

High Altitude Thermal Wake Investigation

Student team members: Rachel Hedden, Mara Blish and Amanda Grove, St. Catherine University, St. Paul, MN

Erick Agrimson, Faculty Advisor, St. Catherine University, St. Paul, MN
epagrimson@stkate.edu

James Flaten, Faculty Advisor, University of Minnesota and MN Space Grant, Minneapolis, MN
flaten@aem.umn.edu

Using various temperature sensors and data loggers, we continue to investigate various thermal effects during high altitude balloon flights. Of particular interest is the thermal wake generated by ascending balloons. During daytime flights the temperature of the air directly beneath the balloon, where payloads typically are located, is warmer than the surrounding air due to solar radiation hitting the balloon which, in turn, warms the air passing close to the balloon that forms the wake. One reference suggests that this thermal effect is only significant within 25 feet of the base of the balloon. We fly a “wake boom” near the top of our payload stack, less than 25 feet from the neck of the balloon, with temperature sensors which extend horizontally from directly below the balloon to outside the predicted width of the wake. We have used different wake boom designs on multiple flights to measure temperature profiles in the wake region.

I. Introduction

In a paper presented by Agrimson and Flaten at the third annual Academic High Altitude Balloon conference, introductory work related to the use of HOBO data loggers and sensors as a way of determining the temperature in the atmosphere was presented (1). A summary of that report was as follows as well as the following modifications:

“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 temperature ranges but the results seem to indicate performance that is reasonable. The sensors themselves do individually have slightly-temperature-dependent offsets associated with them, so calibration is tricky. Individual channels on the data loggers also have small offsets, though well within the manufacturer’s tolerances. One should take to time to understand the differences in each channel before making any final conclusions about temperatures being measured in a specific channel. It is unclear whether pressure affects the sensors in any way at this stage.”

According to the manufacturer, HOBO temperature probes are recommended to be used with sun shields (2). The data from our series of flights show a difference (see figure 7 of reference (1), occurring when using sun shields. The use of HOBO temperature probes without the use of sun shields appears to have a more rapid response to temperature changes in the atmosphere (1). It was determined that the time lag produced by sun shields, as well as the semi – insulated property of the cowls (allowing temperatures to read warmer than non-shaded probes), was not worth the effort of flying. All flights of the wake boom flown in 2013 now have white painted sensors flown without sun shades. Data shows that after burst the exposed temperature sensors all reach a similar temperature within minutes of burst (this was not always the case with the sun- shaded sensors). We suggest a light coat of white paint to be applied to the sensors, versus using the out-of-the-box aluminum color. Painting the temperature probes white increases the reflective properties of the temperature probe, which will hopefully result in the sun’s rays having less of an effect on the temperature readings. The color of the payload and the proximity of the box to the sensors also need to be taken into account.

Further research is needed in studying the thermal wake. “Preliminary results show an effect at lower pressures (i.e. above the tropopause) consistent with the references”. Looking at constructing version two of the boom may be beneficial to the experiment. The placement of the temperature sensors and the distances between them will be measured with precision to accurately depict changes in temperature across the thermal wake. Our research shows little to no evidence that there is a compelling change in temperature change beyond about 50 cm from the center of

the boom. “A significant number of flights should have the wake experiment on board. At least a couple of flights should have minimal loads so as to reach very high altitudes – under those circumstances the temperature gradient should theoretically be even greater than that already observed”.

Placement of sensors has been and continues to be an interesting experimental question. One of the challenges we have faced is the use of differing size balloons. All the wake references, and as one critically thinks about the issue, suggest that for a more thorough study, balloons of the same size should be used with a careful consideration of how much Helium is used in filling the balloon. We are still adjusting the locations of the temperature sensors, as each flight tells us more about the spatial extent of the thermal wake for a certain balloon size. Careful placement of the sensors should allow us to experimentally characterize the wake and compare its features to theory as discussed in the references and in the additional parameters (section A) at the end of this paper.

II. The Thermal Wake

A thermal wake exists below an ascending balloon (3-5). 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 Brasefield, C.J “...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 1° C, so long as measurements are made at least 25 ft below the balloon” (5). So as to be “in the wake” we typically made temperature measurements within 20 ft of the base of the balloon, near the top of our stack. The length of the wake is not as clearly defined and it is apparently presumed to be even larger in extent (3 & 4). In addition to the daytime phenomena, an opposite effect 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 (3). The cool skin temperature of the balloon cools the air beneath the balloon, affecting temperature measurements below the balloon. The effect in both the daytime and nighttime is said to be stronger with a decrease in air pressure. “Reynolds numbers smaller than 10^5 , the thickness of the heat exchange layer will increase with decreasing pressure, where $d \approx (\bar{P})^{-1}$, (P = air pressure) (3).”

