Characterizing Weather in a Thermosyphon:

An Atmosphere that Hangs on a Wall

A Thesis Presented

by

Darcy Glenn

to

The Faculty of the College of Arts an Sciences

of

The University of Vermont

In Partial Fullfillment of the Requirements
for the Degree of Bachelor of Arts
Specializing in Mathematics

May, 2013

Accepted by the Faculty of the College of Arts and Science, The University of Vermont, in partial fulfillment of the requirements for the degree of Bachelor of Arts, specializing in Mathematics.

Thesis Examination Committee:

Advisor
Chris Danforth, Ph.D.

Darren Hitt, Ph.D.

Chairperson
Dennis Clougherty, Ph.D.

Date: April 17, 2013

Abstract

Climate change and extreme weather events are becoming more prominent public issues, increasing the need for improved short-term weather forecasting. Extending weather forecast skill beyond a few days will require a better understanding of the chaotic nature of the atmosphere. In an effort to develop an experimental test bed, we study a thermal convection loop or *thermosyphon*, a simple proxy atmosphere. It consists of a vertically oriented, circular tube that is heated from the bottom and cooled from the top, causing the water inside to rotate. The direction of rotation is observed to switch in a chaotic manner. The rate of heating and cooling represents the climate, and the switching rotation direction represents the weather. Based on desired improvements identified in tests with an existing thermosyphon, a new thermosyphon was designed and constructed using a single flexible tube. The flow reversed in a chaotic manner, and at its peak symmetry spent 58.2% in the clockwise regime and 41.8% of the time in the counterclockwise regime. For the 71 reversals in the symmetric run and the 90 reversals in the non-symmetric run the final oscillation amplitude and residency time were determined. A multi-day data collection run will have to be conducted in order to draw concrete conclusions about the 1796 reversals in the computer simulations.

Acknowledgments

I'd like to take this opportunity to thank Chris Danforth for all his guidance throughout the process, Floyd Vilmont for helping me understand how the first thermosyphon worked, and Dave Hammond for helping me build three new physical models. I would like to thank Dennis Clougherty for heading my committee and Darren Hitt for sitting on it. They gave excellent critiques.

Table of Contents

List of Figures

1 Background

In the early 1960s the National Weather Service used a linear deterministic model to forecast atmospheric phenomena. The idea was that if enough data could be collected about the weather at a given time, one could use physical principles to calculate what the weather was, and will be, as far in the past and future as one chooses. In 1963, Edward Lorenz's paper 'Deterministic Nonperiodic Flow' on convection in a Rayleigh-Bernard cell, changed the field of weather forecasting. Lorenz used 3 deterministic equations to describe the motion in a thermal convective cell (Lorenz 1963). Despite his simplified mathematical representation of the motion, he found that the equations gave complicated results when solved numerically (Lorenz 1963). Specifically, when the difference between the hottest and coldest temperatures fell into a certain range, Lorenz found that the motion became nonperiodic. Since short-term weather patterns also exhibit nonperiodic motions, his findings prompted scientists to abandon the old deterministic approach to forecasting with an approach that recognized the significance of chaos.

Lorenz's model can be thought of as a simple mathematical description of 3-D convection in a tube. The thermosyphon is an experimental apparatus for studying convection that acts as a simple proxy atmosphere. It is a vertically oriented tube of circulating fluid that is heated across the bottom and cooled across the top. The directional changes in the circulation can be thought of as weather patterns. Predicting when the direction changes is analogous to predicting the weather. The effect of a changing climate on weather patterns is important to accurately characterize. However, the current mathematical models only allow forecasts to accurately predict weather a few days in advance (Danforth 2011). A working thermosyphon will enable study and demonstration of the difficult concept that small changes in climate can result in more drastic changes in future weather patterns.

Despite the importance of the Lorenz equations, there have been very few experimental apparatuses developed to demonstrate the motion. The University of Vermont currently has a thermosyphon that was used by Ashley McKhann (McKhann 2011). In early tests of this apparatus, there were issues with obtaining the proper temperature difference to induce chaotic motion. Once those issues were resolved, the thermocouples (the sensors used for measuring temperatures) were found to not function properly. There was not enough time to collect data from the experimental device; so computational fluid dynamics simulation data was analyzed with the Eureka software for her investigation.

