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VAB Temperature and Humidity Study

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April 2014

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Tables

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Abbreviations and Symbols

%	percent
%RH	percent relative humidity
°C	degree Celsius
°F	degree Fahrenheit
°R	Rankine
2-D	two-dimensional
3-D	three-dimensional
HB	High Bay
K	Kelvin
km	kilometer
KSC	John F. Kennedy Space Center
m	meter
mg	milligram
mL	milliliter
MPCV	Multi-Purpose Crew Vehicle
RTD	resistance temperature detector
SLS	Space Launch System
T&H	temperature and humidity
VAB	Vehicle Assembly Building

Definition

thermograph: As it relates to this report, a thermograph is a color-coded graph showing temperature or humidity as a color-coded value plotted on a 2-D graph. The relationship between color and value plotted (temperature or humidity) is decoded by a color bar key to the right of the graph. The horizontal position is time and the vertical position is a distance. In the VAB, this distance corresponds to vertical height or level number. For wind towers, this distance is roughly a distance from the tower to the VAB.

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1 INTRODUCTION

Current Vehicle Assembly Building (VAB) upgrades and modifications are well underway in preparation for KSC's future spaceport operations and launch services. These construction alterations are designed to accommodate NASA's future Space Launch System (SLS), Multi-Purpose Crew Vehicle (MPCV), as well as the commercial business portion of KCS's future spaceport services. Part of these facilities upgrades involves 3-D volume characterization of the VAB environment, specifically temperature and humidity (T&H) throughout the year. This data is expected to assist in quantifying the VAB environment and in preparing the facilities for future spaceport and launch operations.

2 SUMMARY

In 2012, 17 data loggers were placed in the VAB to measure temperature and humidity at 10-minute intervals over a one-year period. In 2013, the data loggers were replaced with an upgraded model and slight adjustments to their locations were made to reduce direct solar heating effects. The data acquired by the data loggers was compared to temperature data provided by three wind towers located around the building. It was found that the VAB acts as a large thermal filter, delaying and reducing the thermal oscillations occurring outside of the building. This filtering is typically more pronounced at higher locations in the building, probably because these locations have less thermal connection with the outside. We surmise that the lower elevations respond more to outside temperature variations because of air flow through the doors. Temperatures inside the VAB rarely exceed outdoor temperatures, only doing so when measurements are made directly on a surface with connection to the outside (such as a door or wall) or when solar radiation falls directly on the sensor. A thermal model is presented to yield approximate filter response times for various locations in the building. Appendix A contains historical thermal and humidity data from 1994 to 2009.

3 INSTRUMENTATION LOCATION

To provide the data needed for temperature and humidity characterization, 17 temperature and humidity sensors were installed vertically along towers B and E in late December 2011. The goal was to collect data about every 20 meters (m) from the ground level to the ceiling, corresponding to approximately five levels per sensor. Figure 3-1 (left) shows the south Tower B elevator, as seen from the west end of Tower B, where each door corresponds to a level. The ceiling at Level 41½, just below the roof (approximately 158 m above the ground level), is shown in the upper right of the image. Figure 3-1 (right) shows a typical data logger installation as used at each of the 17 sites. The data loggers were fastened with Velcro (later replaced with strapping tape) to the railing or other convenient location, as shown in Figure 3-1 (right). The data loggers were programmed to acquire temperature and humidity readings every 10 minutes. Figure 3-2 shows the distribution of the 17 sensors that were located between the south side of Tower B and the north side High Bay 2 and between the north side of Tower E and the south side of High Bay 3. In addition, data loggers were placed on the ground (Level 1) and on the ceiling (Level 41½) in High Bay 4.

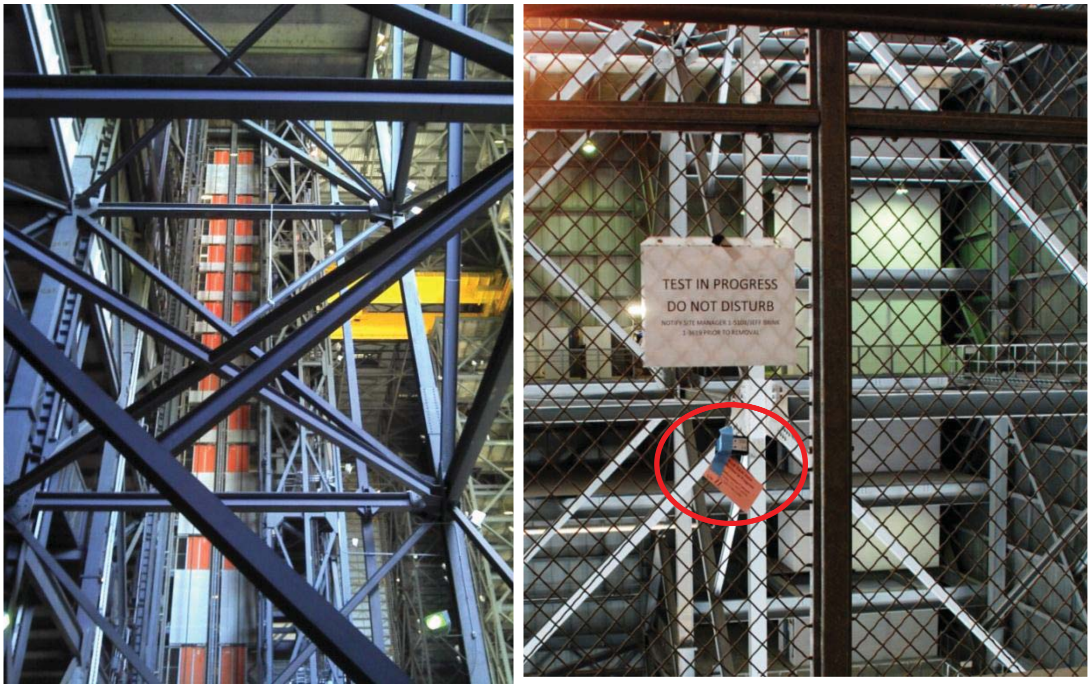


Figure 3-1. Tower B elevators as seen from Tower B west end (left). A temperature and humidity data logger and typical mounting location on a wire fence railing (right).

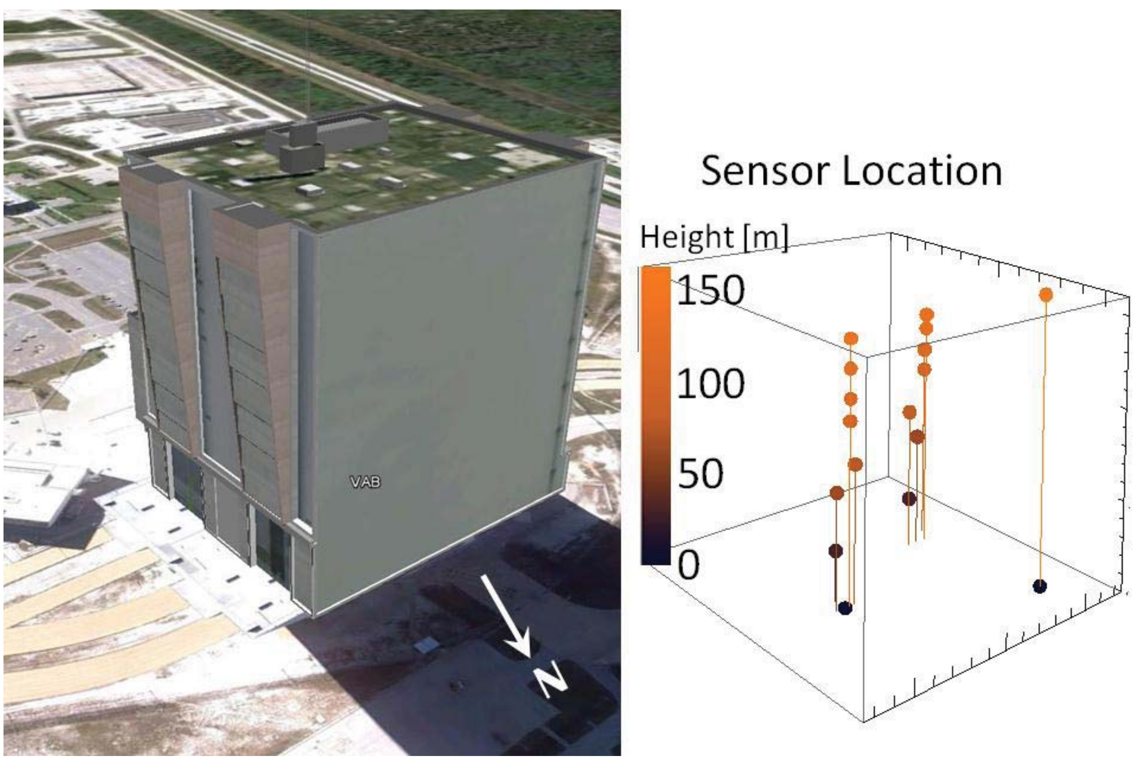


Figure 3-2. Location of T&H sensors in the VAB. Sensor location: (Left to right) The first column of sensors is along Tower E and High Bay 3 and the second column of sensors is along Tower B and High Bay 2. The two sensors stacked vertically (shown at the far right) are in High Bay 4.

3.1 Temperature and Humidity Data Logger: MadgeTech RHTemp101A

The MadgeTech RHTemp101A temperature and humidity data logger is a state-of-the-art, low-cost, compact sensor that is ideal for this task (see Figure 3-3). The RHTemp101A provides a 10-year battery life, a 1-second reading rate, and 1,000,000 readings per channel, making it ideal for short- or long-term deployments. Additional features include a multiple start/stop function, optional memory wrap, precision resistance temperature detector (RTD) sensing element, battery life indicator, optional password protection, programmable high/low humidity alarms, and more. With the free MadgeTech Data Logger Software for data analysis and reporting, data can be viewed in °C, °F, K, °R, %RH, mg/ml water vapor concentration, and dew point. The data can also be automatically exported to Excel for further calculations. This software can be downloaded directly from the manufacturer's website (www.madgetech.com) and installed on multiple computers.

The MadgeTech RHTemp101A temperature and humidity data logger uses a precision RTD element to measure temperatures between –40 °C and 80 °C. It has a temperature resolution of 0.01 °C and an accuracy of ± 0.5 °C. It uses an internal semiconductor to measure humidity over a range of 0 to 95 %RH. Its resolution is 0.1 %RH and its accuracy is ± 3.0 %RH.

Figure 3-3. Front view of the temperature and humidity data logger, 36 mm × 57 mm × 16 mm in size.

3.2 2012 Installation Locations

The 2012 installation of 17 data loggers is summarized in Table 2-1. Initially, sites 16 and 17 were located at the north and south turnstiles, respectively, but these two sensors failed in the first month due to water intrusion from rain. The replacement data loggers shown in this table were relocated to Level 1 of High Bay 4 (HB-4) and High Bay 3 (HB-3), respectively.

Table 2-1. 2012 Data logger locations and serial numbers

Site Number	Serial Number	VAB Location
1	N66116	Lev 41½ (ceiling)
2	N66112	Lev 36E
3	N66115	Lev 40B
4	N63090	Lev 32E
5	N63082	Lev 28E
6	N66117	Lev 25E
7	N63083	Lev 19E
8	N63086	Lev 16E
9	N63081	Lev 7E
10	N63088	Lev 32B
11	N66118	Lev 28B
12	N63089	Lev 25B
13	N66113	Lev 20B
14	N66114	Lev 16B
15	N63085	Lev 7B
16	N79493	Lev 1 HB-4
17	N66112	Lev 1 HB-3

3.3 2013 Installation Locations

In March 2013, all of the data loggers were replaced with the latest version from MadgeTech. This new version had substantially increased memory so that the practice of zeroing-out memory after data downloading was ended and all subsequent measurements were kept in data logger memory for the length of the test (March 2013–April 2014). Because of the increased memory, the sample rate was doubled, decreasing the sample period from 10 minutes to 5 minutes. The data logger at site 16 in High Bay 4 was moved from the telescope sway table (which was in full view of the High Bay 4 hanger door) to a nearby location in High Bay 4, but blocked from the view of the door to reduce direct solar heating. This is a significant detail in interpreting the high 2012 readings ($T > 100$ °F) as compared to the same time period in 2013.

Table 2-2. 2013 Data logger locations and serial numbers

Site Number	Serial Number	VAB Location
1	P03507	Lev 41½ (ceiling)
2	P03521	Lev 36E
3	P03510	Lev 40B
4	P03505	Lev 32E
5	P03516	Lev 28E
6	P03524	Lev 25E
7	P03520	Lev 19E
8	P03523	Lev 16E
9	P03508	Lev 7E
10	P03511	Lev 32B
11	P03515	Lev 28B
12	P03512	Lev 25B
13	P03522	Lev 20B
14	P03526	Lev 16B
15	P03509	Lev 7B
16	P03506	Lev 1 HB-4
17	P03513	Lev 1 HB-3
18	P03519	North Turnstile

4 WIND TOWERS

Knowing the temperature and humidity distribution within the VAB was useful, but to understand this information it was necessary to compare it to the temperature variations that occurred outside of the building. We first attempted to gather outside data by placing data loggers in the turnstiles, but, as mentioned previously, two of these failed because of water intrusion. Also, the one placed in the north turnstile in 2013 showed excessive temperature variations caused by solar heating of this small metallic building and by possible greenhouse heating caused by translucent paneling. Consequently, outside temperature data was obtained from three wind towers located around the VAB (see Figure 4-1 for their locations). The wind towers, also referred to as *meteorological towers* (http://kscwxarchive.ksc.nasa.gov/Reports/WeatherTower) supplied humidity data, but that data is not shown in this report.

The data obtained from the wind towers was updated every 5 minutes, though there were numerous dropouts. Even so, the data density was adequate to use in the comparisons shown in the following figures. Note from Figure 4-1 that the towers are located roughly 2 km to 3 km from the VAB and, on occasion, it is believed that differences in the wind tower data and the VAB data could have been caused by rain falling on one structure but not the other. An example of this is shown in Section 5.4. Also, Tower 311 occasionally shows less extreme temperature variations than the other two towers, possibly because the location is surrounded by water.

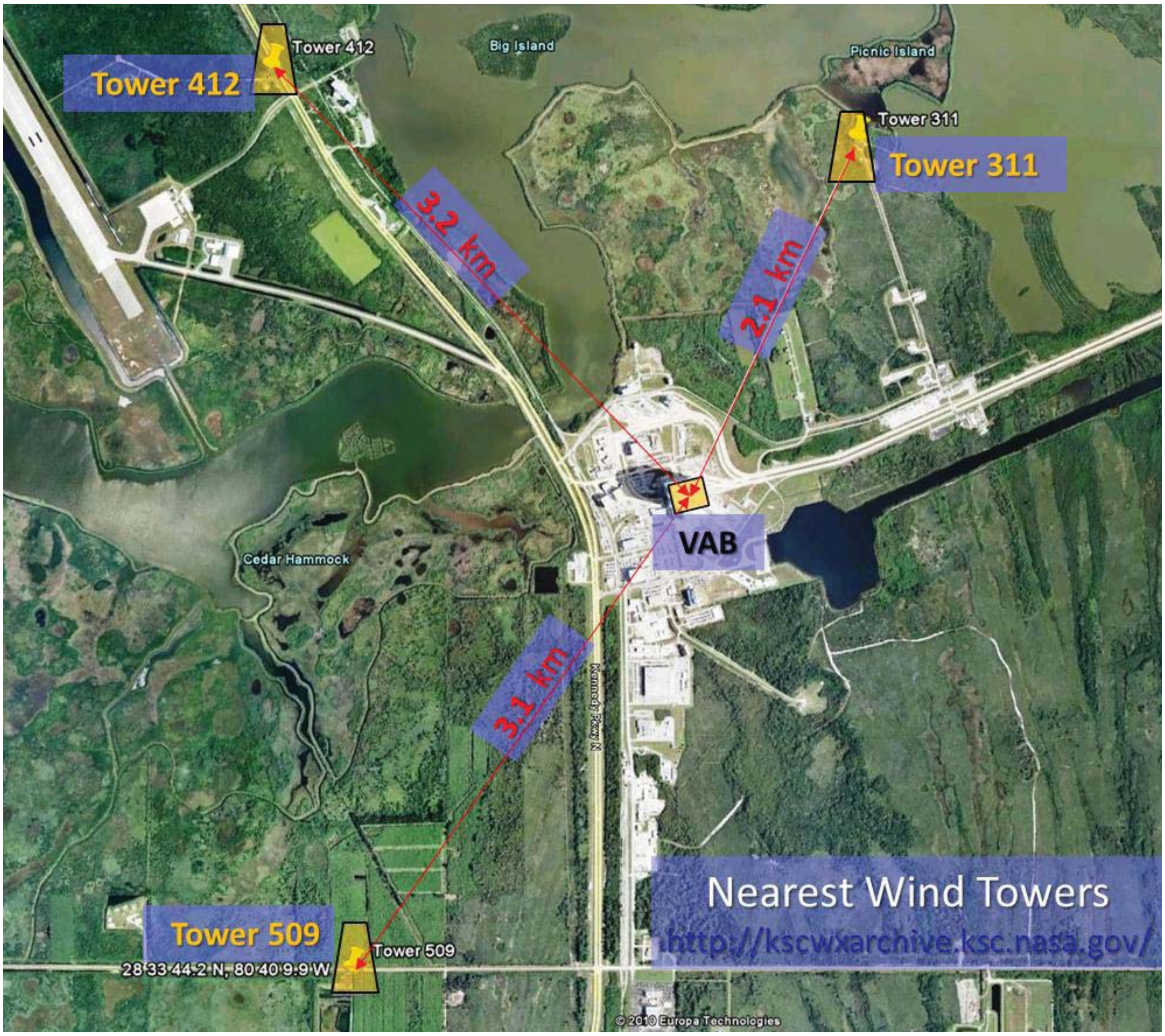


Figure 4-1. Location of the three wind towers used to gather outside temperature and humidity data around the VAB.

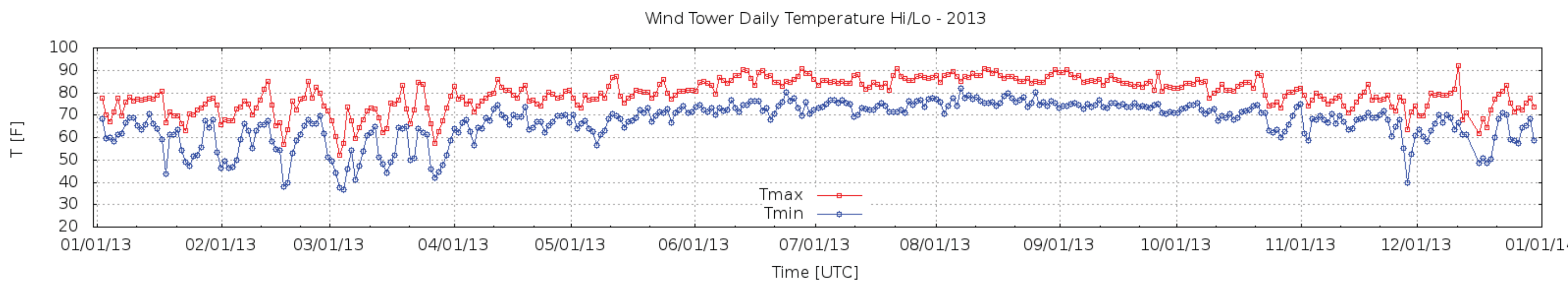


Figure 4-2. 2013 combined daily minimum and maximum wind tower temperatures for towers 311, 412, and 509.

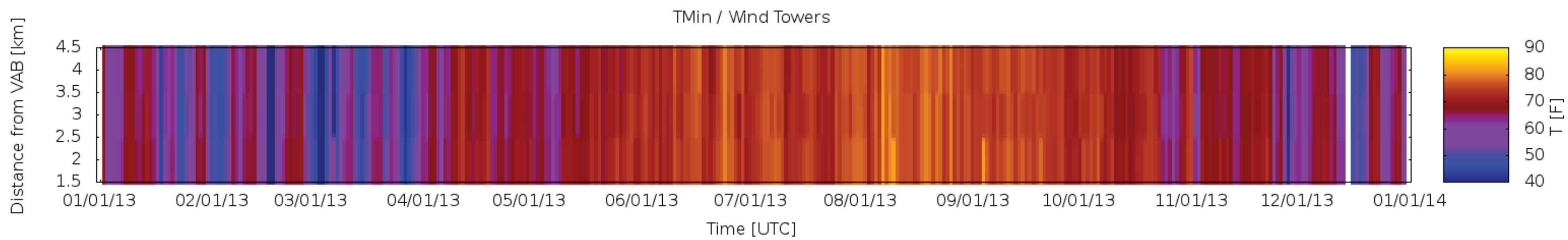


Figure 4-3. Thermograph of daily minimum temperatures for wind towers 311 (shown as 2 km), 412 (shown as 3 km), and 509 (shown as 4 km). Towers 412 and 509 are approximately 3 km each from the VAB.

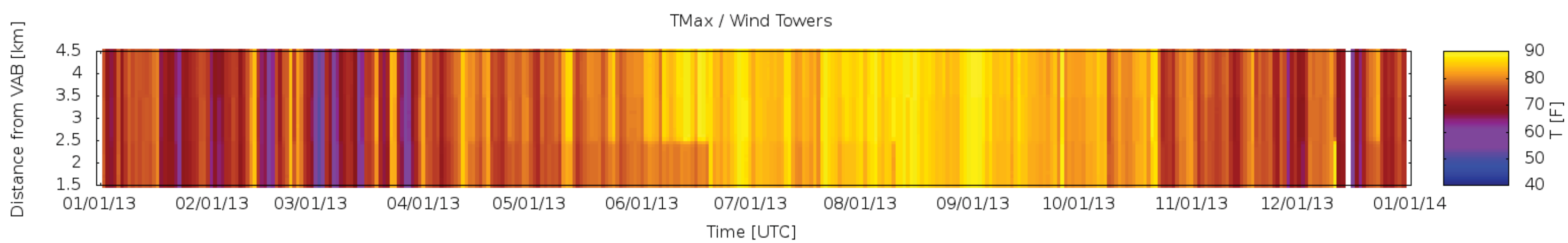


Figure 4-4. Thermograph of daily maximum temperatures for wind towers 311 (shown as 2 km), 412 (shown as 3 km), and 509 (shown as 4 km). Towers 412 and 509 are approximately 3 km each from the VAB.

5 DETAILED DATA ANALYSIS EXAMPLES

Devising a strategy for displaying and analyzing the huge volume of data collected over the past two years was a challenge. This section shows complete sets of temperature and humidity data for a few example short periods, covering a few days at a time. The goal of the section is to understand the detailed data at the highest order of resolution, before going to the remaining sections. The data in the remaining sections is reduced to something more manageable by taking the daily minimum and maximum values. Note that the data logger at Level 1, HB-3 vanished sometime during the spring or summer of 2013, presumably due to construction in the immediate vicinity. It was replaced in September 2013. Therefore, the Level 1, HB-3 data is missing in the plots corresponding to the summer months. The analysis performed in this report attempts to make some predictions concerning the VAB door state, but actual door state data was generally unavailable.

In reference to the graphs in this section, follow these steps to convert Microsoft Dublin Julian date to calendar date.

Step 1: Add the value 2415018.5 to the time from the graph's horizontal time axis.

Step 2: Go to the USNO Julian Date Converter, http://aa.usno.navy.mil/data/docs/JulianDate.php

Step 3: Paste result from Step 1 into Julian Date: under **Julian date to Calendar date** heading.

Step 4: Click **Compute Calendar date**.

5.1 Example 1, Early December 2013

Figure 5-1 shows the temperature and humidity variations measured by the data loggers at 17 locations in the VAB, one at the north turnstile, and the temperature-only data from the three wind towers from December 1 to 6, 2013. The three wind towers are in reasonable agreement in tracking the outside temperature variations over each daily cycle. The north turnstile data tracks with the wind towers during daytime, but indicates the turnstile area is warmer than the outside temperature at night. Most of the VAB's temperatures, as expected, fall between the extremes of the outside temperature variations. The brown trace in Figure 5-1 corresponds to the data logger placed at Level 7, Tower B, HB-2 and shows daily temperature spikes roughly 24 hours apart. The most plausible explanation for these spikes is direct solar heating. If the HB-2 door is open, the sun may shine directly onto the data logger for a few minutes each day.

The humidity data is approximately tracking the inverse of the temperature, which would be expected if the absolute humidity (i.e., the water content of the air) was constant. Note that the temperature spikes at Level 7, Tower B, HB-2, are now relative humidity dips reflecting this inverse dependence. However, a more careful review of the data showed that the filtering seen in the temperature data was reduced in the humidity data. For example, the humidity at Level 1, HB-4, varied more rapidly than the temperature at that location. This may indicate that the data loggers were measuring the temperature of the structure that they were attached to, which was slow to respond to outside temperature variations, while the humidity in the air was not affected by the structural temperature. An alternate explanation is that the air was heated or cooled by the building as it rose from the lowest levels, where the humidity was not affected as much by the building's structure.