Based on this summary from last year’s experiments we set comprised the following list of goals for St. Catherine University’s (SCU) summer scholars program. SCU has a competitive program for select students to spend 10 weeks in the summer working on a research project with a faculty advisor. The 3 student authors of this paper are involved in this program for the summer of 2013.

III. Research questions for summer 2013 investigations

- A) What is the thermal wake effect?
 - A.1.1 Can we distinguish between temperature differences due to instrumentation or nearby payload box color versus the actual thermal wake effect?
 - A.1.2 What is the wake temperature profile as a function of altitude for the daytime effect?
 - A.1.3 What is the wake temperature profile as a function of altitude for the nighttime effect?
 - A.1.4 How do different temperature sensors add to the knowledge of the thermal wake effect? i.e We have used HOBO sensors thus far, but realize that more sophisticated temperature sensors exist – how much can be learned from the use of different temperature sensors?

- B) How does sensor shading and sensor placement (geometry) affect the reading?
 - B.1.1 How do sun shades versus exposed sensors alter the readings?
 - B.1.2 Does placement of the sensors horizontally versus vertically alter the readings? That is to say how many sensors are needed on a boom to define the spatial extent of the wake?
 - B.1.3 How does geometry of the sensor affect the readings? -i.e Spherical sensors have a different profile versus cylindrical ones (4) a cylindrical thermometer: $F = \text{Power conducted per degree temperature difference between thermometer and air} / \text{Power radiated per degree temperature difference between thermometer and black body temperature}$

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

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 will therefore be a more effective thermometer.

C) How many flights (n) and in what configurations are necessary to draw firm conclusions?

C.1.1 What series of daytime and nighttime flights would be best and in what order should the flights take place?

C.1.2 Does the time of year a significant player in determining n?

D) How do calibration issues and/or sensor drift influence data?

D.1.1 What type of temperature drift can occur with our sensors?

D.1.2 Do other Near-Space conditions, such as low pressure, influence temperature sensors (2)?

IV. Methods

Of note: we have continued using HOBO data loggers for the beginning of the summer's research. We are aware of more sophisticated apparatus of measuring the temperature. We have wanted to see how far we can go with the off the shelf system that is low cost, easy to use and is very easily modifiable in many different configurations. We are in the proof of concept and basic practice portion of the study at this point. As the study progresses we will be utilizing other types of temperature sensor methods for crosschecking our data. As of this writing, the wake-boom experiment has been flown on 3 daytime balloon missions since our summer 2012 report (1). For numbering continuity with summer 2012, these flights will be called 6D, 7D, and 8D, where "D" refers to a daytime flight. The basic parameters of the 2013 flights are as follows:

6D: The boom was flown to 80,410 ft under a 600-gram Kaymont balloon. The boom had 6 temperature sensors, one white-painted and one unpainted (aluminum-colored) located 7 cm from the (black) payload box, then white-painted sensors taped under the (black) boom at 53 cm, 94 cm, and two at 156 cm from the center of the wake. Sensors were located on both sides of the boom because the wake has been shown to be horizontally symmetrical.

7D: The boom was flown to approximately 90,000 ft (tracking challenges required us to estimate the maximum height) under a 1500-gram Kaymont balloon. The boom had 8 white-painted temperature sensors, two located at 7 cm on either side of the (black) payload box, then sensors taped under the (black) boom at 35 cm, 53 cm, 78 cm, 94 cm, 142 cm, and 156 cm from the center of the wake.

8D: The boom was flown to 84,846 ft under an 800-gram Hwoyee balloon. The boom had 8 white-painted temperature sensors, two located at 7 cm on either side of the (half white; half black) payload box, then sensors taped under the (now-white) boom at 13 cm, 19 cm, 25 cm, 35 cm (this sensor malfunctioned so its data is not presented), 43 cm, and 155 cm from the center of the wake.

Note that we don't expect the balloon manufacturer to make a difference – all balloons are light-colored latex rubber – but the balloon mass (and hence the ultimate size prior to burst) is expected to influence the width of the thermal wake.

