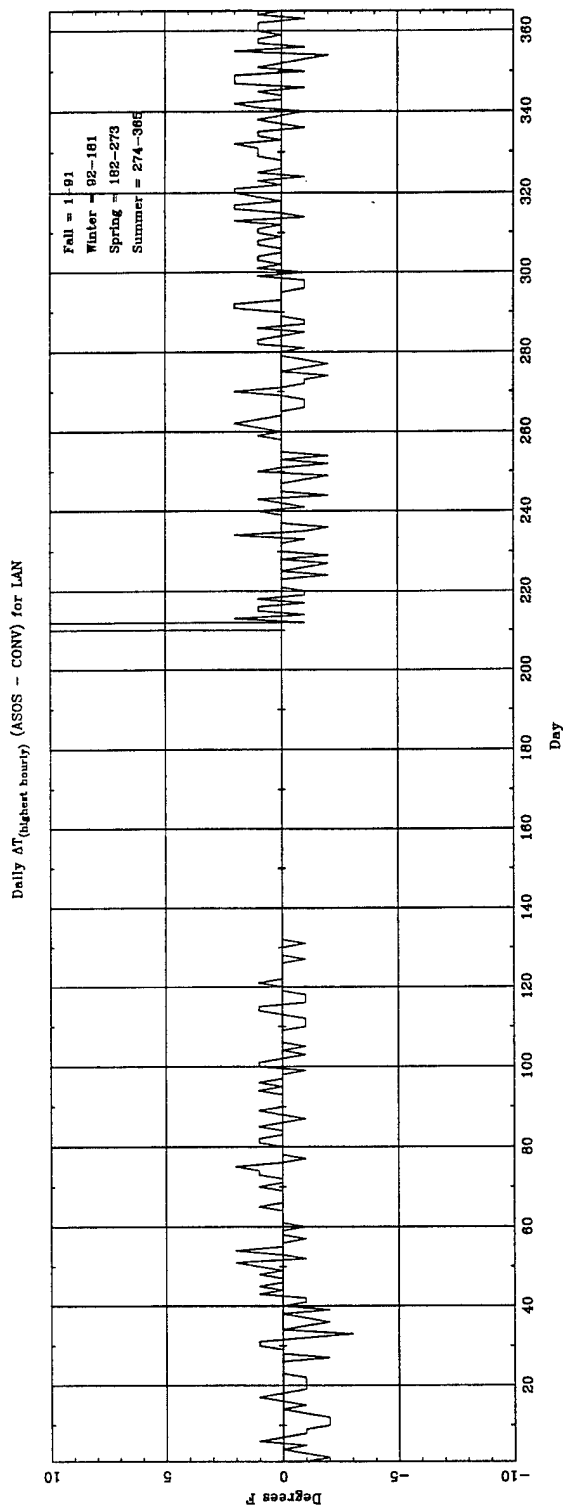


Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for JKL

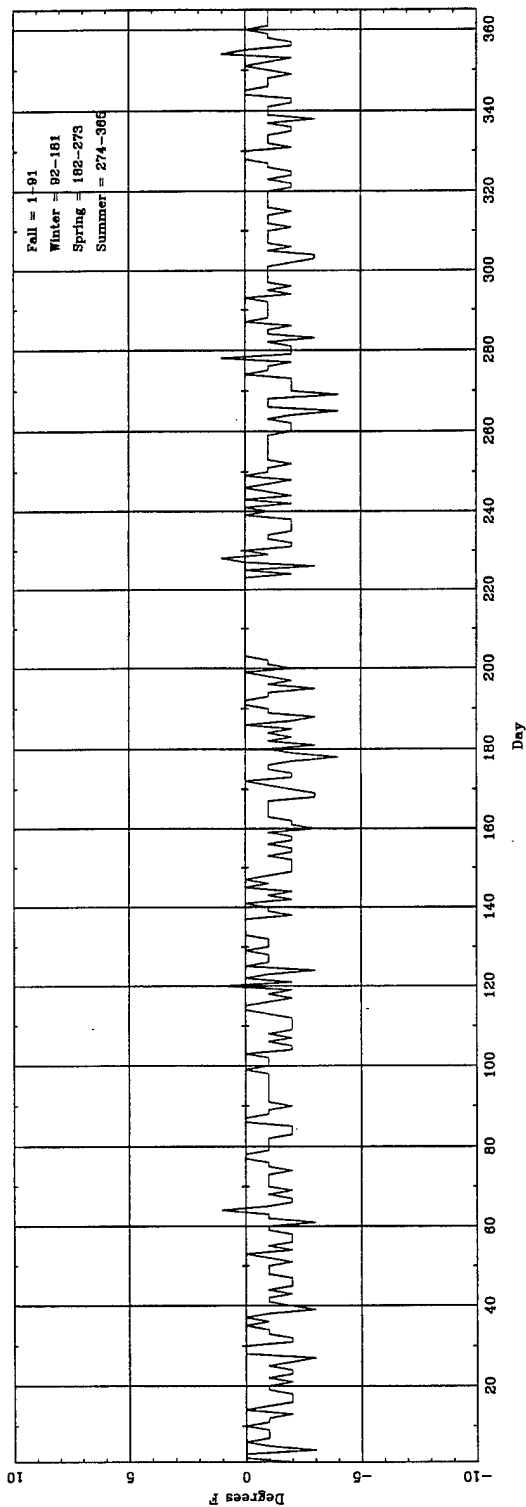


Daily $\Delta T_{\text{(forest hourly)}}$ (ASOS - CONV) for JKL

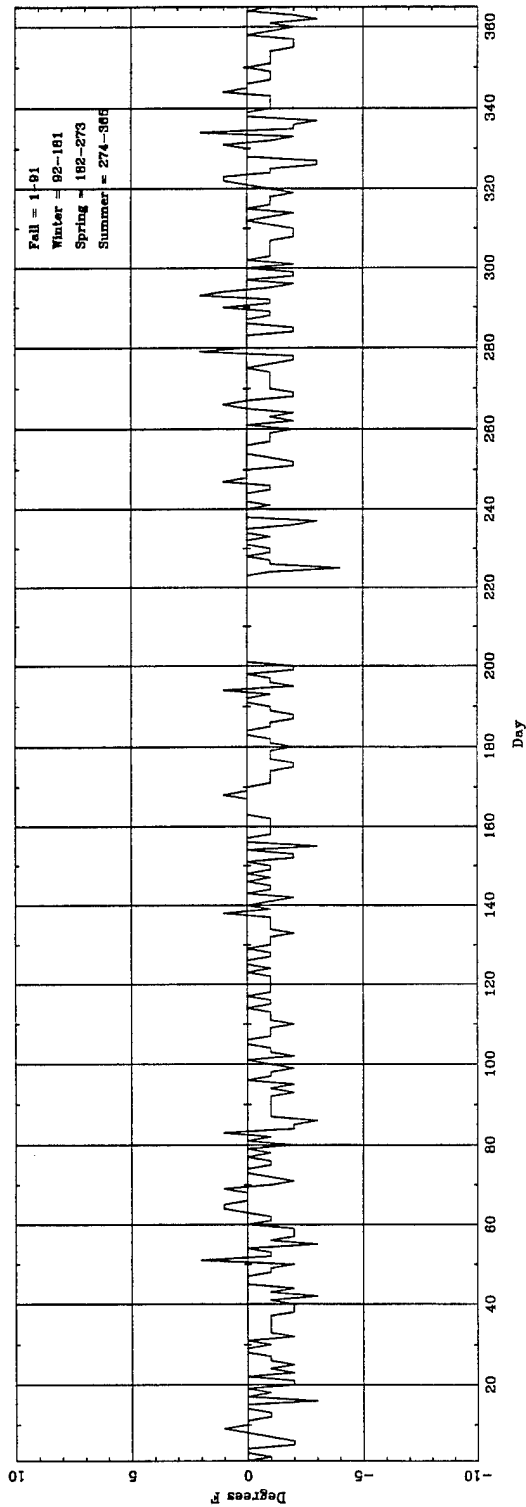




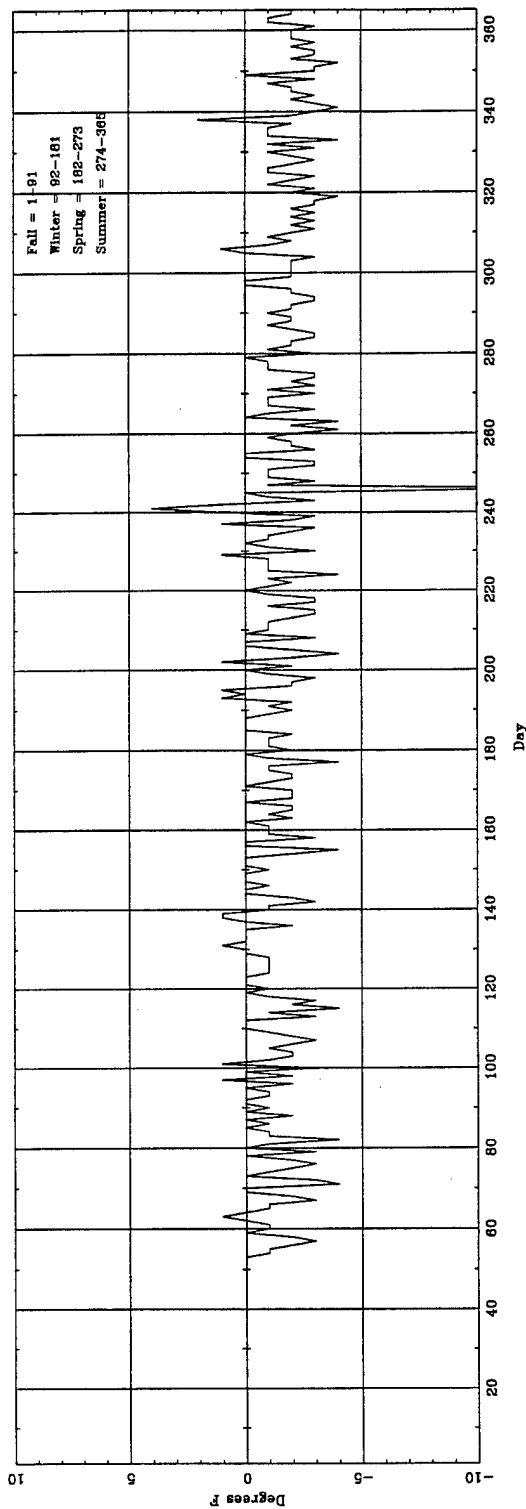
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for LAS



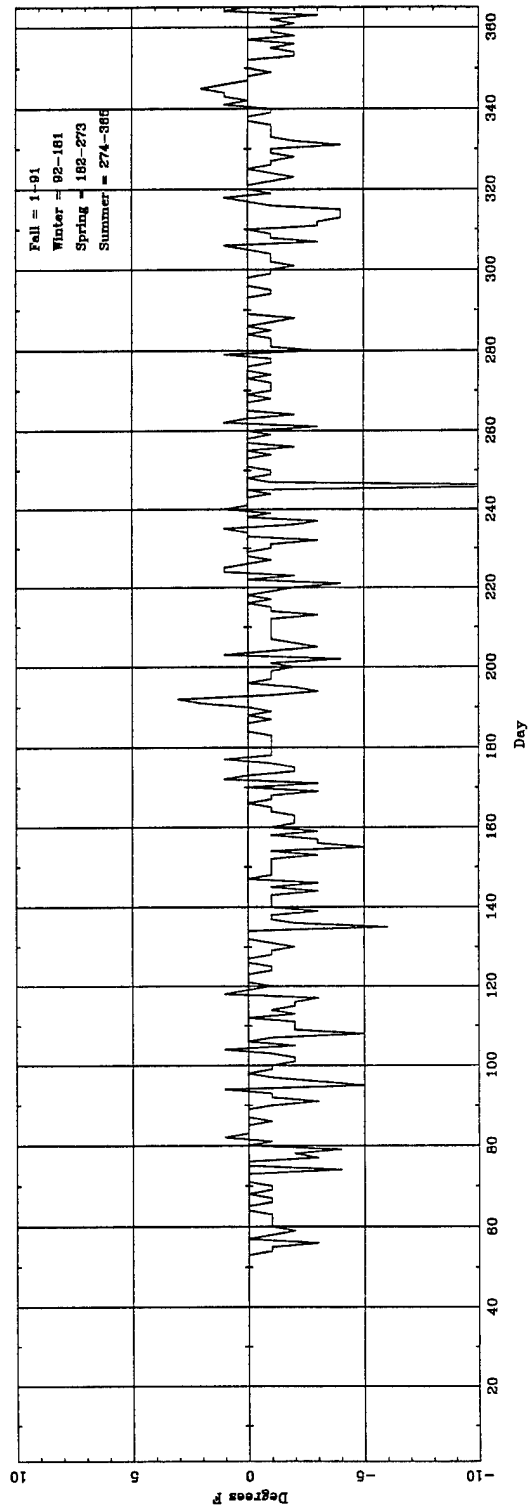
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for LAS



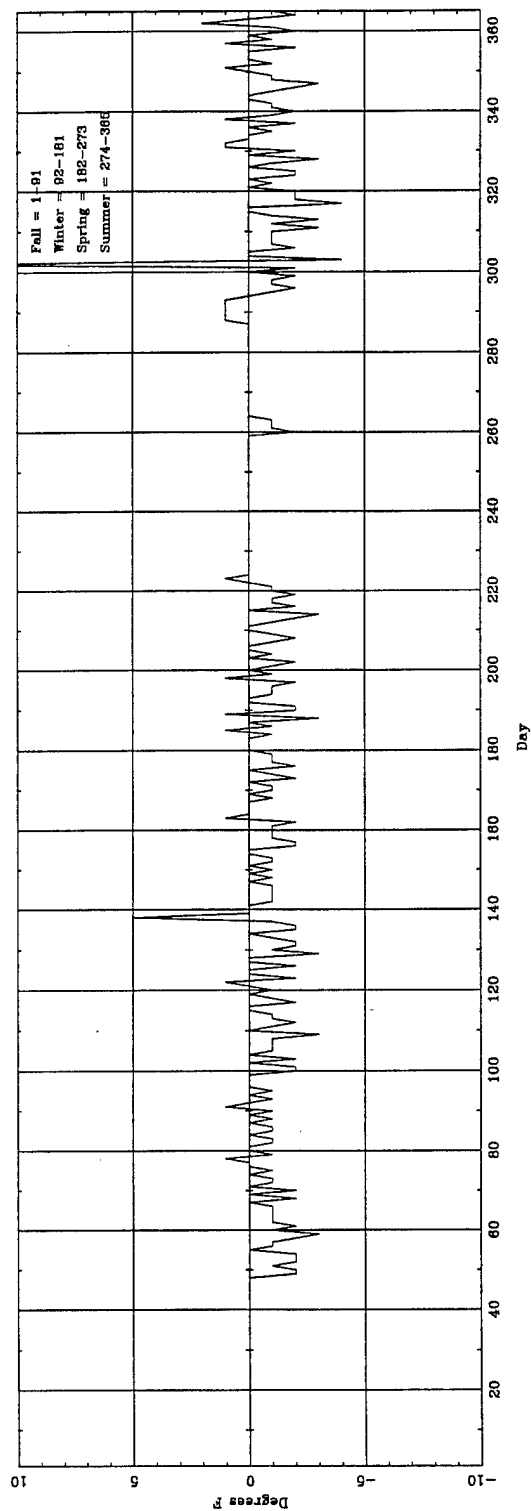
Daily $\Delta T_{\text{highest bounty}}$ (ASOS - CONV) for LBB



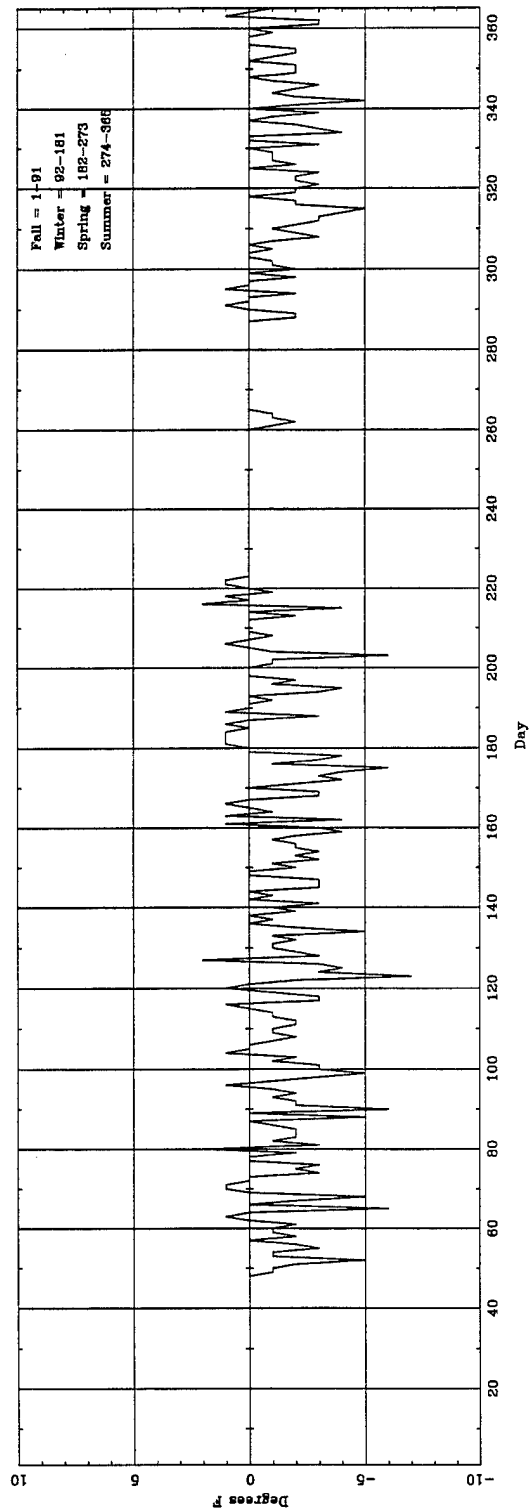
Daily $\Delta T_{\text{lowest bounty}}$ (ASOS - CONV) for LBB



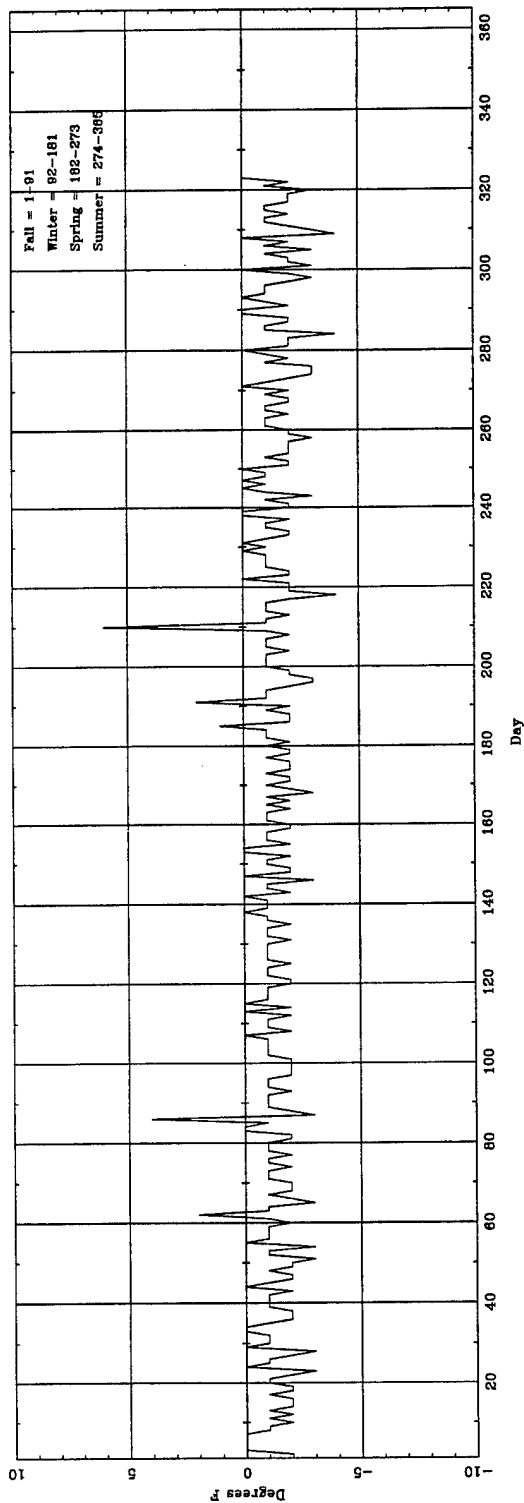
Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONV) for LBF



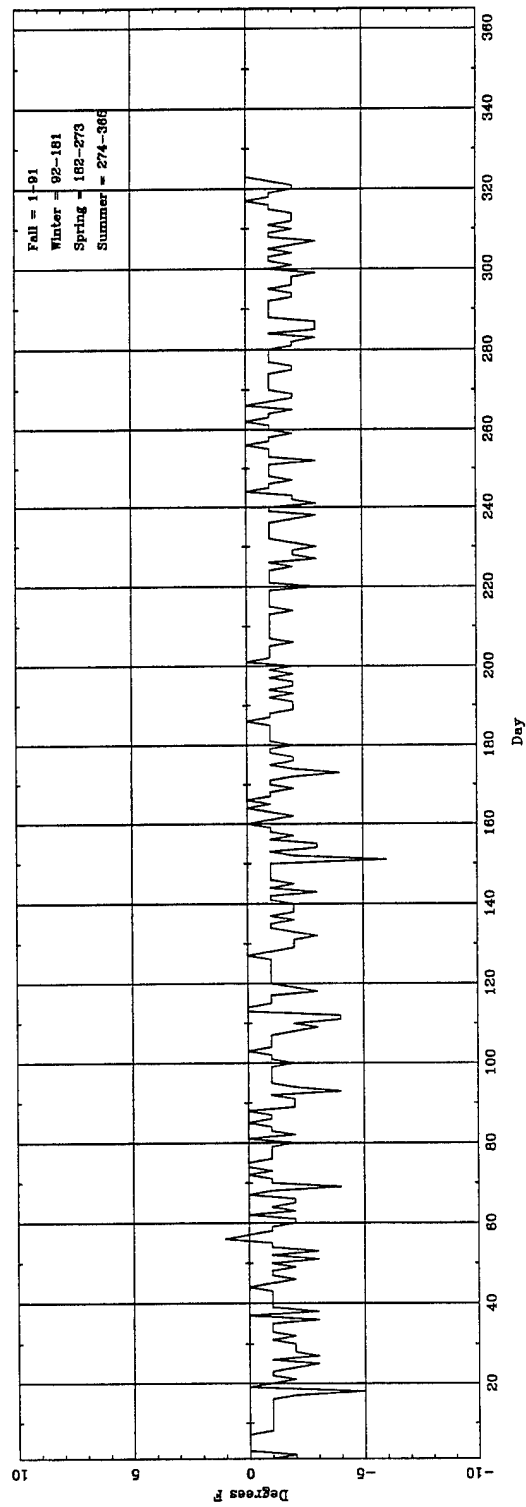
Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for LBF



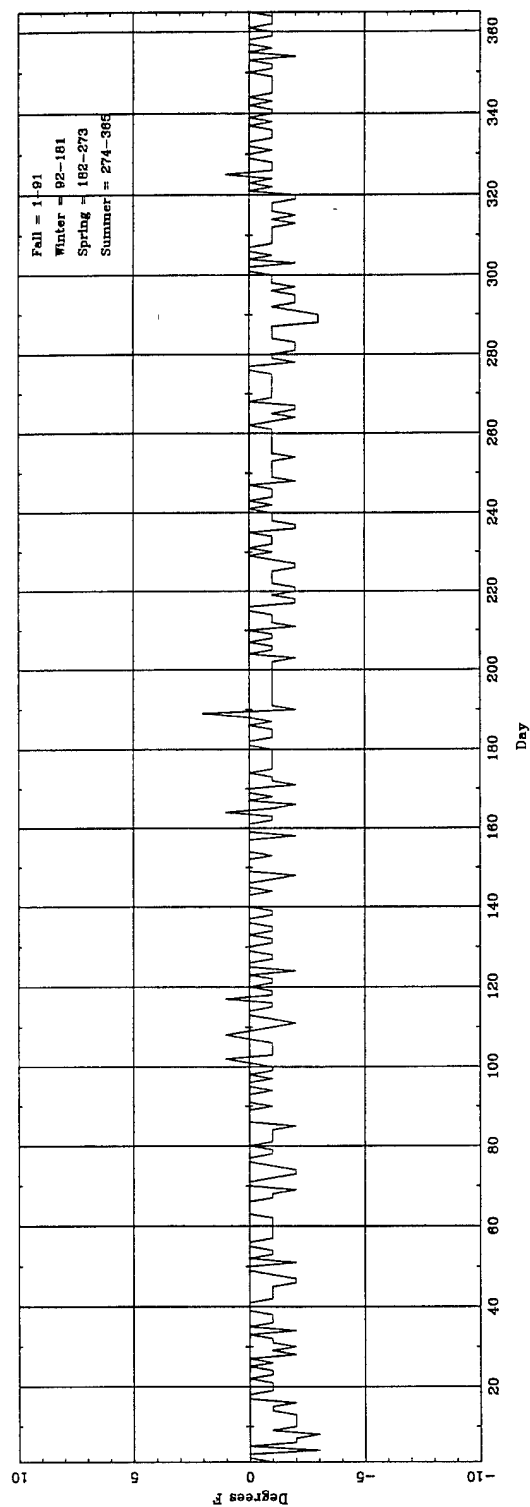
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for LCH



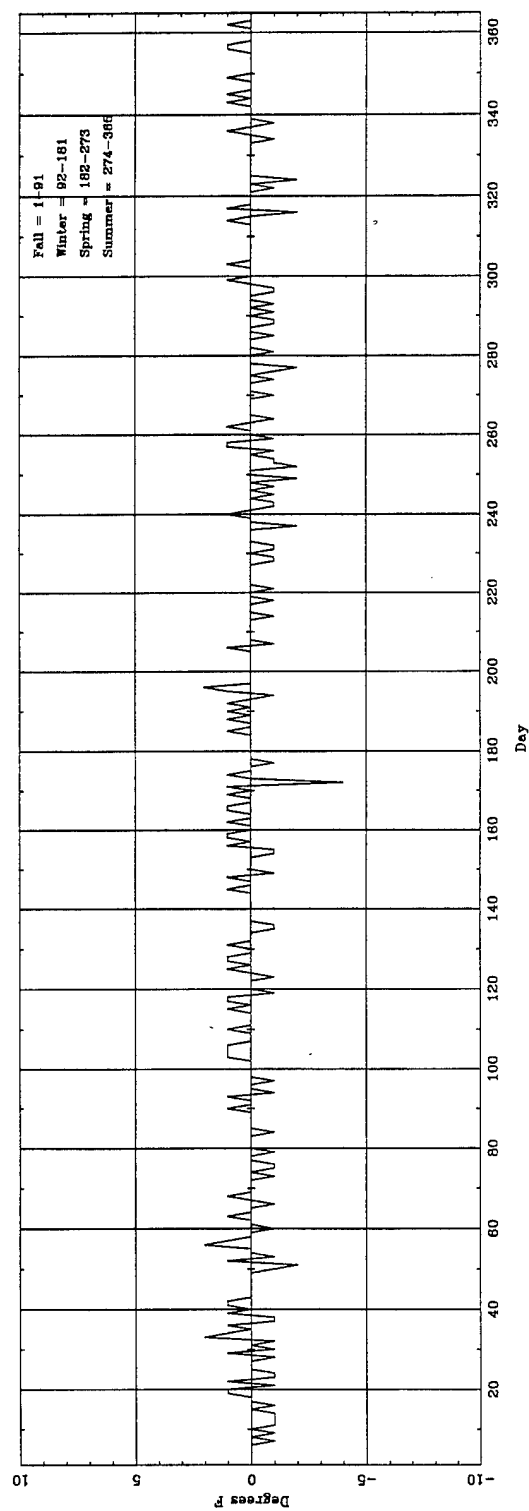
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for LCH



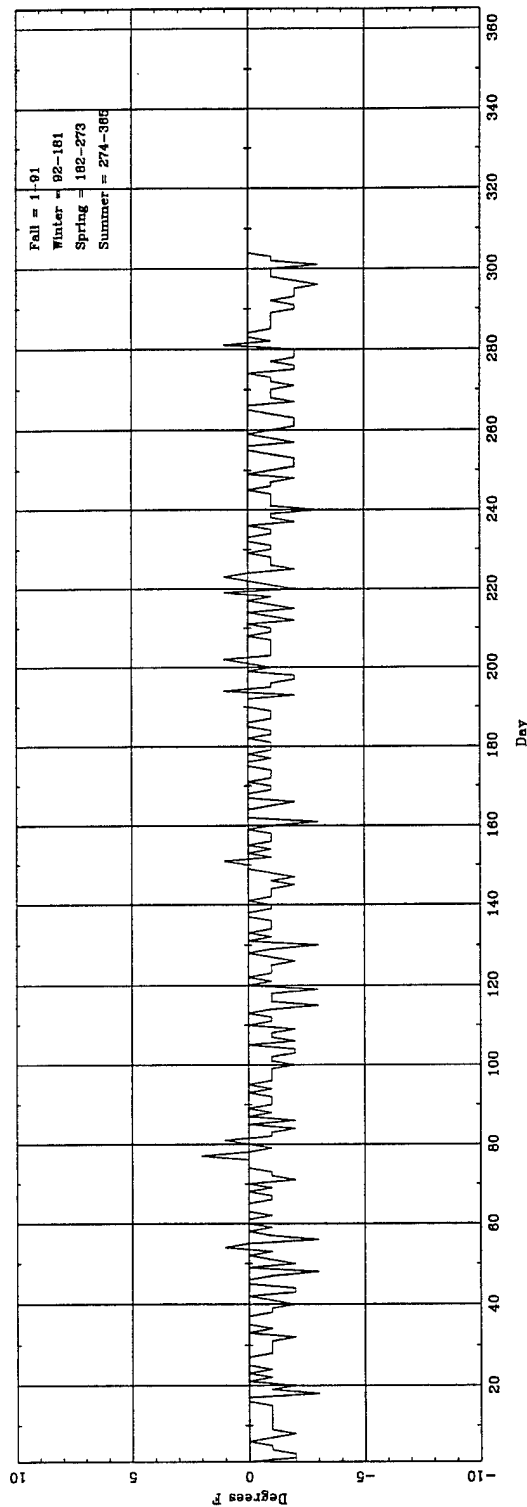
Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONV) for LEX



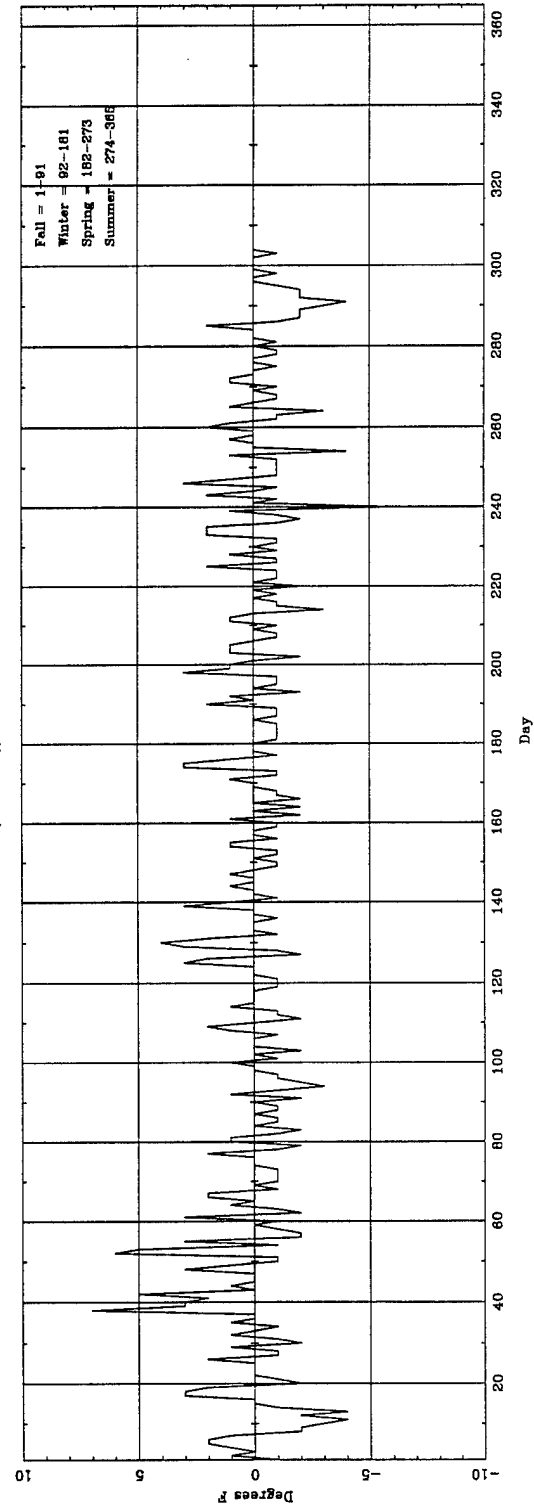
Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for LEX

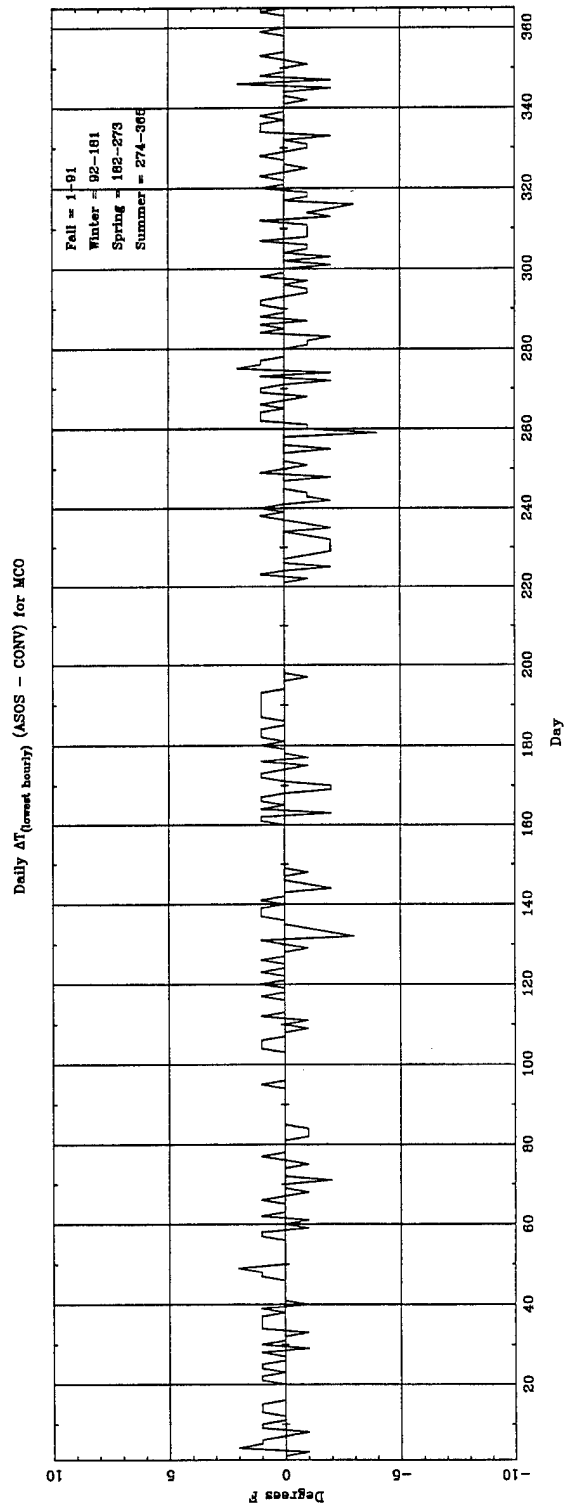
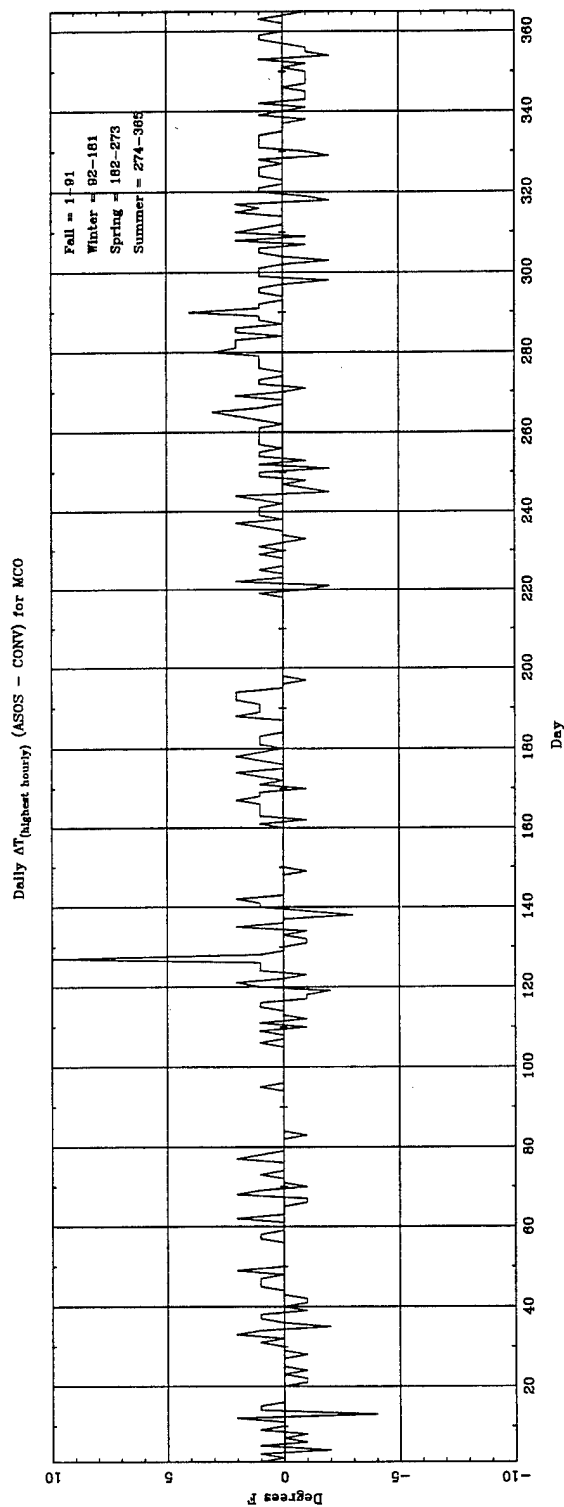


Daily $\Delta T_{\text{surface hourly}}$ (ASOS - CONV) for MCI

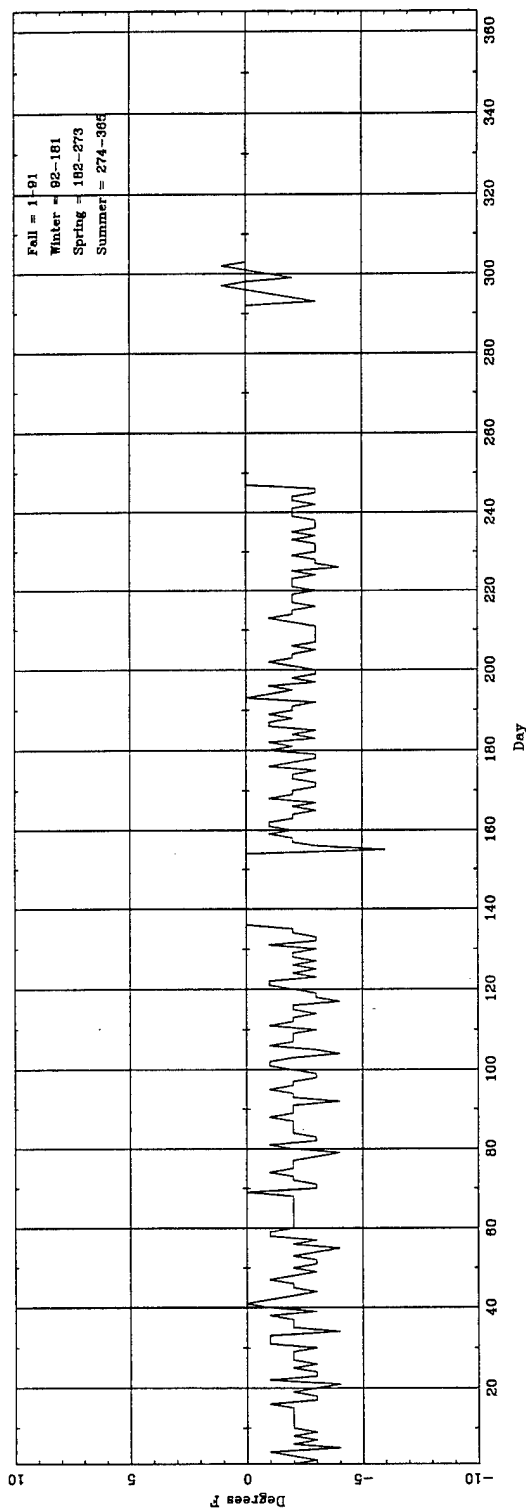


Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for MCI

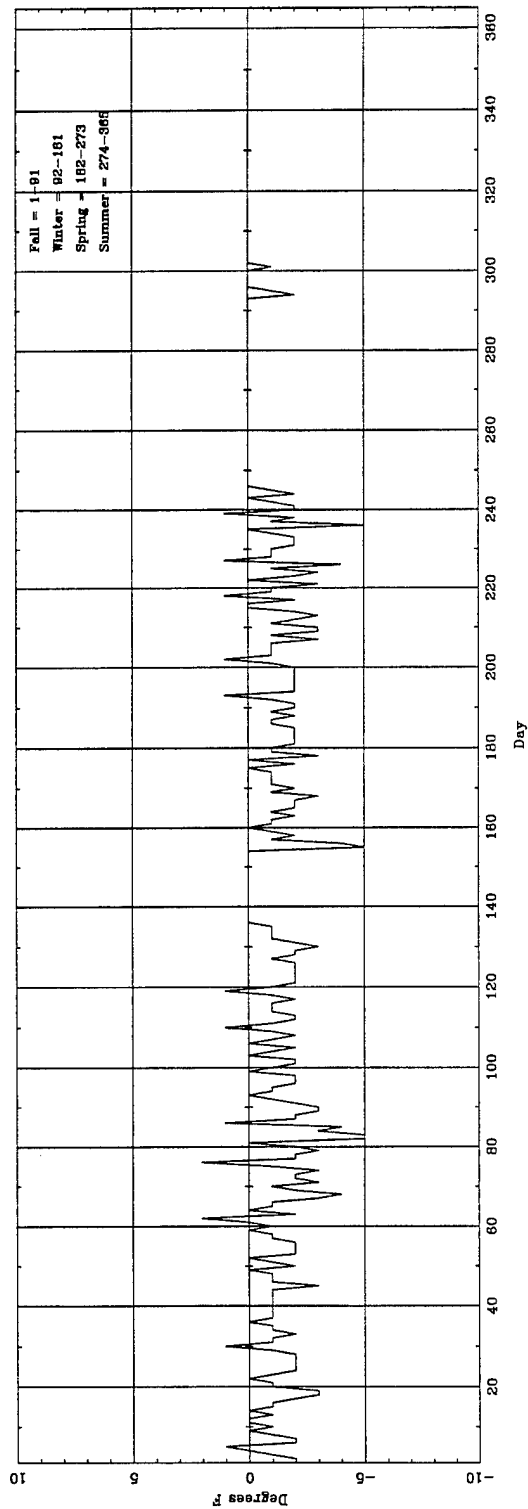




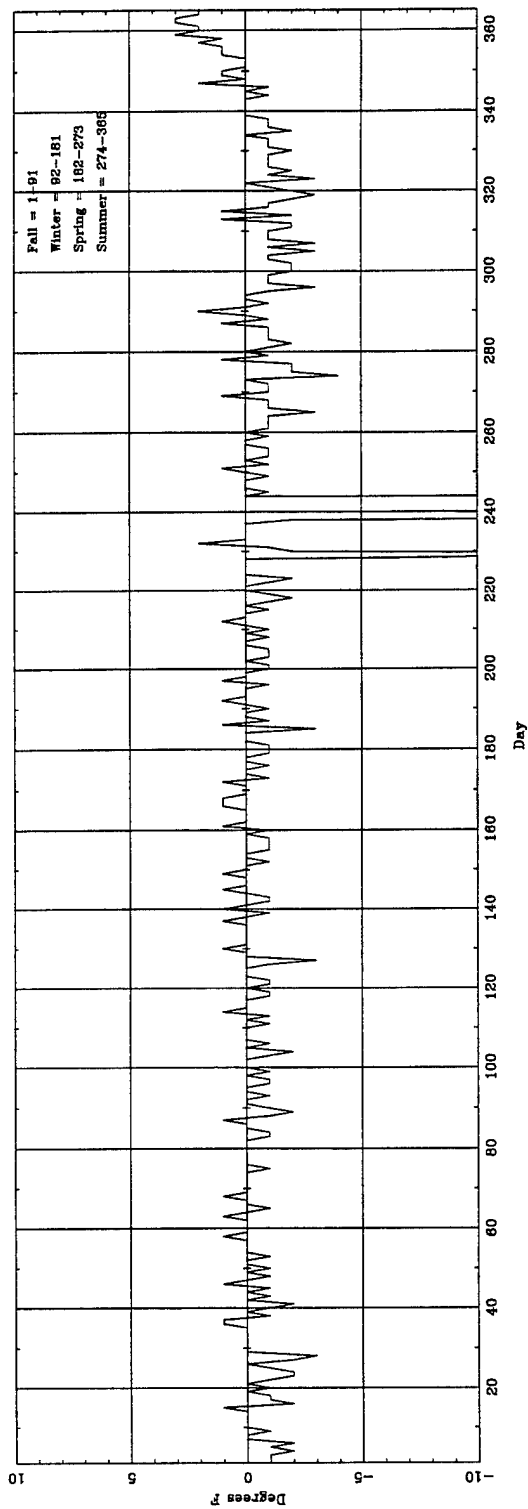
Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONV) for MGM



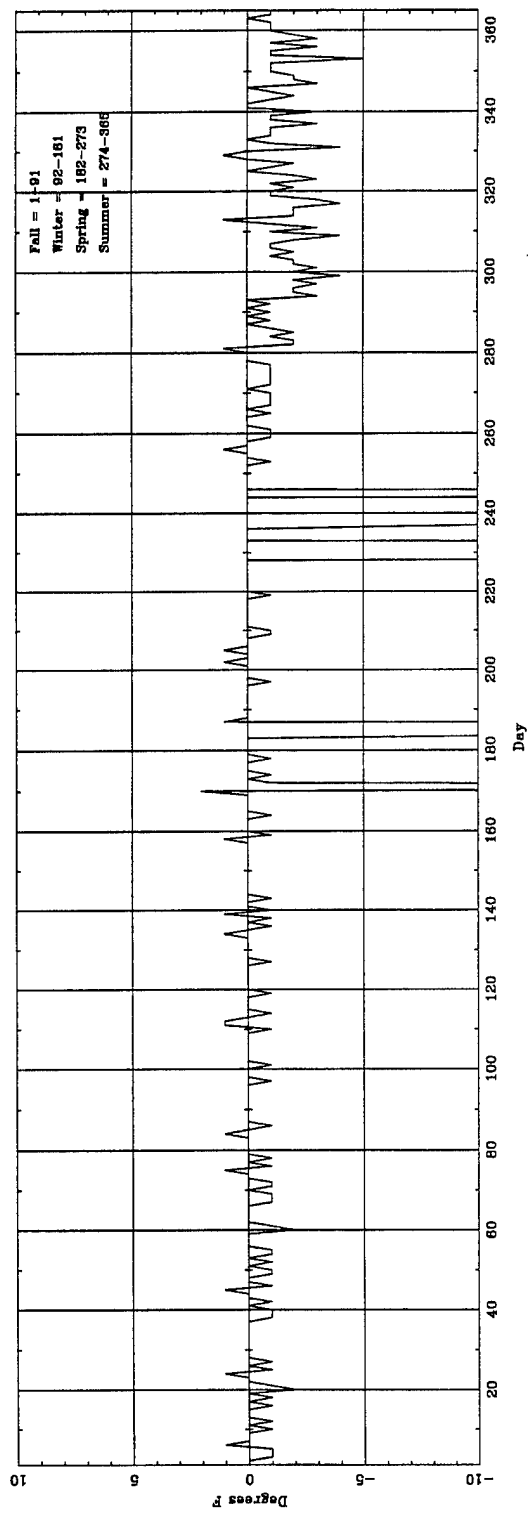
Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for MGM



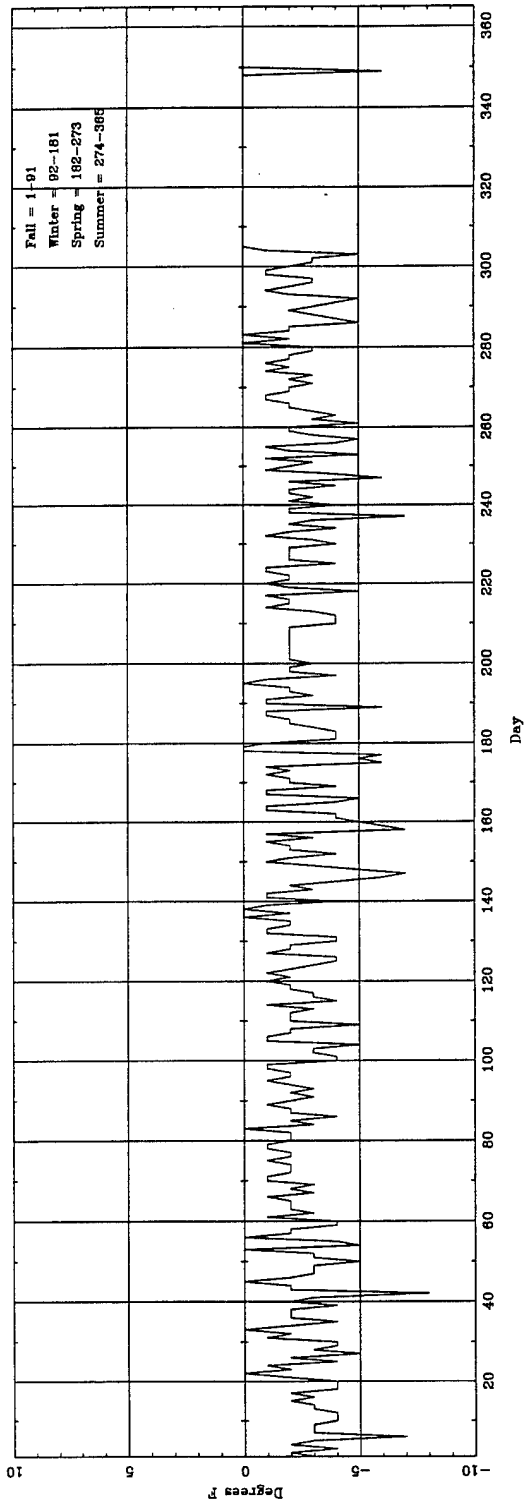
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for MHS



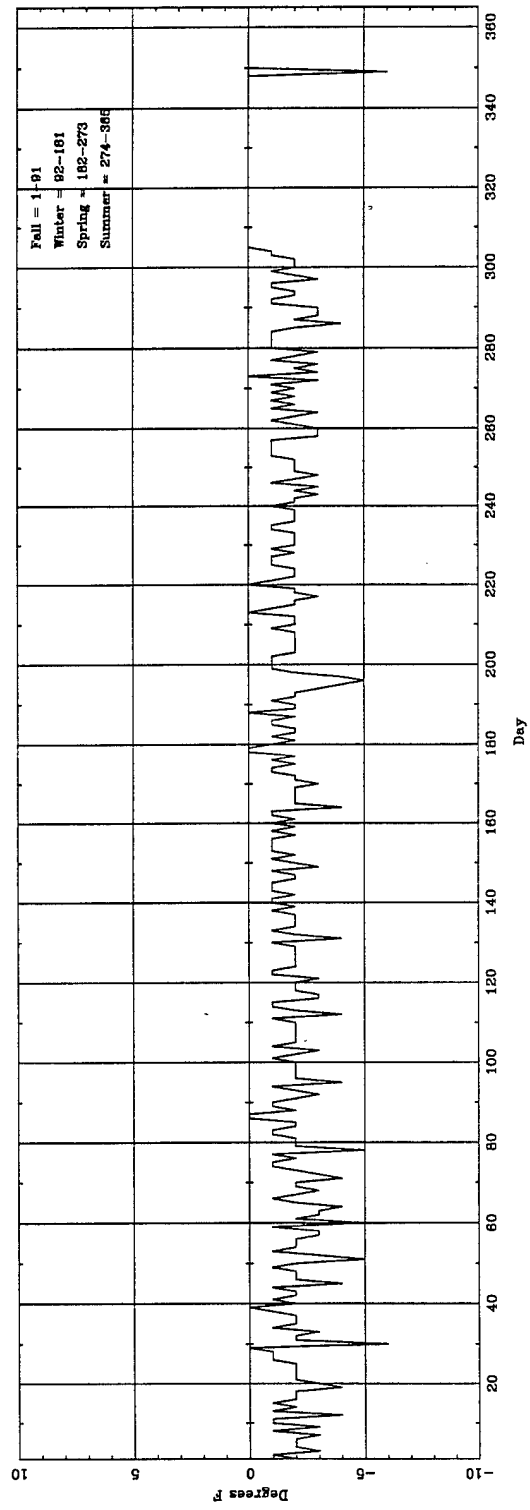
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for MHS



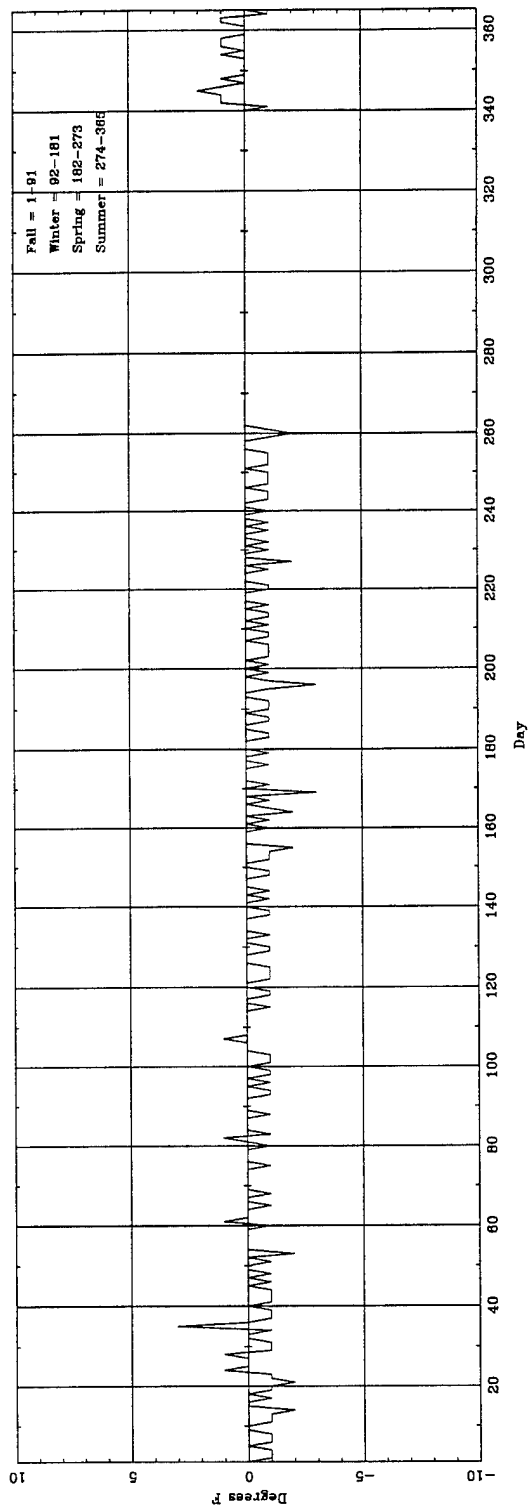
Daily $\Delta T_{\text{(highest hourly)}} (ASOS - CONV)$ for MKE



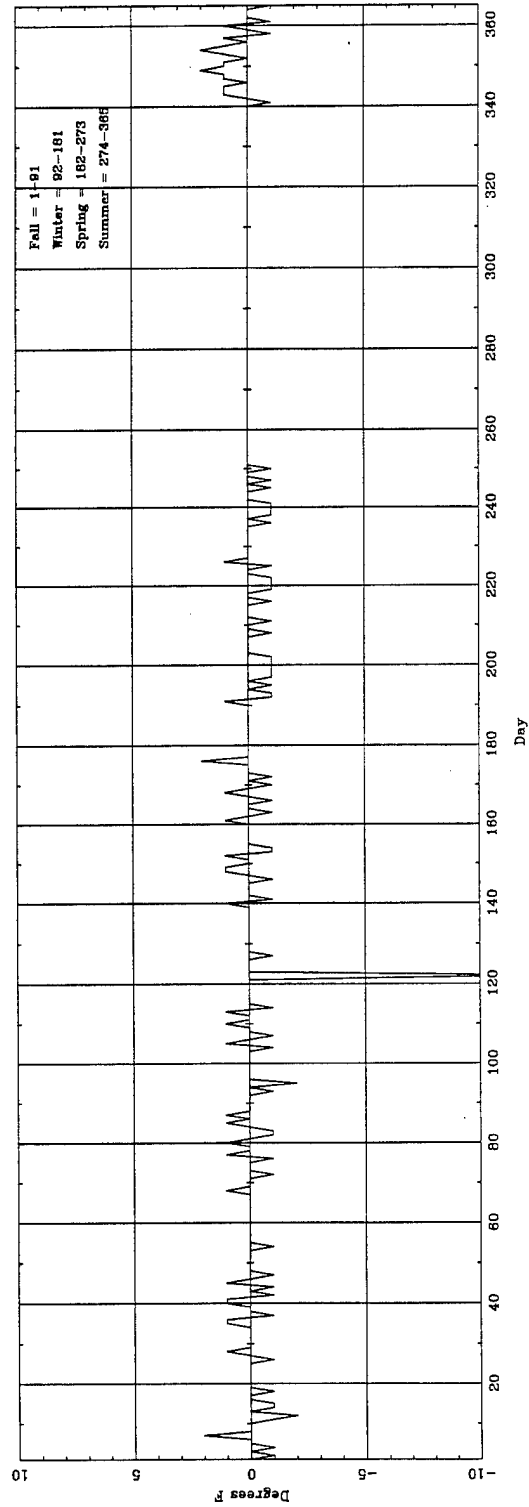
Daily $\Delta T_{\text{(lowest hourly)}} (ASOS - CONV)$ for MKE



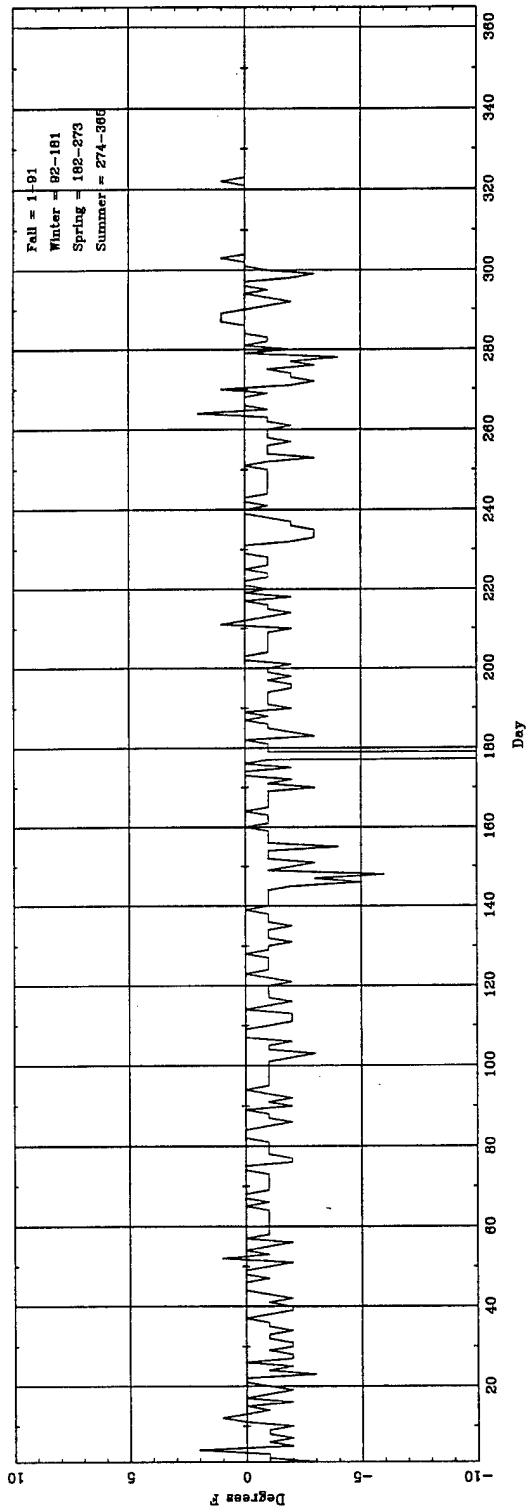
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for MKG



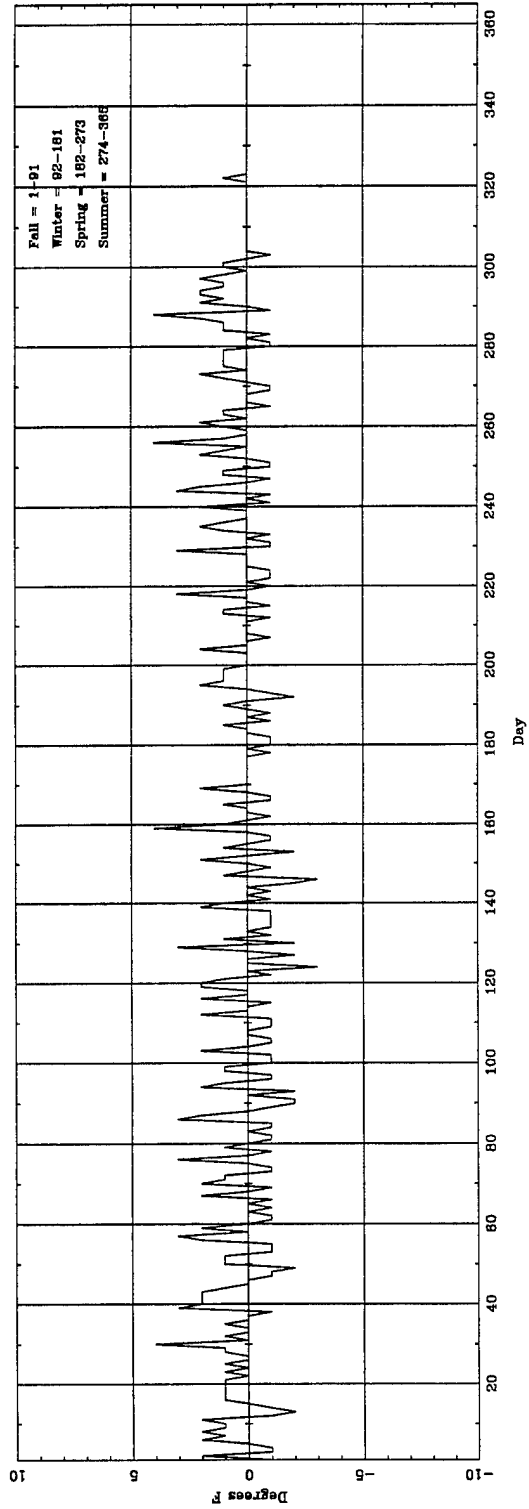
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for MKG



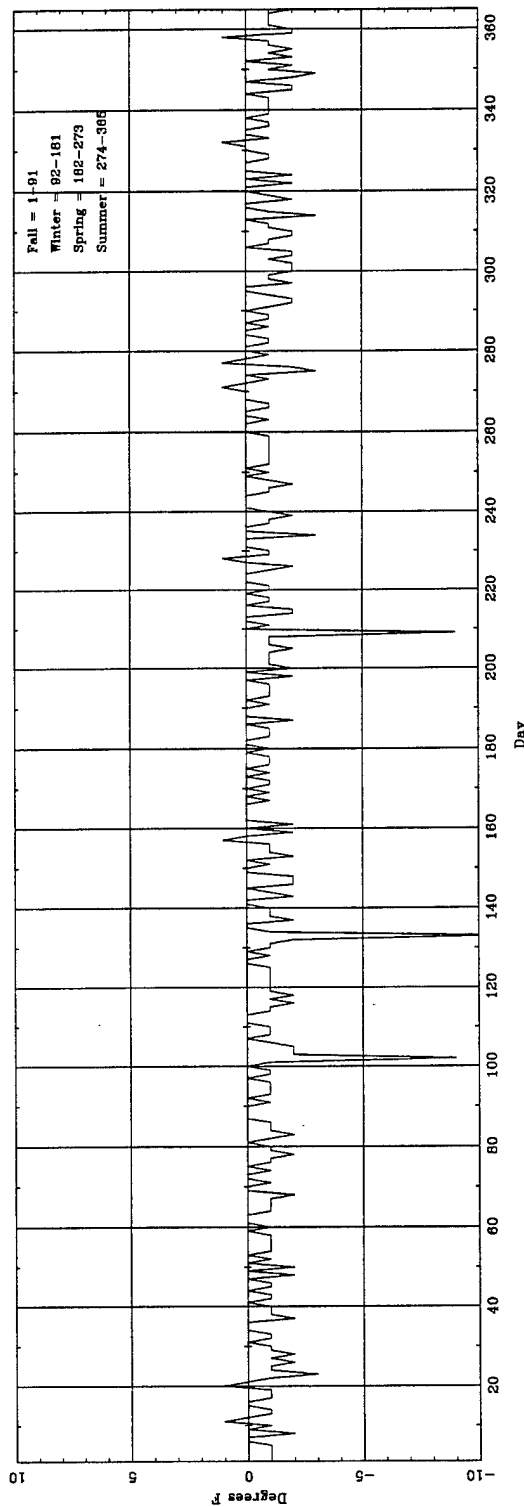
Daily ΔT (highest hourly) (ASOS - CONW) for MLI



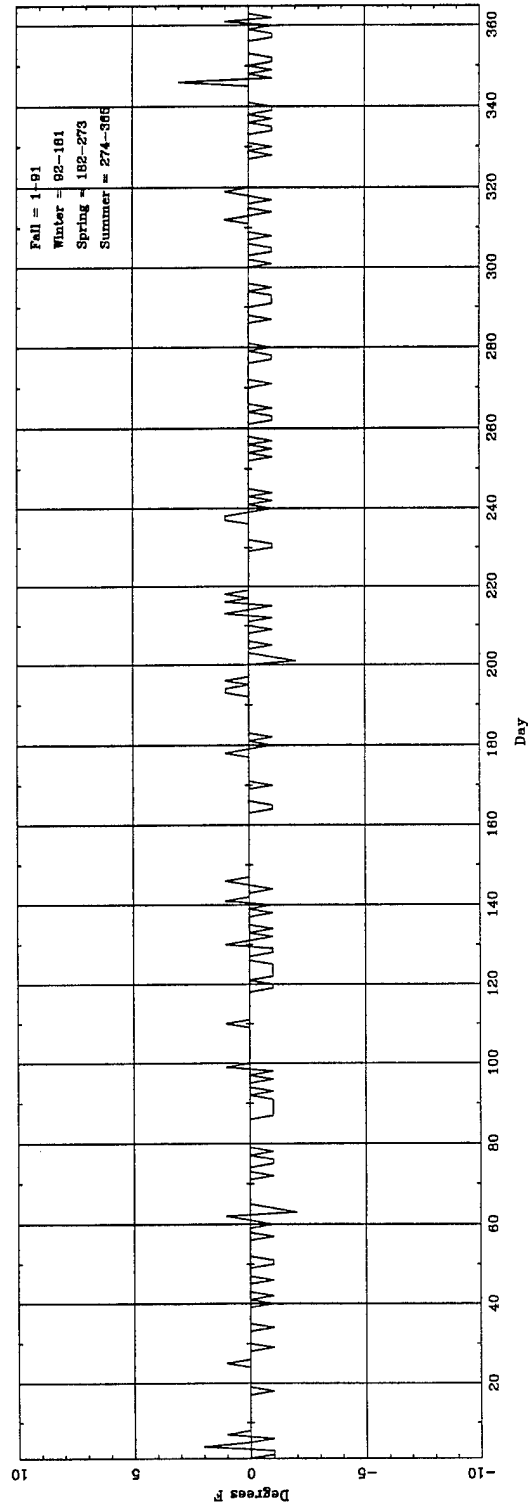
Daily ΔT (lowest hourly) (ASOS - CONW) for MLI



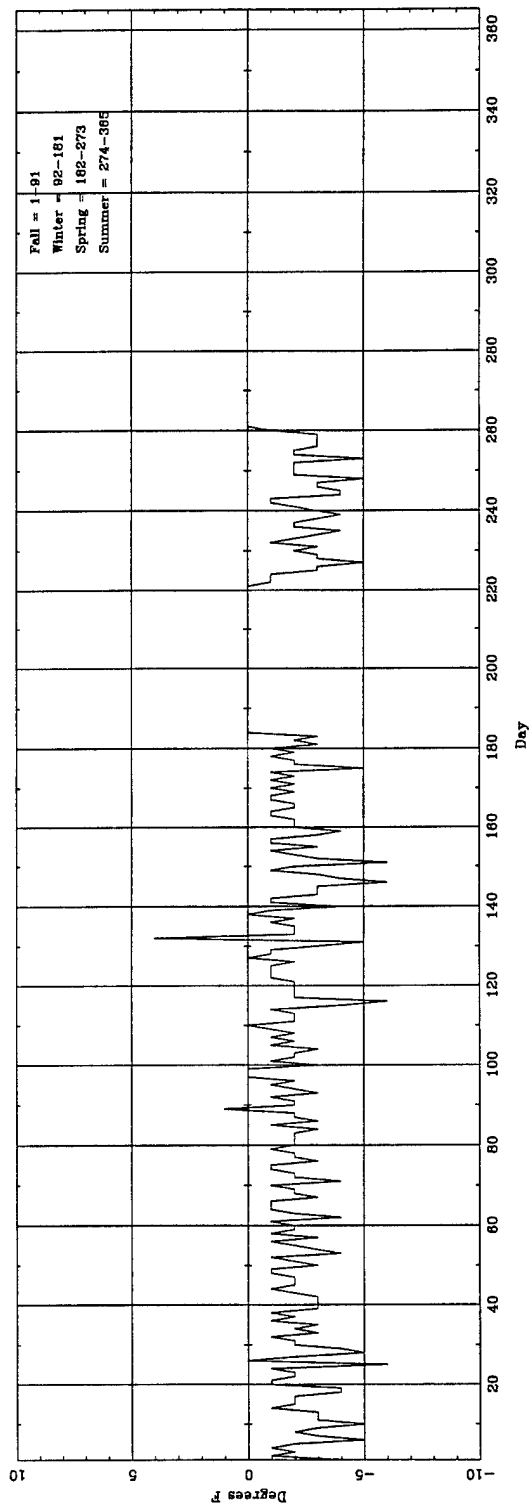
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for MOB



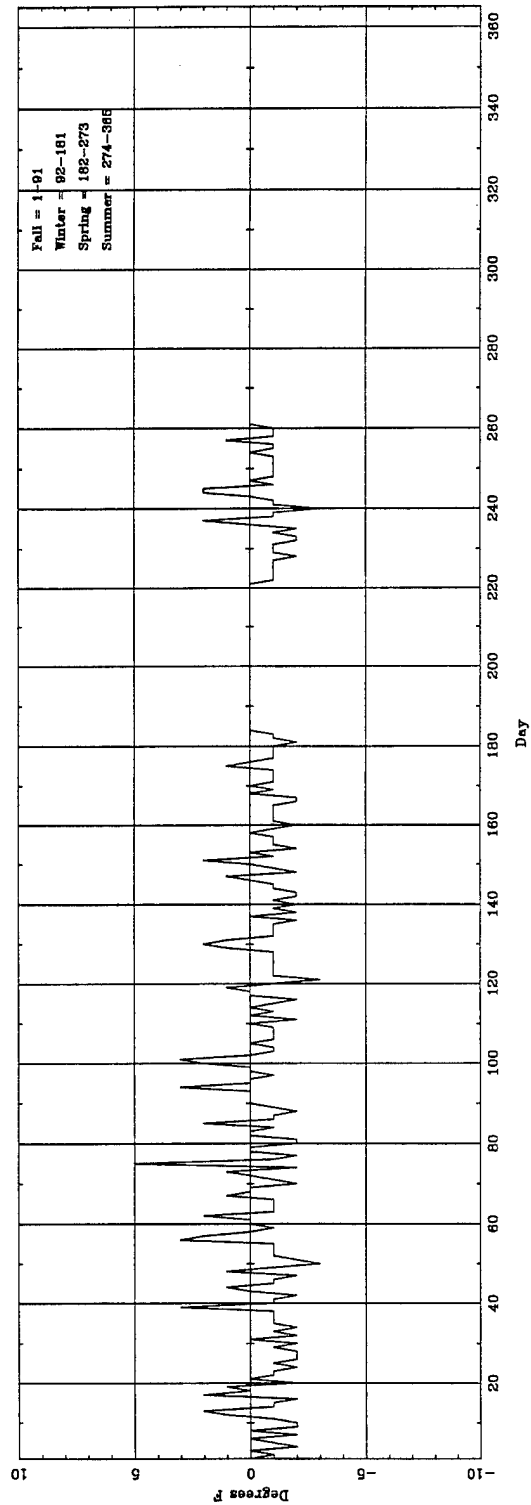
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for MOB