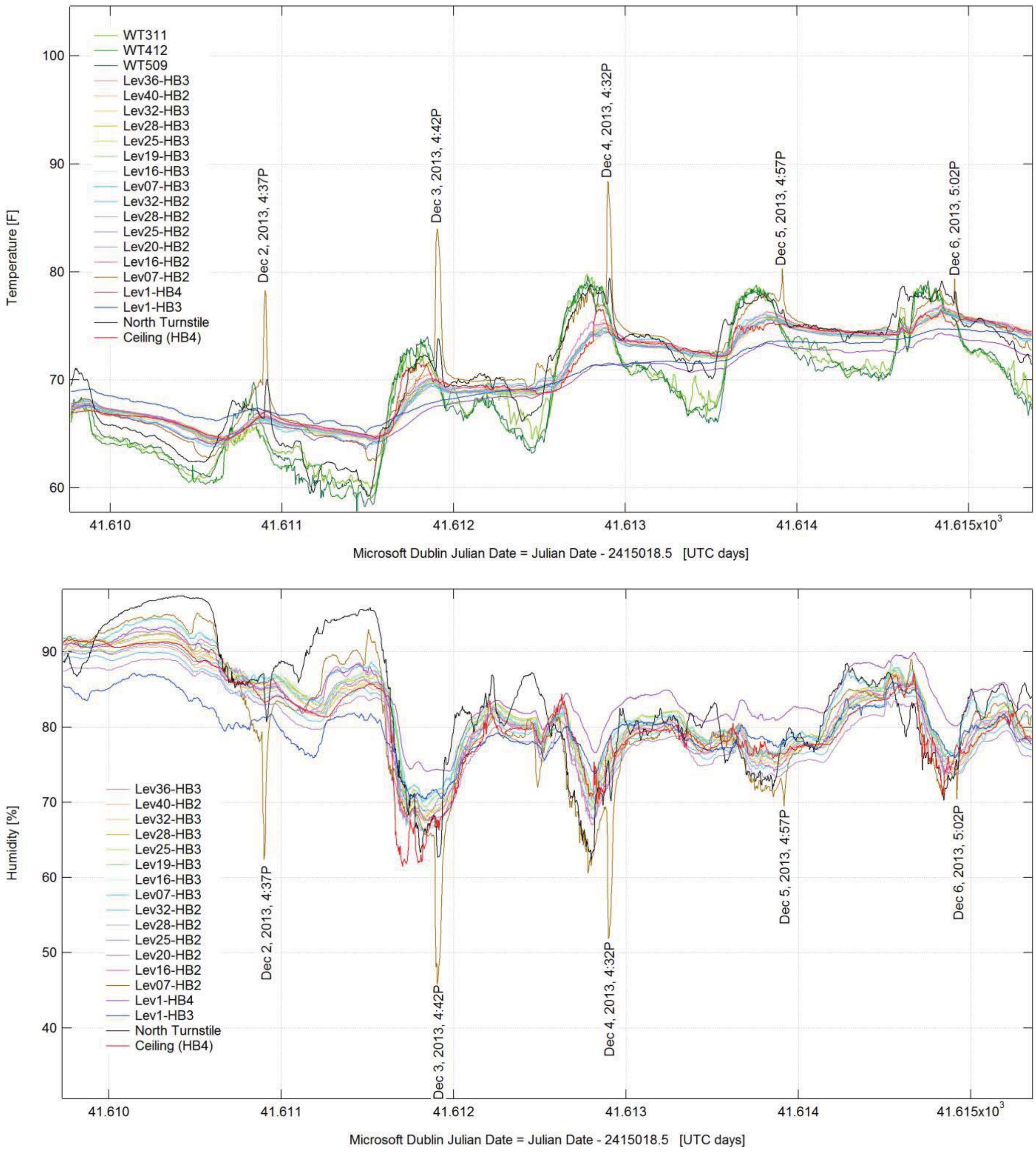


Figure 5-1. Detailed temperature and humidity data for December 1-6, 2013.

5.2 Example 2, November 27-28, 2013

Figure 5-2 shows the temperature drop associated with a cold front arriving during the night of November 27, 2013. As the cold front came in, the three wind towers and the north turnstile all tracked closely, except that the north turnstile had a late afternoon heating spike. We suspect this was caused by the late afternoon sun entering the turnstile through its translucent wall and causing greenhouse heating. The green spike was caused by a wind tower data anomaly and should be ignored.

This figure shows that all of the locations within the VAB dropped in temperature because of the cold front, exhibiting a variety of time-delayed responses. The peak temperature delay between the wind towers and Level 1, HB-4 and HB-3, is about 0.7 hours. The peak delay between the ceiling and wind towers is about 2.2 hours. The temperature at HB-3, Level 1, tracks the temperature at HB-4, Level 1, but is about 5 degrees warmer. This suggested that the HB-3 doors were closed and the HB-4 doors could have been open. The plots also indicate that the HB-2 doors were letting in air; however, the general trend here is that the time delays in responding to outside temperatures changes increase with increasing height in the building.

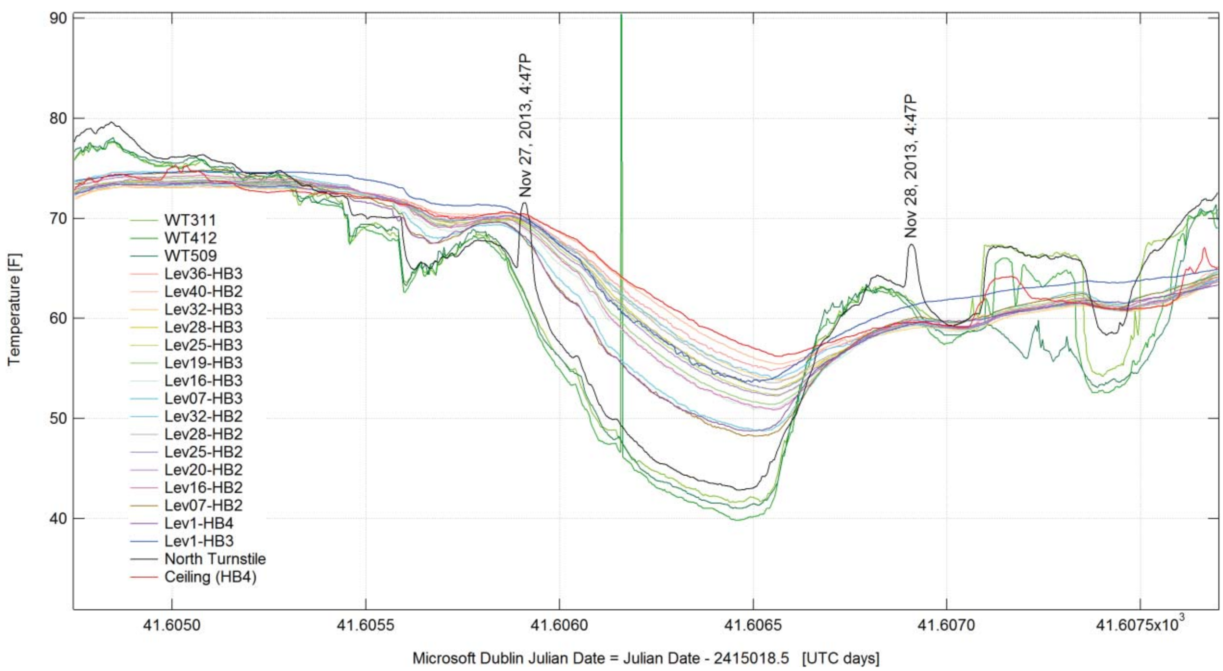


Figure 5-2. Detailed temperature data for November 27-28, 2013.

5.3 Example 3, January 5-8, 2014

Figure 5-3 shows the wind tower and VAB temperatures from January 5 to 8, 2014. The outside temperature on January 6 was warming due to solar heating and the building temperatures followed this rise. At about 1:15 p.m., a sudden cold front came through that resulted in a 40 degree drop outside by the next morning. When the cold front first arrived, temperatures in the VAB continued to rise for a short time and then began to drop; the Level 7, HB-2, location reached its peak 17 minutes after the cold front arrived, and the VAB ceiling reached its peak about 28 minutes after this 1:15 p.m. event.

This data set is interesting because of the response curves of the various locations in the VAB. Each location in the VAB had a different response time, with the low levels of the building responding quickly and the highest levels of the building responding more slowly. It appears that in the morning of January 7, the HB-2 doors were opened, causing the data logger at Level 7, HB-2, to suddenly become colder and then to track the outside temperature more closely for the rest of the day. This location showed a small temperature spike at about 5:30 p.m., likely due to solar heating from the setting sun coming through the HB- 2 doors and warming the data logger.

The humidity dropped along with the temperature (contrary to the inverse relationship in Example 1) because the absolute water content of the air was lower behind the cold front. Also, all locations within the VAB dropped at the same rate, indicating that the air was being circulated throughout the entire building within a few hours after the cold front arrived.

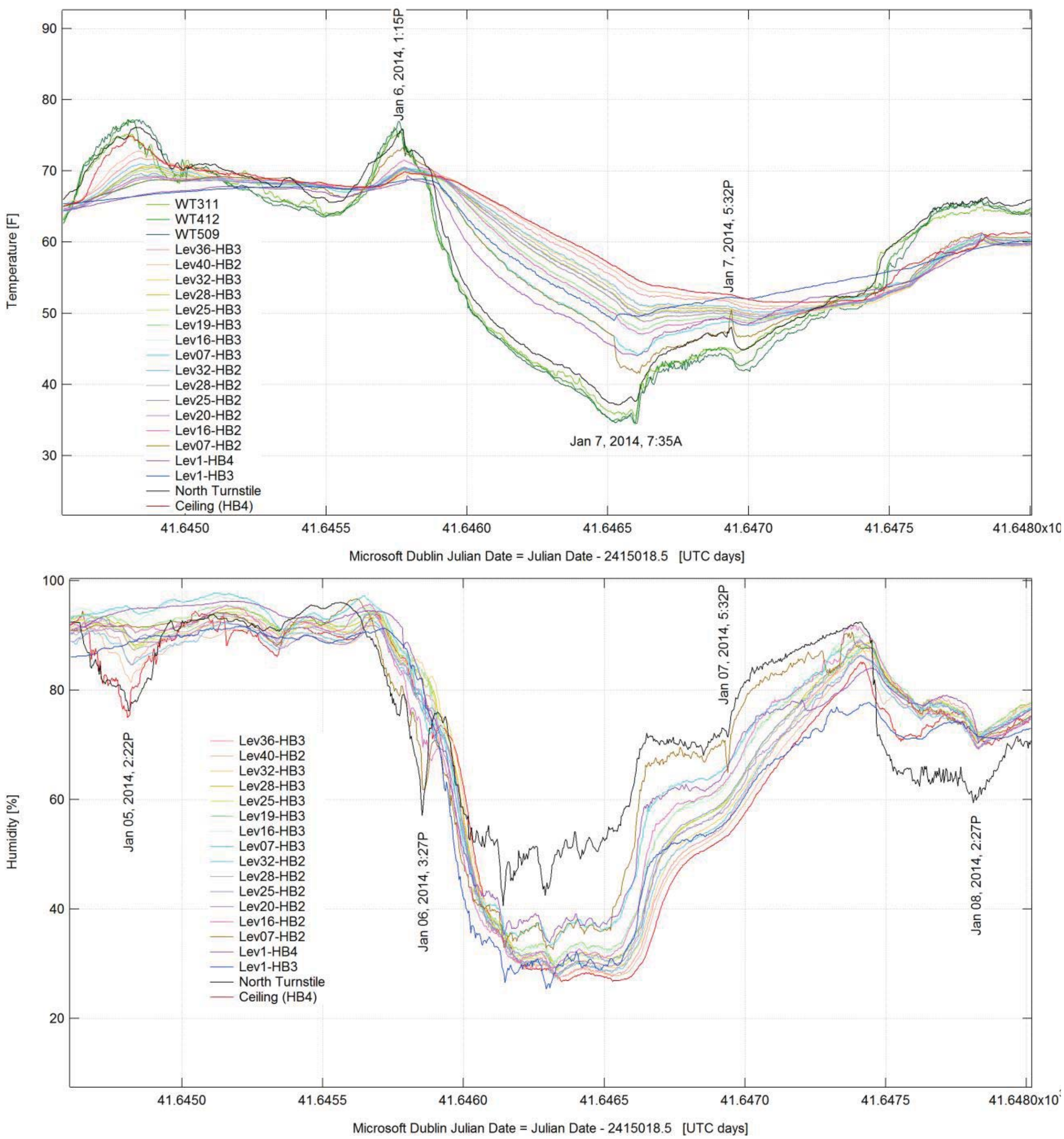
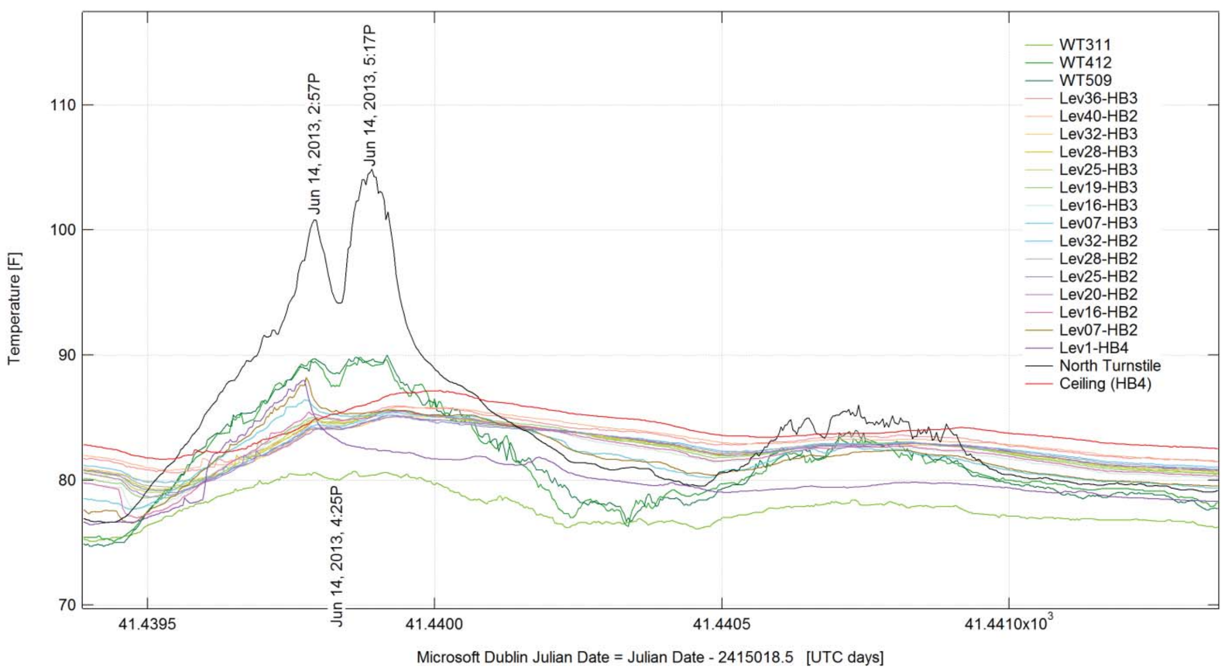


Figure 5-3. Detailed temperature and humidity data for January 5-8, 2014.

5.5 Example 4, June 14-15, 2013

Figure 5-4 shows the temperature variations from the wind towers and the VAB locations for June 14 and 15, 2013. In this case, the north turnstile began to reach excessively high temperatures that then suddenly fell. After this, the temperature climbed again and then fell again. This suggests one or two short afternoon rainstorms, common in Florida, coupled with localized cloud cover. Note that Wind Tower 311, located east of the VAB, was substantially cooler than the other two wind tower locations, which might be due to differential cloud cover or to the presence of water near this wind tower.

Most areas in the VAB follow typical filtered temperature profiles, averaging and delaying the outside temperature. However, the data suggests that the High Bay 4, and possibly the High Bay 2, doors were open before the first rain event, causing the corresponding temperatures to track the wind towers. Then, when the rain started, the doors appear to have been closed, causing a sudden cooling, especially at Level 1, HB-4. This conjecture is further substantiated by the humidity data. The humidity values throughout the VAB responded rapidly until the rain started and then for the next day and a half, the humidity readings vary more smoothly, indicating less exchange with the outside air.



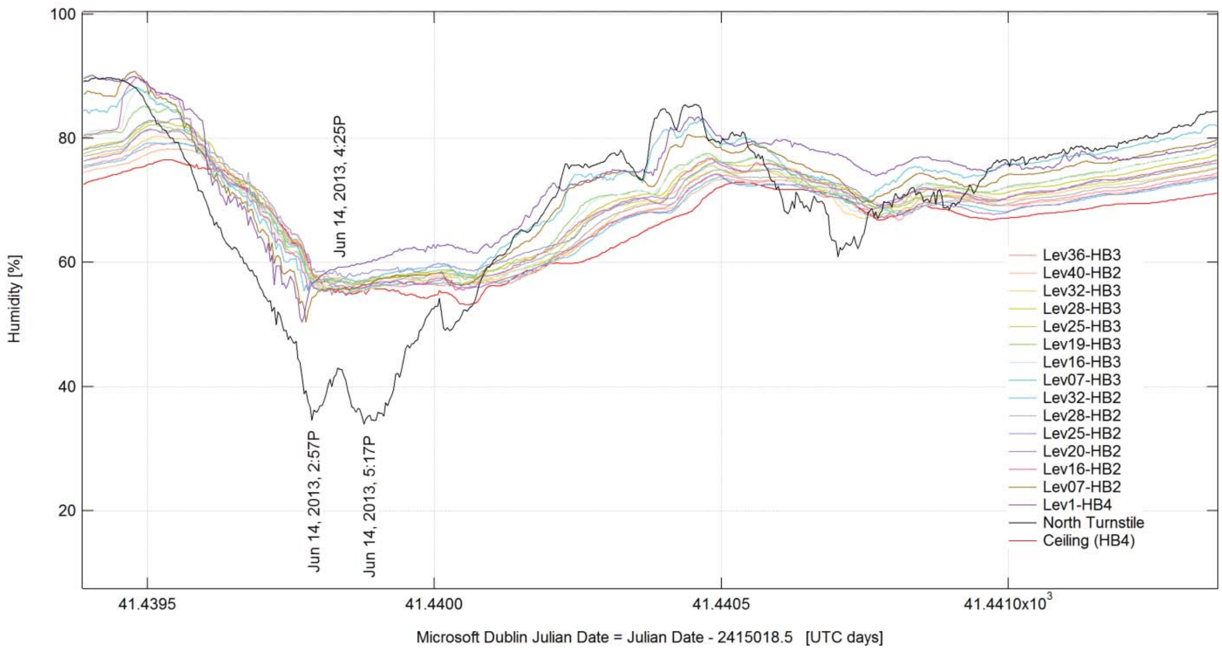


Figure 5-4. Detailed temperature and humidity data for June 14-15, 2014.

5.6 Example 5, August 30-31, 2013

Figure 5-5 shows temperature and humidity data for August 30 and 31, 2013. On August 30, the north turnstile showed high temperatures, while most of the temperatures inside of the VAB are following typical averaged, delayed, profiles. At around 11:47 a.m., the north turnstile reached its peak temperature and fell rapidly, which likely indicated rainfall. It is interesting to note that the VAB ceiling temperature, which normally has a delayed response relative to outside temperature changes, responded quickly in this case, suggesting that the ceiling had been chilled by the rain. On the second day, the ceiling showed signs of responding more quickly than the rest of the VAB to outside temperature changes, possibly indicating that the ceiling vents were open. The humidity data also reflects this rapid response of the ceiling environment, which is contrary to the prior data shown.

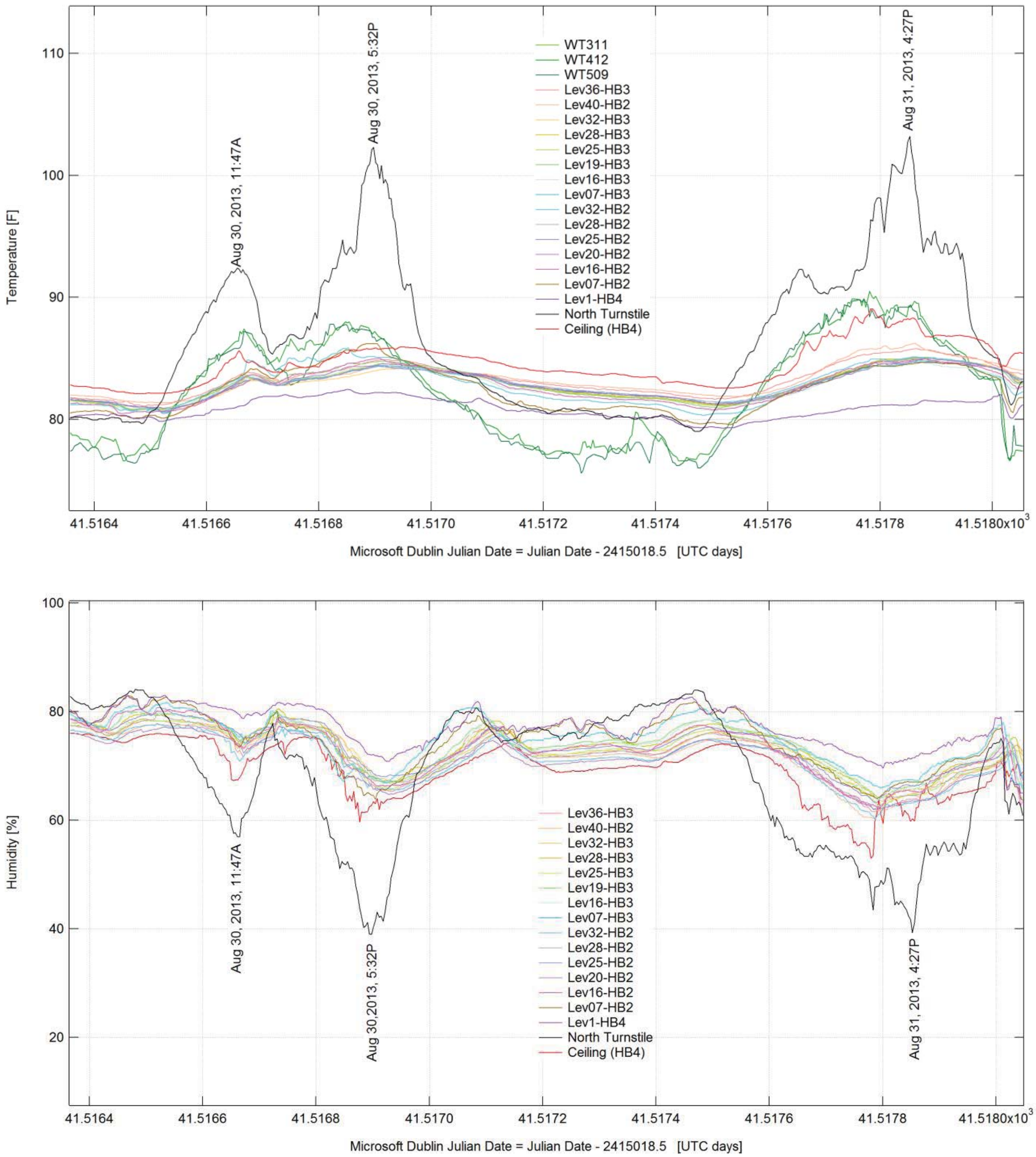


Figure 5-5. Detailed temperature and humidity data for August 30-31, 2013.

6 2012 DATA

This section summarizes the temperature and humidity data taken during 2012.

6.1 Temperature

Thermographs in the following pages show the maximum and minimum temperatures recorded throughout the year versus height in VAB towers B and E. Following this is a plot of the maximum and minimum temperatures seen in VAB towers B and E over the year. The extremely high temperatures measured in Tower B in the summer and fall are due to the site at Level 1 of High Bay 4, where the data logger was apparently exposed to sunlight repeatedly for many days. Detailed analysis of that event shows that the time of day the data logger was exposed to sunlight was almost always around 5:00 p.m. local time.

Table 6-1. Summary of temperature statistics, including all instrumented levels per tower.