The temperature probes were roughly the same distance from the center of the payload on both sides for flight 6D and 7D. The most recent version of the wake boom (flight 8D) the wake was covered half in all in white tape and half in all black tape (Figure 1a and 1b). This was unlike prior versions of the wake boom, where the boom was all black. The carbon fiber tubes comprising the structure of the wake boom are naturally black. For flight 8D we taped over the black carbon fiber tubing to reduce any effect caused by color variations of the central payload box or the boom structure itself (Figure 1 and 1b). This could potentially influence temperature readings in the sensors taped along the horizontal boom.

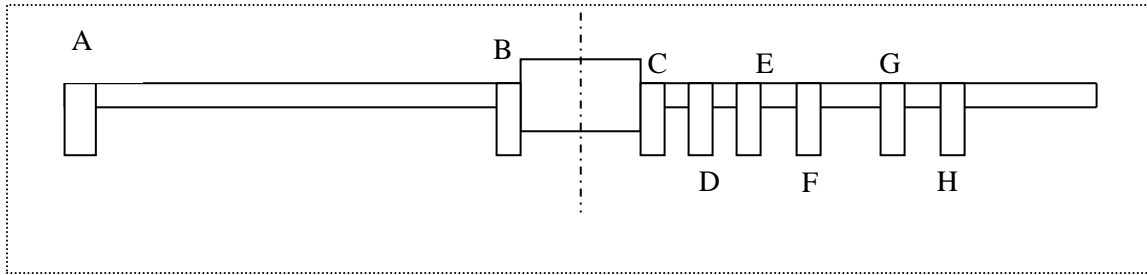


Figure 1a: Boom schematic for the 8D flight. The dimensions of the box were: 26.2cm X 17.9cm X 11.5 cm.

The length of the carbon fiber tubing that held the temperature probes were 318.4 cm and was covered in white electrical tape. The side of the box with six temperature probes was colored white with Scotch decorate and repair tape while the side with two temperature probes was colored black with Gorilla tape. The letters above correlate with the position of a temperature probe (cm) on the box: A 168.2, B 20.2, C 20.2, D 26.6, E 32.4, F 38.2, G 56.0, and H 67.7. The model of the wake boom for the 6D flight was similar to this, but the box was all black (using gorilla tape) and the temperature probes were the following lengths (in centimeters) from the center of the box: 20.2, 20.3, 48.5, 66.4, 91.4, 107.0, 154.9, and 169.2.



Figure 1b: Photo of the wake boom experiment and the SCU student team (Starting from the left: Rachel Hedden, Amanda Grove, and Mara Blish).

V. Results

Temperature sensor values along the length of the boom diverge the most above the tropopause, as shown in Figure 2a from flight 8D (although the tropopause itself was not very abrupt in this particular flight). The sensors were more-closely spaced during this flight than in previous flights, to better capture the spatial (horizontal) extent of the thermal wake, as shown in Figure 2b.

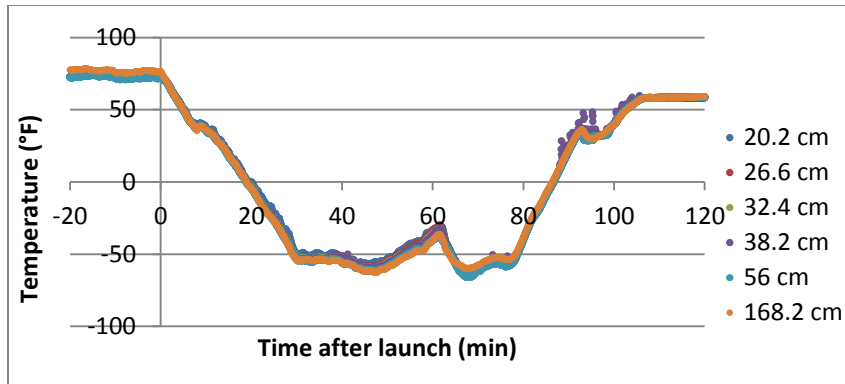


Figure 2a: The change in temperature throughout the 8D flight for 6 white-painted temperature sensors on the wake boom.

This graph shows the typical profile using non-shaded sensors showing the increase in temperature as the balloon enters the stratosphere. This graph is a representation of the entire time the probes were collecting data.