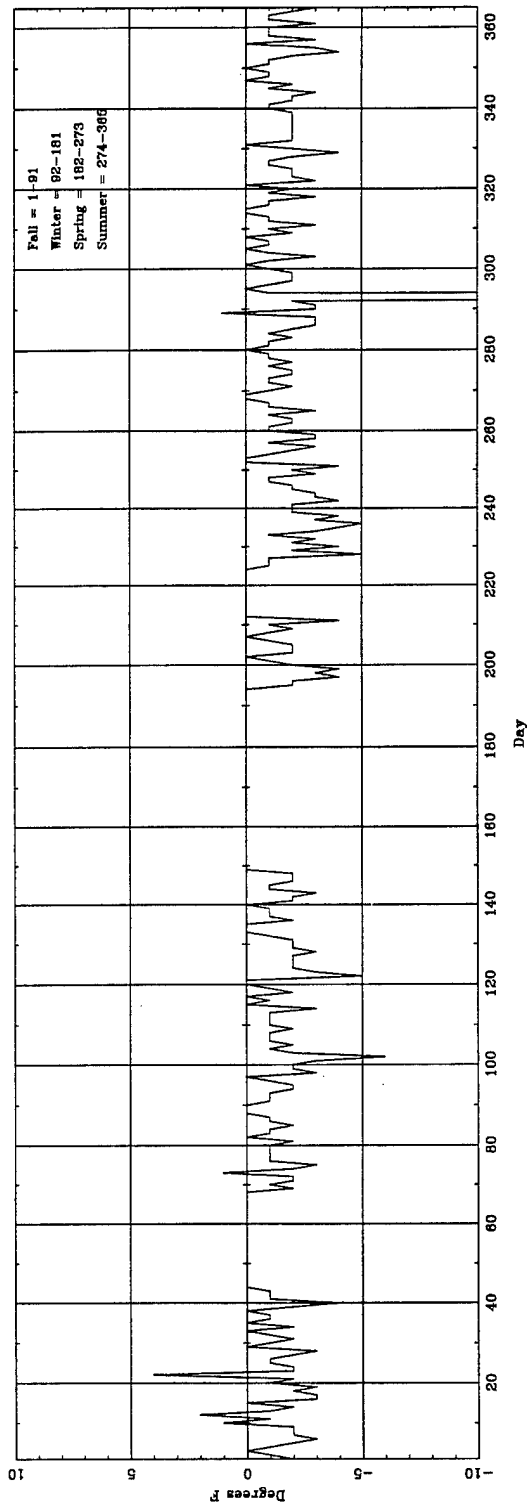
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for MSN



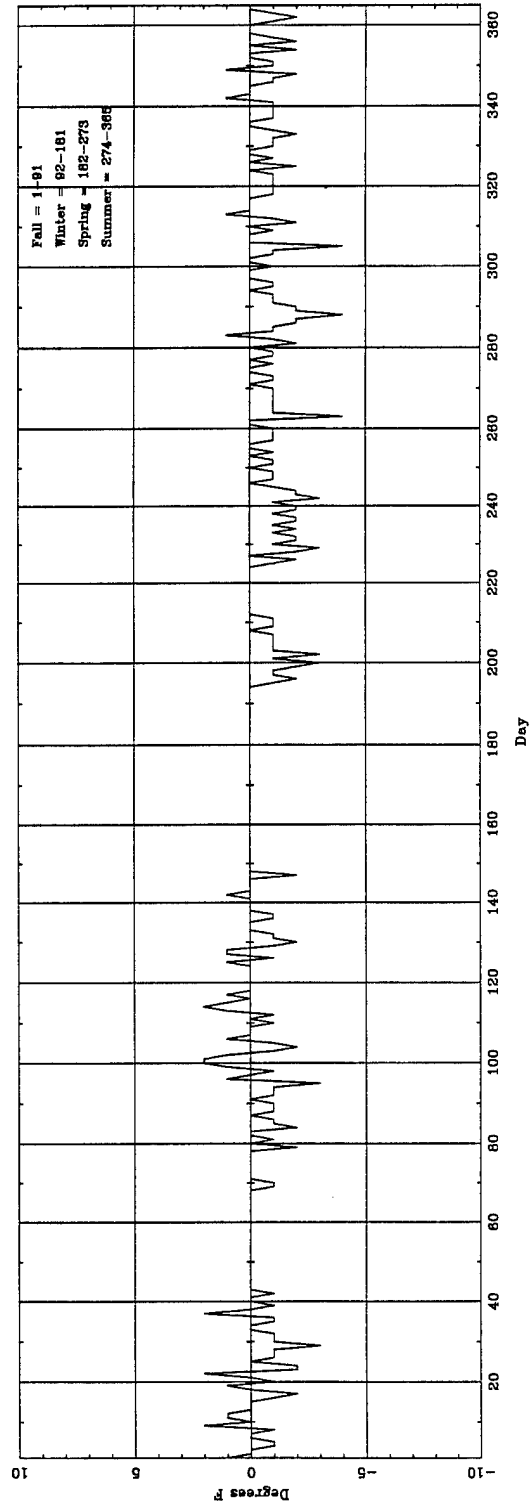
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for MSN



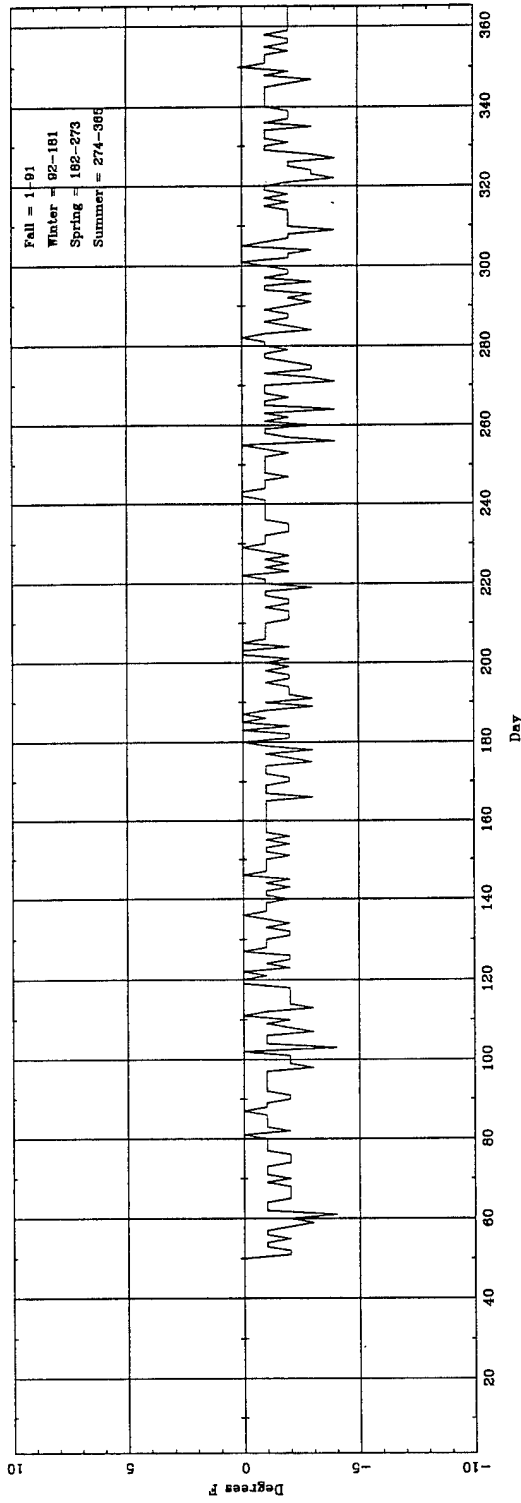
Daily $\Delta T_{\text{quietest hourly}}$ (ASOS - CONV) for MSO



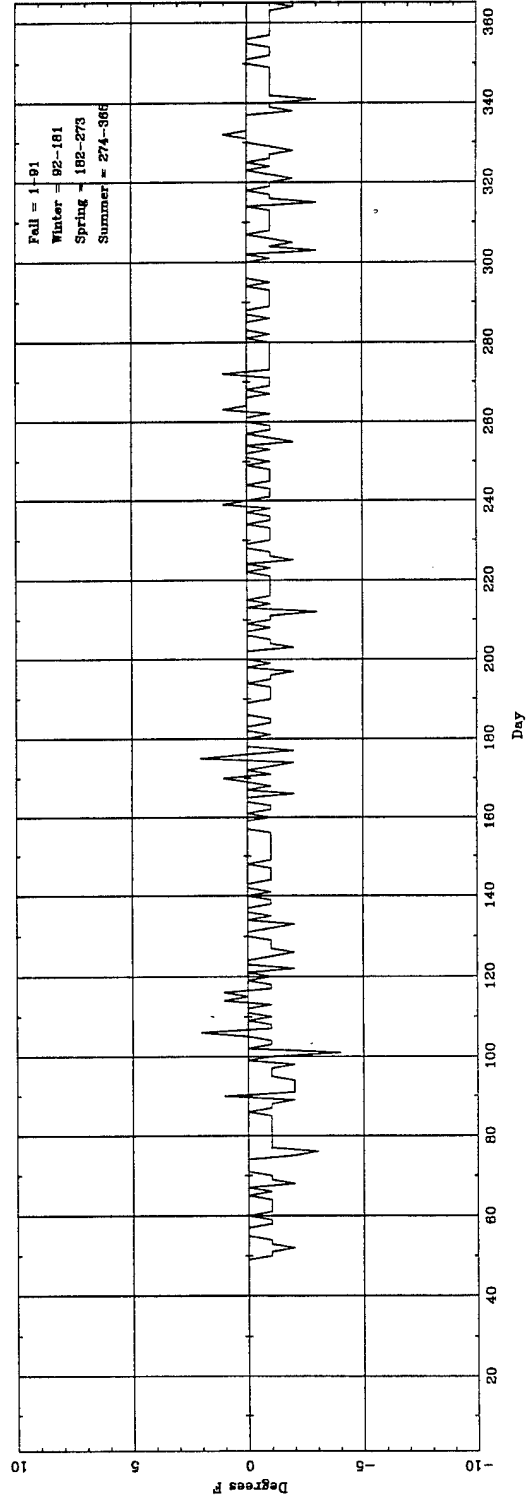
Daily $\Delta T_{\text{sunniest hourly}}$ (ASOS - CONV) for MSO



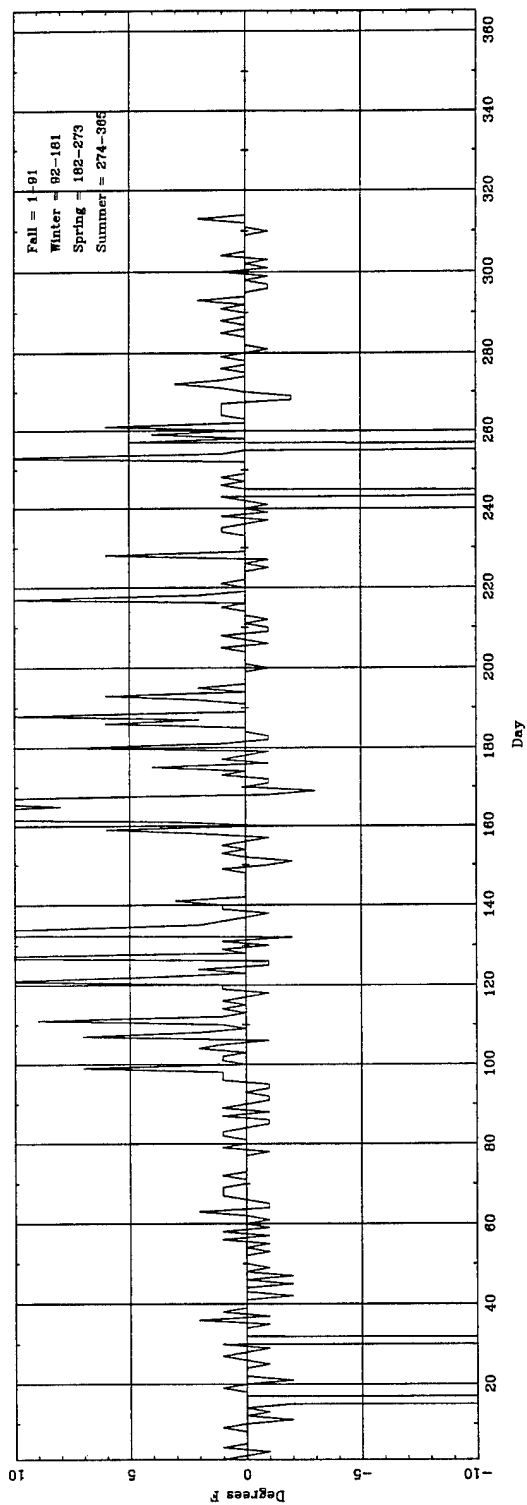
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for OFK



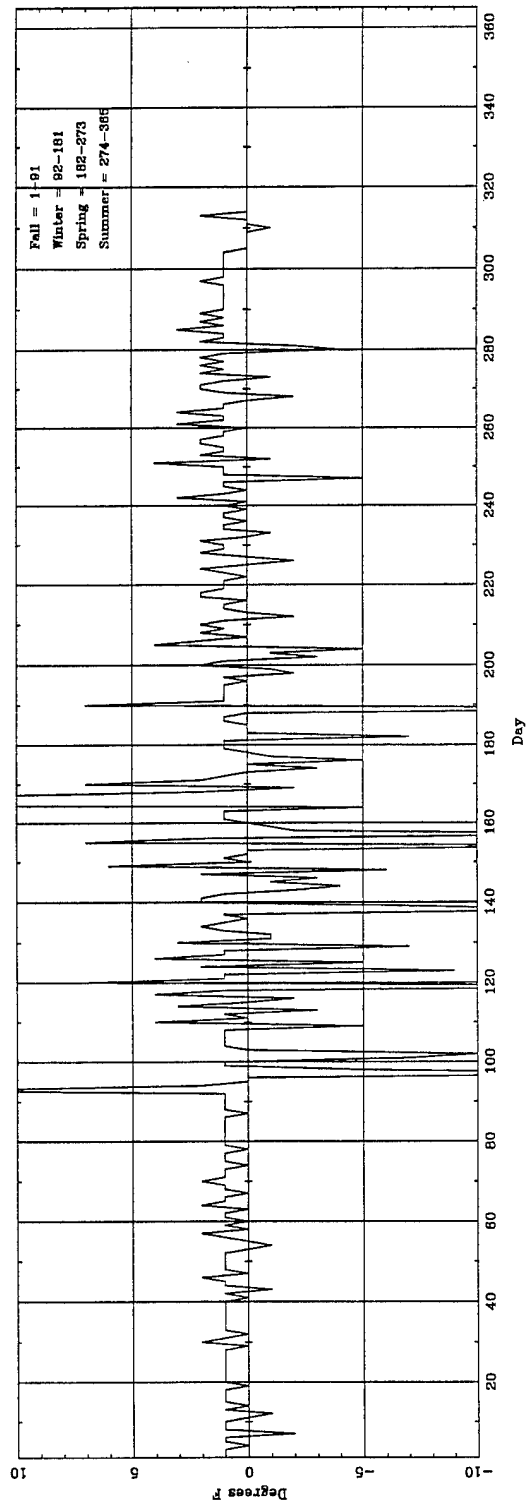
Daily $\Delta T_{\text{(forest hourly)}}$ (ASOS - CONV) for OFK



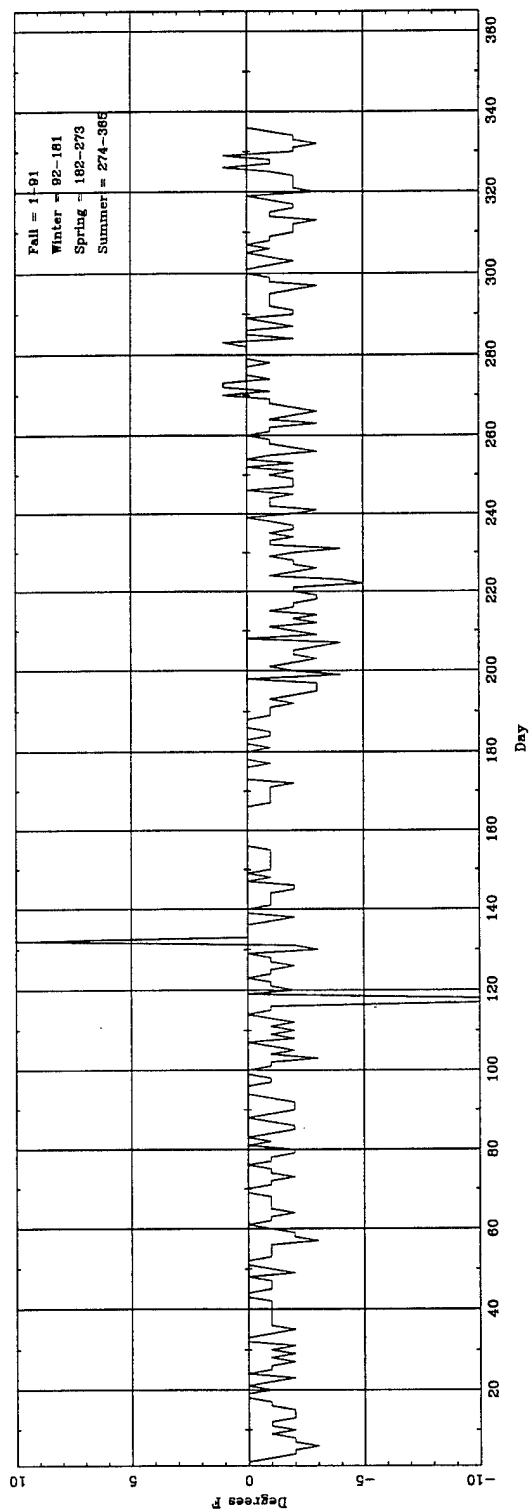
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for ORH



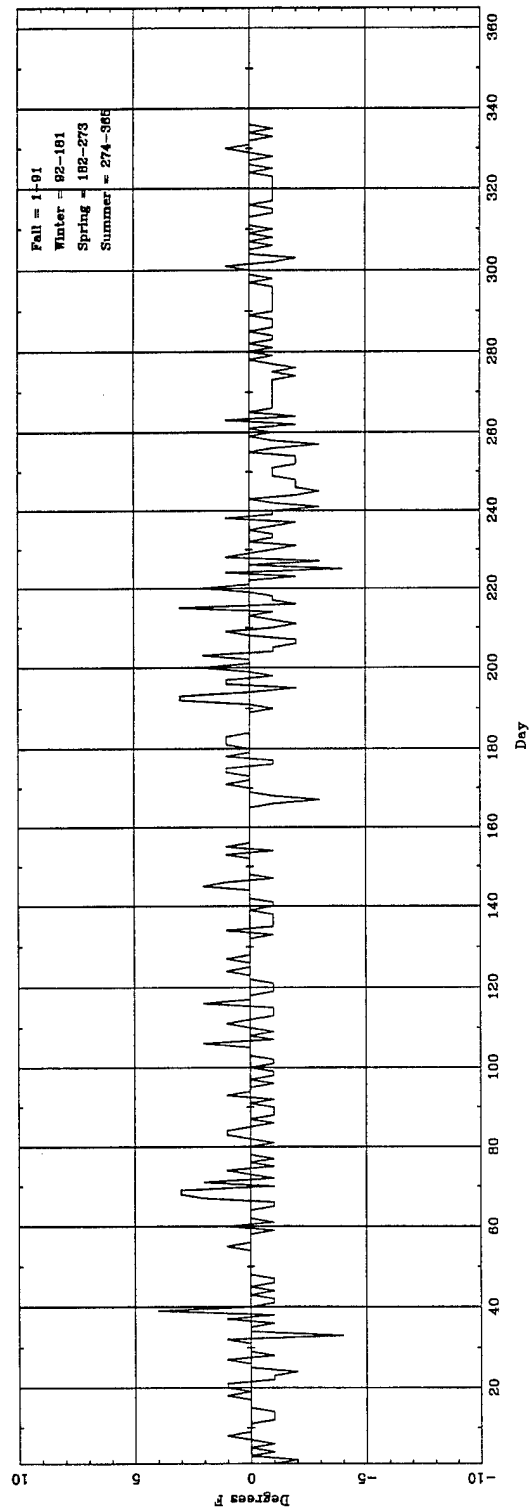
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for ORH



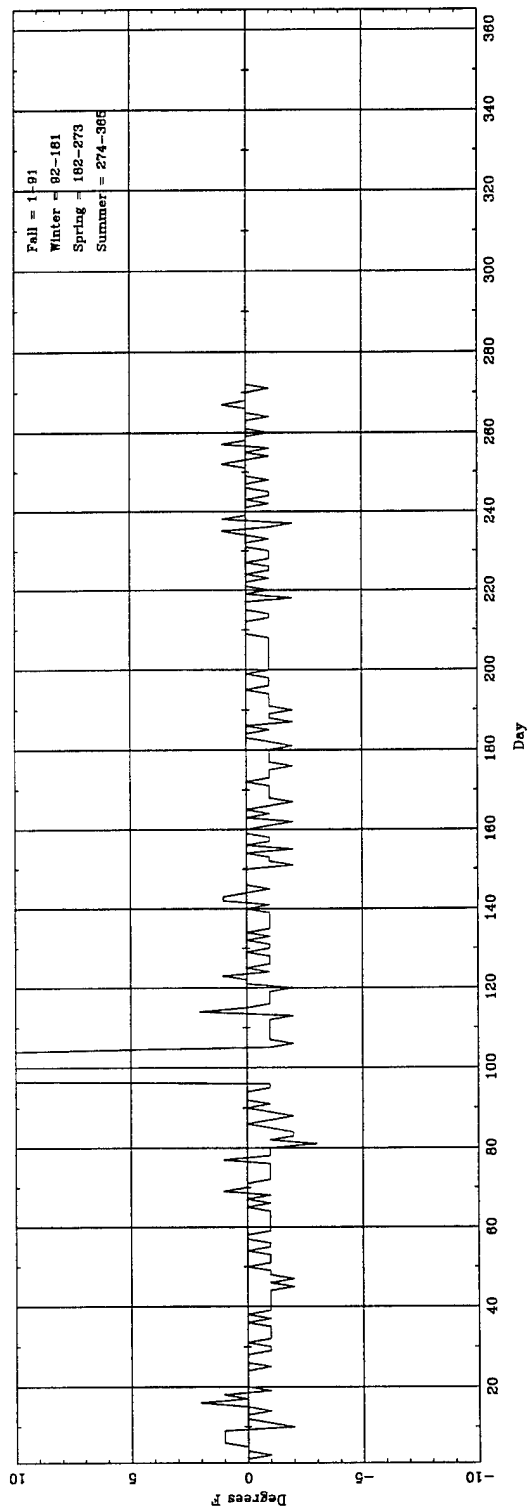
Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONV) for PAH



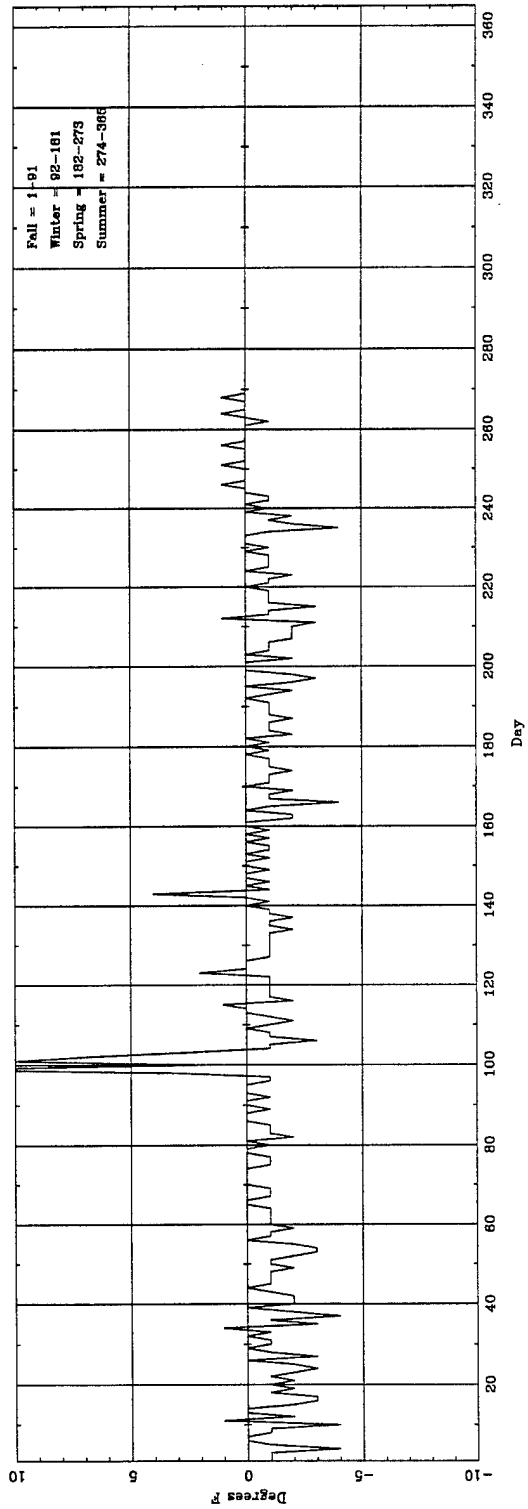
Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for PAH

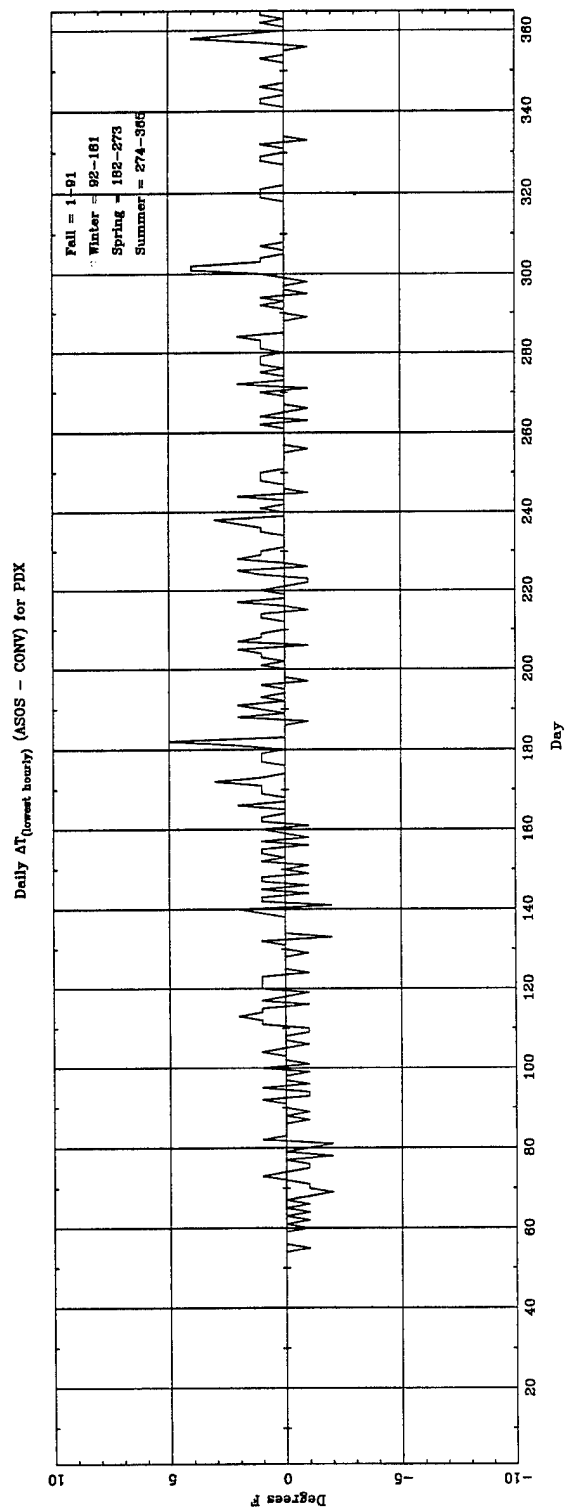
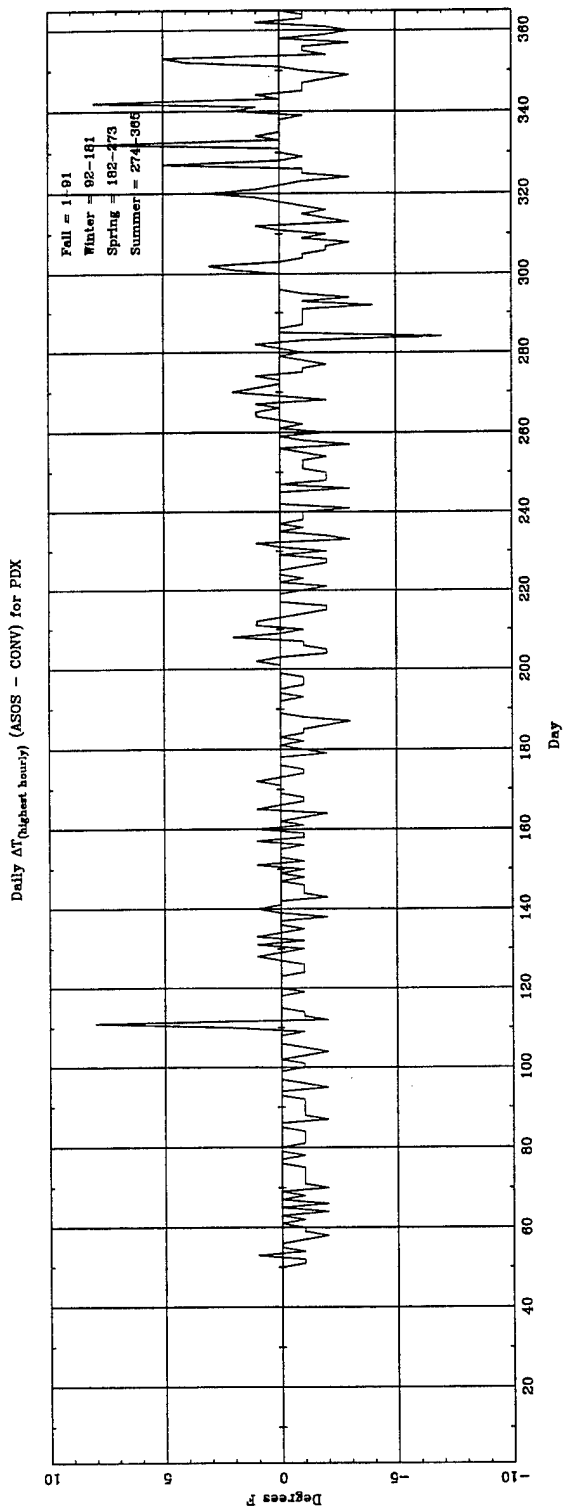


Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONV) for PDT

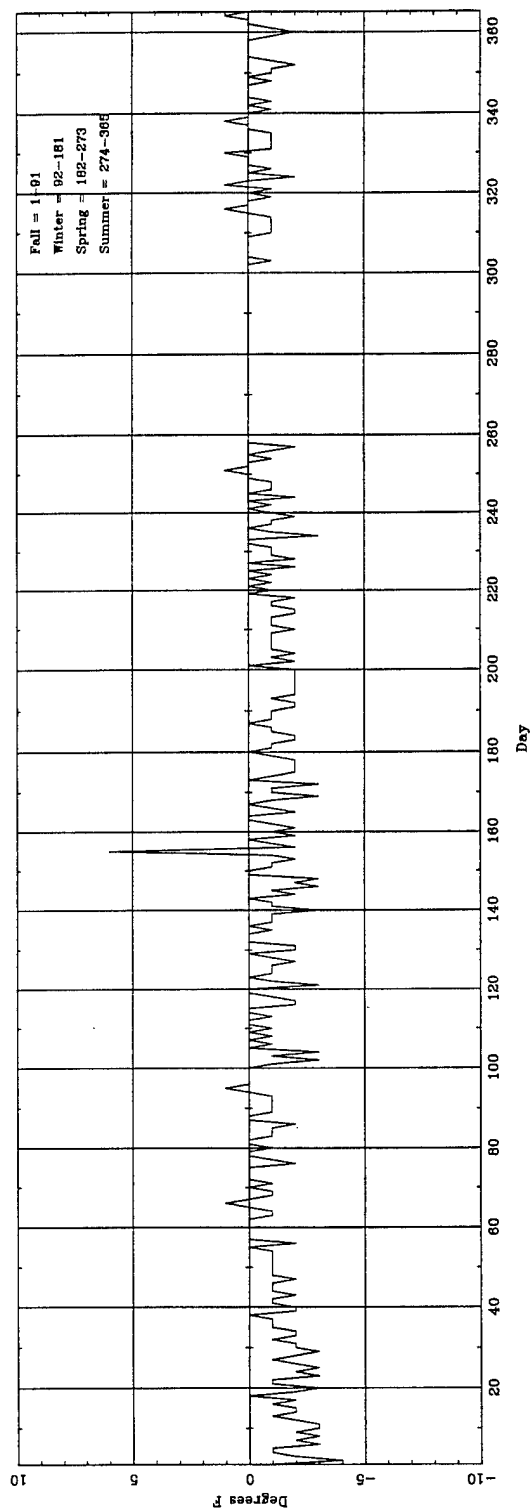


Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for PDT

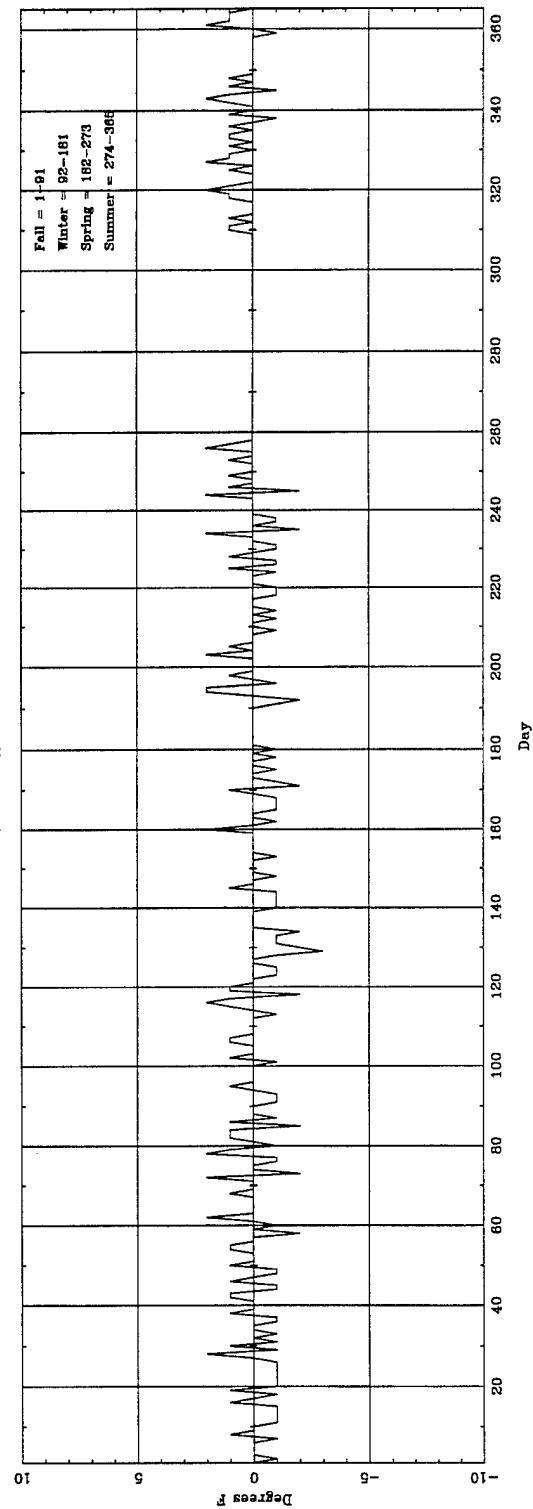




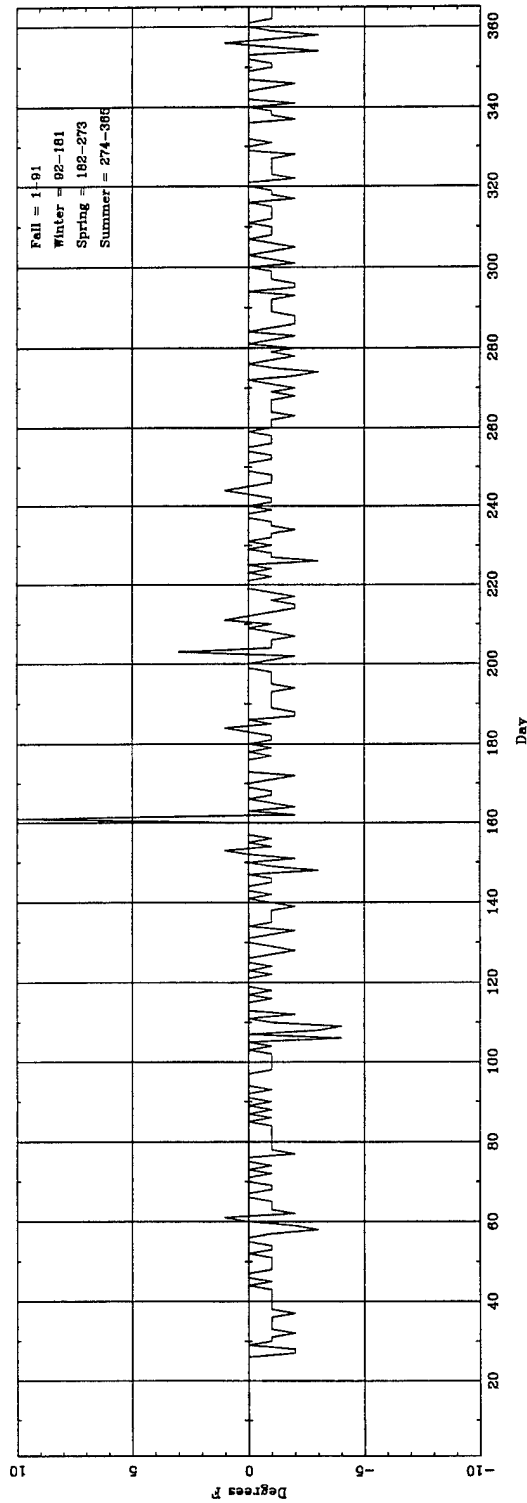
Daily $\Delta T_{\text{(highest hourly)}} (ASOS - CONV)$ for PIA



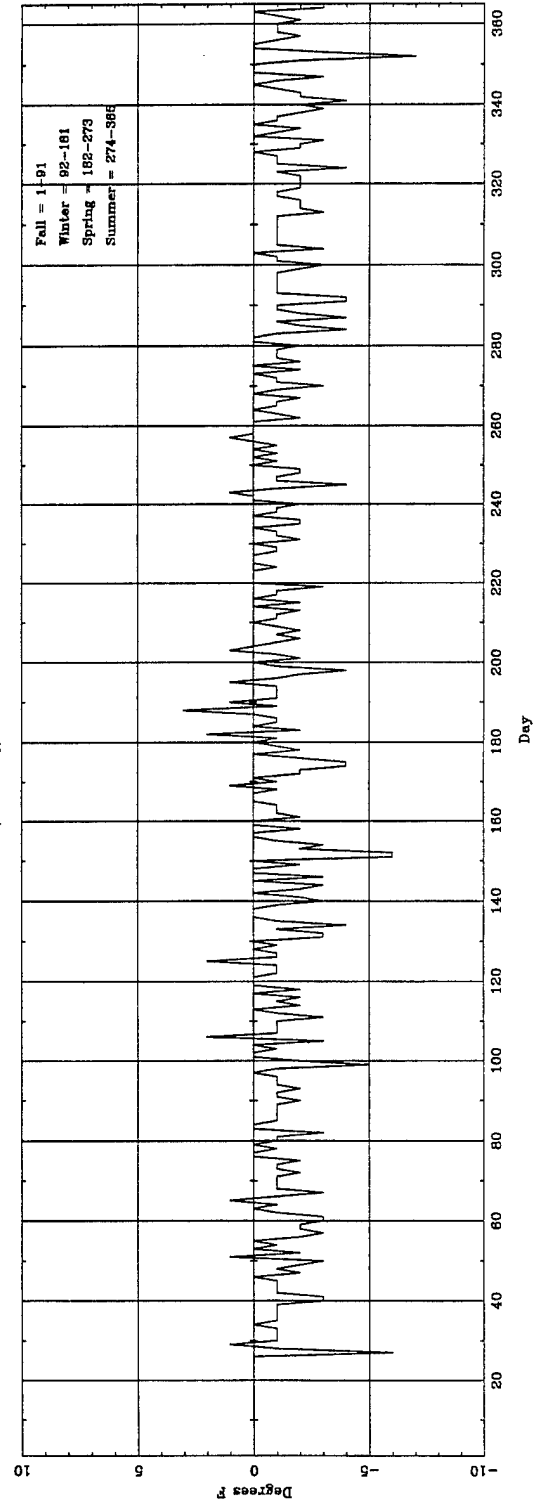
Daily $\Delta T_{\text{(lowest hourly)}} (ASOS - CONV)$ for PIA



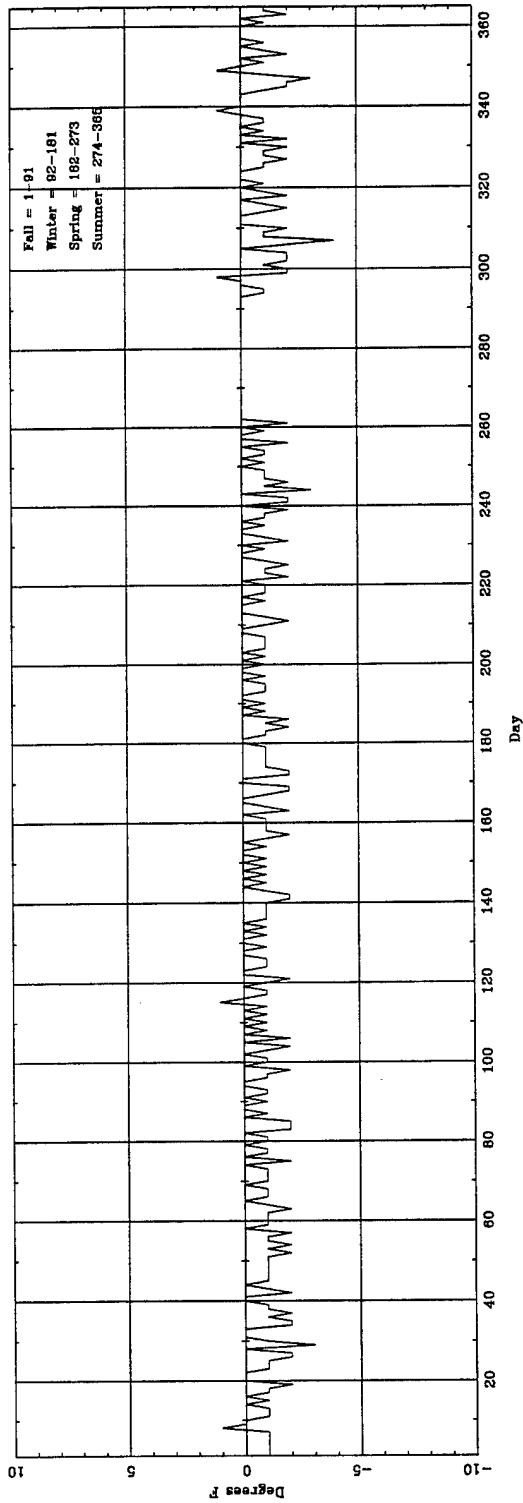
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for RAP



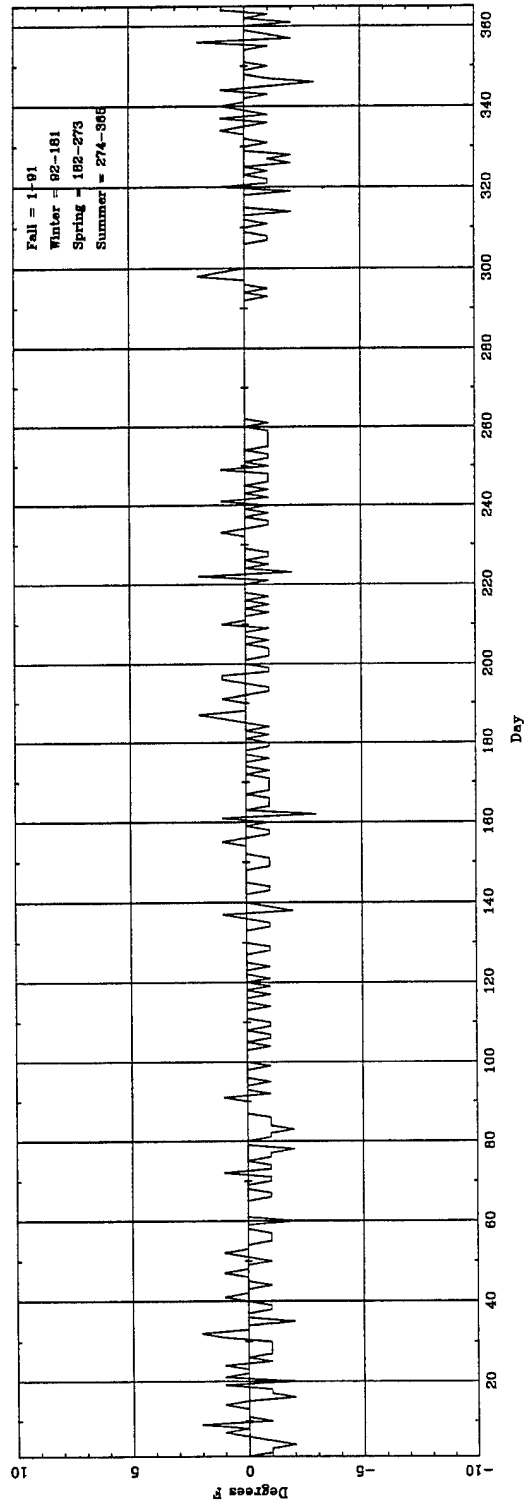
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for RAP

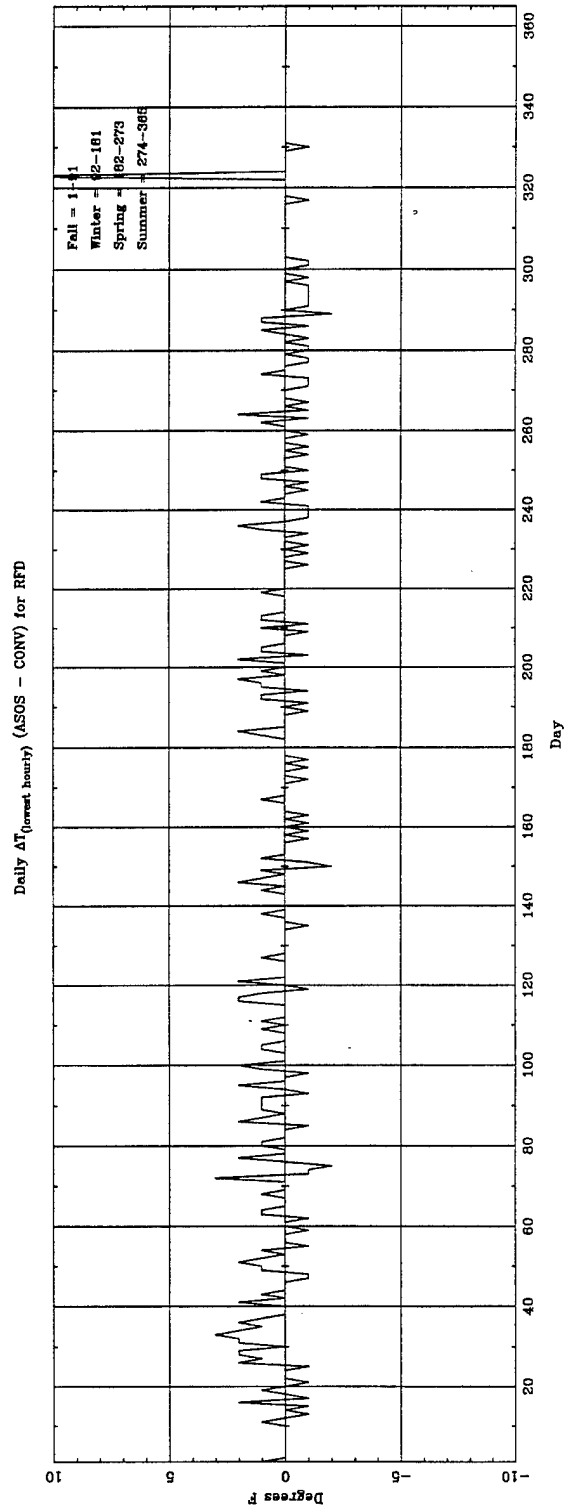
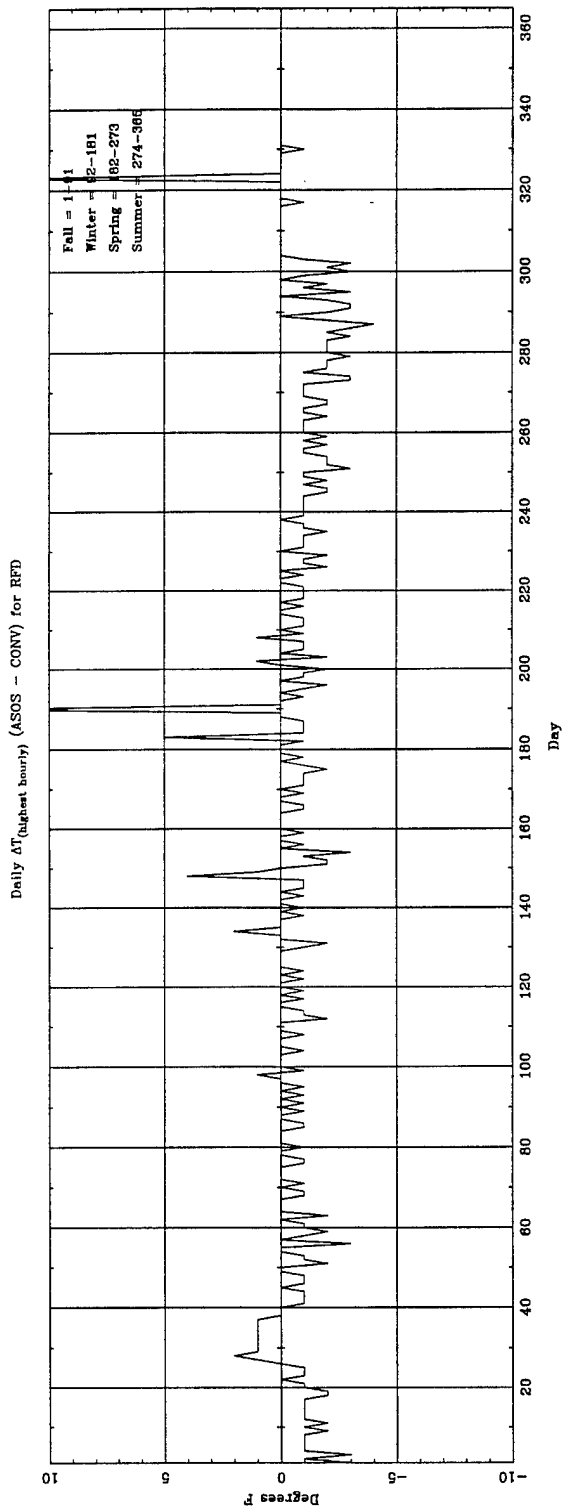


Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for RDD

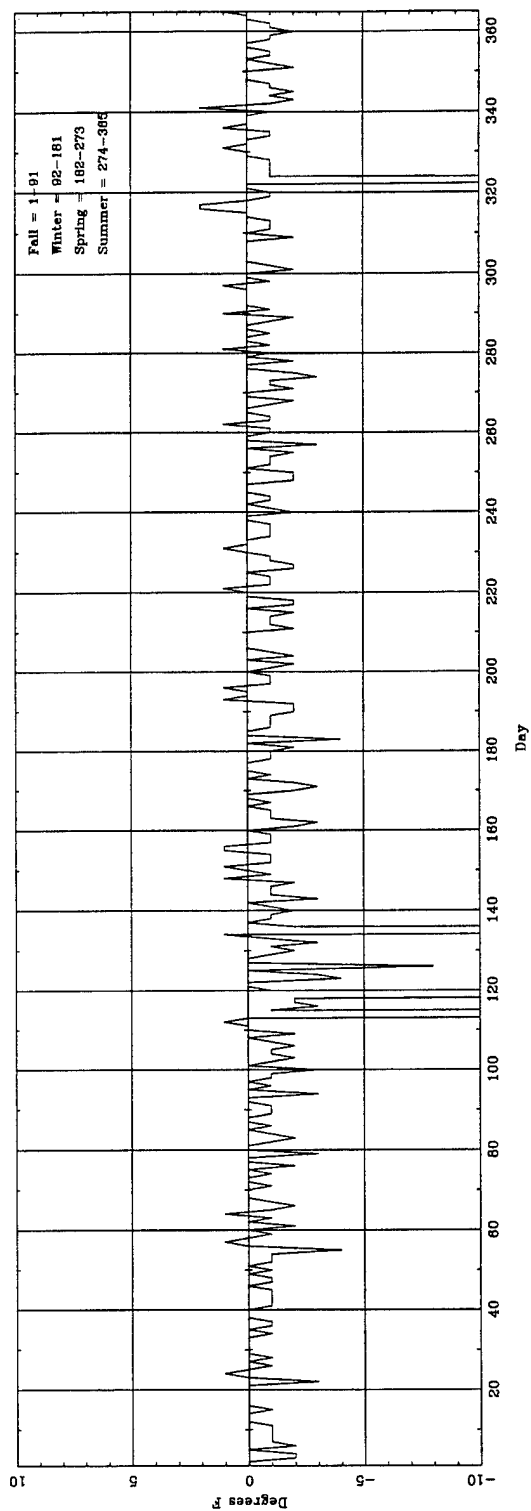


Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for RDD

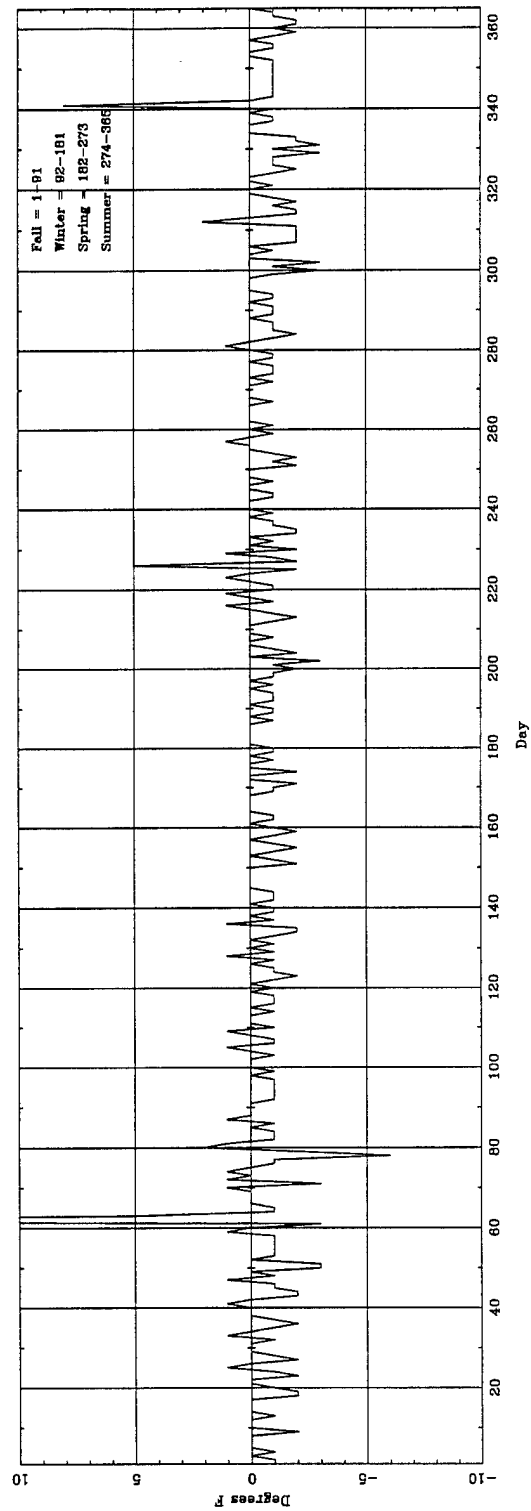


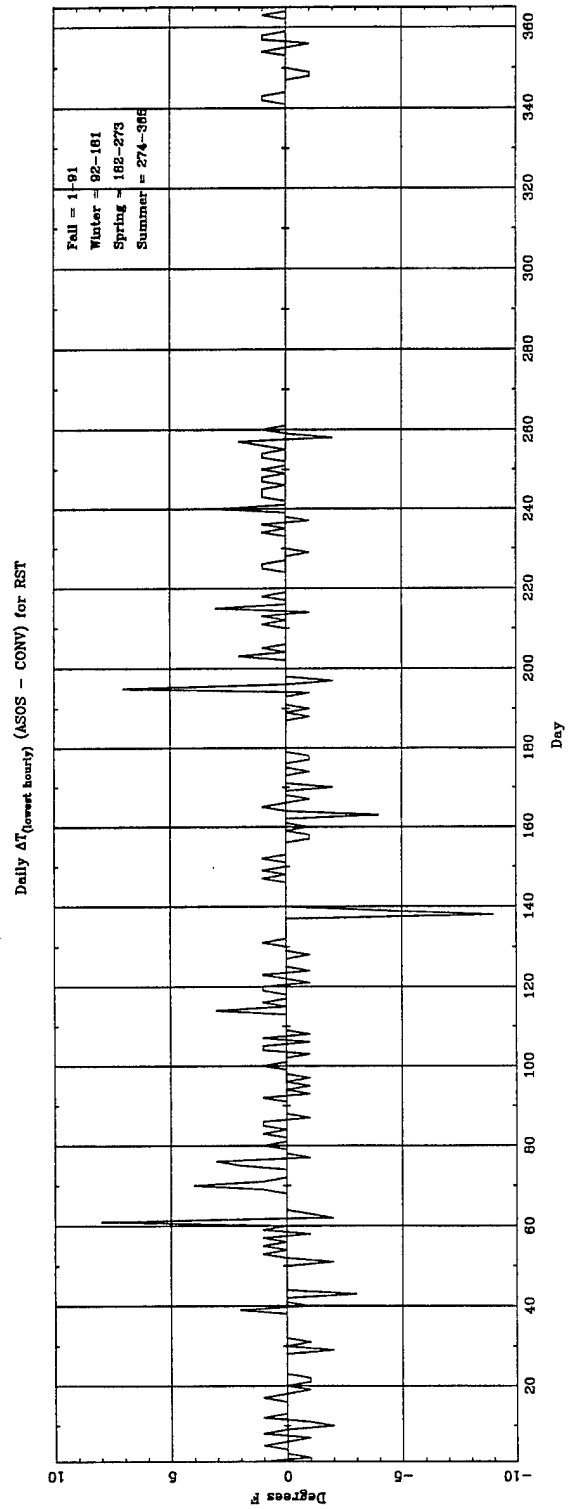
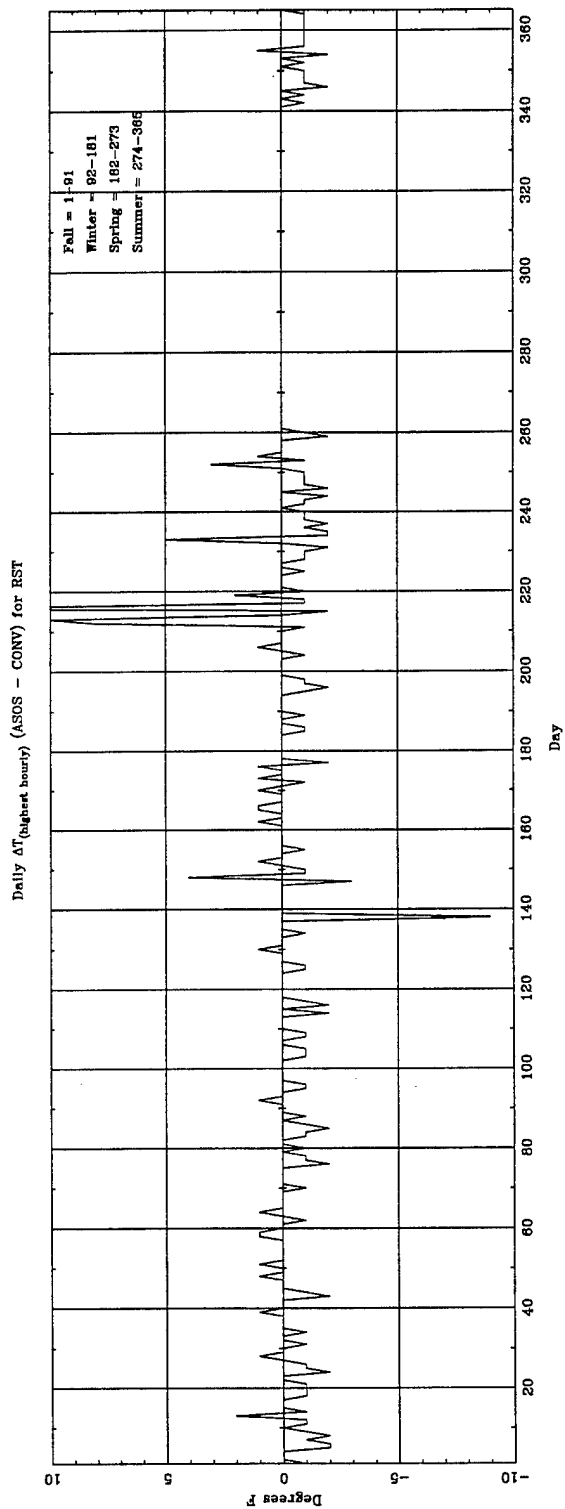


Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for RSL

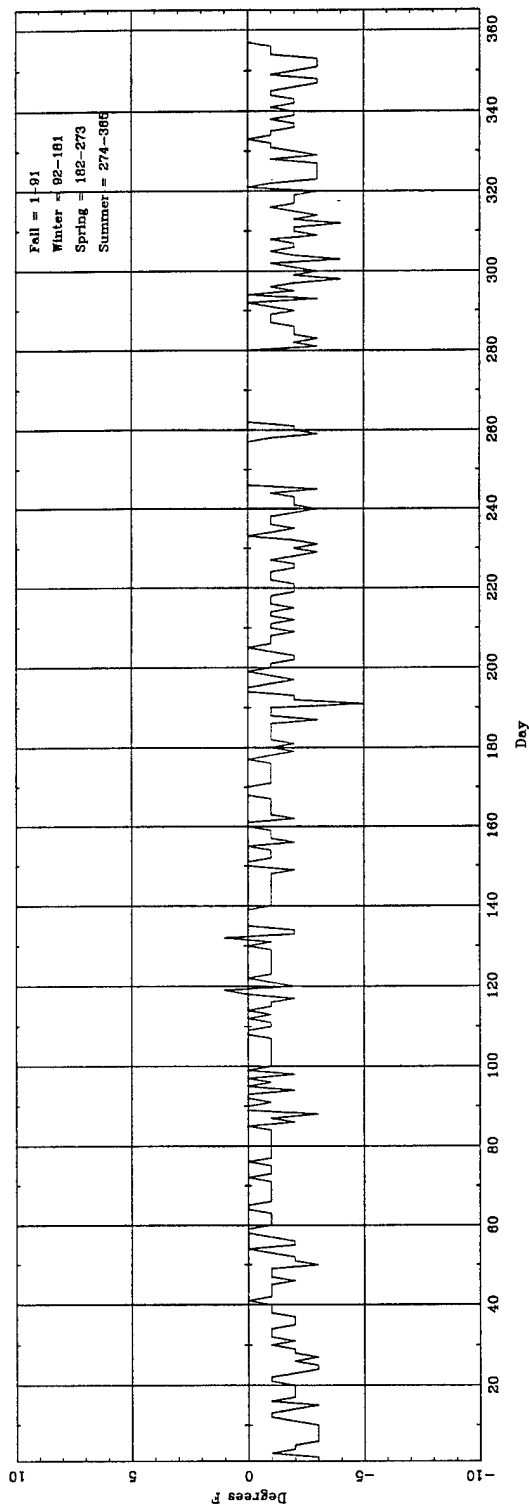


Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for RSL

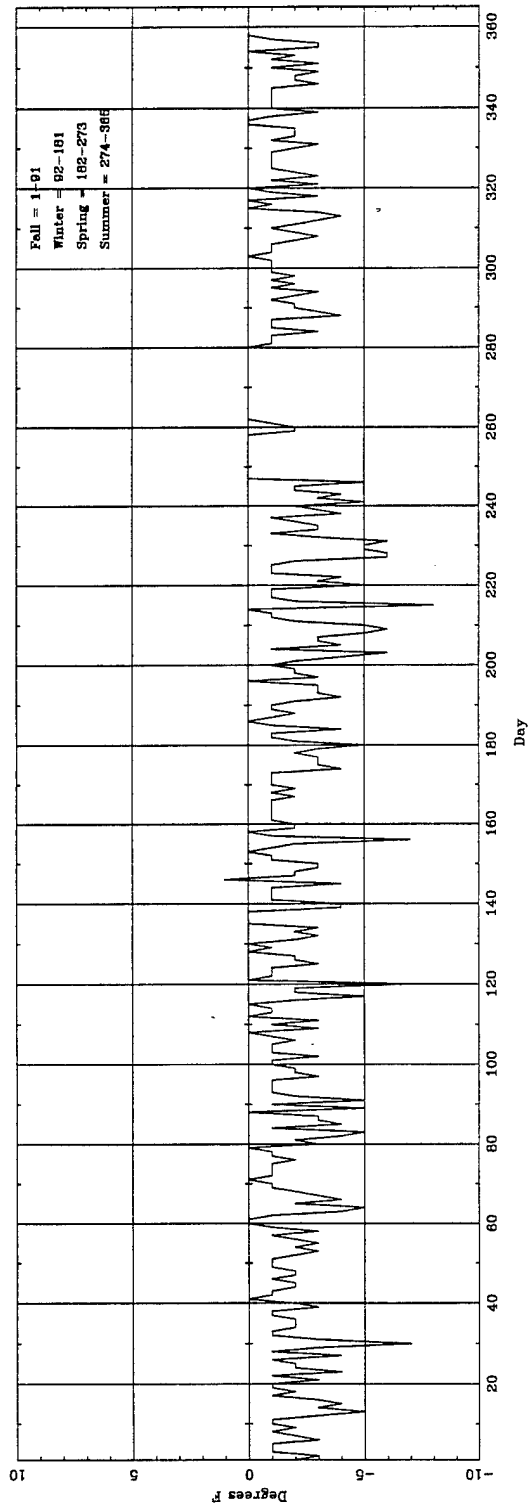




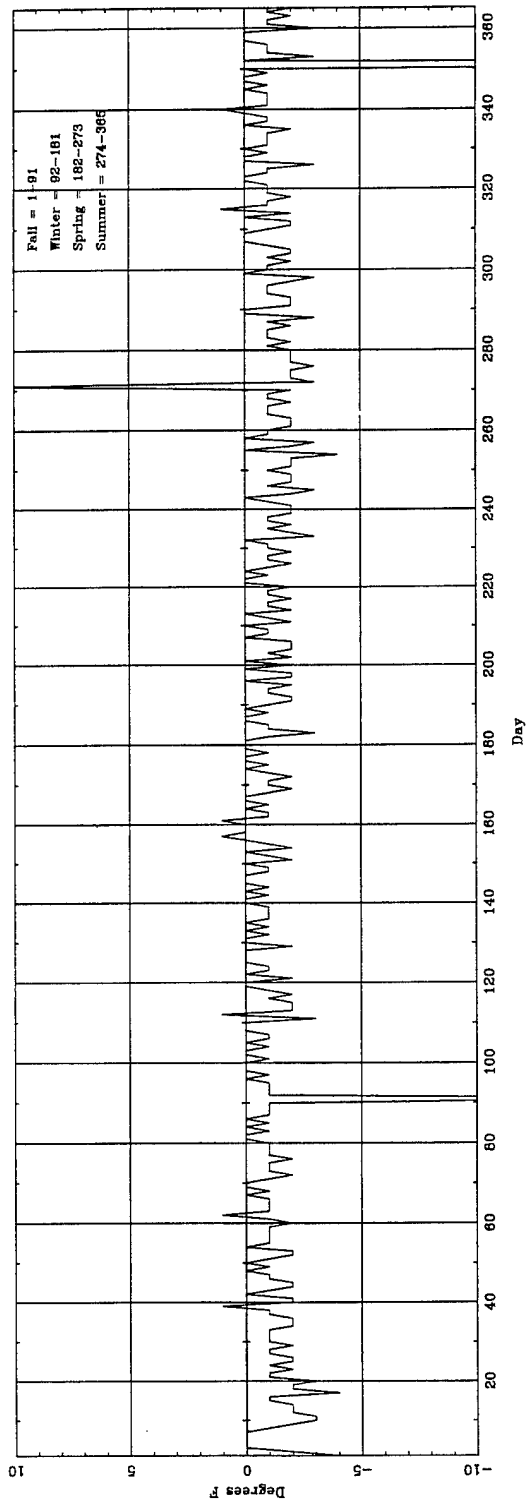
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for SAV



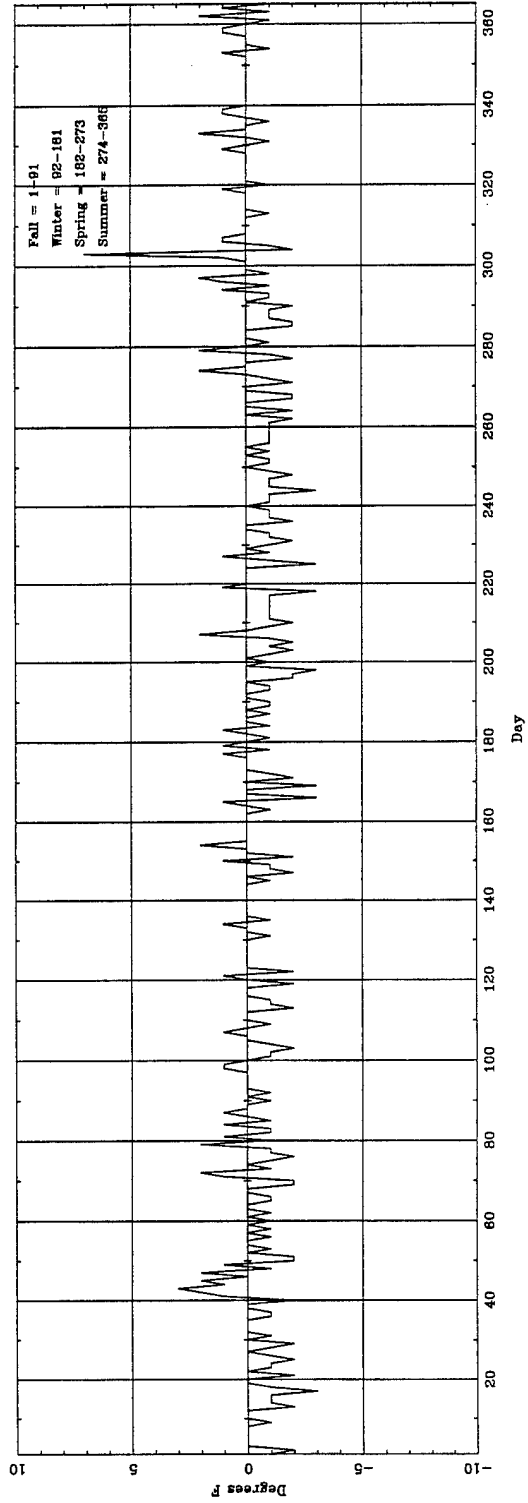
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for SAV