Depending on the temperature range, the water in a thermosyphon may change the direction of its rotation, defined here as the flow regime. The amount of time the flow spends in a given regime is called the *residency time*. The amplitude of the oscillation (defined as the peak difference in temperature between 3 o'clock and 9 o'clock positions) before a flow reversal is related to the amount of time the flow will spend in the new regime. Initially, the pattern of when the flow regime changed seemed to be described by the Lorenz equations. A low amplitude oscillation generally results in a short residency time, producing a circulation pattern that rocks back and forth between clockwise and counterclockwise flow. As the warm pockets of rising water on one side of the thermosyphon cool, the cool pockets of sinking water on the other side warm, causing the temperature difference between 3 o'clock and 9 o'clock to return to a nearly uniform temperature and the system to return to its original non-circulating state. This allows a larger pocket of hot water to build up at the bottom so when it finally does rotate, the buoyancy of the hot water pocket prevents it from entering the bottom 'heating' half too many times. A high amplitude oscillation generally results in a long residency time, since small hot and cool water pockets remain when the new regime starts. This allows the hot water pocket to continue to build up while circulating through the 'heating' section. Similarly, the cold water pocket continues to build up as it circulates through the 'cooling' section. This allows the circulation to continue longer until the warm water pockets sufficiently fill the upper half so that their buoyancy stops the flow. These motions are described by the Ehrhard-Müller system of Lorenz-type ordinary differential equations, show here in their dimensionless form (Ehrhard and Müller 1990; Harris, Ridouane, Hitt, and Danforth 2012).

$$\frac{dx_1}{dt'} = \alpha(x_2 - x_1) \tag{1}$$

$$\frac{dx_2}{dt'} = \beta x_1 - x_2(1 + Kh \mid x_1 \mid) - x_1 x_3 \tag{2}$$

$$\frac{dx_3}{dt'} = x_1 x_3 - x_3(1 + Kh \mid x_1 \mid) \tag{3}$$

However, Kameron Harris's theoretical experiment predicts that if the final oscillation is large enough, the residency time after the switch will be very short (Harris 2009). To have short residency times after high oscillations is a non-Lorenz behavior decribed in Equations 1-3 (Figure 1).

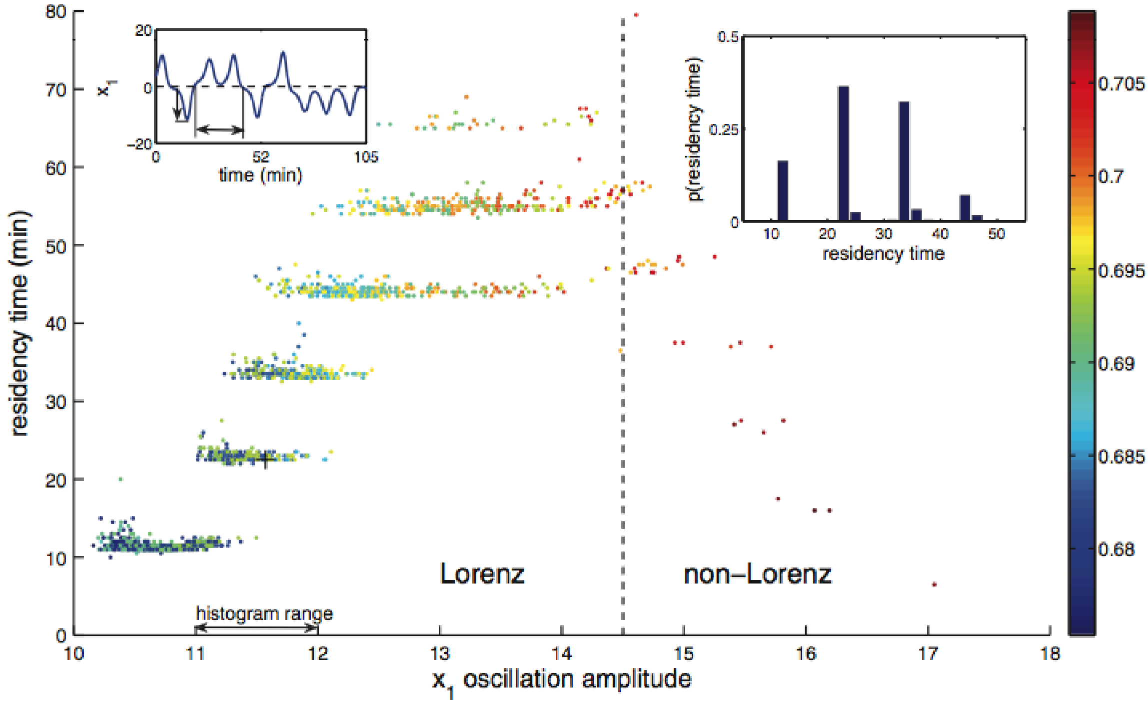


Figure 1: Kameron Harris's Residency Time vs. Oscillation Amplitude
"Residency time in the new rotational state is plotted versus the amplitude of x_1 (proportional to the mass flow rate) at the last extremum before flow reversal. This amplitude is calculated from the EM model EKF analysis of thermosyphon observations, using a 30 s assimilation window. This figure contains over 39 d of simulated flow and 1796 flow reversals." (Harris, Ridouane, Hitt, and Danforth 2012)

University of Vermont's past research into the workings of the thermosyphon have focused on developing a mathematical model of the behavior and the theory behind the model's behavior. Having experimental data will enable evaluations of the mathematical model. The working thermosyphon will result in a test bed for new mathematical techniques for weather prediction.