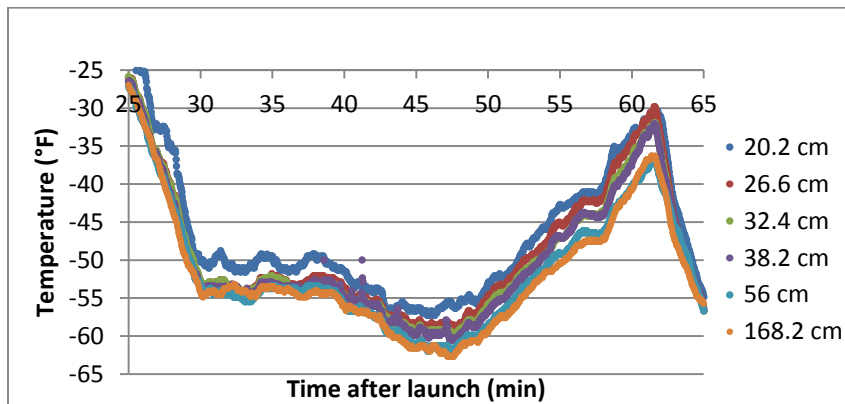


Figure 2b: Temperature versus time for 6 white-painted sensors on the wake boom during flight 8D.

This graph shows the typical profile using non-shaded sensors showing the increase in temperature as the balloon enters the stratosphere. This graph is a representation of the entire flight.

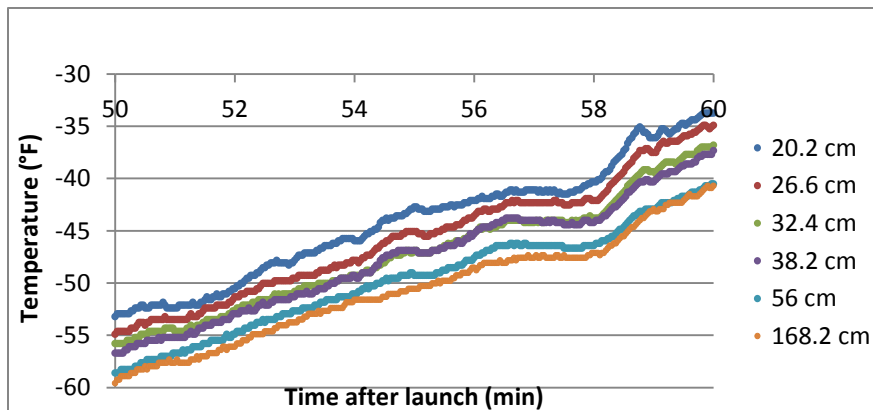


Figure 2c: Temperature versus time for 6 white-painted sensors of the wake boom during the 8D flight for the time just before balloon burst.

The above listed graph shows the typical profile using non-shaded sensors showing the increase in temperature as the balloon enters the stratosphere. The start of this graph is a representation of when the payload leaves the stratosphere and enters the troposphere via the tropopause until the time of burst. This time was chosen due to it showing the greatest representation of the thermal wake phenomena and our desire to study near-space atmospheric conditions.

