Using HOBO data loggers with Air/Water/Soil temperature probes to measure free-air temperature on high-altitude balloon flights

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Abstract

HOBO data loggers with Air/Water/Soil temperature probes are commonly used to measure atmospheric temperature during high-altitude balloon flights. Inconsistencies between results from sensors mounted in different ways and between results from a given sensor between ascent and descent confirm that there are many subtleties to making such a measurement properly. These may include, but are not limited to, (a) whether the sensors are exposed to the sun or shaded in some way, (b) where the sensors are physically located with respect to nearby payload boxes (and the color of those boxes), and (c) whether the sensors are surrounded by a thermal wake trailing below the balloon. We will present preliminary results from our investigation and suggest some "best practices" for using these user-friendly temperature sensors on missions to near-space.

Introduction

Measuring the environmental/air temperature, also called the free-air temperature, is one of the most common atmosphere-related data collected during high-altitude balloon flights. A robust yet user-friendly device one can use to make this measurement is a HOBO data logger coupled with an Air/Water/Soil temperature (TMCx-HD) sensor from Onset Computers, where the x refers to the length of sensor cable, in feet. [http://www.onsetcomp.com/products/hobo-data-loggers] Figure 1 shows a typical installation, with the HOBO data logger strapped inside an insulated (and possibly heated) payload box and the temperature sensor dangling outside. Aside: This particular 2-channel U12 HOBO also has a built-in thermometer within its case, allowing one to measure the interior temperature of the payload as well as the outside air temperature.

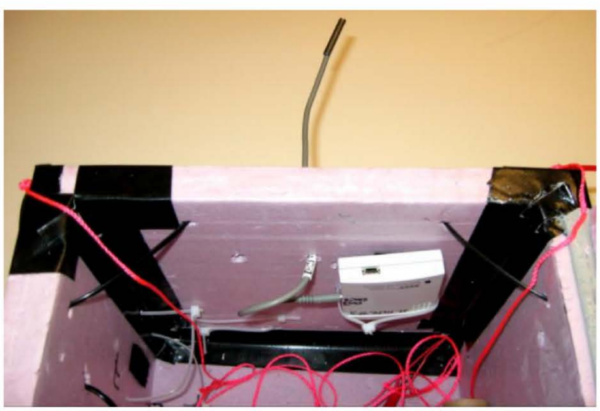

Figure 1: Typical installation of a U12 HOBO data logger and an Air/Water/Soil temperature sensor poking through the payload wall to measure the free-air temperature.

Figure 2a shows typical temperature versus time data collected in a near-space mission. This data is from a StratoStar command pod but data from a HOBO thermometer setup is often similar, though without altitude values attached. One can identify the decreasing temperature during ascent through the troposphere, the increasing temperature during ascent above the tropopause, then same temperature features in reverse time order (but more quickly) during the descent under parachute.

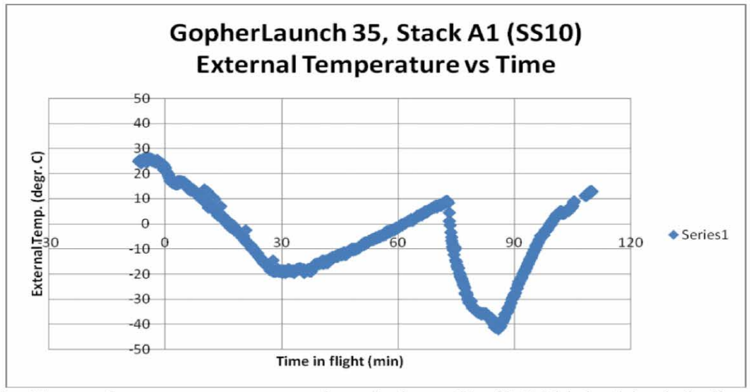

Figure 2a: External temperature versus time during a U of MN high-altitude balloon flight.

One troubling feature of this very common type of data is the fact that the minimum temperature (at the tropopause) on descent is nearly always recorded as being colder than the minimum temperature on ascent, sometimes dramatically so. This discrepancy is even more apparent when the same temperature data is displayed versus altitude, instead of versus time, as in Figure 2b. Clearly this is not the case in the actual atmosphere, indicating a systematic error associated with the temperature measurement itself. This problem, and other nuances regarding measuring free-air temperature found in the literature, motivated us to investigate HOBO U12 data loggers with Air/Water/Soil temperature sensors, trying to better understand their limitations and to reach some conclusions about best practices for their use in high-altitude ballooning missions.

