Thermal Wake Studies During the August 21\textsuperscript{st} 2017 Total Solar Eclipse

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A thermal wake occurs when a high altitude balloon (HAB) influences and changes the surrounding ambient atmospheric temperature of the air through which it passes. This effect warms the air below the balloon to greater than the ambient temperatures during daytime flights, and cooler than ambient temperatures during nighttime flights. The total solar eclipse of August 21\textsuperscript{st}, 2017, provided us with an opportunity to study these balloon induced temperature transitions from daytime, to eclipsed induced night conditions over the scale of a single flight. To measure these transitions, St. Catherine University and the University of Minnesota, Morris, flew over 40 temperature sensors suspended beneath weather balloons ascending within the path of totality. Stratospheric temperature data collected during the eclipse show evidence of both daytime and nighttime wake temperature profiles.

I. Nomenclature

\begin{itemize}
  \item \textit{P} = Air Pressure
  \item \textit{D} = Day flight
  \item \textit{N} = Night flight
  \item \textit{E} = Eclipse flight
  \item \textit{Wake boom} = device with thermistor and digital temperature sensors, suspended beneath a weather balloon – can be linear of X (two dimensional)
  \item \textit{d} = heat exchange layer
\end{itemize}

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II. Introduction

The total solar eclipse of August 21st, 2017, (Figure 1) provided researchers with an opportunity to investigate atmospheric based changes on the earth and above while the moon shadowed the earth. Building upon St. Catherine University’s experience investigating the thermal wake effect of ascending HABs, and inspired by the possibility to observe stratospheric thermal changes during totality, St. Catherine University prepared to study thermal transitions in the stratosphere during the solar eclipse event. The opportunity to utilize our experience measuring stratospheric temperatures was an exciting proposition for us, and this paper presents data showing how the thermal wake of ascending HABs changed as the Moon shadowed the Earth.

![Figure 1. Source: https://eclipse.gsfc.nasa.gov/SEplot/SEplot2001/SE2017Aug21T.GIF](https://eclipse.gsfc.nasa.gov/SEplot/SEplot2001/SE2017Aug21T.GIF)

The St. Catherine University High Altitude Balloon team traveled to Nebraska for the August 21st eclipse where totality entered the western edge of the state at 11:48 MDT, and exited the eastern edge of the state at 13:06 CDT. The eclipse day launch location in Aurora, Nebraska, experienced 2 minutes and 35 seconds of totality. To fully characterize the atmosphere for eclipse day measurements, we flew four balloons outfitted with temperature sensors during the two days prior to the eclipse (two balloons on Aug. 19th and two balloons on Aug. 20th). During the eclipse we launched two balloons outfitted with temperature sensors for a total of six balloons carrying temperature-measuring equipment launched within a 48-hour window around and during the eclipse. All of the flight launches were conducted within a one-hour window between 11:30 CDT and 12:30 CDT. As Ramkumar states, “reducing the diurnal temperature variation effects an important consideration when dealing with this type of data”. The path of totality as well as the flight paths of the balloons launched on Aug. 21st are shown in Figure 2.
III. Overview of the thermal wake

A thermal wake\(^7\)\(^-\)\(^9\) occurs below an ascending balloon. During a daytime flight the temperature of the air directly beneath the balloon will be warmer than the ambient air temperature due to solar radiation hitting the balloon. An opposite effect occurs during night flights when the adiabatic expansion of the gas inside the balloon lowers the balloon skin temperature, cooling the air beneath the balloon. According to Brasefield\(^7\), “...it may be concluded that, to altitudes of 100,000 ft., the air temperature below a balloon does not differ from the true ambient temperature by more than 1º C, so long as measurements are made at least 25ft below the balloon.” To be “in the thermal wake” we make temperature measurements within 20ft of the base of the balloon, near the top of the stack. The effect in both the daytime and nighttime is stronger with a decrease in air pressure. For “Reynolds numbers smaller than 10\(^5\), the thickness of the heat exchange layer d will increase with decreasing pressure, where d $\approx (\sqrt{P})^{-1}$, (P = air pressure).” In addition, as Jumper\(^10\) states, the effect is more pronounced with Helium versus Hydrogen lift gas as the specific heat ratio for Helium is larger and thus the thermal wake produced will be more significant. Barat\(^11\) also suggests that wake interactions are more likely to arise in low wind shear conditions.