	Winter	**Spring**	**Summer**	**Fall**
	Jan-Feb-Mar	**Apr-May-Jun**	**Jul-Aug-Sep**	**Oct-Nov-Dec**
VAB Tower B				
Hi:	81.8	86.8	108.5	107.7
Lo:	39.5	59.3	74.1	45.4
Hi-Lo:	42.3	27.4	34.4	62.3
Avg:	68.6	76.2	81.0	70.0
VAB Tower E				
Hi:	81.6	87.6	89.6	84.5
Lo:	39.7	59.6	74.8	47.8
Hi-Lo:	41.9	28.0	14.8	36.7
Avg:	68.6	76.3	81.2	70.1

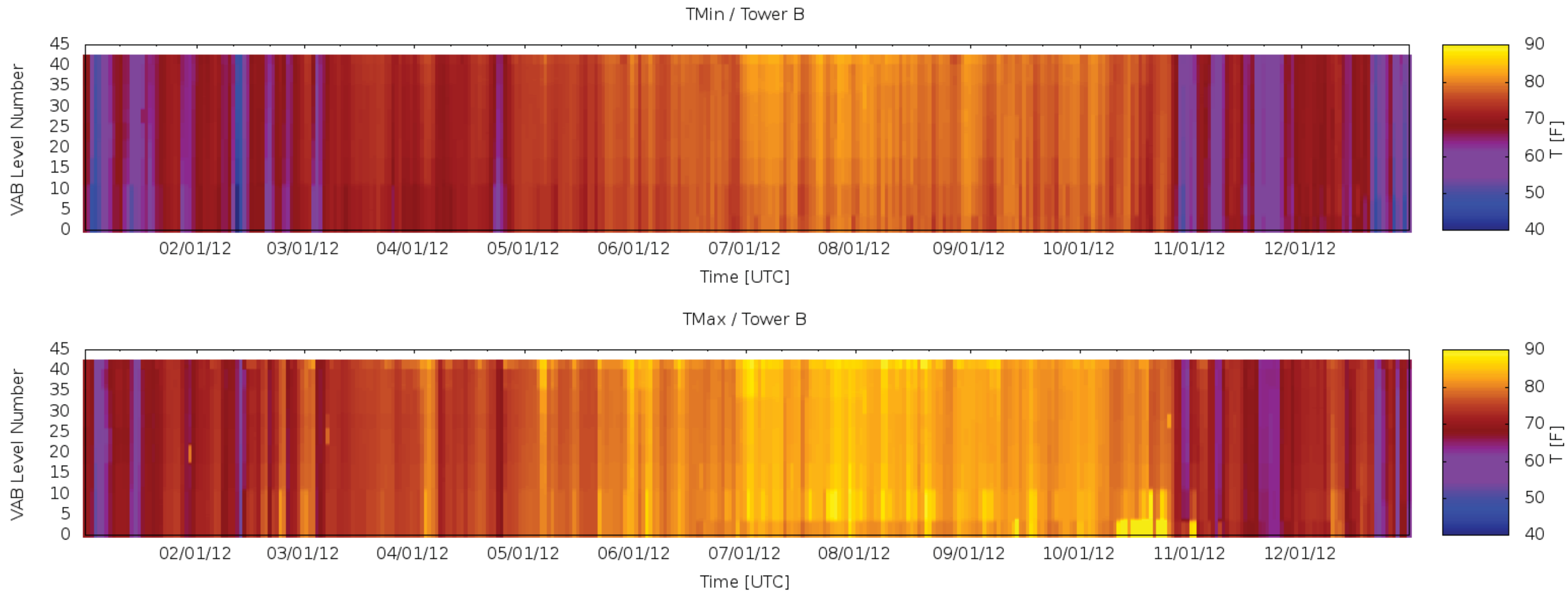


Figure 6-1. Minimum and maximum temperature thermographs throughout the year for Tower B.

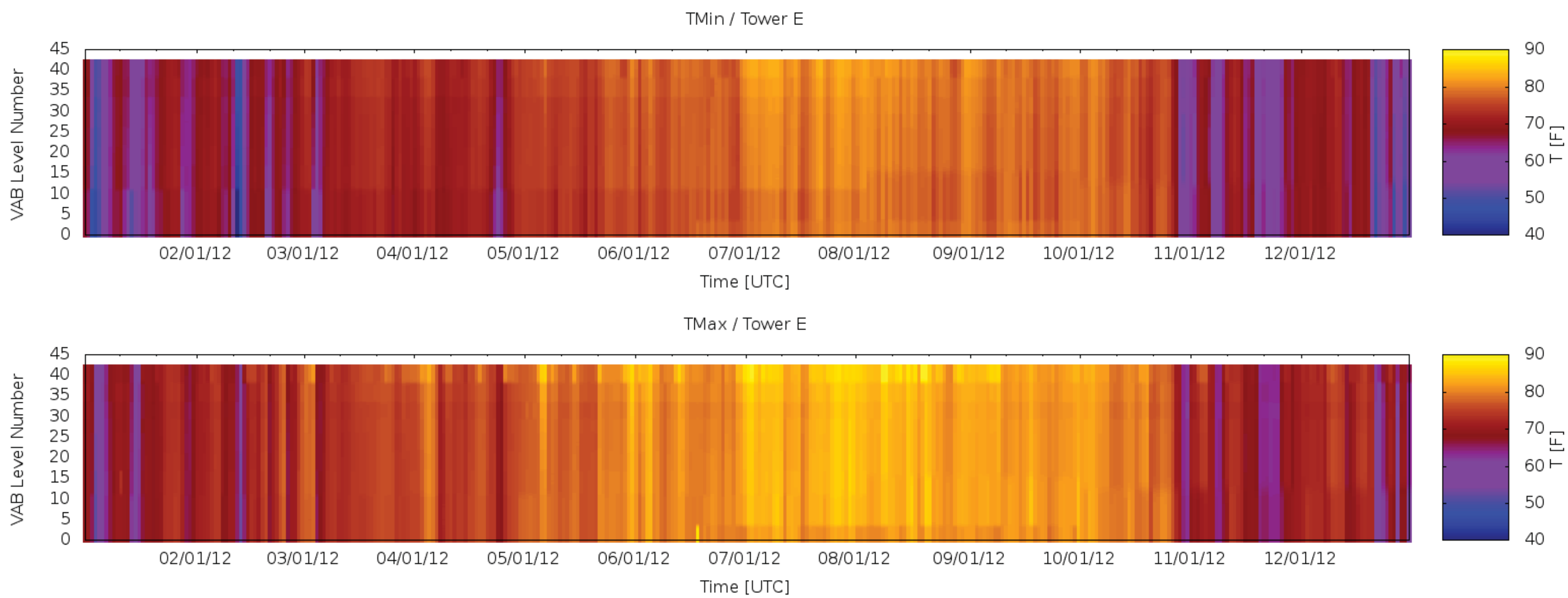


Figure 6-2. Minimum and maximum temperature thermographs throughout the year for Tower E.

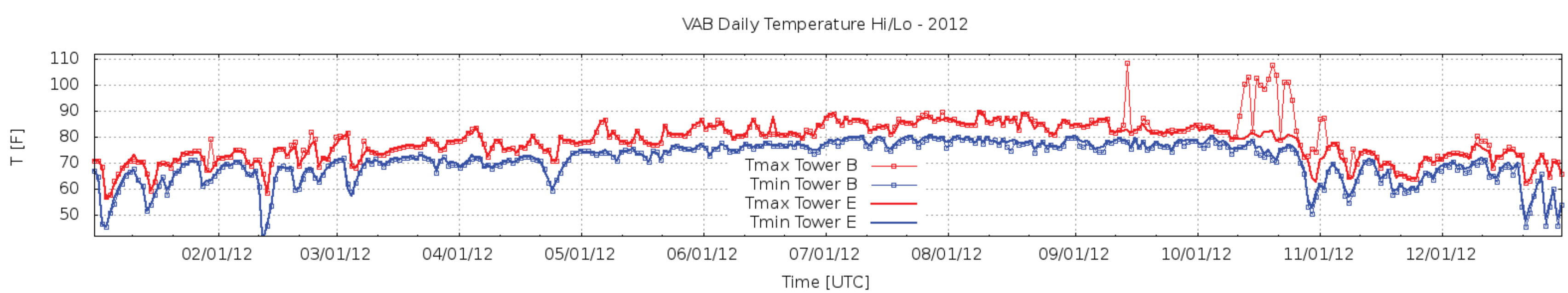


Figure 6-3. Daily minimum and maximum temperature readings for towers B and E for all levels per tower.

6.2 Humidity

Thermographs in the following pages show the maximum and minimum humidity values throughout the year seen versus height in VAB towers B and E. Following this is a plot of the maximum and minimum humidity values in VAB towers B and E over the year. Humidity values cover nearly the full range, but the average is around 70%, with a drop of a several percentage points in the winter months and a peak of several percentage points above average in the summer months.

Table 6-2. Summary of humidity statistics, including all instrumented levels per tower.

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB Tower B			
Hi:	96.1	94.4	95.9	98.9
Lo:	18.1	23.6	28.6	18.6
Hi-Lo:	78.0	70.8	67.3	80.3
Avg:	67.1	71.3	76.4	71.8
	VAB Tower E			
Hi:	94.2	95.8	95.9	98.9
Lo:	18.2	23.6	51.9	26.0
Hi-Lo:	76.0	72.2	44.0	72.9
Avg:	67.3	71.7	76.5	72.1

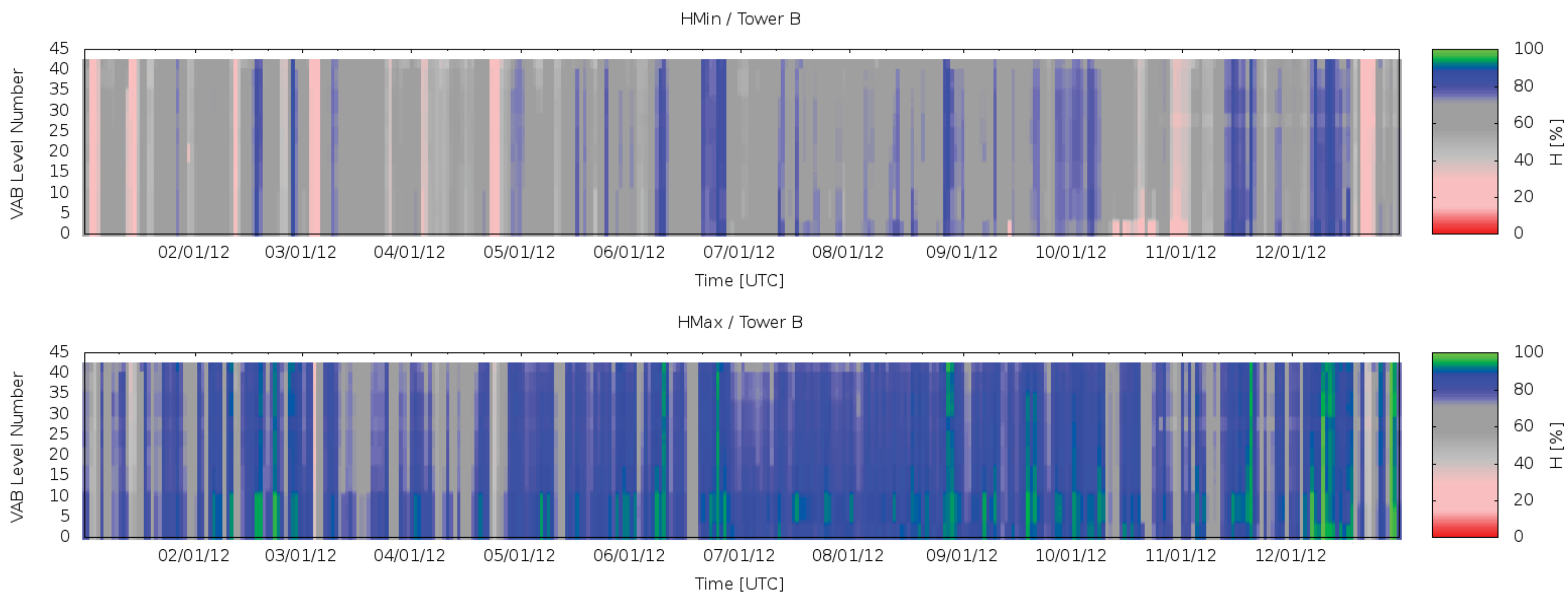


Figure 6-4. Daily minimum and maximum humidity thermographs for Tower B versus height.

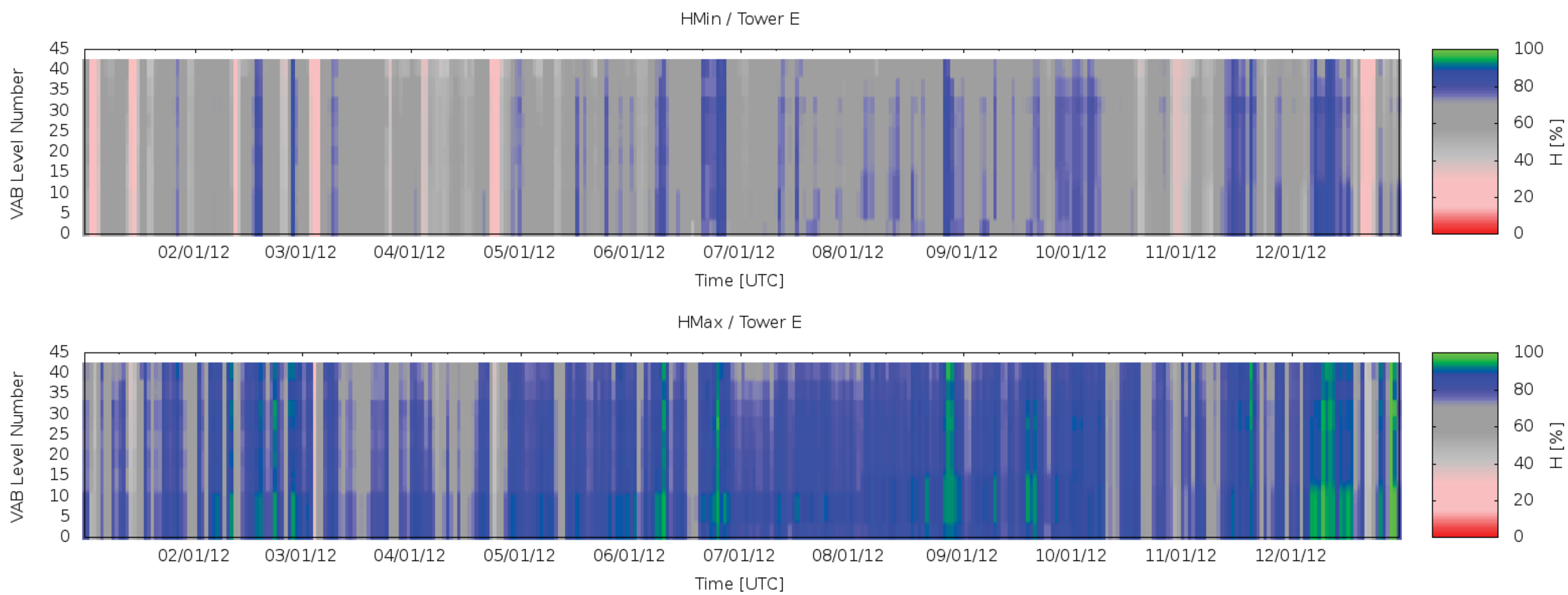


Figure 6-5. Daily minimum and maximum humidity thermographs for Tower E versus height.

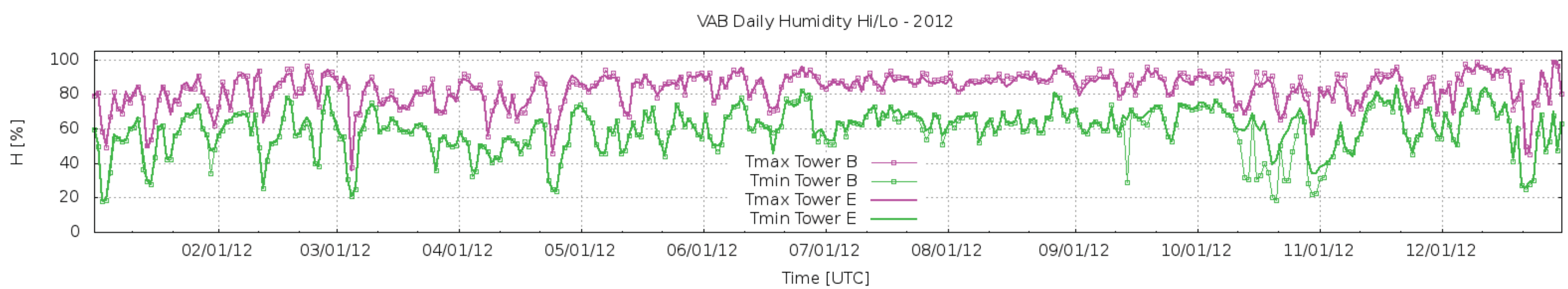


Figure 6-6. Daily minimum and maximum humidity readings for towers B and E for all levels per tower.

7 2013 DATA

This section summarizes the temperature and humidity data recorded during 2013.

7.1 Temperature

Thermographs are provided showing the maximum and minimum temperature throughout the year versus height in VAB towers B and E. Following this is a plot of the maximum and minimum temperatures seen in VAB towers B and E over the year. The temperature extremes in High Bay 3 adjacent to Tower E are more representative of the actual VAB interior temperatures. Direct sunlight was apparently not a condition in this area during the data collection period. High Bay 4, Level 1, sensor was hidden from the door during this data collection period. However, Level 7 between Tower B and High Bay 2 experienced direct sunlight conditions during a few days when the sun was at the correct elevation and azimuth angles, leading to higher than normal temperatures. Note the gap in March 2013 data where the old data loggers were replaced by latter model loggers with expanded memory.

Table 7-1. Summary of temperature statistics, including all instrumented levels per tower.

	Winter **Jan-Feb-Mar**	**Spring** **Apr-May-Jun**	**Summer** **Jul-Aug-Sep**	**Fall** **Oct-Nov-Dec**
		VAB Tower B		
Hi:	90.3	89.7	89.9	88.5
Lo:	44.2	61.7	73.8	48.2
Hi-Lo:	46.0	28.1	16.0	40.3
Avg:	67.3	76.5	81.2	73.5
		VAB Tower E		
Hi:	78.7	87.2	89.5	85.6
Lo:	46.8	64.6	74.3	48.8
Hi-Lo:	31.9	22.6	15.3	36.8
Avg:	67.1	76.7	81.3	73.6

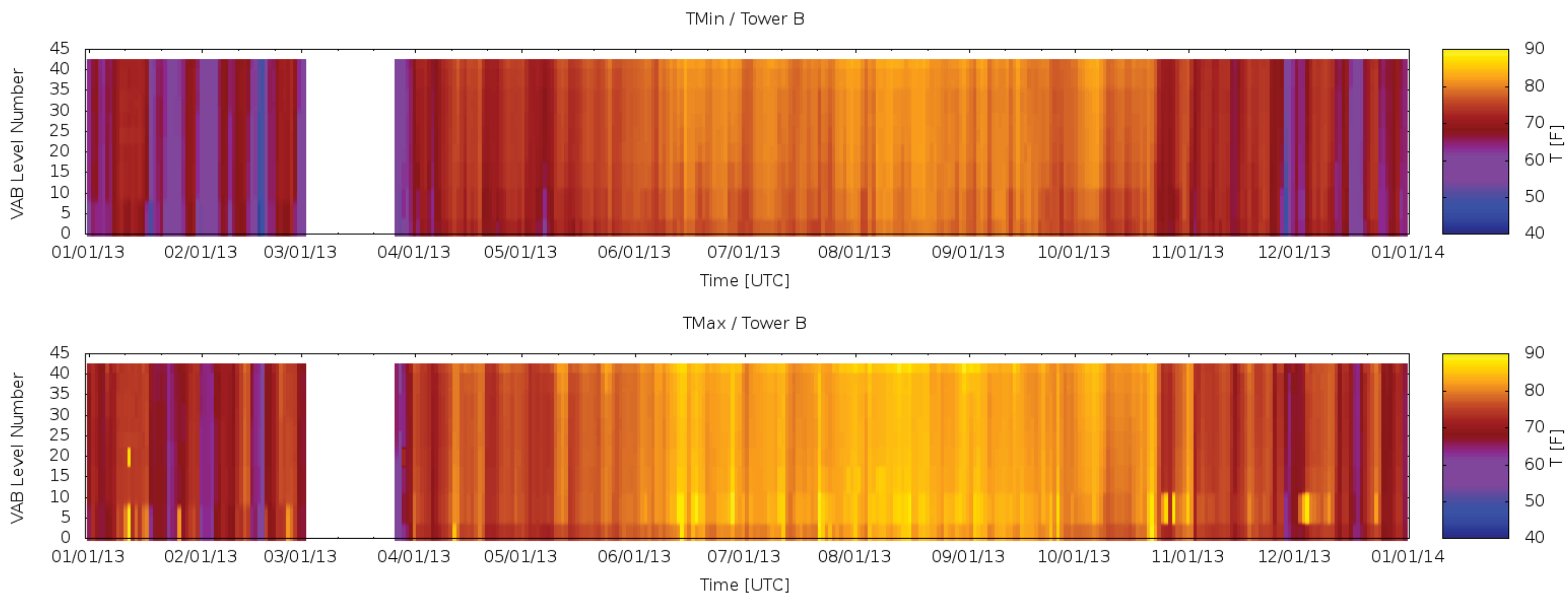


Figure 7-1. Daily minimum and maximum temperatures thermographs for Tower B versus height.

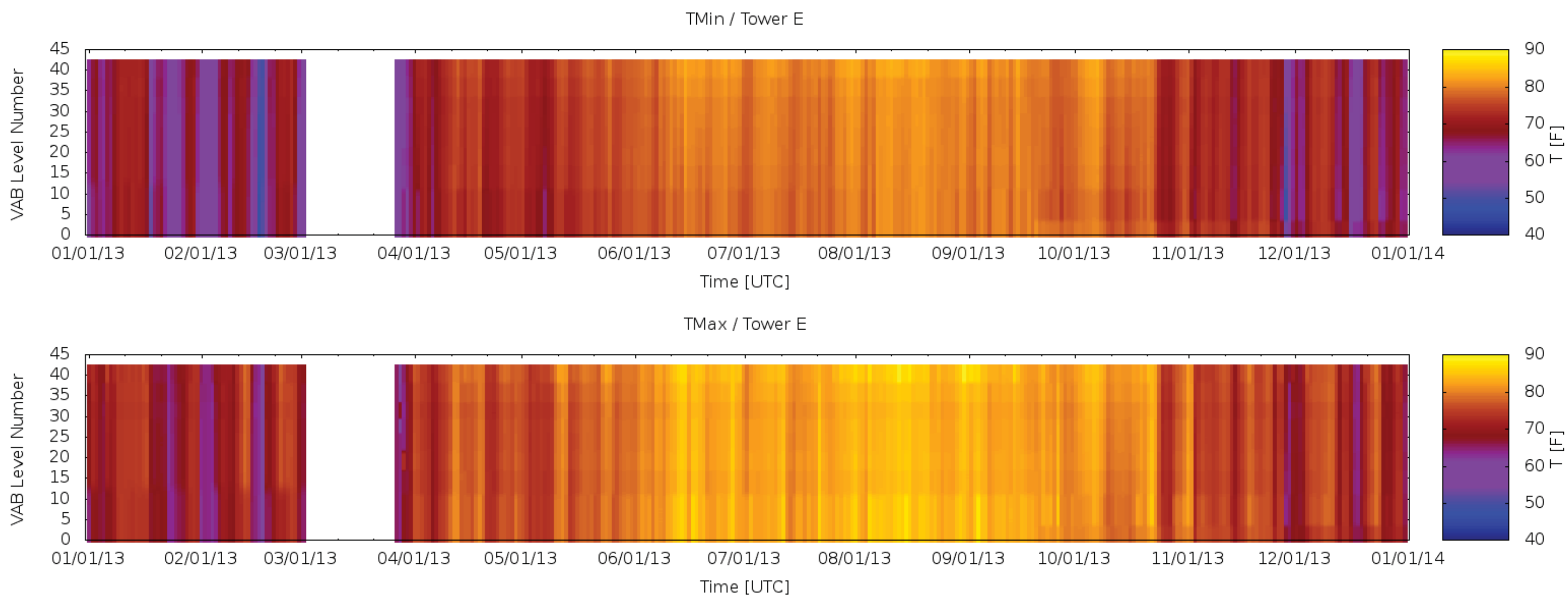


Figure 7-2. Daily minimum and maximum temperature thermographs for Tower E versus height.