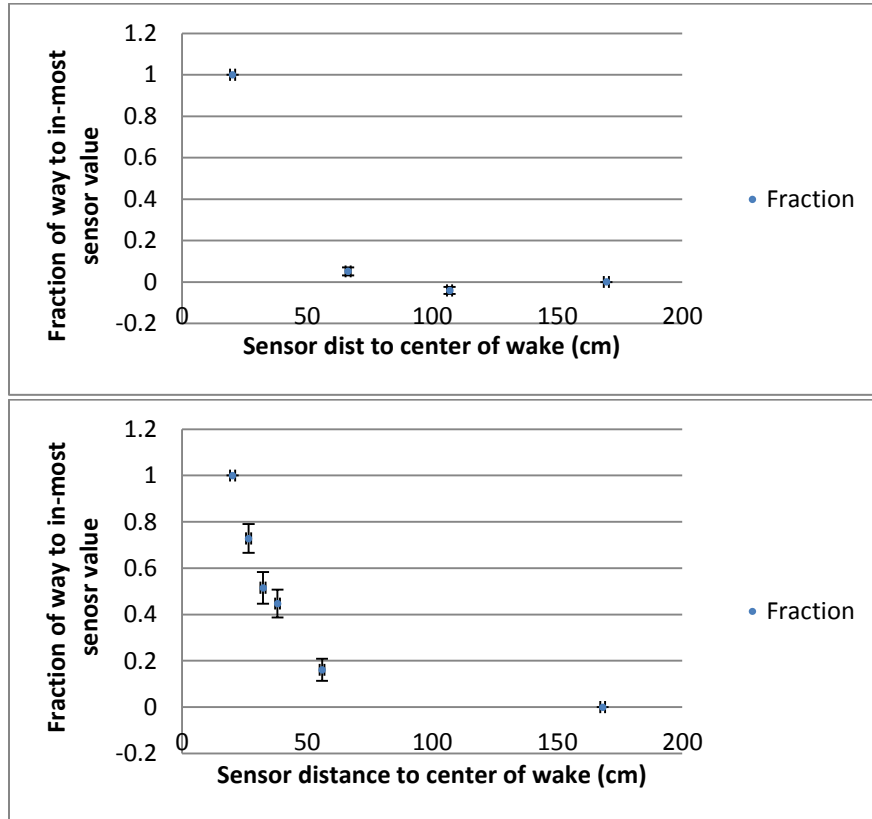


Figure 3a (6D top) and 3b (8D bottom): The effect of the sensor distance from the center of the wake boom on the fraction of way to in-most sensor value.

This graph is a comparison of how the mid-sensor values on flights 6D and 8D compared to the inner-most sensor (assumed to be essentially the center of the thermal wake) and the outer sensor (assumed to be outside the thermal wake). The wake was constructed as described in figure 1. On flight 6D all but the inner-most sensors appear to be outside the thermal wake. On flight 8D only the outer-most sensor appears to be outside the wake. For 6D (which used a smaller balloon) we conclude that the radius of the wake was no more than 60 cm. For 8D the radius of the wake appears to be at least 70 cm. Data in both cases was a 5-minute average starting roughly 10 minutes before balloon burst.

The last 5 minutes of the ascent the color of the payload box did in fact make a large difference, with the sensor near the black side of the box registering significantly higher than that near the white side ~ 8.5 degrees F warmer (Figure 4). Wake width data for Figure 2c was taken more than 5 minutes before burst for each flight, out of deference to this potential systematic error.

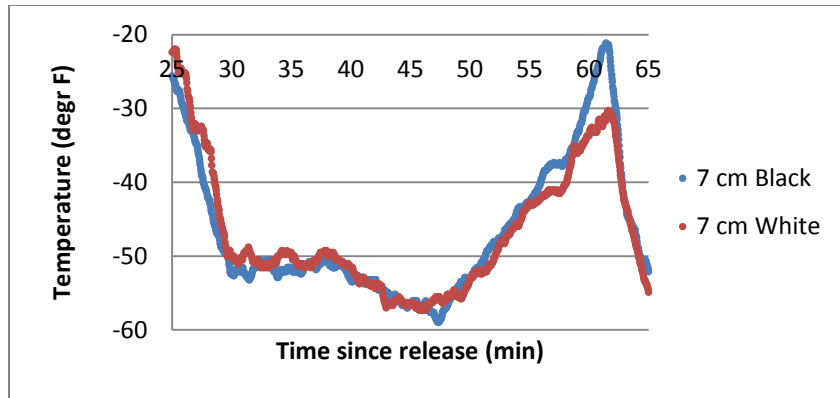


Figure 4: Impact of a black versus a white-colored payload box.

Each probe was 20.3 cm from the central axis or 7 cm from the side of the payload, from flight 8D. As the flight nears burst, the heating of the black box has a significant impact on the sensor readings, with a difference of over 5 degrees Fahrenheit occurring. This effect must be distinguished from the elevated temperature near the payload box due to the thermal wake. Additional flights with this measurement are warranted to see if this is a one-time anomaly.

The payload box is able to influence the temperature in the area around itself or it is possible that as one monitors temperature much lower on the stack that we are out of the region of the thermal wake (Figure 5).

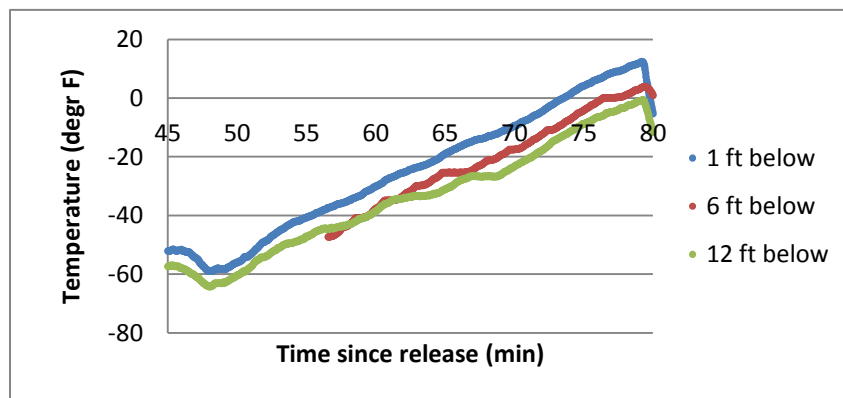


Figure 5: The effect of time on the temperature of flight 7D using temperature probes 1ft, 6ft and 12ft directly below the payload.