Figure 3 from Ref. 8 (modified here) suggests an asymmetry in the thermal wake during daylight flights when the sun-side of the balloon receives more thermal energy than the anti-sun (shadow) side, resulting in a thermal wake that is warmer on the sun-side and cooler on the anti-sun side, but still warmer that the ambient air temperature. During a night flight the thermal wake is predicted to be uniformly colder than the ambient air temperature. Data presented in this paper will show temperature data during a time slice – one instant in time – typically in the stratosphere where the thermal wake becomes significant.
Figure 3: Symmetrical and Asymmetrical temperature wake profiles beneath ascending balloons during Day and Night ascents. Blue is representative of the adiabatic cooling of the He gas which is always present but is dwarfed by solar activity during the day. Figure modified from Reference 8.

IV. Methods

Over the past two years, our research team has tested different off the shelf temperature measuring systems to determine which are suitable for use in this work \(^{(5, 12)}\). Based on a combination of factors including cost, flexibility and performance in the low temperature and pressure conditions experienced during a HAB flight, we are currently using two types of temperature sensors: Type 1 – Maxim DS18B20 digital band-gap temperature sensors combined with an Arduino Mega microcontroller, and Type 2 - Onset HOBO temperature sensors combined with an Onset data logger \(^{(3, 5, \text{and} 12)}\). Temperature sensors are mounted on a 3 m wide wake boom arm built from carbon fiber tubing. During a flight this wake boom arm is suspended below the neck of the balloon, in the thermal wake region, but above the payload stack. The boom arm is centered beneath the balloon thereby allowing measurement of thermal wake asymmetries. Characteristics of the temperature sensors are listed in Table 1.

| Sensor Brand       | HOBO TMC6-HD           | Dallas DS18B20          |
|--------------------|------------------------|-------------------------|
| Sensor Type        | Thermistor             | Digital band gap        |
| Listed Temperature Range | -40 to 100 °C          | -55 to 125 °C           |

Table 1: Listing of sensor specifications and type used for wake measurements.

On any given HAB flight, 20 to more than 40 temperature sensors are logging data for the duration of the flight. Ground based work with these sensors has shown that sensor to sensor variability under the same temperature and pressure conditions can be as much as ±0.5 °C at room temperature and pressure, but increases to as much as ±2 °C at -40 °C and 1000 Pascal pressure – closer to the conditions found in the environments where the sensors are used. To account for sensor-to-sensor variations, each sensor goes through a calibration process \(^{(12 \text{ and } 13)}\) prior to a HAB flight. After a flight, data for each sensor is analyzed using a calibration curve unique to the particular sensor. By calibrating the sensors, we feel confident that we are able to measure even potentially small temperature variations as part of the thermal-wake effect \(^{(12)}\). However as pointed out by Flaten \(^{(14)}\), temperature measurements are prone to many sources of error, one of those being the fact that temperatures will by definition lag the actual raw temperature by some value. We recognize this lag time exits and trust that the reader understands this significant fact as we present data in this report.
Figure 4. The fundamental payload constituents used to log the thermal wake: Onset HOBO data loggers, Arduino logging GPS and temperature sensors and maintaining box temperature with “life support”.

In prior work\(^3,5\) we have referred to flights as “N” denoting a nighttime flight and “D” denoting a daytime flight. We continue this lettering and numbering continuity for this work. In addition, we introduce the notation “E” to signify a flight during the eclipse.

4N: 8-4-16 –We present this data as representative of nighttime wake flight temperature results. A one-dimensional boom was flown from Madelia, MN, to an altitude of 33,385 meters. The flight landed near Waseca, MN, after a balloon burst at 0:53 CDT. The wake boom had eleven DS18B20 sensors on one side at locations of 10, 20, 30, 40, 50, 60, 70, 80, 90, 100 and 110 cm. The same locations were repeated on the other side of the wake arm. In addition, a HOBO data logger with sensors at 10, 20, 30, 40, 50, 60, 70, 90 and 100 cm was also flown.

13D: Pre-eclipse flight 1: 8-19-2017 – A one-dimensional boom was launched at 11:45 CDT from the Stuhr Museum in Grand Island, NE, to an altitude of 32,716 meters. The flight landed near Hampton, NE after a balloon burst at 13:02 CDT. The wake boom had sensors at 10, 20, 30, 40, 50, 60, 80, 100, 120, 140 and 160 cm. In addition, a HOBO data logger with sensors at 5, 25 and 45 cm on one side of the boom and 15, 35 and 65 cm on the other side of the boom was also flown. Digital sensors on one side of the wake boom malfunctioned just before launch and therefore we have data only from one side of the wake boom.