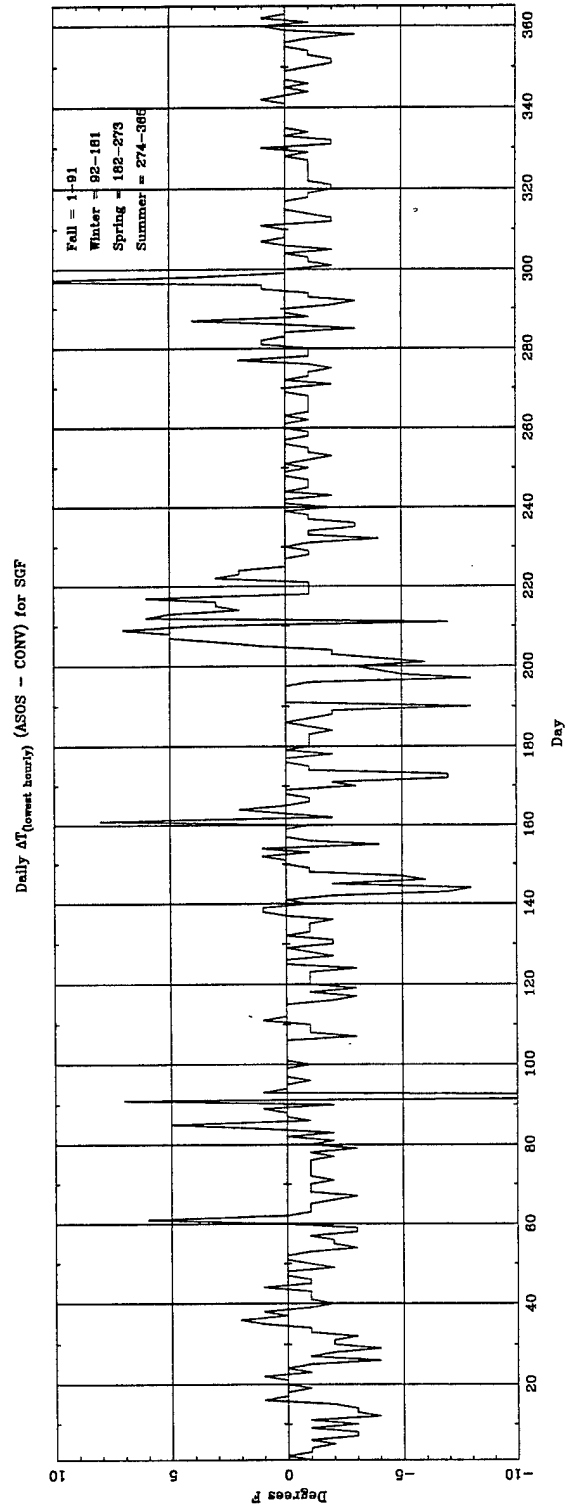
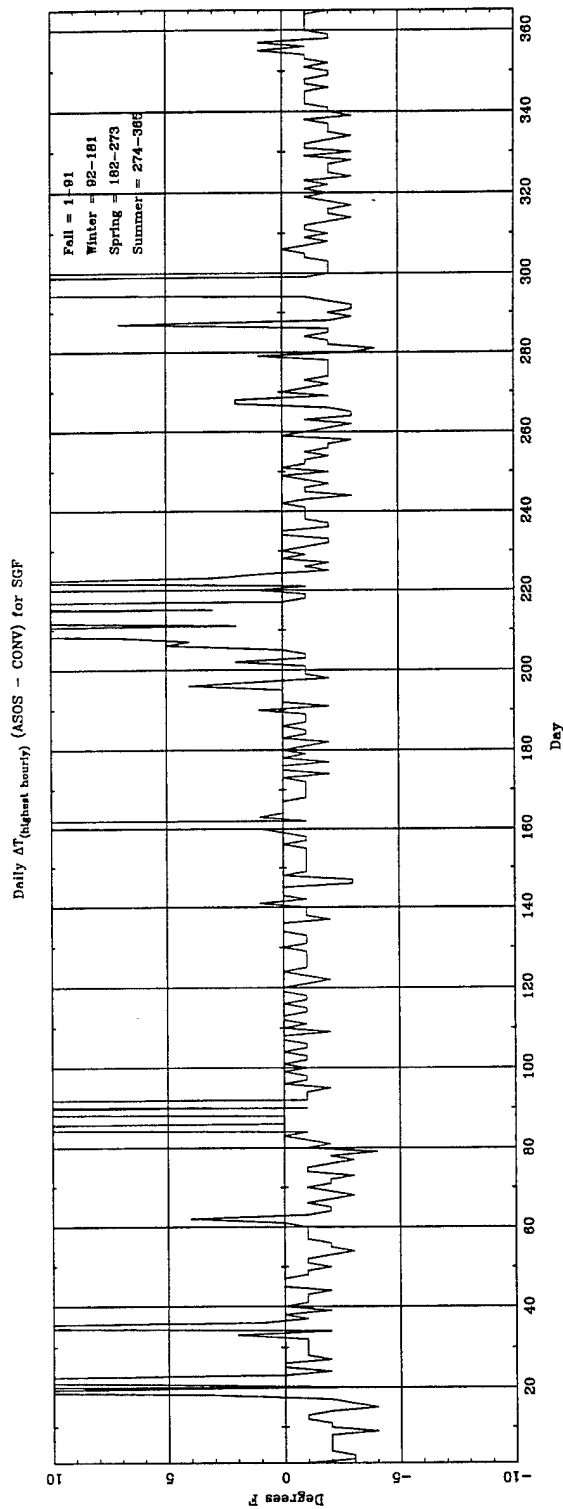


Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for SBN

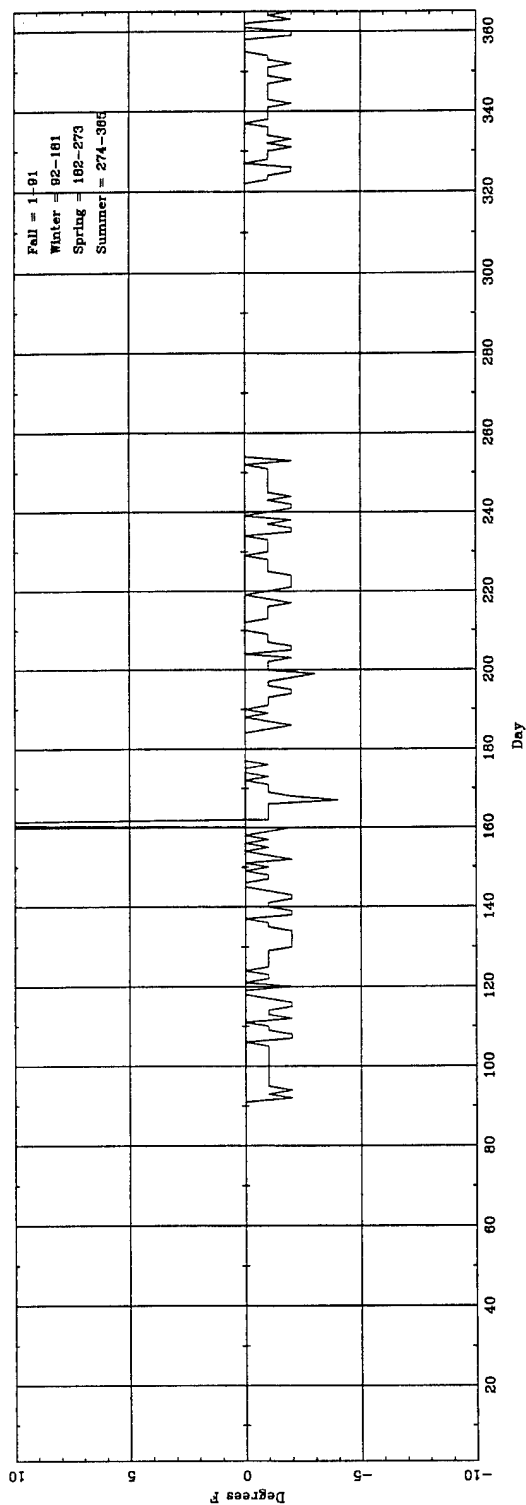


Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for SBN

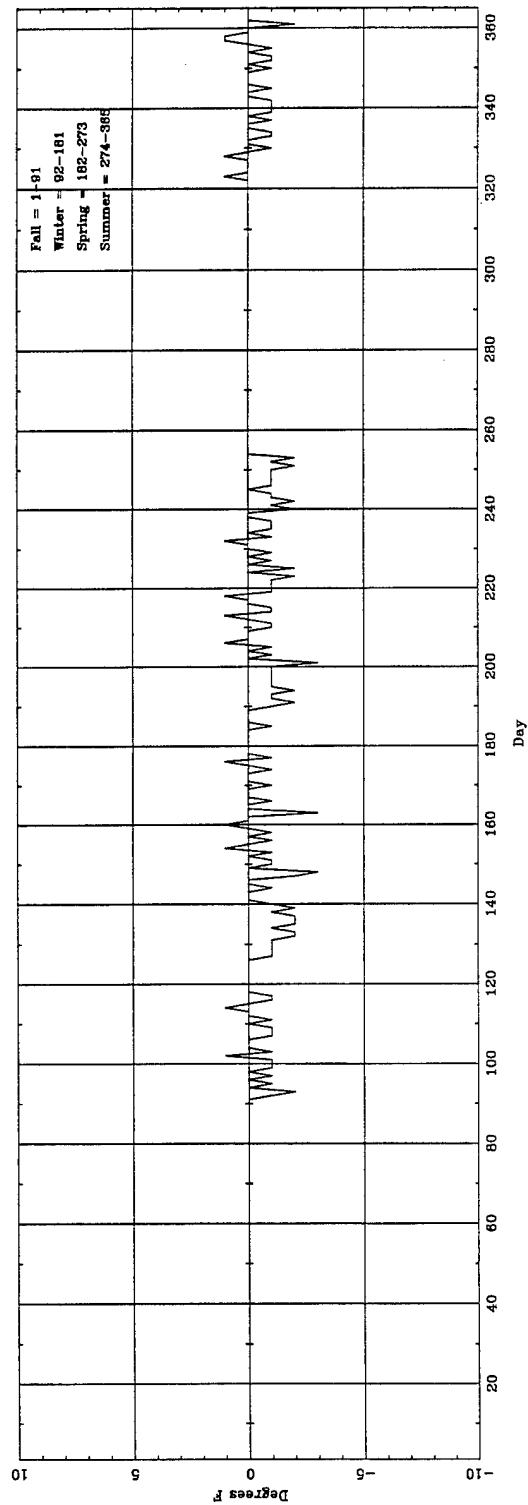




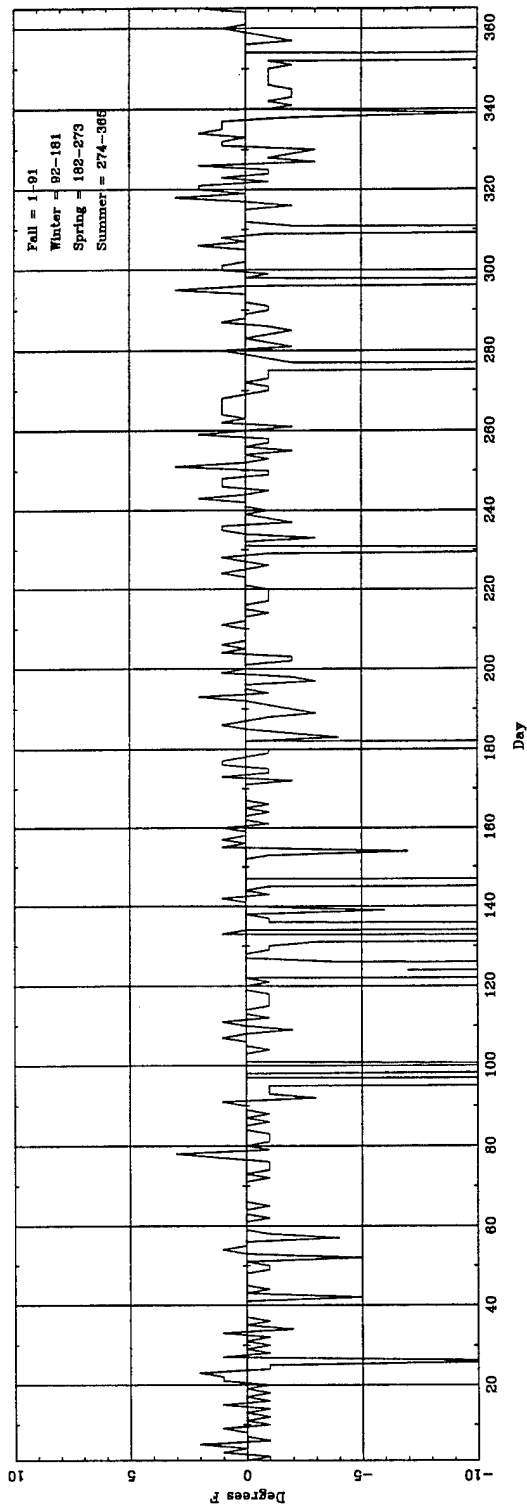
Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONW) for SIT



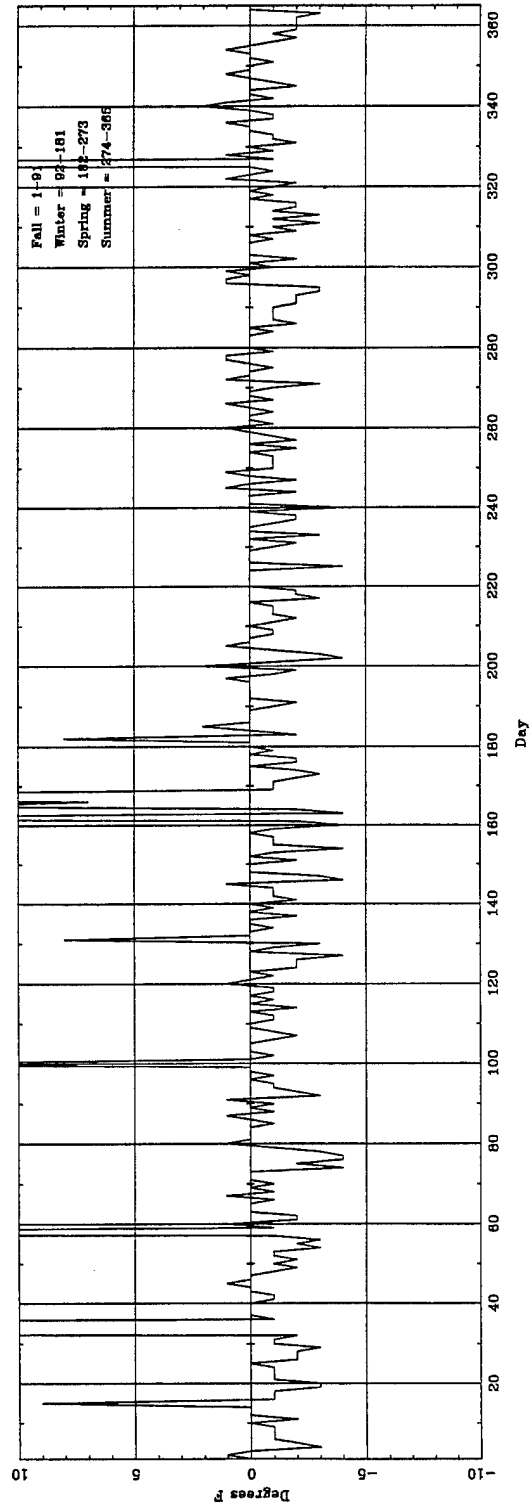
Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONW) for SIT



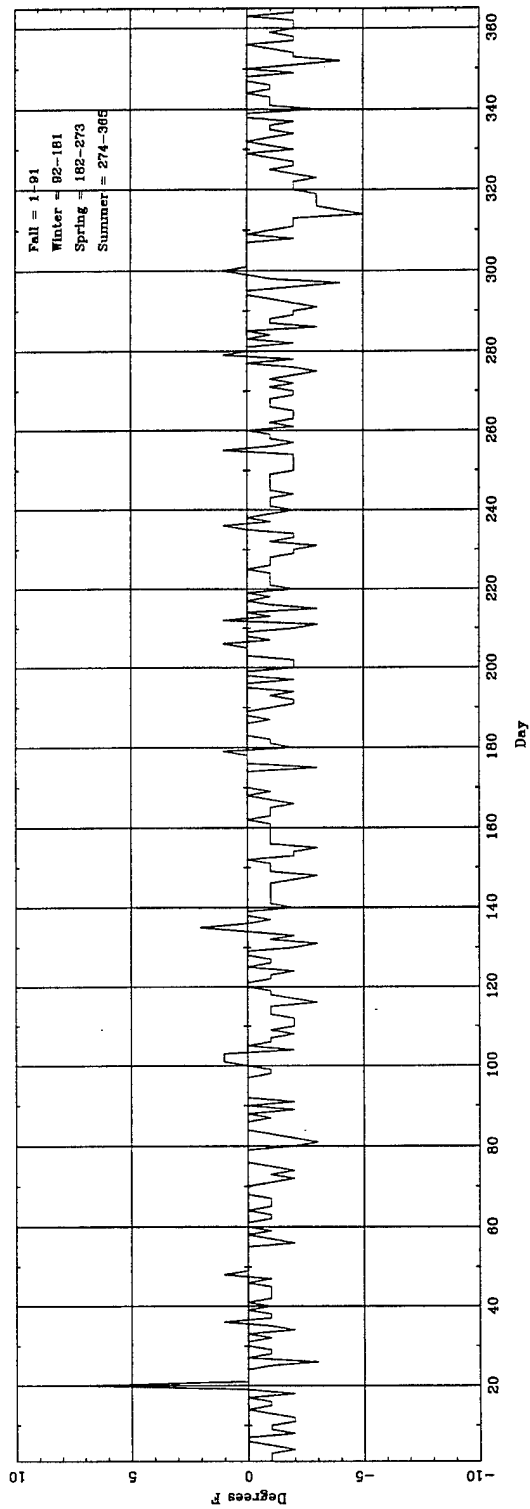
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONY) for SLN



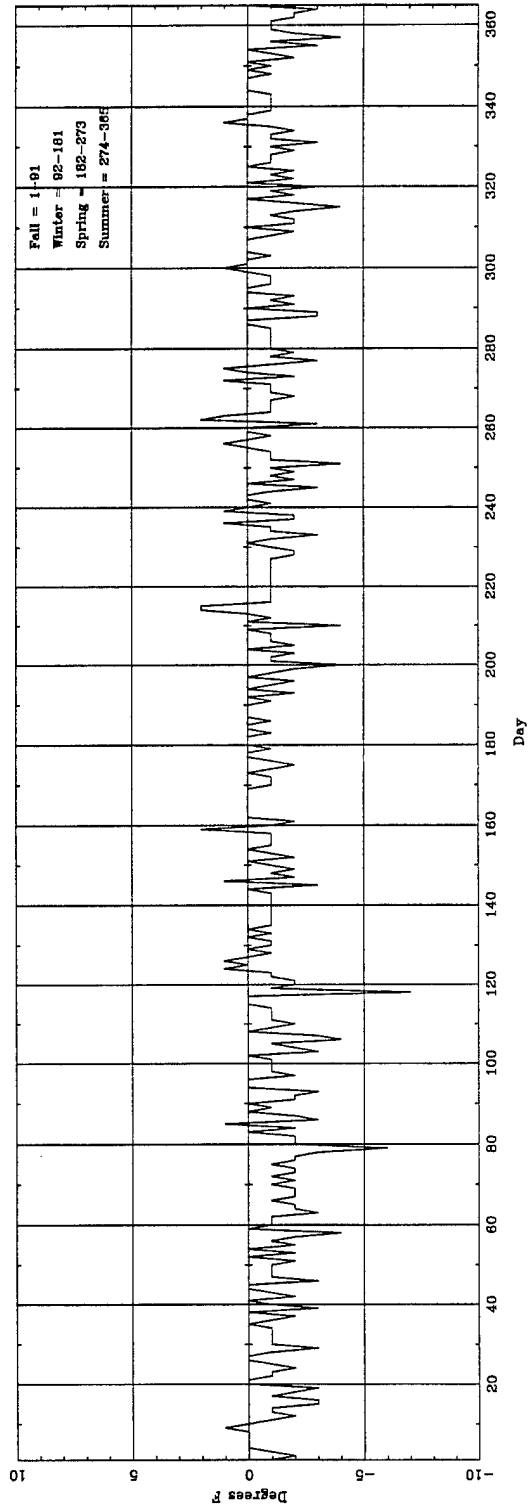
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONY) for SLN



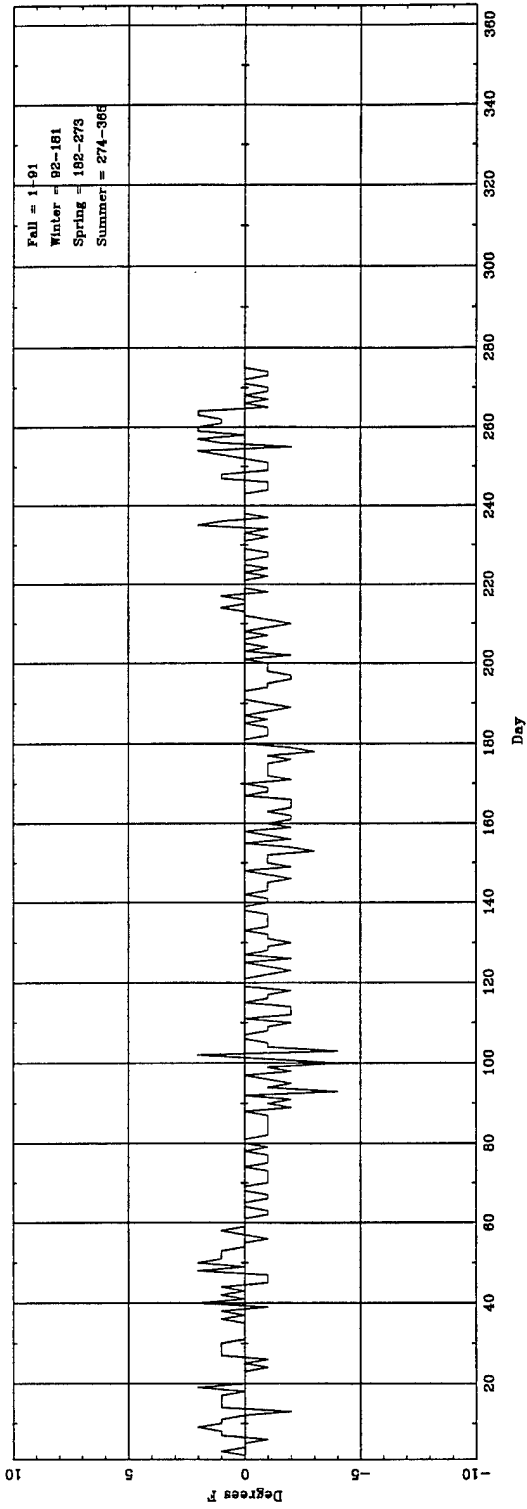
Daily $\Delta T_{\text{(nightest hourly)}}$ (ASOS - CONV) for SPI



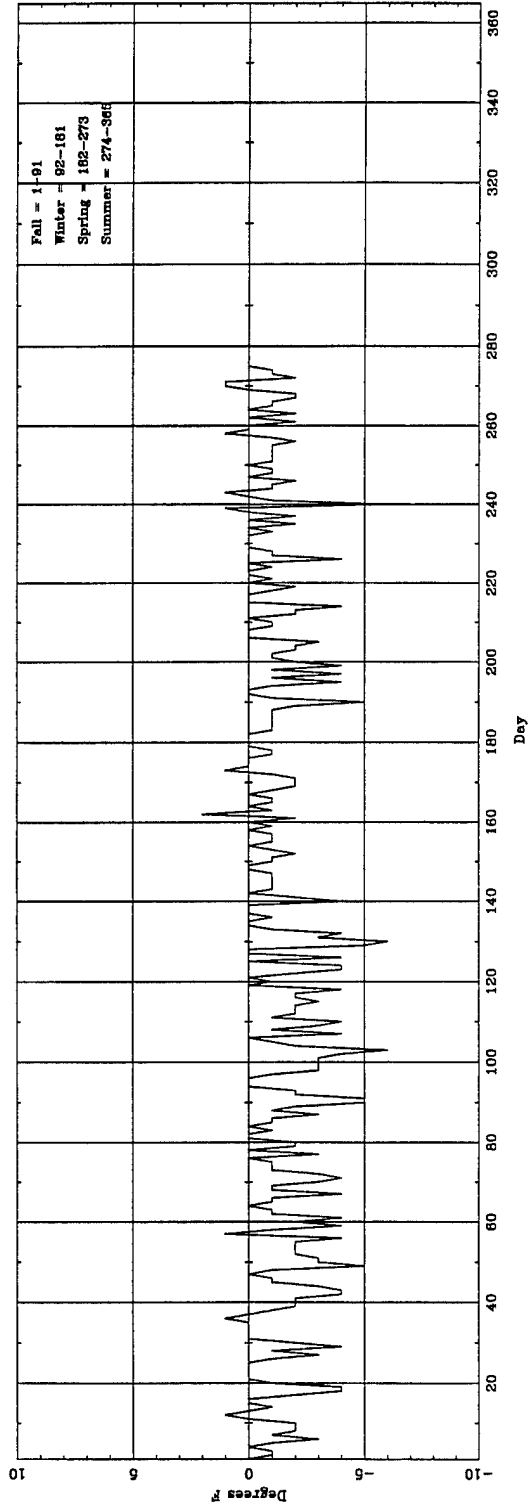
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for SPI



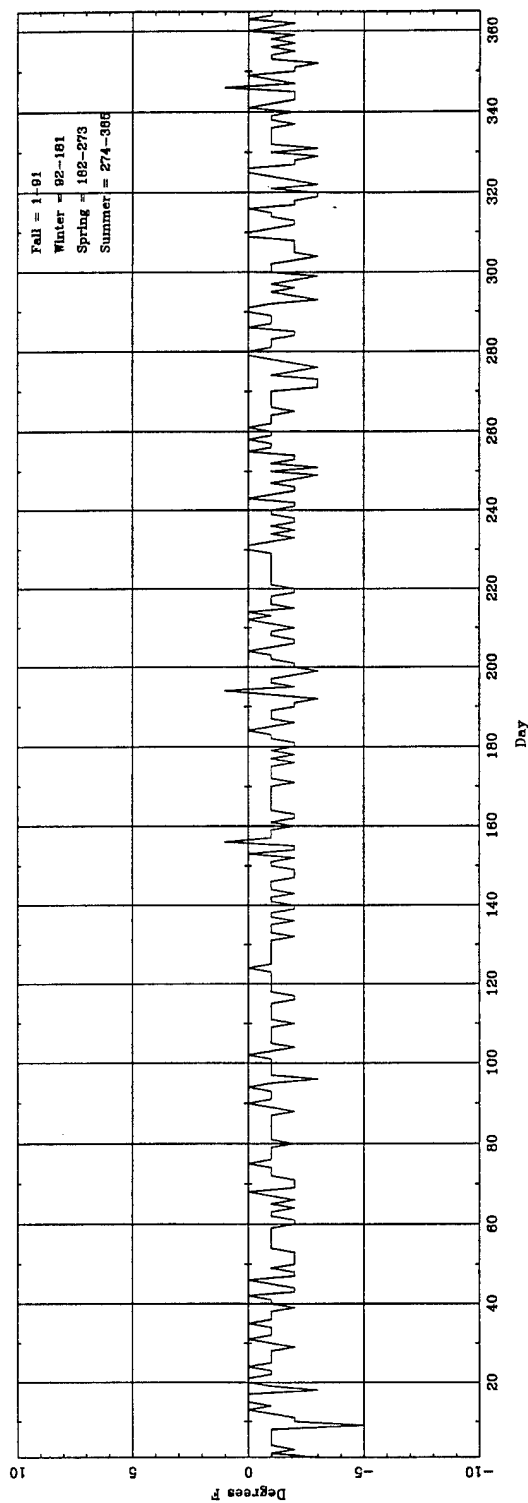
Daily $\Delta T_{\text{lightest hourly}}$ (ASOS - CONV) for SUX



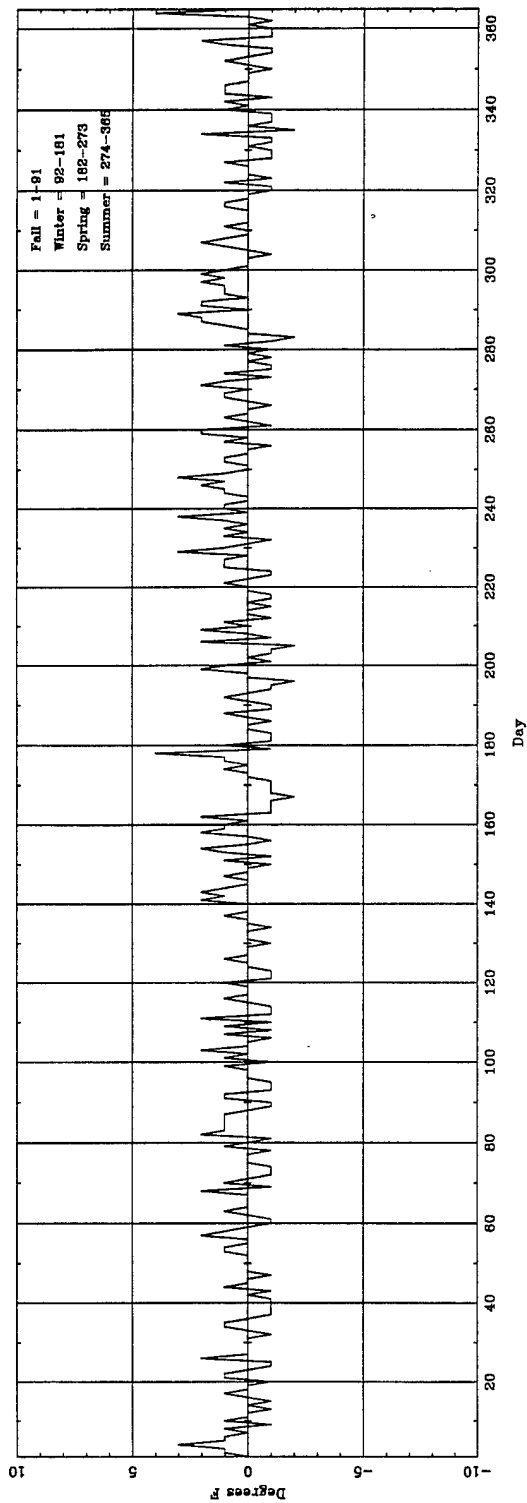
Daily $\Delta T_{\text{lightest hourly}}$ (ASOS - CONV) for SUX



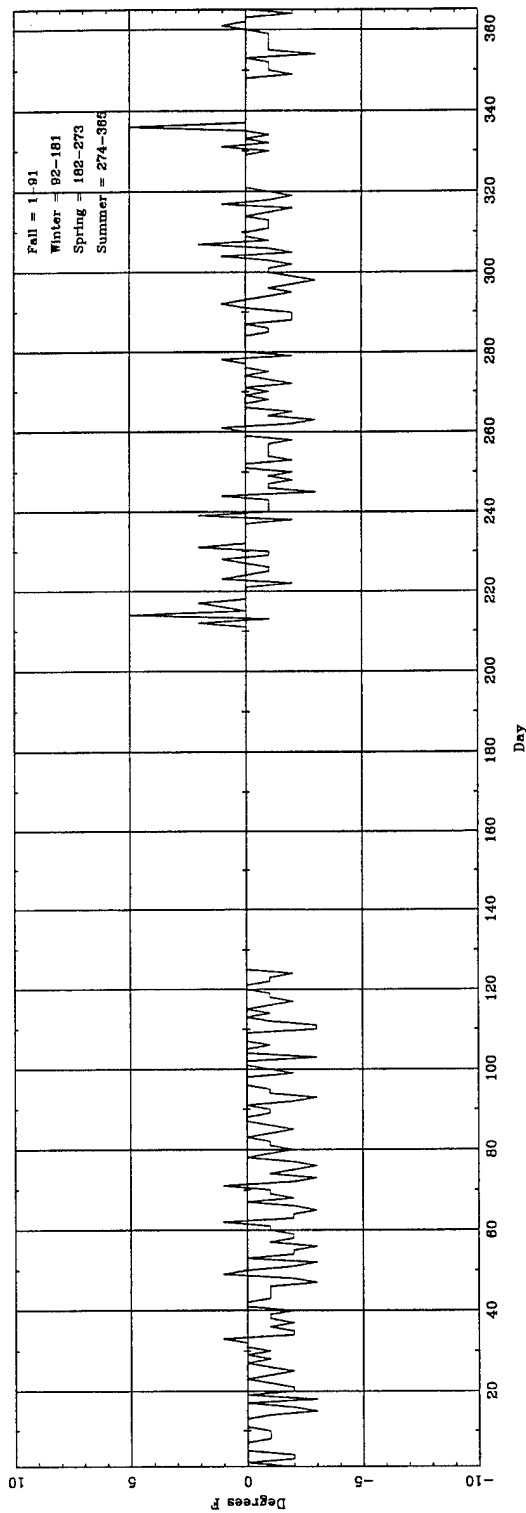
Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for TLH



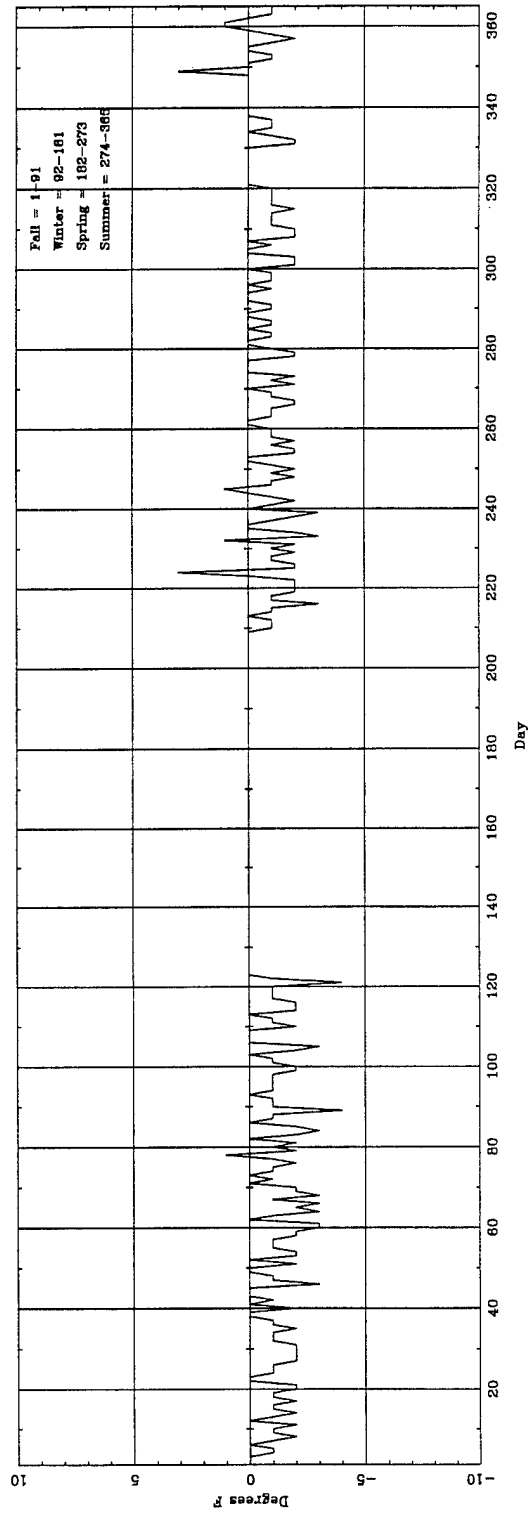
Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for TLH



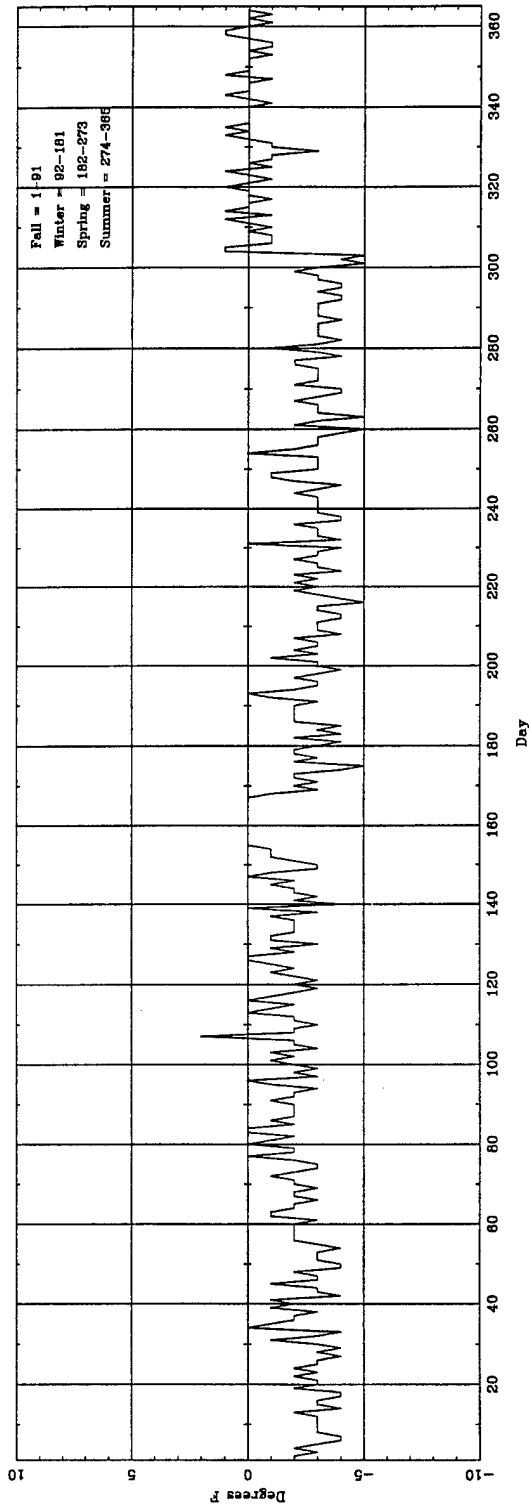
Daily $\Delta T_{\text{highest hourly}}$ (ASOS - CONV) for TRI



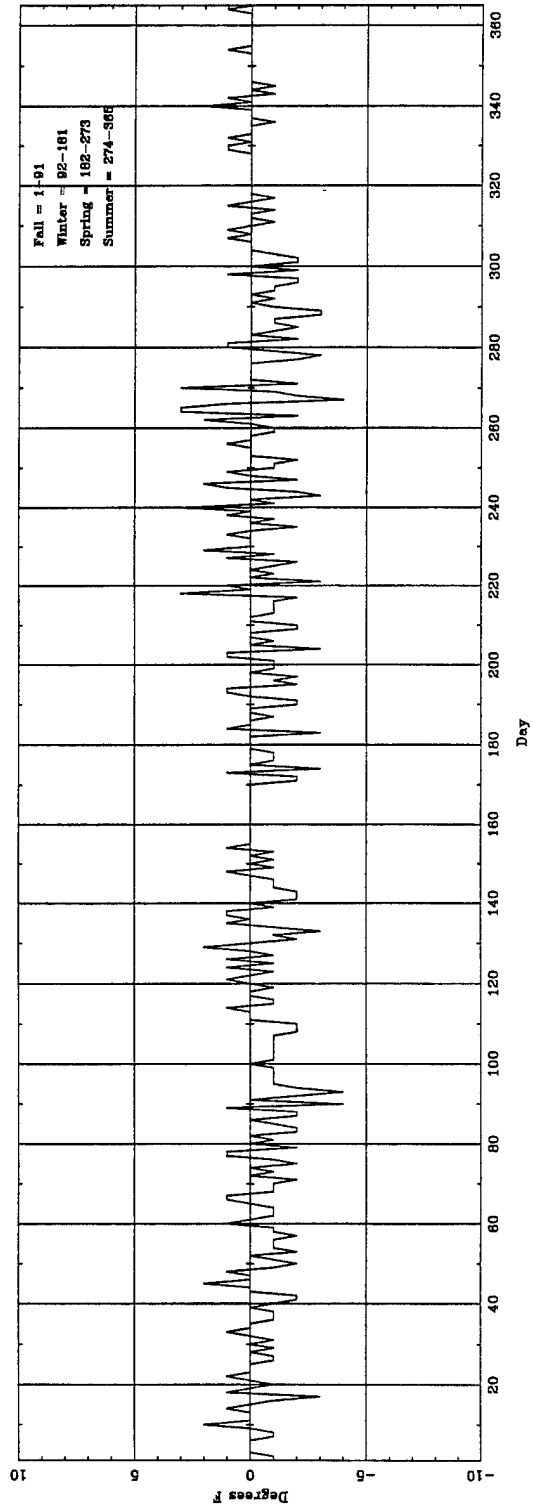
Daily $\Delta T_{\text{lowest hourly}}$ (ASOS - CONV) for TRI

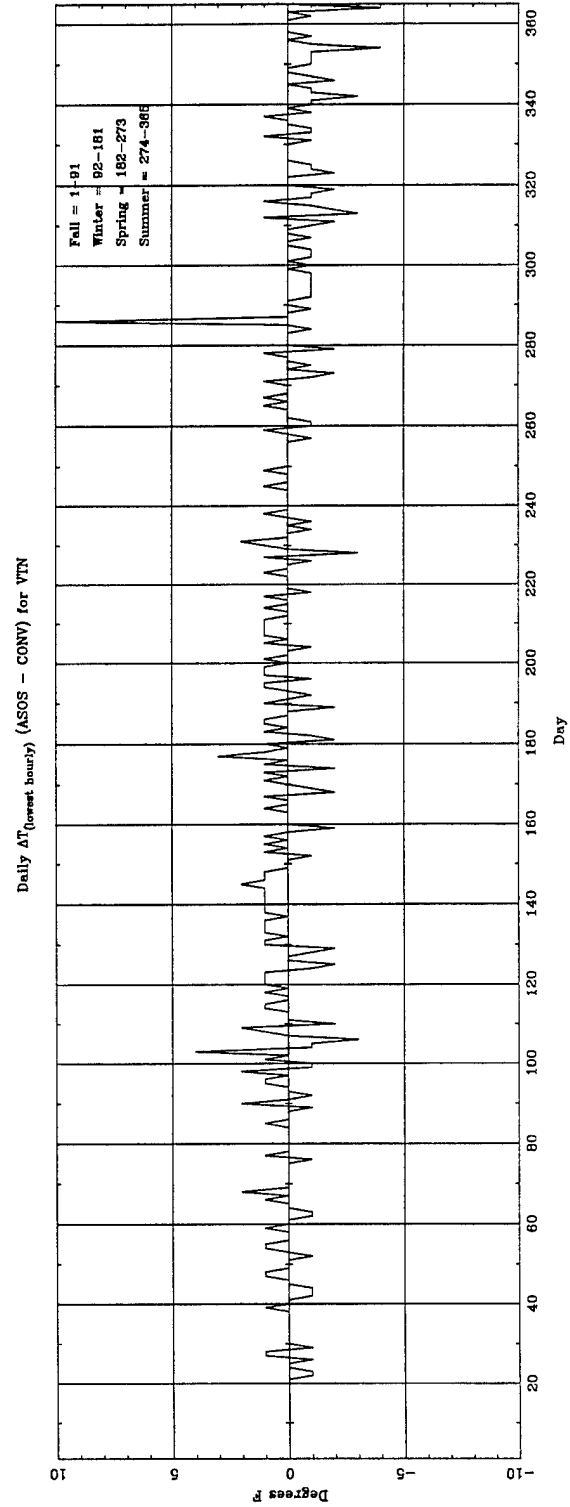
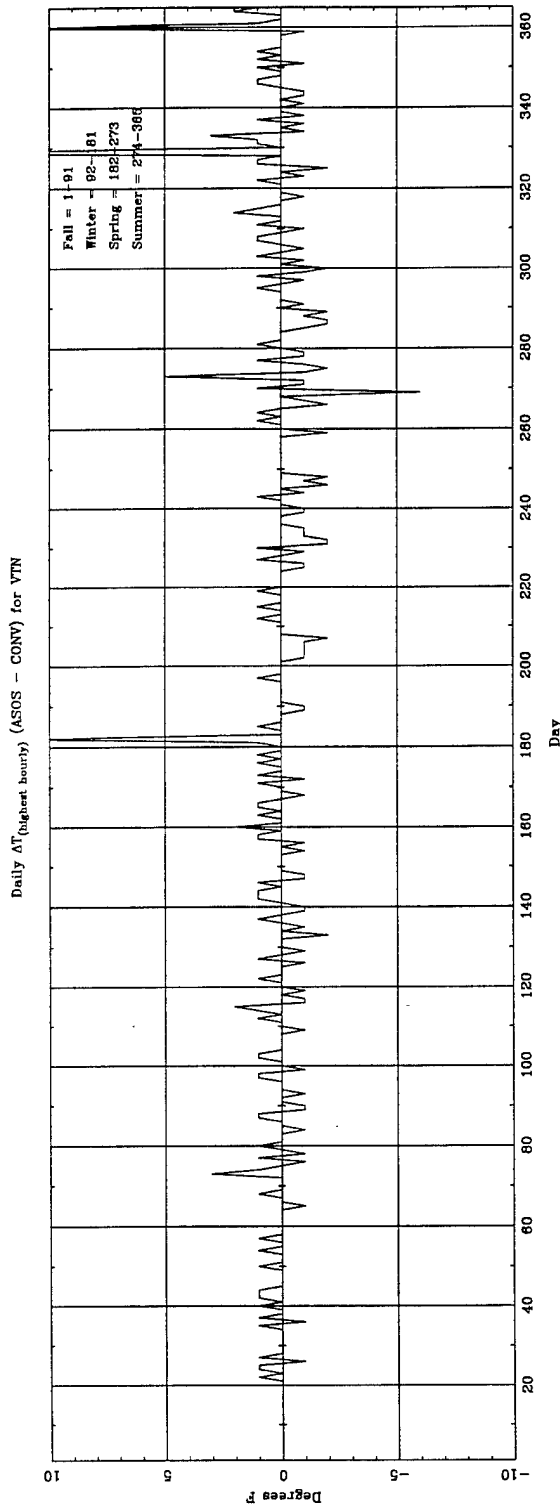


Daily $\Delta T_{\text{(highest hourly)}}$ (ASOS - CONV) for TUS

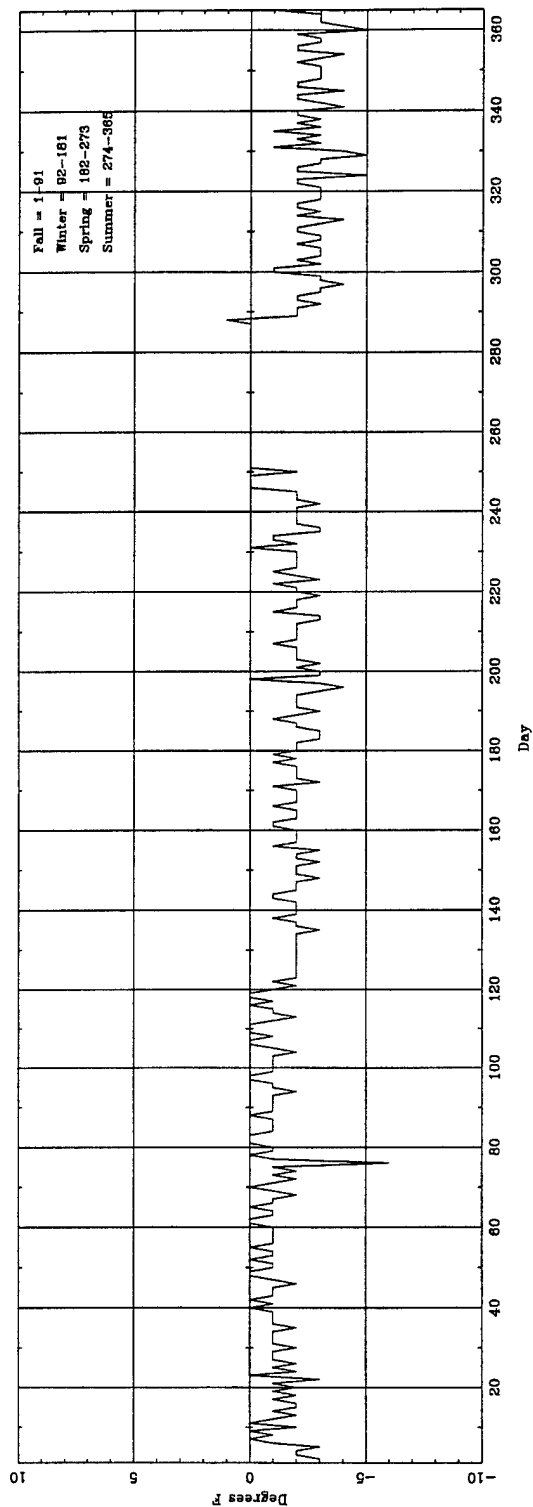


Daily $\Delta T_{\text{(lowest hourly)}}$ (ASOS - CONV) for TUS

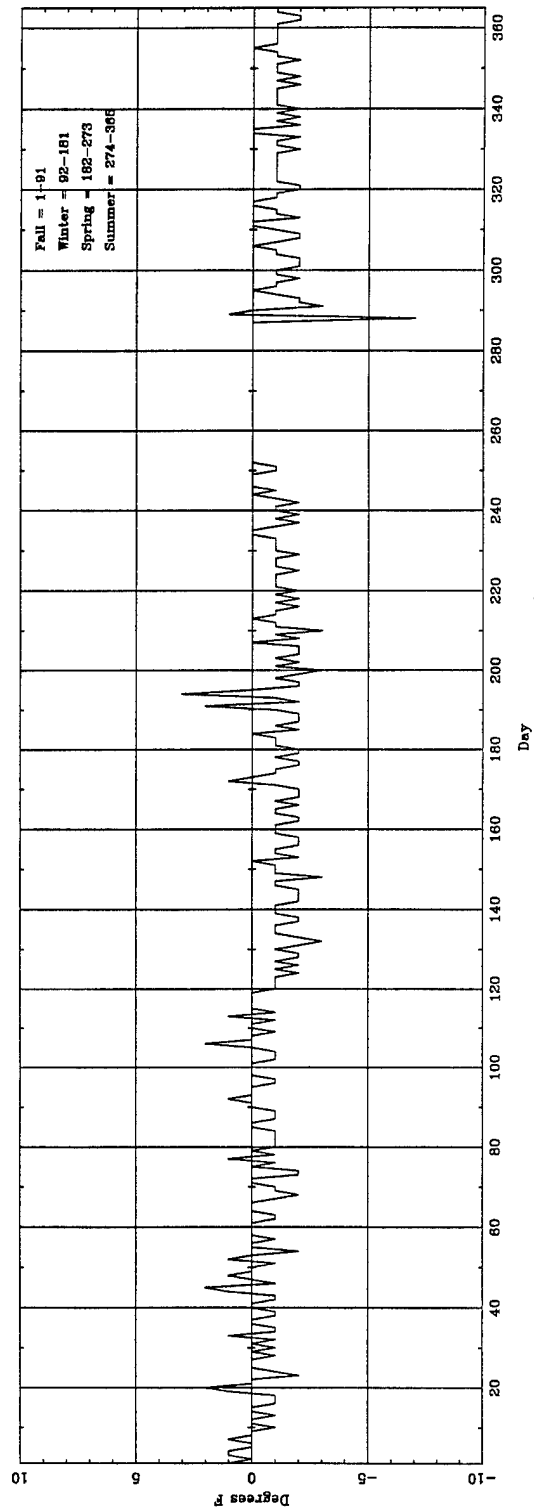




Daily $\Delta T_{\text{(nightly hourly)}}$ (ASOS - CONV) for YNG



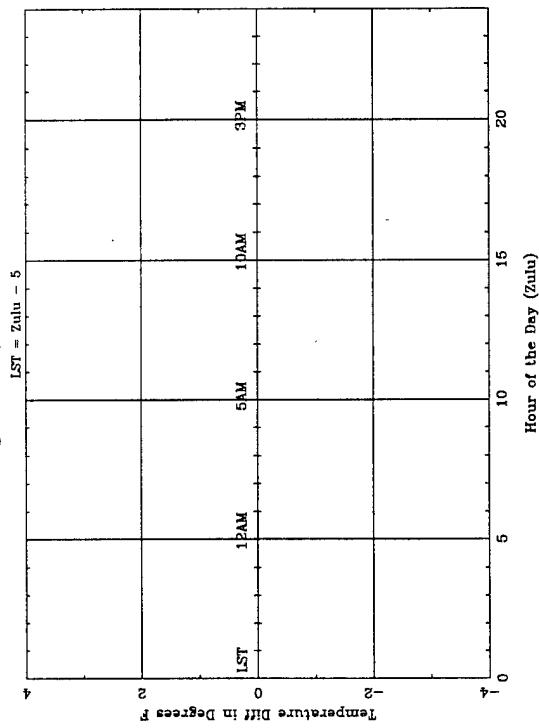
Daily $\Delta T_{\text{(overcast hourly)}}$ (ASOS - CONV) for YNG



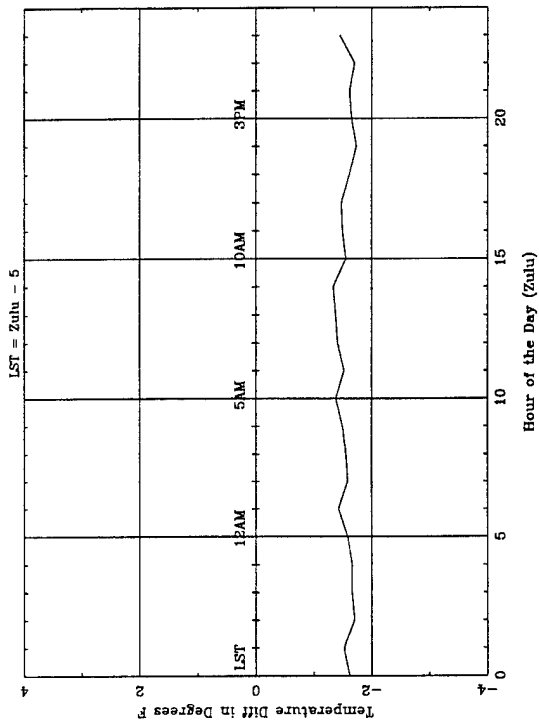
APPENDIX B: Seasonal Diurnal ΔT Cycles

The following graphs depict the seasonal diurnal cycles of temperature difference as a function of the hour of day at each station. The hour of day is plotted in Zulu time at the bottom of each graph with a LST reference plotted above the "0" temperature difference line. Temperature difference is averaged over all hourly values during each season and plotted with a range of $-4^{\circ}\text{F} \leq \Delta T \leq +4^{\circ}\text{F}$ along the y-axis.

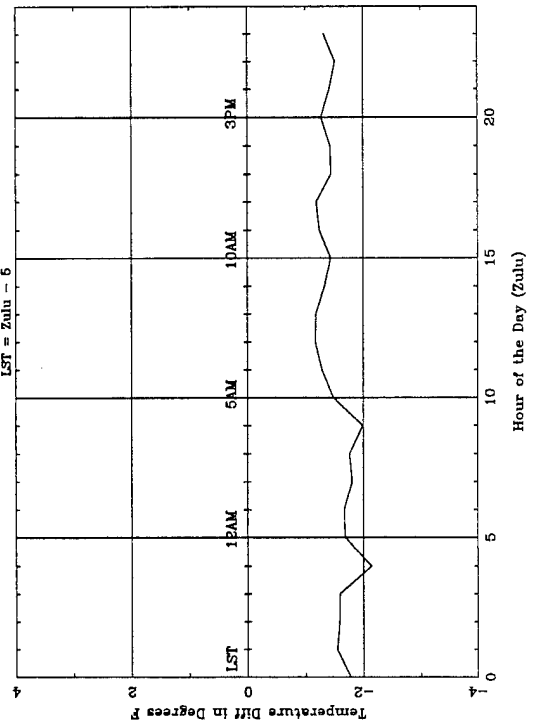
Average Diurnal Cycle for ABE - fall



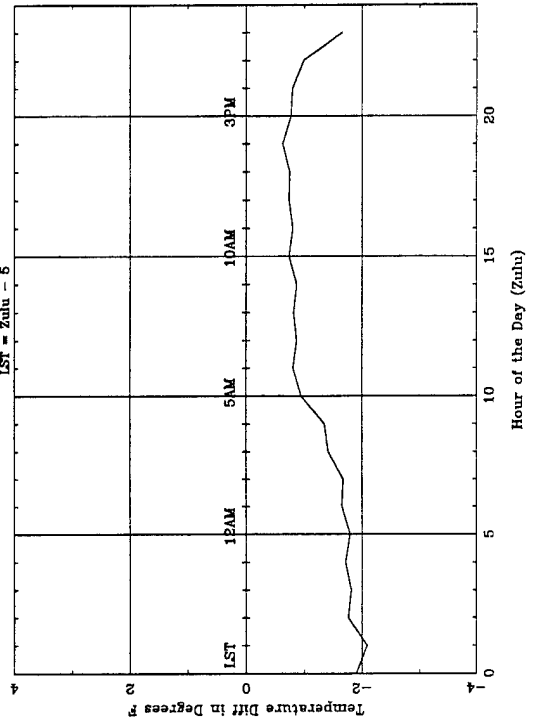
Average Diurnal Cycle for ABE - winter



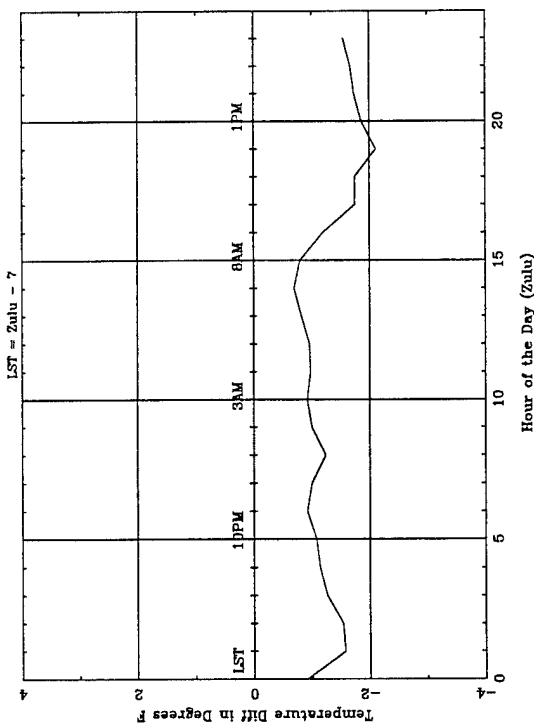
Average Diurnal Cycle for ABE - spring



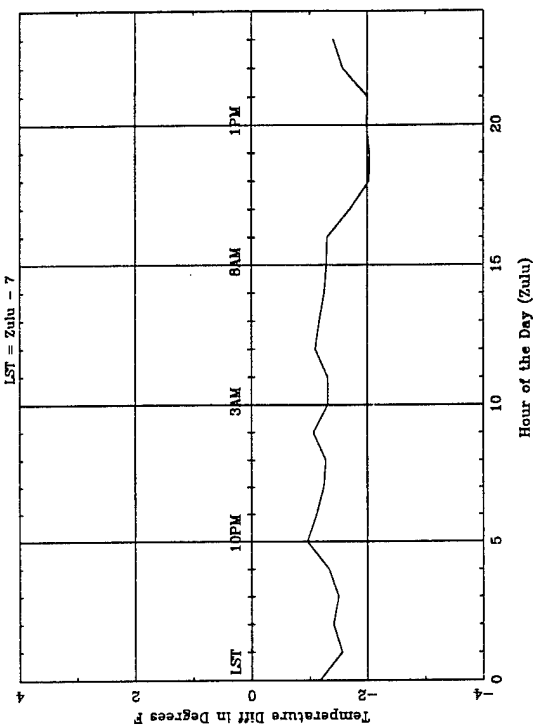
Average Diurnal Cycle for ABE - summer



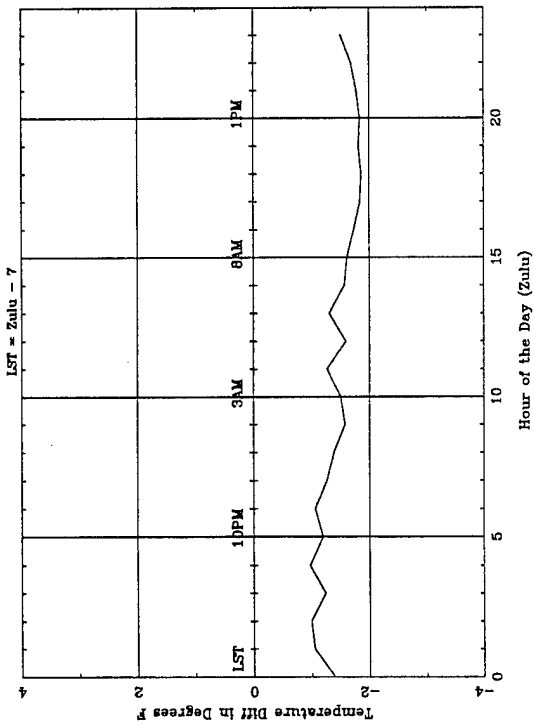
Average Diurnal Cycle for ABQ - fall



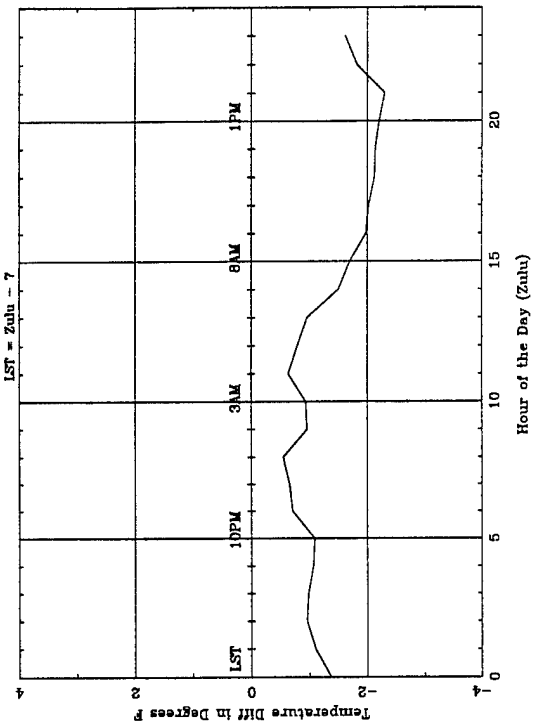
Average Diurnal Cycle for ABQ - winter

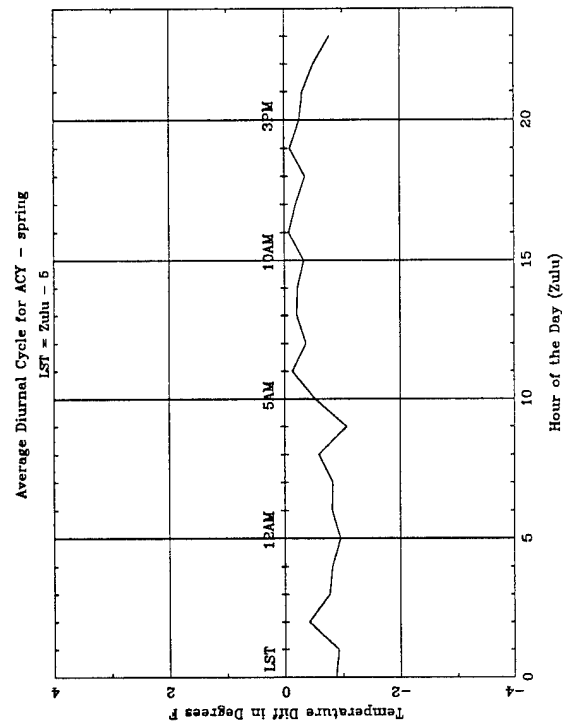
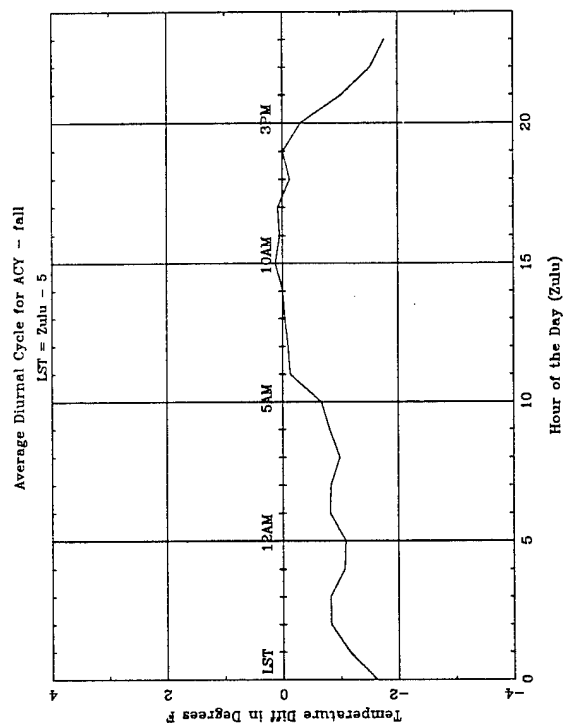
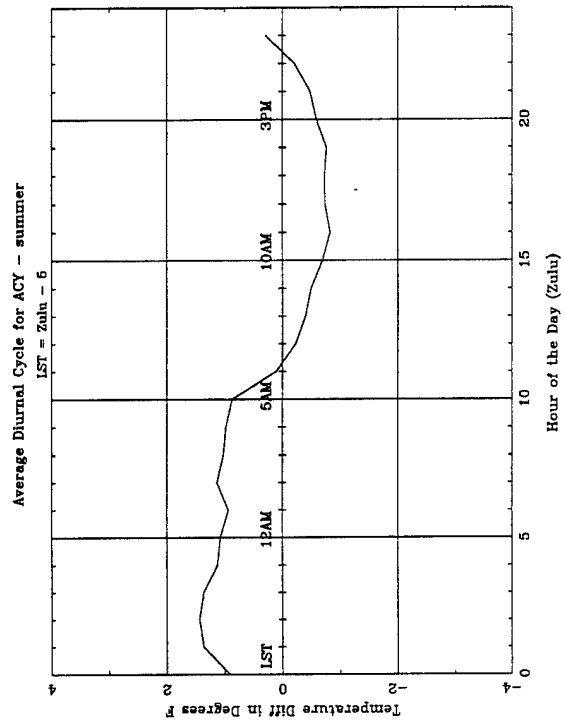
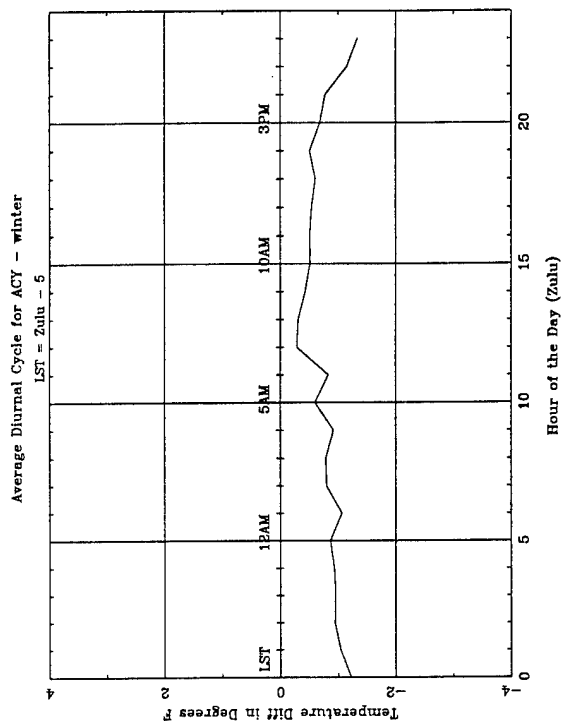


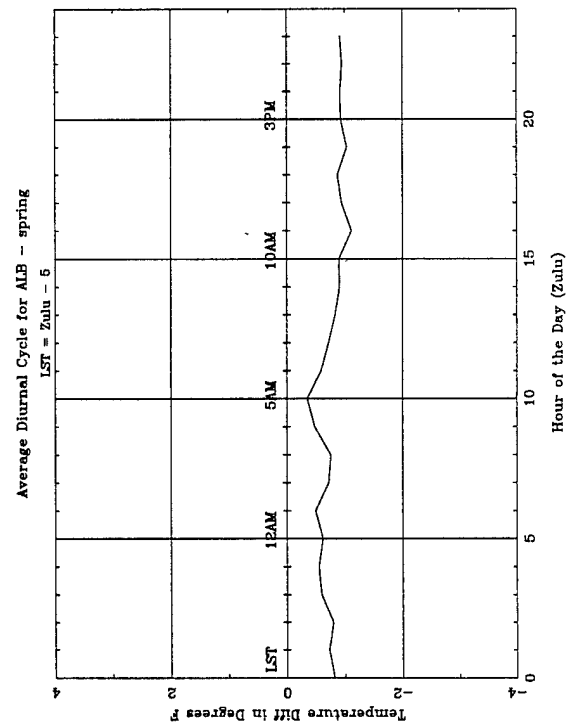
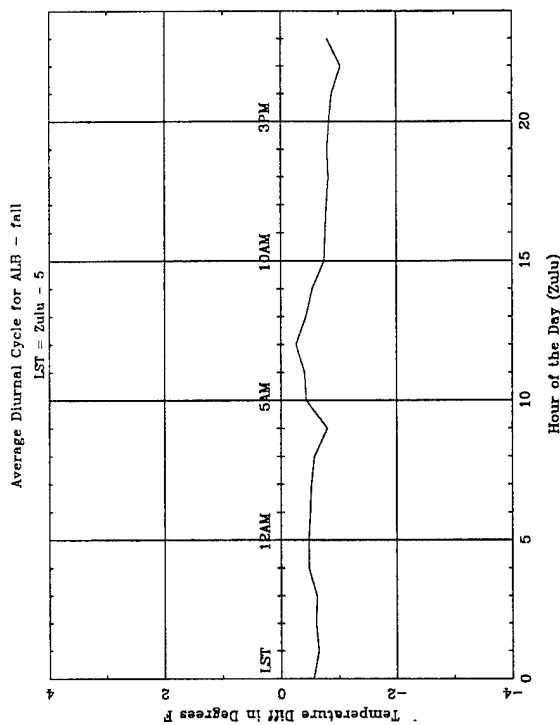
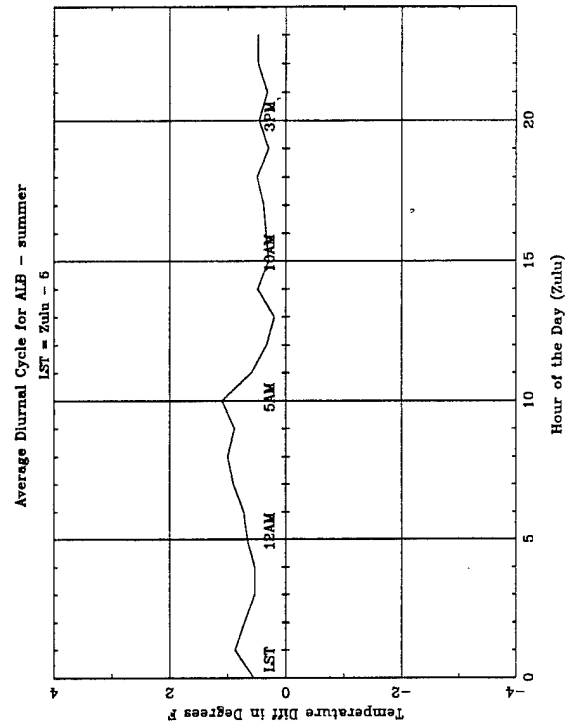
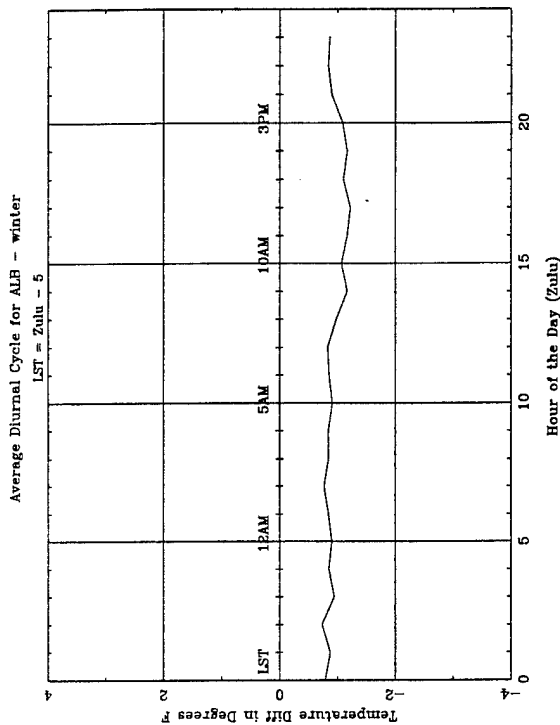
Average Diurnal Cycle for ABQ - spring