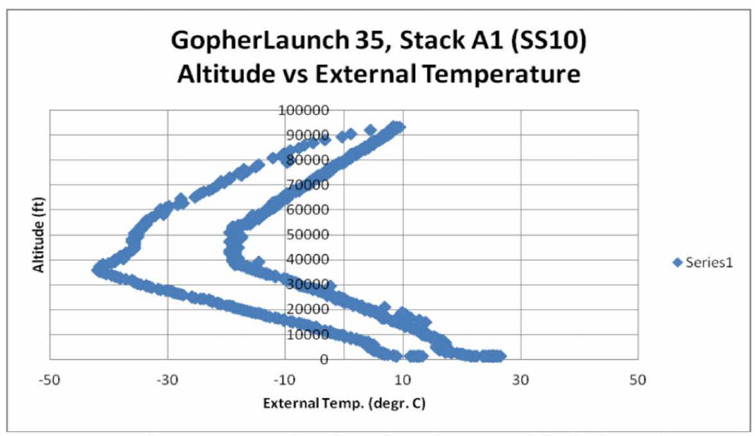

Figure 2b: The same external temperature data but plotted versus altitude instead. Ascent data is on the right; descent data is on the left.

Manufacturer's specs

According to Onset Computers, when used with U12 HOBO data loggers the Air/Water/Soil temperature sensors have a range of -40° to 212°F (-40° to 100°C) in air, with an accuracy of ±0.45°F from 32° up to 122°F (±0.25°C from 0° up to 50°C), a resolution of 0.05°F at 68°F (0.03° at 20°C), and a response time of <3 min in 3 ft/sec (1 m/sec) air flow. Also "(a solar) radiation shield (is) strongly recommended for use in sunlight." Physically, the temperature sensor measures 0.2 x 1.2 inches (0.5 x 3.1 cm) and is embedded in a solid (perhaps potted in epoxy) and covered by plastic then a copper-plated metal jacket which is silver in color.

HOBO operation at low temperatures and low pressures:

Onset Computers does not make any claims about whether HOBO data loggers can operate in the low-temperature, near-vacuum, and/or high (cosmic) radiation environments. We conducted a series of lab tests to study the performance of multiple HOBO U12 data loggers and multiple Air/Water/Soil temperature sensors, with an eye toward their utility in near-space. Our results suggest that HOBOs are effective even when they get moderately cold, down to about -4°F (-18°C). Our attempts to determine whether HOBOs are influenced by low pressure were inconclusive, but flight experience suggests that HOBOs can operate down to less than 1 psi.

Speed of Response and Calibration Consistency:

Our "wake boom" experiment, described in more detail below, made use of 6 temperature sensors monitored by one 2-channel and one 4-channel U12 HOBO. To check the calibration, we tried all 6 sensors in all 6 HOBO channels. The results suggested that the room temperature reading for a single sensor does not vary more than 0.39 °F as it is plugged into different HOBO channels and the variation in readings from different sensors plugged into a single HOBO channel was not more than 0.12 °F. The sensor values are within the manufacturer's specs mentioned above.

Figure 3a below shows how the readings on the 6 sensors in the configuration used for the wake boom flights compared when the set of sensors was put into a deep freezer. The variation among sensor readings at room temperature is about 0.75°F, as shown in Figure 3b. The variation among sensor readings at freezer temperatures is about 2.0°F, as shown in Figure 3c. Notice that the sensors take about 15 minutes to reach equilibrium after being subjected to a temperature drop of about 85°F. Temperatures change most rapidly, about 10 to 15°F/min, during the early part of the descent. This data suggests that that rate may be sensor-limited, and merits further experimentation. Notice that the warmest-to-coldest order of sensors is different at the two temperatures in Figures 3b and 3c, from which we conclude that the calibration discrepancies for HOBO thermometers are in fact temperature dependent.