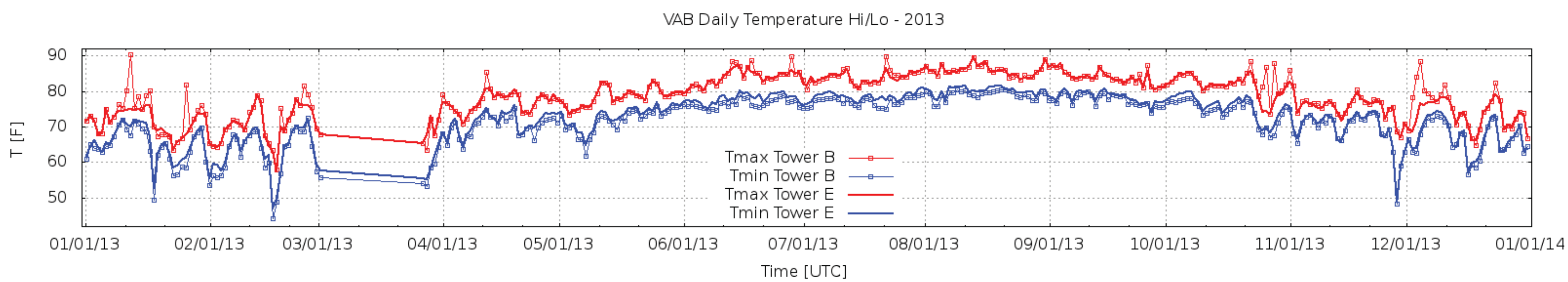


Figure 7-3. Daily minimum and maximum temperature readings for towers B and E for all levels per tower.

7.2 Humidity

The following thermographs show the maximum and minimum humidity throughout the year seen versus height in VAB towers B and E. Following this is a plot of the maximum and minimum humidity seen in VAB towers B and E over the year. Humidity values cover nearly the full range, but the average is around 70%, with a few percent drop in winter months and a few percent rise in the summer months.

Table 7-2. Summary of humidity statistics, including all instrumented levels per tower.

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB Tower B				
Hi:	98.2	93.2	95.9	97.9
Lo:	21.8	36.3	49.8	37.9
Hi-Lo:	76.4	56.9	46.1	60.0
Avg:	71.1	74.1	77.5	74.0
VAB Tower E				
Hi:	97.2	92.2	94.6	97.9
Lo:	22.6	36.4	49.8	39.8
Hi-Lo:	74.6	55.8	44.8	58.1
Avg:	70.8	74.3	77.8	74.0

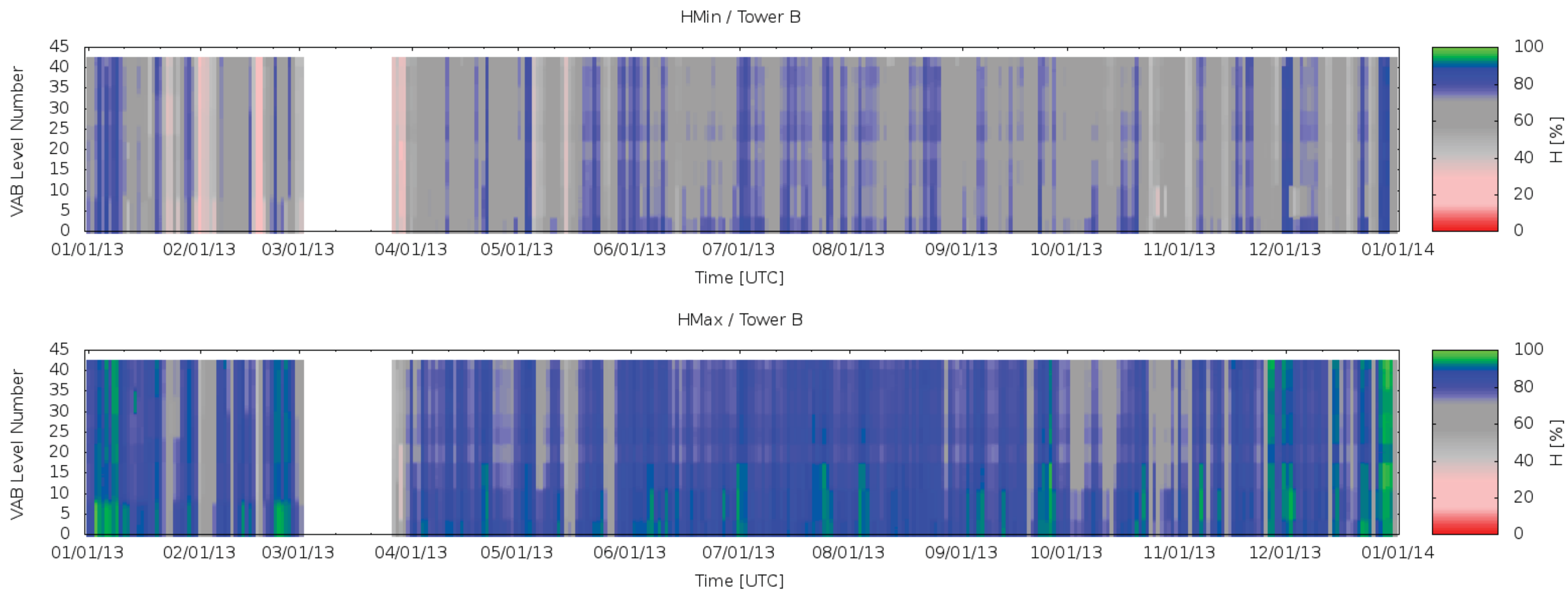


Figure 7-4. Daily minimum and maximum temperature thermographs for Tower B versus height.

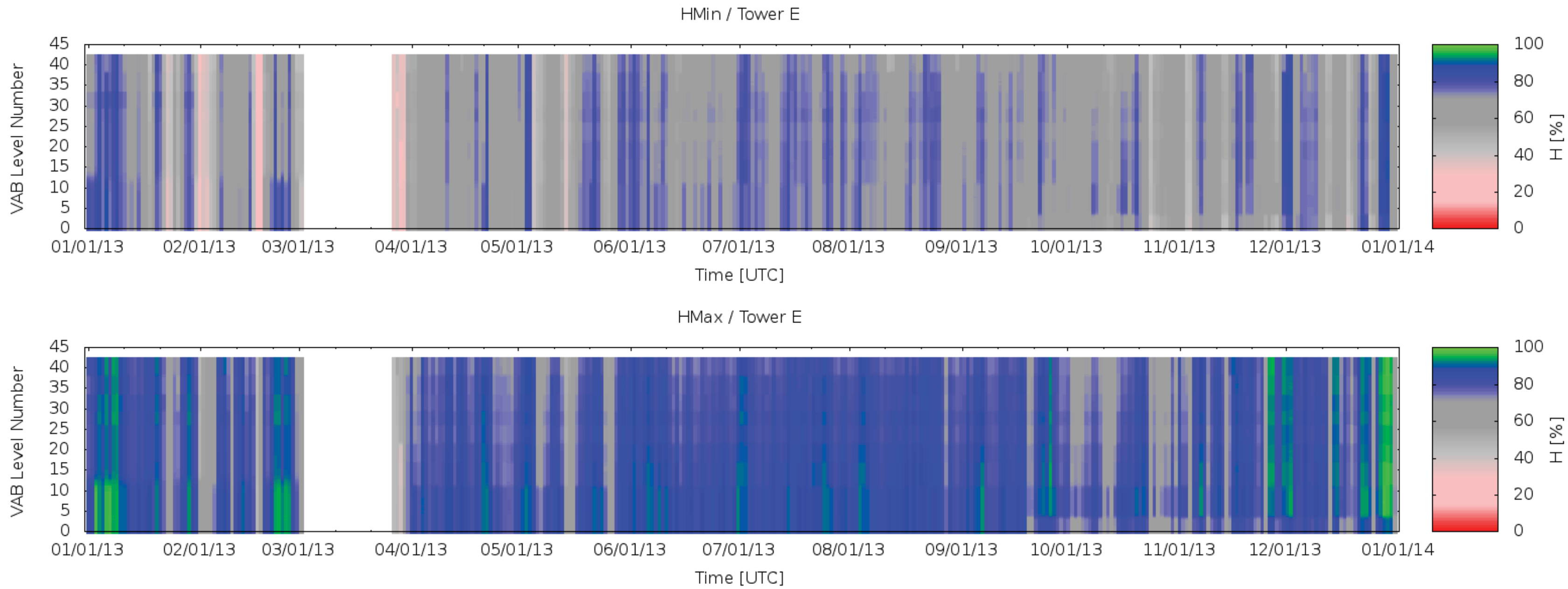


Figure 7-5. Daily minimum and maximum temperature thermographs for Tower E versus height.

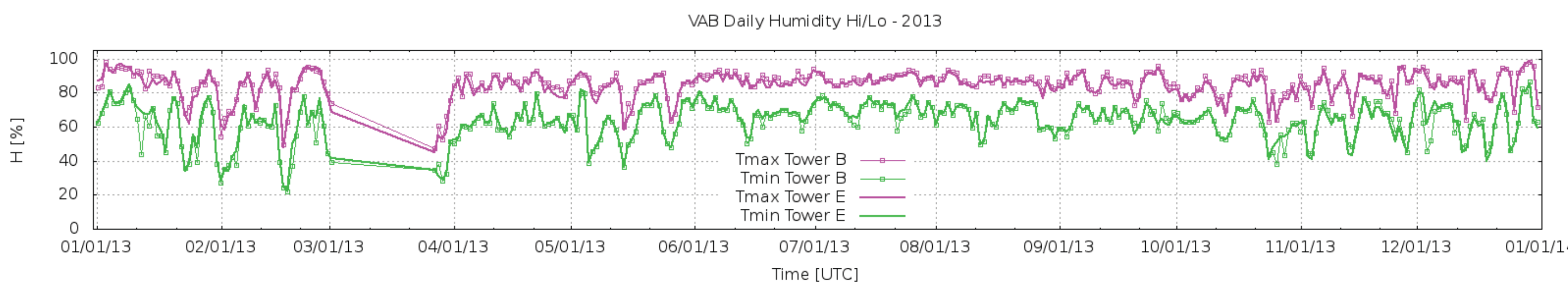


Figure 7-6. Daily minimum and maximum humidity readings for towers B and E for all levels per tower.

8 MODELING VAB TEMPERATURE VARIATIONS

8.1 Setting up the Model

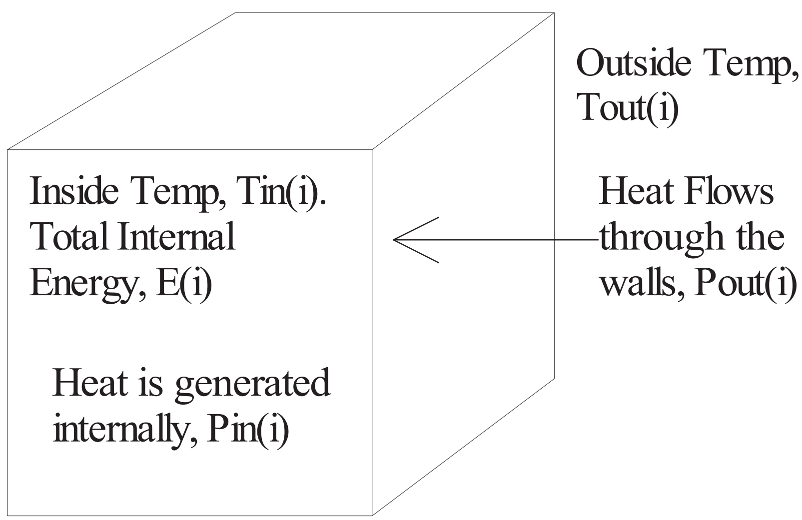
This section develops a simple two-parameter thermal model for a building such as the VAB. The parameters are: the time constant of the building and an internal temperature offset, the definitions of which will become clear in the development.

It is assumed that the temperature outside of the building, $T_{out}(i)$, is being monitored at equally spaced time intervals (for example, every hour) and is known. The index, i, is a counter in time pointing to each temperature reading. The goal is to predict the temperature inside of the building, $T_{in}(i)$.

To develop the model, three standard thermal equations are needed. The first equation states that the difference in temperature between the inside and the outside of the building causes energy to flow into or out of the building. This is a net power flow and the equation, sometimes called Fourier's Law, is written as

$$P_{walls}(i) = k(T_{out}(i) - T_{in}(i)) \tag{1}$$

where $P_{walls}(i)$ is the power flow and k is the building's effective thermal conductivity (including both conductive and convective coupling through the walls, ceiling, doors, etc., between the inside and the outside of the building). Arbitrarily, positive power flow has been chosen as occurring when energy flows into the building.



The second equation is a heat capacity expression that relates the temperature inside of the building to the total heat energy, $E(i)$, inside of the building. It is typically written as

$$E(i) = cT_{in}(i) \tag{2}$$

where c is the heat capacity of the building.

The third equation recalls the definition of power as the change in energy per unit of time. The change in the total heat energy in the building is given by the sum of two powers, the one introduced above describing the power flowing through the walls, and the power flowing into the building through other means, $P_{other}(i)$, such as electrical consumption, air conditioning, engine operation, etc.

$$\frac{\Delta E(i)}{\Delta t} = \frac{E(i) - E(i-1)}{\Delta t} = P_{walls}(i) + P_{other}(i) \tag{3}$$

where Δt is the time interval for data collection.
These three equations can be combined and solved for the temperature inside of the building, yielding the following expression with three terms.

$$T_{in}(i) = \frac{\Delta t}{\Delta t + (c/k)} \frac{P_{other}(i)}{k} + \frac{c/k}{\Delta t + (c/k)} T_{in}(i-1) + \frac{\Delta t}{\Delta t + (c/k)} T_{out}(i).$$

Starting from the right-hand side, the first term is the contribution from the other heat energy sources and sinks; the second term is the contribution from the building's latent heat; and the third term is the contribution from the heat flowing through the walls. This equation can be simplified in two ways. First, note that the heat capacity and thermal conductivity only show up as a ratio, c/k, which has units of time. So replace this with the parameter, t_b, which will be shown below to be the building's thermal time constant. Also, assuming that the term $P_{other}(i)/k$ is a constant, then it can be replaced with a building temperature offset parameter, T_b. This parameter, T_b, is the average difference in temperature between the inside and the outside of the building. Making these changes yields

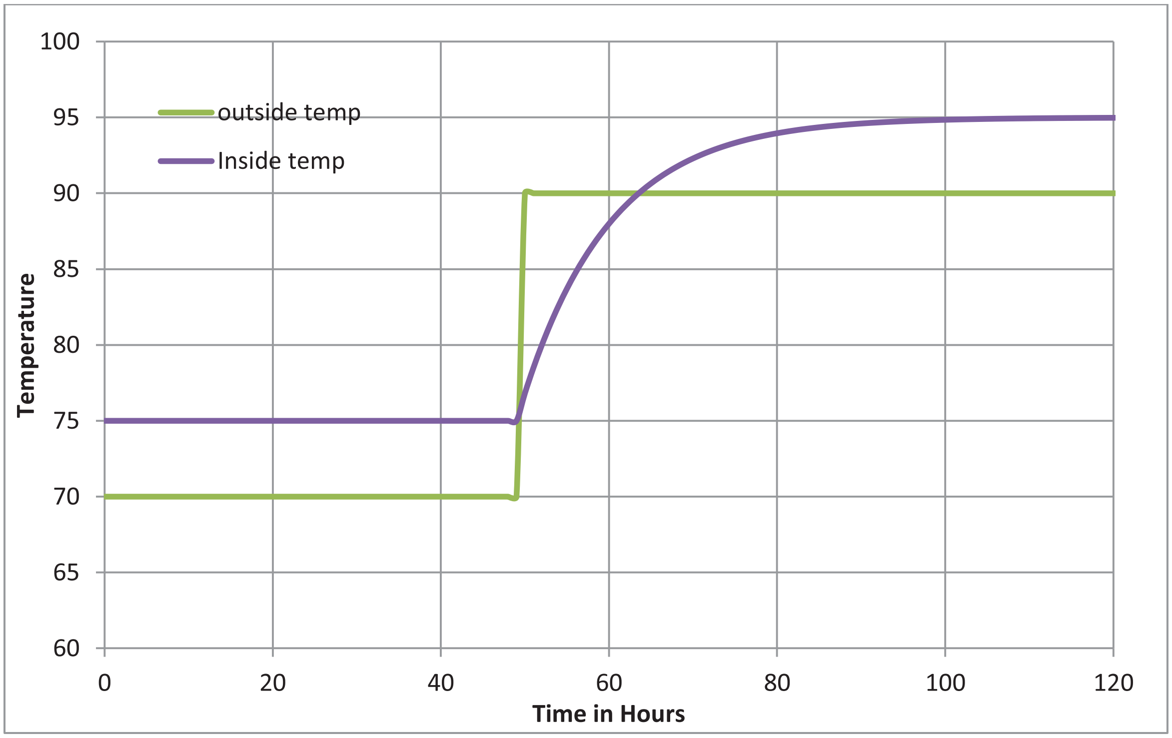
$$T_{in}(i) = \frac{t_b}{\Delta t + t_b} T_{in}(i-1) + \frac{\Delta t}{\Delta t + t_b} (T_b + T_{out}(i)).$$

Two examples are shown in the following section.

8.2 Examples

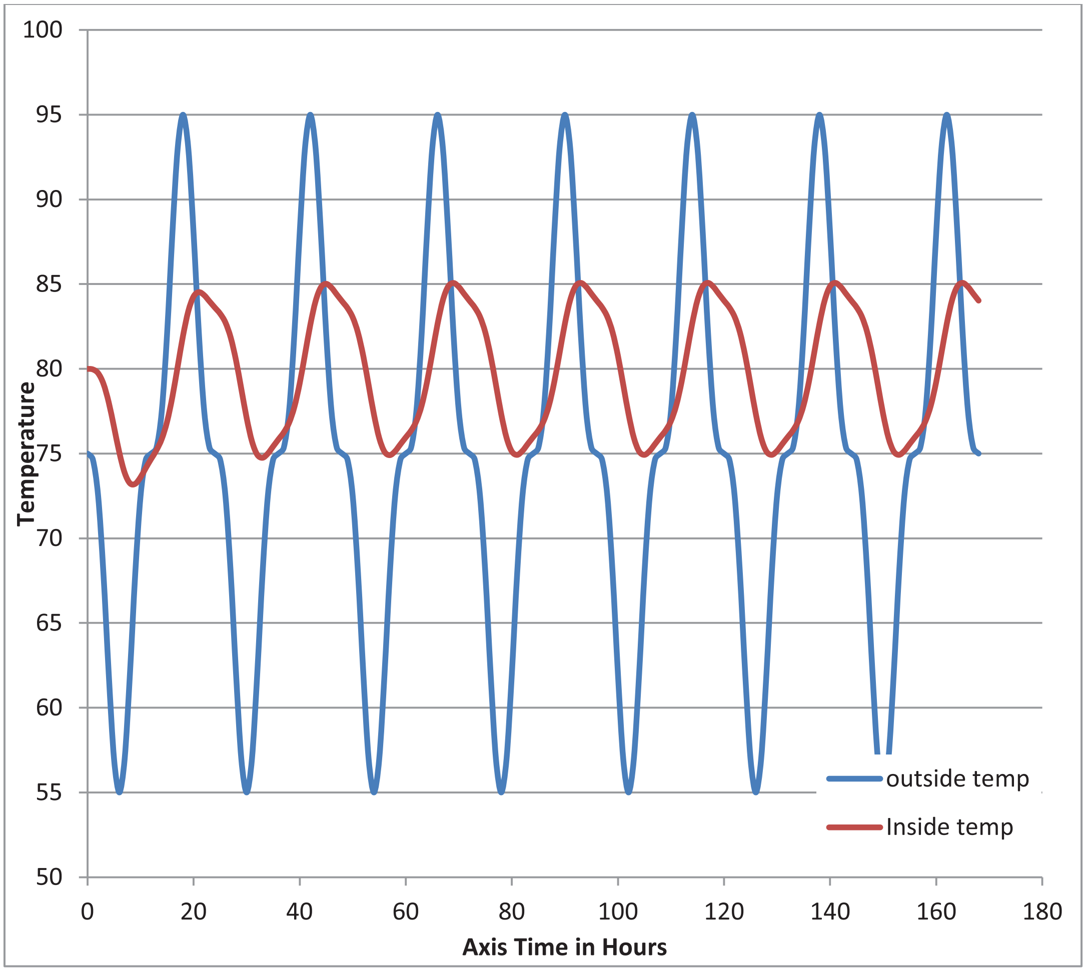
Example 1:

In this case the outside temperature stays steady at 70 degrees for 50 hours and then jumps by 20 degrees to 90 degrees where it stays for the next few days. This is of course a nonphysical occurrence, but shows the role that the two parameters play. The building temperature offset has been set to 5 degrees (the building inner temperature was started at 75 degrees) and the building inner temperature stays 5 degrees higher than the outside temperature until the temperature jump occurs. A few days after this jump, the building has returned to a stable temperature equal to 5 degrees higher than the outside temperature, i.e., 95 degrees. The building time constant, t_b, has been set equal to 10 hours and it can be seen that 10 hours after the temperature jump, at hour 60, that the temperature inside of the building is about 88 degrees, which is 65 percent of the way to the final temperature of 95 degrees. In other words, the parameter, t_b, is indeed the time constant of the building (the time needed to move about 63 percent of the way to the final stable value). The following figure shows the role of the two parameters in the modeling of the building's temperature.



Example 2:

This example is a little more realistic in that a day/night cycle is shown for the outside temperature. Again, the building time constant has been set to 10 hours and the building temperature offset has been set to 5 degrees, yielding the prediction shown for the building's internal temperature. The building's internal temperature oscillates, but is delayed in time and reduced in amplitude when compared to the outside temperature. While the outside temperature oscillates by 40 degrees (peak to peak), the inside of the building only oscillates about 10 degrees. Also note that the peak temperature inside of the building occurs several hours after the outside temperature peaks. Finally, the average temperature outside is 75 degrees but the average temperature inside of the building is 80 degrees, reflecting the 5 degree building temperature offset.



8.3 VAB Data

The model described above can be generalized to apply to specific locations within the VAB. Each location has its own response time and its own offset temperature. These response times can be affected by changes in the building's configuration, for example, opening the VAB doors and ceiling vents will allow the building to respond more quickly to changes in the outside temperature. Analyzing two short time periods during the 2013 year provided insight into the magnitude of the response times seen by various locations within the VAB.

The two time periods studied were six days in December 2013 (December 5-10) and five days in July 2013 (July 5-9). The temperature variation during these two periods was relatively periodic allowing the outside and inside temperatures to be correlated against a 24-hour period sinusoid. From the analysis above, we can think of the building's response to the outside temperature variation as similar to that of a first-order filter. If the outside temperature variation is periodic, then the inside temperature variations will also be periodic. These periodic variations can be decomposed into Fourier series and the fundamental components can be compared to obtain a phase difference, ϕ_i , between the outside and inside temperatures for each location (note that all phases presented here are in radians). Then the response time for that location, t_i, can be found from the low-pass filter phase shift equation

$$t_i(\text{hours}) = -24\tan[\phi_i]/(2\pi)$$

For example, the outside temperature variation at wind tower 412 over the six days in December is plotted below along with a best-fit fundamental sinusoid (the amplitude of the sinusoid is arbitrary). The peaks of the sinusoid are shifted from the temperature peaks due to the ramp shape in the outside temperature (slow cool-off in the evening followed by rapid warming the next morning). Contrast this with the warmer temperatures seen in the July plot where the temperature plots are more symmetrical and the sinusoid peaks better correspond to the temperature peaks.

The table on the next page shows the phase delay for the best fit to each wind tower's temperature data compared to a sinusoid. This phase is averaged to find a phase for the outside temperature variation.

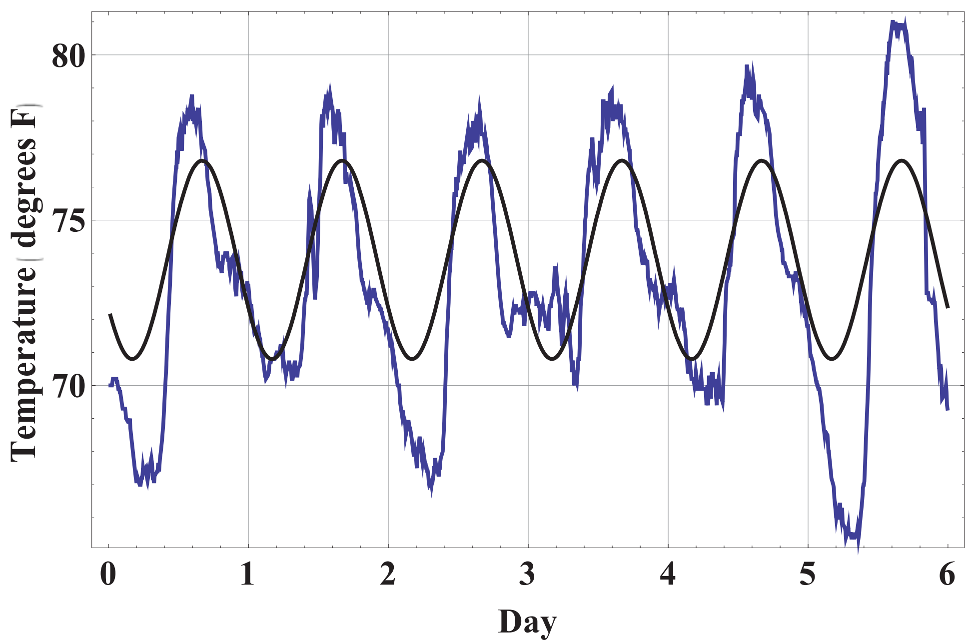


Figure 8-1. December 5-10, 2013, wind Tower 412 and a sinusoidal fundamental.