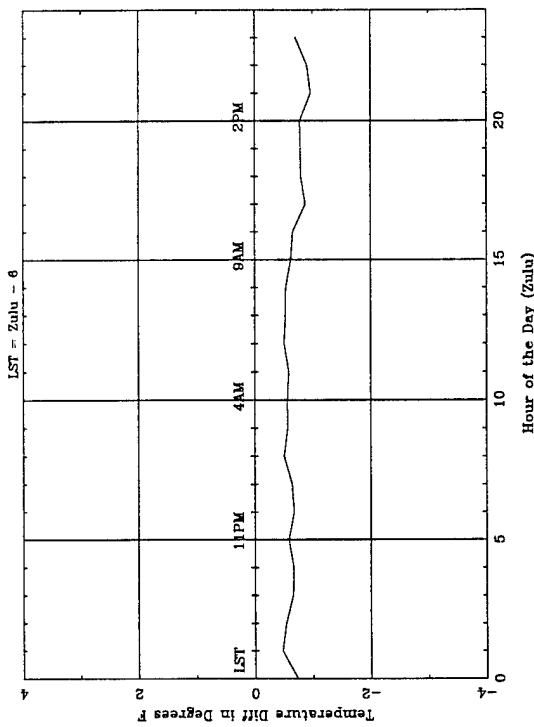
Average Diurnal Cycle for ABQ - summer



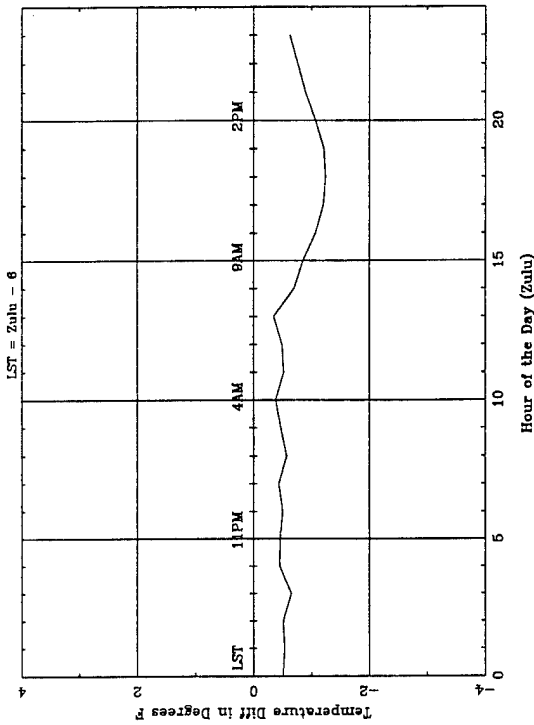




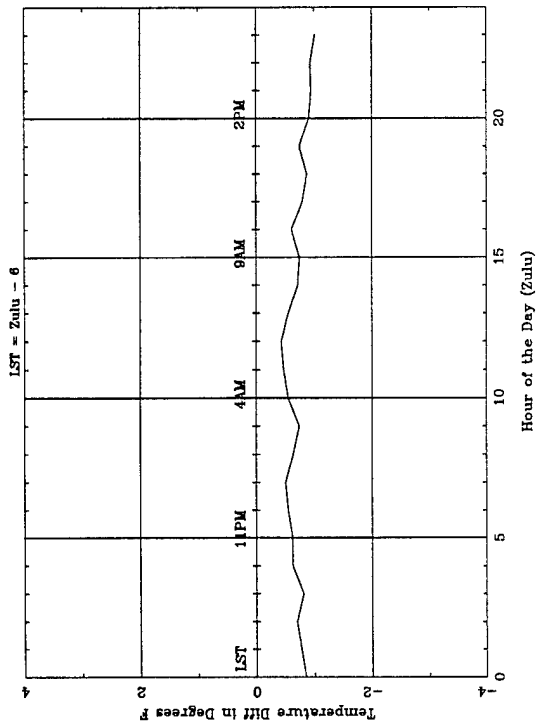
Average Diurnal Cycle for ALO - fall



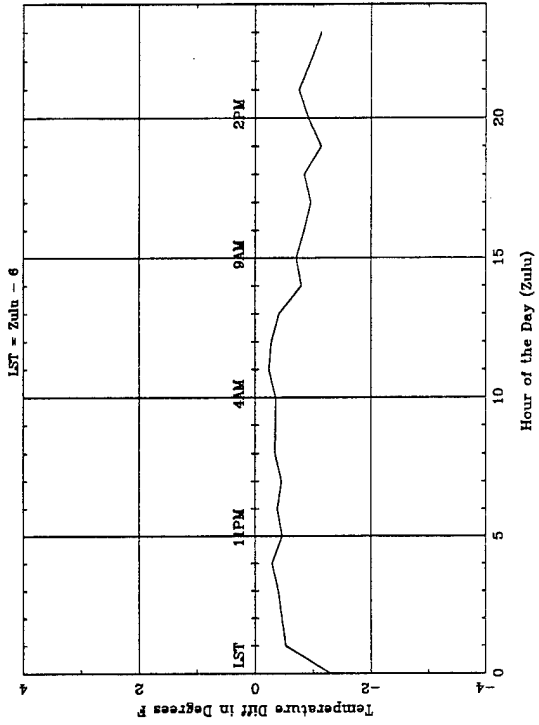
Average Diurnal Cycle for ALO - winter



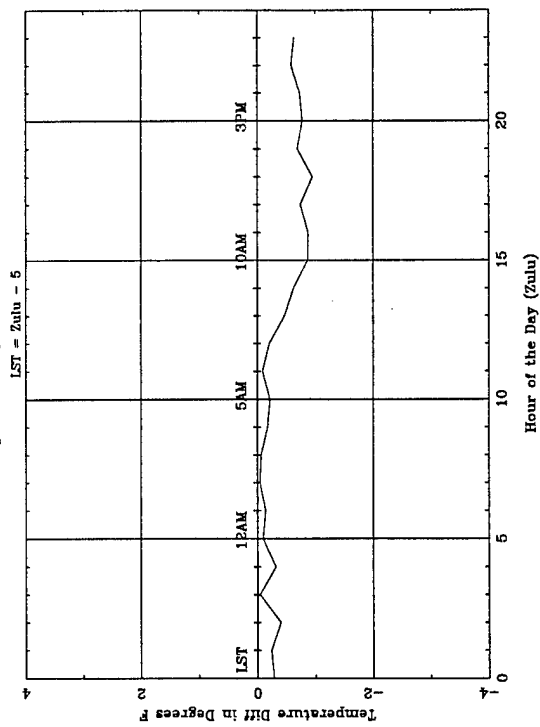
Average Diurnal Cycle for ALO - spring



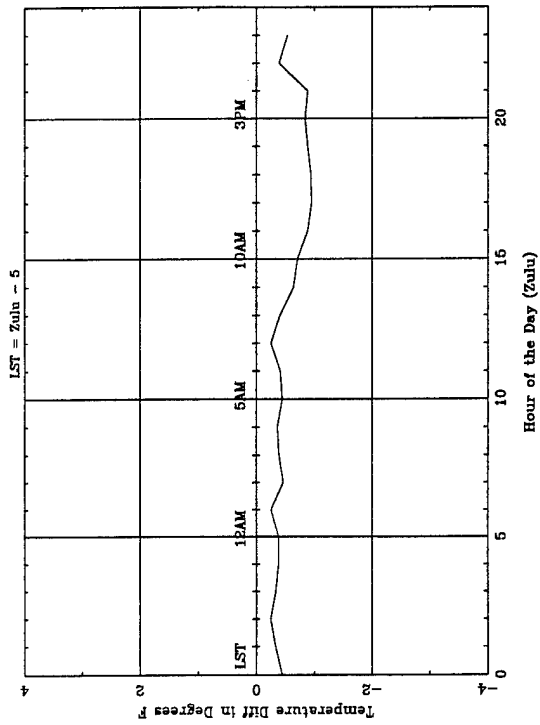
Average Diurnal Cycle for ALO - summer



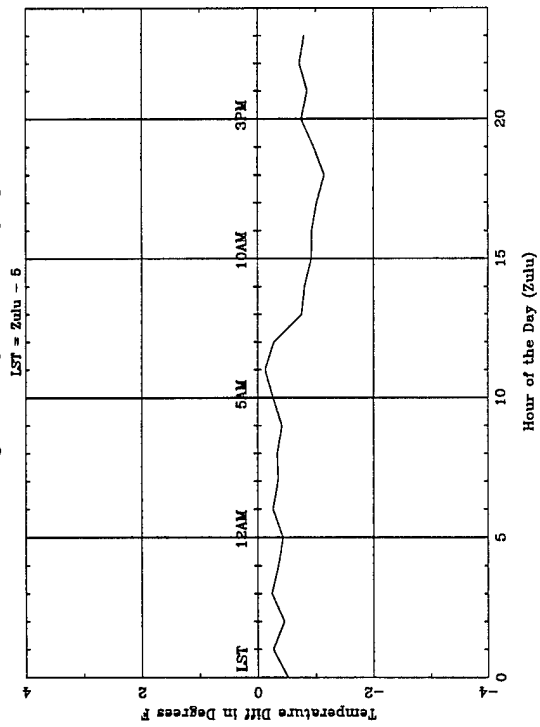
Average Diurnal Cycle for APN -- fall



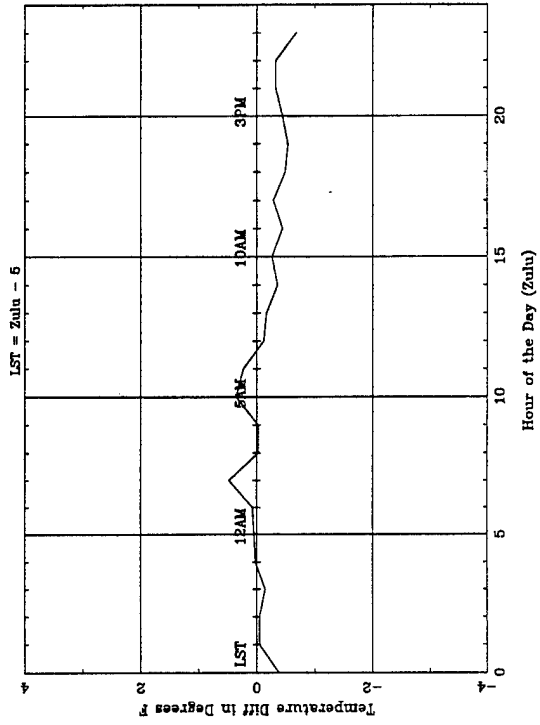
Average Diurnal Cycle for APN -- winter



Average Diurnal Cycle for APN -- spring

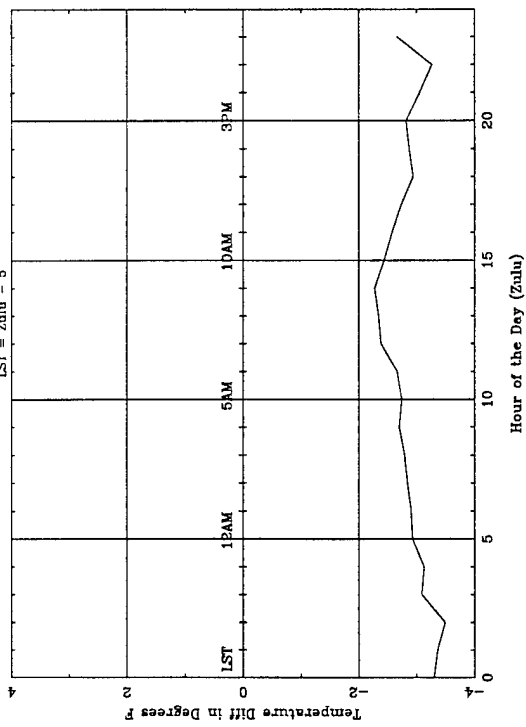


Average Diurnal Cycle for APN -- summer



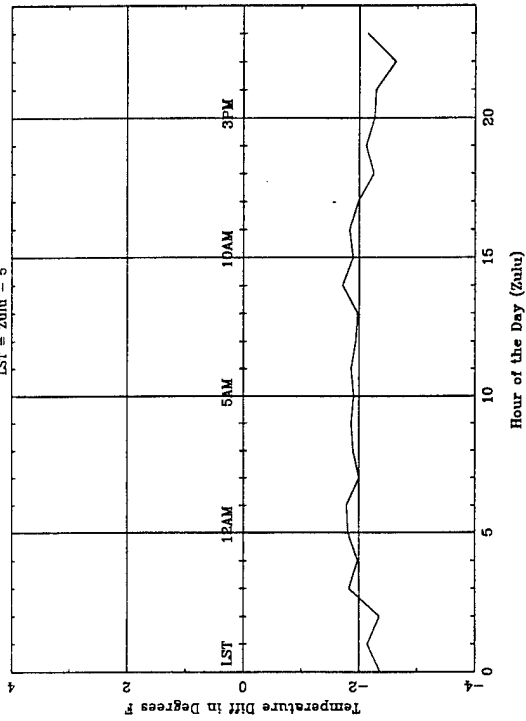
Average Diurnal Cycle for ATL - fall

LST = Zulu - 5



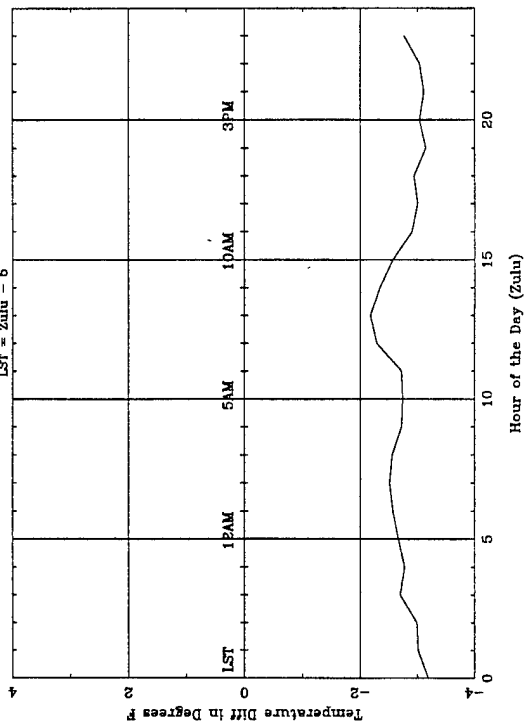
Average Diurnal Cycle for ATL - winter

LST = Zulu - 5



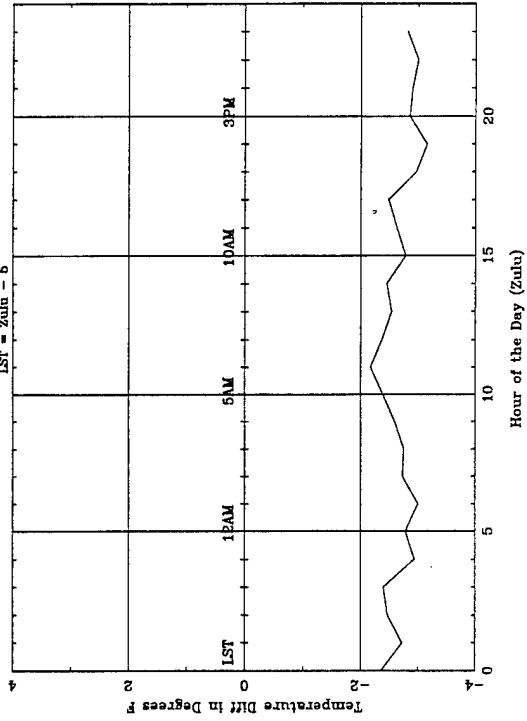
Average Diurnal Cycle for ATL - spring

LST = Zulu - 5

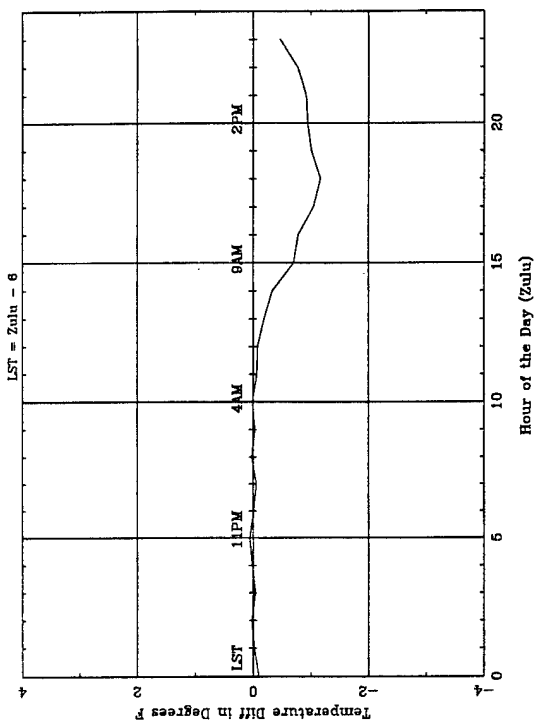


Average Diurnal Cycle for ATL - summer

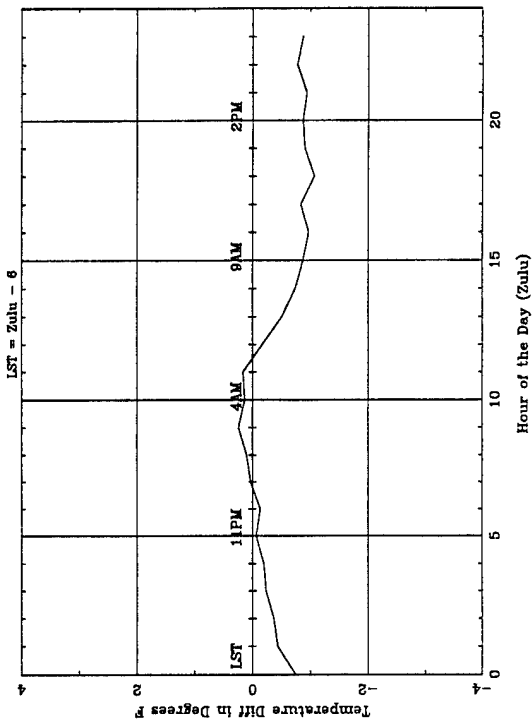
LST = Zulu - 5



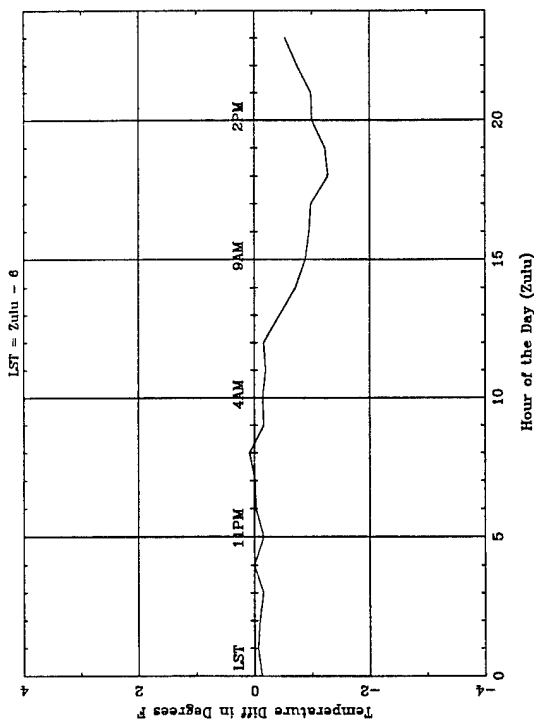
Average Diurnal Cycle for AUS - winter



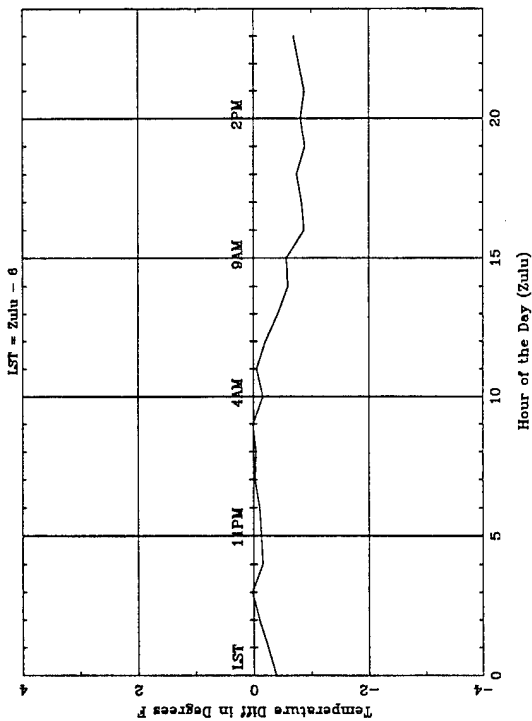
Average Diurnal Cycle for AUS - summer



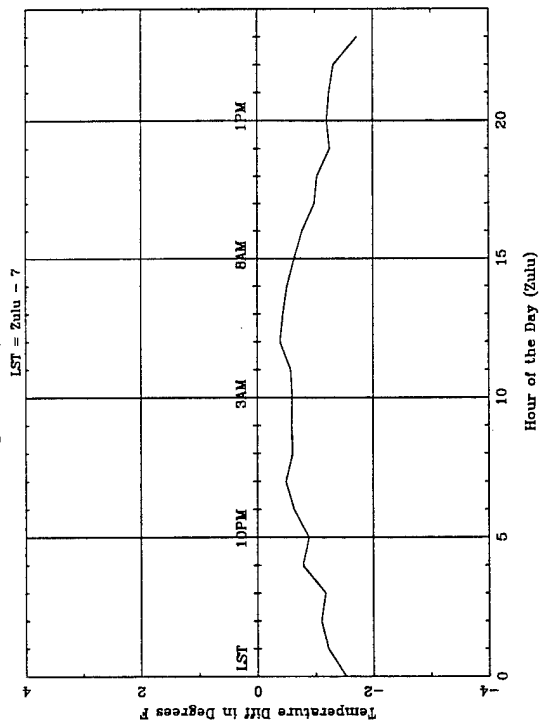
Average Diurnal Cycle for AUS - fall



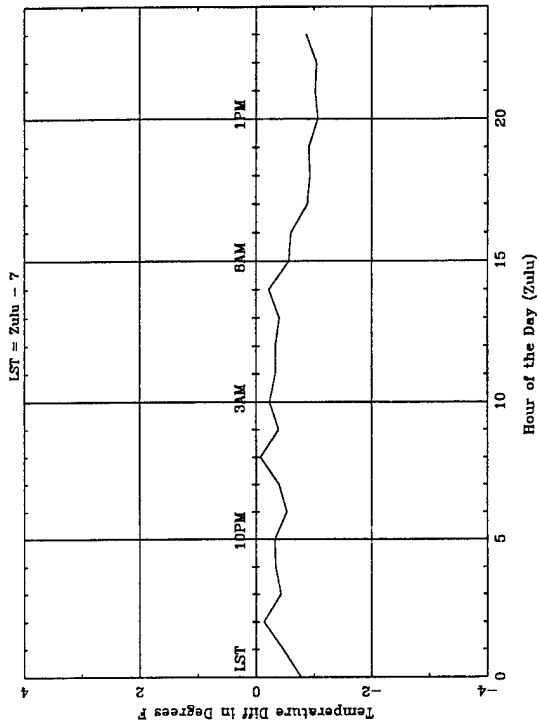
Average Diurnal Cycle for AUS - spring



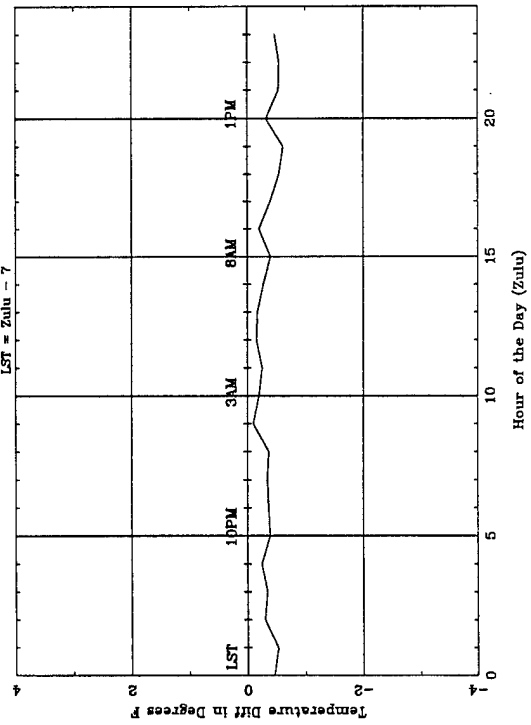
Average Diurnal Cycle for BFF - fall



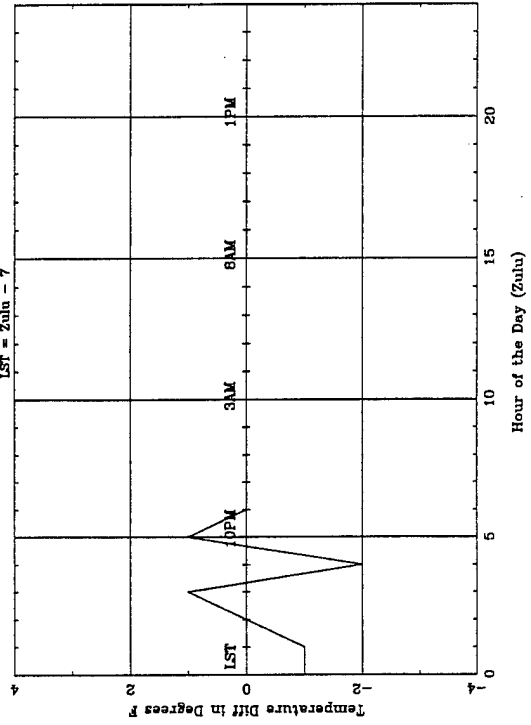
Average Diurnal Cycle for BFF - winter



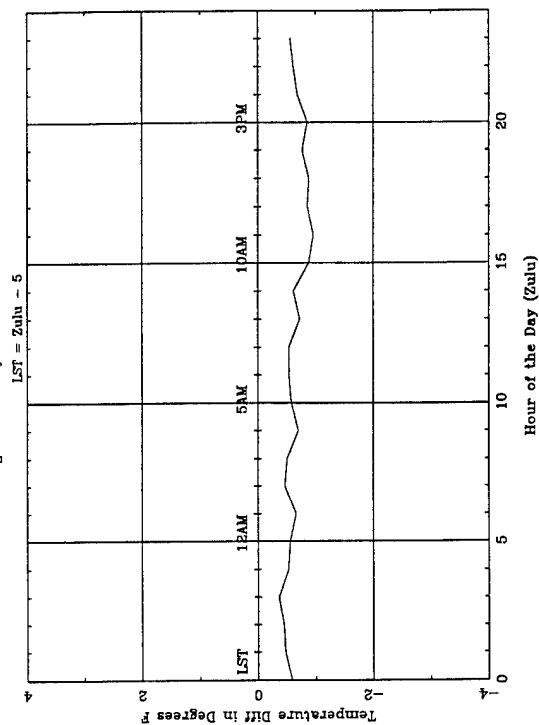
Average Diurnal Cycle for BFF - spring



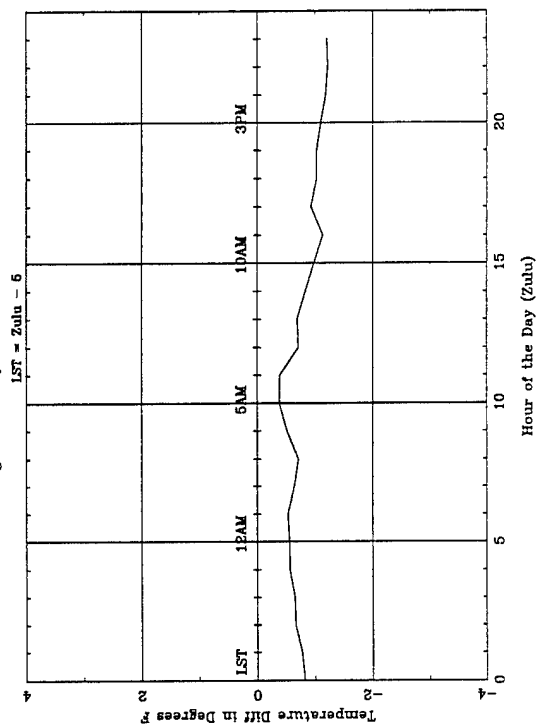
Average Diurnal Cycle for BFF - summer



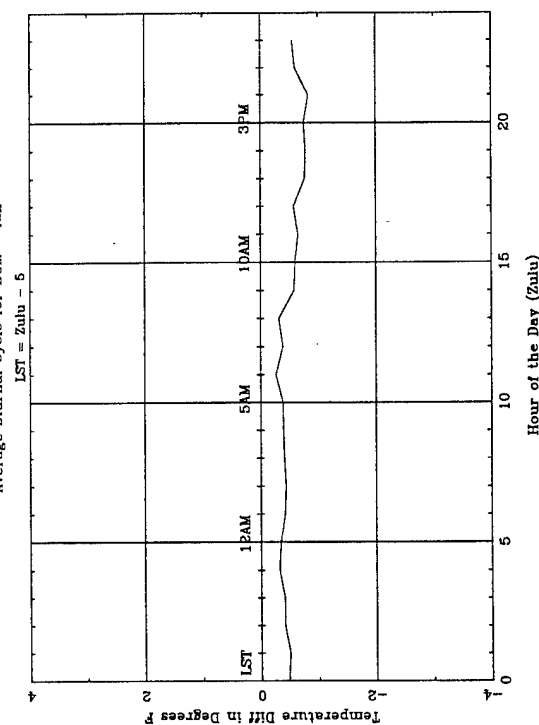
Average Diurnal Cycle for BGM - winter



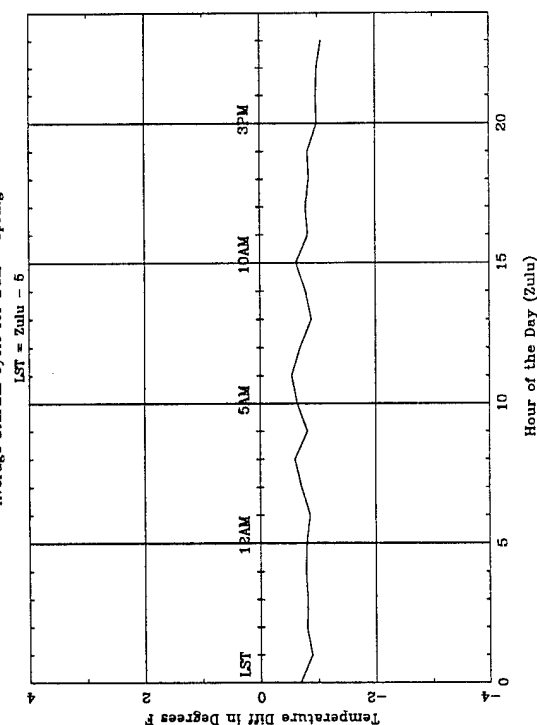
Average Diurnal Cycle for BGM - summer



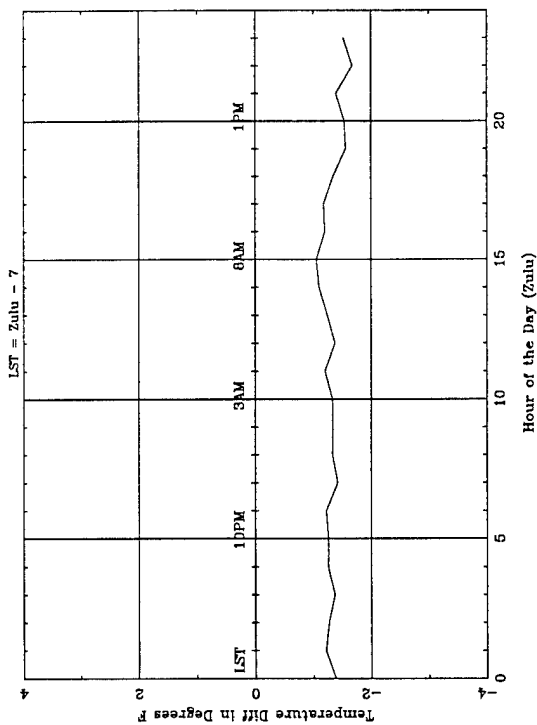
Average Diurnal Cycle for BGM - fall



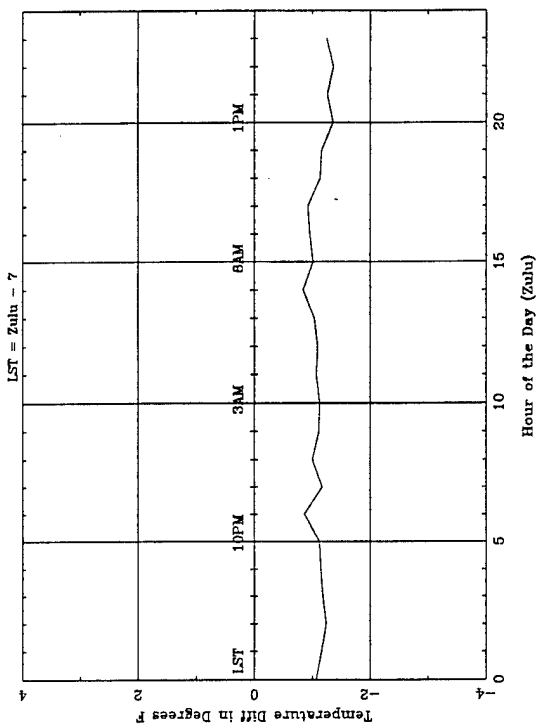
Average Diurnal Cycle for BGM - spring



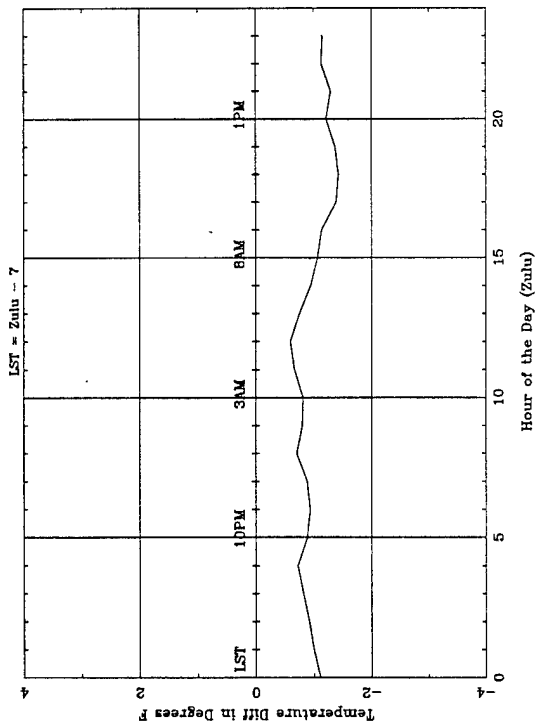
Average Diurnal Cycle for BIL - fall



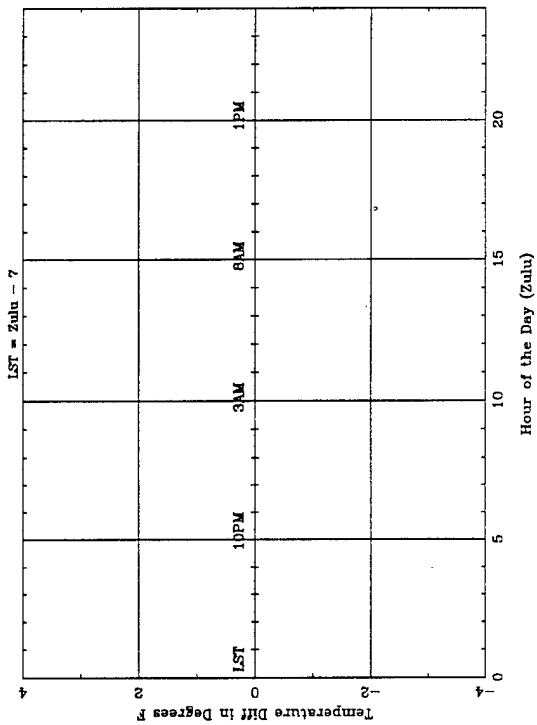
Average Diurnal Cycle for BIL - winter

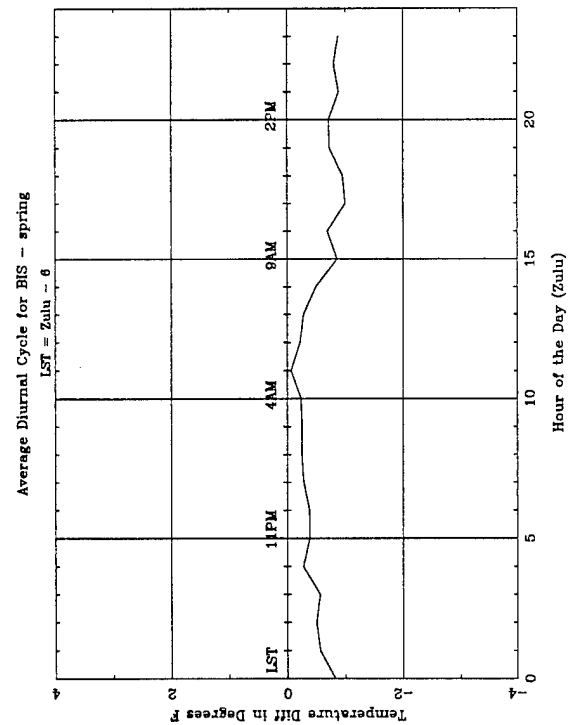
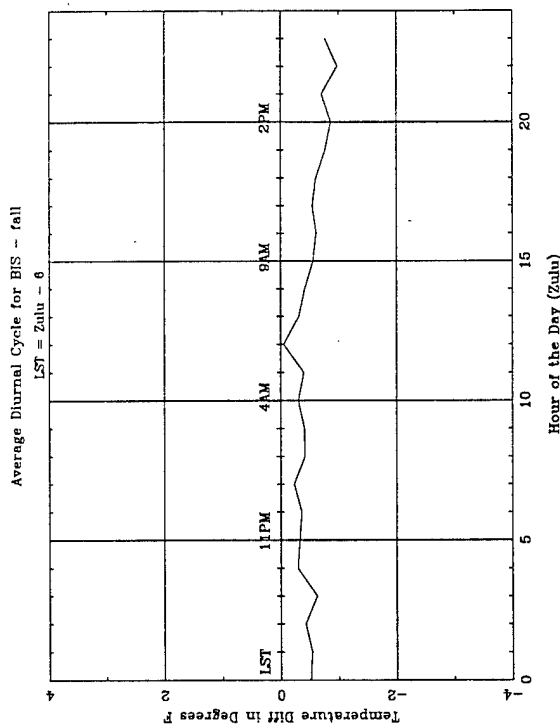
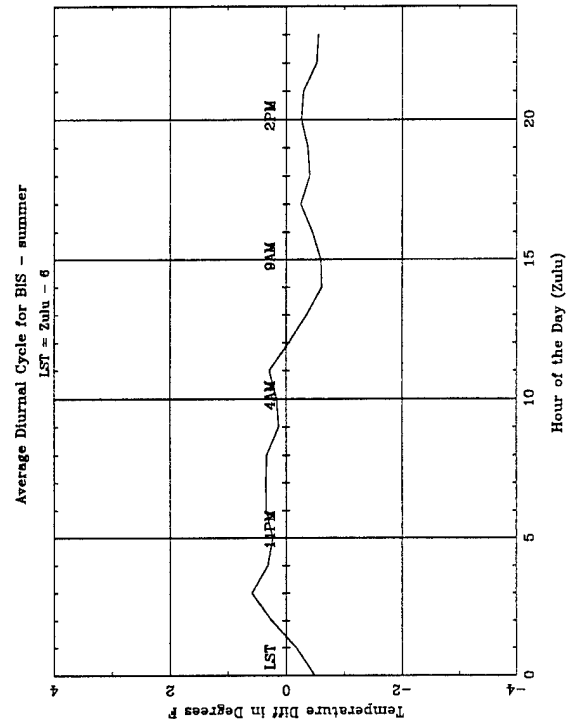
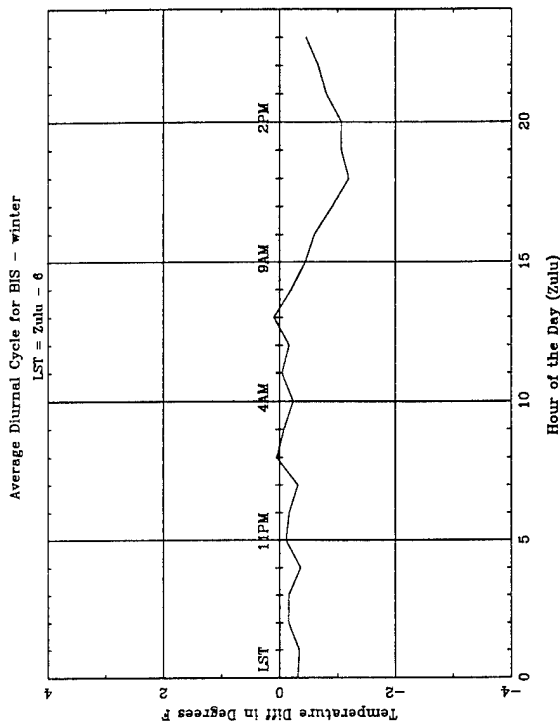


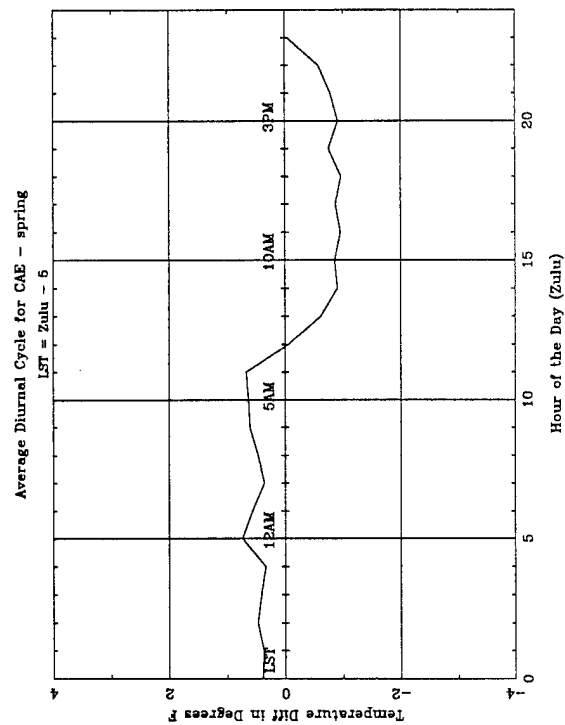
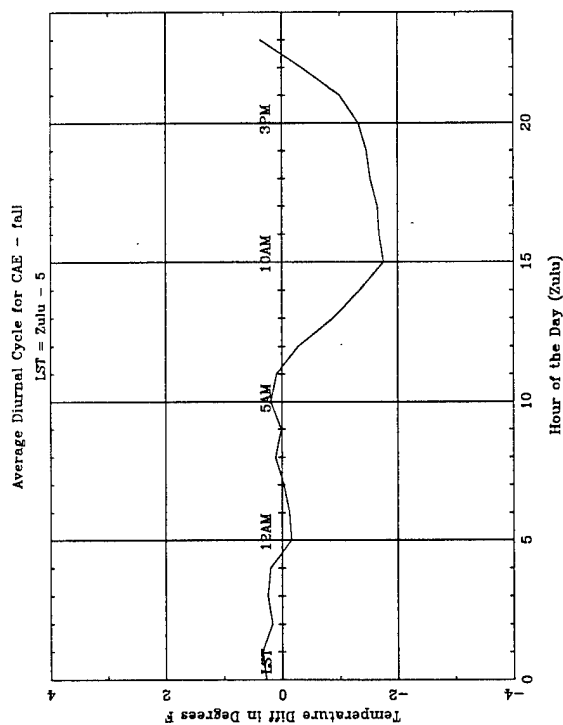
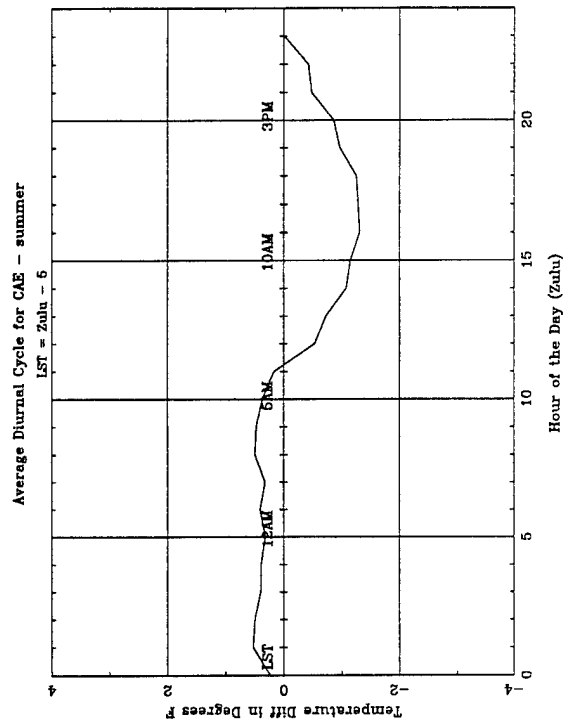
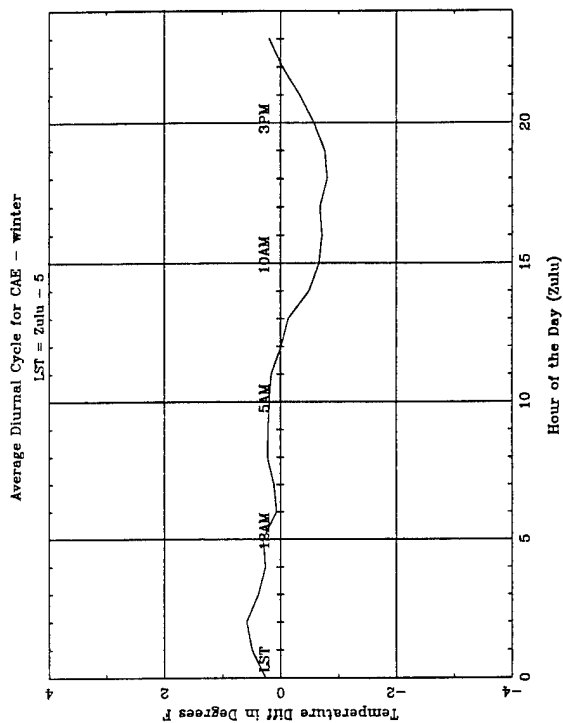
Average Diurnal Cycle for BIL - spring



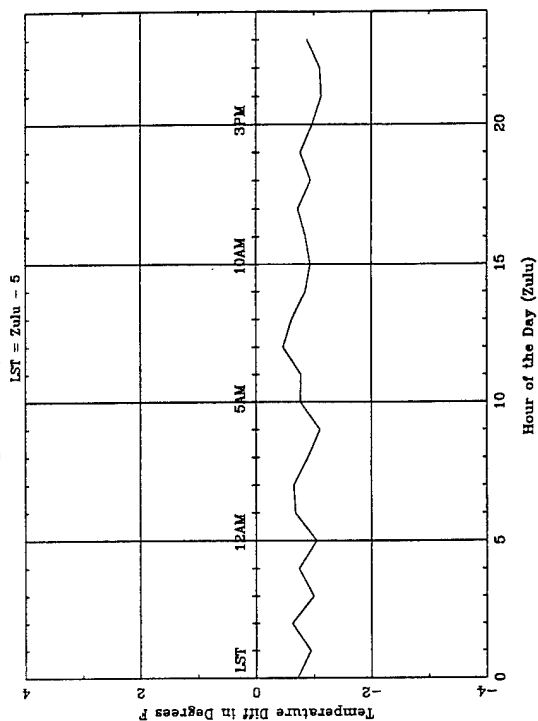
Average Diurnal Cycle for BIL - summer



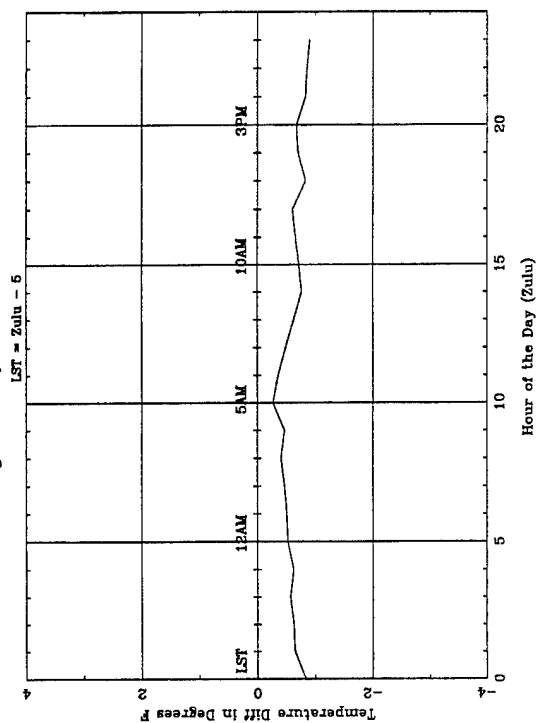




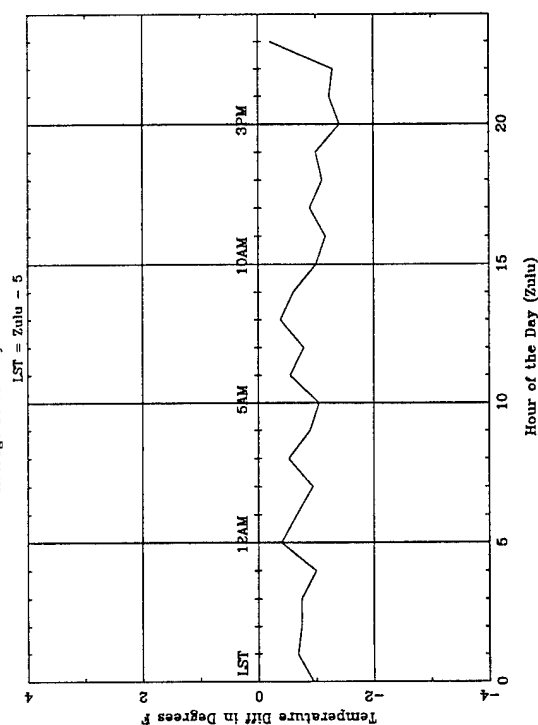
Average Diurnal Cycle for CAK - winter



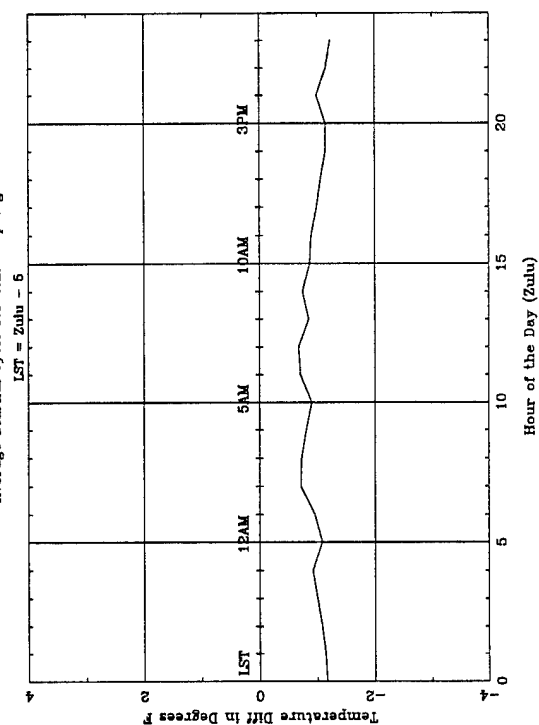
Average Diurnal Cycle for CAK - summer

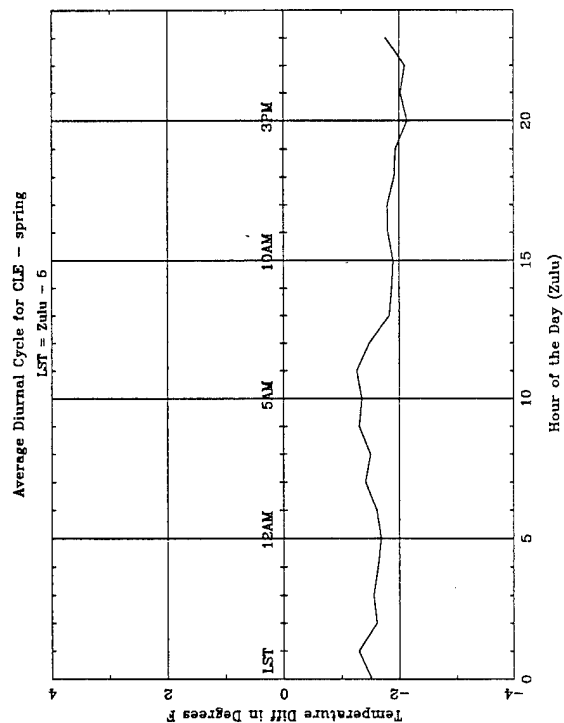
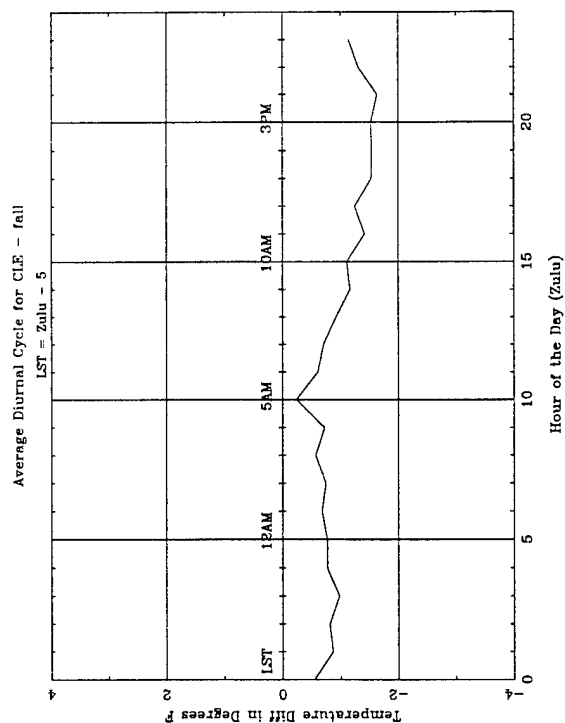
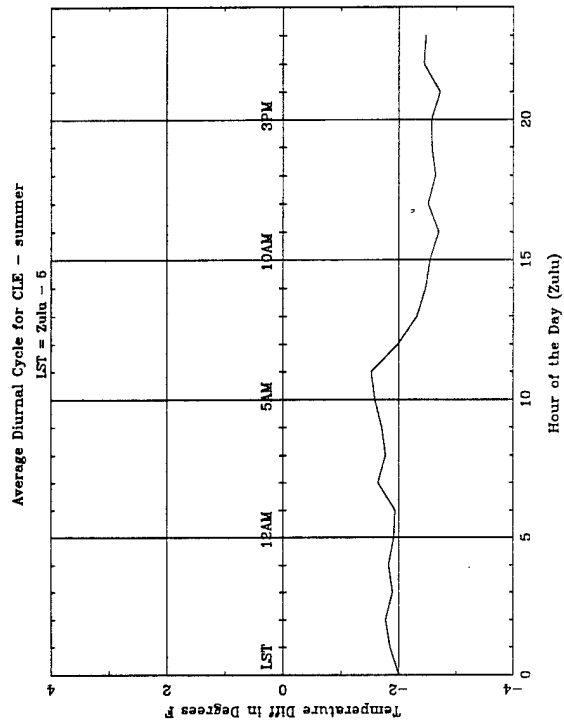
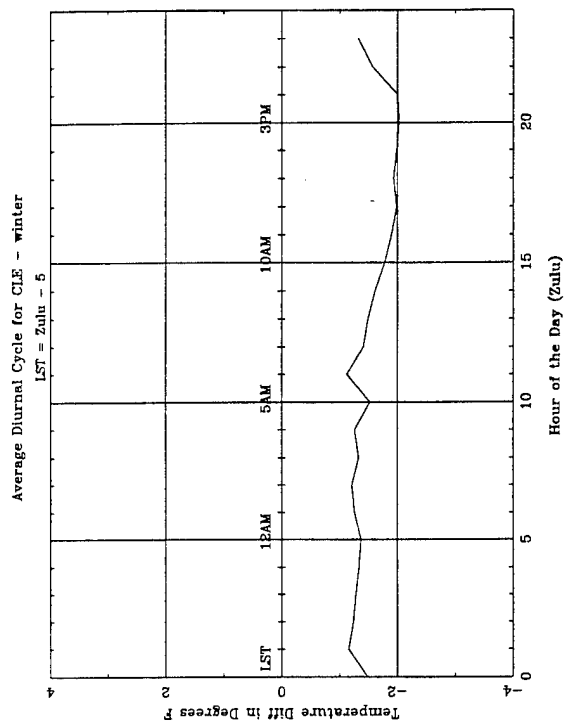


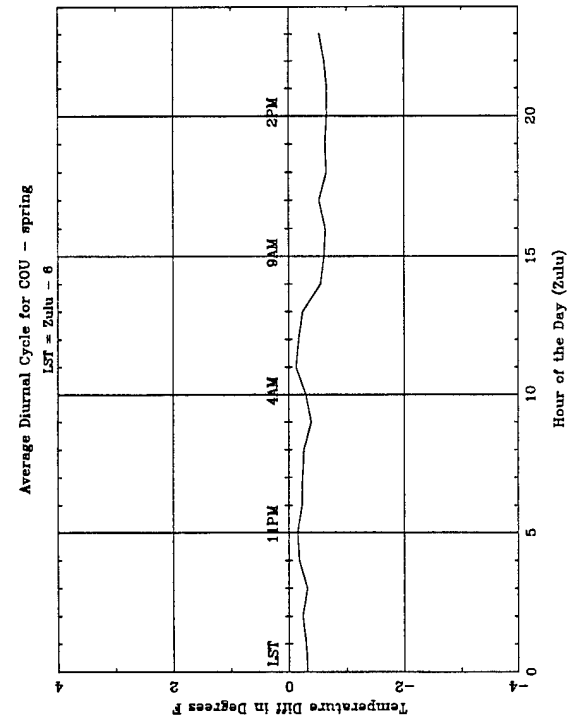
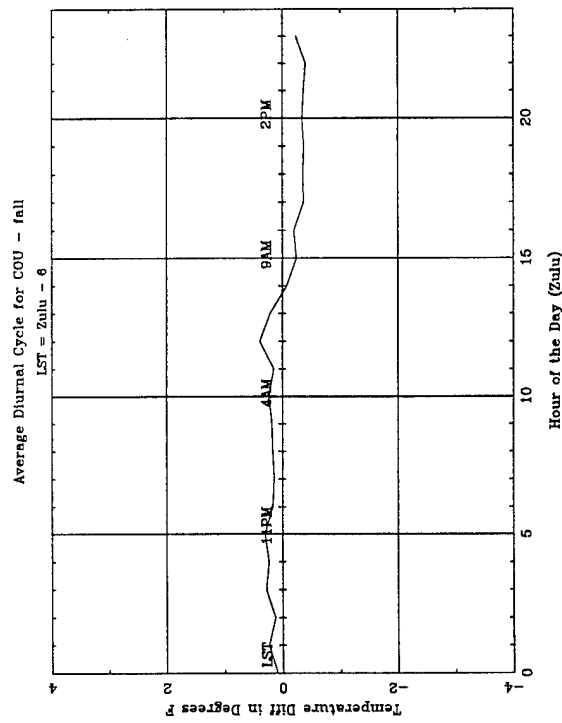
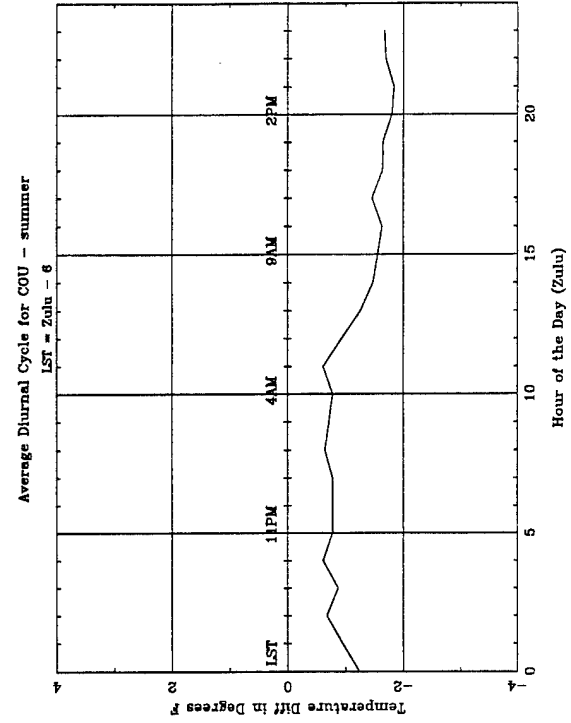
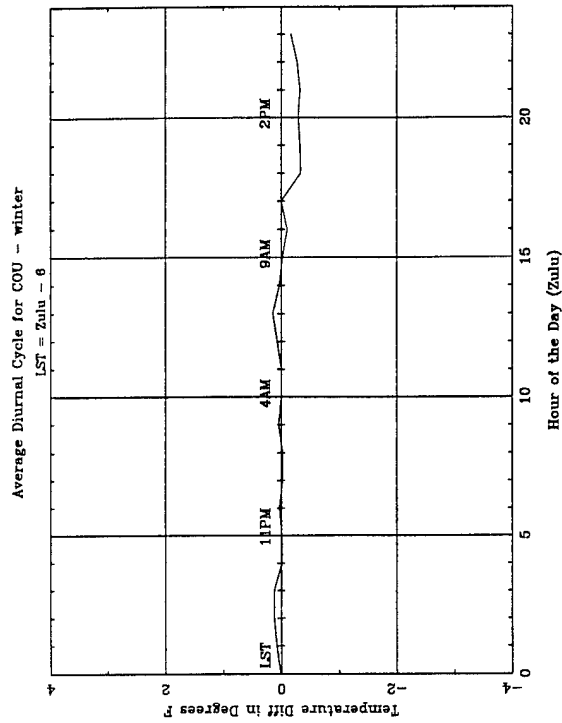
Average Diurnal Cycle for CAK - fall

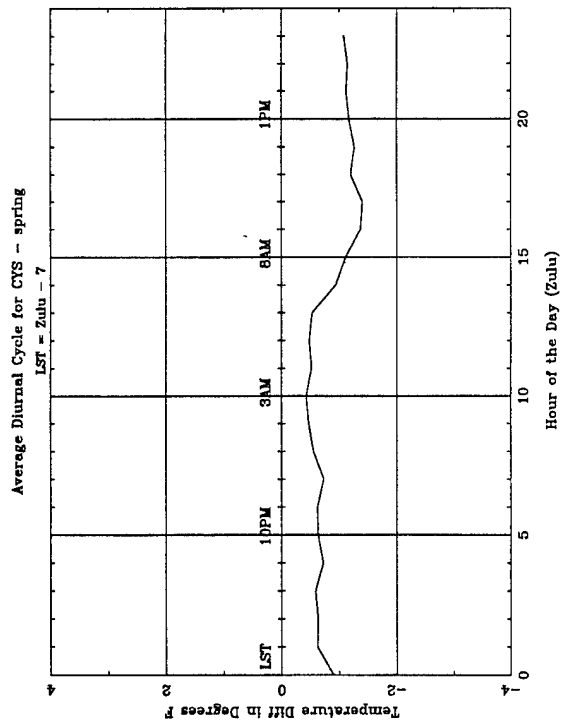
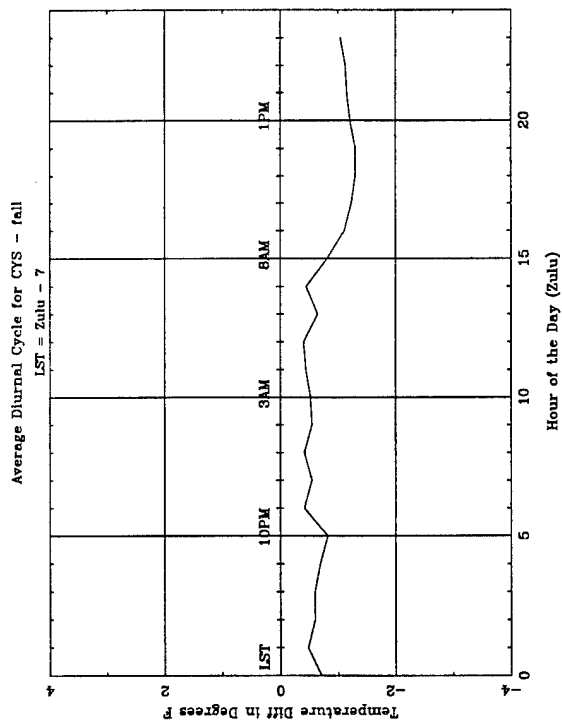
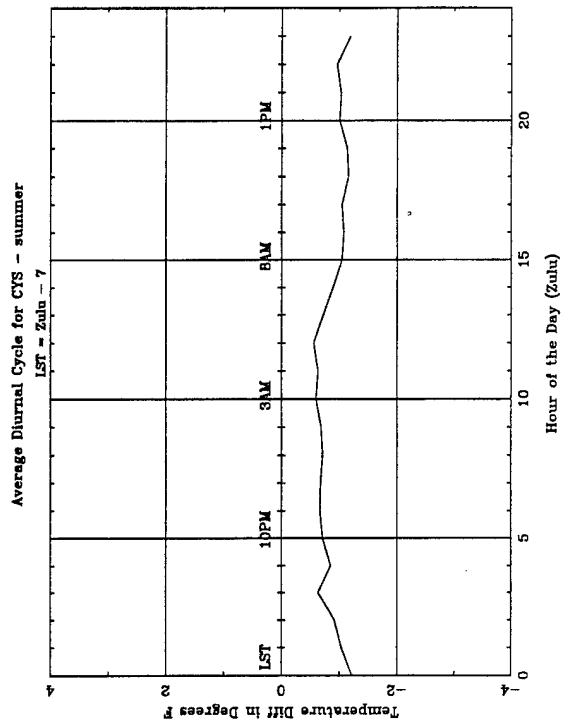
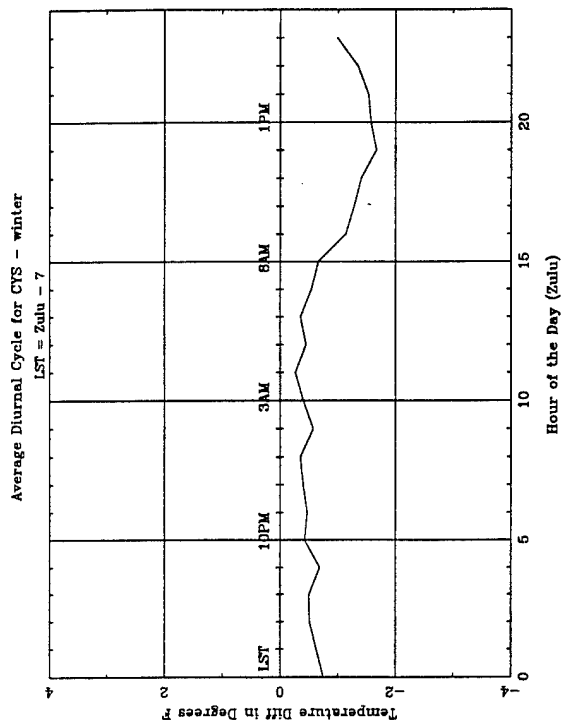


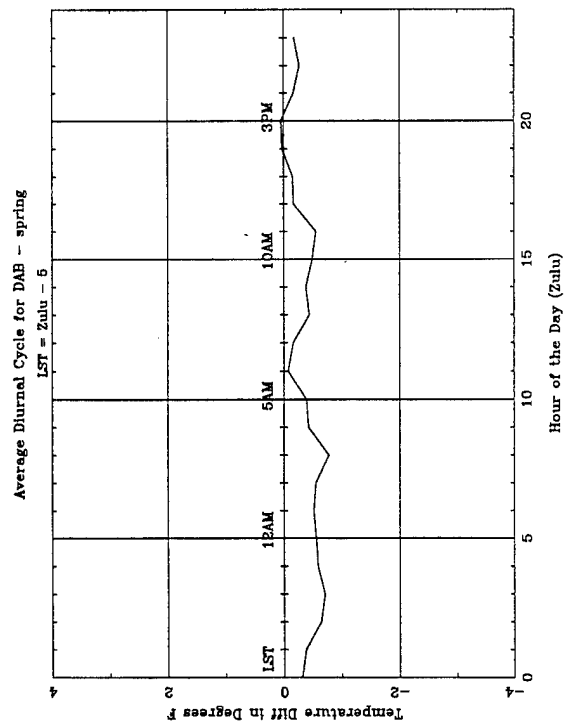
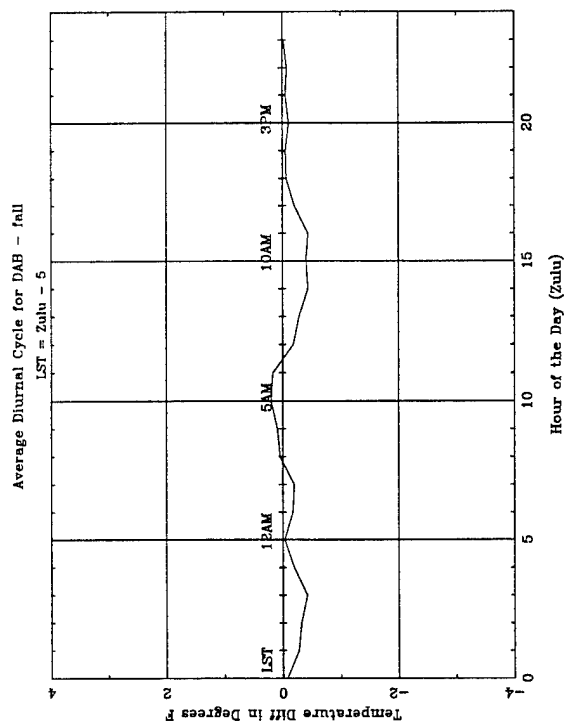
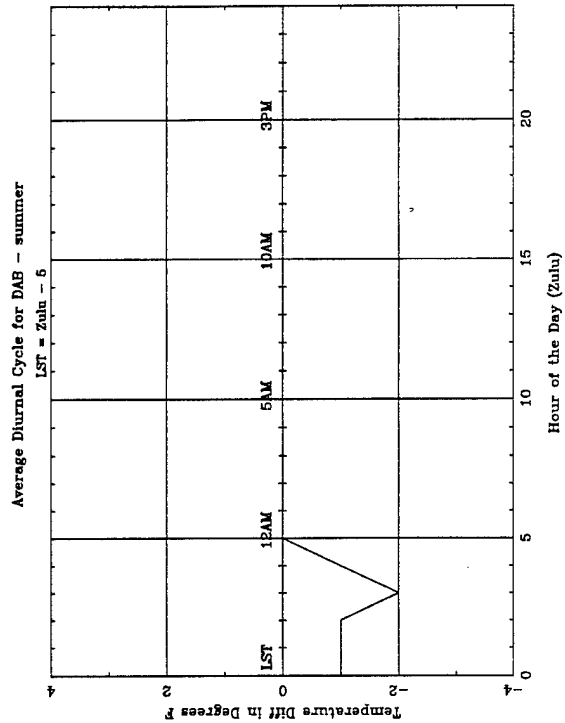
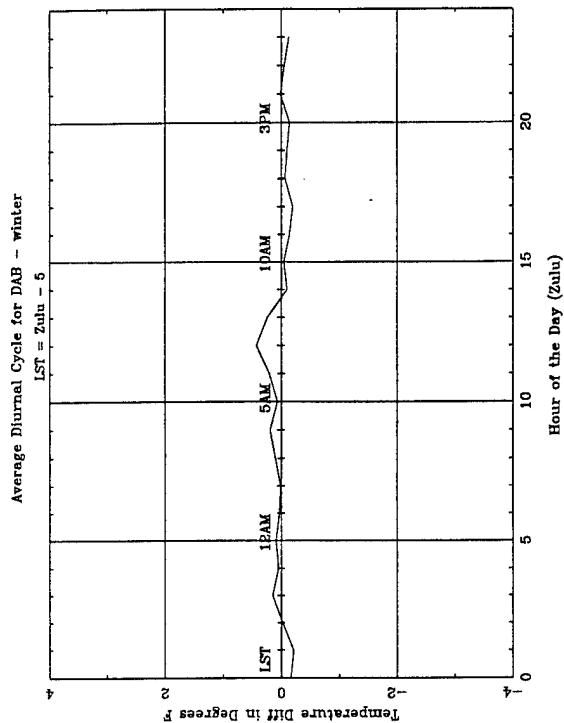
Average Diurnal Cycle for CAK - spring