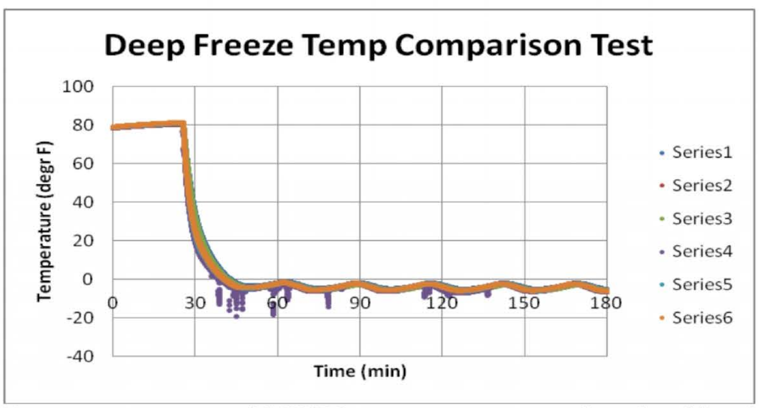

Figure 3a: Temperature response of 6 HOBO temperature sensors when placed in a deep freeze.

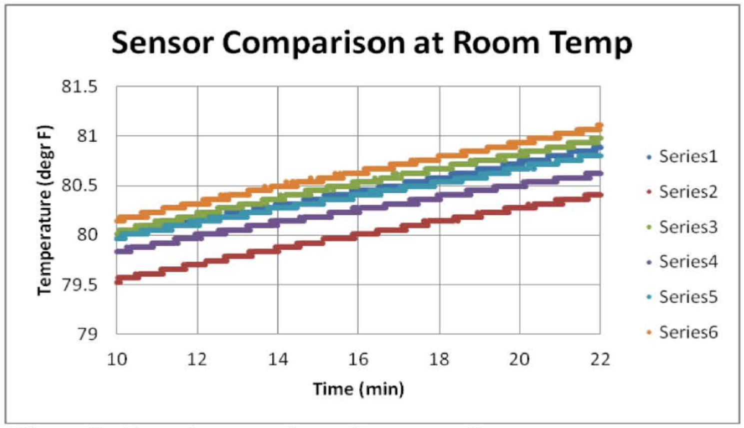

Figure 3b: Zoom-in comparison of sensor readings at room temperature.

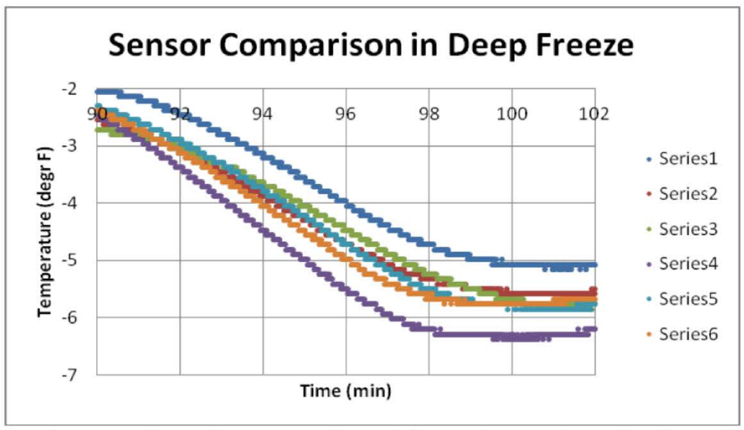

Figure 3c: Zoom-in comparison of sensor readings at freezer temperature, showing a different order.

<u>Effect of Sensor Color, Sun Shades, and Nearby (Typically-Warm) Objects</u>

Not unexpectedly, exposure to direct sunlight can influence the reading of a HOBO temperature sensor. Ground tests comparing reading in the sun to those made in the shade suggest this effect may be on the order of 6.5°F (3.6 °C). Figure 4 shows an apparatus we used to document the effect on temperature readings of sun shades with various interior and exterior colors.

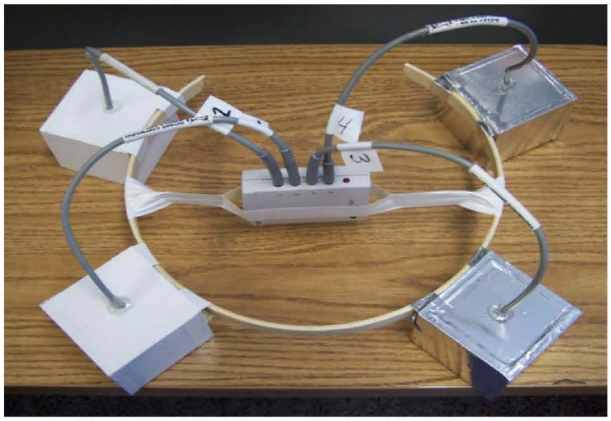

Figure 4: Sun shade ground-testing apparatus.