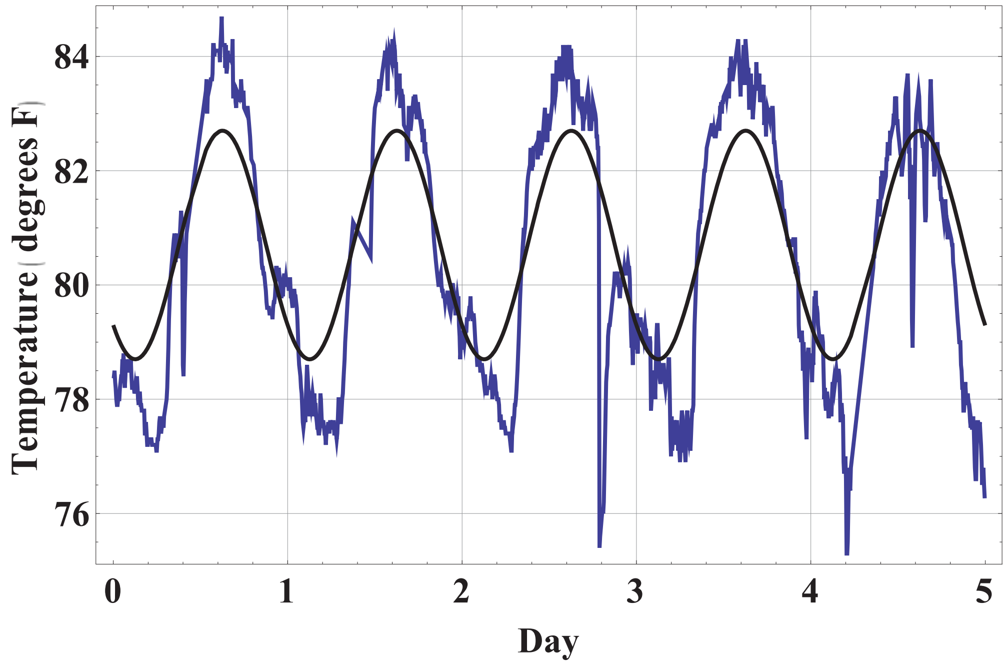


Figure 8-2. July 5-9, 2013, Wind Tower 412 and a sinusoidal fundamental.

	Tower 412	Tower 509	Tower 311	Average	Peak time
July phase	3.92	3.96	3.91	3.93	15 hours
December phase	3.65	3.68	3.73	3.69	15.9 hours

The relative phase of the fundamental for each window tower during the July and December periods compared to a sinusoid. The average phases (in radians) and peak times are also shown.

Now, consider the temperature variations inside of the VAB over the same periods. Again, a best 24-hour period sinusoid fit is found to this data in order to obtain a phase shift. The plot below shows a sample of this data taken at location 6, Level 25-E, HB-3, during December 5-10. Note that, as expected, the data variations are less than those outside of the VAB and are shifted to the right (later in the day).

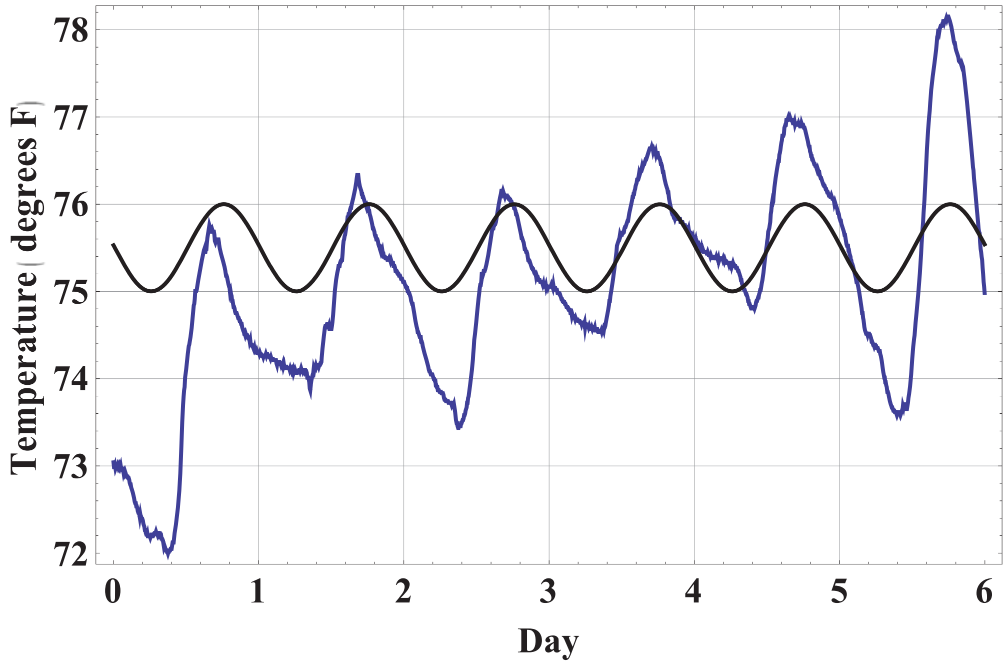


Figure 8-3. December 5-10, 2013, plot of the temperature variation at Level 25-E, HB-3, along phase matched fundamental.

Location	Dec phase	Peak times	Phase Diff	Time Response (hours)
Ceiling HB-4	2.96	18.7	–0.73	3.4
Lev 36-E, HB-3	3.09	18.2	–0.60	2.6
Lev 40-B, HB-2	3.05	18.3	–0.64	2.8
Lev 32-E, HB-3	2.98	18.6	–0.71	3.3
Lev 28-E, HB-3	3.07	18.3	–0.62	2.7
Lev 25-E, HB-3	3.07	18.3	–0.62	2.7
Lev 19-E, HB-3	3.09	18.2	–0.60	2.6
Lev 16-E, HB-3	3.12	18.1	–0.57	2.5
Lev 7-E, HB-3	3.27	17.5	–0.42	1.7
Lev 32-B, HB-2	3.12	18.1	–0.57	2.5
Lev 28-B, HB-2	3.04	18.4	–0.65	2.9
Lev 25-B, HB-2	3.04	18.4	–0.65	2.9
Lev 20-B, HB-2	3.03	18.4	–0.66	3.0
Lev 16-B, HB-2	3.14	18	–0.55	2.4
Lev 7-B, HB-2	3.4	17	–0.29	1.1
Lev 1, HB-4	3.1	18.2	–0.59	2.6
Lev 1, HB-3	2.96	18.7	–0.73	3.4
North Turnstile	3.67	15.9	–0.00	0

Location	July Phase	Peak Times	Phase Diff	Time Response (hours)
Ceiling HB-4	2.70	19.7	–1.22	10.6
Lev 36-E, HB-3	3.16	17.9	–0.77	3.7
Lev 40-B, HB-2	2.9	18.9	–1.03	6.3
Lev 32-E, HB-3	3.14	18.0	–0.79	3.9
Lev 28-E, HB-3	3.22	17.7	–0.71	3.3
Lev 25-E, HB-3	3.25	17.6	–0.68	3.1
Lev 19-E, HB-3	3.33	17.3	–0.60	2.6
Lev 16-E, HB-3	3.41	17.0	–0.52	2.2
Lev 7-E, HB-3	3.73	15.8	–0.20	0.8
Lev 32-B, HB-2	3.14	18.0	–0.79	3.9
Lev 28-B, HB-2	3.14	18.0	–0.79	3.8
Lev 25-B, HB-2	3.15	18.0	–0.78	3.8
Lev 20-B, HB-2	3.18	17.8	–0.75	3.5
Lev 16-B, HB-2	3.35	17.2	–0.58	2.5
Lev 7-B, HB-2	3.61	16.2	–0.32	1.3
Lev 1, HB-4	3.55	16.4	–0.38	1.5
North Turnstile	3.92	15.0	–0.01	0.0

These two tables supply the fundamental harmonic phase delay (compared to a sinusoid) and corresponding peak times for each location in the VAB for the December and July periods. Phase differences compared to the wind towers are shown and from this time responses are obtained.

The two tables shown above provide the results of the analysis and show the December and July phases for the fundamental component of the temperature variation at various locations within the VAB. These tables also show the corresponding time of the peak for the fundamental, the difference in phase compared to the phase of the outside fundamental, and the time response of that location within the VAB.

The North Turnstile is a small independent building outside of the VAB that is open to the environment. The matching phase relationship between the data logger in this location and the wind towers helps to support the analysis. Higher levels within the building have the longest response times, peaking with the ceiling. In July the outside temperature fundamental peaks at about 3 p.m., but the ceiling temperature fundamental does not peak until nearly 8 p.m. This long time-delay yields an even longer time constant (due to the nonlinear response of the tangent function) of more than 10 hours for that location.

Level 7 is anomalous, likely due to sunlight heating the area near the data loggers; causing these sites to peak in temperature earlier than the other locations and yielding a corresponding smaller time constant. It is difficult to draw other conclusions from the data since the building configuration may have varied during these time periods; for example, the doors were likely in different positions in July than in December. However, knowing that most locations in the VAB have 2 to 3 hour delays in response to changes in the outside temperature may be useful in predicting interior conditions.

9 DISCUSSION

The VAB is rarely in thermal equilibrium internally, i.e., the air temperature and the structural temperature are usually different. The VAB humidity data presented in this report suggests that the air within the building is recirculated within a couple of hours, but the thermal data shows response times for some areas in the building of many hours, reflecting the slow thermal response of the VAB structure. The temperature measurements shown in this document appear to be a combination of the air temperature and the structural temperature. Objects placed in the VAB will be convectively coupled to the air, but also coupled to the structure through conduction and radiation, and will be affected by both the temperature of the air and the temperature of the structure. The physics connecting temperature, humidity, air, and building mass is important to characterize, but to describe that complex relationship with a sufficient description is beyond the scope of this work. To quantify these relationships would be useful to future operations in the VAB and is, therefore, a prime candidate for future work.

APPENDIX A. 1994–2009 HISTORICAL DATA

This appendix presents temperature and humidity data for the VAB that were gathered before the present activity was initiated. This data is being included for completeness, allowing this report to show the recently acquired 2012-2013 data, as well as data gathered during the Space Shuttle period. However, we do not know how this data was collected and, consequently, its accuracy is not known. In addition, this data was only taken at Levels 7 and 11 and should not be used to infer the temperature or humidity at higher locations within the VAB.

A.1 1997 Data Summary

Table A-1a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	80.6	87.9	89.2	83.8
Lo:	44.4	63.3	76.0	52.4
Hi-Lo:	36.1	24.5	13.2	31.4
Avg:	70.3	76.9	82.2	71.4
	Pads 39A+39B			
Hi:	85.0	90.2	89.4	84.2
Lo:	32.6	51.0	69.4	41.4
Hi-Lo:	52.4	39.2	20.0	42.8
Avg:	66.2	73.8	80.7	68.2

Table A-1b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	99.8	100.0	100.0	100.0
Lo:	6.8	25.2	37.9	19.5
Hi-Lo:	92.9	74.8	62.1	80.5
Avg:	67.6	73.3	76.1	66.2
	Pads 39A+39B			
Hi:	100.0	100.0	99.8	100.0
Lo:	23.0	25.0	46.0	22.4
Hi-Lo:	77.0	75.0	53.8	77.6
Avg:	83.4	81.0	82.6	78.4

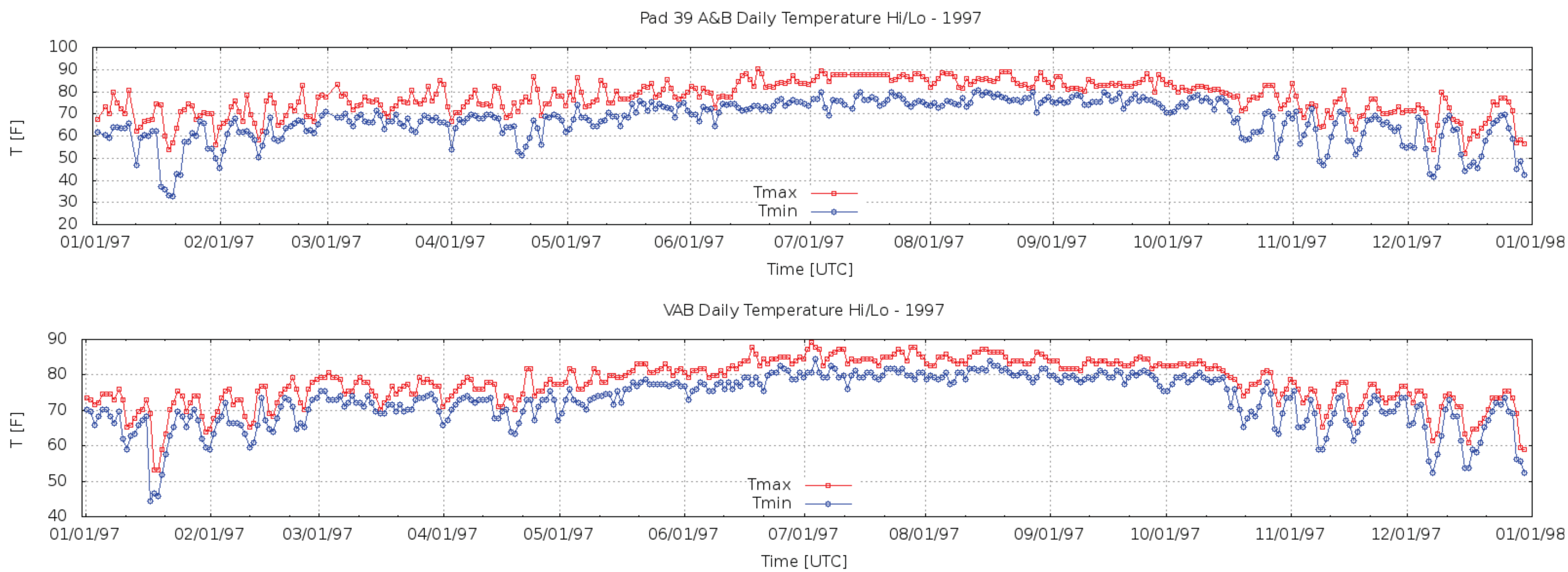


Figure A-1a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

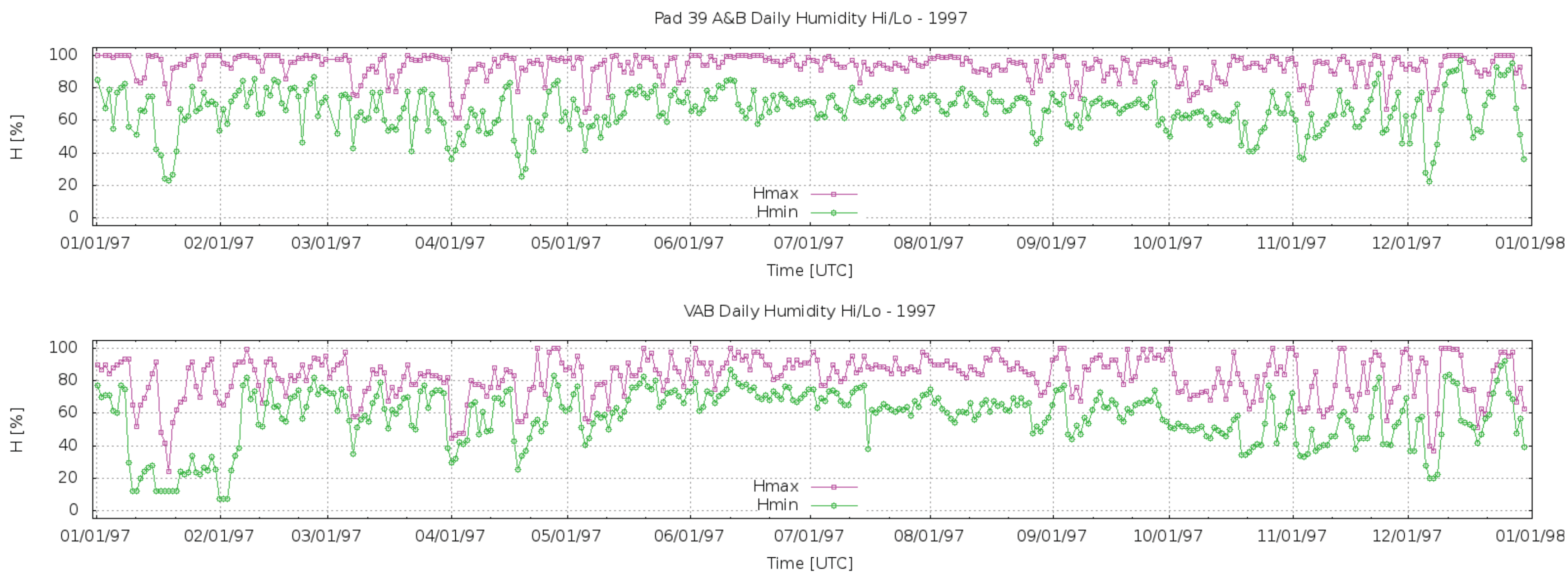


Figure A-1b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.2 1998 Data Summary

Table A-2a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	76.0	93.4	90.6	85.8
Lo:	52.4	61.4	77.3	53.1
Hi-Lo:	23.6	32.0	13.3	32.8
Avg:	66.1	78.0	82.6	76.2
	Pads 39A+39B			
Hi:	80.8	96.9	97.1	96.2
Lo:	42.8	53.4	73.2	48.4
Hi-Lo:	38.0	43.5	23.9	47.8
Avg:	62.1	76.2	81.2	74.3

Table A-2b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	100.0	92.2	96.8	100.0
Lo:	26.8	10.8	41.3	31.0
Hi-Lo:	73.2	81.4	55.5	68.9
Avg:	64.5	60.7	73.3	67.3
	Pads 39A+39B			
Hi:	100.0	99.8	100.0	100.0
Lo:	24.6	19.8	40.7	47.6
Hi-Lo:	75.4	80.0	59.3	52.4
Avg:	78.7	75.3	84.9	79.5

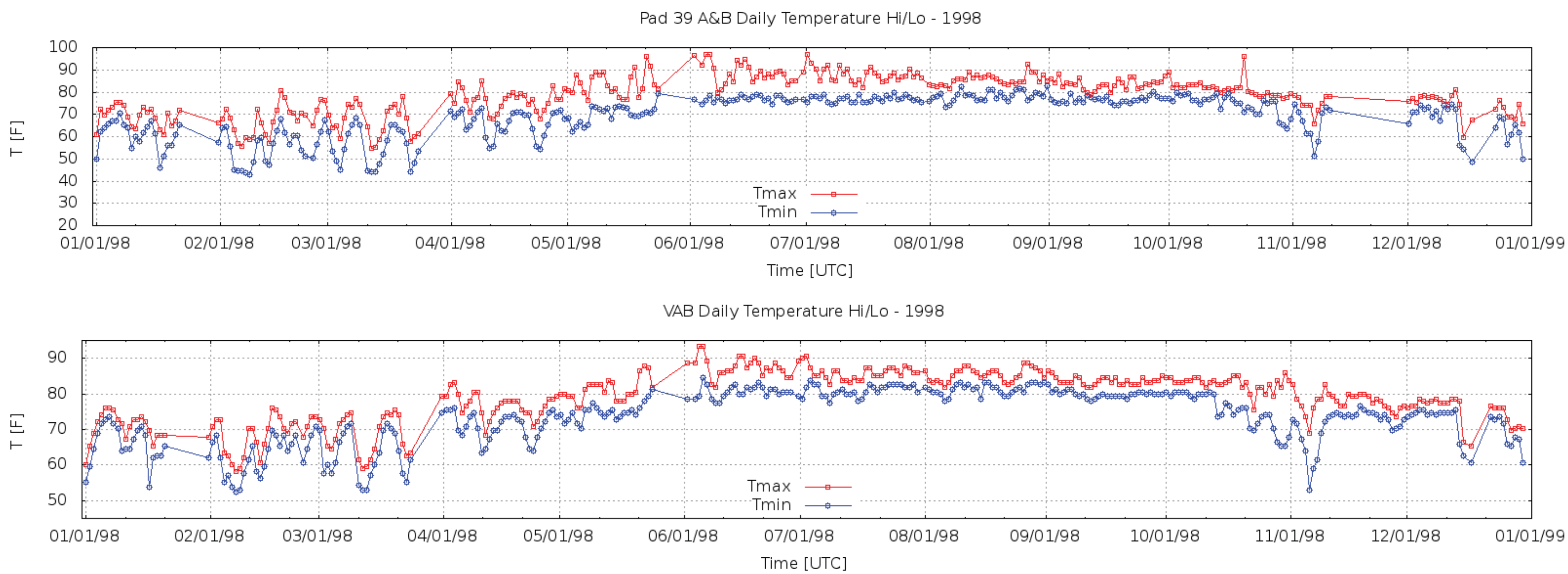


Figure A-2a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

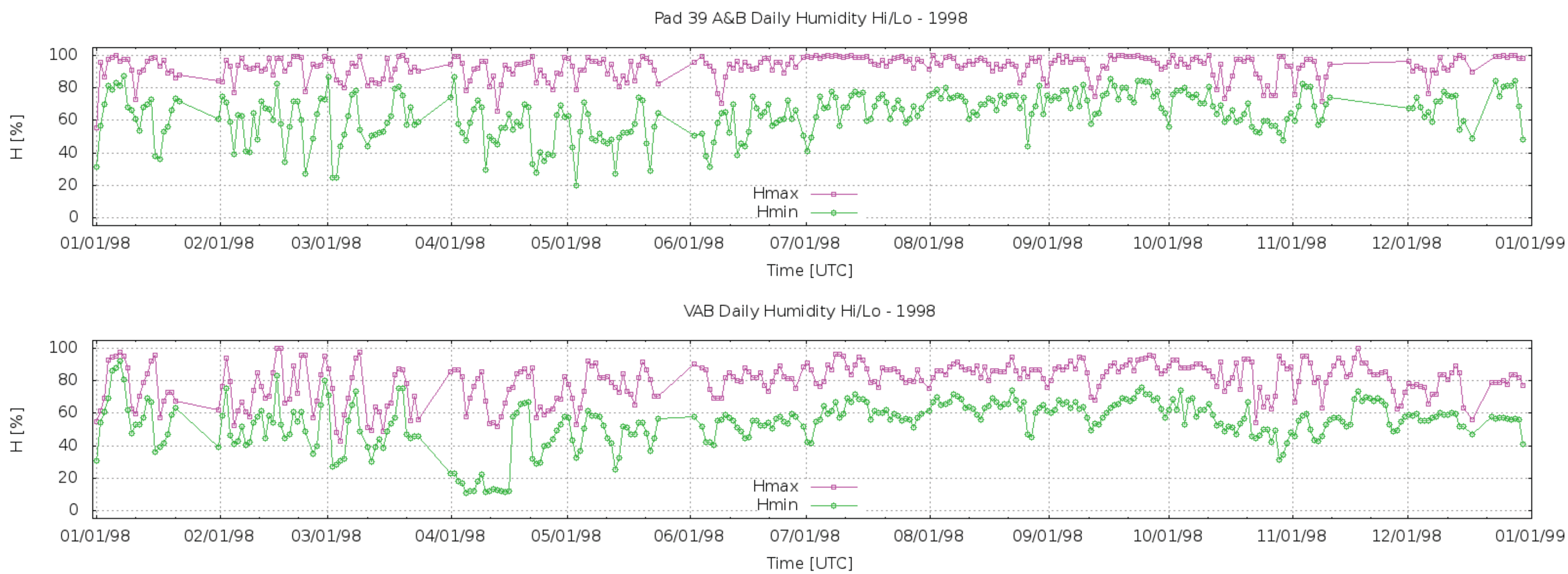


Figure A-2b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.3 1999 Data Summary

Table A-3a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	78.0	84.5	90.6	83.2
Lo:	46.5	60.8	74.8	52.4
Hi-Lo:	31.5	23.7	15.9	30.8
Avg:	68.2	76.3	82.1	72.8
Pads 39A+39B				
Hi:	80.5	91.1	95.3	83.5
Lo:	32.8	52.2	69.4	39.7
Hi-Lo:	47.7	38.9	25.9	43.8
Avg:	65.3	74.8	80.5	70.0