This study focuses on a thermosyphon built with Dave Hammond to examine the chaotic behavior of the circulation. It will test the hypothesis that even though changes in the direction of motion appear chaotic, the duration of flow in one direction can be a predictor of the duration of flow in the opposite direction after a switch.

2 Methods

2.1 Existing UVM Thermosyphon

A prebuilt metal thermosyphon containing both a hot and cold water bath and the circulating water was available to take data.

Sixteen thermocouples were evenly spaced around the thermosyphon to collect measurements of the circulating water temperature. Each stainless steel sheathed, iron thermocouple from Omega had to pass by the water baths to reach the circulating water (Figure 2). It is believed that the two-hour warm up time was long enough for the metal around the baths to leak heat to the thermocouple's measurement rod despite plastic's low conductance. The stainless steel covering the measurement rod would have allowed heat to travel down to the tip of the thermocouple and affect the reading. Unfortunately, the amount of insulation needed to isolate the thermocouple from the water bath to get proper data would involve completely remodeling the thermosyphon. The thermocouples were too delicate to create a thermal barrier by removing a piece of the metal casing and replacing it with a nonconducting material, such as rubber.

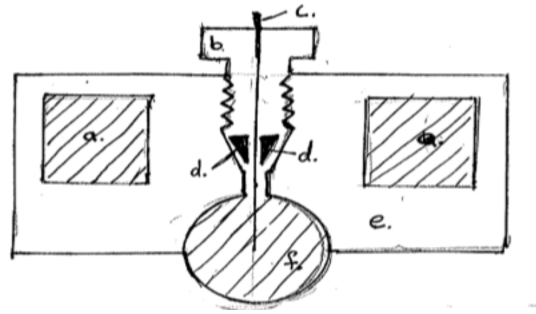


Figure 2: Original Thermosyphon Cross Section
Half cross section of original thermosyphon. Size of screw exaggerated for clarity. a)Water baths, b) Plastic screw, c) Thermocouple, d)Plastic wedges, e) Metal casing, f)Circulating water (Vilmont 2013)

2.2 First New Thermosyphon

The most direct course of action to obtain laboratory data for this study was to build a brand new thermosyphon. Two new models were simultaneously built, the first based on Professor Danforth's original thermosyphon (Danforth 2001). It was decided to avoid over-engineering by sticking to the simple yet effective plastic tube. But unlike the original thermosyphon, the new models were not heated and cooled using water baths. The bottom halves were heated by a heating rope with a resistance of 31Ω wrapped around the outside of the thermosyphon. The top halves were cooled by the 62°F room temperature air.

The first new thermosyphon was a bent semi-flexible plastic tube with a 10-foot heating rope wrapped around the bottom half of the upright circle. The tubing used was light-transmitting clear THV from McMaster-Carr, with an inner diameter of 7/8 inch, a wall thickness of 1/16 inch, and a maximum operating temperature of 200°F. The outer diameter of the circular thermosyphon was 32.25 inches. This produced a ratio of about 1:36 inner tubing radius to outside thermosyphon radius (Danforth 2001). There were 1 inch 'windows' when the heating cable was coiled in a helix pattern around the outside of the tube, so the heating is not exactly uniform. The bottom half was then insulated using aluminum foil, which allowed fluid in the bottom half to reach 176°F. A forcing of 57 V, or 105 Watts, was required for the heating cable so that chaotic motion was observed. Temperature was measured at the 3 o'clock and 9 o'clock positions using unsheathed copper thermocouples from Omega. The thermocouples where glued in place to prevent leaking.

The difference between the two measurements shows which way the water is rotating. If 9 o'clock is hotter than 3 o'clock, the water is rotating clockwise. The heating rope heats the water as is moves from 3 to 9, and the air cools the water as it moves from 9 to 3. If 3 o'clock is hotter than 9 o'clock, the water is rotating counterclockwise.

At first the water was rotating clockwise 71.7% of the time and counterclockwise 28.3% of the time over a five-hour test run. While the direction of water flow appeared chaotic, if conditions were ideal, the water flow direction should have been in the clockwise and counterclockwise directions for roughly an even period of time. The two immediate corrections made were insuring that the torus kept its circular shape and making sure that the bottom was evenly heated. Initially the new thermosyphon was only being held around the 3 oćlock and 9 oćlock positions, allowing it to sag under its own weight. A circular stand was build, so the thermosyphon could be supported from all angles and keep its circular shape. The heating coil was rewrapped to be as symmetrical as possible. It was suspected that the 9 o'clock side had been wrapped higher or had a higher density of heating coil. After the corrections, both sides of the thermosyphon had the same height and density of heating coil and insulating aluminum foil. After the corrections, the water was observed to rotate clockwise 58.2% of the time and counterclockwise 41.8% of the time over a five-hour test run.