However there are also drawbacks to trying to shade temperature sensors, not the least of which is that they tend to register the temperature of the shading device itself rather than the free-air temperature. Using reflective or white-colored sun shades, rather than dark-colored one, can alleviate this issue to some degree, but our experiences suggest that using sun shades tends to even out potentially-legitimate variations in temperature measurements and increase the response time to genuine changes in free-air temperature. Reference (3) suggests that a better solution may be to leave temperature sensors exposed to direct sunlight, but color them white so they don't absorb much solar radiation. Preliminary ground testing of Air/Water/Soil temperature sensors suggests that in direct sunlight white-painted ones average about 2.1°F (1.2°C) cooler and black-painted ones average 2.9°F (1.6°C) warmer than standard silver-colored ones. In the shade black-painted sensors essentially match silver-colored ones, but white-painted sensors still average 0.6°F (0.3°C) cooler.

Whether the sensors is shaded or not, the presence of a nearby warm object (such as the payload box in which the HOBO data logger itself is mounted) can also influence the temperature readings. Indeed, sensors mounted adjacent to or within the walls of a payload box will return temperatures of the payload wall material rather than the free-air temperature, or a mixture of these two temperatures. We conducted one flight with a "multi-colored" payload (see Figure 5) which had exposed HOBO temperature sensors mounted near black and silver-colored walls, as well as sensors in sun shades a few inches and 20' and 50' below the payload. The results from this flight showed that a shaded sensor just below the payload was, on average, about 3°F (1.7°C) warmer than an exposed sensor at the same location, speaking to the influence of the warm shade and/or the warm payload box nearby. Near the peak of the ascent an exposed sensor just outside a black payload side grew in temperature relative to an exposed sensor outside a silver payload side until it was a full 10°F (5.5°C) warmer, again attesting to the non-negligible impact of a nearby warm object. Shaded sensors 1' and 20' below the payload nearly matched in temperature right up to burst, but a shaded sensor 50' below the box stayed 10°F (5.5°C) colder during the warming in the stratosphere, possibly indicating that that lowest sensor was below the thermal wake of the balloon (see discussion of wake experiment below).

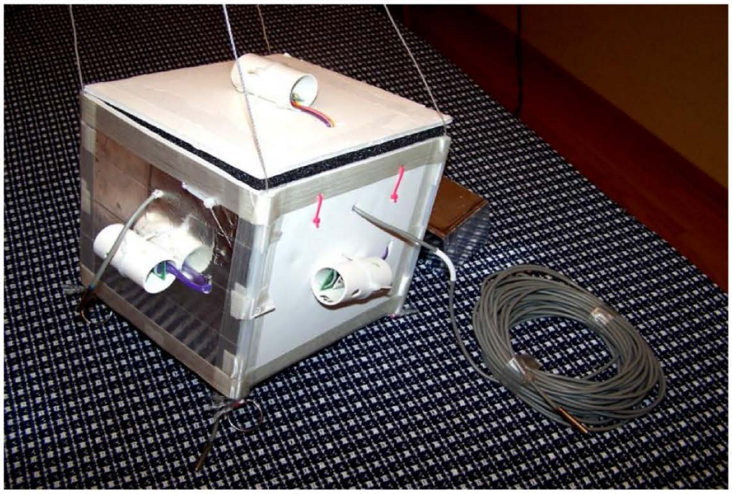

Figure 5: “Multi-colored” payload showing white side and silver side. The other sides were black and pink. HOBO thermometers, some shaded (not shown) and others exposed, some dangling many feet below the payload were used to study how the presence of the payload itself affected the recorded temps.

As a portion of a University of St. Catherine class project in May 2012, sun shades were added to sensors that were then flown on two different flights to date. Students predicted that the effect of covering the sensor would not show a significant change in temperature. It was revealed during data analysis that indeed a significant effect (> 4° F difference in temperature between the covered sensor and uncovered sensor occurred -well outside of calibration differences of the sensors) See Figure 6 to see a picture of the second generation setup.