Table A-3b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	86.6	96.9	94.3	100.0
Lo:	20.9	28.5	48.7	26.9
Hi-Lo:	65.7	68.4	45.6	73.1
Avg:	60.0	66.0	73.1	62.6
Pads 39A+39B				
Hi:	99.9	100.0	100.0	100.0
Lo:	19.5	27.9	40.6	31.0
Hi-Lo:	80.4	72.1	59.4	69.0
Avg:	73.6	81.1	82.8	77.8

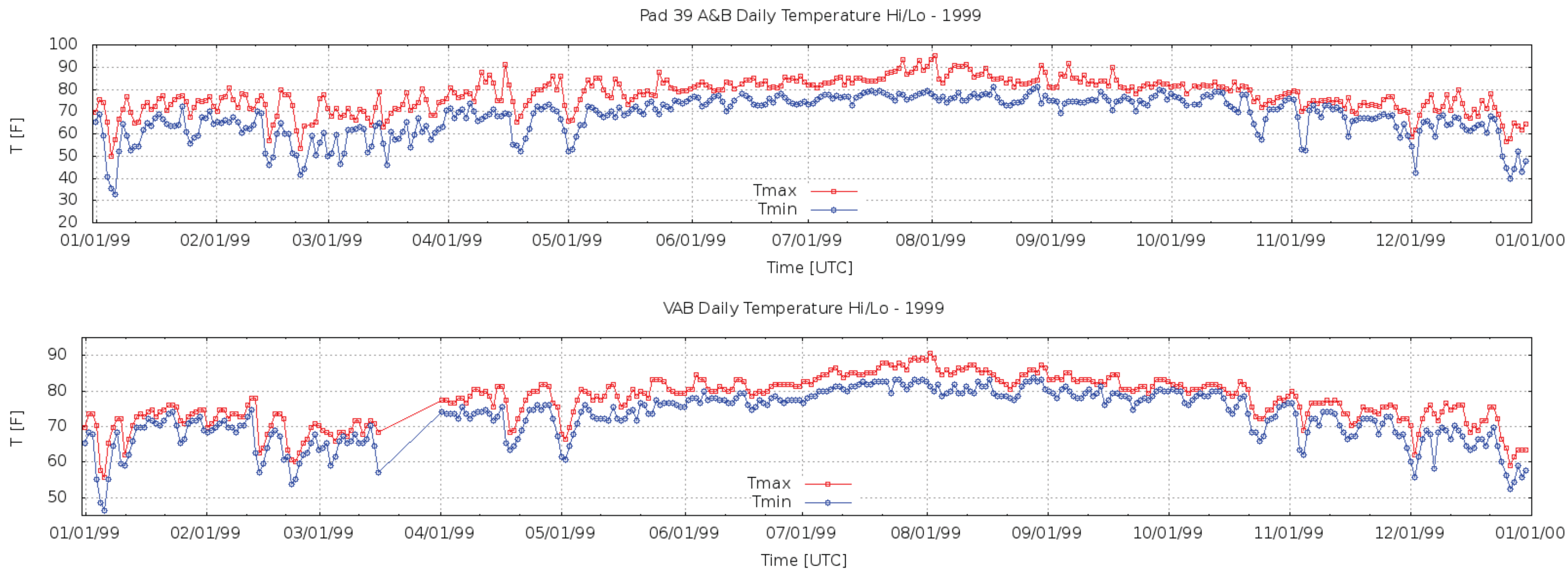


Figure A-3a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

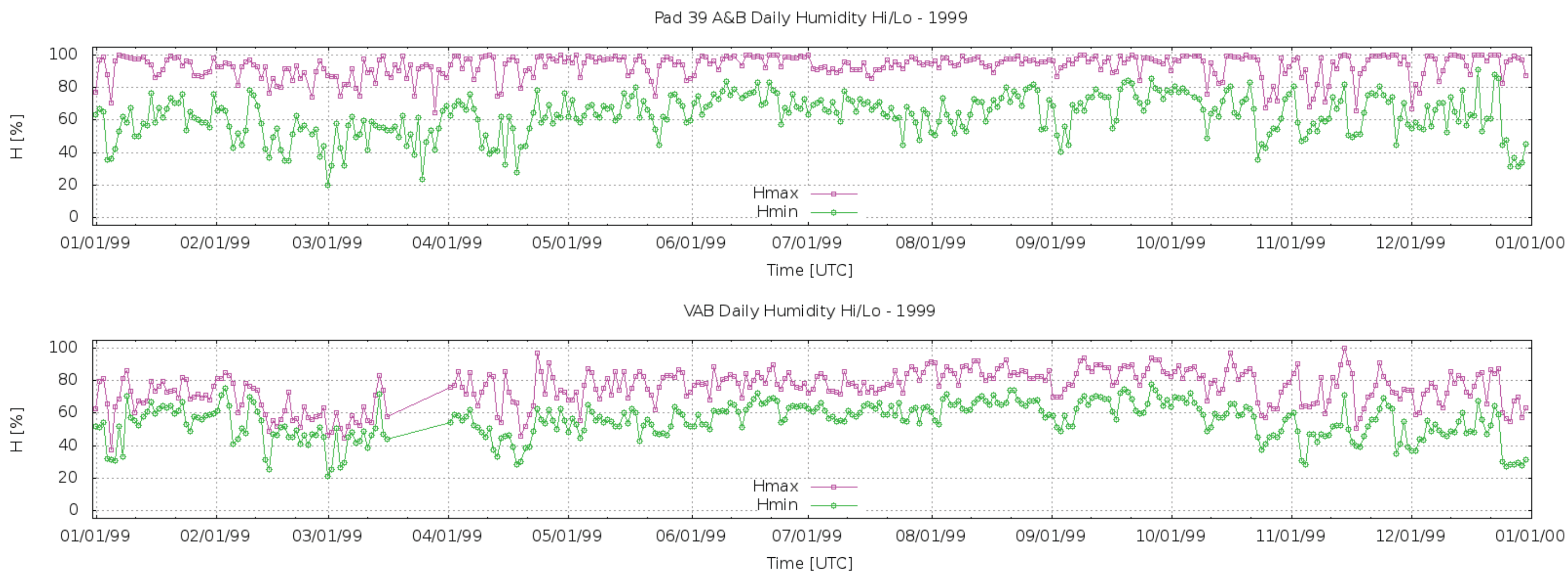


Figure A-3b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

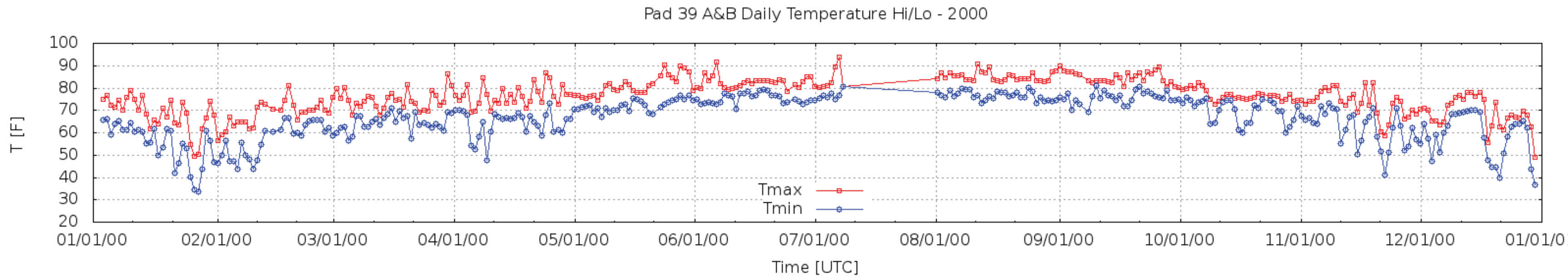
A.4 2000 Data Summary

Table A-4a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	82.5	84.5	90.6	82.5
Lo:	46.5	59.5	76.0	41.7
Hi-Lo:	36.1	25.0	14.6	40.9
Avg:	67.7	76.1	82.0	70.6
Pads 39A+39B				
Hi:	86.5	91.7	94.0	82.5
Lo:	33.6	47.8	69.2	36.7
Hi-Lo:	52.9	43.9	24.8	45.8
Avg:	64.4	74.3	80.7	68.9

Table A-4b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	91.7	91.4	97.2	91.0
Lo:	27.3	25.6	49.4	23.1
Hi-Lo:	64.4	65.8	47.9	67.9
Avg:	60.1	66.3	71.5	61.7
Pads 39A+39B				
Hi:	100.0	99.5	100.0	100.0
Lo:	29.6	27.8	43.4	32.0
Hi-Lo:	70.4	71.7	56.6	68.0
Avg:	77.7	74.9	80.5	77.6



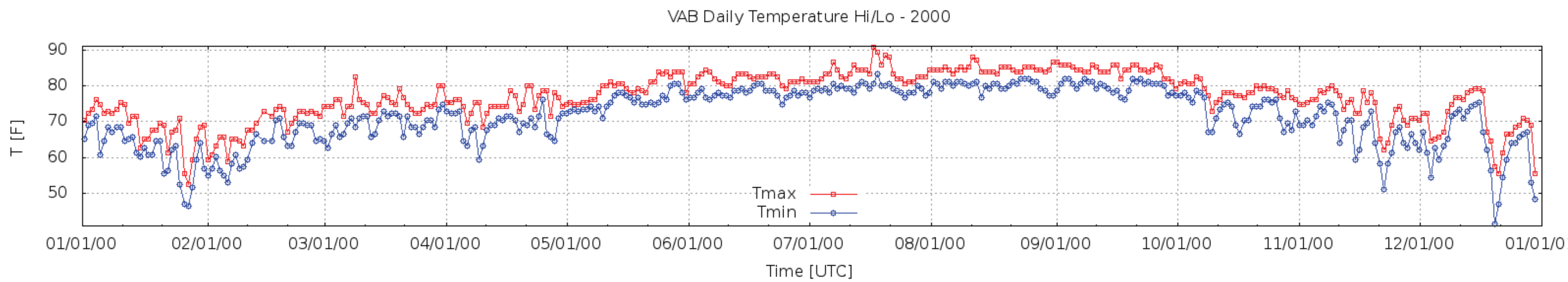
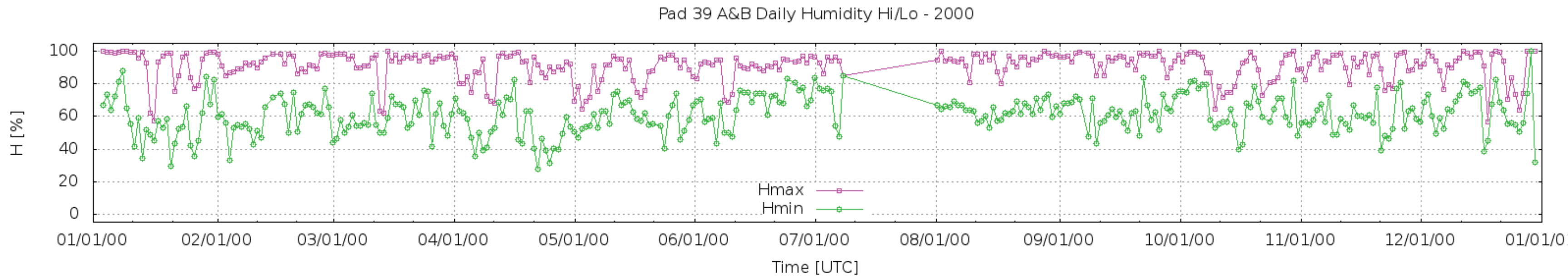


Figure A-4a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.



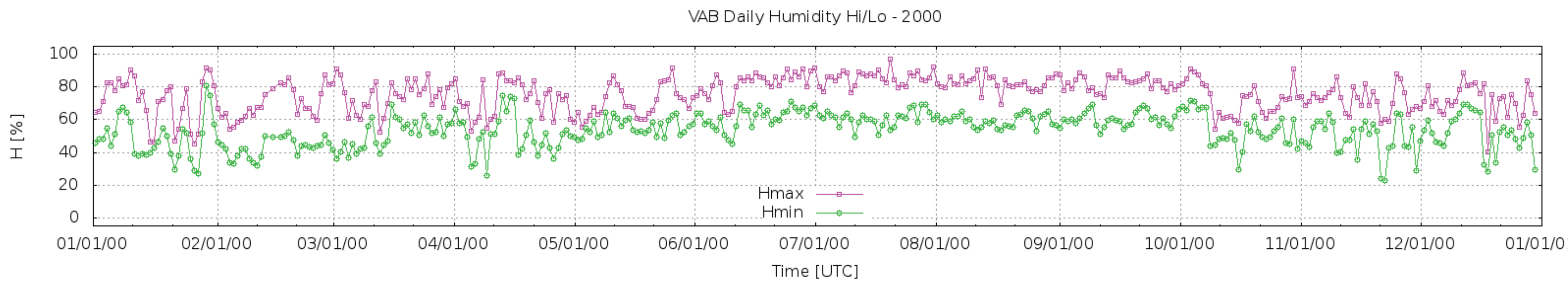


Figure A-4b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.5 2001 Data Summary

Table A-5a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	80.6	87.2	88.6	83.2
Lo:	43.0	57.0	72.8	52.4
Hi-Lo:	37.5	30.2	15.7	30.8
Avg:	66.1	77.2	81.6	74.0
Pads 39A+39B				
Hi:	86.5	92.5	90.1	88.2
Lo:	31.1	51.3	67.3	41.3
Hi-Lo:	55.4	41.2	22.8	46.9
Avg:	62.9	75.0	79.4	71.5

Table A-5b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	92.2	85.1	86.7	88.4
Lo:	15.3	28.5	48.0	19.7
Hi-Lo:	76.9	56.5	38.6	68.7
Avg:	63.1	62.8	70.7	63.0
Pads 39A+39B				
Hi:	100.0	99.6	99.9	100.0
Lo:	15.1	11.0	58.7	15.0
Hi-Lo:	84.9	88.6	41.2	85.0
Avg:	79.6	76.3	85.6	78.1

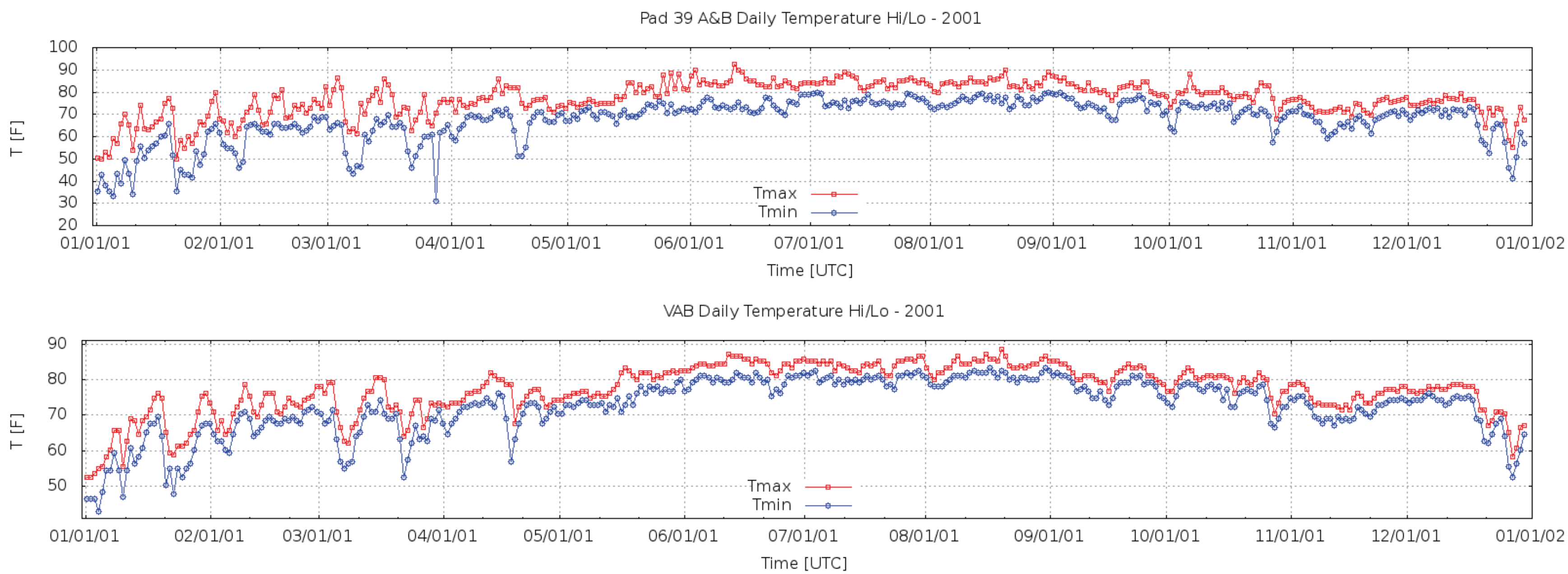


Figure A-5a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

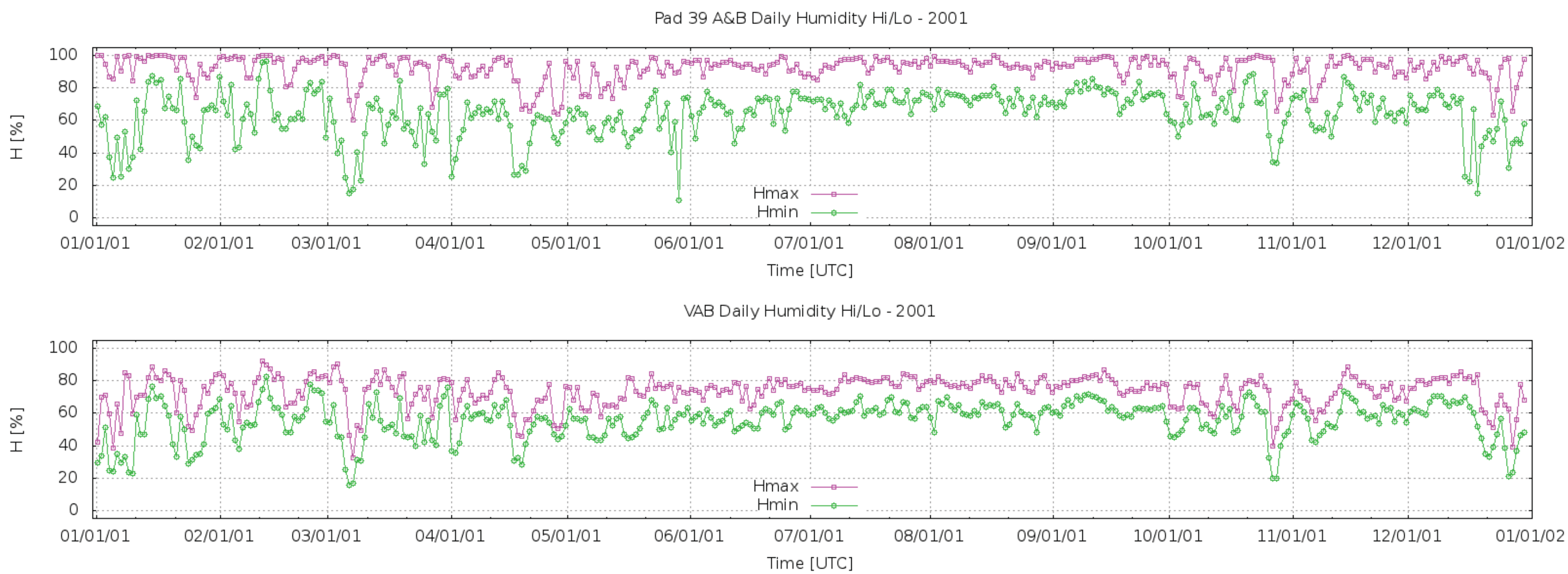


Figure A-5b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.6 2002 Data Summary

Table A-6a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	79.3	85.8	87.9	83.2
Lo:	45.8	67.8	75.4	52.4
Hi-Lo:	33.5	18.1	12.5	30.8
Avg:	67.3	76.9	80.9	70.4
	Pads 39A+39B			
Hi:	82.9	89.7	110.0	86.1
Lo:	32.2	66.0	66.7	42.0
Hi-Lo:	50.7	23.7	43.3	44.1
Avg:	64.9	76.4	80.7	69.4

Table A-6b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	90.6	86.2	86.6	95.8
Lo:	14.6	36.9	49.3	28.9
Hi-Lo:	75.9	49.3	37.3	66.9
Avg:	63.6	67.2	72.0	68.0
	Pads 39A+39B			
Hi:	100.0	100.0	100.0	100.0
Lo:	24.1	42.2	49.0	9.3
Hi-Lo:	75.9	57.8	51.0	90.7
Avg:	79.1	78.9	82.4	77.9

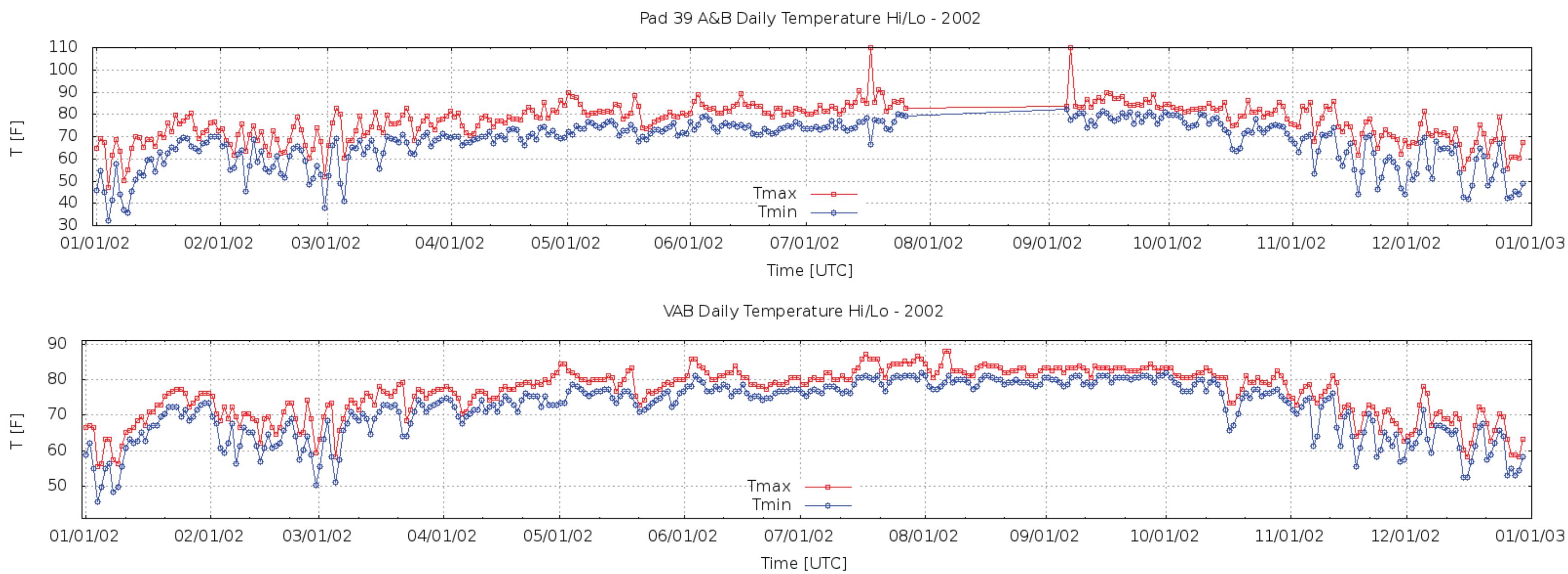


Figure A-6a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

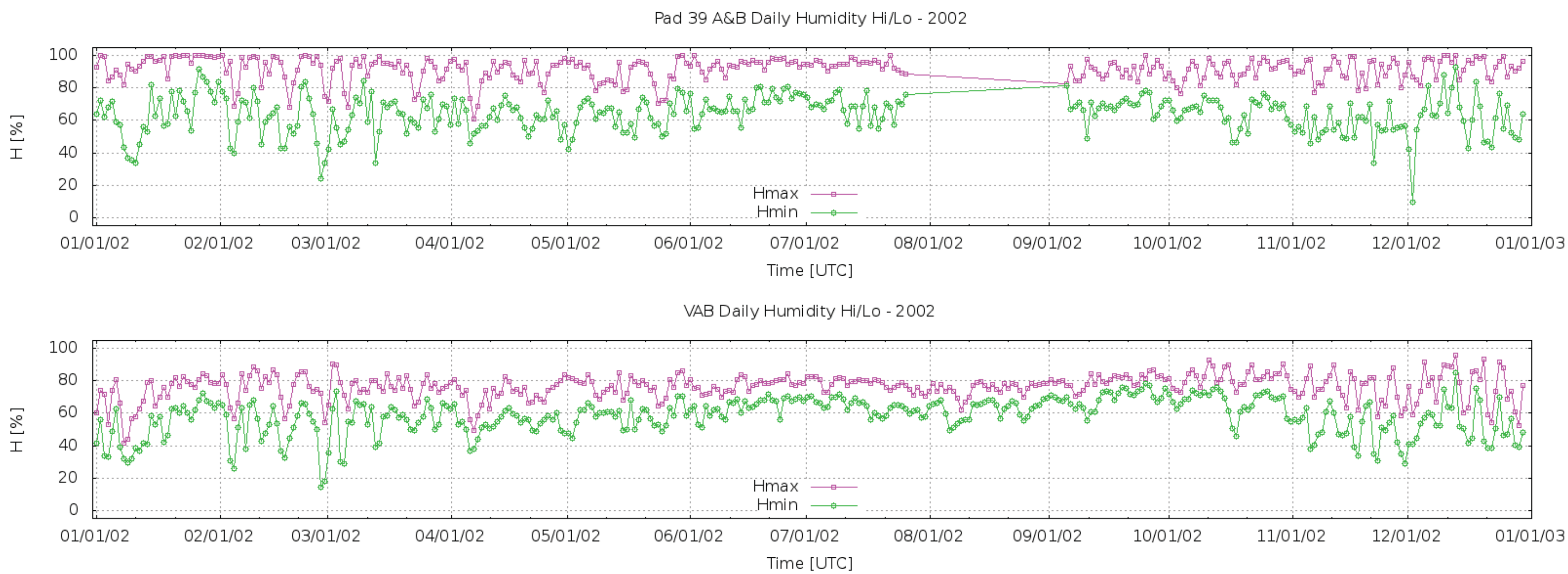


Figure A-6b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.7 2003 Data Summary