14D: Pre-eclipse flight 2: 8-19-2017 – A one-dimensional boom was launched at 12:30 CDT from the Stuhr Museum in Grand Island, NE, to an altitude of 31,588 meters. The flight landed near Hampton, NE after a balloon burst at 14:07 CDT. The wake boom had sensors at 10, 20, 30, 40, 50, 60, 80, 100, 120, 140 and 160 cm. In addition, a HOBO data logger with sensors at 15, 35, 55 and 85 cm on one side of the boom and 5, 25, 45 and 65 cm on the other side of the boom was also flown.

15D: Pre-eclipse flight 3: 8-20-2017 - A one-dimensional boom was launched at 11:29 CDT from the Leadership Center in Aurora, NE, to an altitude of 31,793 meters. The flight landed near Gresham, NE after a balloon burst at 12:52 CDT. The wake boom had sensors at 10, 20, 30, 40, 50, 60, 80, 100, 120, 140 and 160 cm. In addition, a HOBO data logger with sensors at 15, 35 and 85 cm on one side of the boom and 5, 25, 45 and 65 cm on the other side of the boom was also flown – this was the same boom as 14D.

16D: Pre-eclipse flight 4: 8-20-2017 - A one-dimensional boom was launched at 12:04 CDT from the Leadership Center in Aurora, NE, to an altitude of 29,820 meters. The flight landed near Gresham, NE after a balloon burst at 13:22 CDT. The wake boom had sensors at 10, 20, 30, 40, 50, 60, 80, 100, 120, 140 and 160 cm. In addition, a HOBO data logger with sensors at 15, 35, 55 and 85 cm on one side of the boom and 5, 25, 45 and 65 cm on the other side of the boom was also flown – this was the same boom as 14D.

1E: Eclipse flight 5: 8-21-2017 - A one-dimensional boom was launched at 11:35 CDT from the Leadership Center in Aurora, NE, to an altitude of 30,138 meters. The flight landed near Garrison, NE after a balloon burst at 12:55 CDT. The wake boom had sensors at 10, 20, 30, 40, 50, 60, 80, 100, 120, 140 and 160 cm. In addition, a HOBO data logger with sensors at 15, 35 and 85 cm on one side of the boom and 5, 25, 45 and 65 cm on the other side of the boom was also flown – this was the same boom as 15D.

2E: Eclipse flight 7: 8-21-2017 - A one-dimensional boom was launched at 12:25 CDT from the Leadership Center in Aurora, NE, to an altitude of 31,494 meters. The flight landed near Garrison, NE after a balloon burst at
13:49 CDT. The wake boom had sensors at 10, 20, 30, 40, 50, 60, 80, 100, 120, 140 and 160 cm. In addition, a HOBO data logger with sensors at 15, 35, 55, 65 and 85 cm on one side of the boom and 5, 25, 45 cm on the other side of the boom was also flown.

V. Results

Figure 5 shows calibrated temperature data plotted as distance from the center of the wake boom for night flight 4N. Time slices of temperature data from the troposphere, 9 km, and the stratosphere, 23.2 and 30.5 km, are shown on this graph with the 30.5 km time slice near burst. The data show an increasing thermal wake effect as the balloon ascends in altitude into the nighttime stratosphere; the wake effect is not present in the 9 km data but increases as the balloon ascends to 30.5 km, showing an approximately 3 °C lower temperature in the center region of the boom arm, 0 cm to ±40 cm, and warming as one moves outward horizontally along the boom arm. Because the thermal wake is a characteristic of decreasing pressure and an increasing heat transfer layer, one expects the effect to become more pronounced at increasing altitudes as the data shows.

![Figure 5: Plot of calibrated night wake data showing thermal wake increase with altitude.](image)

Data collected from 13D, 14D and 16D (pre-eclipse flights) show the characteristic daytime thermal wake profile with warmer temperatures beneath the neck of the balloon, in the region from 0 cm to ±40 cm, and cooler temperatures at locations >40 cm as one moves outward horizontally along the boom arm. To illustrate a typical temperature profile, we show data from flight 14D in Figure 6. The sun would appear to be closer to the left side of the boom as compared to the right side as temperatures here are warmer.