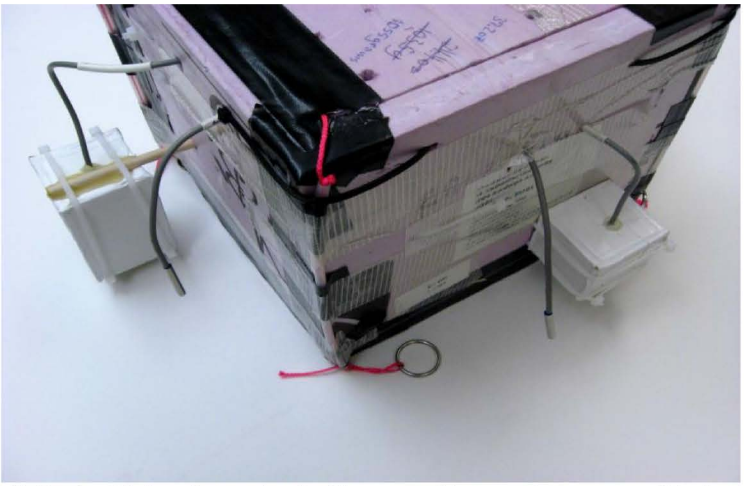

Figure 6: St. Catherine University payload with exposed temperature sensors (2) plus sun shielded sensors, one on a boom.

The second generation of probe/box configuration was arranged in such a way as to try and isolate the covered probe from the effects of heating from the payload itself. We present (Figure 7) data derived from GL 50 a nighttime flight.

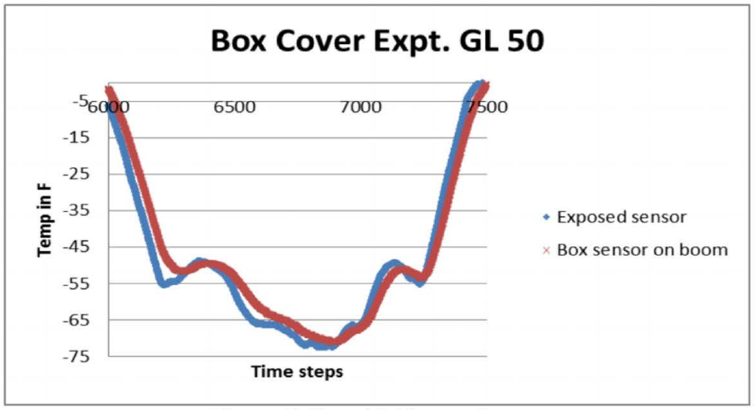

Figure 7: Sun shield experiment.

The data show the trend seen with both boxes attached to the payload itself as well as isolating the box on a boom in that the box senor data indicates a warmer reading > 4 degrees F as well as the box experiences a "time lag" measuring minima at a time later that seen by the exposed sensor. This trend holds also for daytime flights for which the sun shield was developed. The covered sensor has been warmer than the exposed sensor and tends to be so by at least 4 degrees F in all of the flight data collected thus far.

The Thermal Wake Experiment:

As cited in papers (1-3) a thermal wake exists below an ascending balloon. On a daytime flight the temperature of the air directly beneath the balloon will be warmer due to solar radiation hitting the balloon and this in turn affects the air beneath the balloon. According to (3) "…it may be concluded that, to altitudes of 100,000 ft, the air temperature below a balloon does not differ from true ambient temperature by more than 1C, so long as measurements are made at least 25 ft below the balloon". So as to be "in the wake" we typically made temperature measurements within 20 ft of the balloon, near the top of our stack. In references 1 and 2 the length of the wake is not as clearly defined and appears to presumed to be even longer in extent. In addition to the daytime phenomena, an opposite effect (1-3) has been shown to occur during night flights when the adiabatic gas temperature inside the balloon is lowered which then lowers the balloon skin temperature. The cool skin temperature of the balloon cools the air beneath the balloon, affecting measurements below the balloon. The effect in both the daytime and nighttime is said to be stronger with a decrease in air pressure as so we except to see the effect after the crossing of the tropopause boundary.