Table A-7a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	78.6	85.2	85.2	81.2
Lo:	41.7	53.1	74.8	49.8
Hi-Lo:	37.0	32.1	10.4	31.4
Avg:	65.1	75.8	79.6	71.0
	Pads 39A+39B			
Hi:	86.1	95.2	89.9	86.3
Lo:	30.6	45.1	70.0	39.3
Hi-Lo:	55.5	50.1	19.9	47.0
Avg:	63.1	75.4	78.8	69.5

Table A-7b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	93.4	87.4	90.3	91.3
Lo:	13.0	23.5	58.6	21.3
Hi-Lo:	80.4	64.0	31.7	70.0
Avg:	66.5	68.5	74.5	65.0
	Pads 39A+39B			
Hi:	100.0	99.0	100.0	99.3
Lo:	23.9	30.9	10.0	6.9
Hi-Lo:	76.1	68.1	90.0	92.4
Avg:	79.7	78.5	84.6	73.7

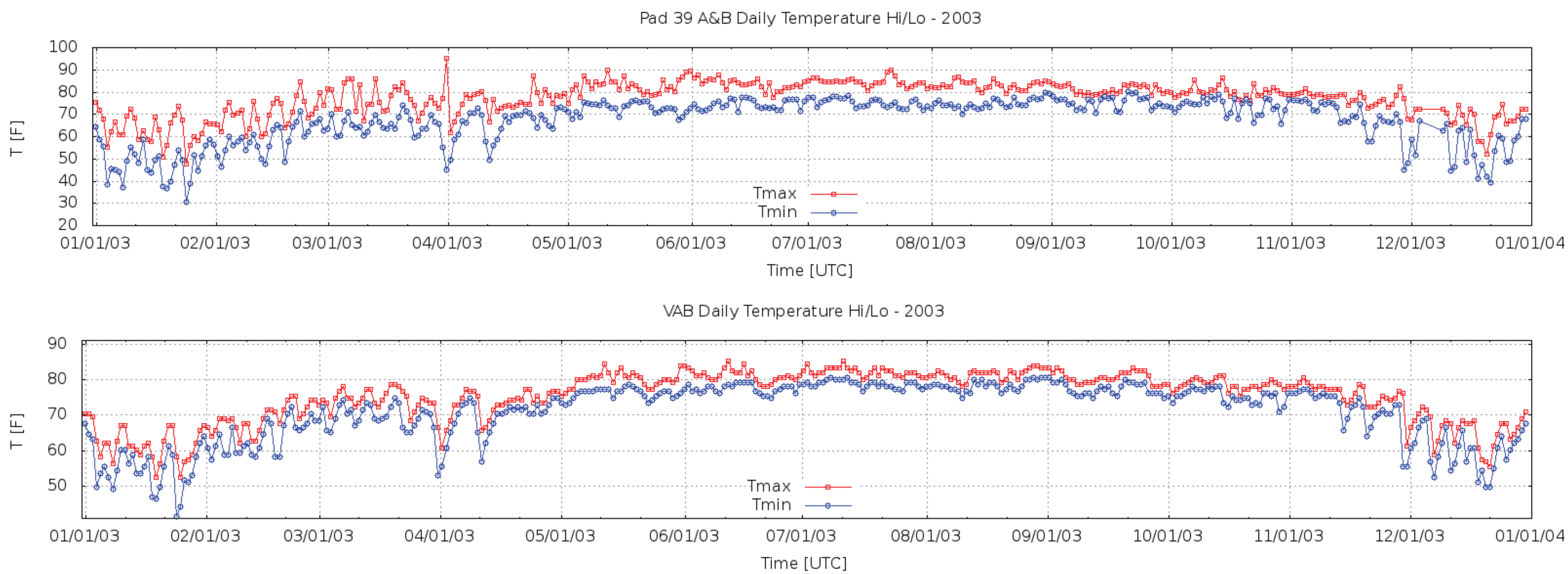


Figure A-7a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

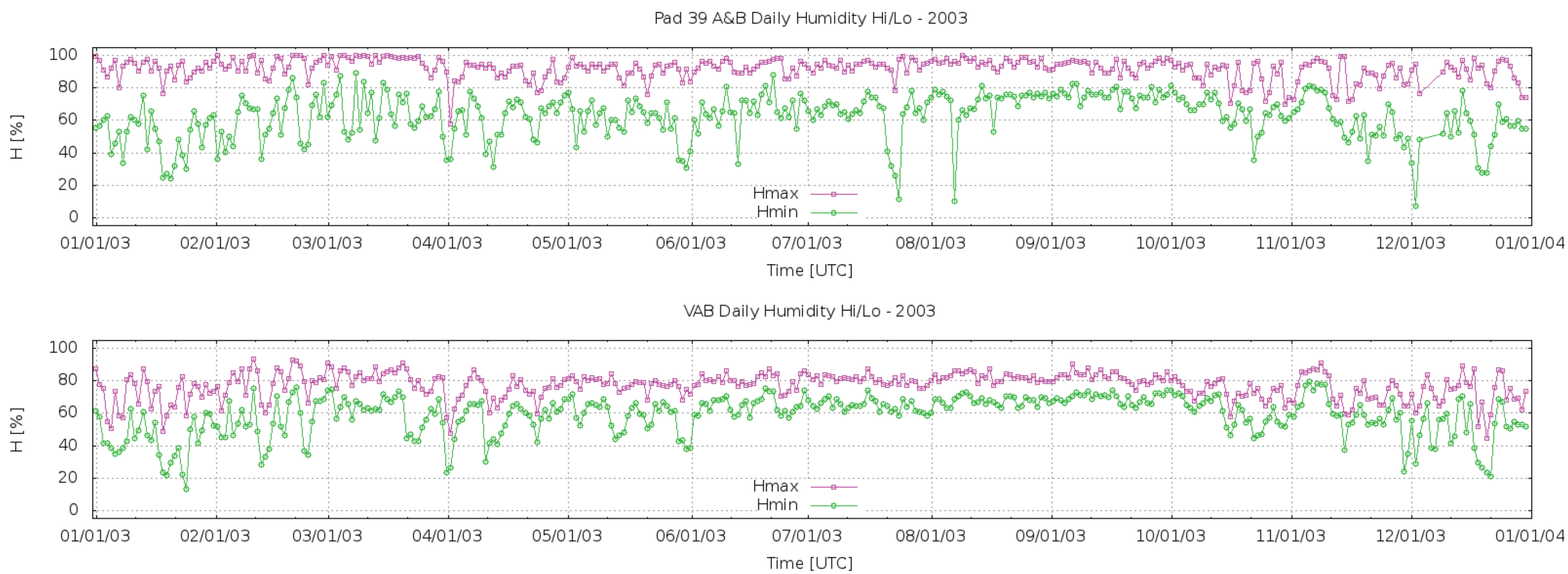


Figure A-7b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.8 2004 Data Summary

Table A-8a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	76.7	85.8	89.2	82.5
Lo:	49.1	59.5	76.0	48.5
Hi-Lo:	27.5	26.3	13.2	34.0
Avg:	65.0	75.3	80.7	71.5
Pads 39A+39B				
Hi:	85.4	95.5	98.2	-
Lo:	30.2	48.9	72.4	-
Hi-Lo:	55.2	46.6	25.8	-
Avg:	62.8	74.5	80.5	-

Table A-8b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	89.8	88.4	100.0	100.0
Lo:	22.4	26.8	45.7	22.5
Hi-Lo:	67.5	61.7	54.3	77.5
Avg:	64.2	65.7	72.8	66.2
Pads 39A+39B				
Hi:	100.0	99.8	97.6	-
Lo:	11.5	25.5	43.8	-
Hi-Lo:	88.5	74.3	53.8	-
Avg:	78.9	77.3	78.1	-

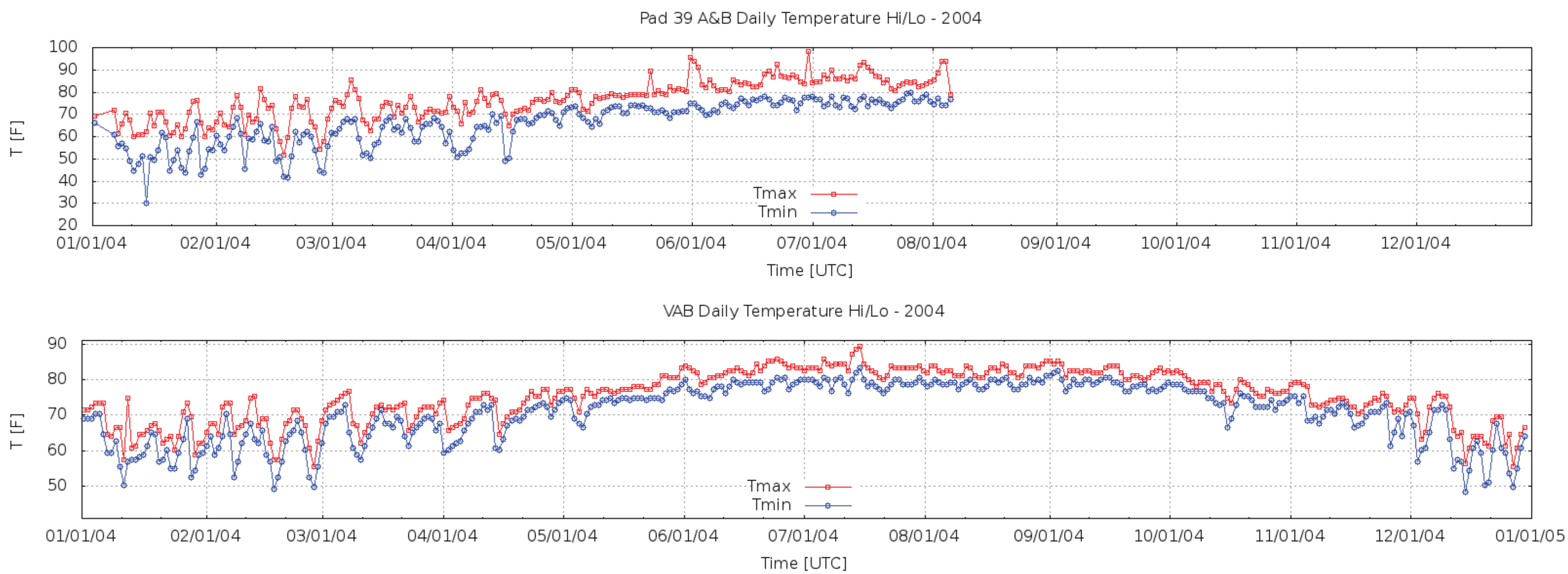


Figure A-8a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

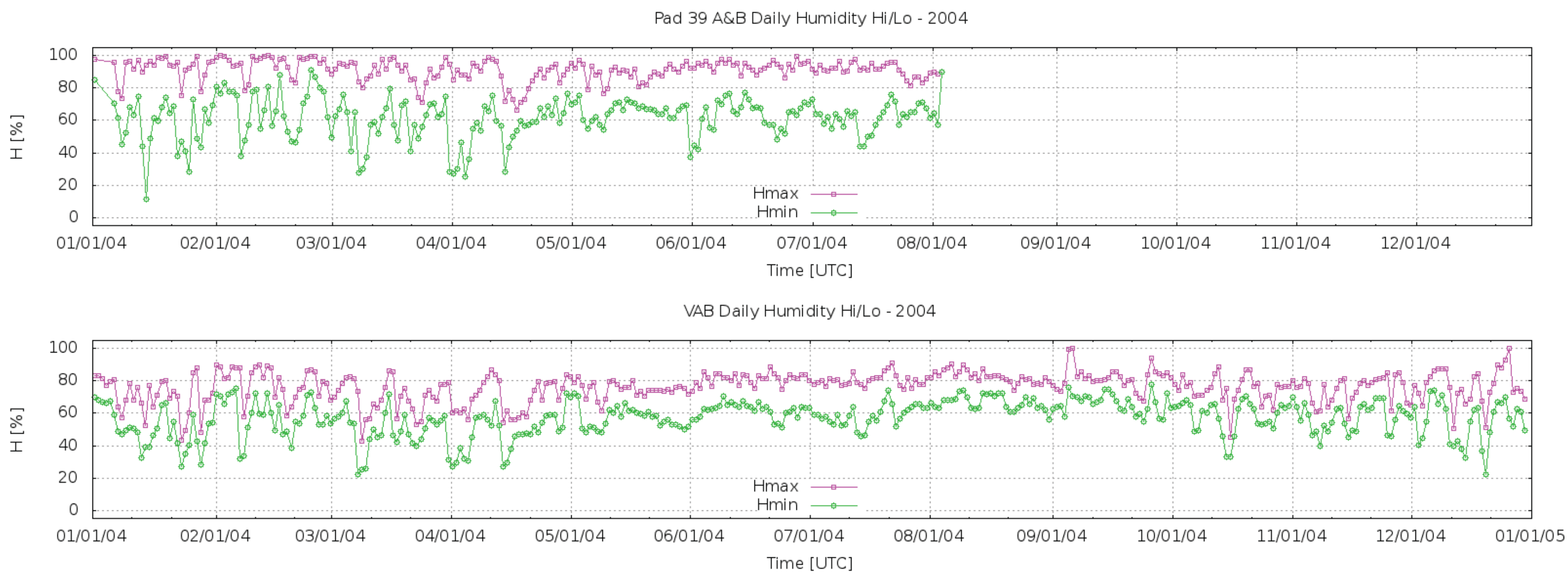


Figure A-8b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.9 2005 Data Summary

Table A-9a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	76.7	81.9	87.2	82.5
Lo:	45.1	56.3	76.7	53.1
Hi-Lo:	31.6	25.6	10.5	29.4
Avg:	65.0	74.3	81.8	69.2
Pads 39A+39B				
Hi:	86.4	89.0	93.1	84.3
Lo:	36.3	51.9	56.8	43.4
Hi-Lo:	50.1	37.1	36.3	40.9
Avg:	61.7	73.7	81.7	69.8

Table A-9b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	100.0	88.7	89.3	100.0
Lo:	23.9	26.1	45.0	30.4
Hi-Lo:	76.1	62.5	44.3	69.7
Avg:	65.4	69.6	73.2	68.8
Pads 39A+39B				
Hi:	100.0	99.4	100.0	100.0
Lo:	6.3	8.8	19.9	28.4
Hi-Lo:	93.7	90.6	80.1	71.6
Avg:	74.3	65.7	76.8	77.9

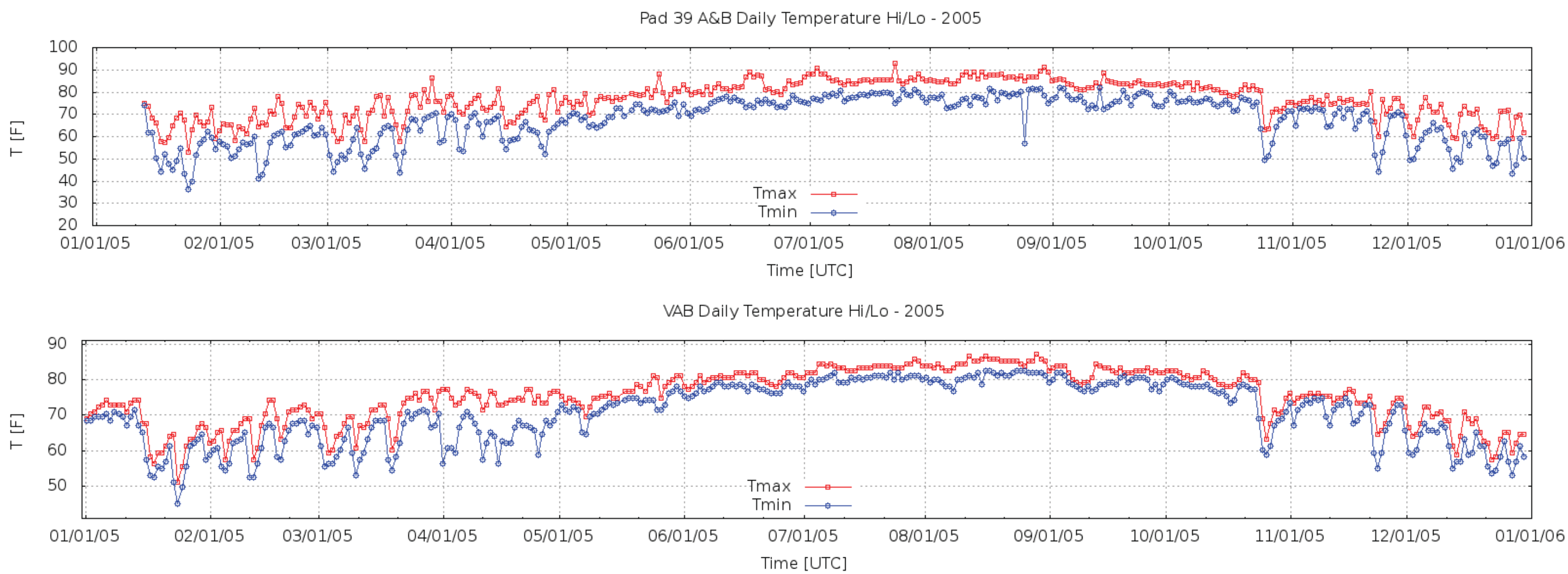


Figure A-9a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

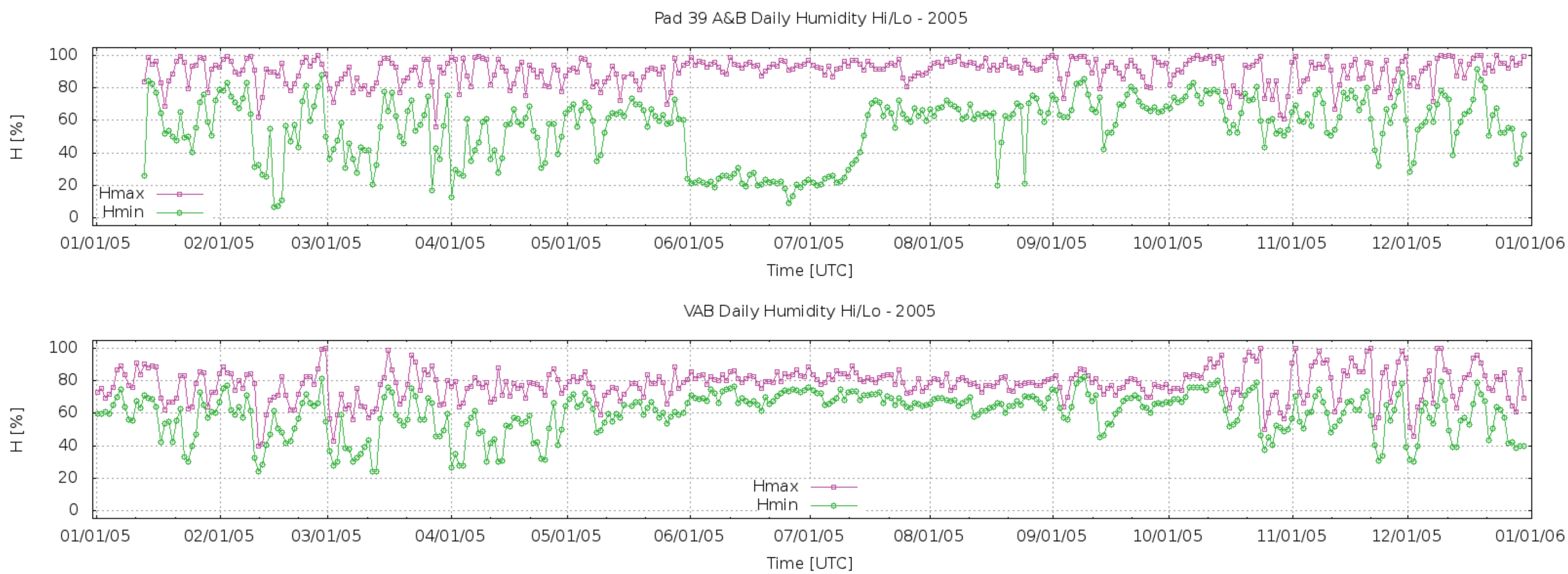


Figure A-9b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.10 2006 Data Summary

Table A-10a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	78.6	83.2	87.2	83.2
Lo:	45.8	65.9	73.5	46.5
Hi-Lo:	32.8	17.3	13.7	36.7
Avg:	64.9	75.8	80.6	70.8
Pads 39A+39B				
Hi:	104.4	99.9	91.5	94.0
Lo:	34.5	16.1	68.9	42.1
Hi-Lo:	69.9	83.8	22.6	51.9
Avg:	64.0	75.8	80.5	70.5

Table A-10b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
VAB (HB-1/L7+HB-1/L11+HB-3/L11)				
Hi:	96.0	87.2	96.6	93.7
Lo:	23.6	33.6	44.5	28.0
Hi-Lo:	72.5	53.6	52.0	65.7
Avg:	62.7	66.7	73.5	69.2
Pads 39A+39B				
Hi:	99.9	100.0	100.0	100.0
Lo:	24.9	16.6	40.0	6.6
Hi-Lo:	75.0	83.4	60.0	93.4
Avg:	74.2	75.9	79.2	73.6