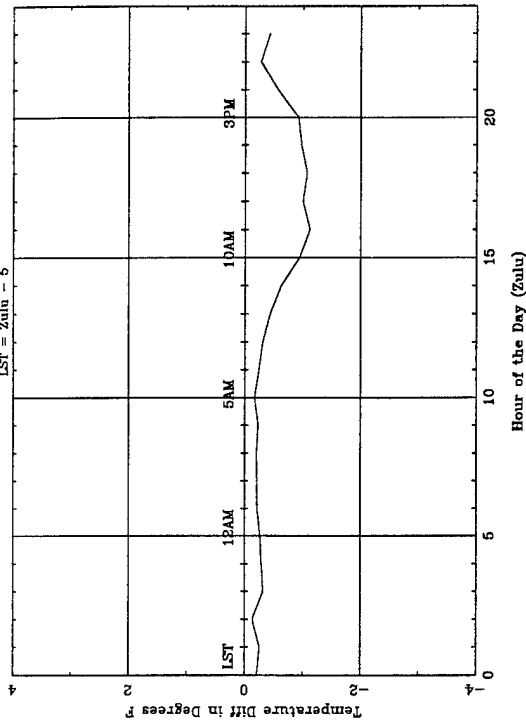




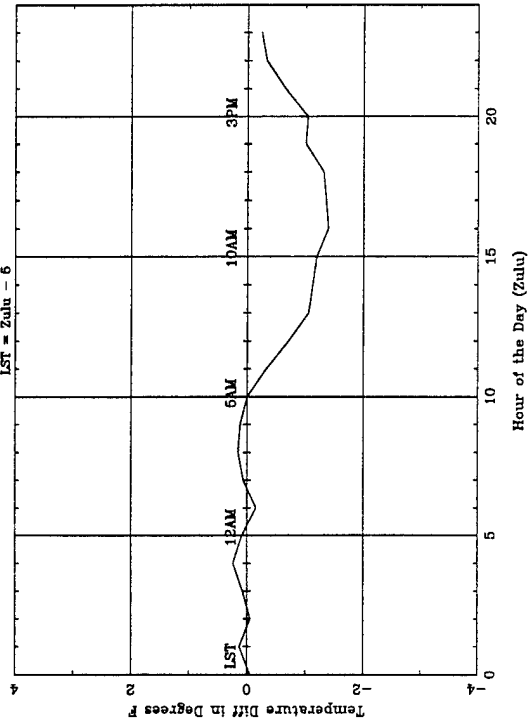




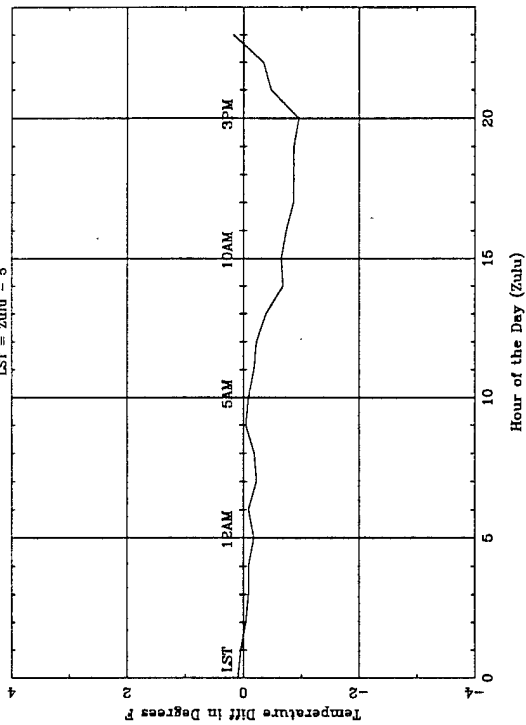
Average Diurnal Cycle for DAY - winter



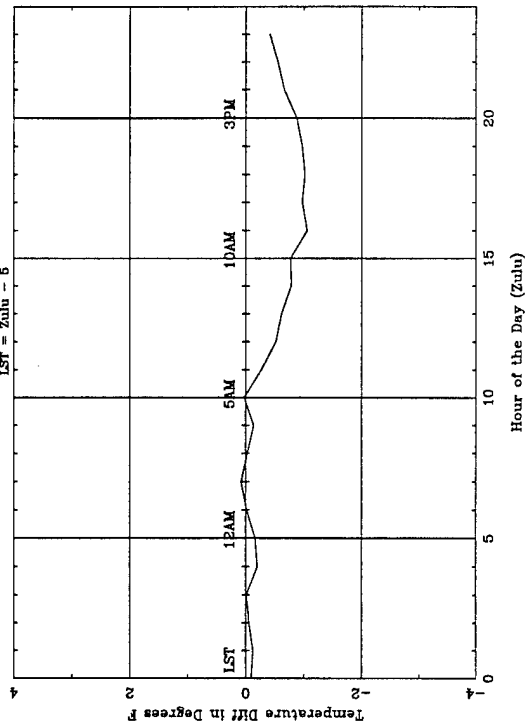
Average Diurnal Cycle for DAY - summer

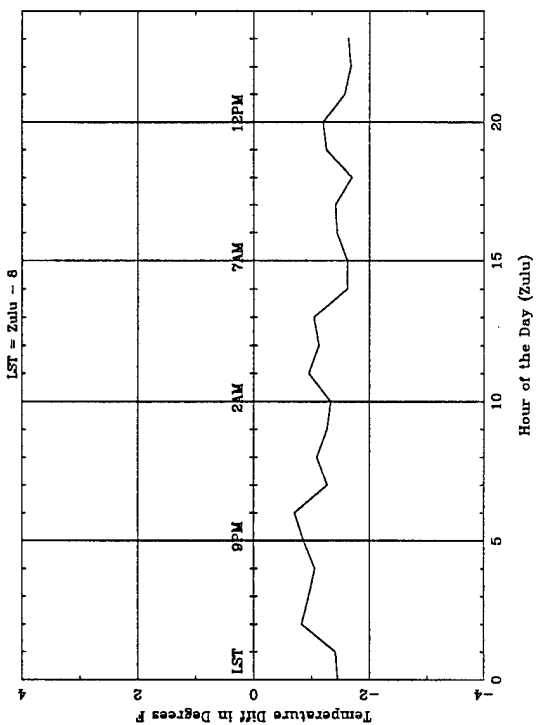
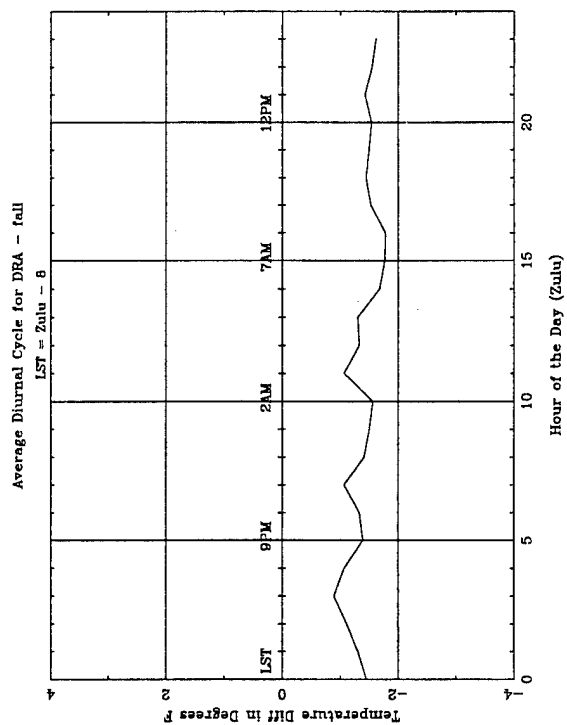
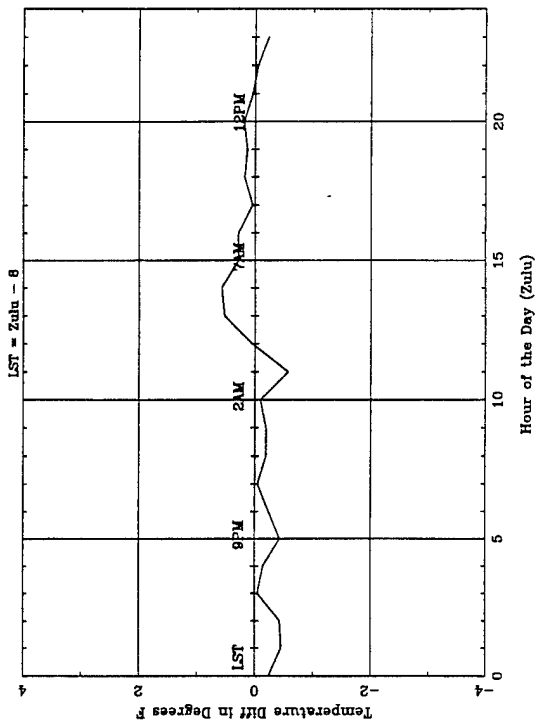
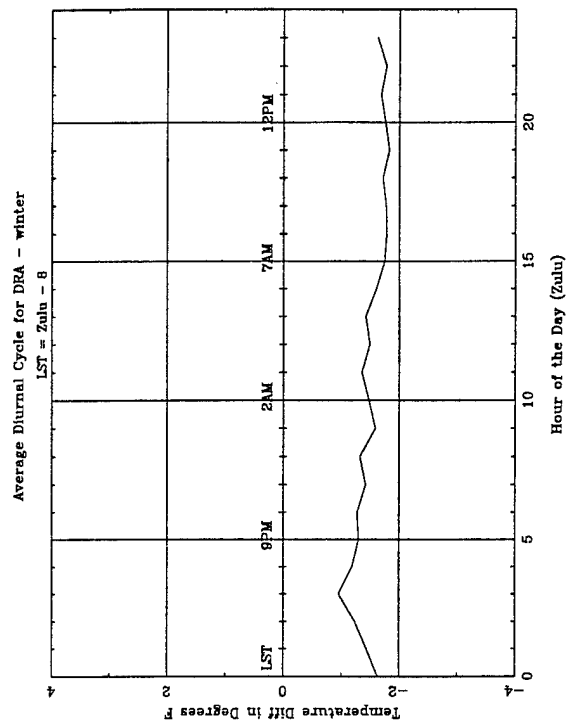


Average Diurnal Cycle for DAY - fall

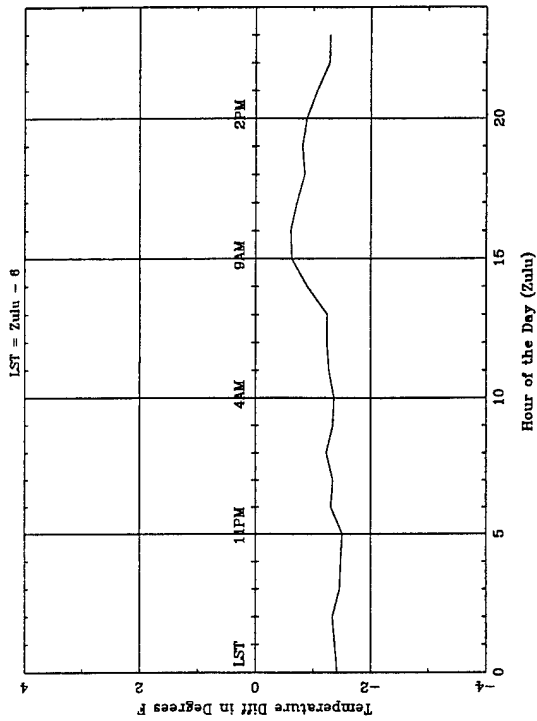


Average Diurnal Cycle for DAY - spring

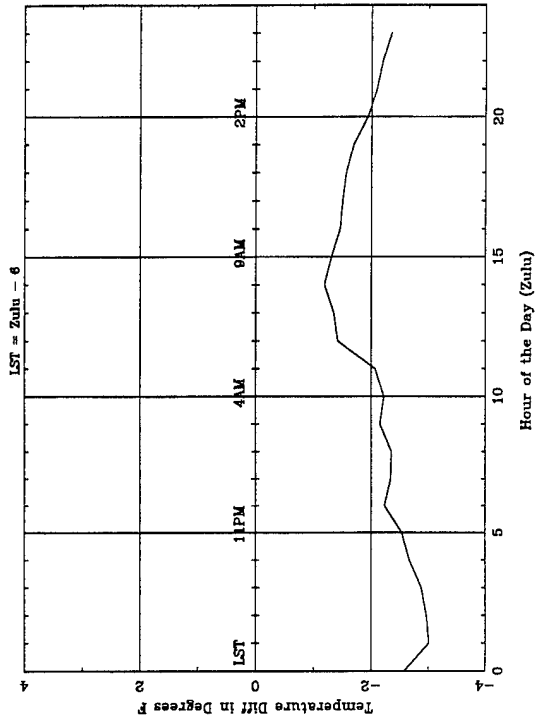




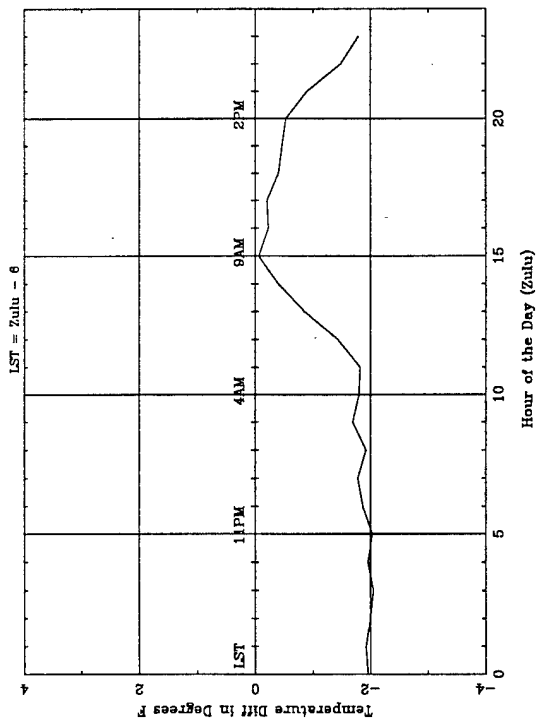
Average Diurnal Cycle for DSM - winter



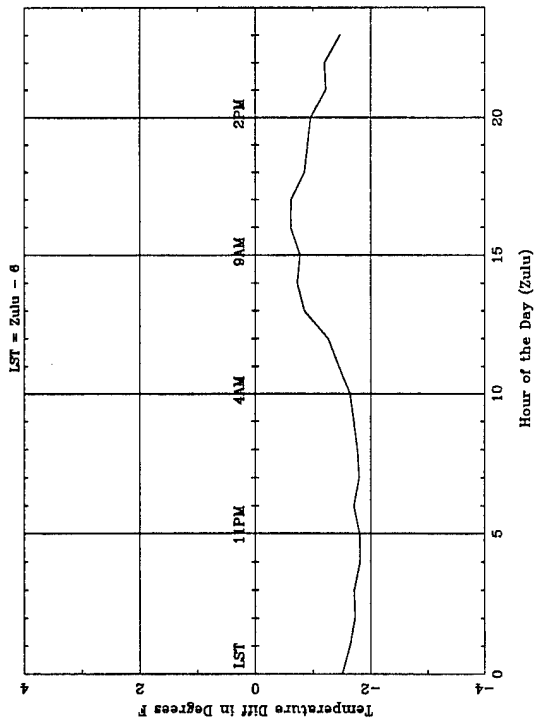
Average Diurnal Cycle for DSM - summer

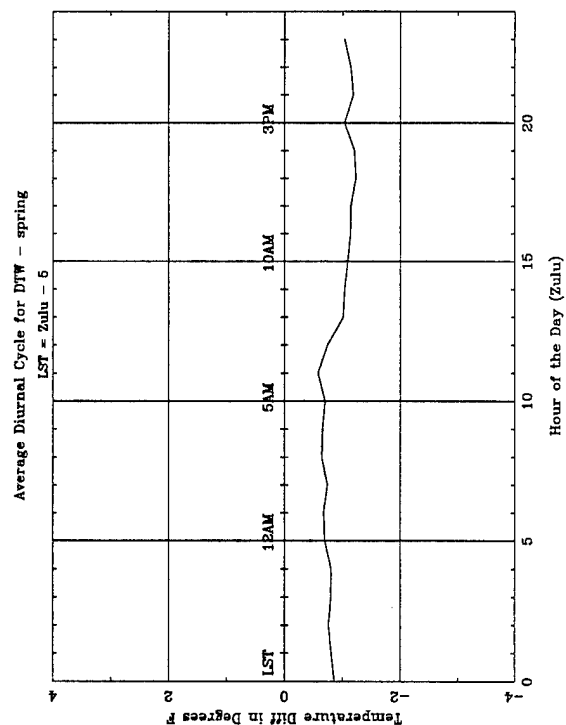
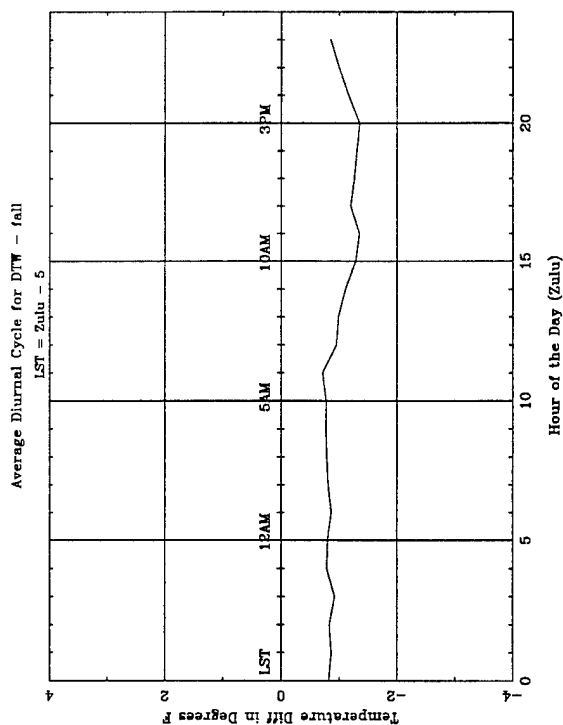
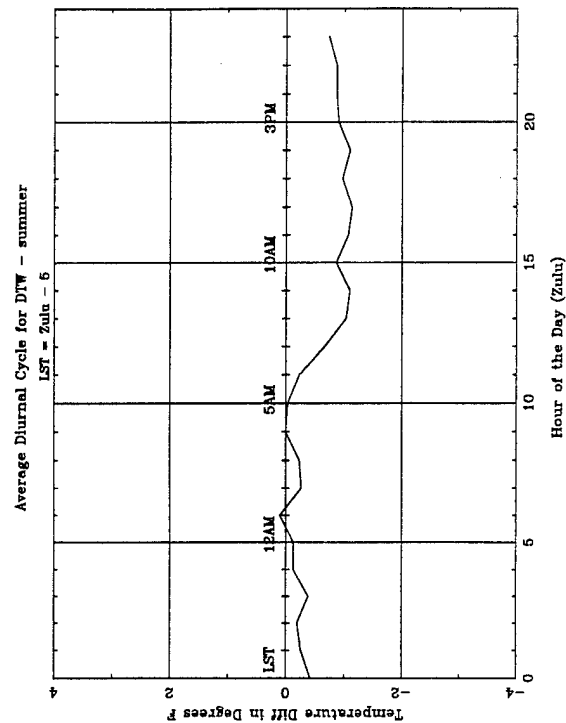
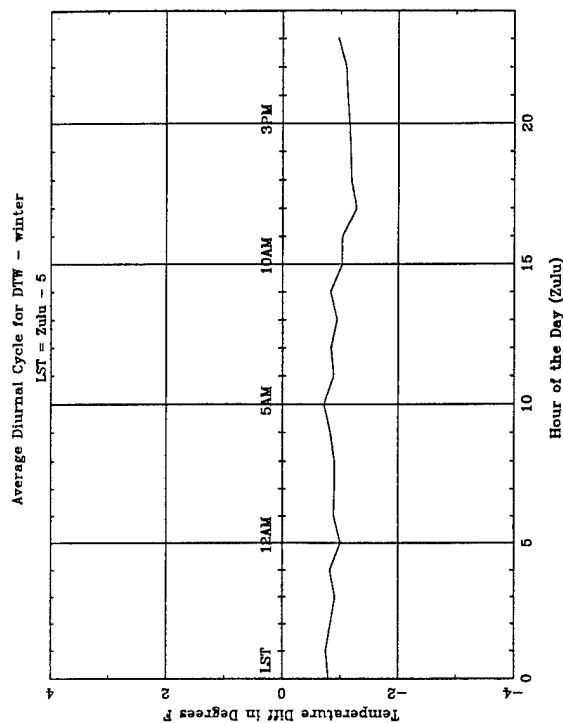


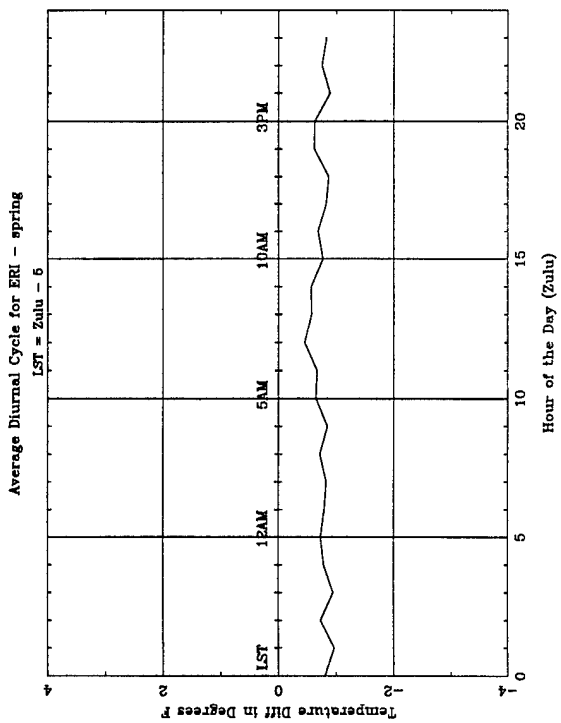
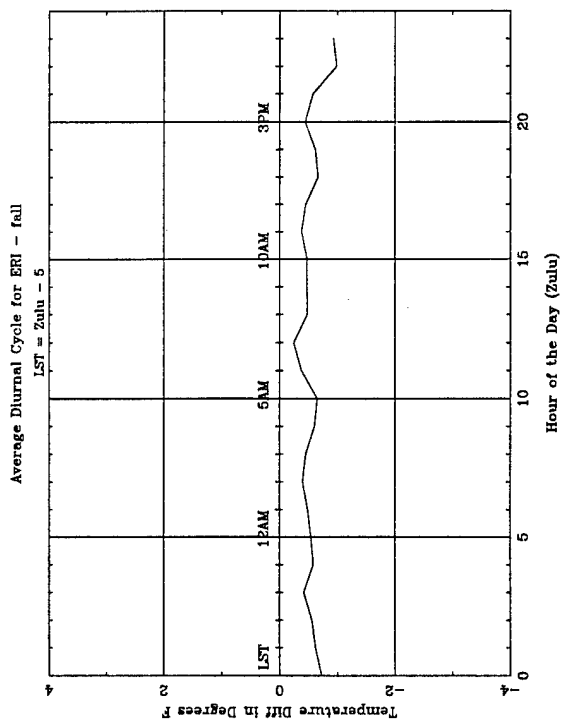
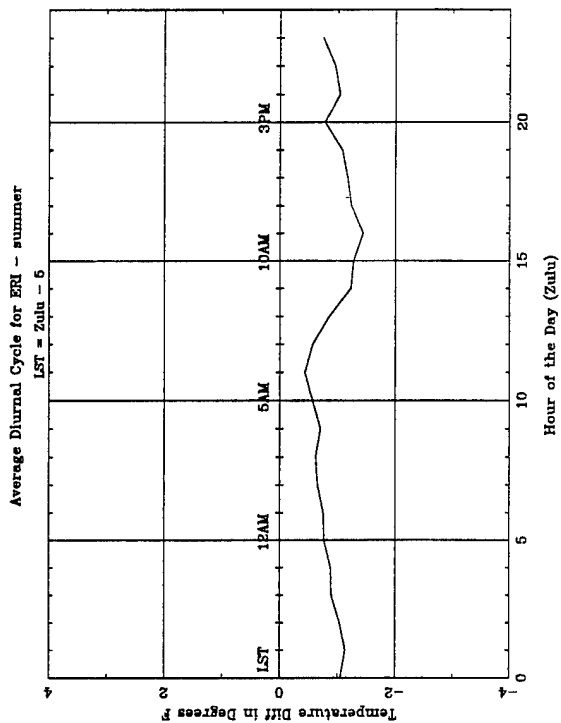
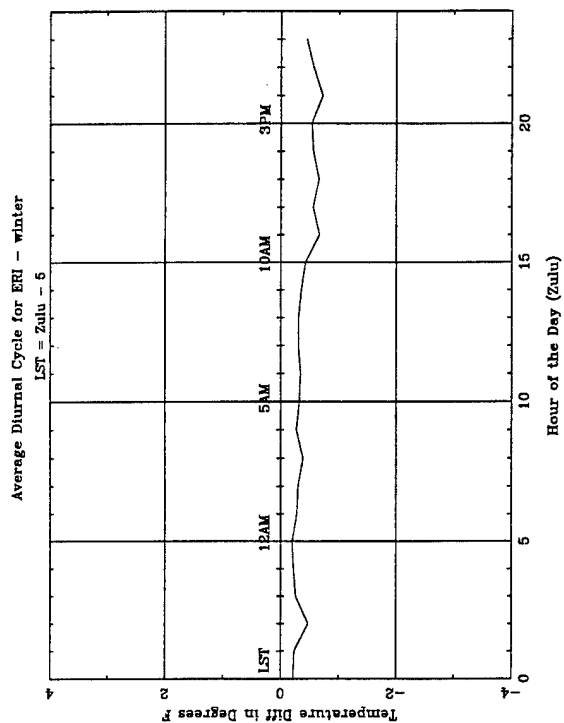
Average Diurnal Cycle for DSM - fall



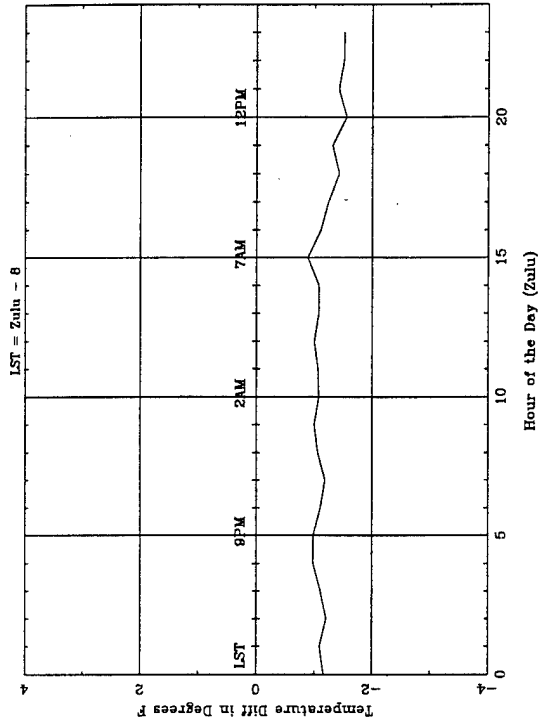
Average Diurnal Cycle for DSM - spring



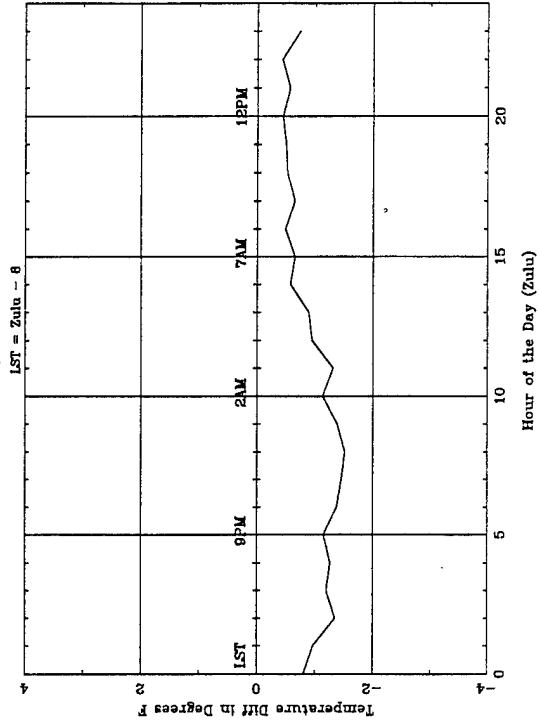




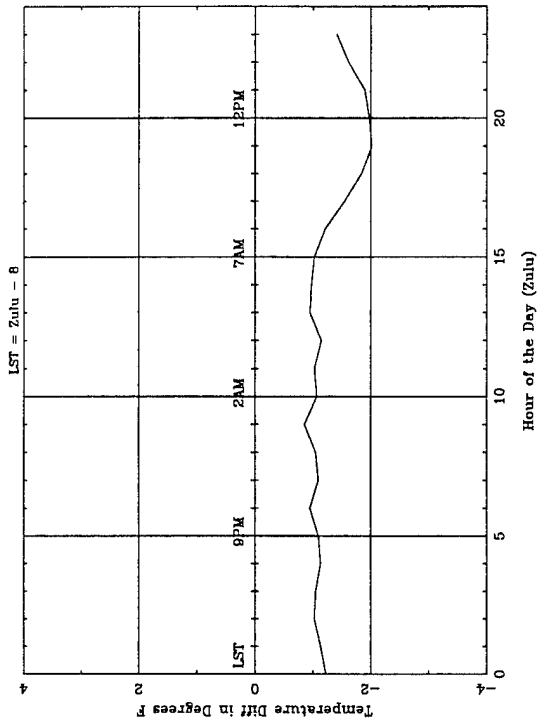
Average Diurnal Cycle for EUG - winter



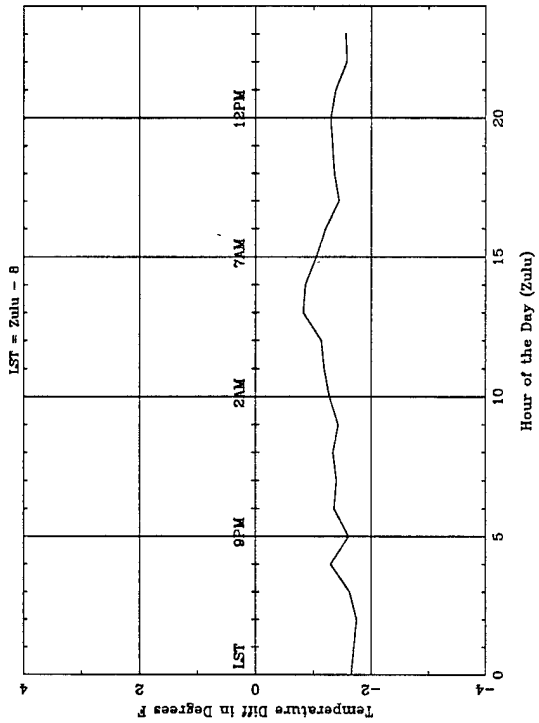
Average Diurnal Cycle for EUG - summer

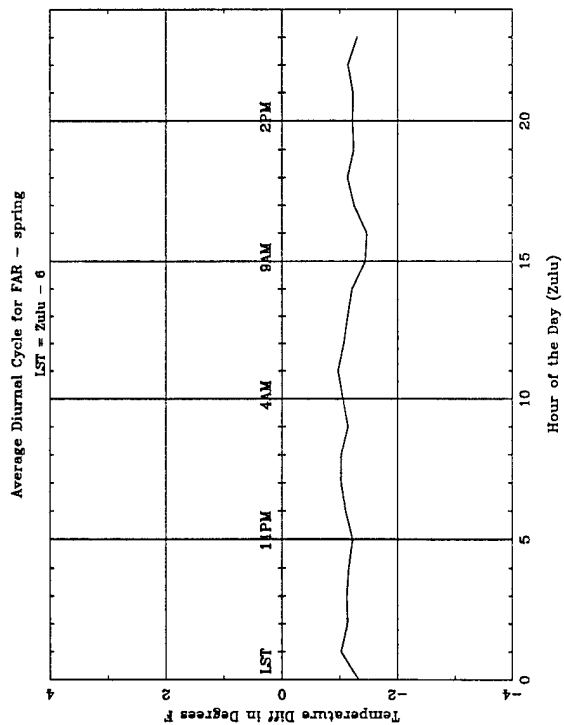
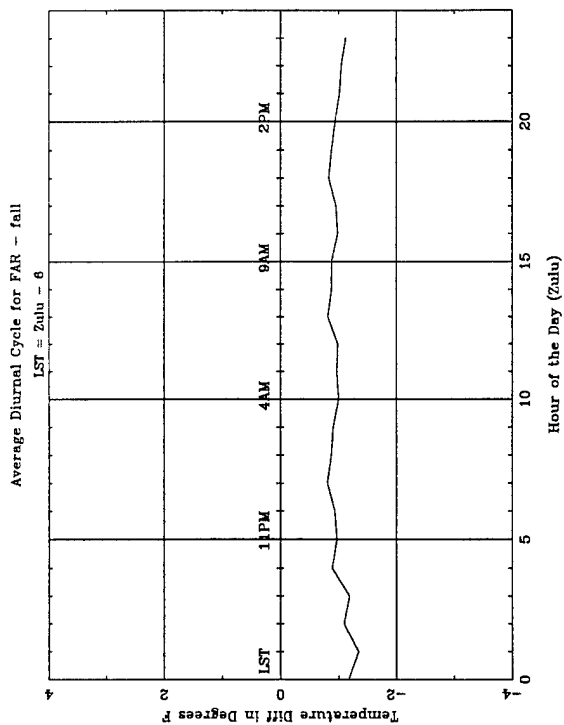
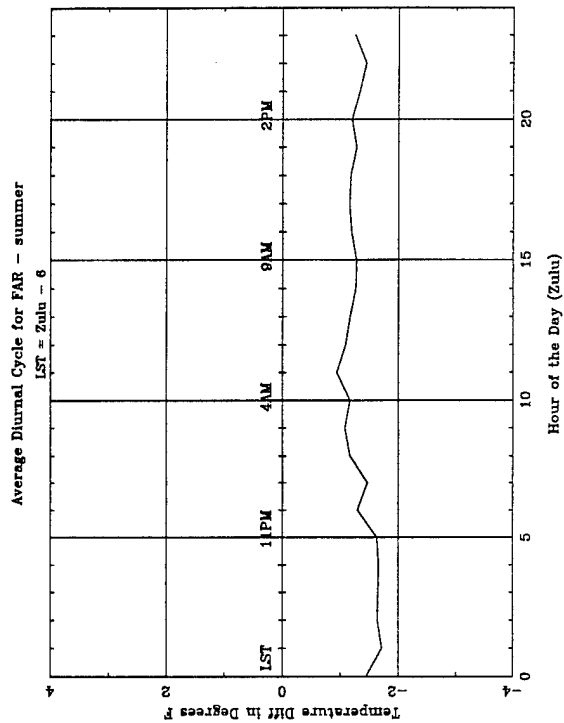
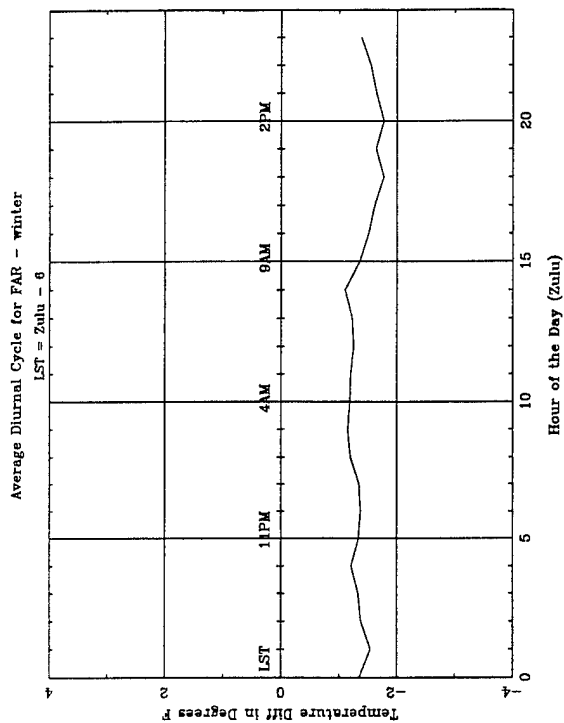


Average Diurnal Cycle for EUG - fall

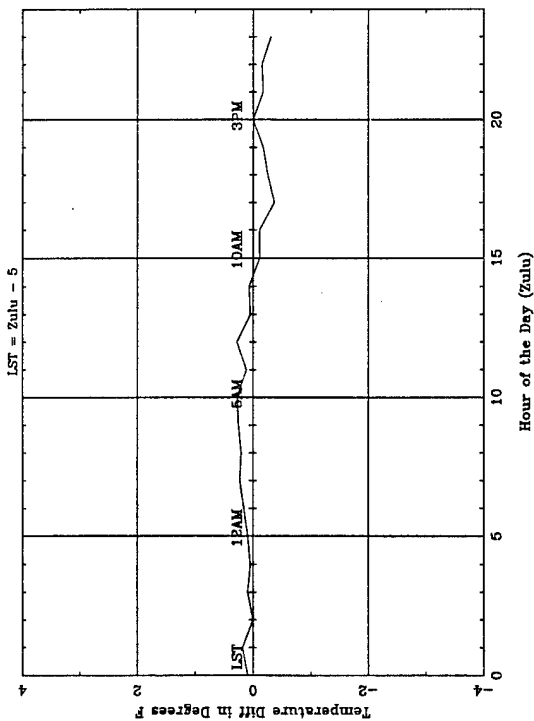


Average Diurnal Cycle for EUG - spring

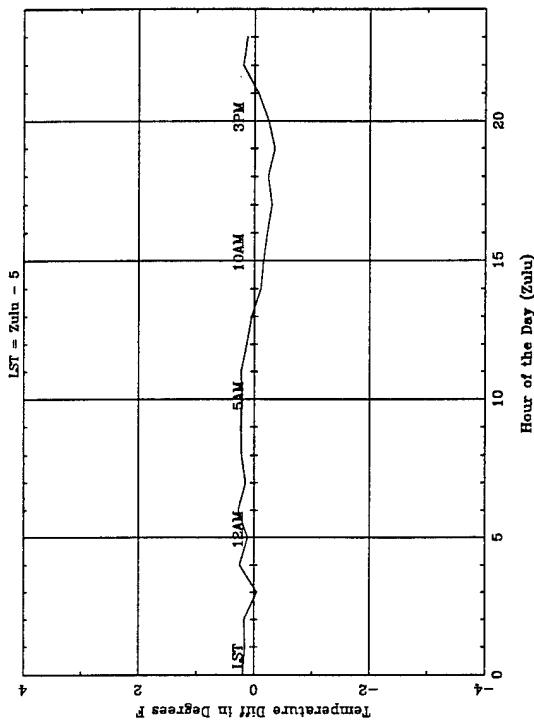




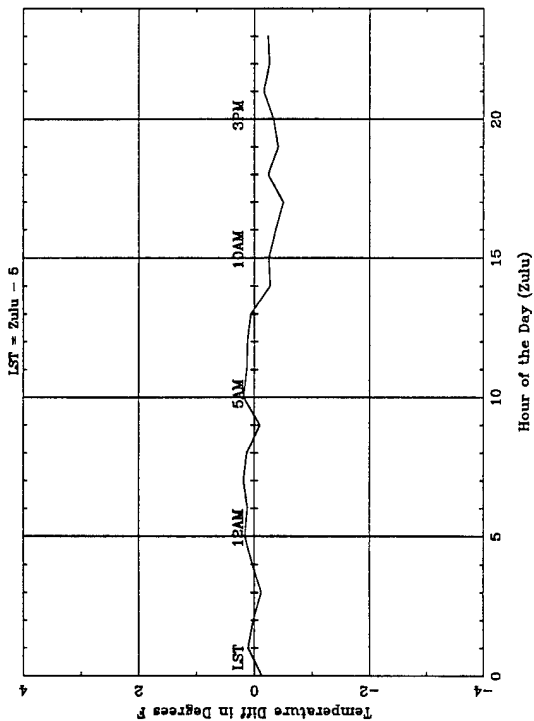
Average Diurnal Cycle for FNT - fall



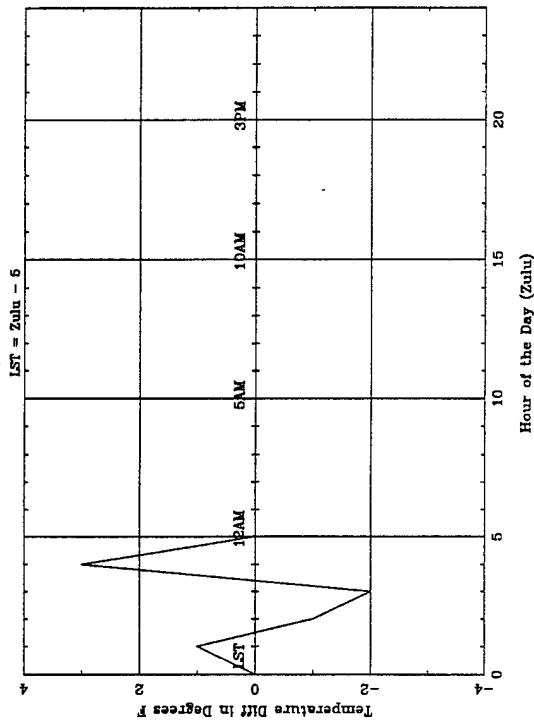
Average Diurnal Cycle for FNT - winter

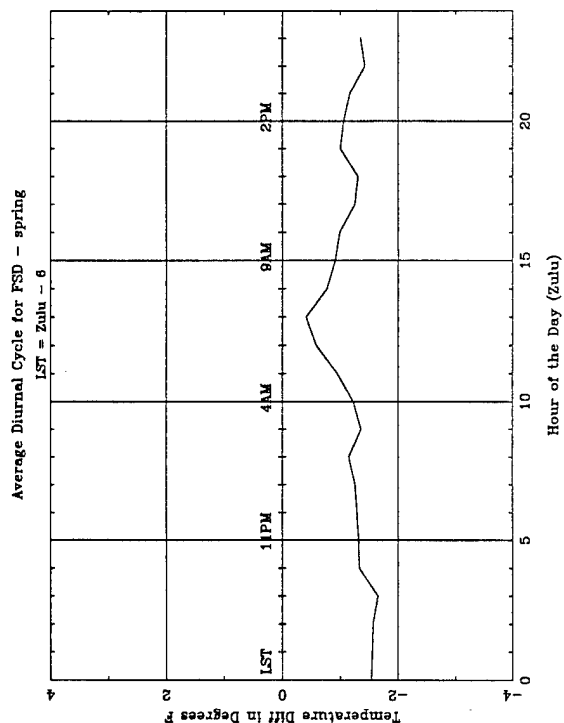
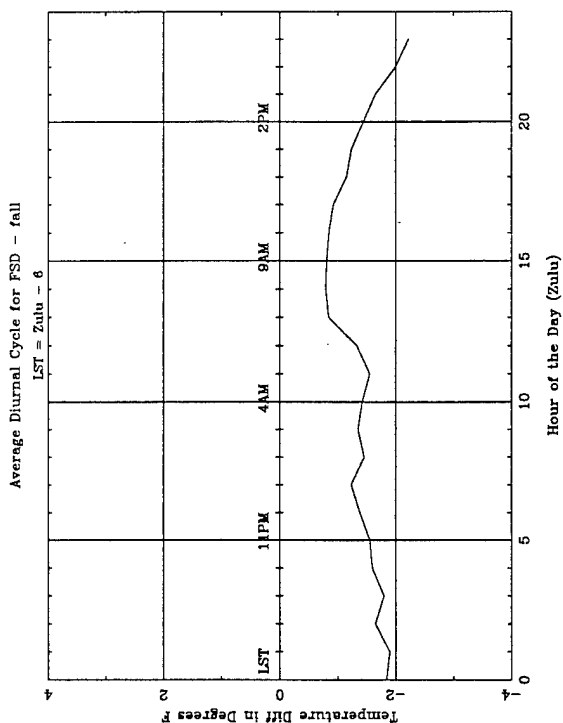
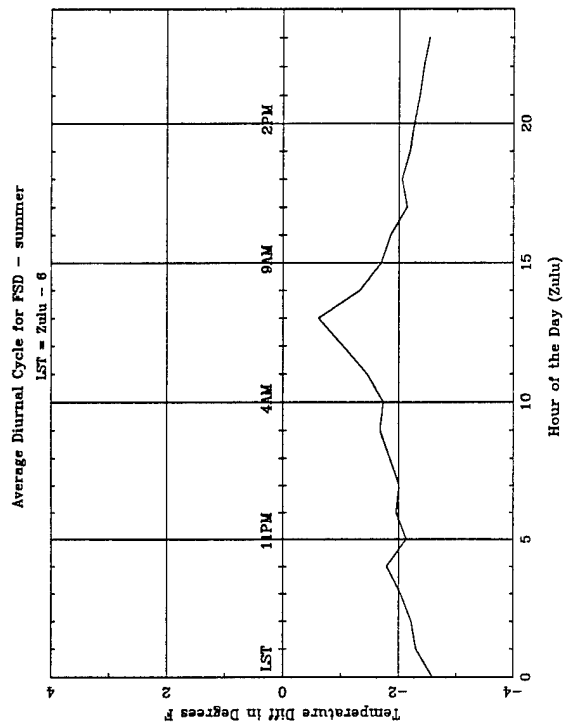
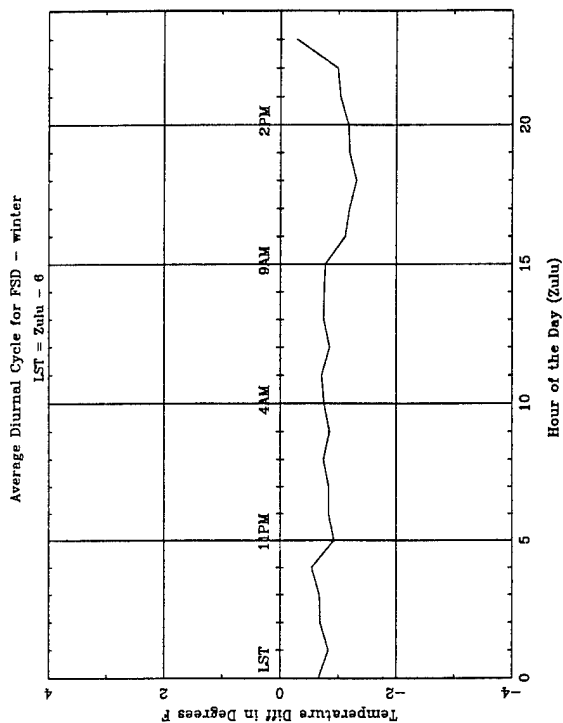


Average Diurnal Cycle for FNT - spring

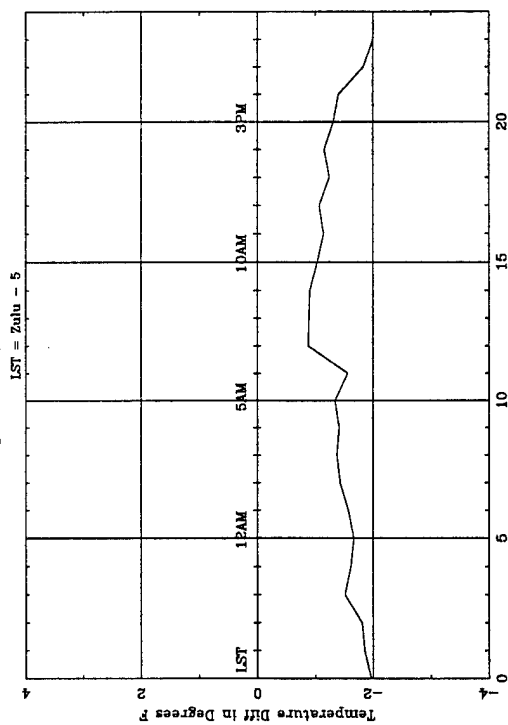


Average Diurnal Cycle for FNT - summer

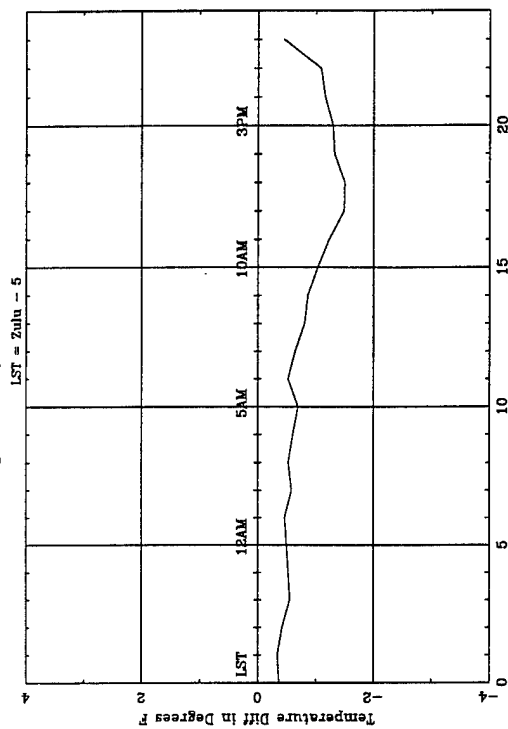




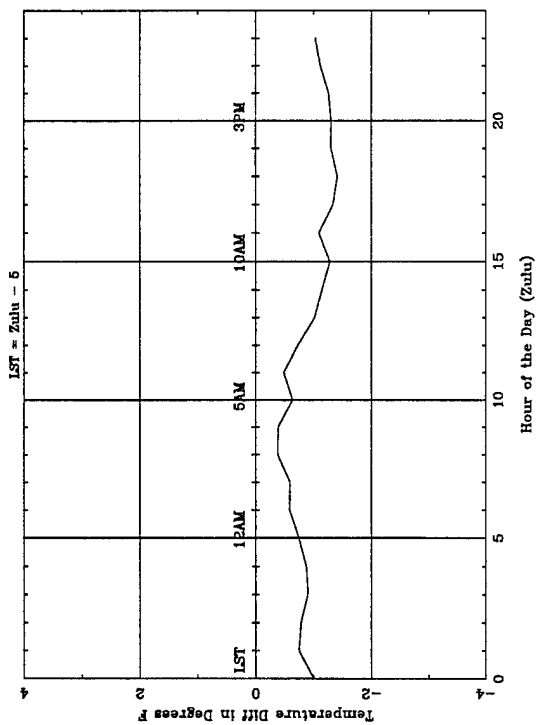
Average Diurnal Cycle for FWA - fall



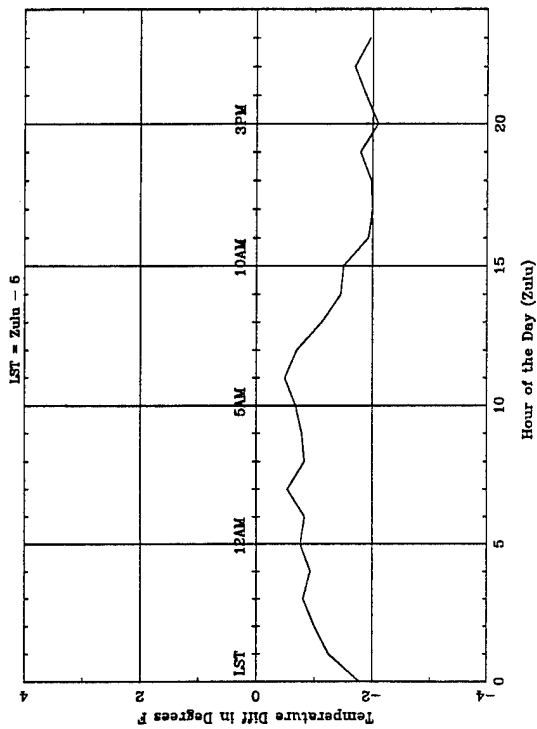
Average Diurnal Cycle for FWA - winter

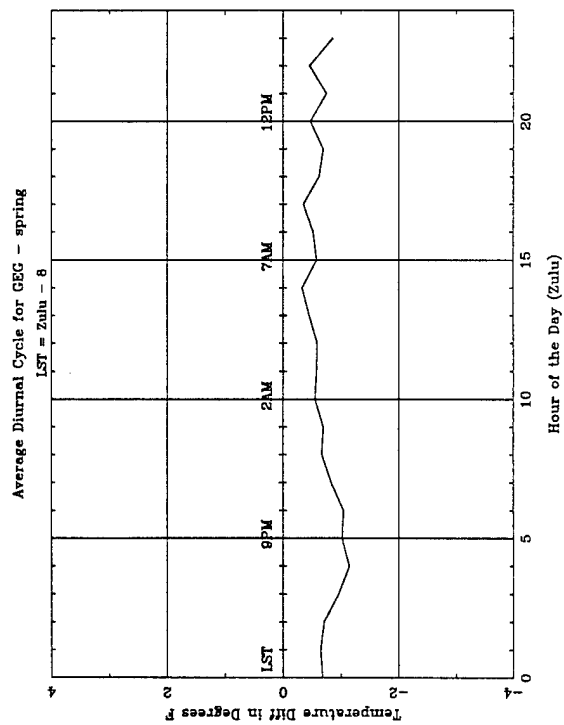
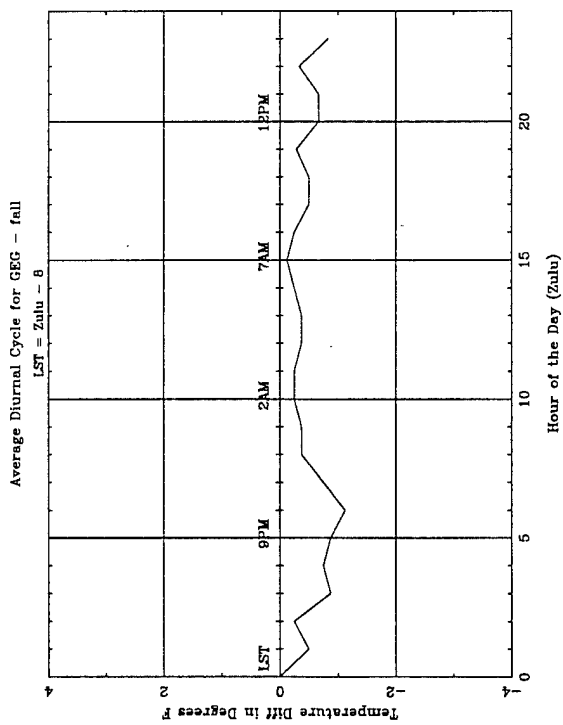
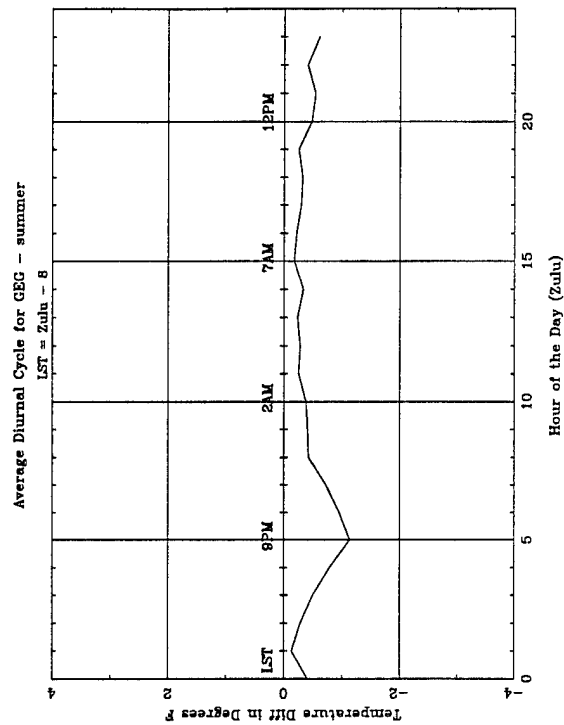
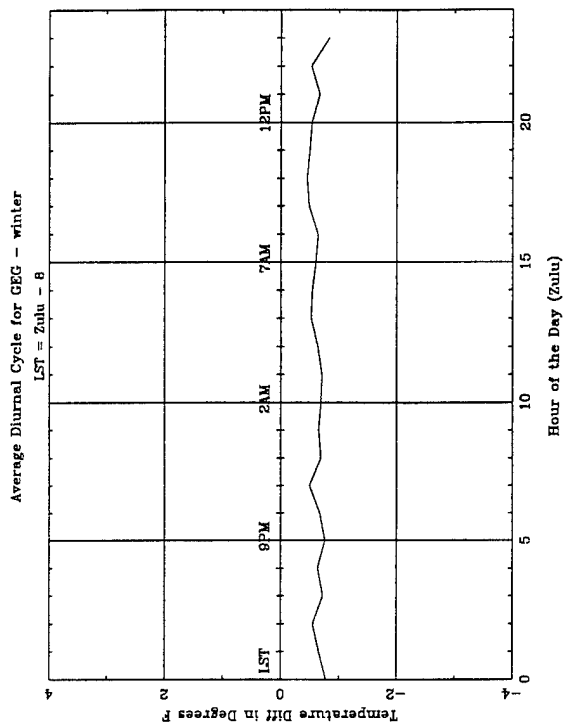


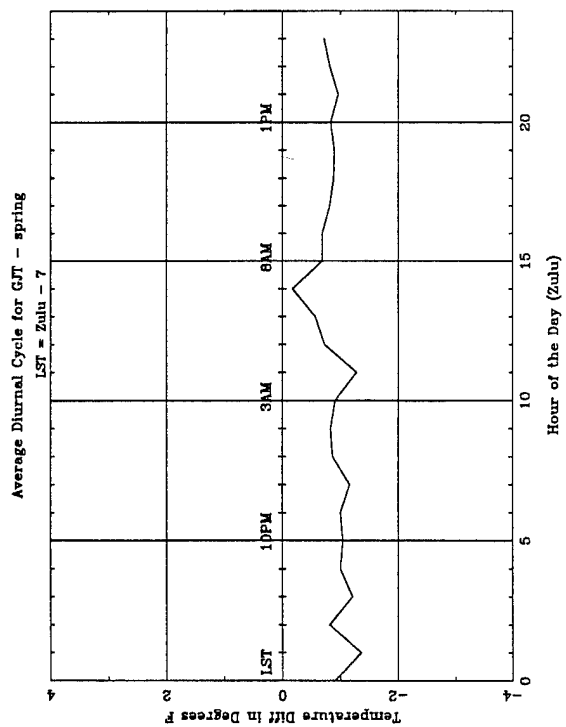
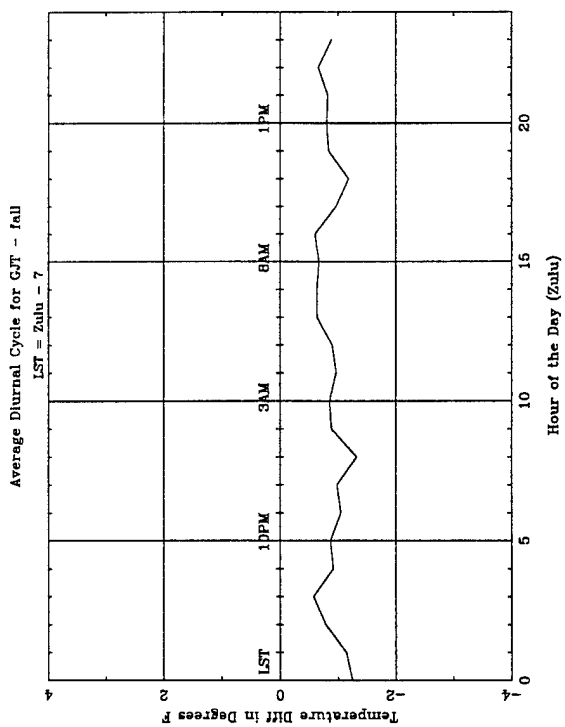
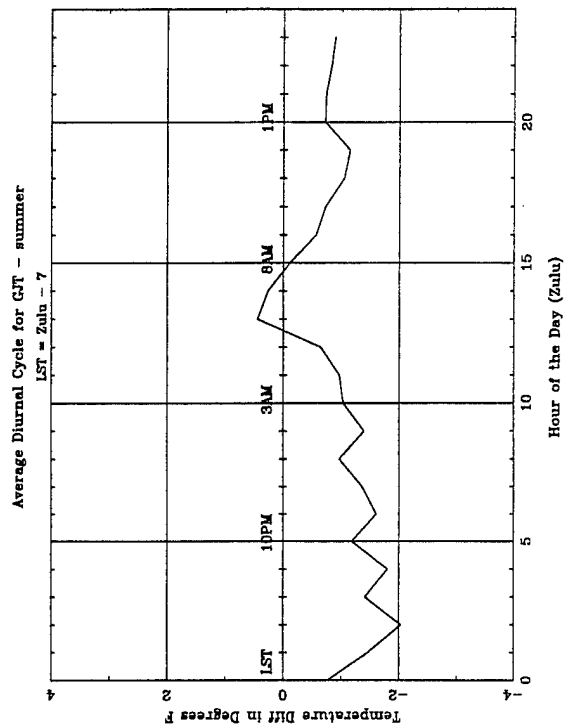
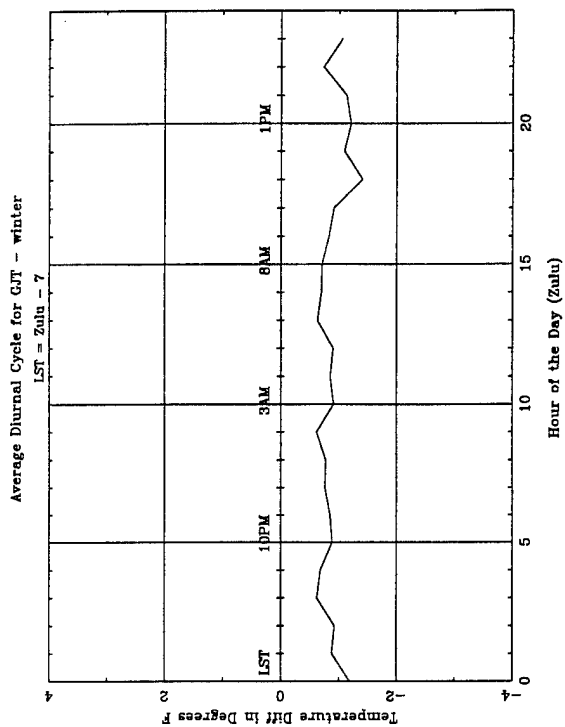
Average Diurnal Cycle for FWA - spring

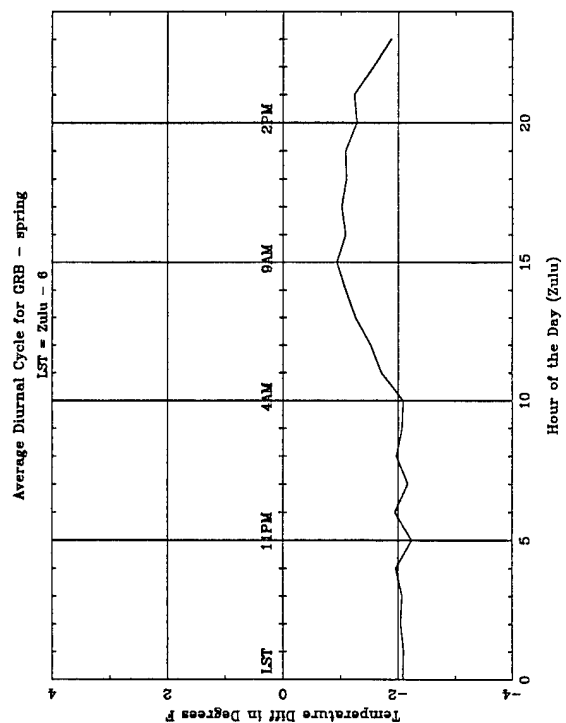
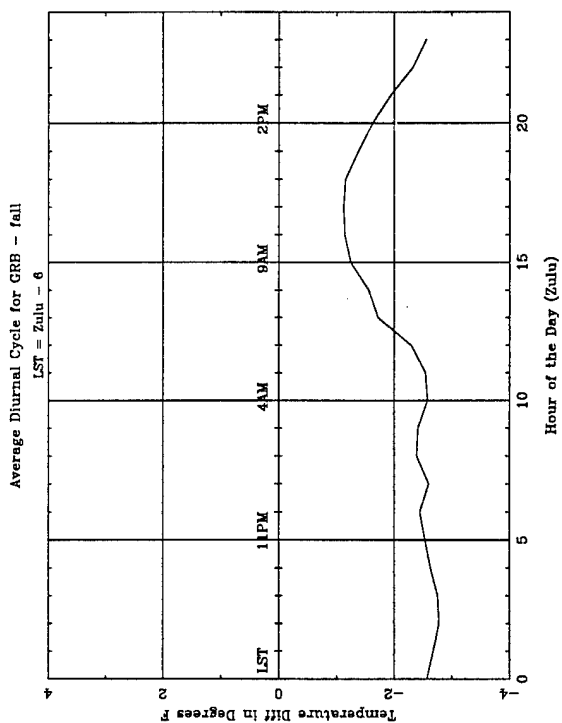
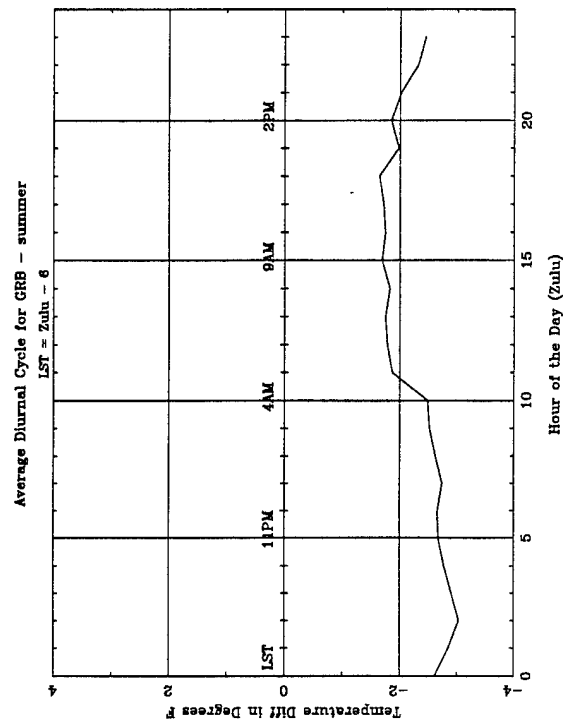
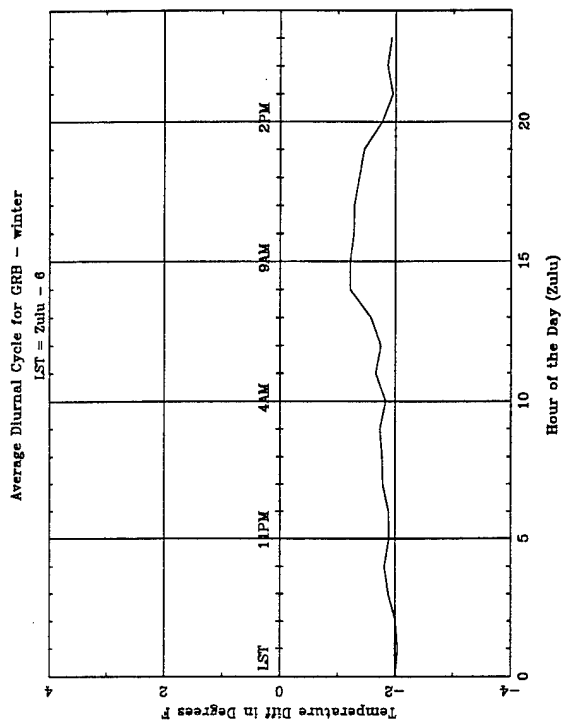


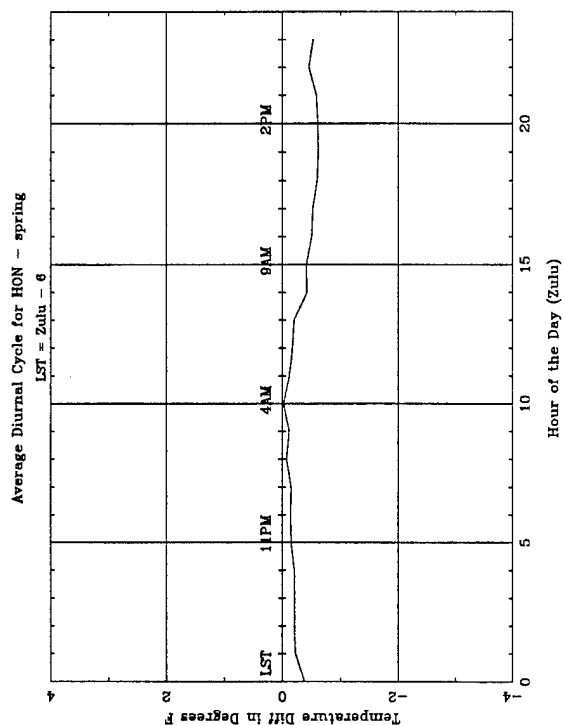
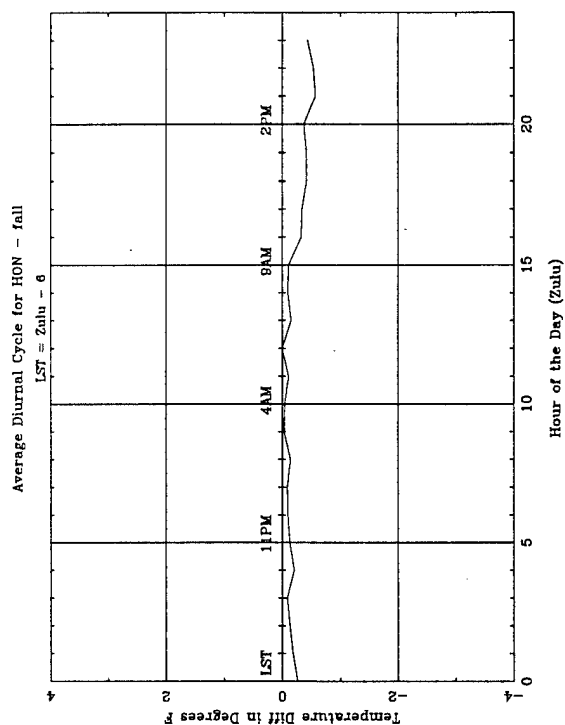
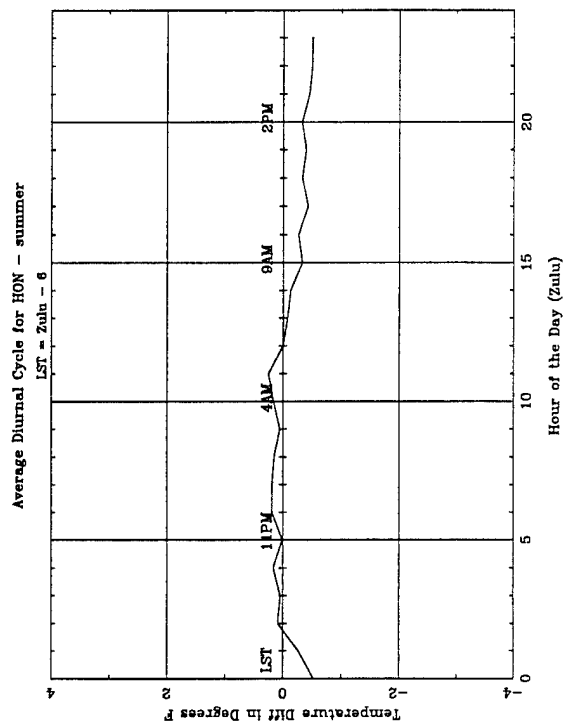
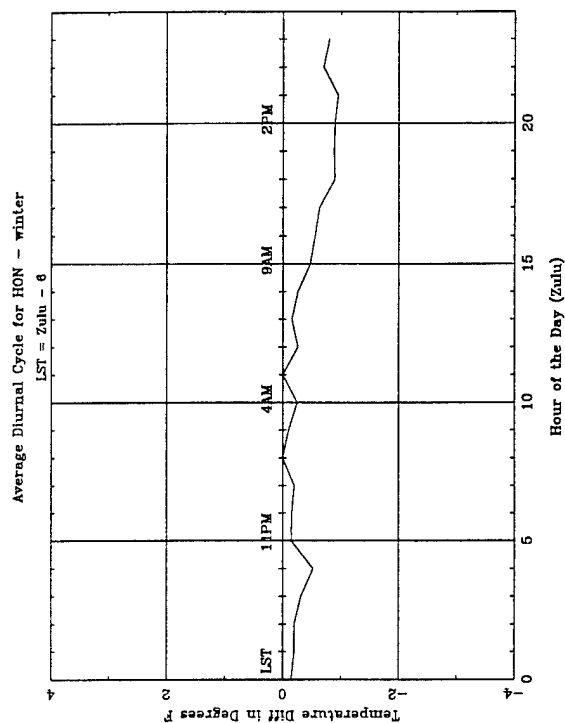
Average Diurnal Cycle for FWA - summer