In addition to the thermal wake, we discovered that the noontime location of the sun resulted in an unexpected artifact being added to our data, the “box effect.” Data on the left hand side of the graph from 20 cm to 0 cm have a significant increase in temperature, which corresponds to the width of our 20 cm payload box suspended beneath the boom arm. This effect is more significant in the stratosphere but the same effect also appears in tropospheric data, which further supports the idea of a thermal box effect. Clearly, making temperature measurements in the stratosphere is a process that is complicated by thermal effects of any and all nearby objects because as shown by our data, even wake arms that are separated by nearly 40 cm via a cable from the payload box are prone to box effects. Having two different types of temperature sensors onboard was also crucial in this determination as we were able to rule out malfunctioning sensors or missed calibration for a particular sensor. The Dallas as well as the HOBO sensors corroborate each other and support the existence of a “box effect.”
Figure 6: Time slice just before burst for flight 14D, the sun appears to be towards the left hand side of the page.

Figures 7 and 8 show data from flights 15D and 1E. These flights used the same wake boom arm flown on a non-eclipse day and during the eclipse. The launch times for these two flights were no more than 5 ½ minutes apart and the burst times are within 3 minutes of each other. The 15D flight achieved an additional ~1600 meters in altitude. In comparing the data, we argue that the diurnal temperature effect (given the small differences at the start and end of the flight) and sensor-to-sensor offset effects (same calibration and sensors) are minimal. Flight 15D exhibits the thermal box effect on the left hand side of the boom, but note the improvement over flight 14D. We attribute this in part to better rigging that provided the prescribed 40cm distance separation between the payload box and wake boom. Also note the expected daytime wake temperature profile with lower temperatures as one moves outward horizontally along the wake boom arm. Flight 1E, an eclipse flight, is notable in the absence of the box effect. As the Moon shadowed the Sun, radiation effects from the box to the wake arm were altered. The collection of profiles from 1E all contained this trait and was an exciting discovery we made as we processed the data.

Figure 7: 15D shows a typical daytime flight with a warmer region in center. Note again the box effect on left hand side.
Figure 8: 1E shows a temperature profile similar to 4N, either no heating present or a cooling region is present.

Additional time slices from flight 16D that correspond to 9 km, 23 km and 29.8 km altitudes are shown in Figure 9. These time and altitude slices show the expected behaviors, cooling followed by increasing temperatures as the balloon ascends into the atmosphere with the thermal wake becoming more evident once the balloon has reached the stratosphere at 29.8 km.

Figure 9: Showing the daytime warming characteristic with box effect especially strong at 30cm.

Figure 10 shows 2E data time slices plotted at 9km, 23km and 30km, corresponding to the times and altitudes shown in Figure 9. Note the horizontal nature of the temperature data at each altitude. This eclipse temperature data, collected near midday, shows profiles much more similar to the 4N night data in Figure 5, than the daytime temperature data in Figures 6 and 9. One would expect to see either a center cooling effect if this data was typical of a night flight or a center warming effect if this data was typical of a day flight but neither profile is obvious in this result. What is obvious (especially in the 23km data) is that the slope temperature profiles become ambiguous due
to the reduction of the radiation heating effects of the box on the wake. This provides us with the cleaner temperature profiles that we typically see during night flights.

![Flight 2E temperature data](image)

**Figure 10:** 2E temperature data during the eclipse – 23km data at 13:27 CDT and 30km at 13:46 CDT.

**VI. Conclusion**

Flights 1E and 2E, solar eclipse flights flown during the day, show clear evidence of non-typical daytime wake temperature profiles. Given the large number of sensors and flights both before and during the eclipse, we feel comfortable making the claim that the 1E and 2E nighttime temperature profiles are directly related to cooling of the atmosphere and the balloon skin during the solar eclipse. We claim that the data presented for flight 1E demonstrate a “nighttime wake” being created during a daytime flight. The wake had the signature characteristics of cooling underneath the neck of the balloon and continued warming near the extrema of the wake structure. 2E data, while not showing a significant wake profile signature that either warms or cools along the wake arm, still shows a temperature profile that more closely resembles a night profile result. Finally, as we have discussed in previous works, measuring temperature in the stratosphere is complicated due to the low temperature and pressures, the fact that we are actual chasing the temperature, and radiation effects of any nearby objects. Indeed, it is radiation effects that help create the actual thing we are trying to measure, the thermal wake, but as we discovered during the eclipse, the box effect is another artifact that is present in our data.

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