We set out to see if we could measure the wake from an ascending balloon using the HOBO data loggers already discussed in early sections of this paper. Would any difference exist in measurements of the temperature at different locals along a horizontal boom placed perpendicular to the wake? A four channel HOBO data logger was used to measure the "non center" temperatures while a two channel HOBO data logger was used to measure the temperature in the central region- one 6ft and one 1ft temperature probe was used to see any discrepancy existed due to probe length. Figure 8 below shows the schematic as well as pictures of the experimental boom. It is important to know that we used white hollow PVC tubes to place the temperature probes in. The hollow nature of the tubes will help air currents reach to sensors.

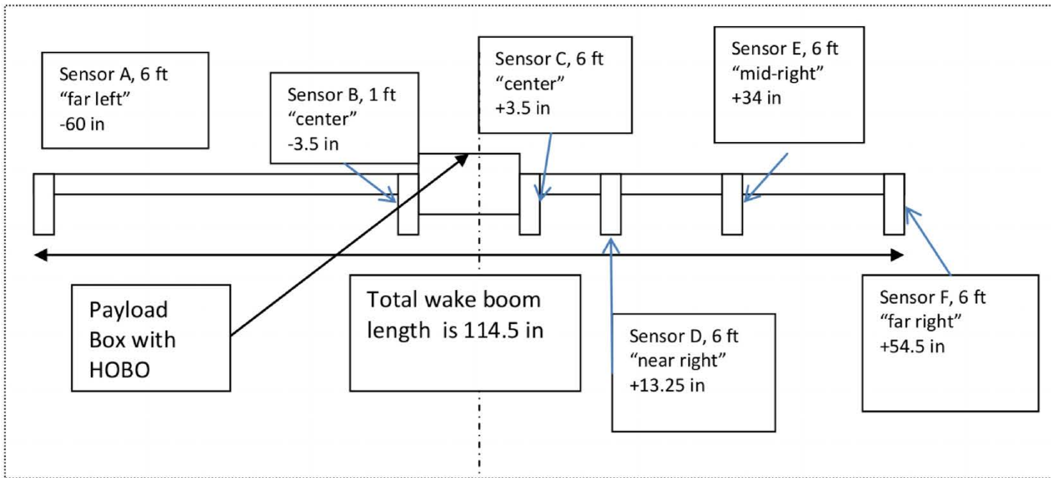

Figure 8a: "Wake Boom" schematic and dimensions.

Figure 8b: Photos of the wake boom experiment.

Figure 8c: The wake boom ready to be launched.

A series of three daytime flights have been conducted as well as one nighttime flight of the wake boom experiment. A data logging issue occurred on the first flight (GL47). Data from (GL 48 and 49) both were similar – we will present (GL 49) flight data related to the daytime ascent. We then present the nighttime flight data from (GL 50).

Daytime ascent data (GL 49): Figure 9a shows the temperature profile for pre-burst and post-burst data. We noticed a difference in the temperature profiles especially towards the end of the accent of the balloon (seconds before burst resulted in the largest temperature differentials).

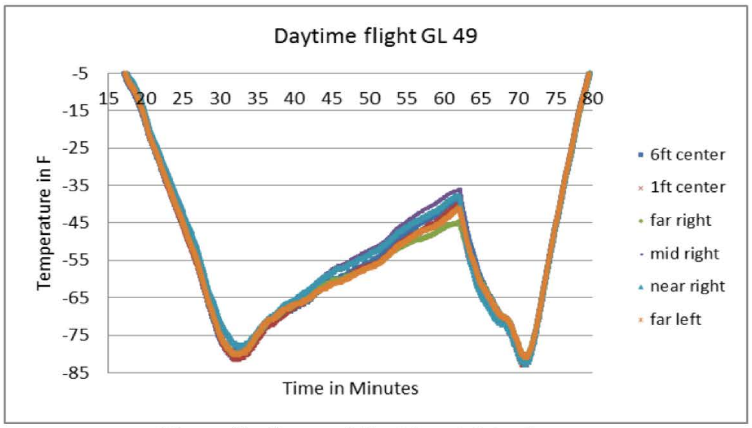

Figure 9a: Pre- and Post-burst data shown.