Three different temperature probes (1ft, 6ft, and 20ft in length) were placed out of the bottom of the payload at the following lengths: 1ft, 6ft, and 12ft. Temperature probes were flown on a payload box to see the vertical extent of the wake. This data could indicate the following:

- A) That the payload itself is influencing the temperature in the area surrounding it.
- B) The payload box itself is generating its own miniature wake
- C) That the lower probes are monitoring the change in the thermal wake vertically in the stack. This data comes from flight that occurred at the same time as 7D but did not fly on the same payload stack.

A possible alternative explanation of the data from flight 6D could possibly be that the central sensor was influenced by its proximity to the (black) payload box and therefore all the other sensors are in fact within, not outside of, the thermal wake. To address this issue the boom was changed from black (the boom is a black carbon fiber tube) to white for flight 8D. The payload box itself was altered to be made half-white, with one sensor 7 cm from the white side of the box and another sensor 7 cm from the black end of the box.

The width of the thermal wake was neatly characterized in flight 8D (figure 2a-c). so the above mentioned alternative explanation of the 6D data, is no longer under consideration. In the future, we plan to use exclusively white booms and boxes to minimize potential color effects. We may also move the boom slightly above the payload box containing the HOBO data loggers, allowing us to place sensors at the very center of the wake in future flights.

VI. Additional parameters for future consideration

Determining the perpendicular diffusion of a wake is of great importance. The process was clearly laid out in (3) in their paper related to the thermal wake, which we have stated here again for reference. The equation for diffusion is given by $\frac{\delta T}{\delta t} = \lambda_T \Delta T$. “Where capital T is the temperature drop or rise, λ_T is the thermal conductivity which is assumed to be constant in many wake papers, and Δ is the Laplacian operator. The two dimensional temperature distribution after heating to the point x_0, y_0 is given by $T = const \frac{1}{t} e^{-\left\{\frac{x-x_0^2 + y-y_0^2}{4\lambda_T t}\right\}}$ with the assumption that the temperature rise/drop and the third dimension z are independent of each other. With an initially heated surface the profile goes as $T(x, y, t) = \frac{1}{4\pi\lambda_T t} T_0 \int \int e^{-\frac{[x-\xi^2 + (y-\eta)^2]}{4\lambda_T t}} d\xi d\eta$ ”
A more detailed study of the temperature profile as a function of distance for future wake booms may be of interest to compare to the theoretical model outlined in (3).

VII. Conclusions

The study of the high altitude wake continues to be a very worthwhile endeavor for St. Catherine University. The study of the thermal wake has allowed the ballooning team to expand and has given us a focus around which other high altitude work occurs. The project at first glance to some appeared to be nothing more than a temperature study of the atmosphere, yet it is so much more. To understand the wake we need to understand more fully the calibration, sensor drift and type, payload makeup including weight and placement, balloon size and characteristics just to name a few items. The wake provides a research question for us to drive to learn and do more with our high altitude launches.

Placement of the sensors should be setup for one or two balloon sizes. A wake boom for a specific balloon size is suggested for measuring the thermal wake phenomena. If using HOBO data loggers, a 4 channel logger should be used in conjunction with at least a two channel HOBO logger, if not a second 4 channel logger – we have found that 4 points of data is just not enough to draw any hypothesis related to the data collected. In addition, we may look at flying three 4 channel HOBOS to add to the data set (this would be 12 channels worth of data) to help fill in gaps should a sensor fail and to add to the positional resolution. Calibration and adjustment of sensors should be done on a regular basis – though admittedly ground conditions do not model upper level atmospheric conditions very well. This process takes time and was a foci of reference (1). One should have a uniform fill of Helium for comparative flights, as well as try to maintain consistent payload weight for wake flights, though no two balloons will rupture at the same altitude keeping these two variables in check will hope to provide consistency in flight predictions at the very least. Placement distance (h) below the balloon should be kept track of for all flights, as tree recoveries usually cause damage to the system. In addition, we recommend setting up a system that has white sensors, a white wake boom and at least a partial white payload box so as to rule out color effects.

Additional work related to the number of sensors used as well as night flights are next on the docket as things to study. By the end of the summer research period we hope to have answers, partial answers and a plan of action to address the research questions that we have laid out.

References

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