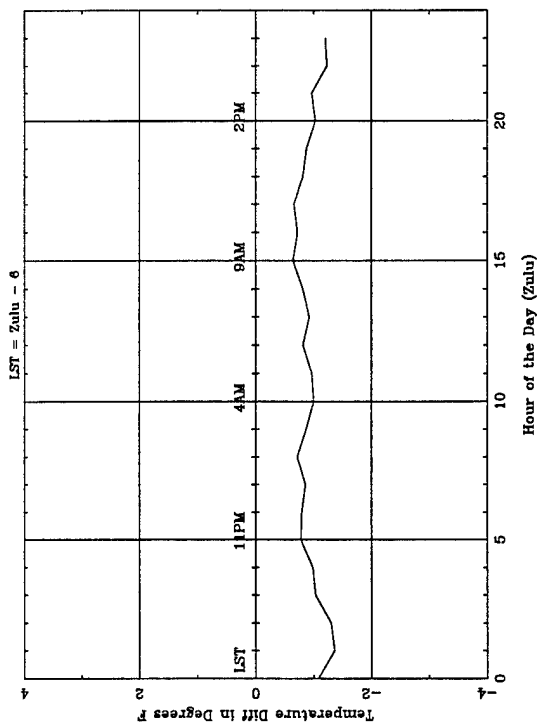




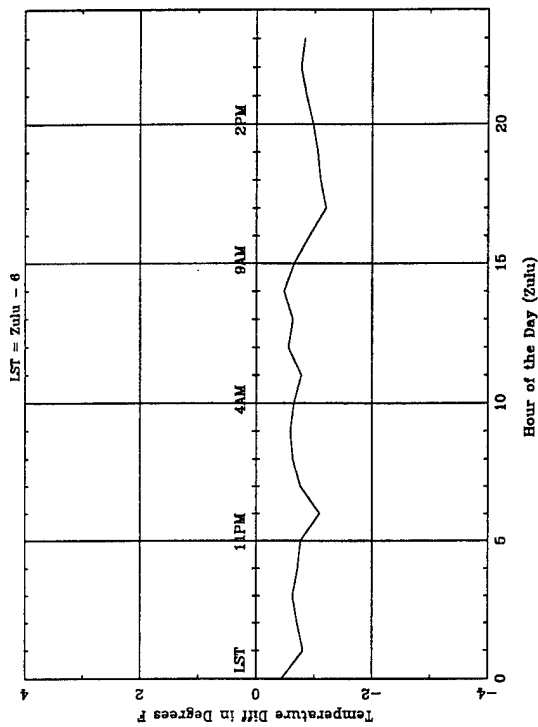




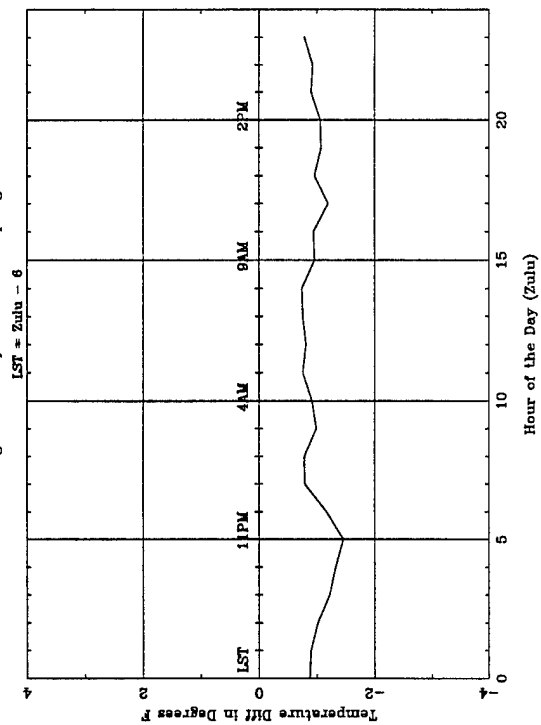
Average Diurnal Cycle for INL - fall



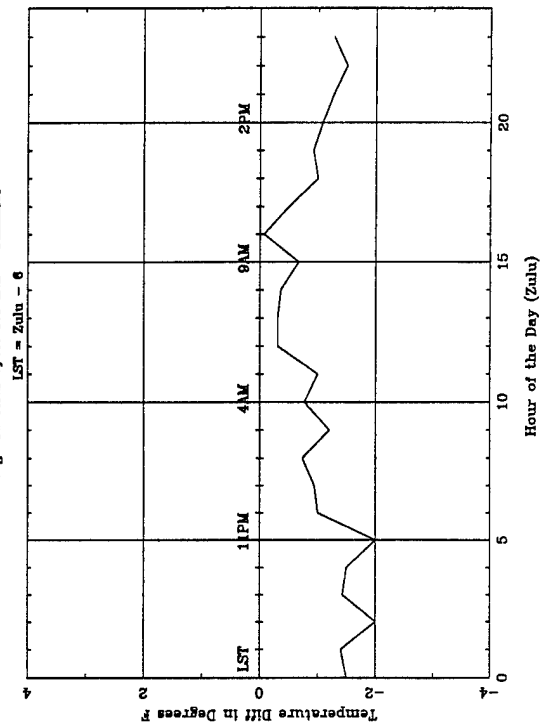
Average Diurnal Cycle for INL - winter



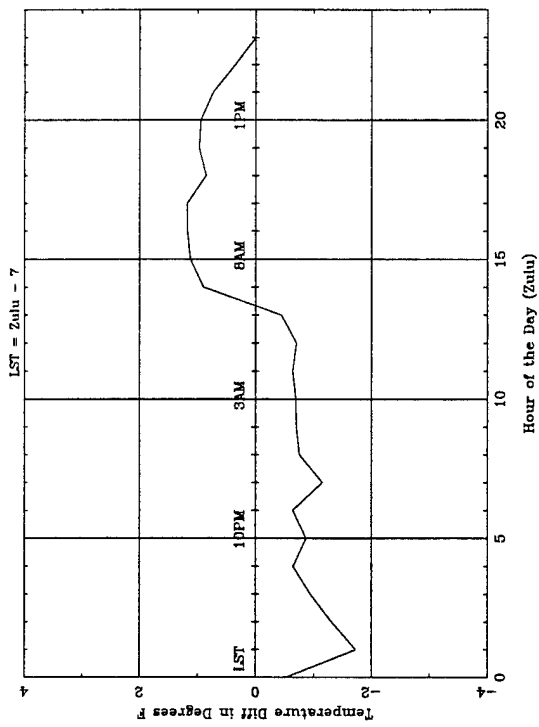
Average Diurnal Cycle for INL - spring



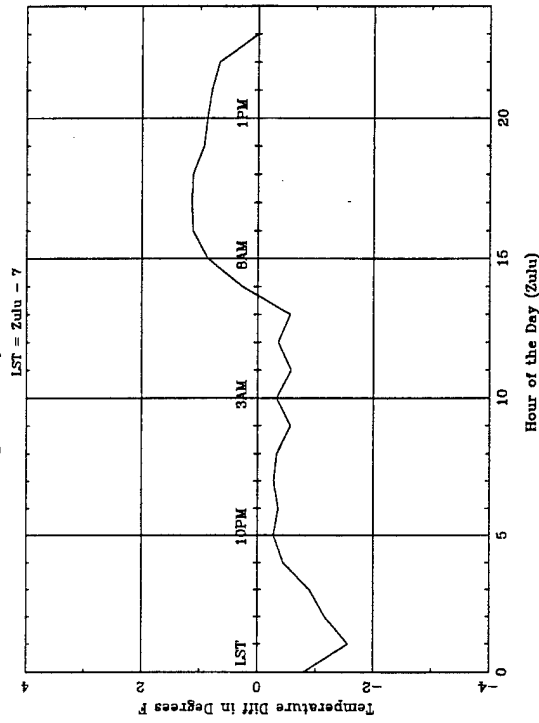
Average Diurnal Cycle for INL - summer



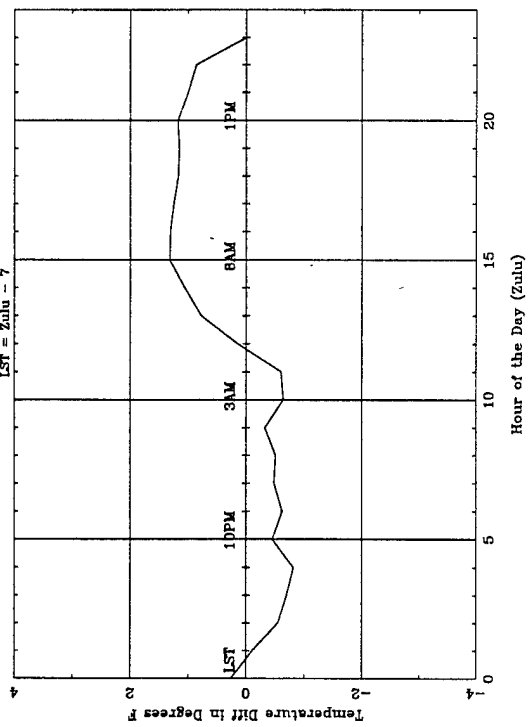
Average Diurnal Cycle for INW - fall



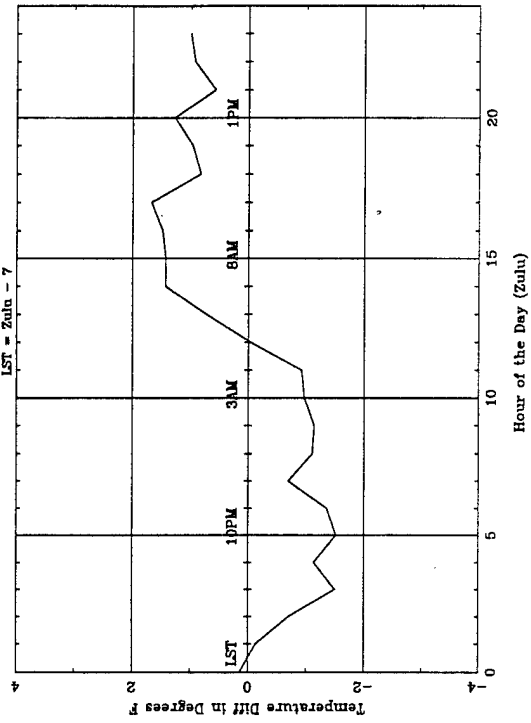
Average Diurnal Cycle for INW - winter

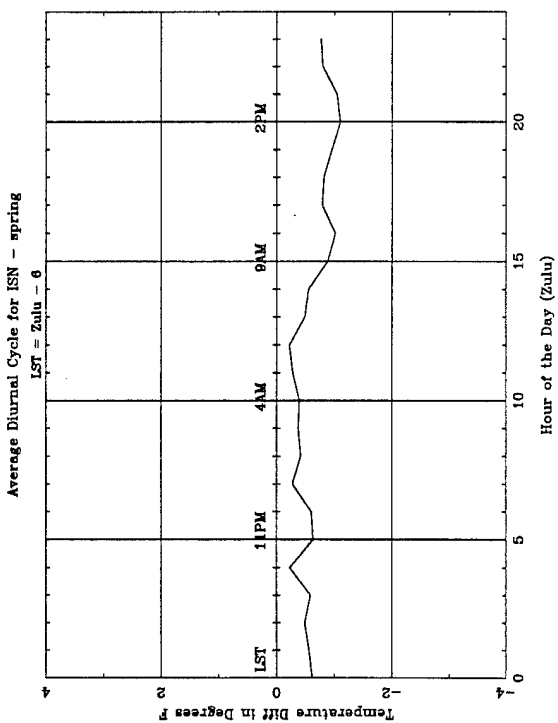
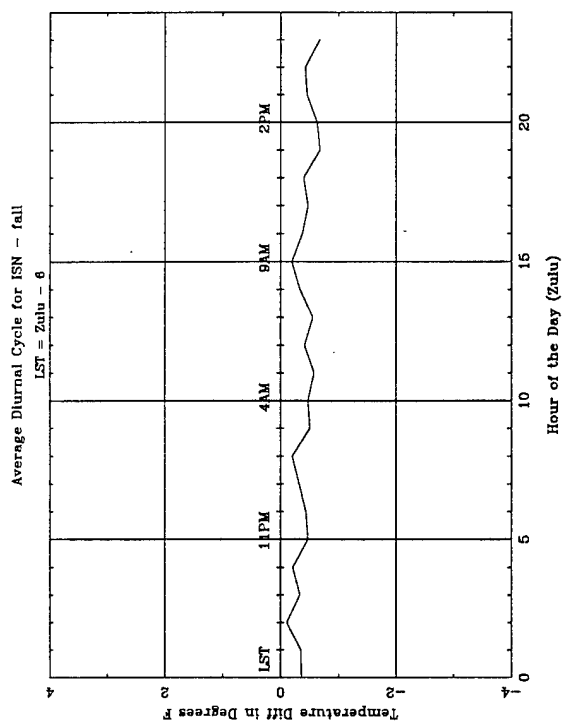
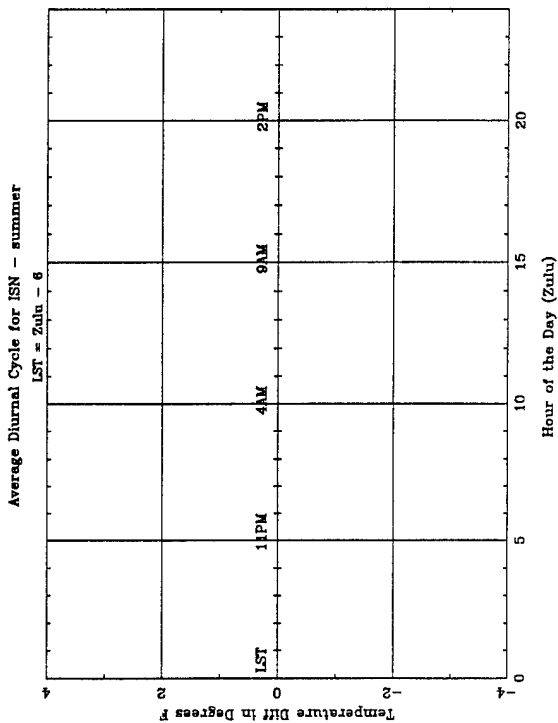
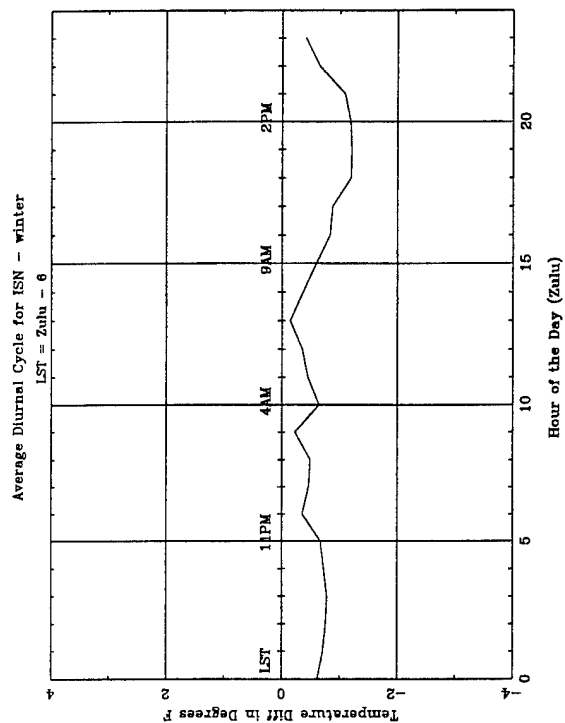


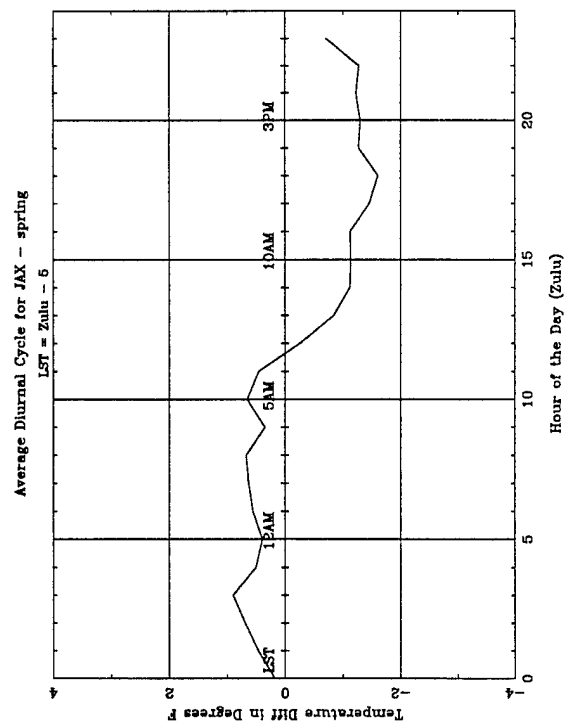
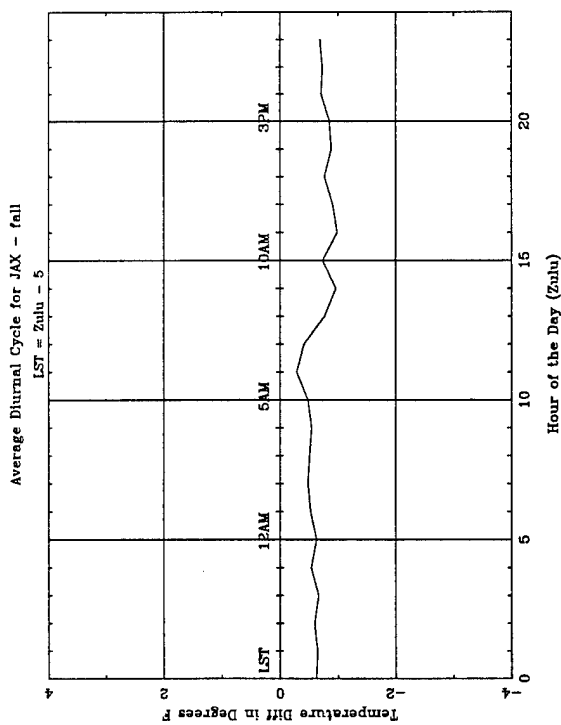
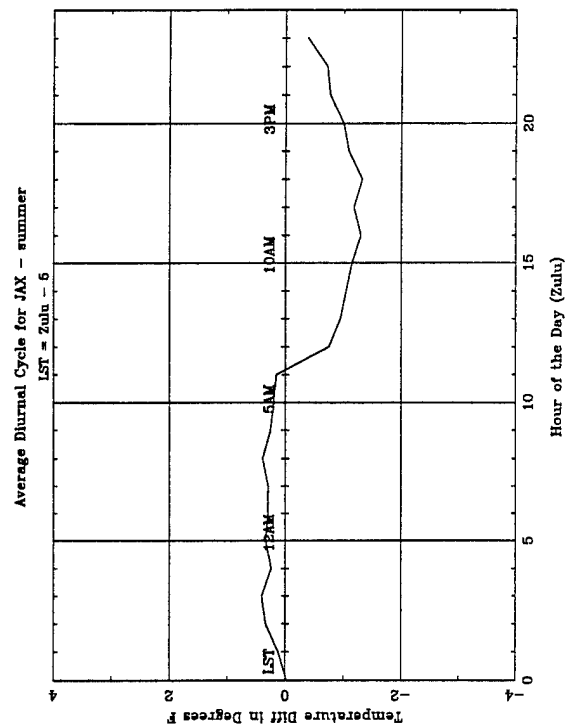
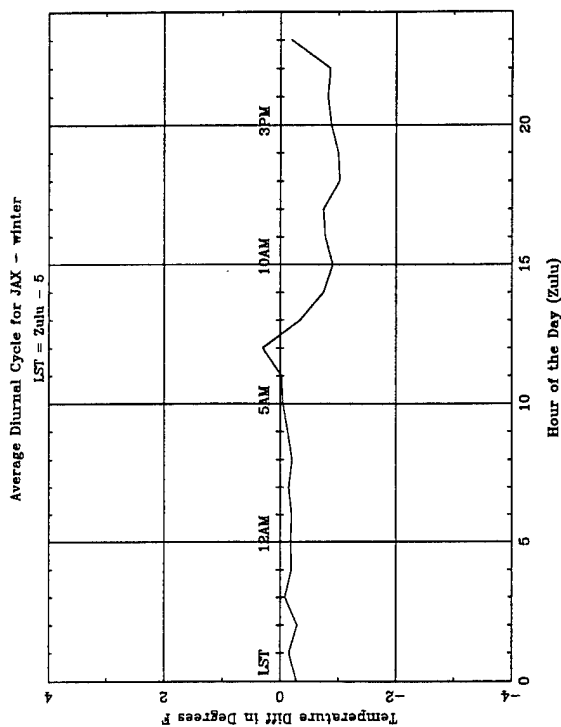
Average Diurnal Cycle for INW - spring



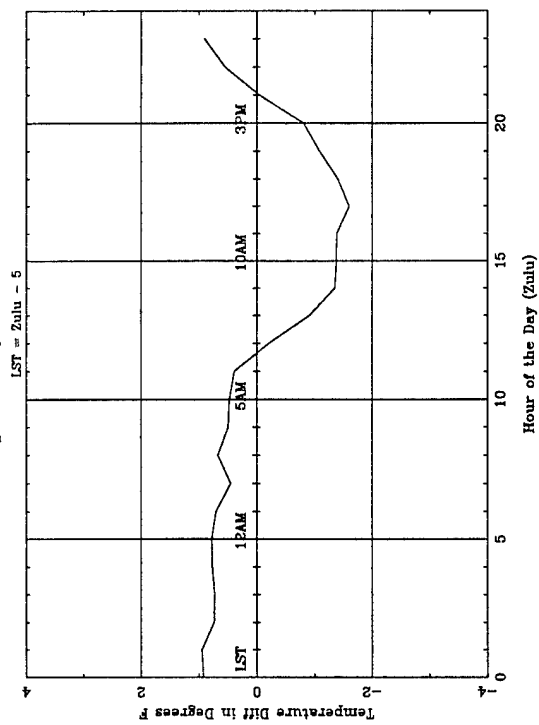
Average Diurnal Cycle for INW - summer



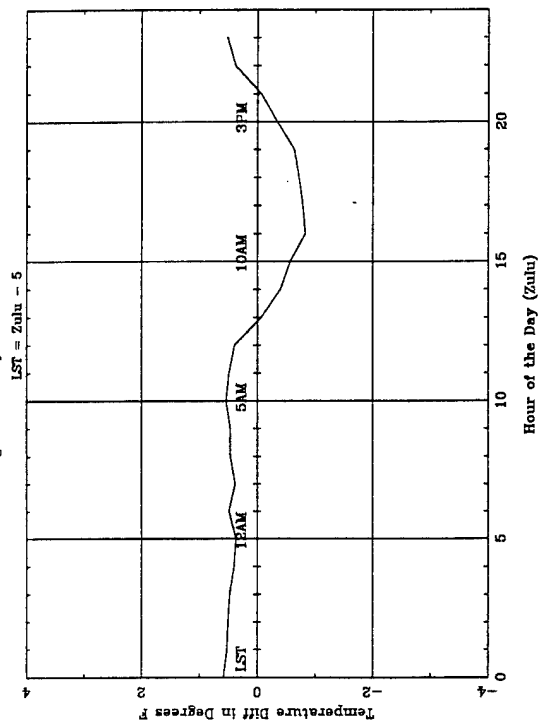




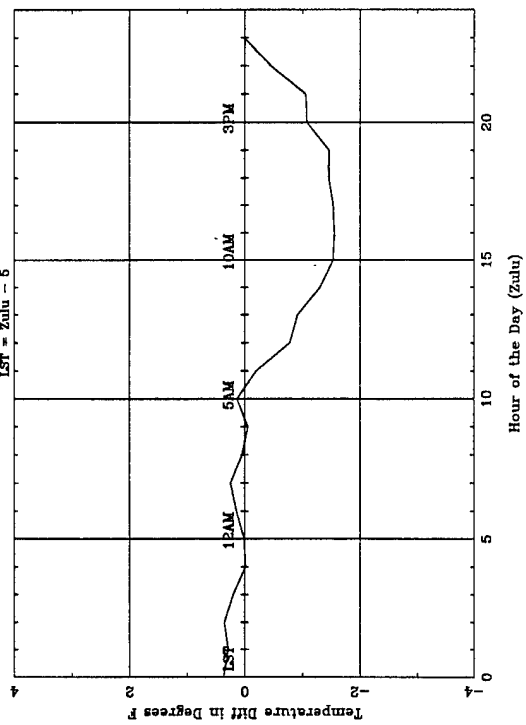
Average Diurnal Cycle for JKL - fall



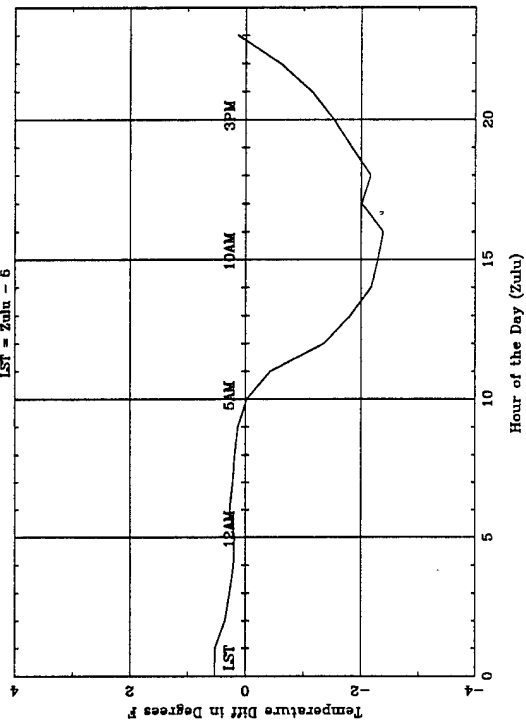
Average Diurnal Cycle for JKL - winter



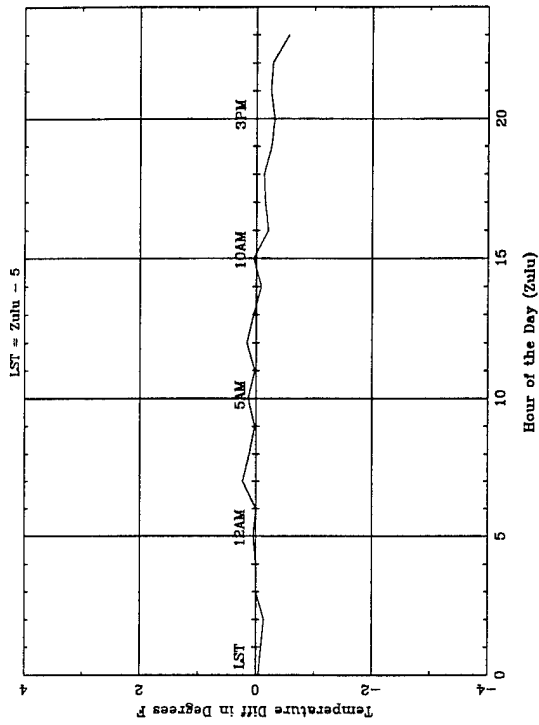
Average Diurnal Cycle for JKL - spring



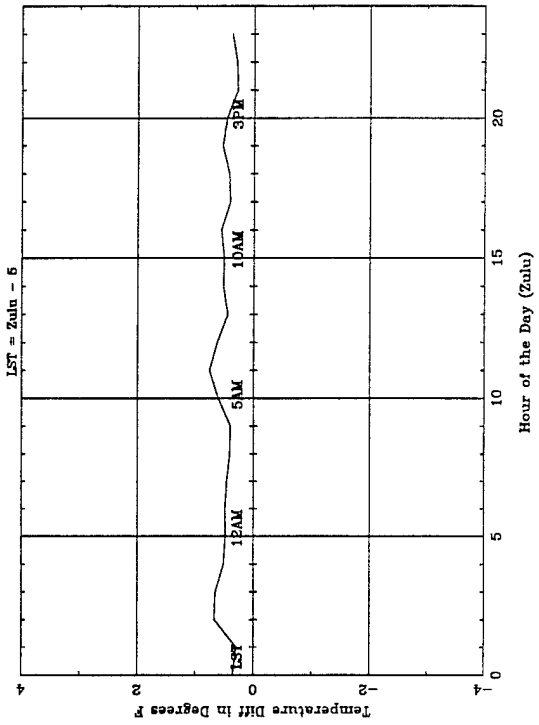
Average Diurnal Cycle for JKL - summer



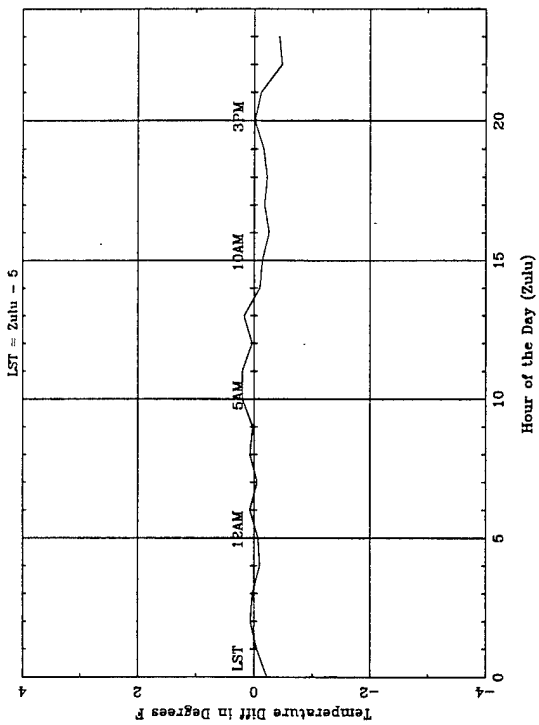
Average Diurnal Cycle for LAN - winter



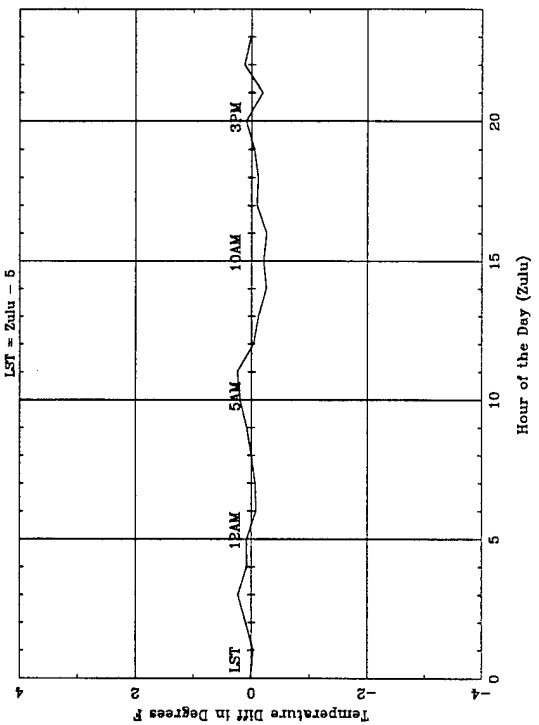
Average Diurnal Cycle for LAN - summer

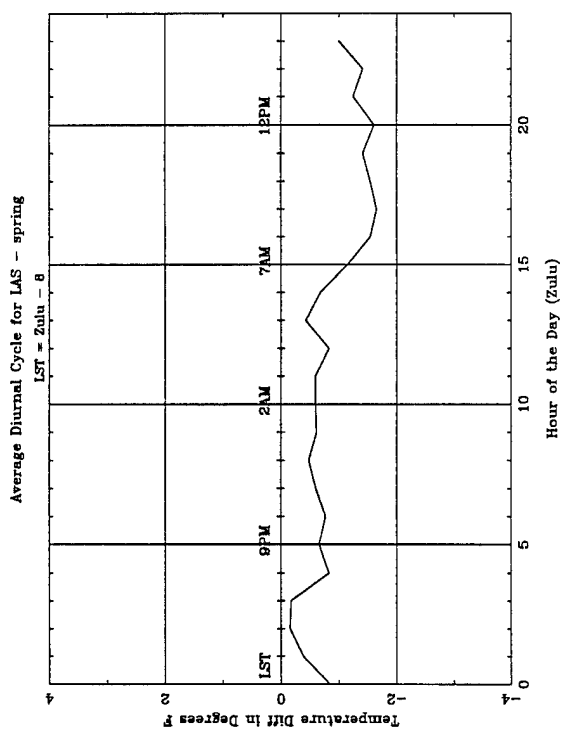
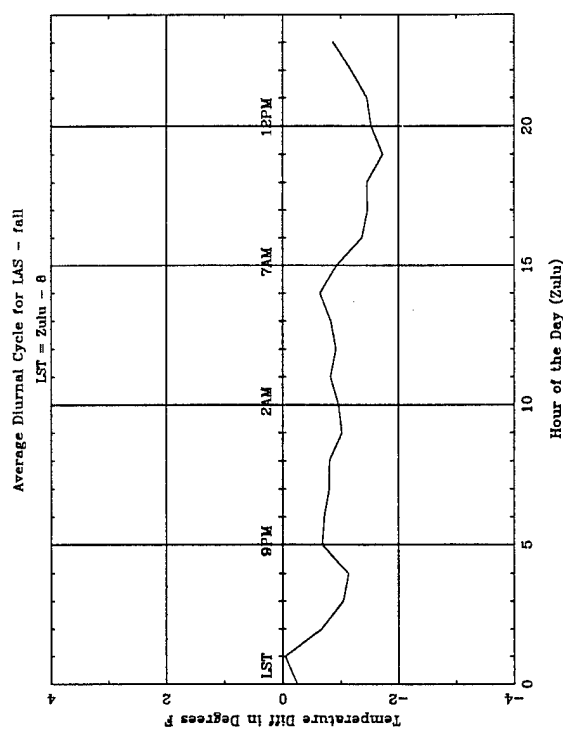
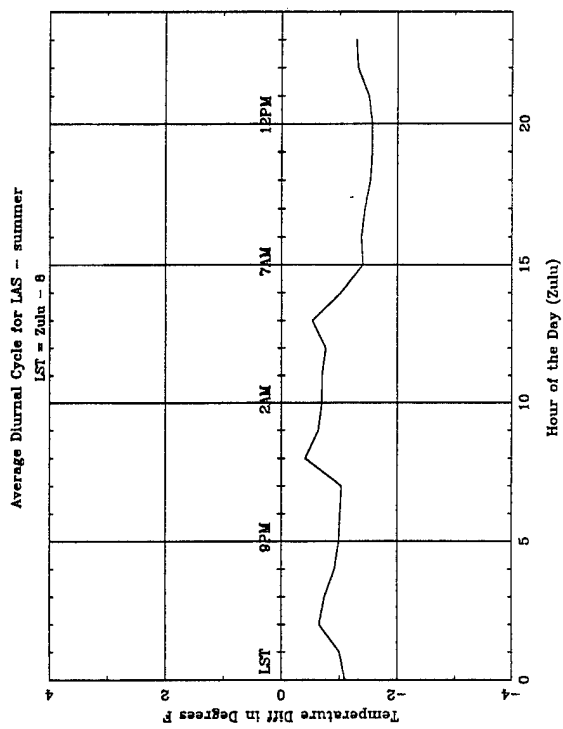
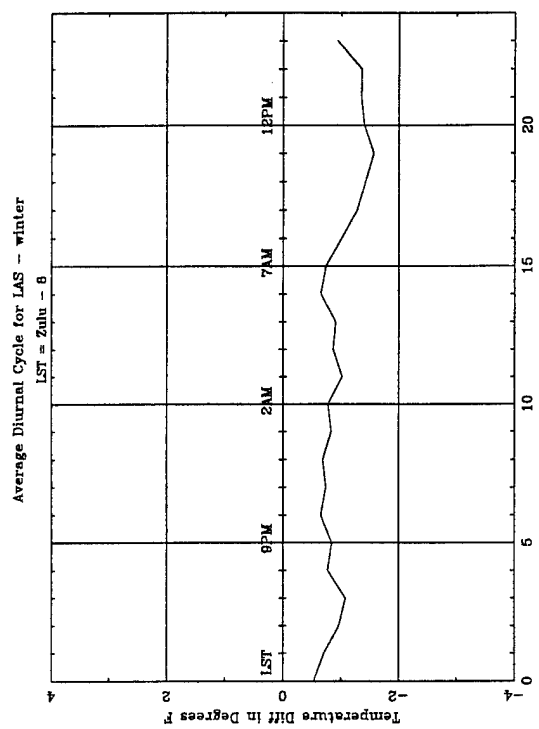


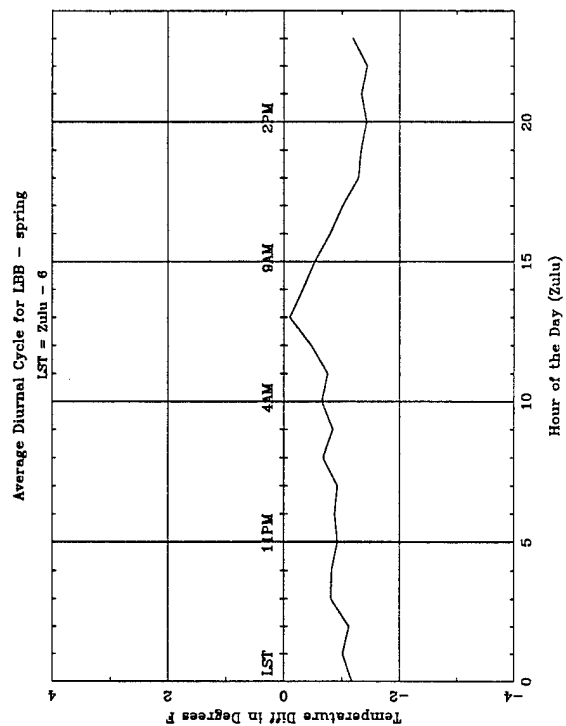
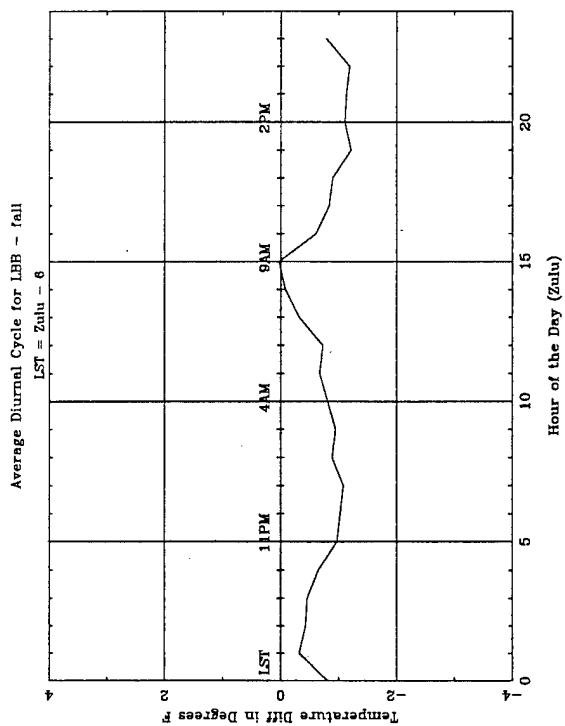
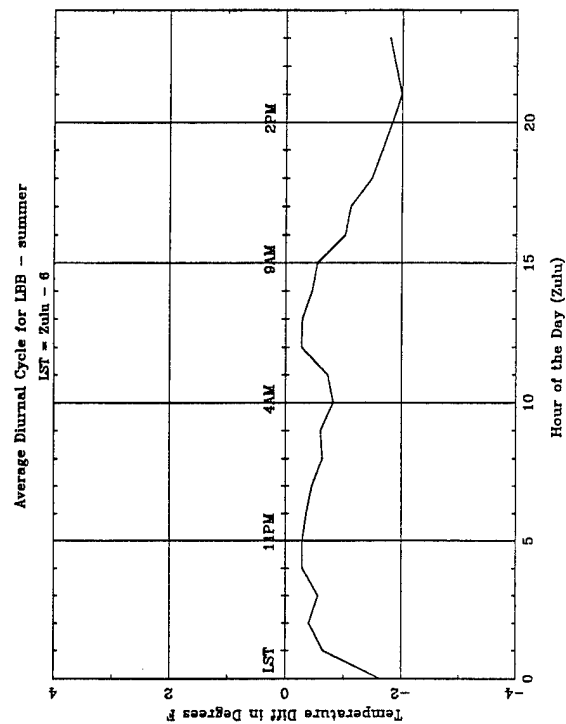
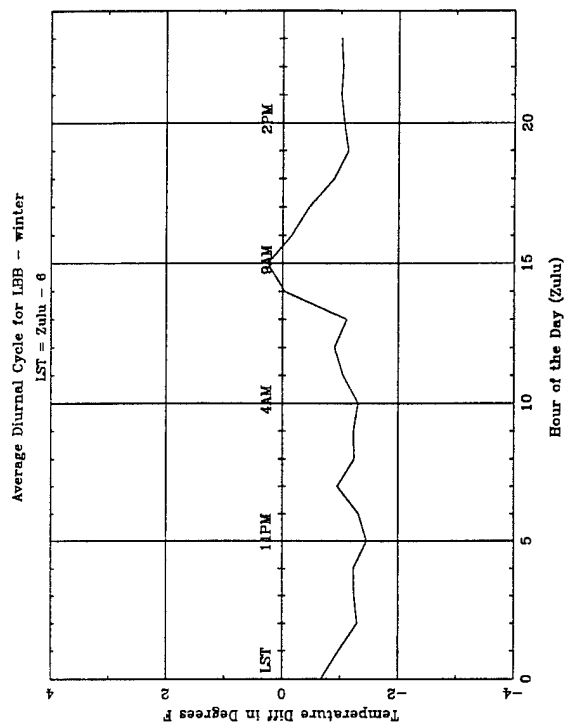
Average Diurnal Cycle for LAN - fall



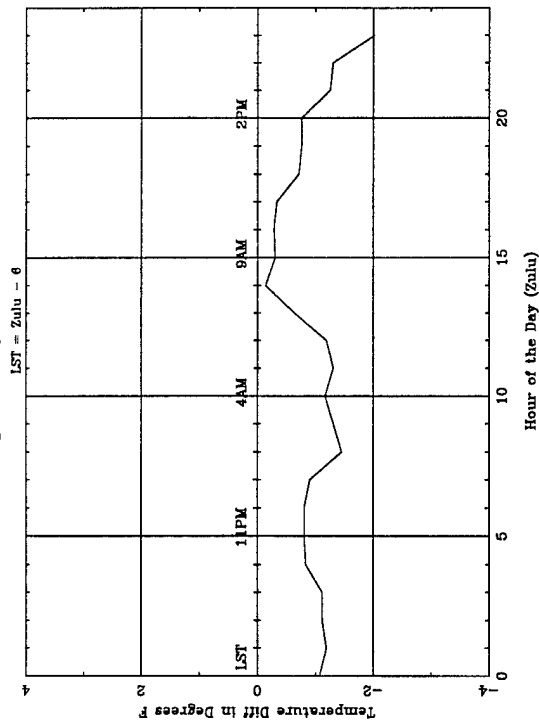
Average Diurnal Cycle for LAN - spring



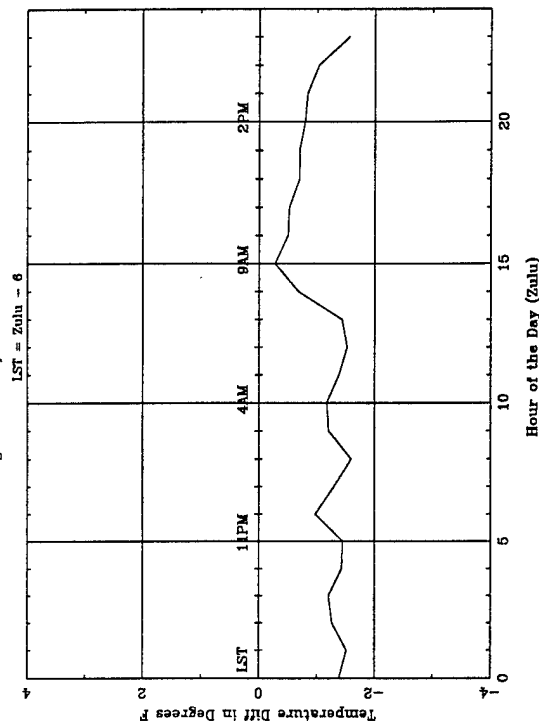




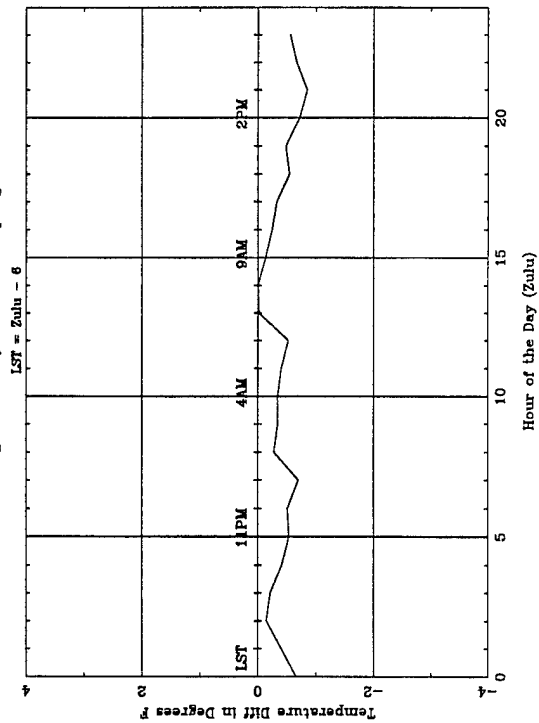
Average Diurnal Cycle for LBF - fall



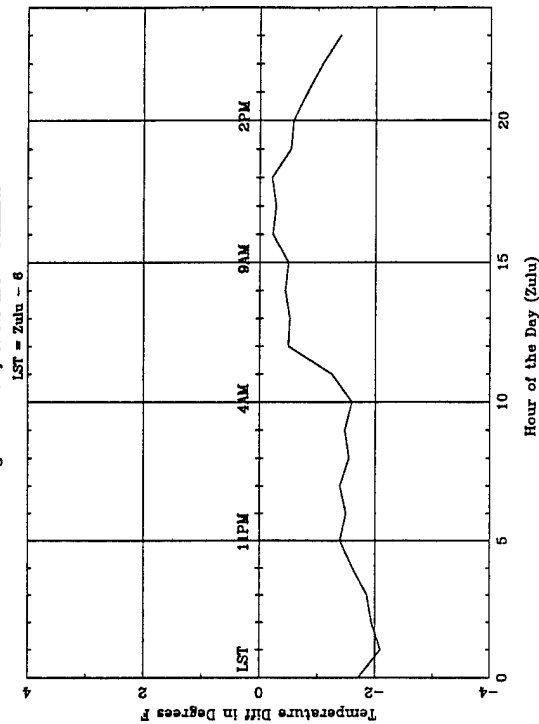
Average Diurnal Cycle for LBF - winter



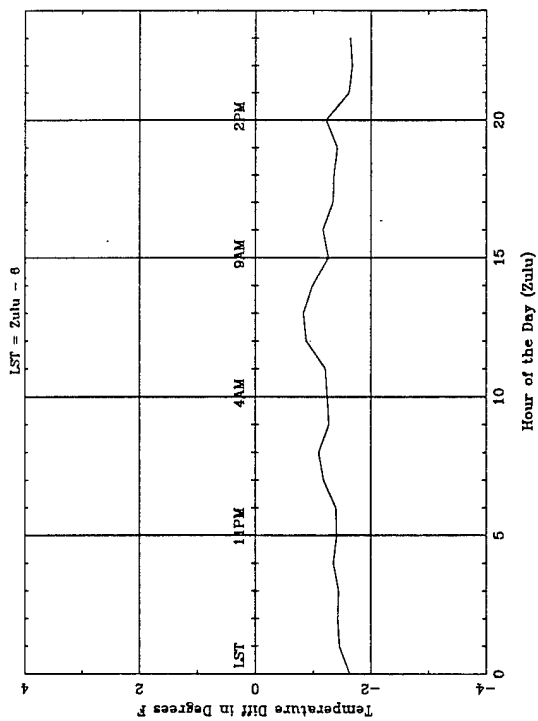
Average Diurnal Cycle for LBF - spring



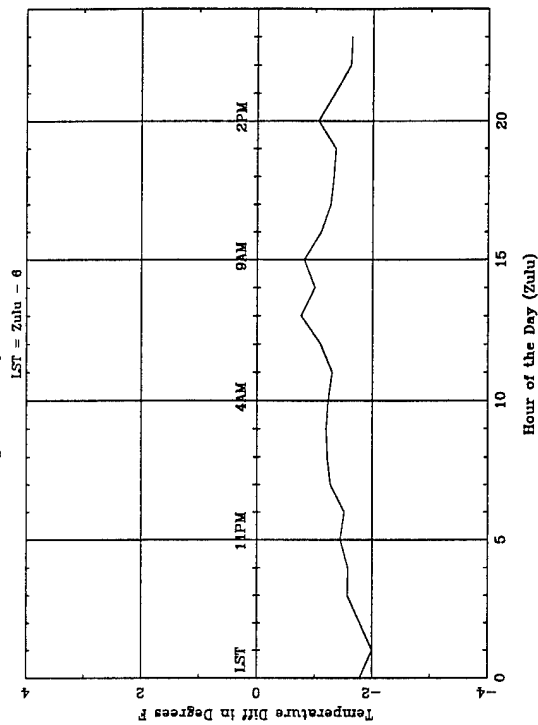
Average Diurnal Cycle for LBF - summer



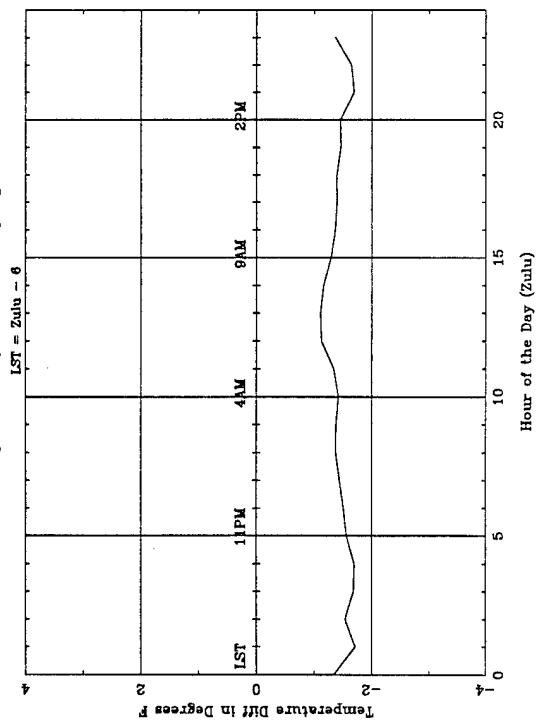
Average Diurnal Cycle for LCH - fall



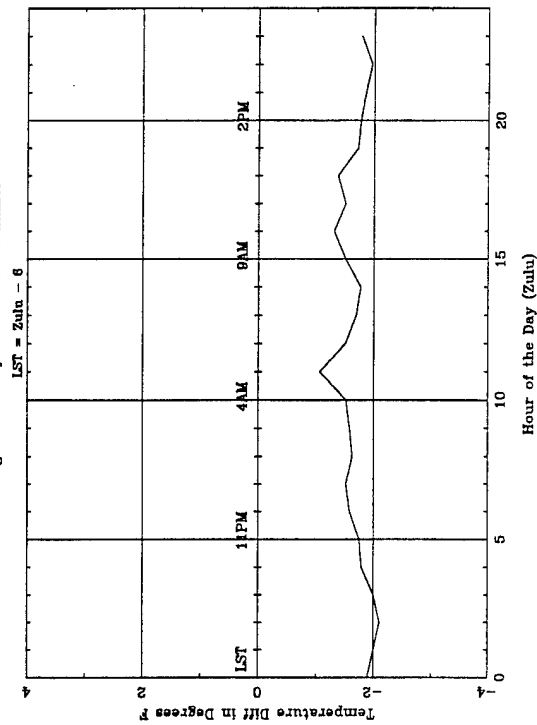
Average Diurnal Cycle for LCH - winter



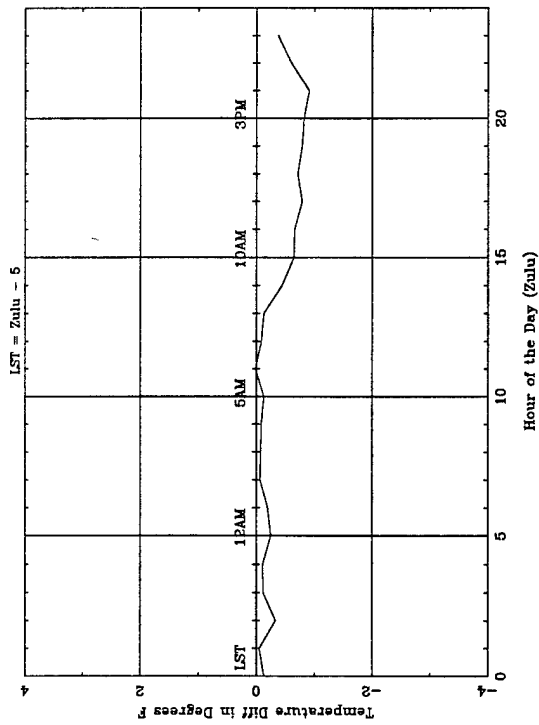
Average Diurnal Cycle for LCH - spring



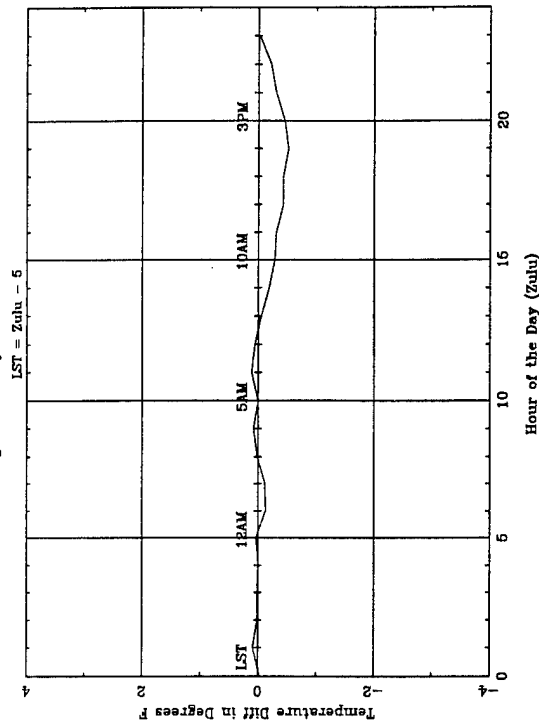
Average Diurnal Cycle for LCH - summer



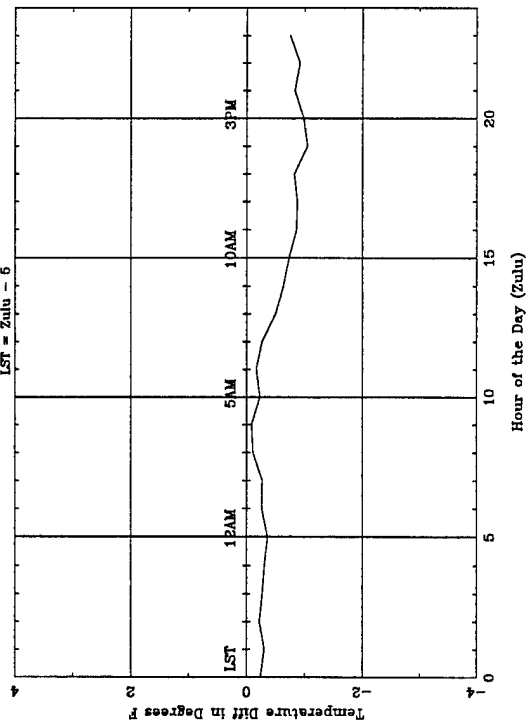
Average Diurnal Cycle for LEX - fall



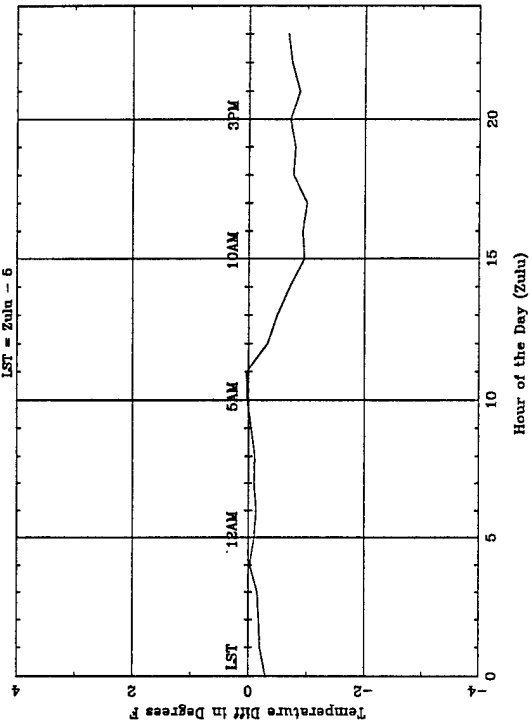
Average Diurnal Cycle for LEX - winter

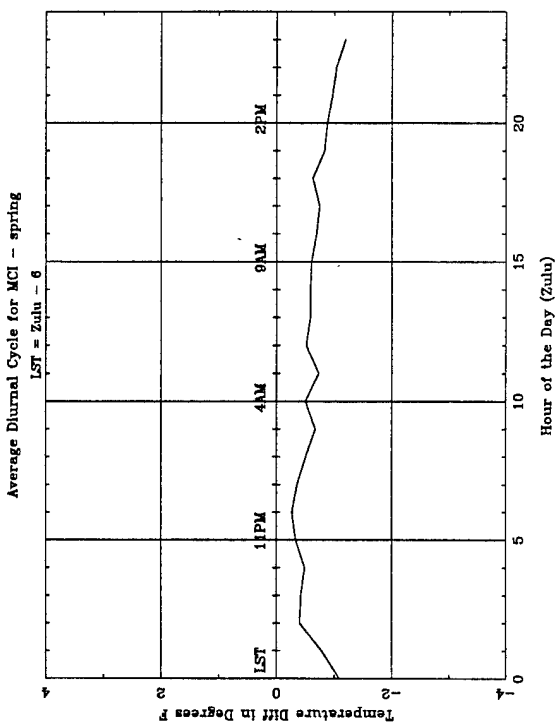
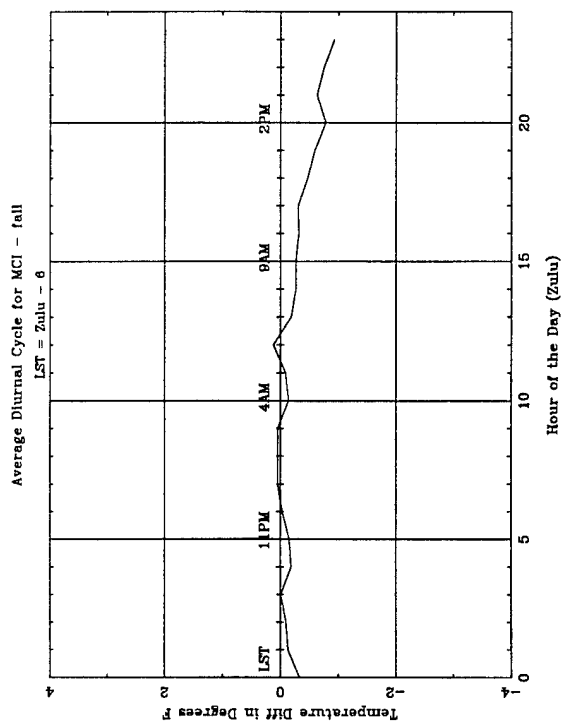
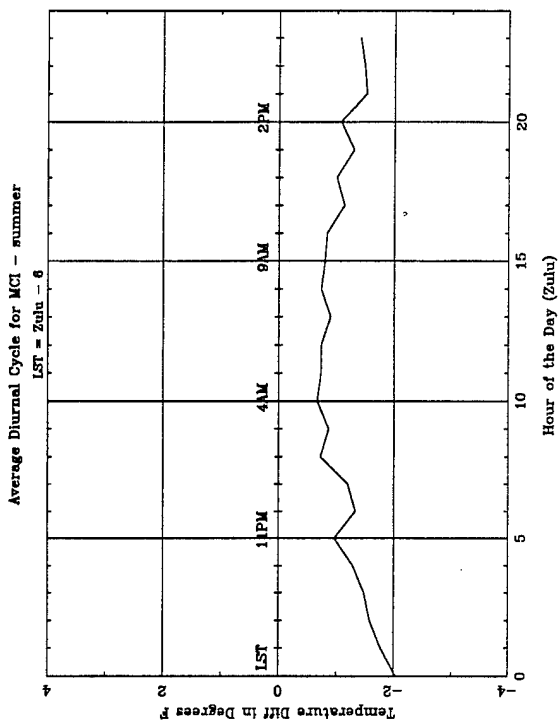
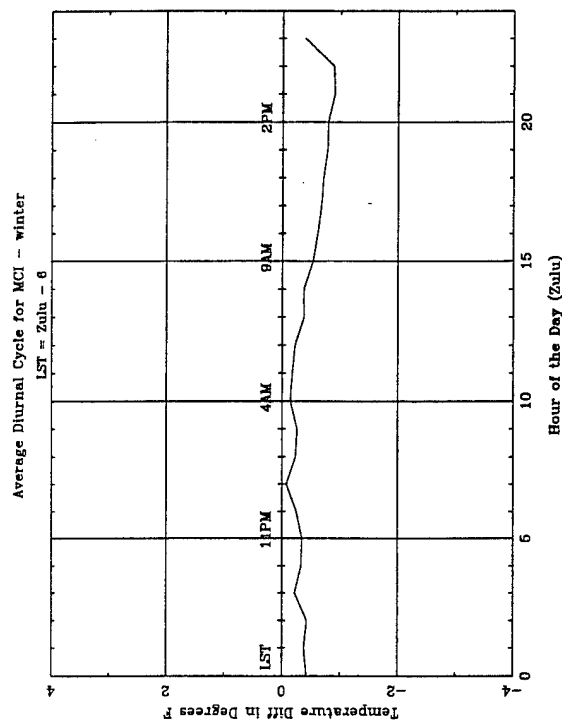


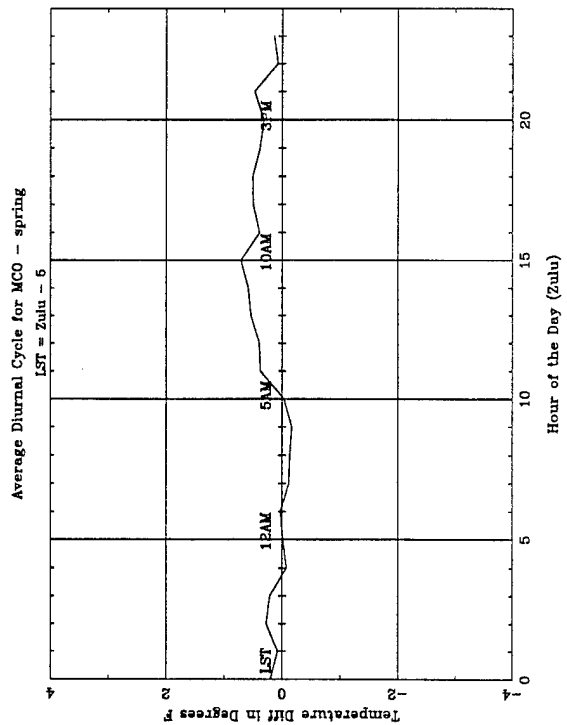
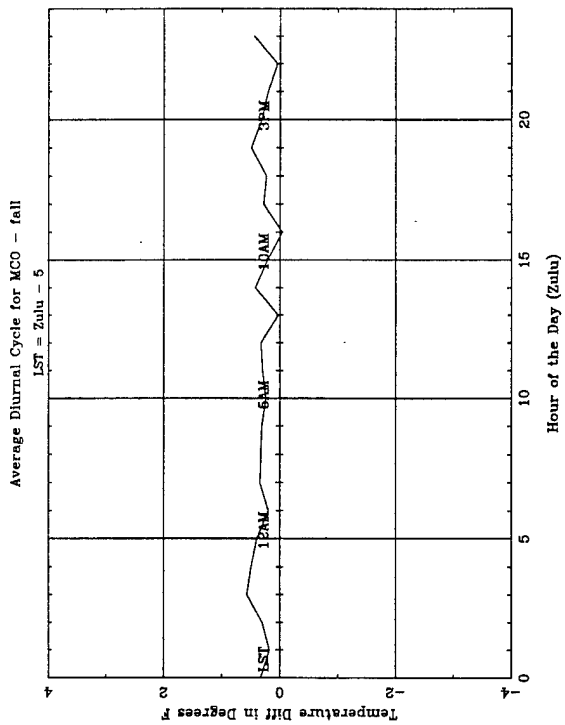
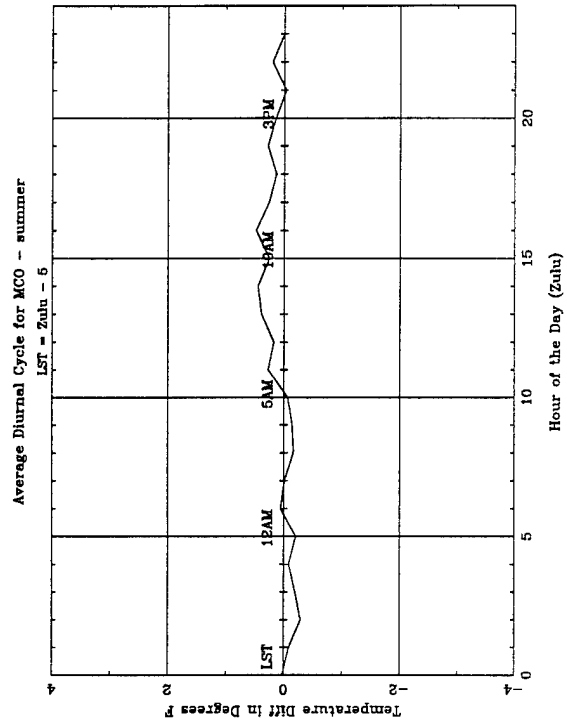
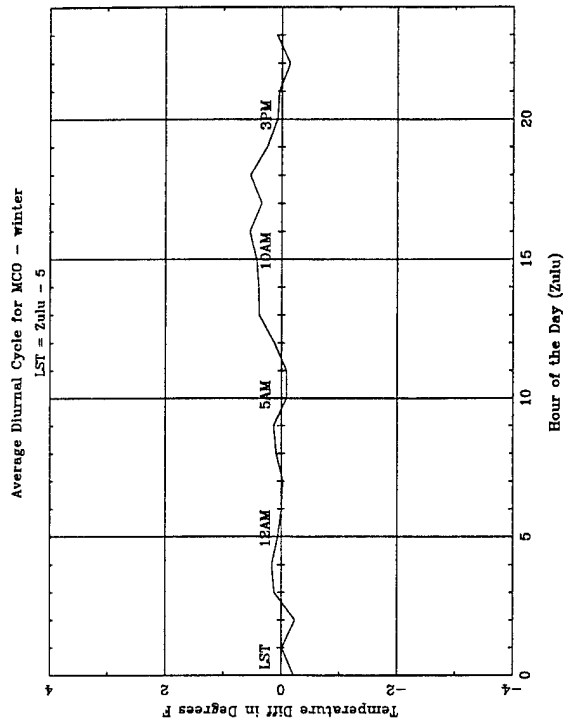
Average Diurnal Cycle for LEX - spring



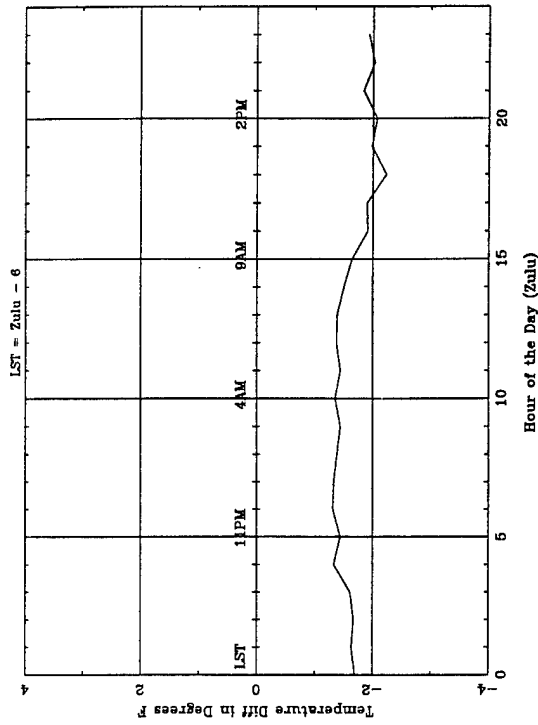
Average Diurnal Cycle for LEX - summer



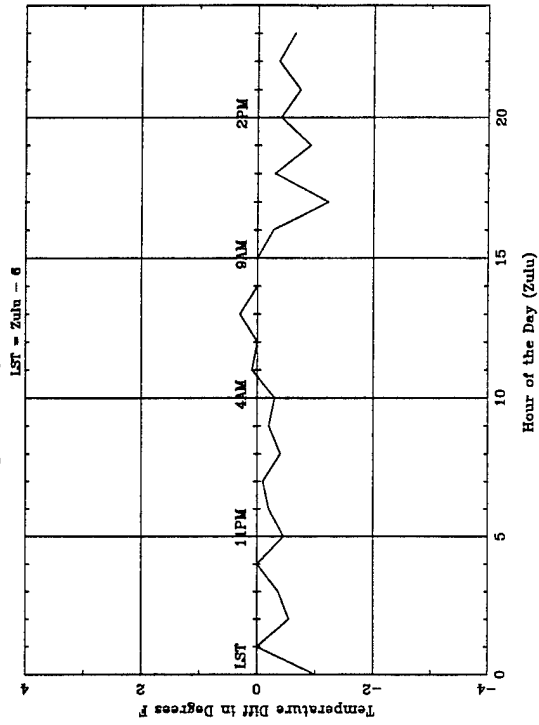




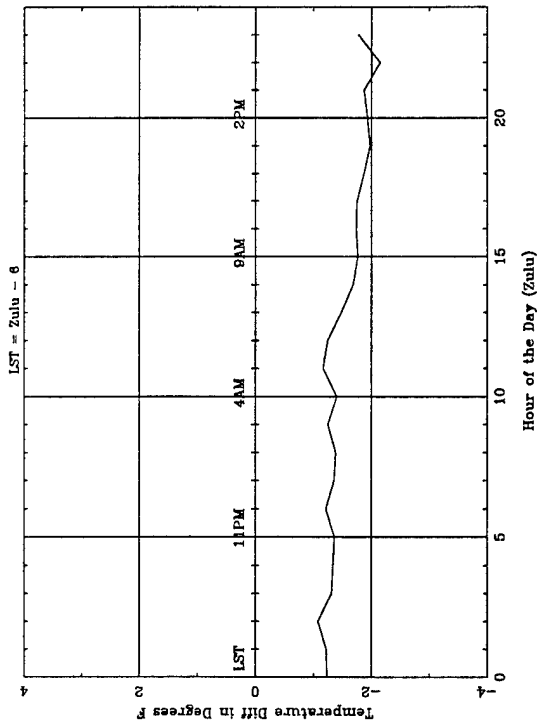
Average Diurnal Cycle for MGM - winter



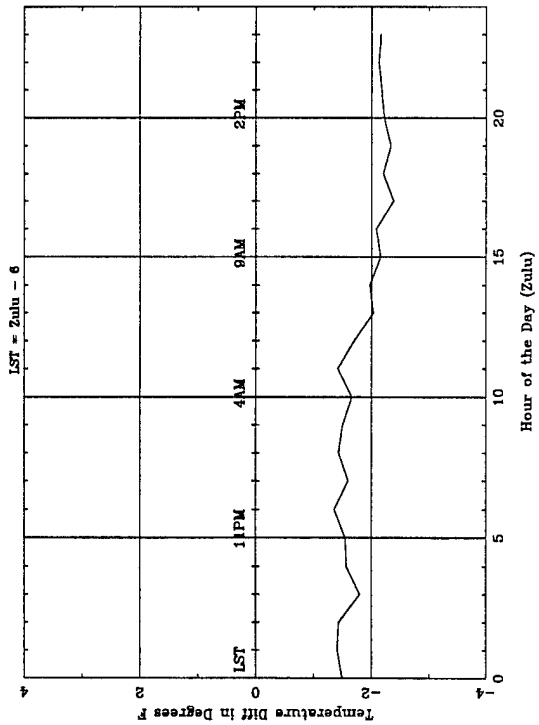
Average Diurnal Cycle for MGM - summer



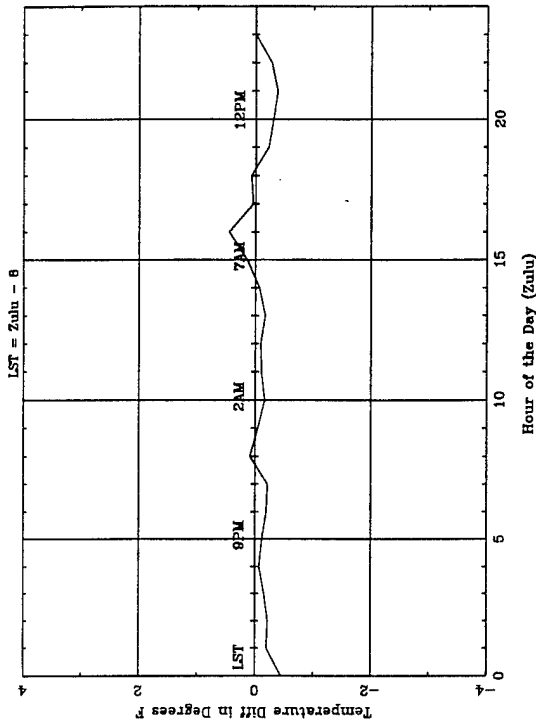
Average Diurnal Cycle for MGM - fall



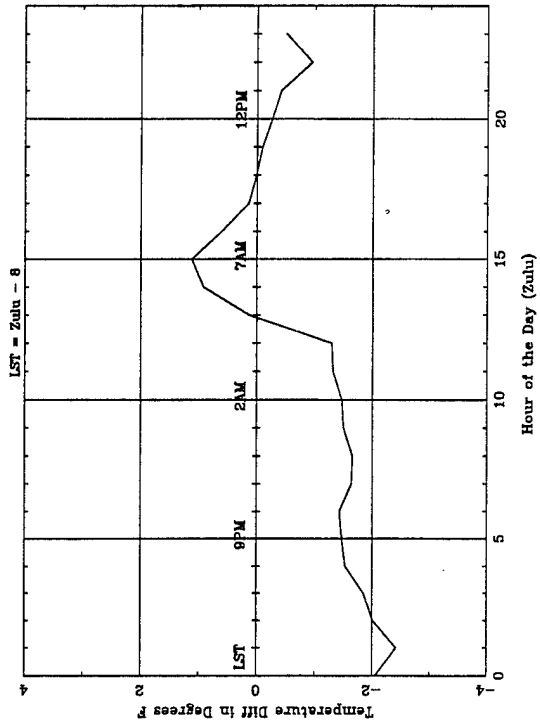
Average Diurnal Cycle for MGM - spring



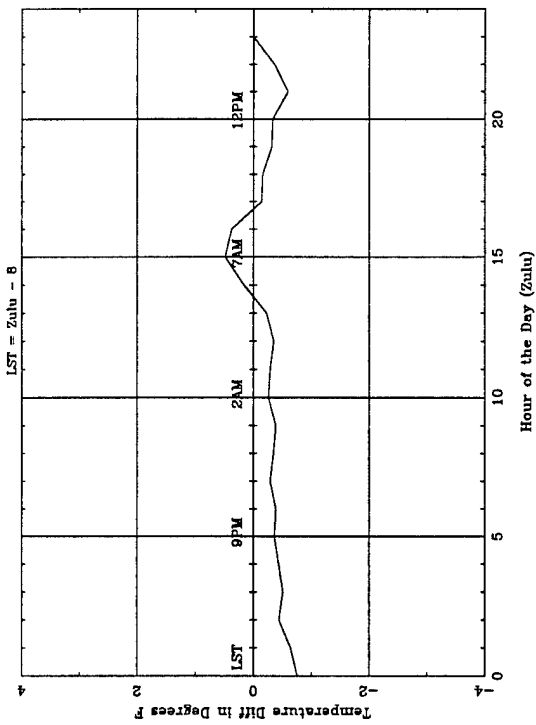
Average Diurnal Cycle for MHS - winter



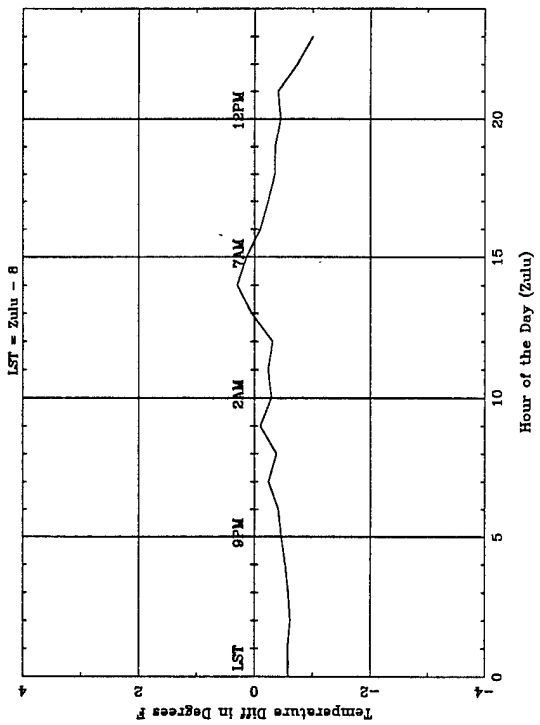
Average Diurnal Cycle for MHS - summer

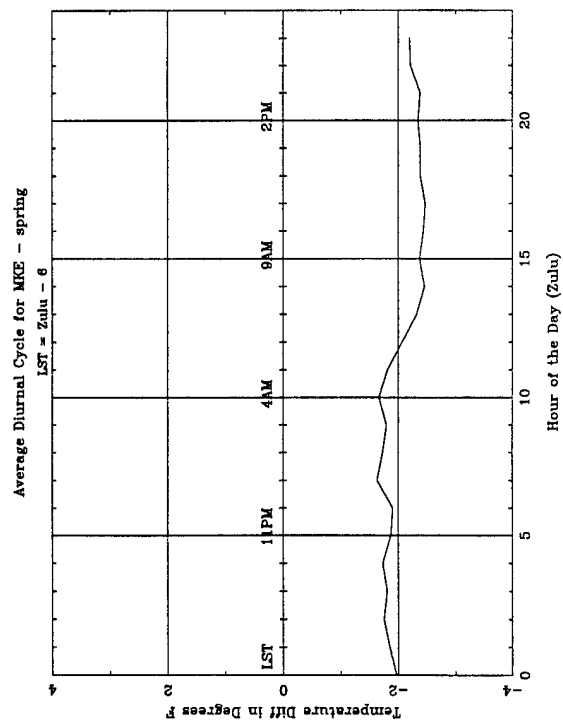
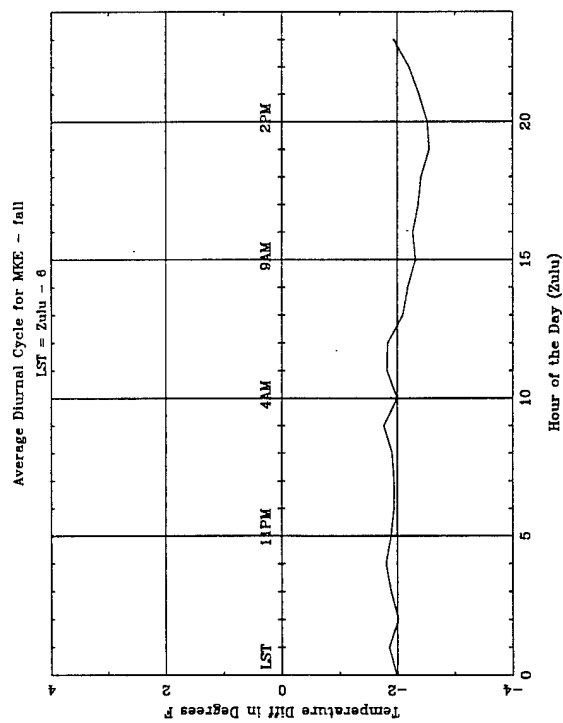
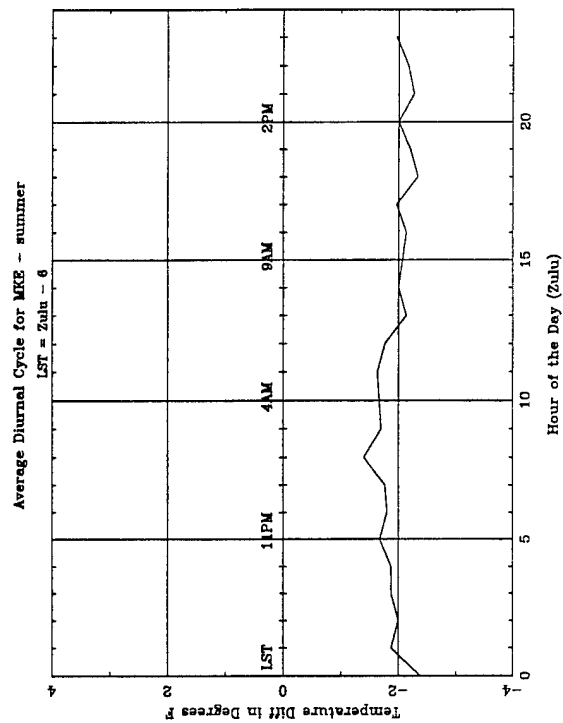
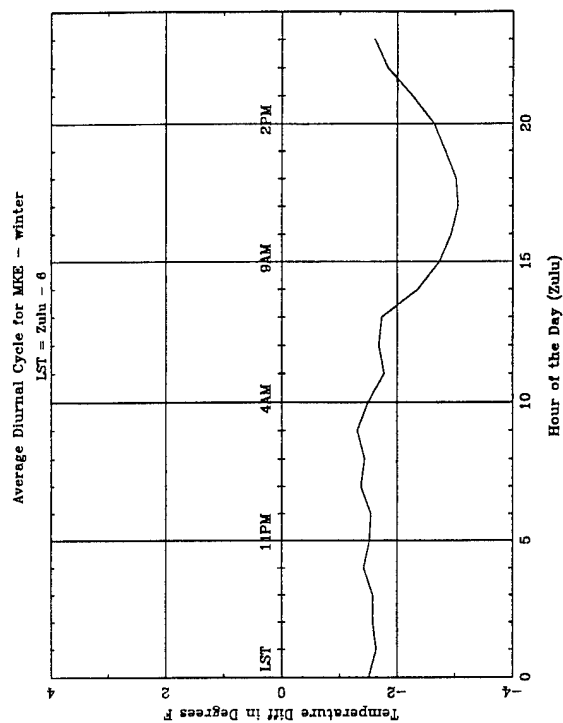