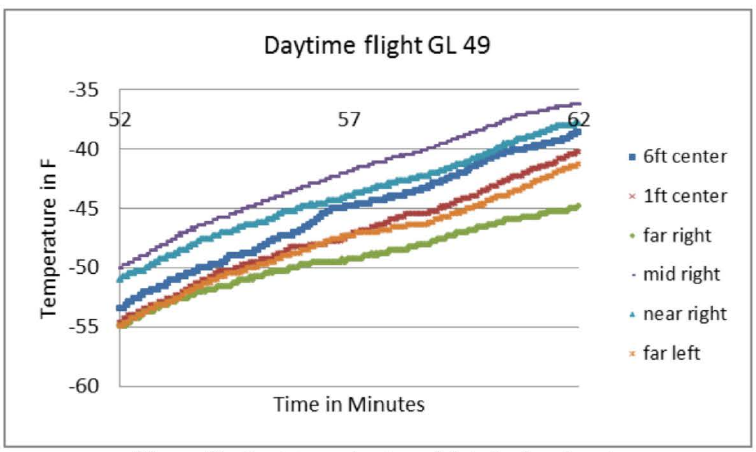

Figure 9b: Last ten minutes of data before burst.

Looking at the data in figure 9b as well as the whole fight record (not shown), it appears that the mid right sensor was always reading about 1°F warmer that it should have been during the flight and afterwards. A trend in both daytime flights was the presence of colder measurement by the far right and far left temperature probes – presumably in the area outside of the wake effect. Looking at the data it would appear that a cold region exists near the payload box, that a warmer region is in the mid range area and that the coolest measurements exist on the ends of the boom. Calibration may account for some of the warm region effects seen in the data in the middle and near temperature sensors. It is interesting to see a small difference in the measurements made by the 1ft and 6ft sensors on the payload. It appears that about a 1°F difference does occur between both of these sensors. Given that the distances were exactly the same we suggest that this difference is all related to differences in the sensors.

Nighttime flight (GL50): Figure 10a contains a plot of the pre and post burst temperature data – this particular flight was launched at approximately 1:00 a.m. CDT.

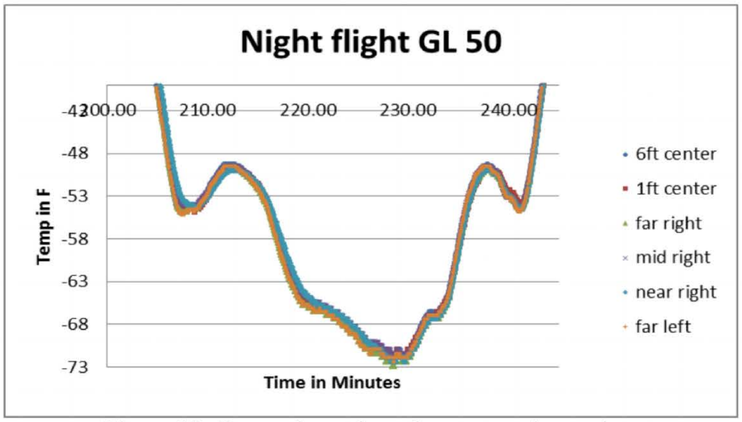

Figure 10a Pre- and post-burst boom experiment data

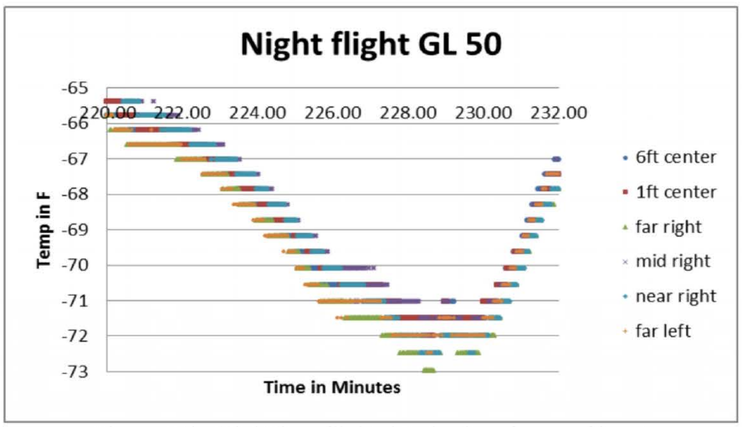

Figure 10b: Nighttime flight data in time frame of burst

According to reference (1) One should observe the "…effect of lower temperature readings during ascents than during descents …" –in all of the wake experiments we seem to see all the sensors reach a common temperature (within 1 degree F) on decent of the balloon. Data from flight GL 50 indicates that the coolest region at the far end of the boom with again the center payload area also being located in colder region (but not as much as the ends) and the mid probes measuring the warmest. Again on this flight it appears that the mid right probe is reading "warm" throughout the flight but not to the extent it was during the GL 49 daytime flight.