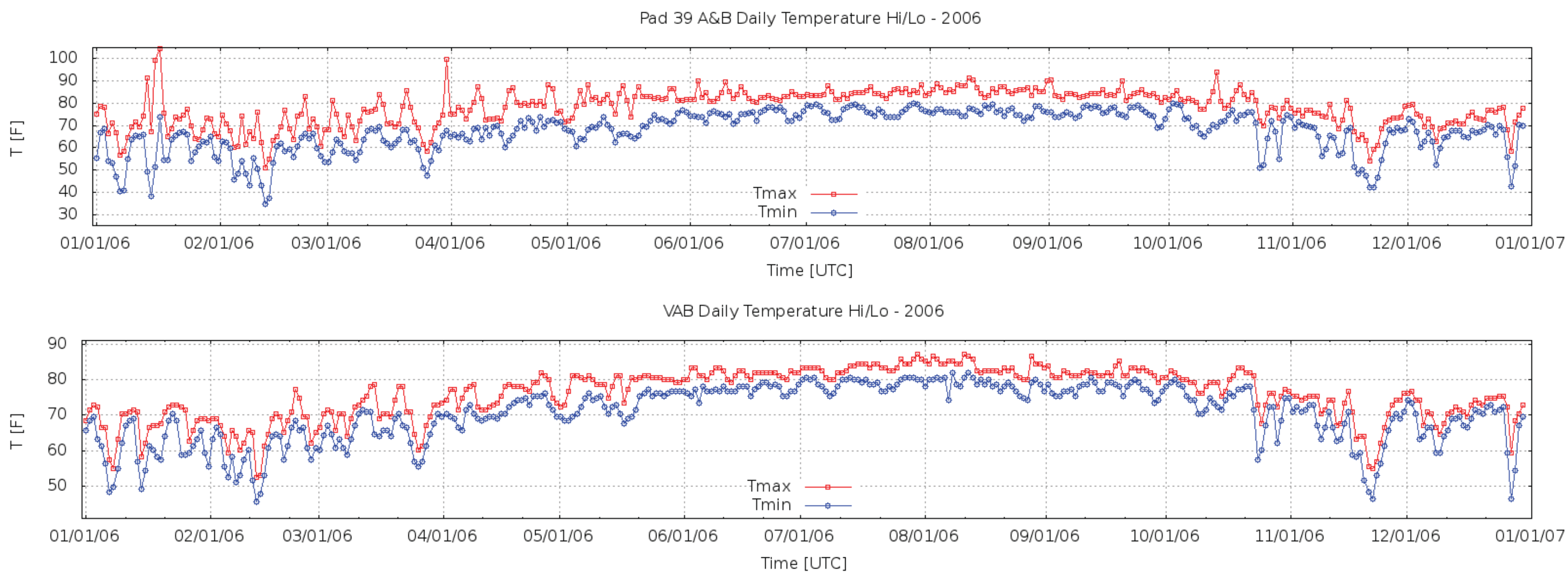


Figure A-10a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

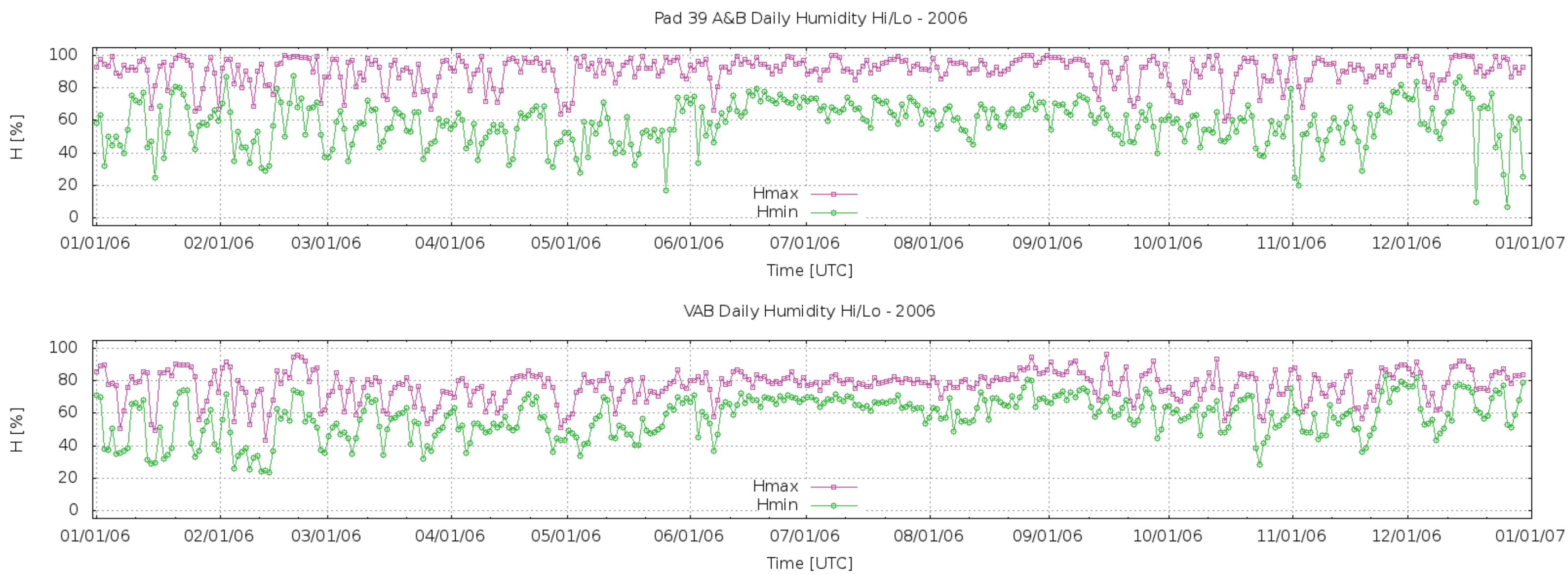


Figure A-10b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

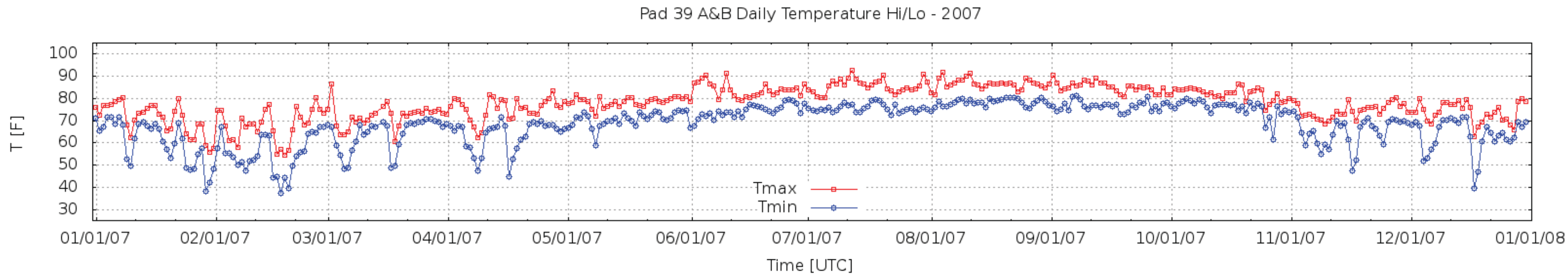
A.11 2007 Data Summary

Table A-11a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	78.0	83.8	88.6	82.5
Lo:	48.5	55.7	73.6	47.1
Hi-Lo:	29.5	28.2	15.0	35.4
Avg:	66.8	75.3	81.4	73.1
	Pads 39A+39B			
Hi:	86.6	91.3	92.6	86.4
Lo:	37.2	44.9	72.3	39.6
Hi-Lo:	49.4	46.4	20.3	46.8
Avg:	64.9	74.3	81.1	72.5

Table A-11b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	97.0	94.4	87.6	87.9
Lo:	27.6	26.4	48.8	23.2
Hi-Lo:	69.4	68.0	38.7	64.7
Avg:	61.4	64.7	71.4	67.7
	Pads 39A+39B			
Hi:	100.0	100.0	99.9	100.0
Lo:	8.6	24.8	23.4	30.3
Hi-Lo:	91.4	75.2	76.5	69.7
Avg:	72.8	72.4	77.8	77.9



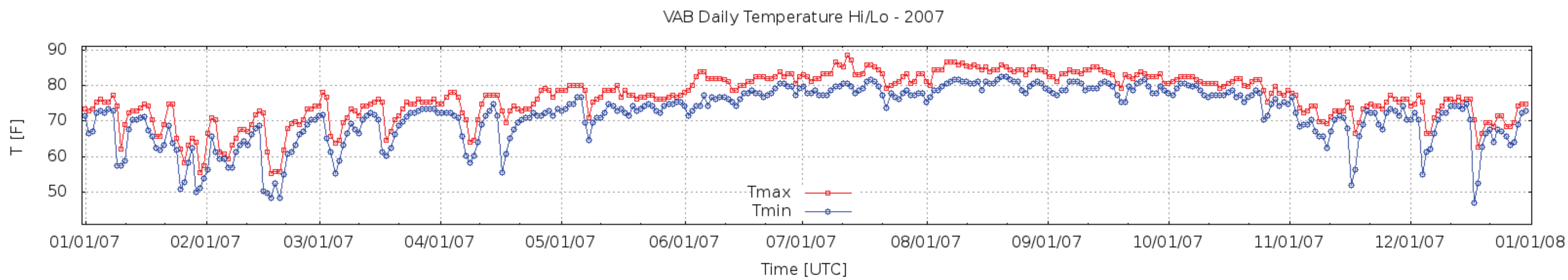


Figure A-11a. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

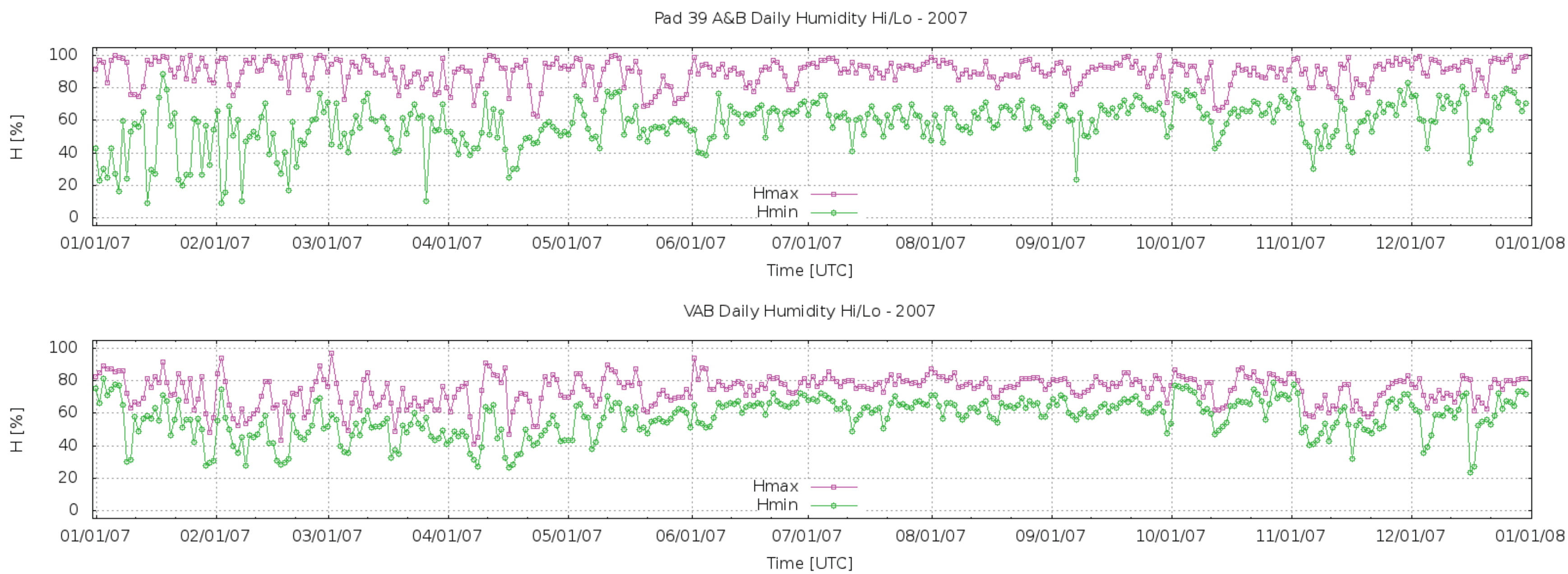


Figure A-11b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.12 2008 Data Summary

Table A-12a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	76.7	83.8	85.8	80.6
Lo:	41.0	53.1	74.1	51.8
Hi-Lo:	35.7	30.8	11.7	28.8
Avg:	66.8	75.7	80.6	70.6
	Pads 39A+39B			
Hi:	86.3	93.7	93.0	84.3
Lo:	35.0	46.8	70.1	44.6
Hi-Lo:	51.3	46.9	22.9	39.7
Avg:	65.3	75.2	80.3	70.4

Table A-12b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	92.1	88.3	94.6	93.7
Lo:	14.2	21.0	51.1	24.3
Hi-Lo:	77.9	67.3	43.4	69.5
Avg:	62.8	67.9	74.6	68.5
	Pads 39A+39B			
Hi:	100.0	100.0	100.0	99.7
Lo:	28.0	18.4	40.8	23.6
Hi-Lo:	72.0	81.6	59.2	76.1
Avg:	75.3	72.2	78.9	74.6

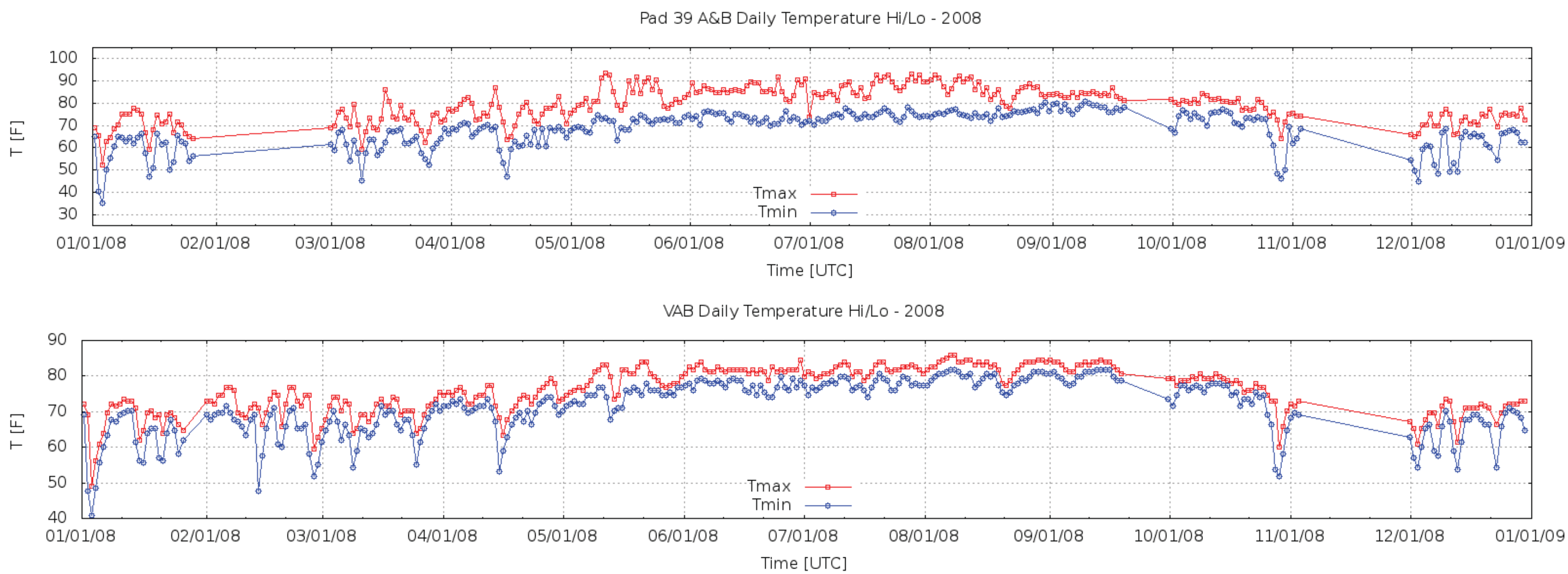


Figure A-12a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

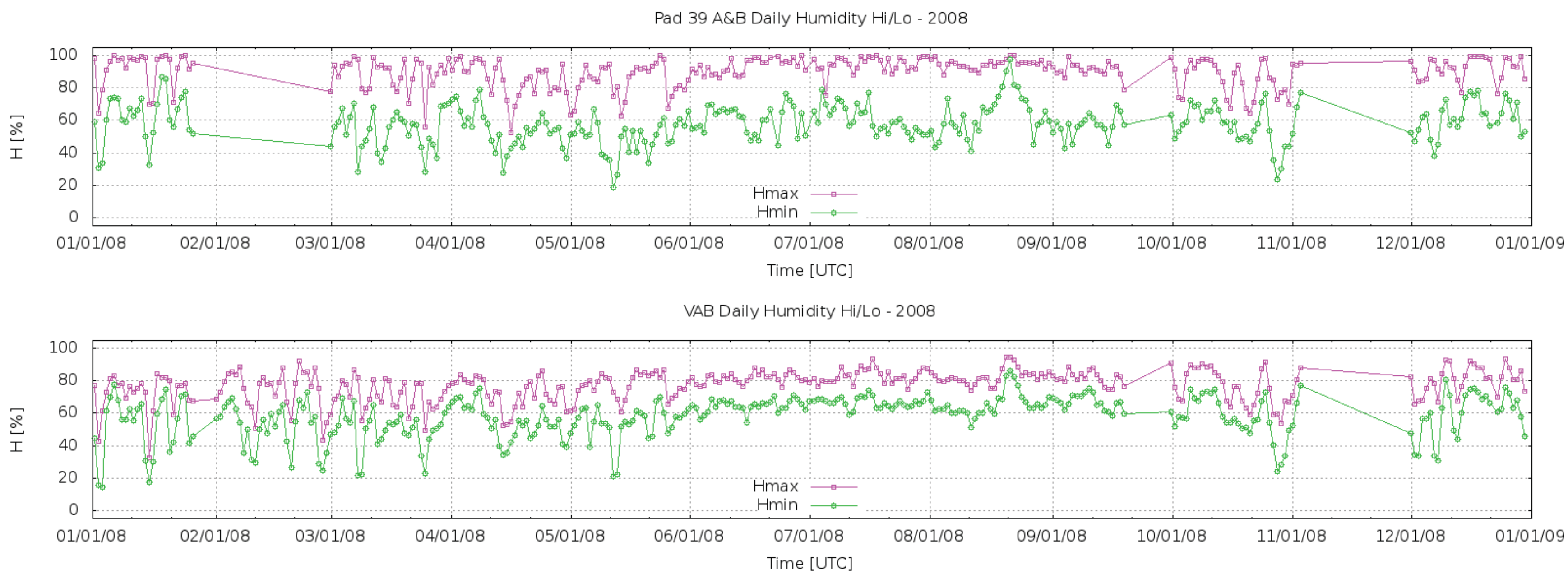


Figure A-12b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

A.13 2009 Data Summary

Table A-13a. Temperature (F°)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	77.3	87.9	87.6	85.8
Lo:	38.8	61.4	75.9	46.9
Hi-Lo:	38.5	26.4	11.7	38.9
Avg:	64.9	76.5	81.5	71.8
	Pads 39A+39B			
Hi:	81.8	93.7	92.1	80.0
Lo:	31.1	45.3	71.6	68.8
Hi-Lo:	50.7	48.4	20.5	11.2
Avg:	62.6	75.8	81.1	no data

Table A-13b. Humidity (%)

	Winter Jan-Feb-Mar	Spring Apr-May-Jun	Summer Jul-Aug-Sep	Fall Oct-Nov-Dec
	VAB (HB-1/L7+HB-1/L11+HB-3/L11)			
Hi:	86.4	88.6	99.4	93.3
Lo:	15.3	19.2	23.8	23.6
Hi-Lo:	71.1	69.4	75.6	69.7
Avg:	58.0	69.2	62.6	59.8
	Pads 39A+39B			
Hi:	99.2	98.3	100.0	86.9
Lo:	15.7	22.9	51.9	49.8
Hi-Lo:	83.5	75.4	48.1	37.1
Avg:	70.8	76.3	83.2	no data

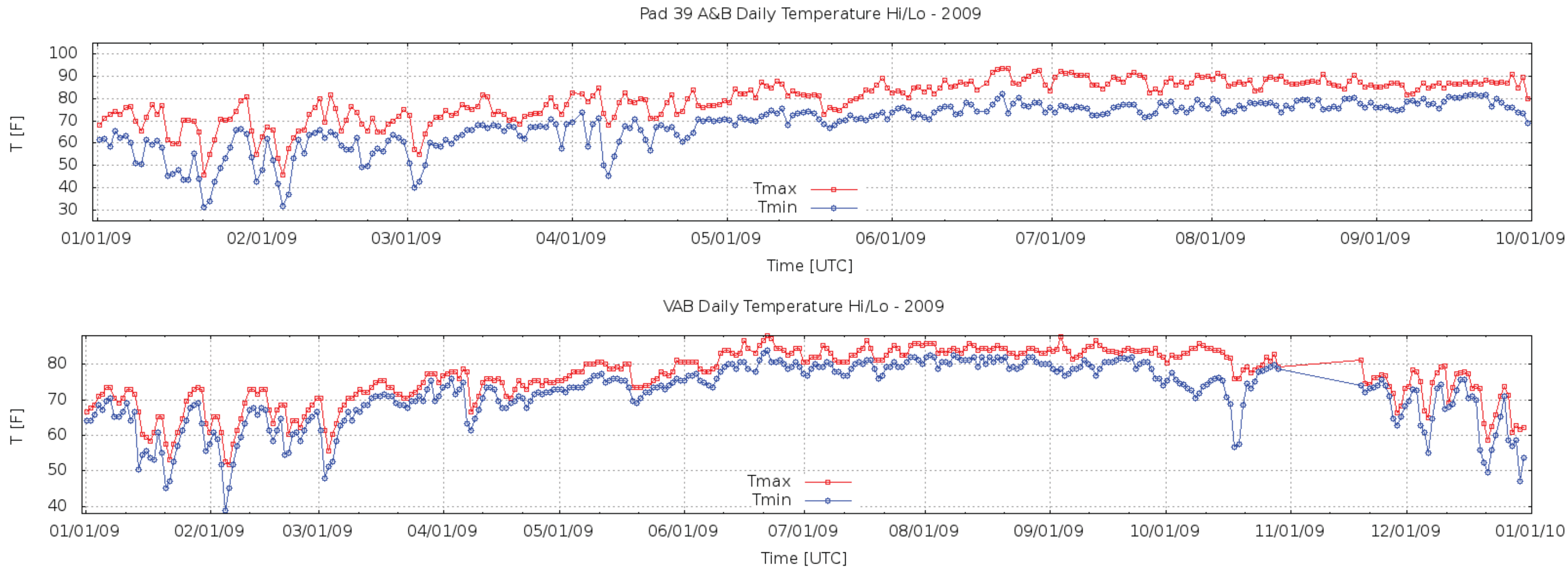


Figure A-13a. Daily minimum and maximum temperature readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

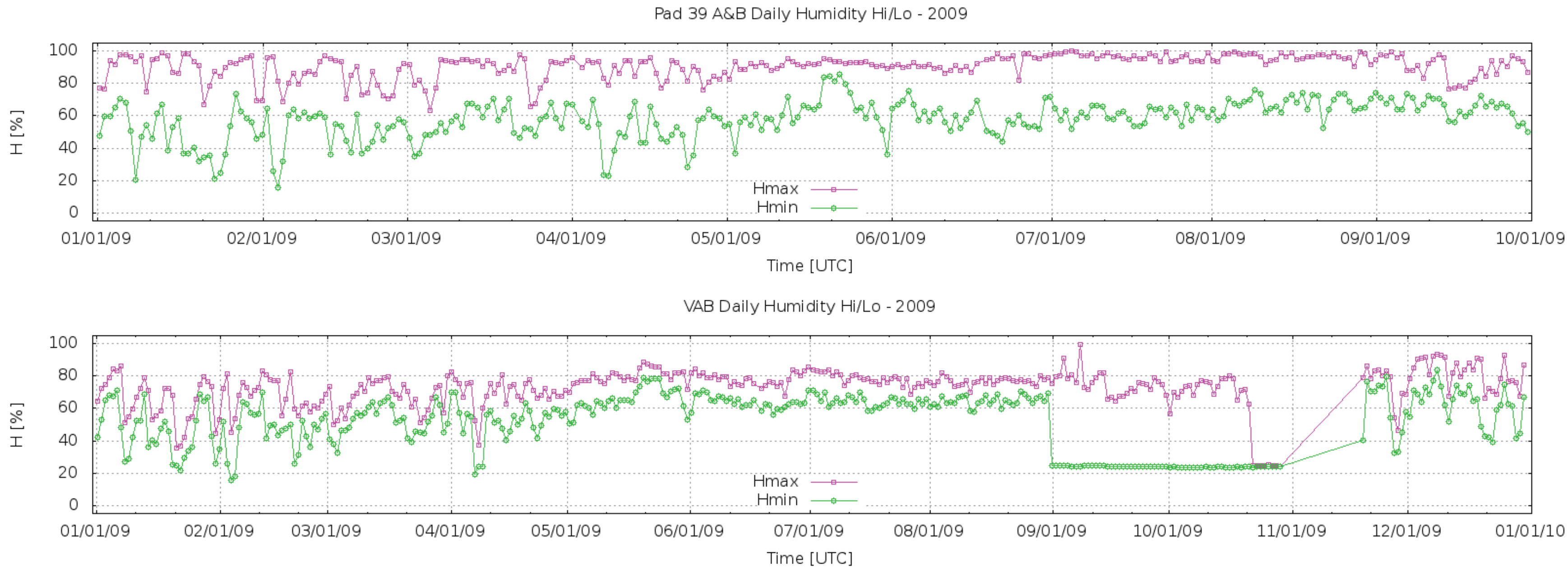


Figure A-13b. Daily minimum and maximum humidity readings for Pad 39A, 39B, and the VAB, including all instrumented levels.

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14. ABSTRACT
In 2012, 17 data loggers were placed in the VAB to measure temperature and humidity at 10-minute intervals over a one-year period. In 2013, the data loggers were replaced with an upgraded model and slight adjustments to their locations were made to reduce direct solar heating effects. The data acquired by the data loggers was compared to temperature data provided by three wind towers located around the building. It was found that the VAB acts as a large thermal filter, delaying and reducing the thermal oscillations occurring outside of the building. This filtering is typically more pronounced at higher locations in the building, probably because these locations have less thermal connection with the outside. We surmise that the lower elevations respond more to outside temperature variations because of air flow through the doors. Temperatures inside the VAB rarely exceed outdoor temperatures, only doing so when measurements are made directly on a surface with connection to the outside (such as a door or wall) or when solar radiation falls directly on the sensor. A thermal model is presented to yield approximate filter response times for various locations in the building. Appendix A contains historical thermal and humidity data from 1994 to 2009.

15. SUBJECT TERMS
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