Average Diurnal Cycle for MHS - fall

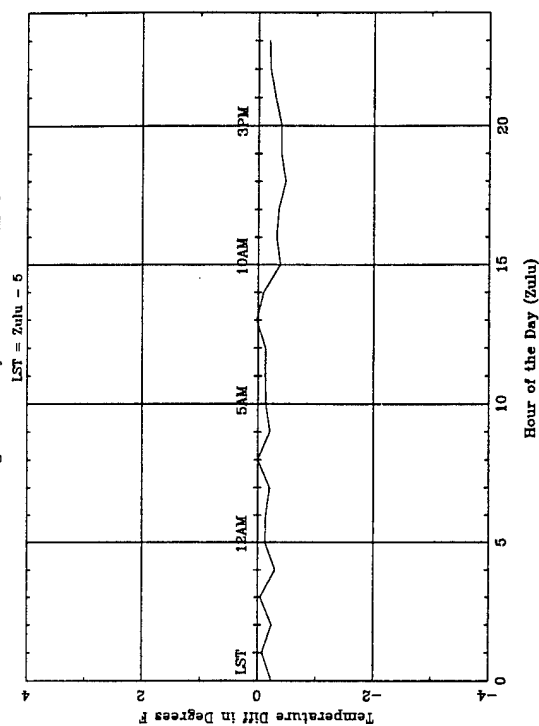


Average Diurnal Cycle for MHS - spring

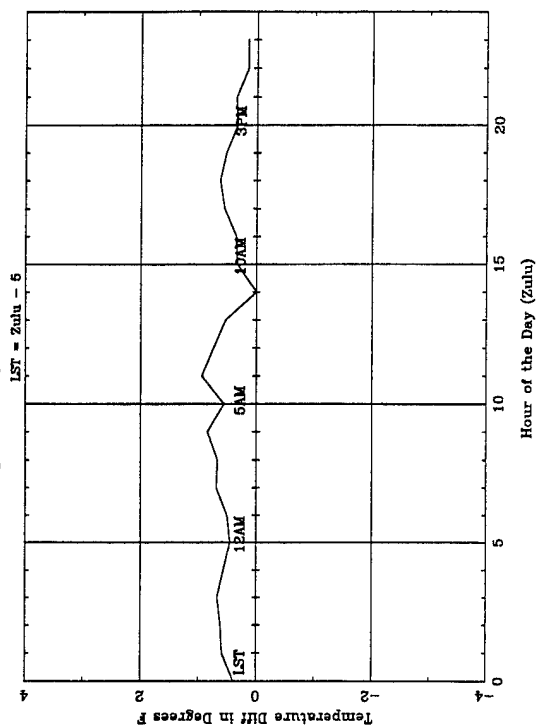




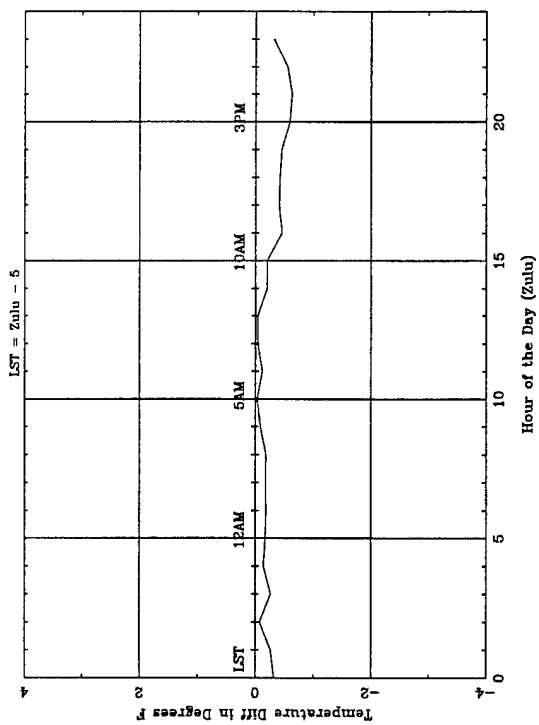
Average Diurnal Cycle for MKG - winter



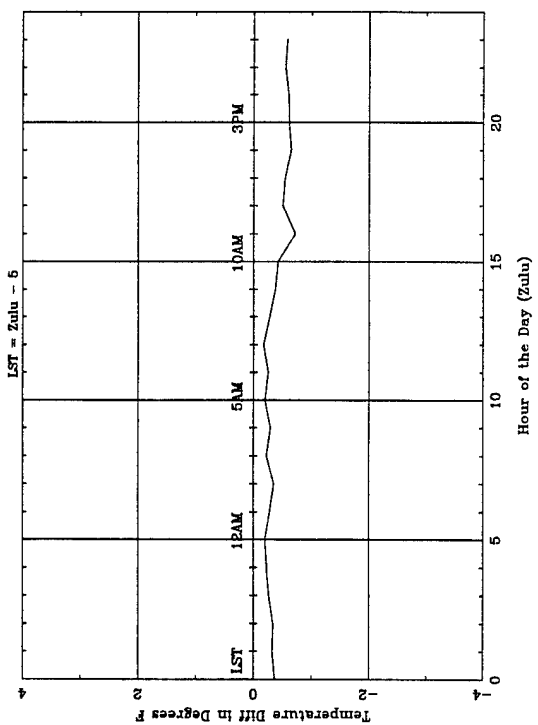
Average Diurnal Cycle for MKG - summer

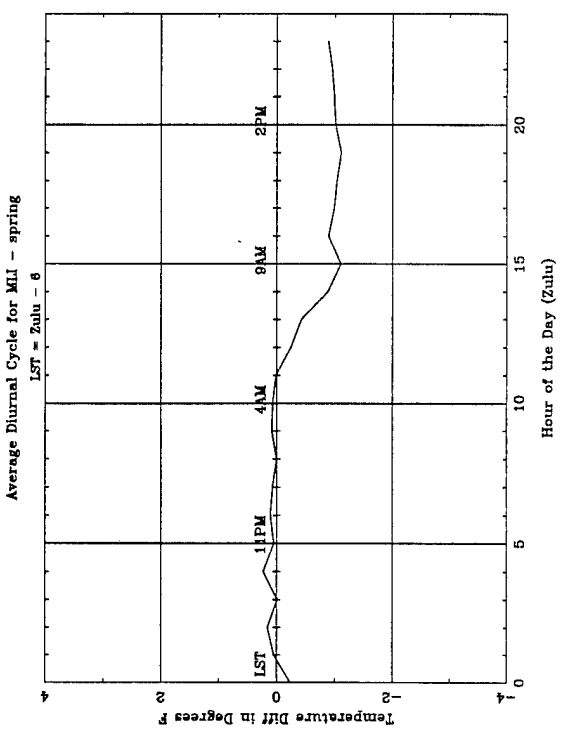
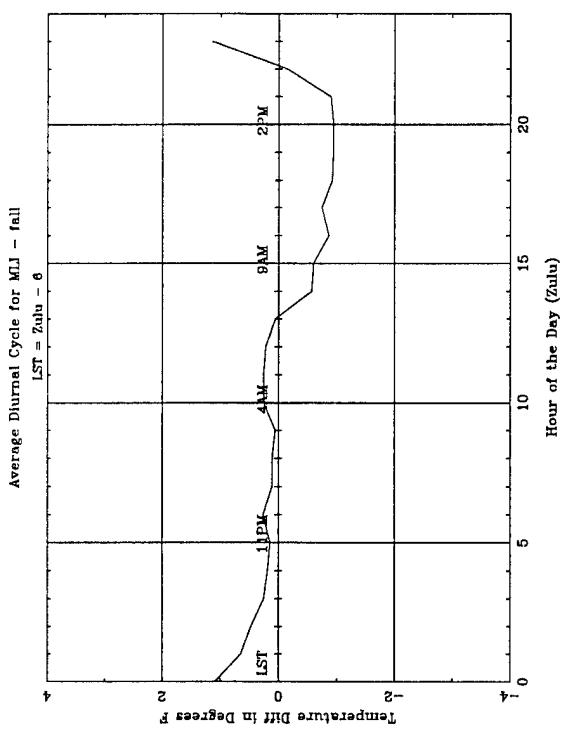
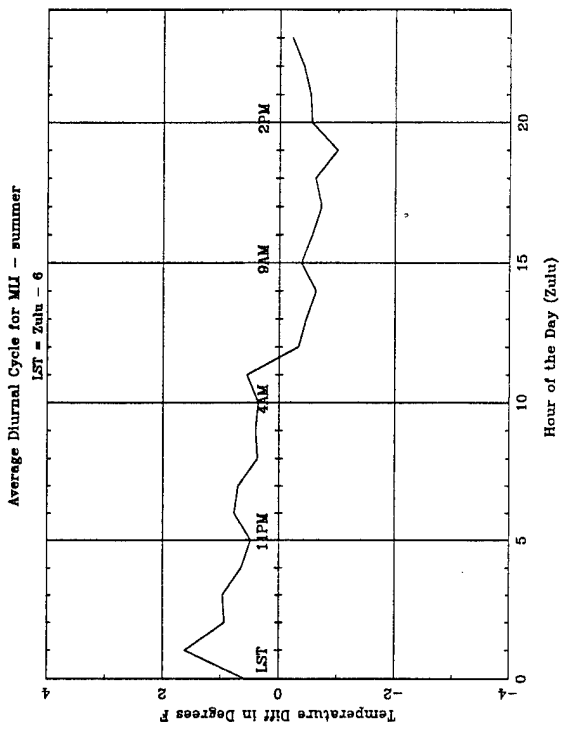
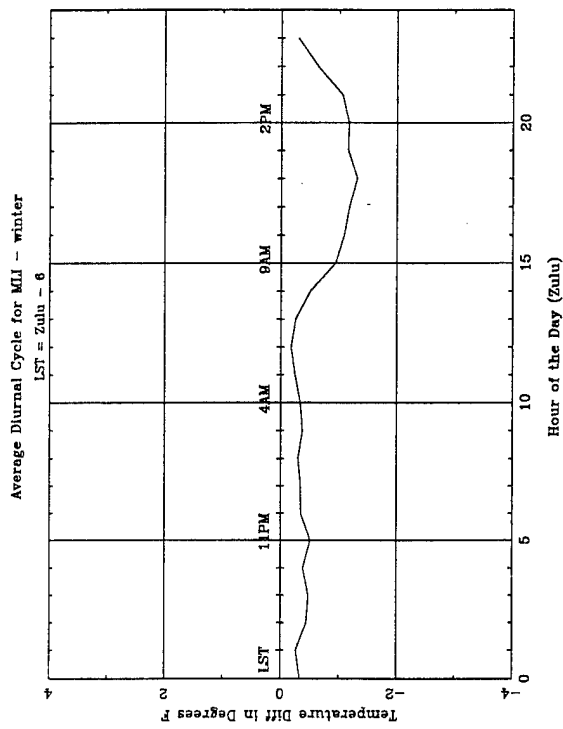


Average Diurnal Cycle for MKG - fall

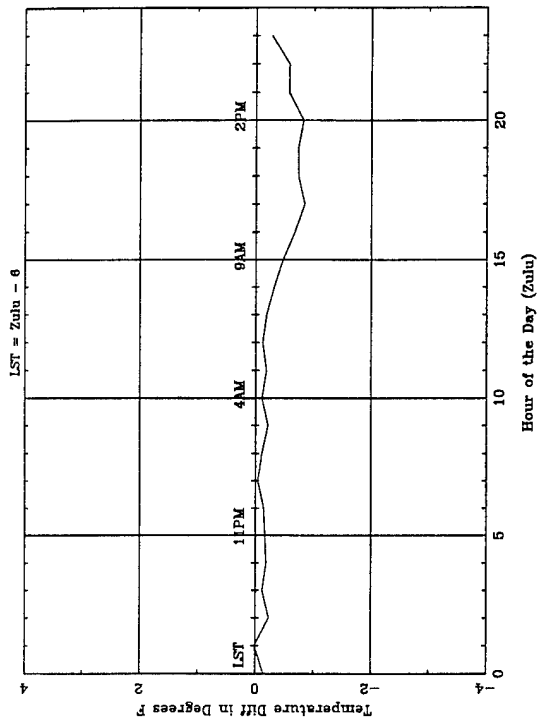


Average Diurnal Cycle for MKG - spring

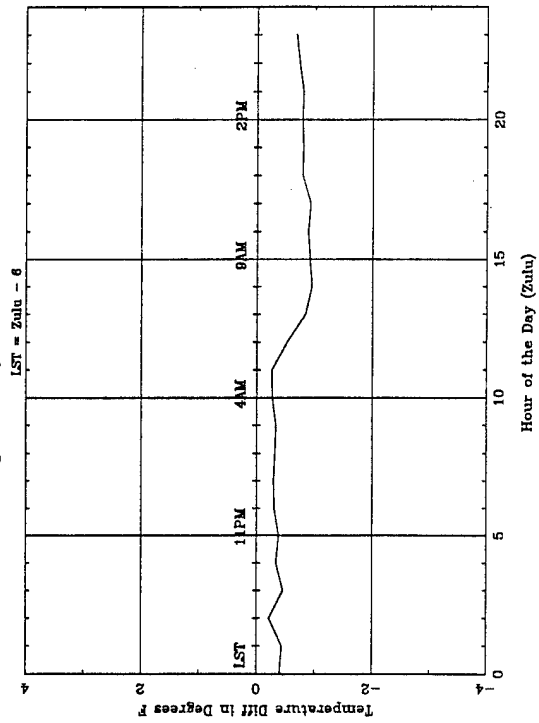




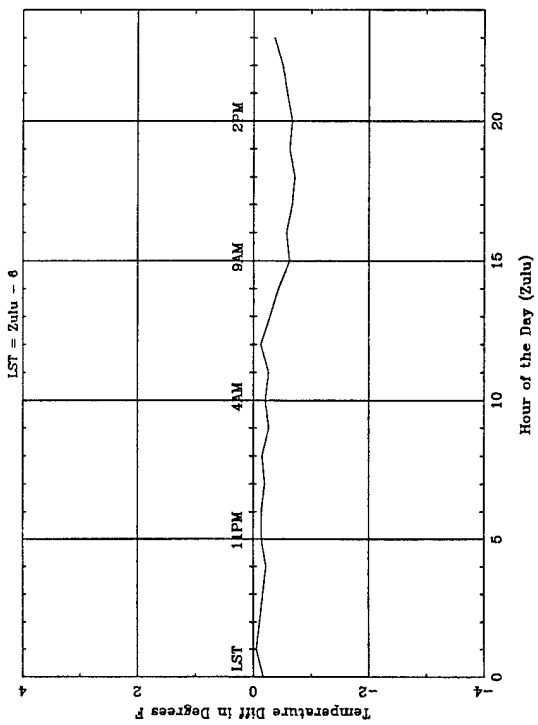
Average Diurnal Cycle for MOB - winter



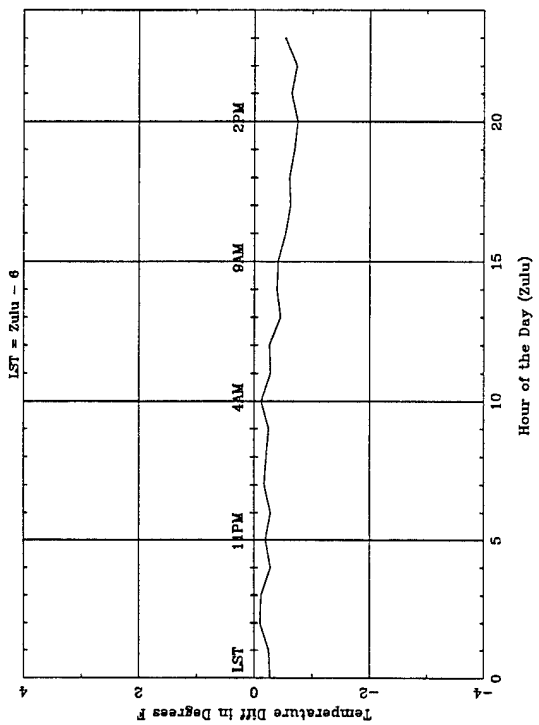
Average Diurnal Cycle for MOB - summer



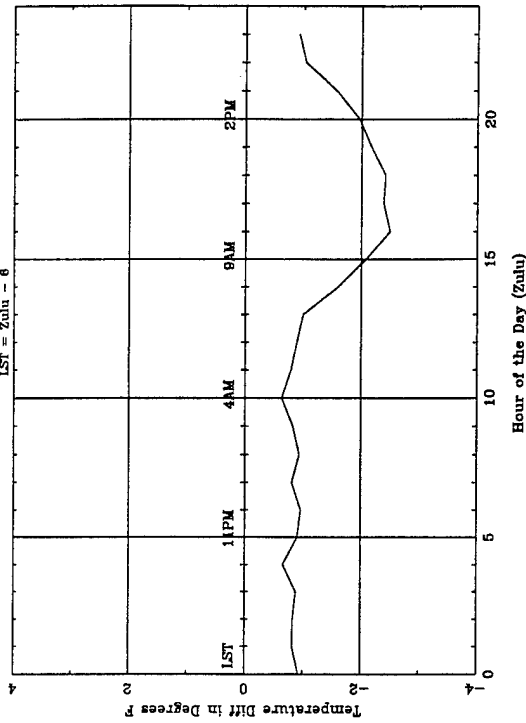
Average Diurnal Cycle for MOB - fall



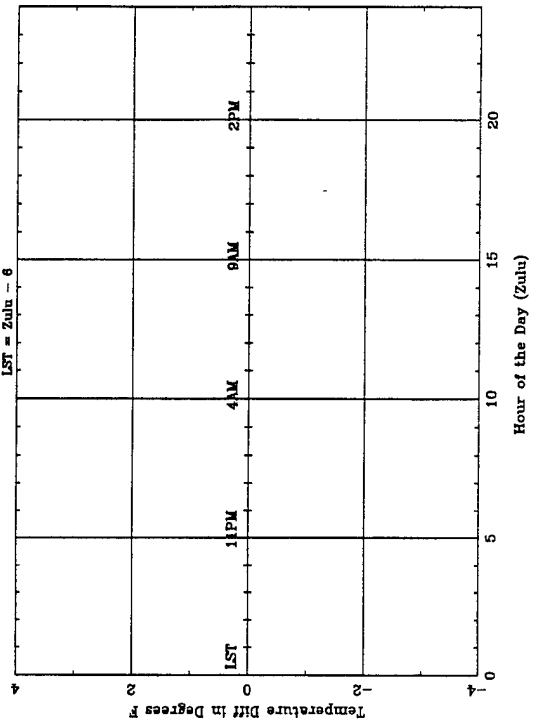
Average Diurnal Cycle for MOB - spring



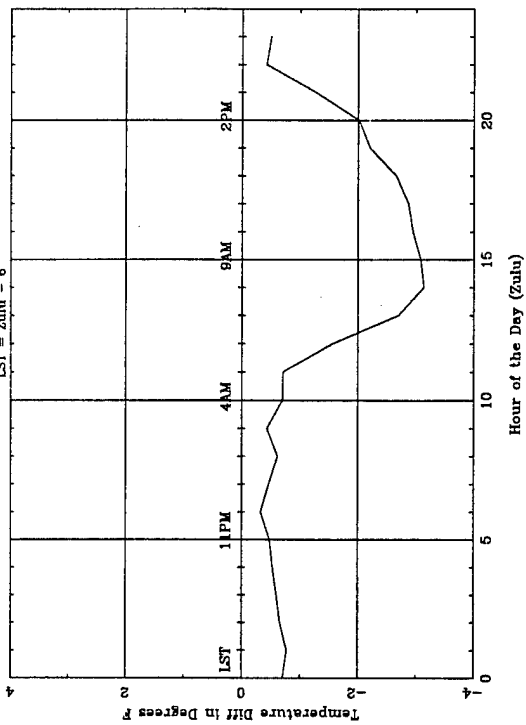
Average Diurnal Cycle for MSN - winter
LST = Zulu - 6



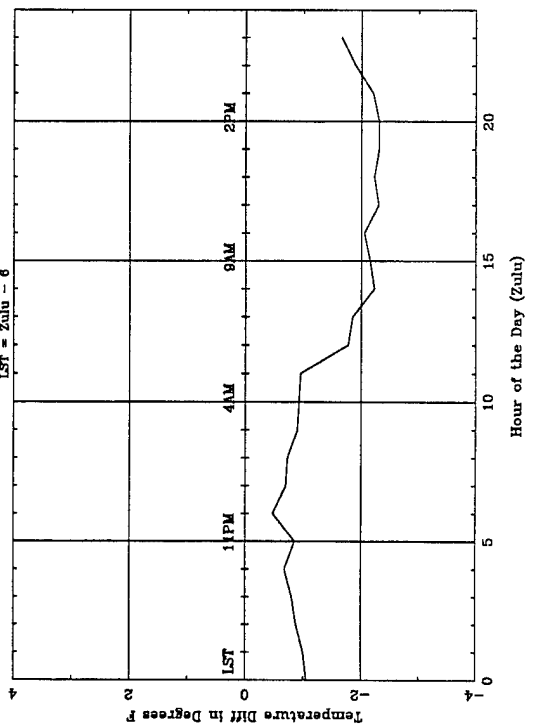
Average Diurnal Cycle for MSN - summer
LST = Zulu - 6

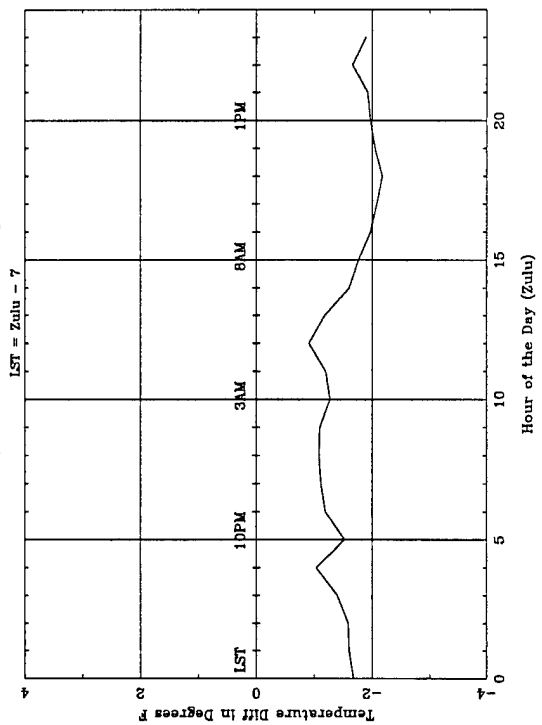
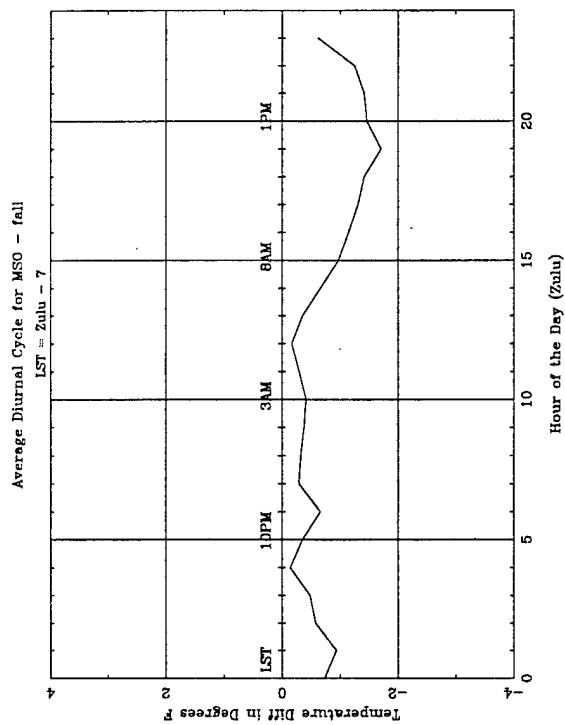
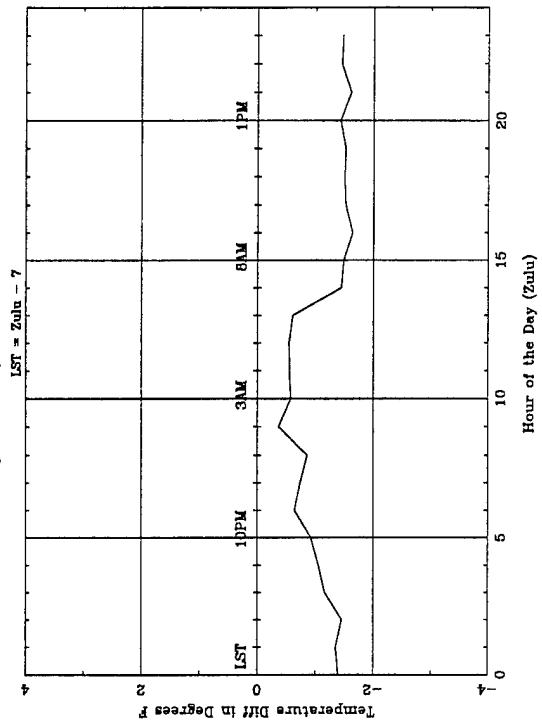
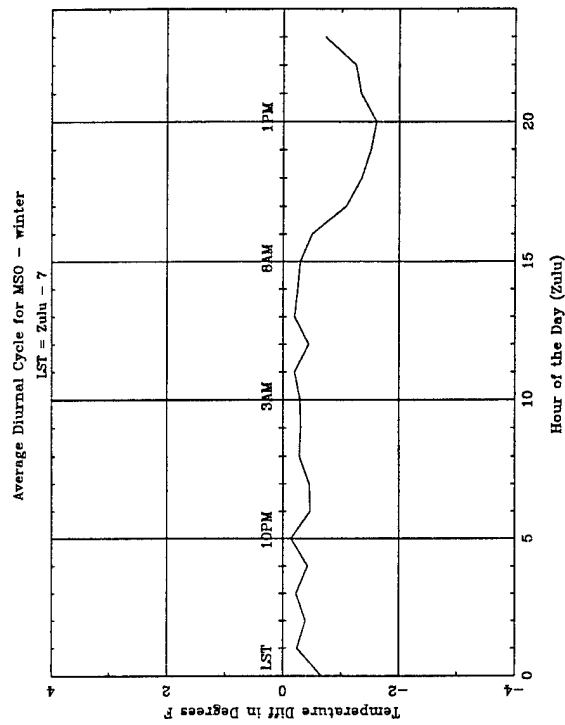


Average Diurnal Cycle for MSN - fall
LST = Zulu - 6

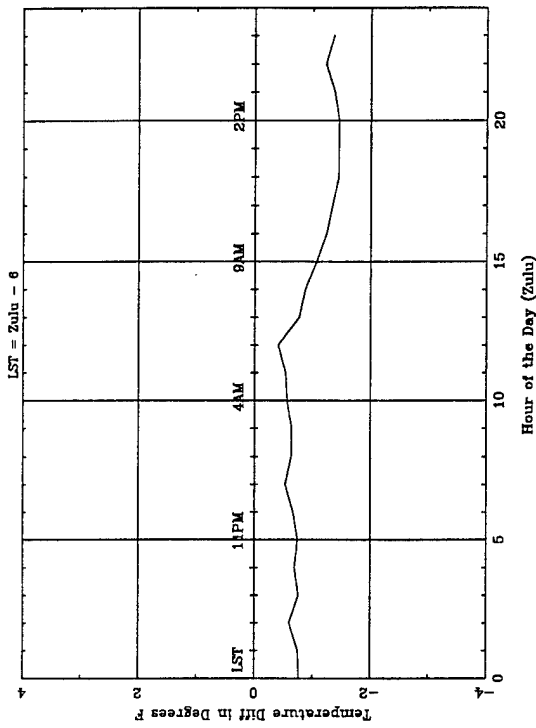


Average Diurnal Cycle for MSN - spring
LST = Zulu - 6

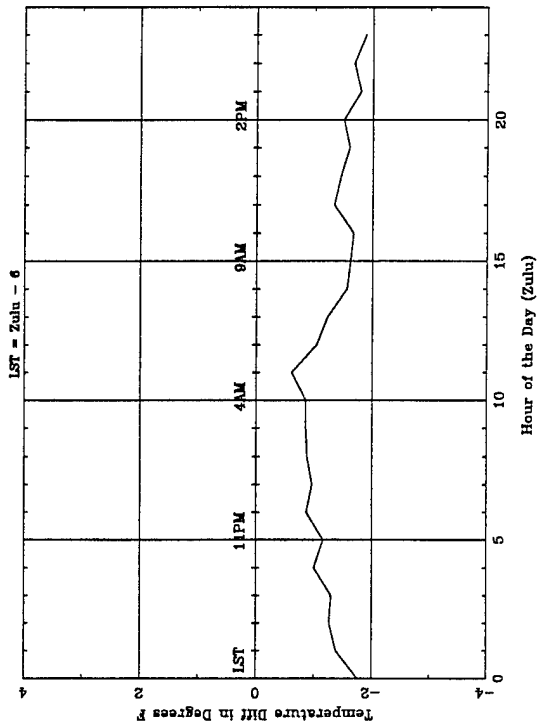




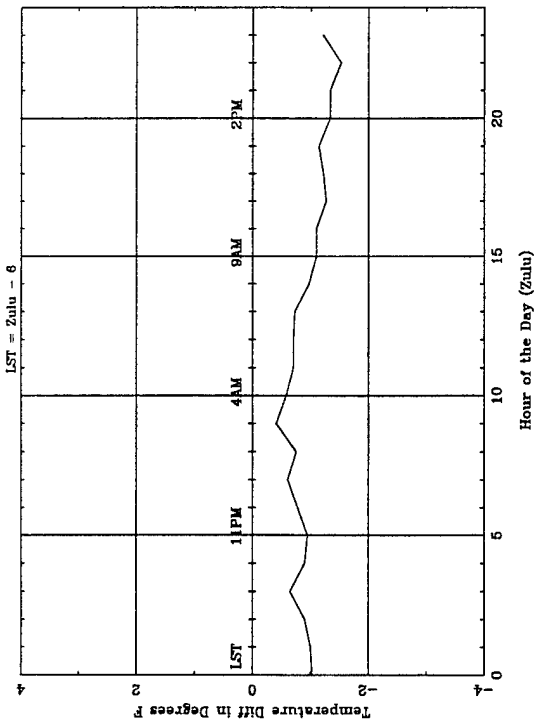
Average Diurnal Cycle for OFK - winter



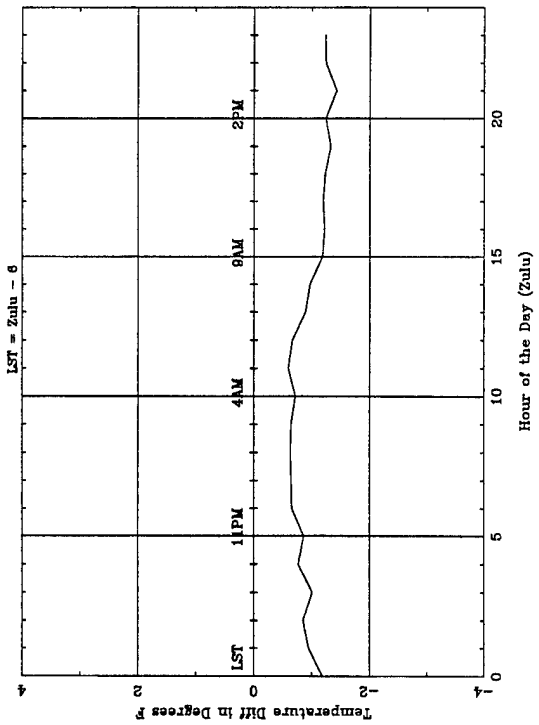
Average Diurnal Cycle for OFK - summer

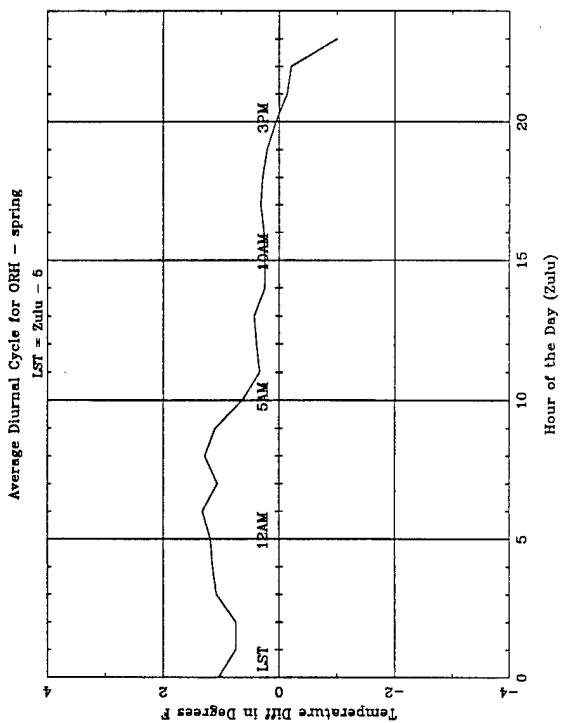
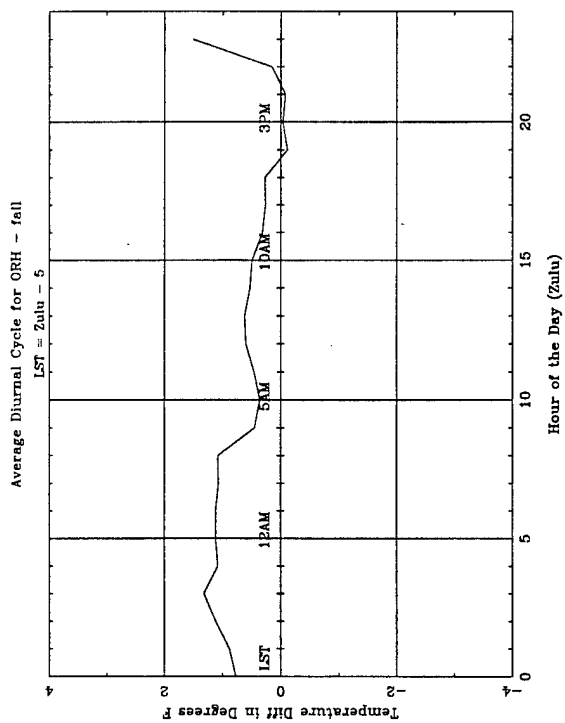
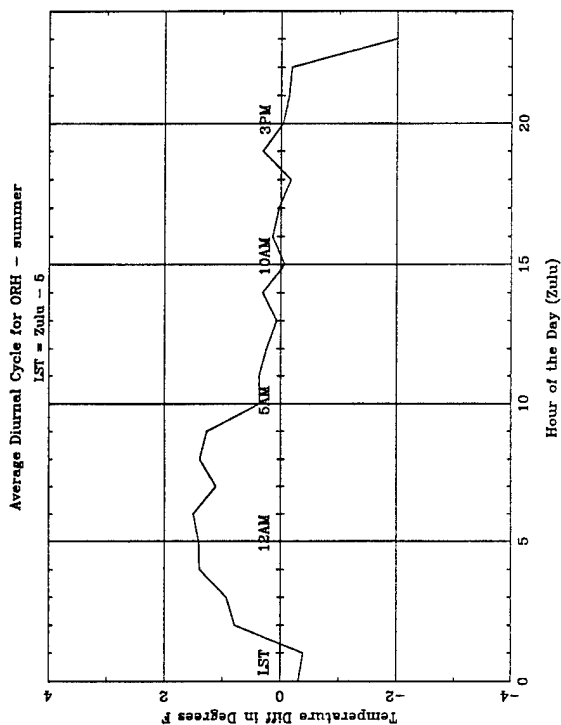
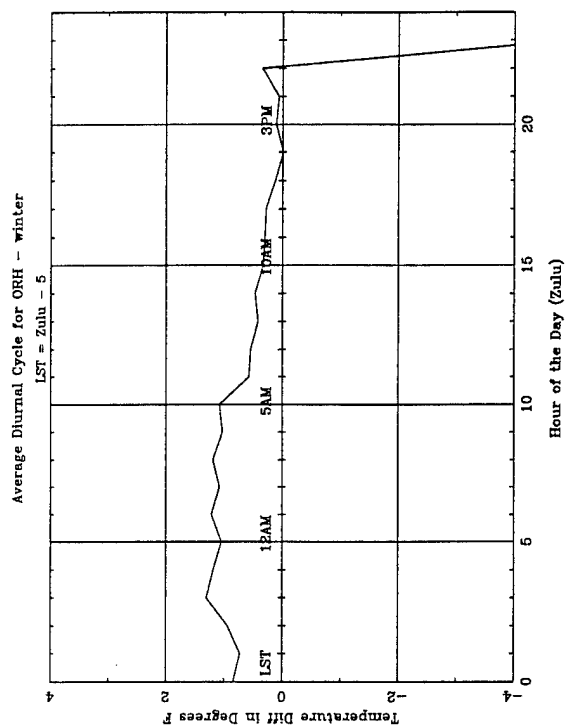


Average Diurnal Cycle for OFK - fall

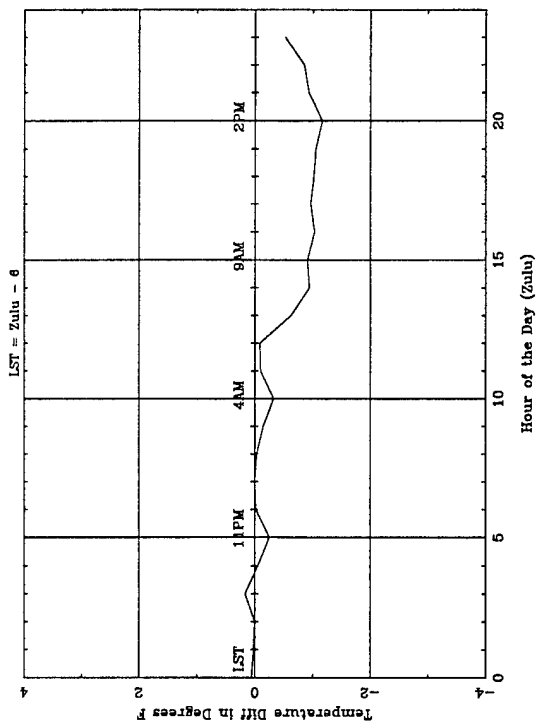


Average Diurnal Cycle for OFK - spring

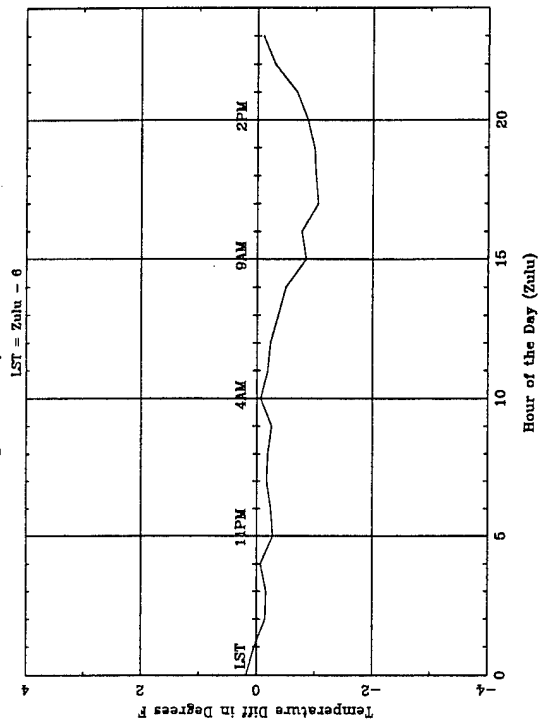




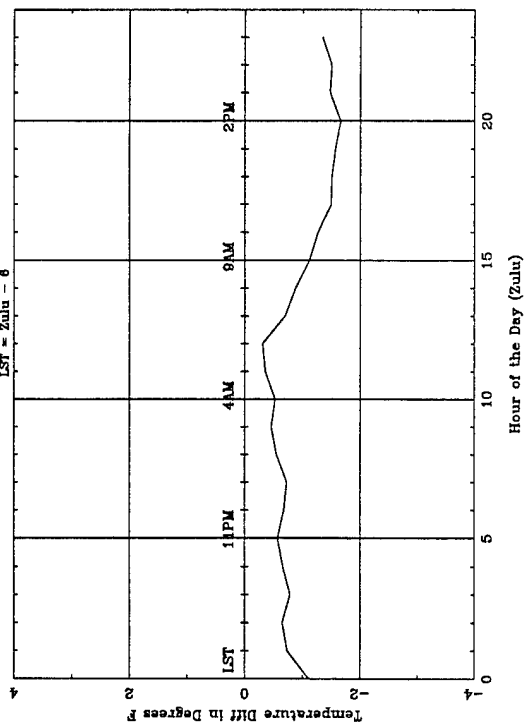
Average Diurnal Cycle for PAH - fall



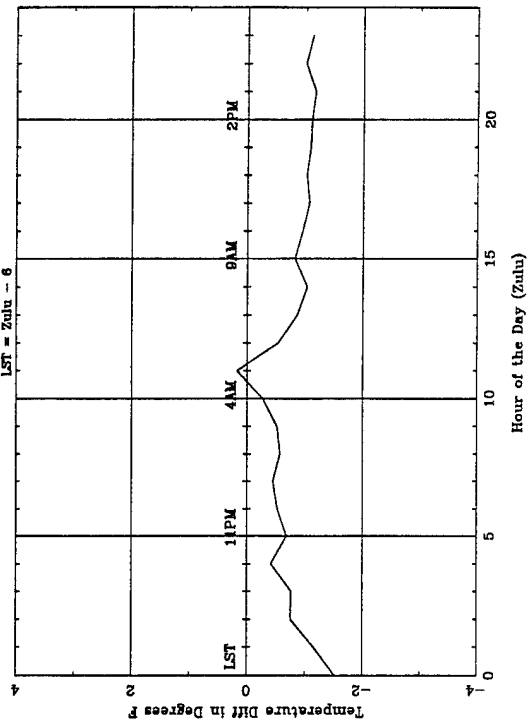
Average Diurnal Cycle for PAH - winter



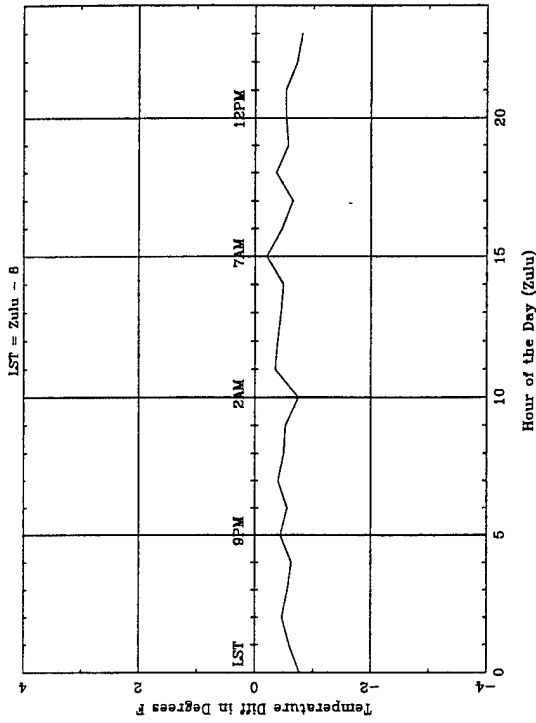
Average Diurnal Cycle for PAH - spring



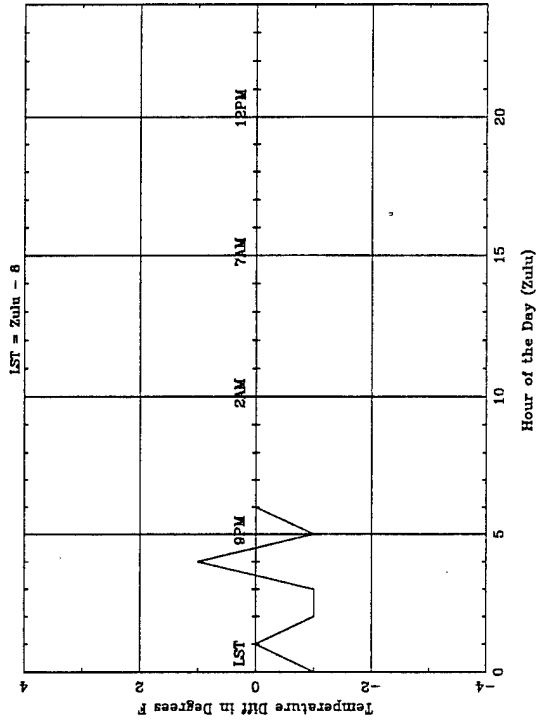
Average Diurnal Cycle for PAH - summer



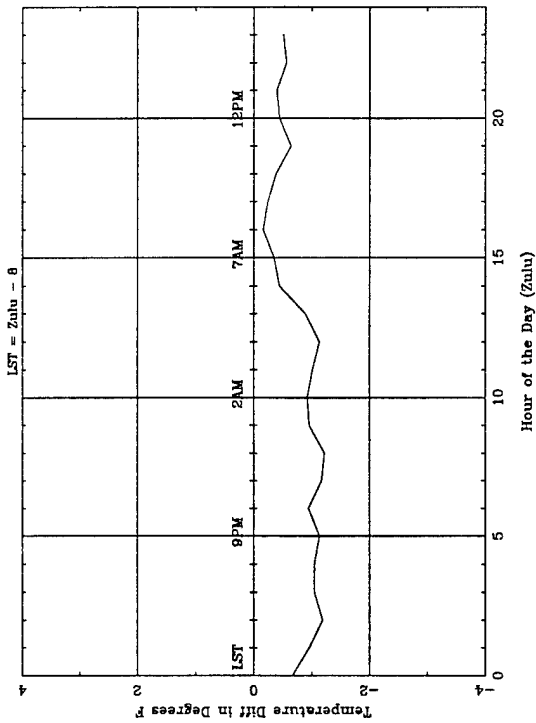
Average Diurnal Cycle for PDT - winter



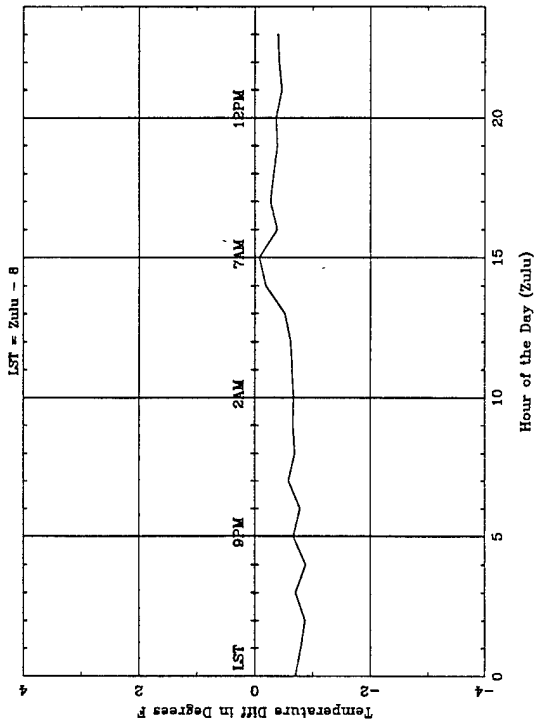
Average Diurnal Cycle for PDT - summer



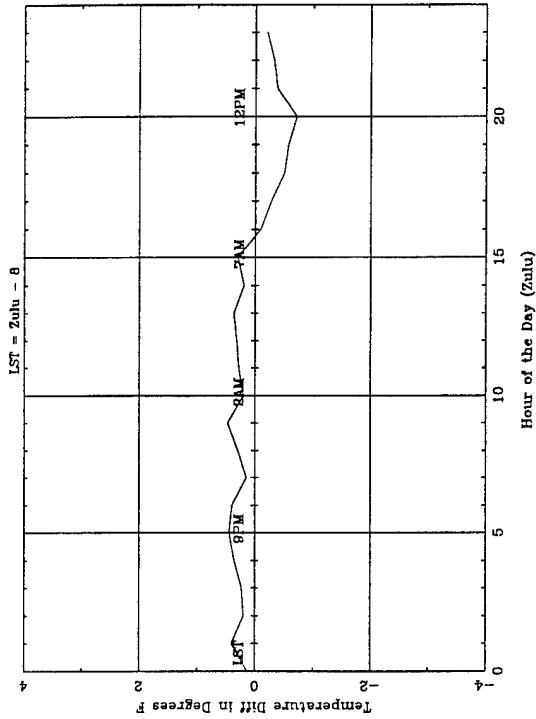
Average Diurnal Cycle for PDT - fall



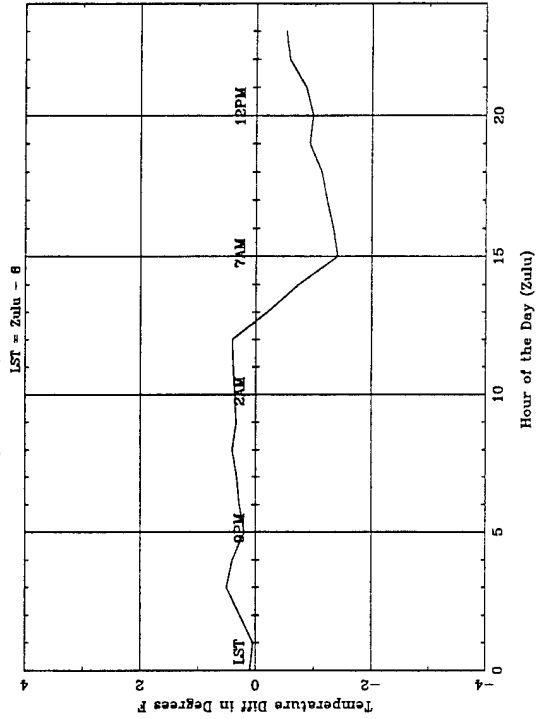
Average Diurnal Cycle for PDT - spring



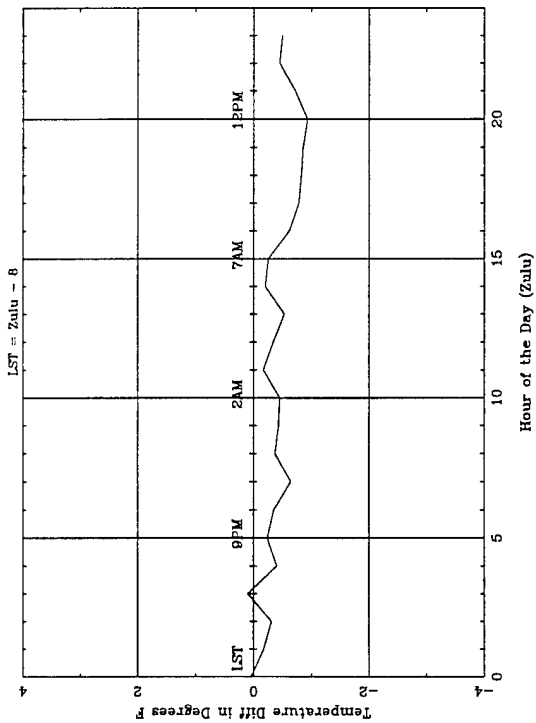
Average Diurnal Cycle for PDX - winter



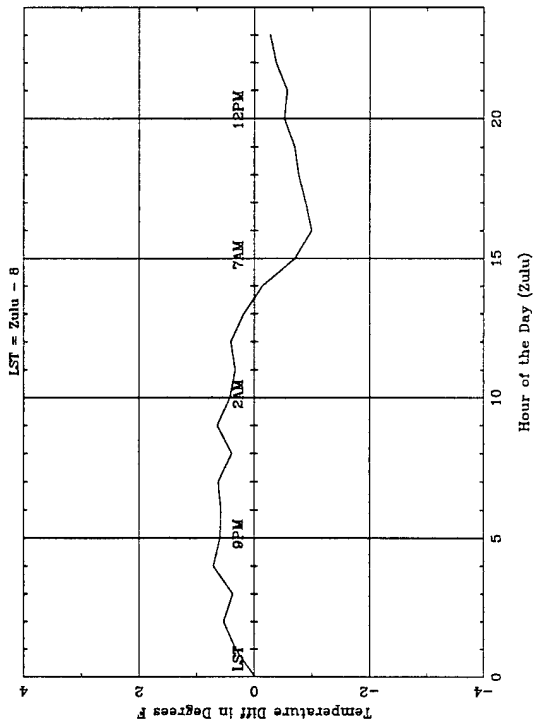
Average Diurnal Cycle for PDX - summer



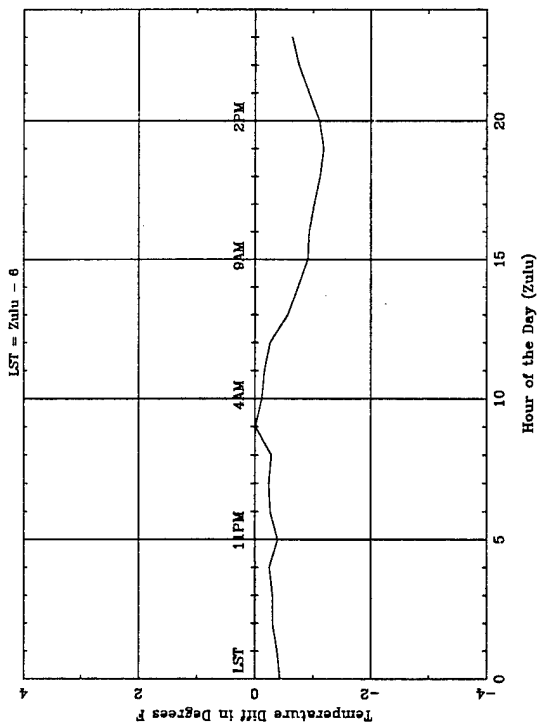
Average Diurnal Cycle for PDX - fall



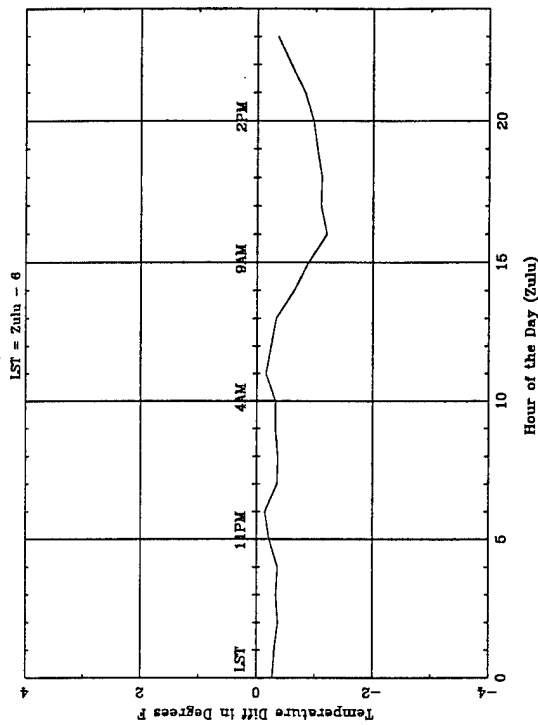
Average Diurnal Cycle for PDX - spring



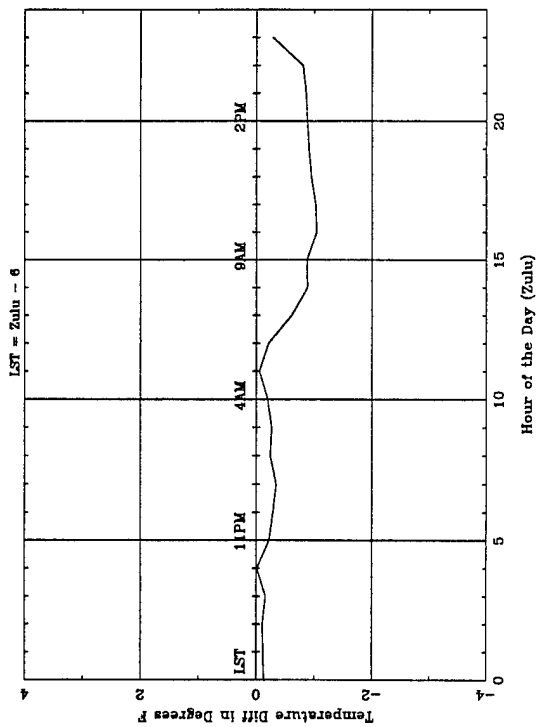
Average Diurnal Cycle for PIA - fall



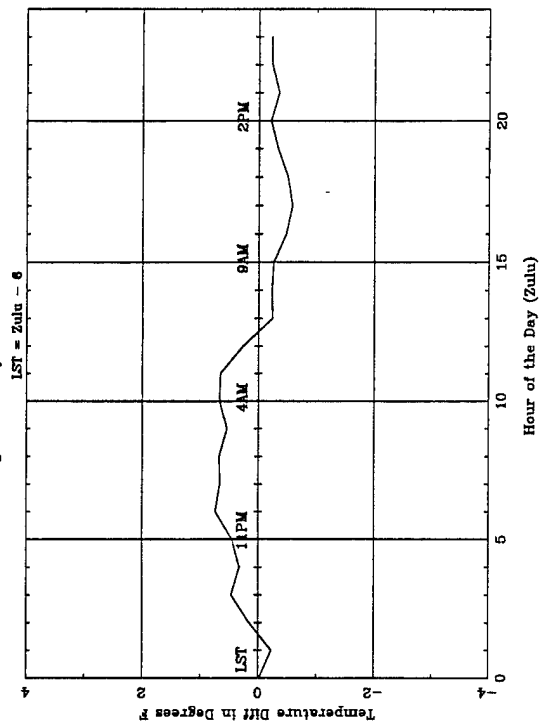
Average Diurnal Cycle for PIA - winter

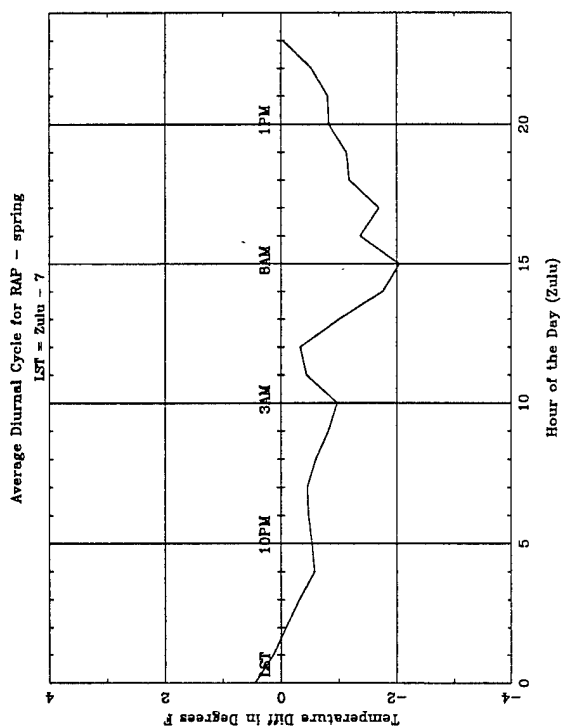
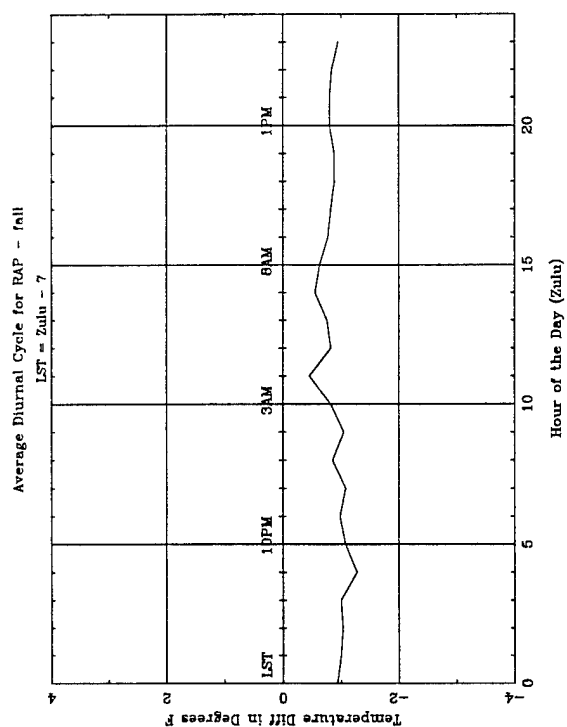
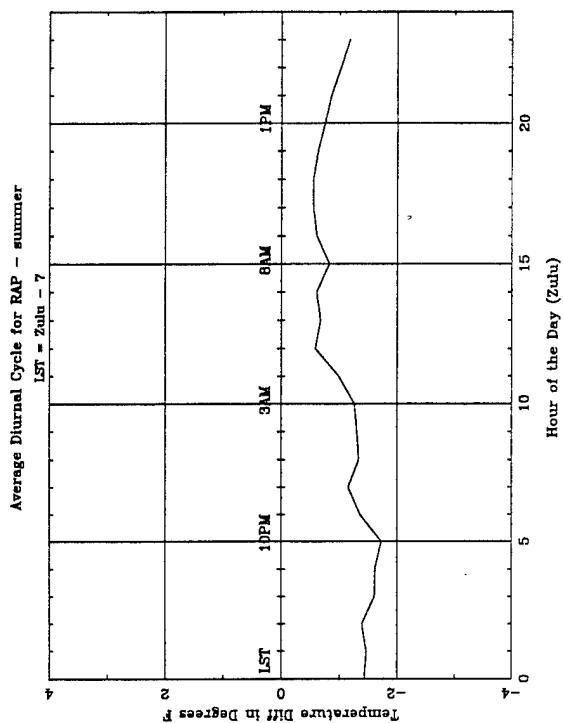
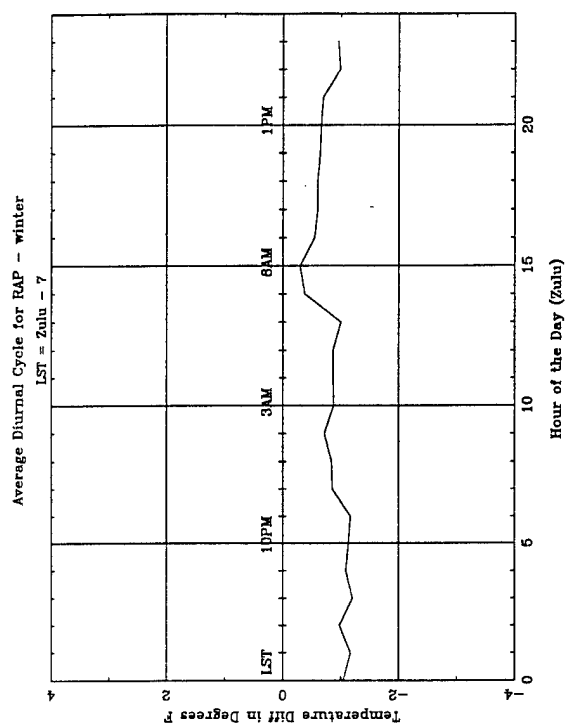