Possible next steps/best practices in the project:

A) It does appear that HOBO's have the capability to measure find temperature changes in an environment that is outside of the "normal" operating range – a need to double check with thermometers that are listed to operate in balloon temperature range
B) Significant calibration of probes and loggers to fine tune offsets for future flights
C) Reconstruction of boom with possible generation two boom – more precise placement of cowls and temperature probes.
D) More Flights – a large data set is needed for both day and night flights. Would time of year influence measurements in any way?
E) Higher altitude – (GL 48 and GL 49 reached altitudes over 100,000 ft and GL 50 reached an altitude of 66,000 ft – we need more night flights!), (the effect is to be more significant with lower pressure – fly minimalist flight package and go for greater height with just wake experiment and tracking equipment.
F) Looking into Geometry of sensors – See supplemental section A

Summary:

HOBO U 12 data loggers with the air/soil/water sensors appear to be in agreement with the manufacturers specifications for "normal operating ranges". We fly the sensors outside of the specified ranges but the results seem to indicate performance that is reasonable. The boxes and sensors themselves do individually have offsets associated with them. The offsets however are temperature dependent and so calibration at any one temperature is tricky. Individual channels on the box do also have a small offset well within the manufacturers range. One should take to time to understand the differences in each channel before making absolute conclusions about temperature being measured in a certain channel. It is unclear whether pressure affects the sensors in any way at this stage.

HOBO data loggers are recommended to have sun shields placed near them. From our series of flights we can conclude that a difference does occur with using sun shields. We would recommend using both exposed and non-exposed sensors for measuring temperature. The exposed sensors appear to measure fine changes in temperature variation much more so than the sun shielded sensors. It also appears that an enclosed shield will cause the temperature measurements to lag exposed sensors. We also suggest experimenting with in a very light coat of while paint to be applied to the sensor versus the out of the box aluminum colored sensor. One need also be very observant of the box color that is flown. A white or silver box is preferable for free air temperature measurements (though black boxes are better at keeping themselves warm). One also needs to be aware of the proximity of the sensor to the box. On very early flights St. Kate's used to fly with the probe just barely (aluminum portion just poking out) outside the box - this is not recommended!

We feel that looking for the thermal wake was a worthwhile endeavor. Preliminary results show an effect at lower pressures as predicted in the references. More flights need to be conducted. Looking at constructing version two of the wake boom is not out of the question. Placement of sensors will need to be adjusted with even more precision and construction of a longer boom can be investigated. A significant number of flights, both daytime and nighttime flights, should have the wake experiment on board. At least a couple of flights should have minimalist load so as to reach very high altitudes – under those circumstances hopefully the temperature differential should be even greater than that already observed.

Supplemental section A:

In paper (2) mentions that for a cylindrical thermometer

F = Power conducted per degree temperature difference between thermometer and air/ Power radiated per degree temperature difference between thermometer and black body temperature

$$F = \frac{K}{4\sigma T^3 \epsilon} \frac{1}{R \ln \frac{L}{R}}$$

where K is the thermal conductivity of the air, σ is Stefan Boltzmann constant, ε is the IR emissivity, R the radius of the probe and L the length of the thermometer. The authors state that a spherical thermometer will have a larger figure of merit and therefore be a better thermometer.

References:

(1) Tiefenau, H. and Gebbeken, A. *Influence of meteorological balloons on Temperature Measurements with Radiosondes: Nighttime Cooling and Daylight Heating,* J. Atmos. and Oceanic Tech. **6** (36-42), 1989

(2) Ney, E., Maas, R. and Huch, W. *The measurement of atmospheric temperature*, J. Meteor., **18** (60-80), 1960

(3) Brasefield, C.J., *Measurement of air temperature in the presence of solar radiation*, J. Meteor., **5** (147-151), 1948