Average Diurnal Cycle for PIA - spring

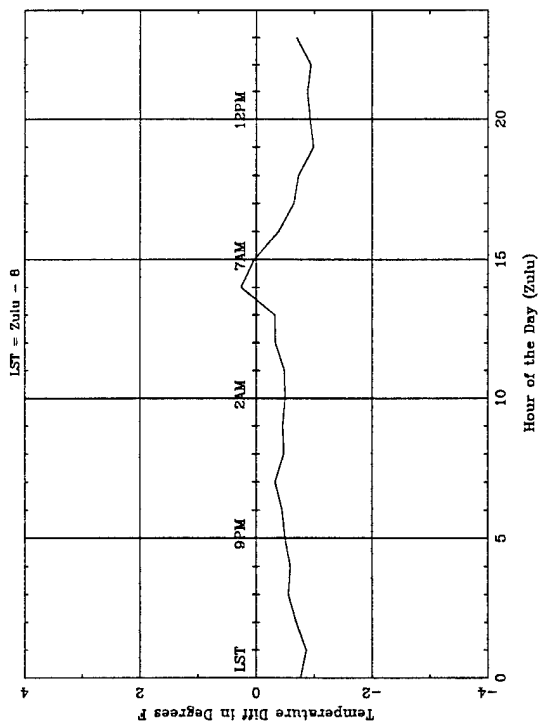


Average Diurnal Cycle for PIA - summer

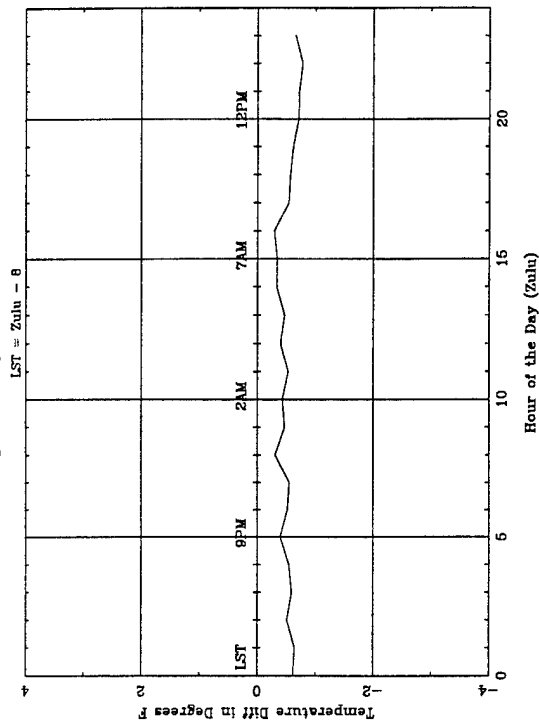




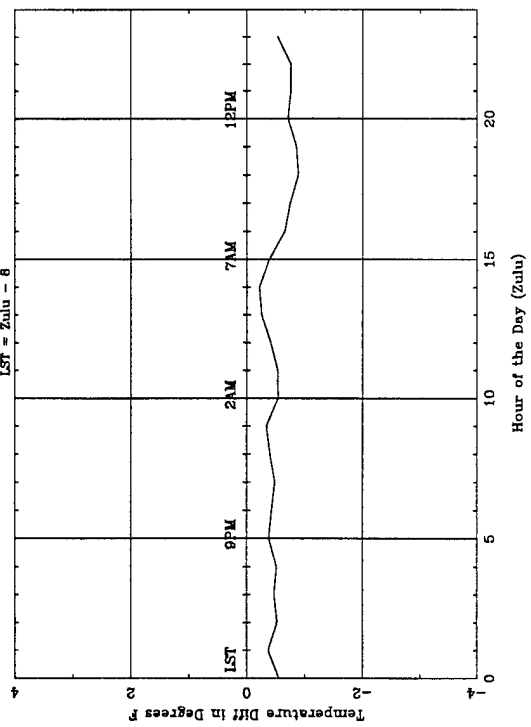
Average Diurnal Cycle for RDD - fall



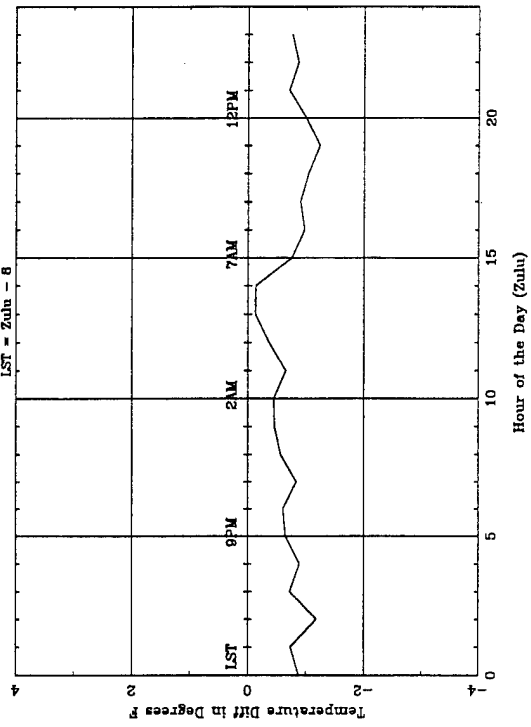
Average Diurnal Cycle for RDD - winter

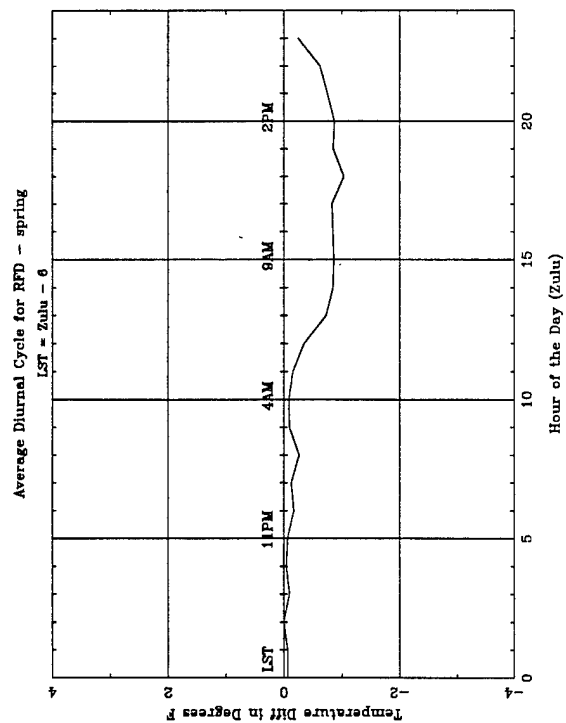
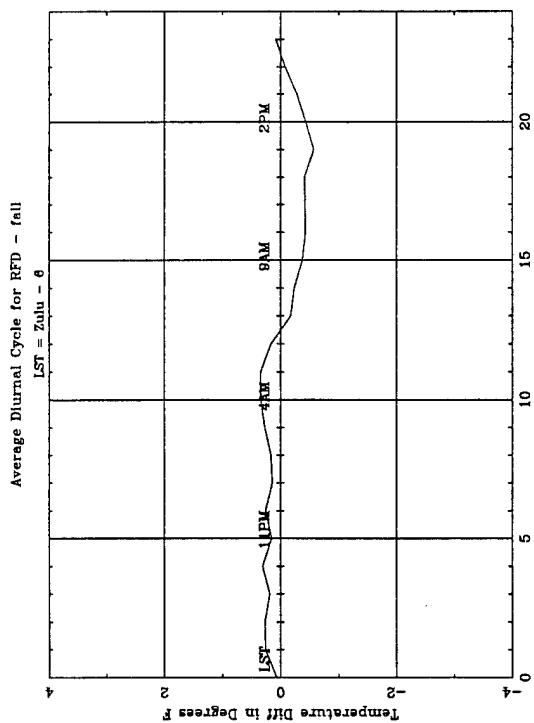
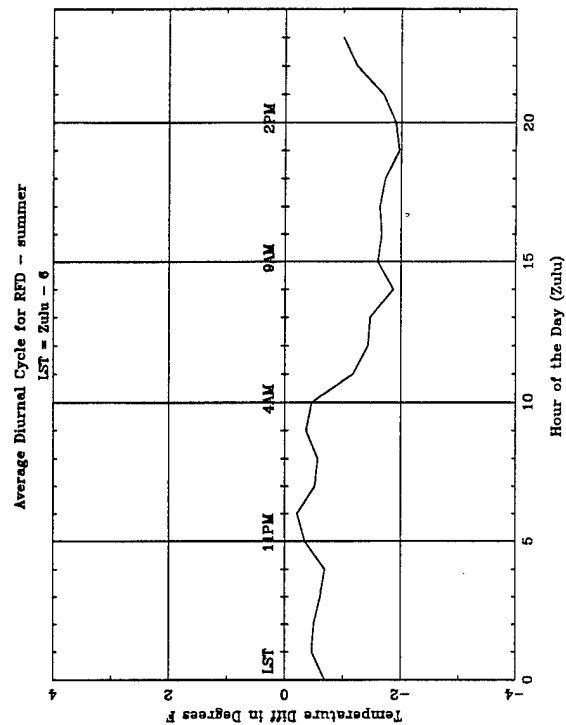
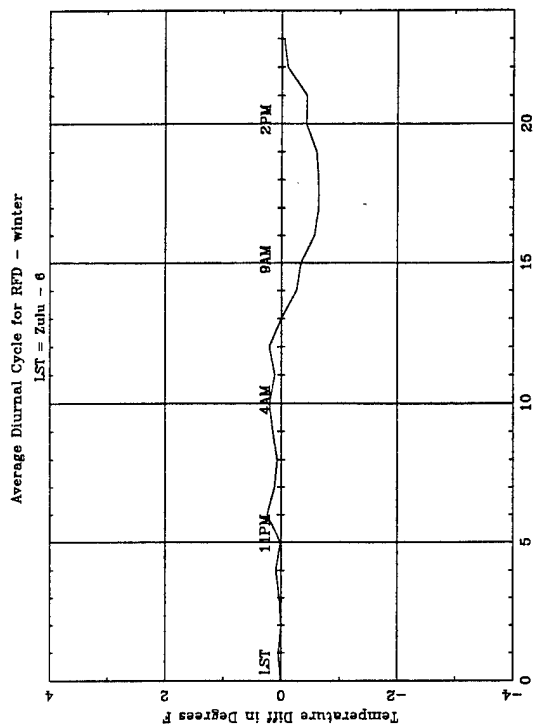


Average Diurnal Cycle for RDD - spring

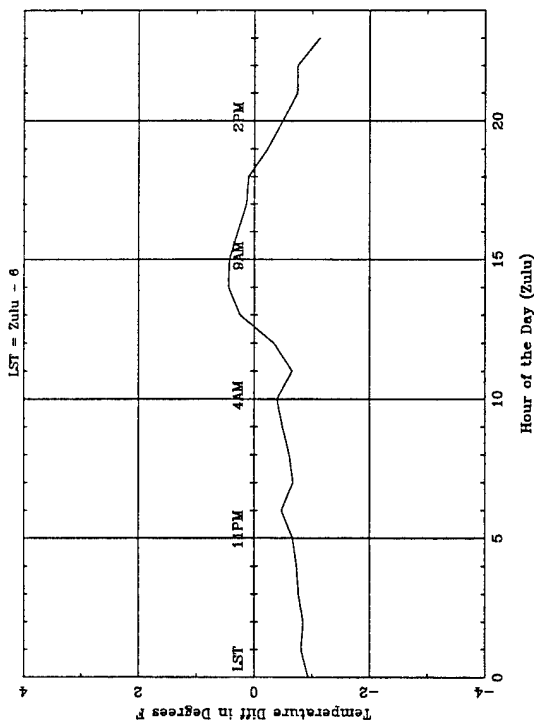


Average Diurnal Cycle for RDD - summer

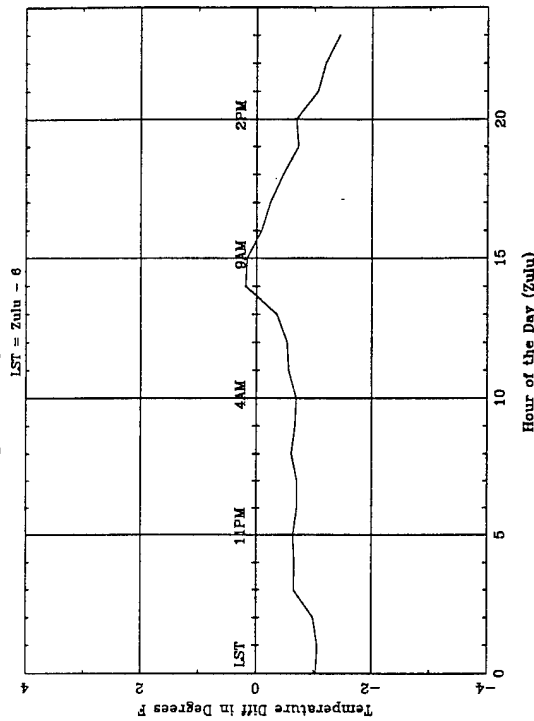




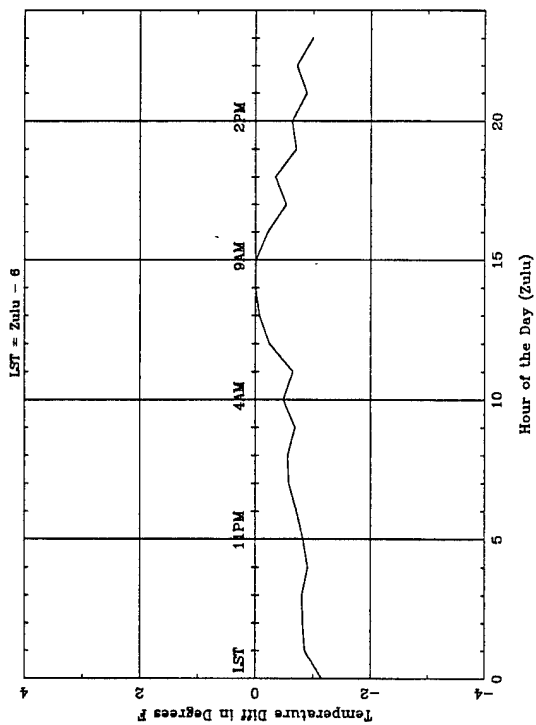
Average Diurnal Cycle for RSL - fall



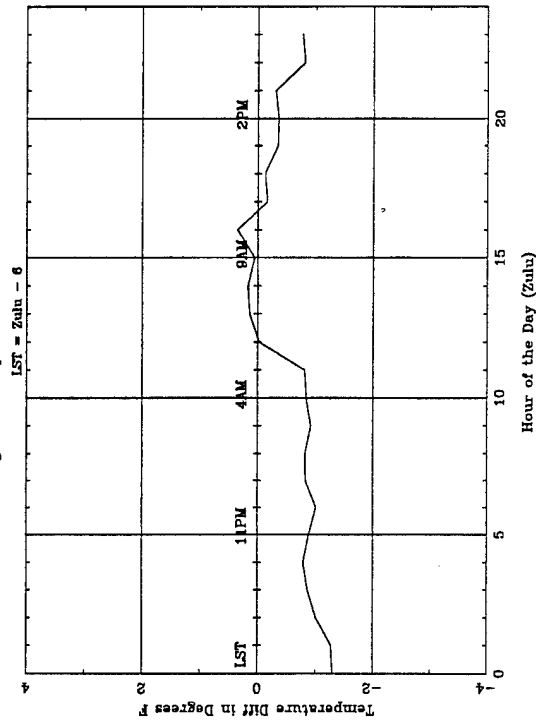
Average Diurnal Cycle for RSL - winter

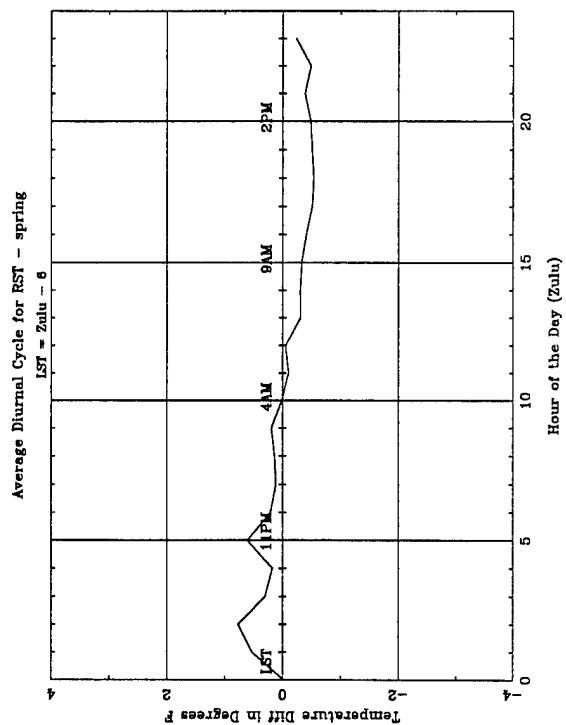
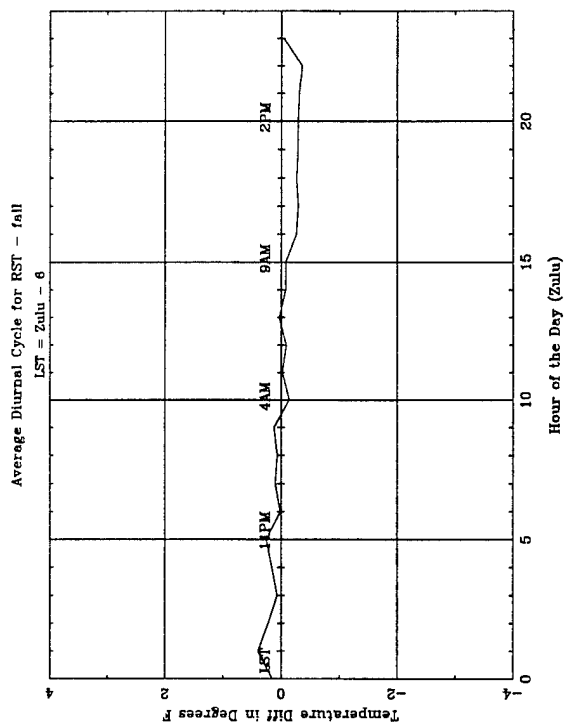
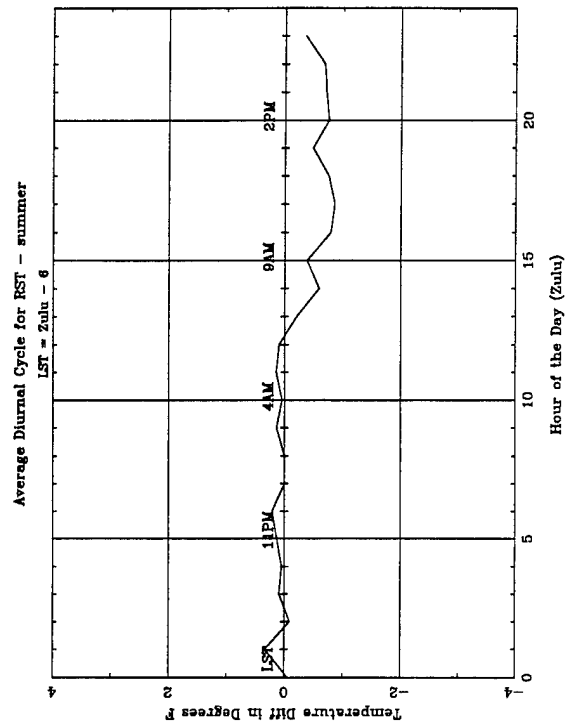
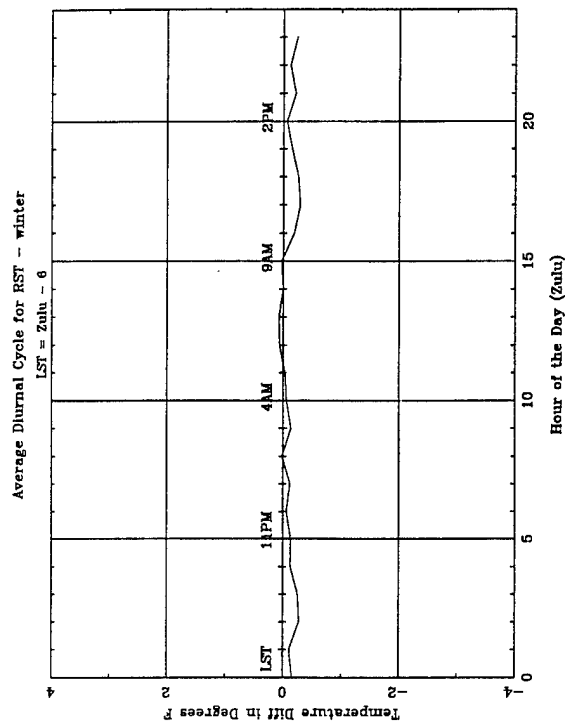


Average Diurnal Cycle for RSL - spring

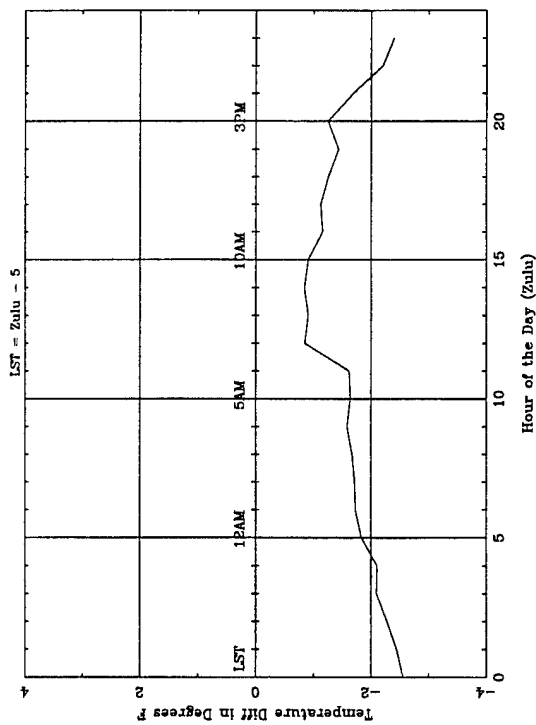


Average Diurnal Cycle for RSL - summer

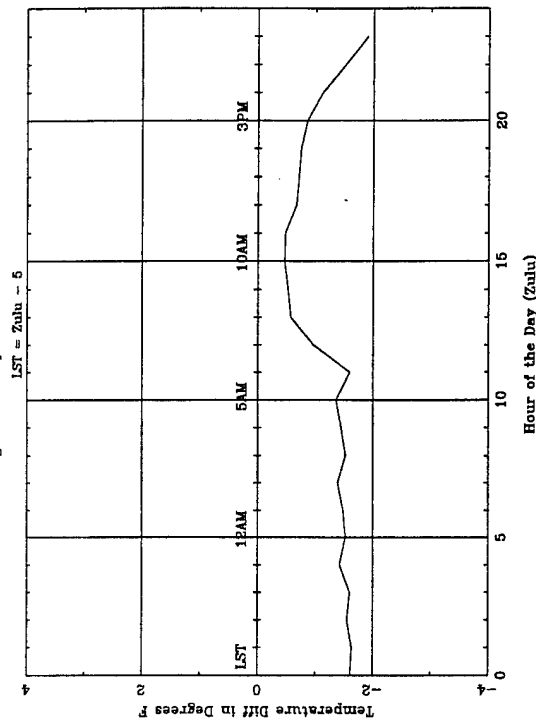




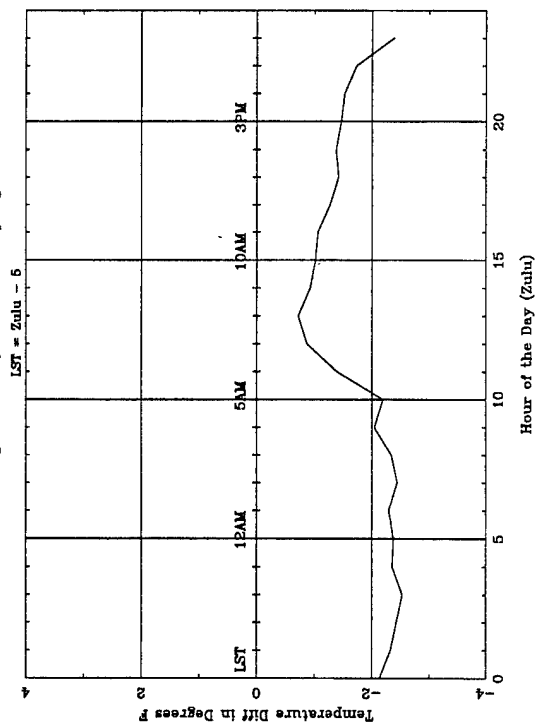
Average Diurnal Cycle for SAV - fall



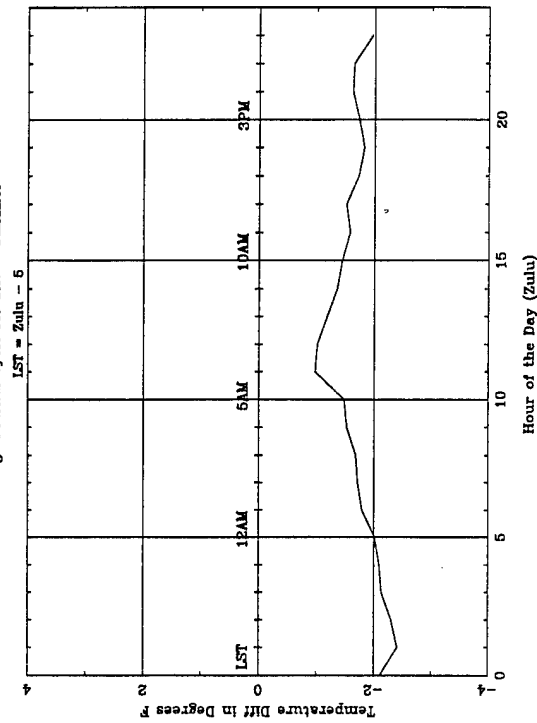
Average Diurnal Cycle for SAV - winter



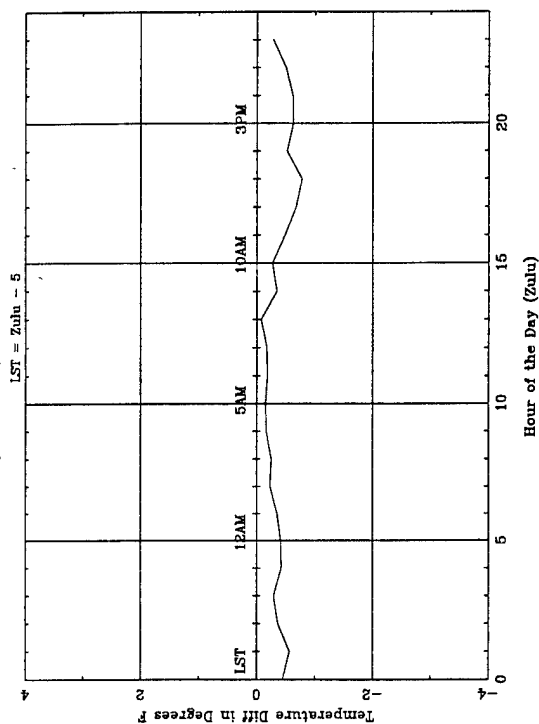
Average Diurnal Cycle for SAV - spring



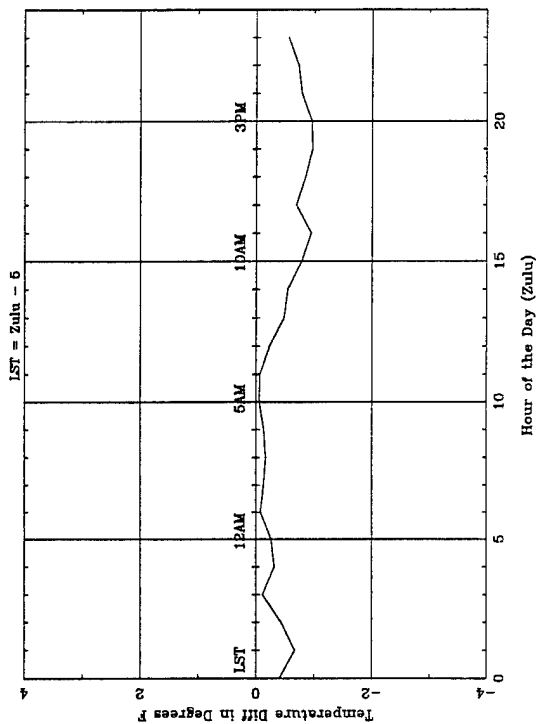
Average Diurnal Cycle for SAV - summer



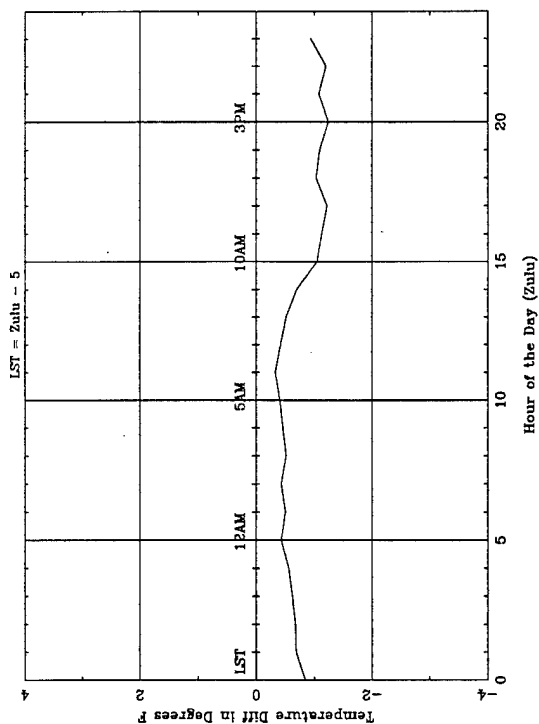
Average Diurnal Cycle for SBN - winter



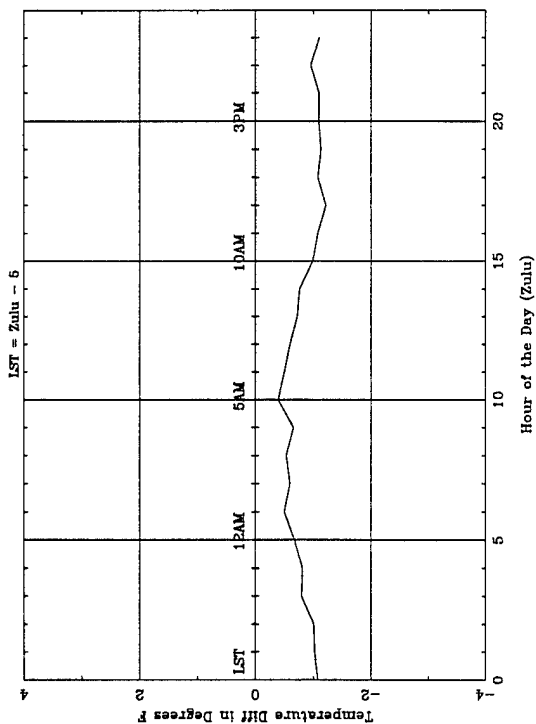
Average Diurnal Cycle for SBN - summer

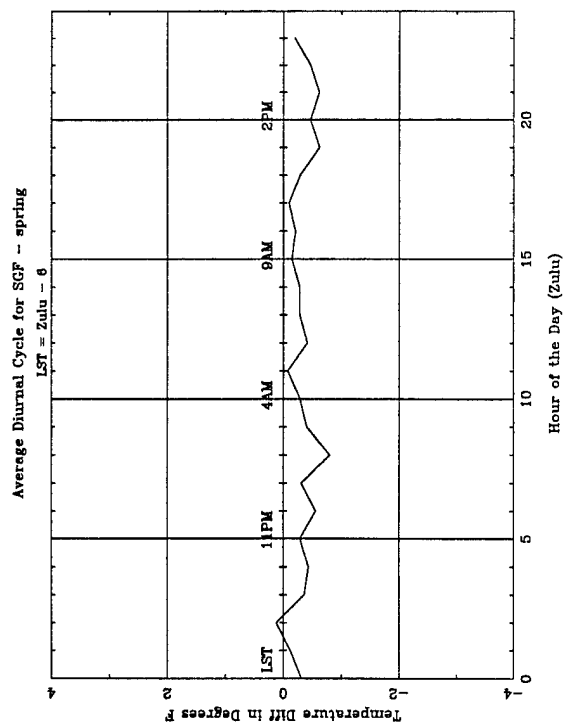
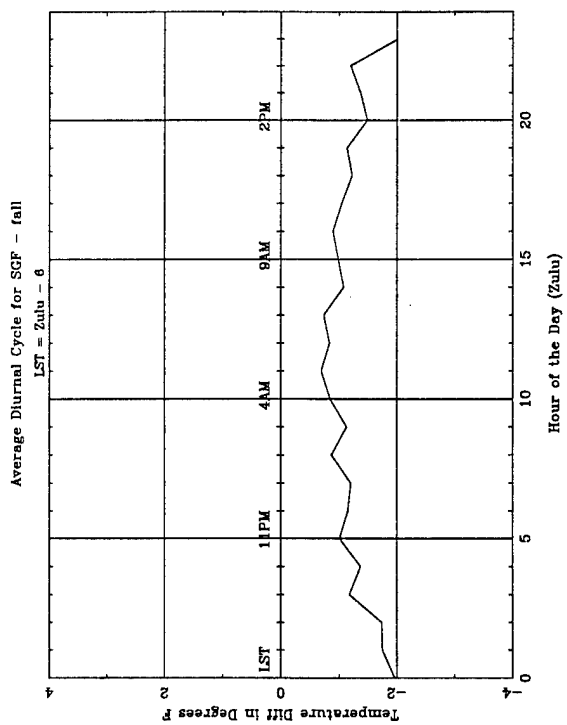
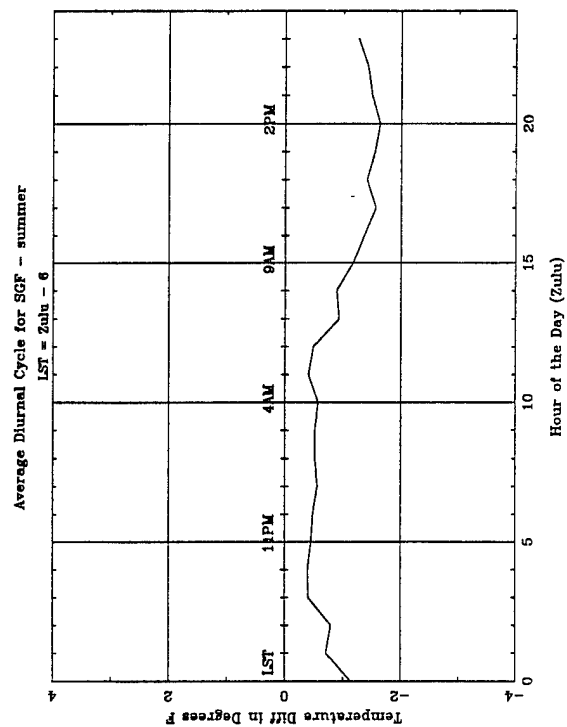
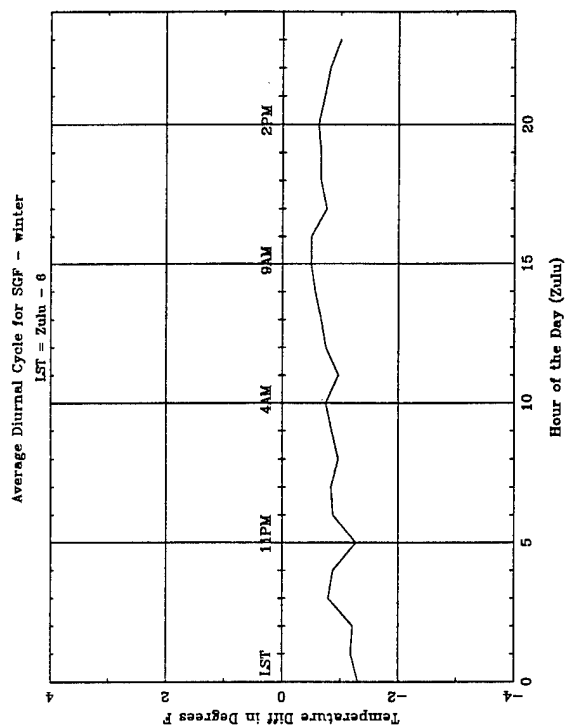


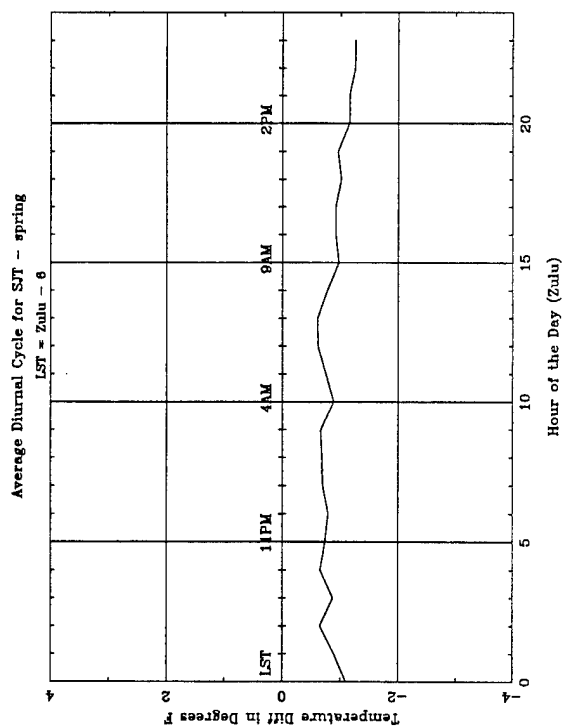
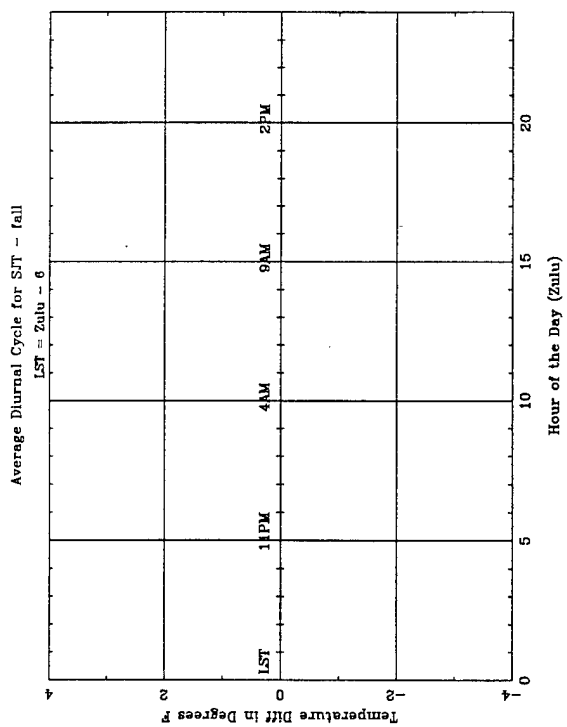
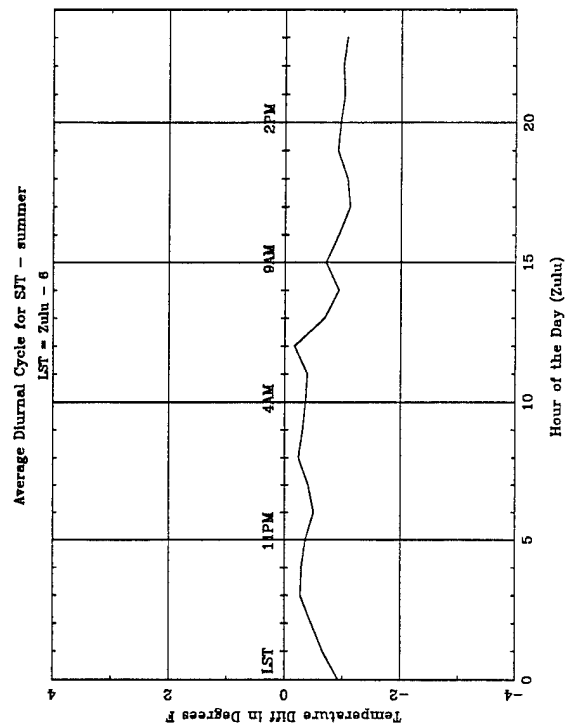
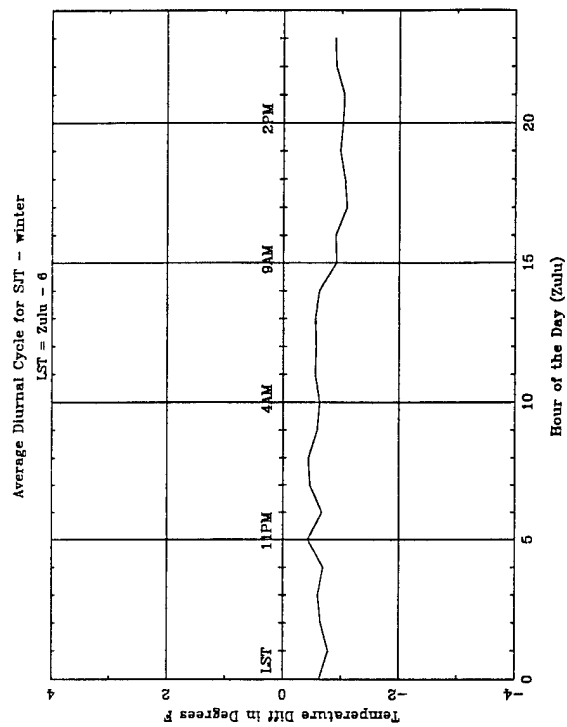
Average Diurnal Cycle for SBN - fall

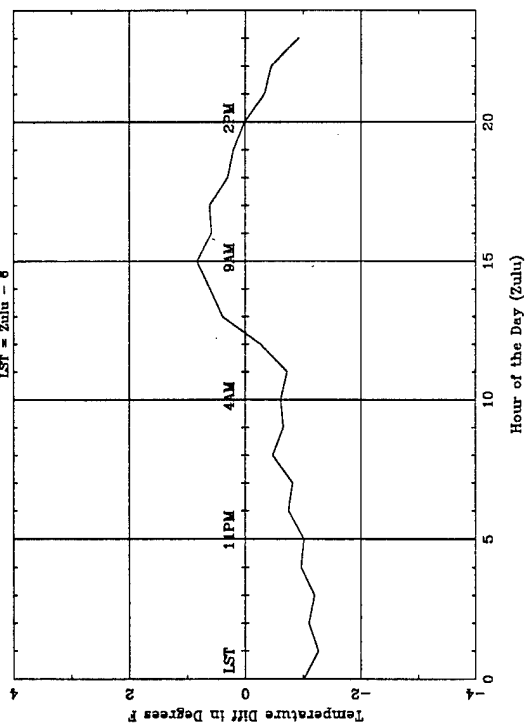
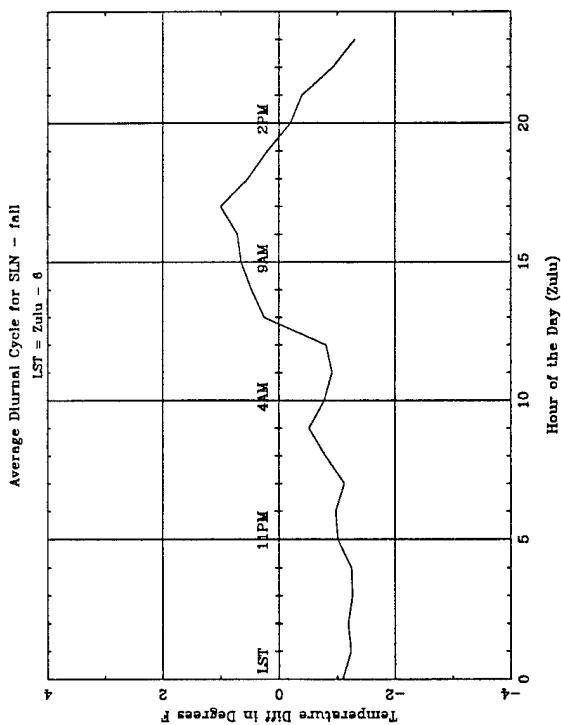
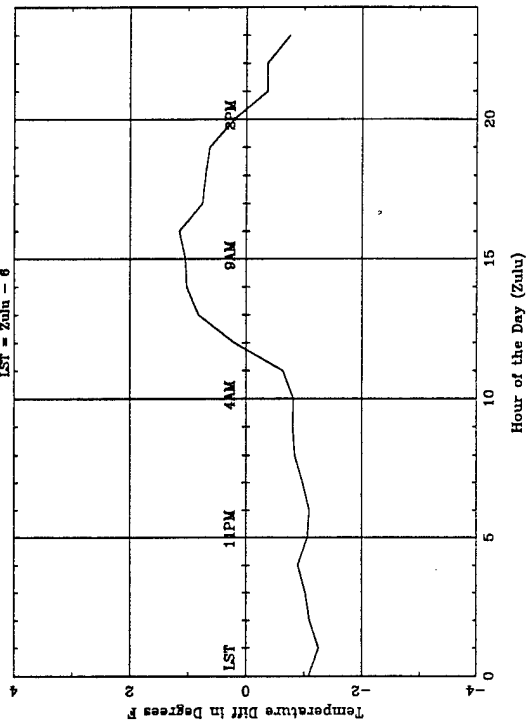
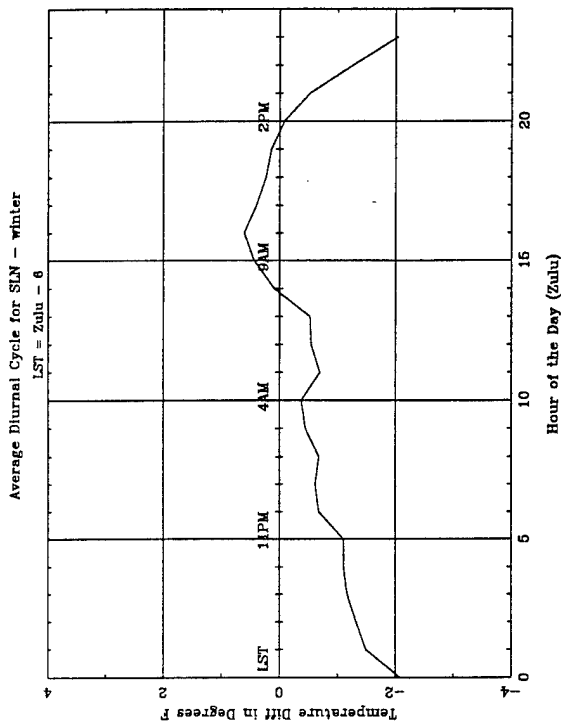


Average Diurnal Cycle for SBN - spring

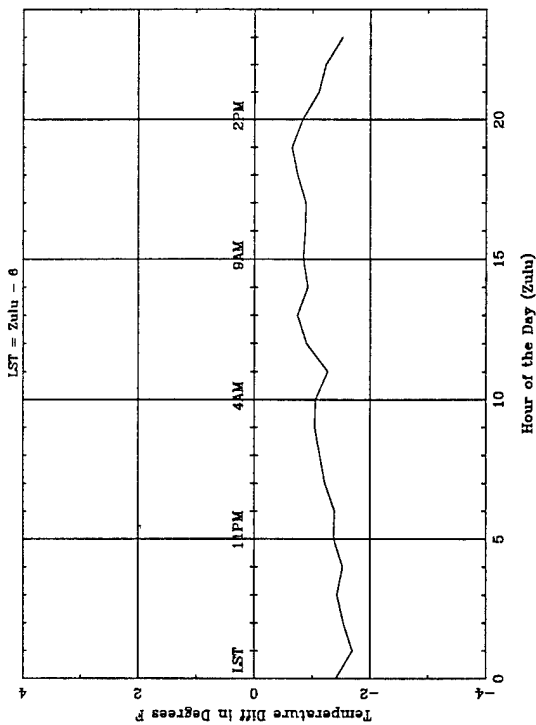




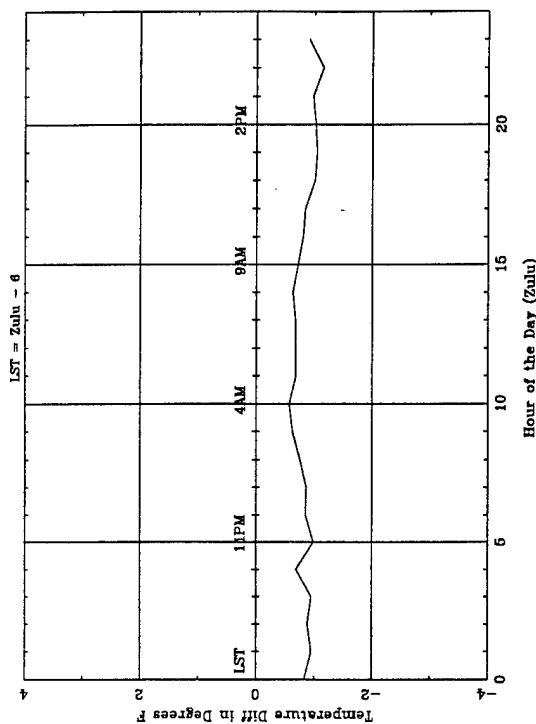




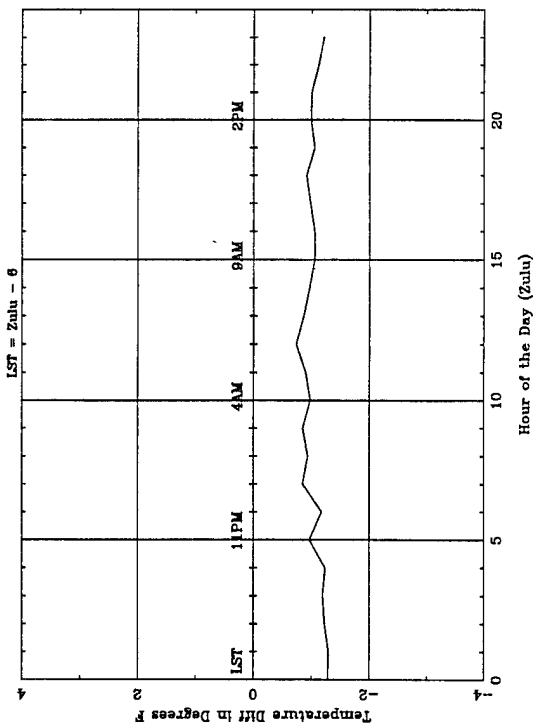
Average Diurnal Cycle for SPI - fall



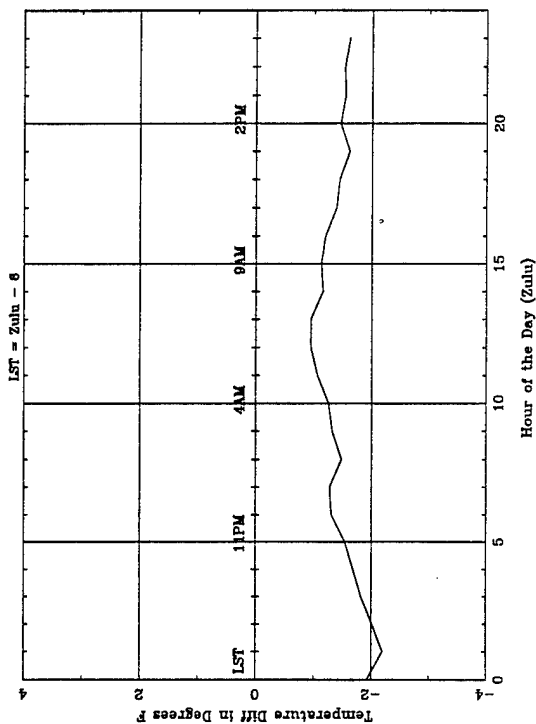
Average Diurnal Cycle for SPI - winter

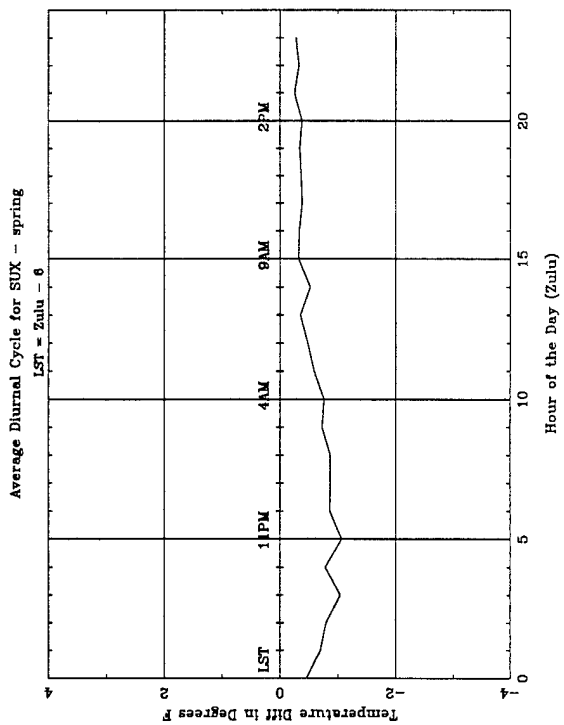
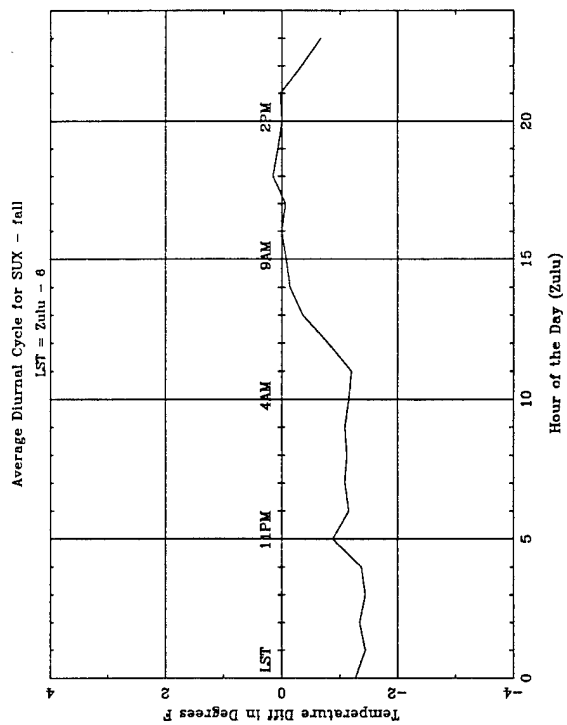
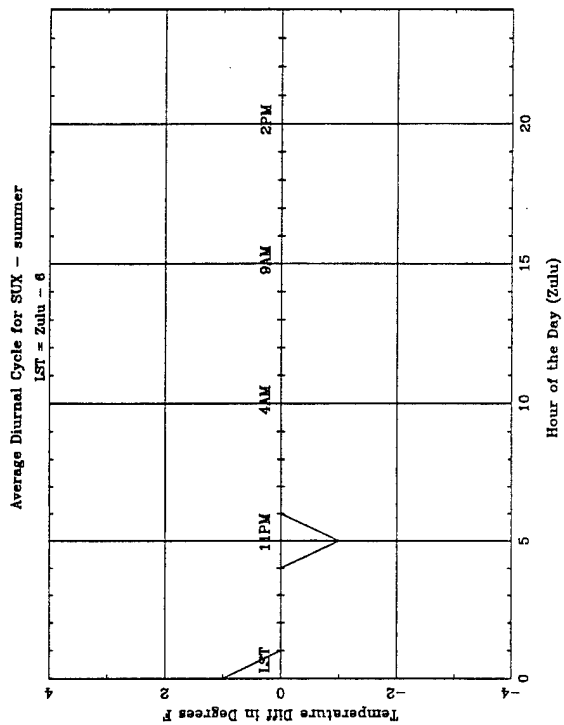
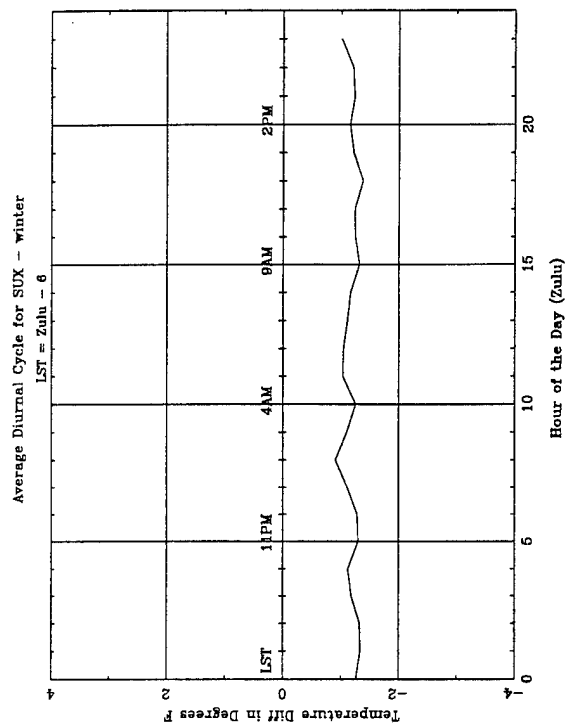


Average Diurnal Cycle for SPI - spring

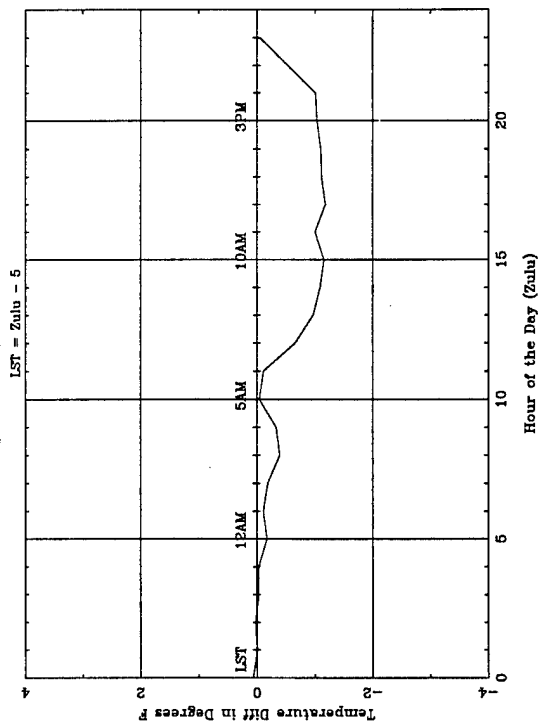


Average Diurnal Cycle for SPI - summer

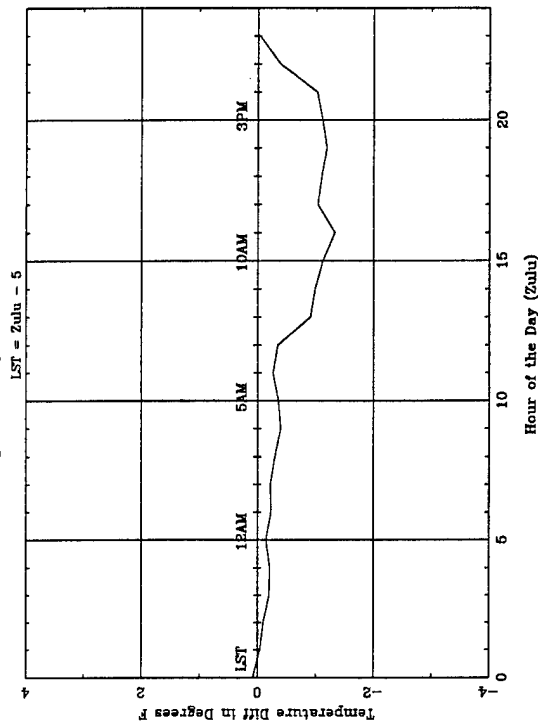




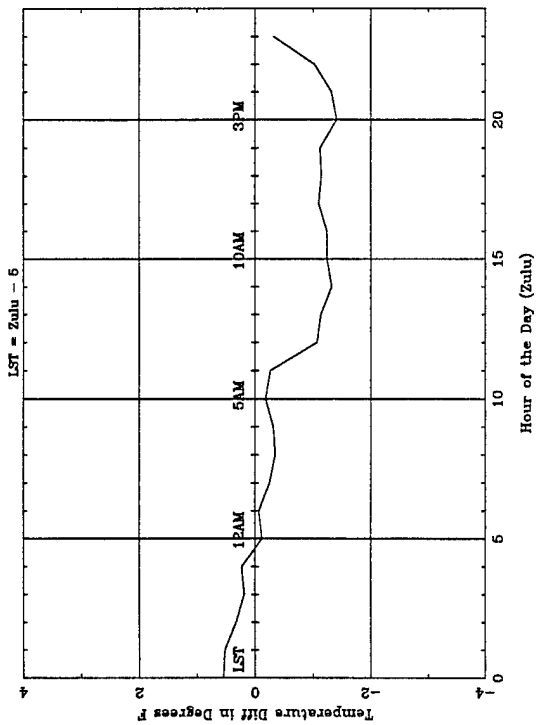
Average Diurnal Cycle for TLH - fall



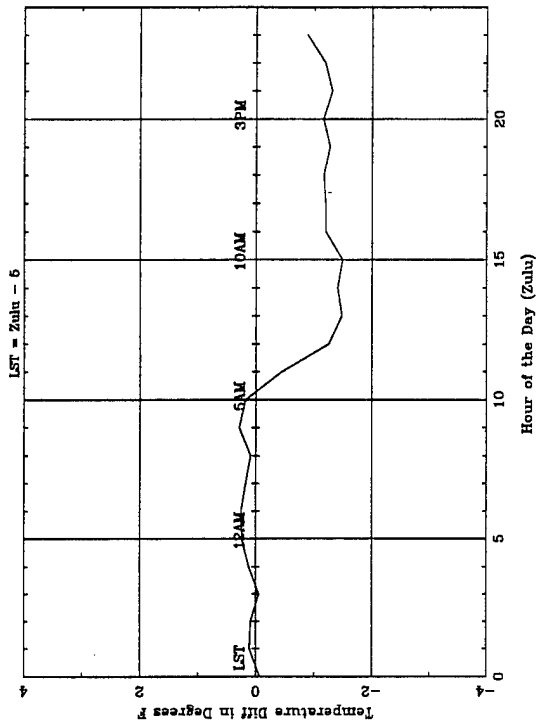
Average Diurnal Cycle for TLH - winter

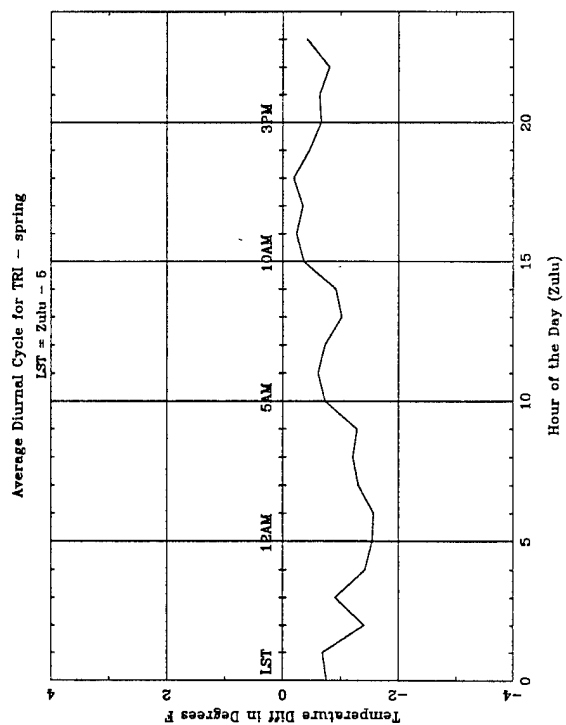
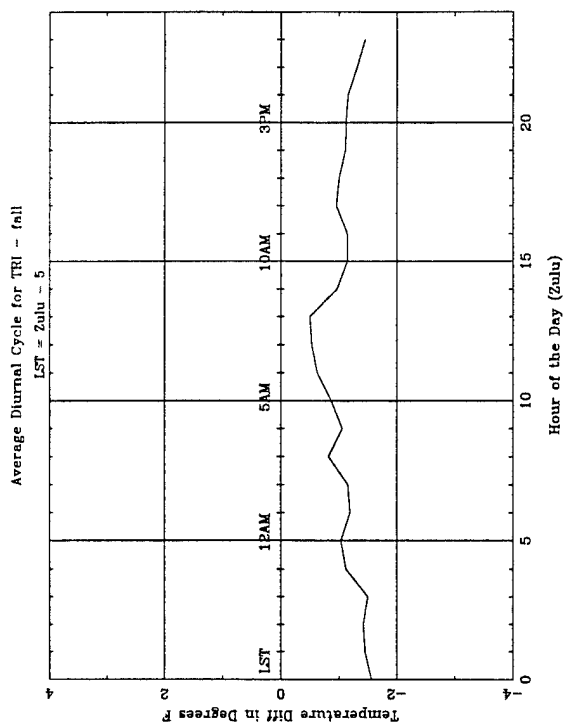
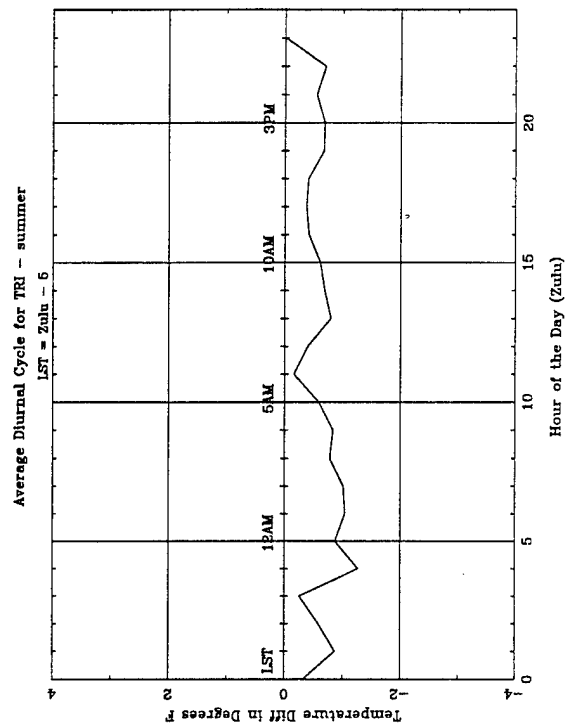
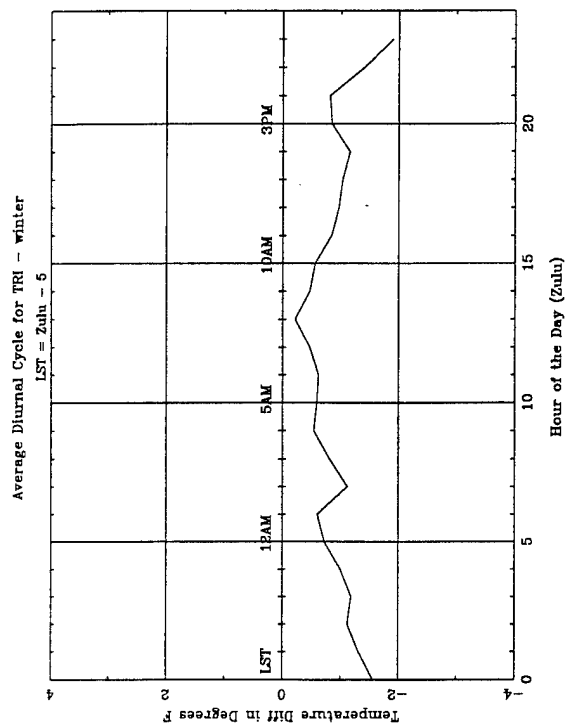


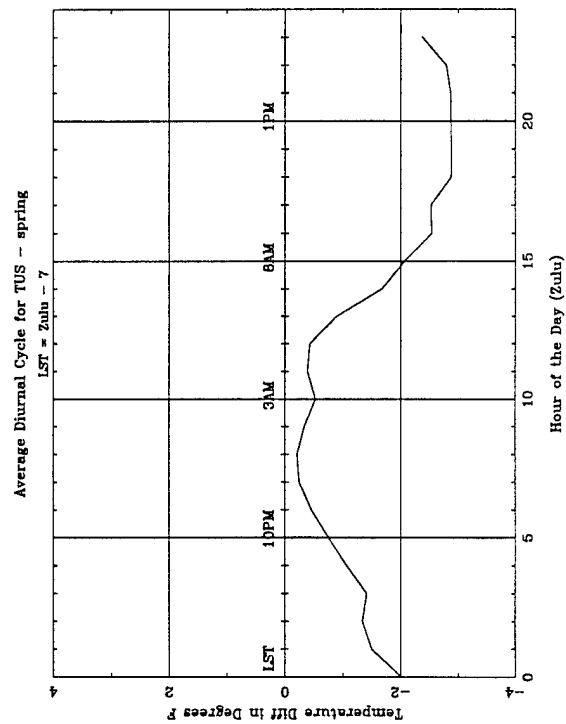
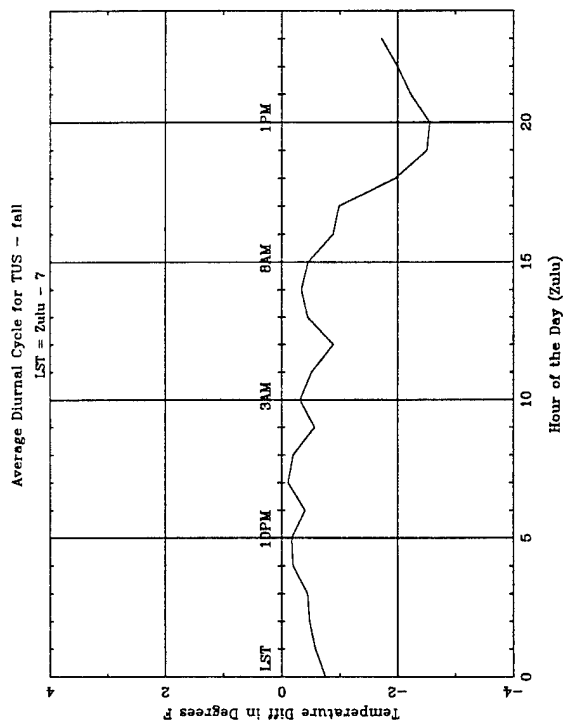
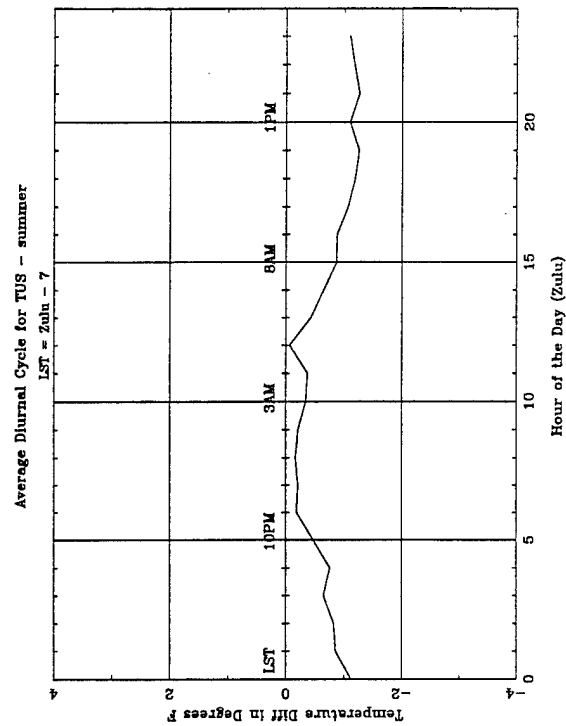
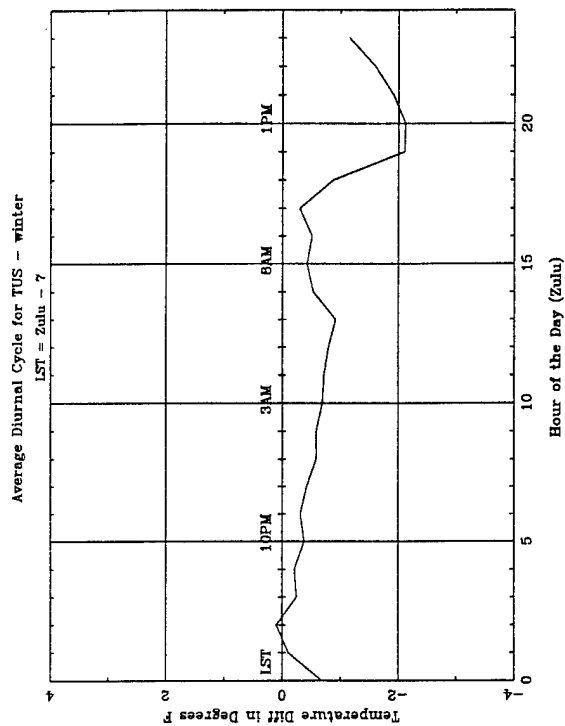
Average Diurnal Cycle for TLH - spring



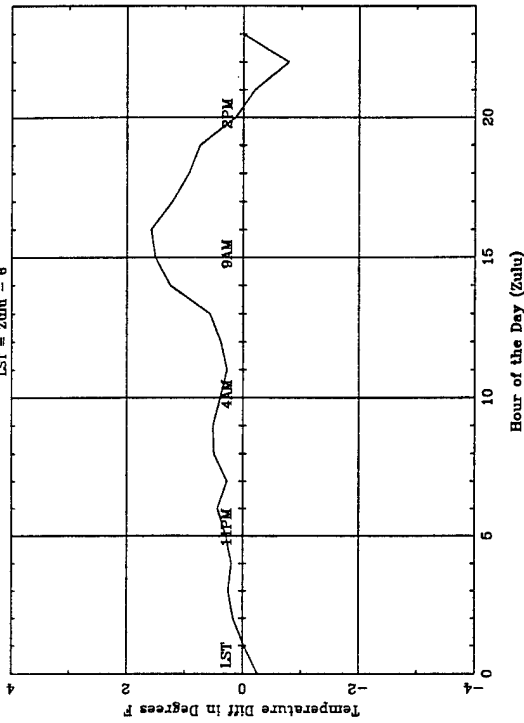
Average Diurnal Cycle for TLH - summer



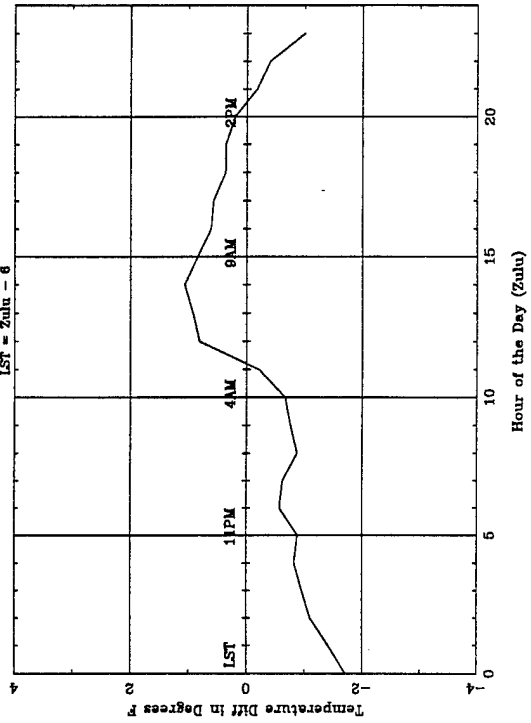




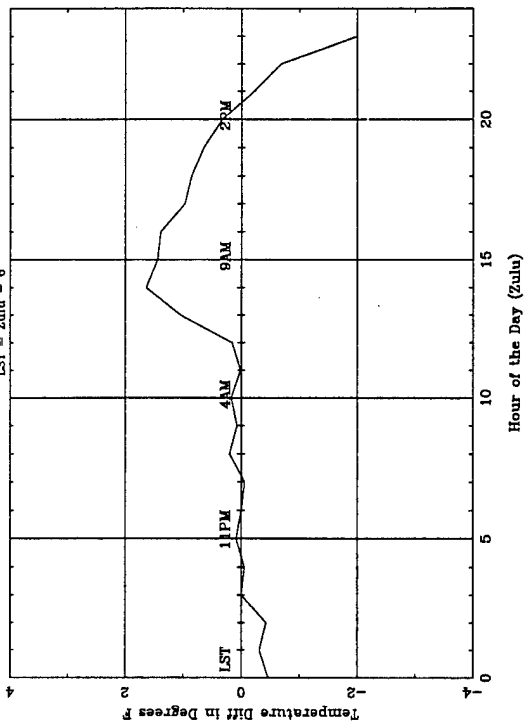
Average Diurnal Cycle for VTN - winter
LST = Zulu - 6



Average Diurnal Cycle for VTN - summer
LST = Zulu - 6



Average Diurnal Cycle for VTN - fall
LST = Zulu - 6



Average Diurnal Cycle for VTN - spring
LST = Zulu - 6