Because the new thermosyphon is clear, neutrally buoyant 1.0-1.2mm fluorescent green polyethylene microspheres coated with Tween 80 Biocompatible Surfactant, both from Cospheric, were added to the water to show currents within the thermosyphon. Since they glow under a black light, a movie of the beads was produced for side-by-side comparisons with the data[1]. This visual confirmation was not possible with the existing metal thermosyphon.

2.3 Second New Thermosyphon

The second new thermosyphon design that was built had a square cross-section, unlike Danforth's torus model. While this affects the mathematical formulation needed to model the chaotic effect, it does not impede chaotic behavior. To build it, two concentric circles were first etched onto two panes of plastic. Then the panes were connected with two strips of plastic that fit within the etched circles. The seam was sealed with silicon, and the panes were kept together by screws going into the plastic strips. The square cross section was one inch by one inch.

3 Results

3.1 Existing UVM Thermosyphon

On January 5, 2013, a 5 hour experiment was run with the existing metal thermosyphon and 16 thermocouples distributed around the circular apparatus. A typical 17 minute segment of that run is discussed here.

The temperature in the bottom half of the thermosyphon was 143.0°F - 143.3°F, corresponding to the upper steady line in Figure 3. The temperature in upper half of the thermosyphon was 58.19°F - 59.23°F, corresponding to the lower steady line in Figure 3. Right below the 3 o'clock

[1] http://www.youtube.com/watch?v=Vbni-7veJ-c

and 9 o'clock positions, temperatures were between 131.4°F and 126.9°F. Right at the 3 o'clock and 9 o'clock positions, temperatures were between 74.86°F (measure slightly above 3 and 9 o'clock) and 79.41°F(measure slightly below 3 and 9 o'clock). These 4 time series correspond to the 2 sets of jagged lines in Figure 3.

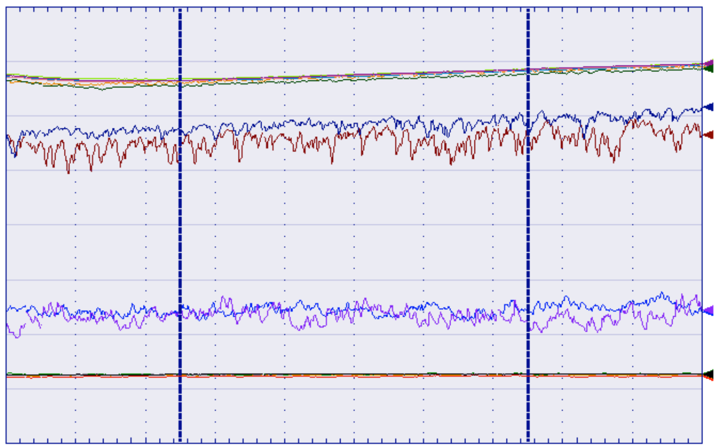


Figure 3: Original Timeseries Segment

17 minutes of raw temperature data from the metal thermosyphon. The x-axis is time and the y-axis is temperature. The stable high temperatures are located between 4 o'clock and 8 o'clock. The variable high temperatures are located just below 3 o'clock and 9 o'clock. The stable low temperatures are located between 10 o'clock and 2 o'clock. The variable low temperatures are located are just above 3 o'clock and 9 o'clock.

The thermosyphon's bath temperatures were measured to be at 143.6°F± 0.9°F (bottom) and 60.8°F± 0.9°F (top), a temperature difference that should have caused the water to circulate. Since the bath temperatures were within a few degrees of the measured temperature at the top and bottom of the thermosyphon, it was determined that the thermocouples were strongly influenced by the bath temperature and were not measuring the actual temperature of the circulating water.

3.2 First New Thermosyphon

Data was collected as soon as there was visual confirmation of a switching circulation direction. On February 21, 2013 and again on March 7, 3013, data was collected for five and a half hours each. The direction water was flowing was found by subtracting the 9 o'clock position's temperature from the 3 o'clock position's temperature. A higher 3 o'clock temperature corresponds to a positive difference and a counterclockwise water flow. A lower 3 o'clock temperature corresponds to a negative difference and a clockwise water flow. The larger the absolute value of the temperature difference, the faster the water was moving.

At first there was an uneven time spent on the two flow regimes (Figure 4). The thermosyphon was going clockwise 71.7% of the time and counterclockwise 28.3% of the time over a five and a half hour trial. While chaos will vary the amount of time spent in each regime, over five and a half hours, it should have evened out to about 50% in each direction if the forcing was truly symmetric.

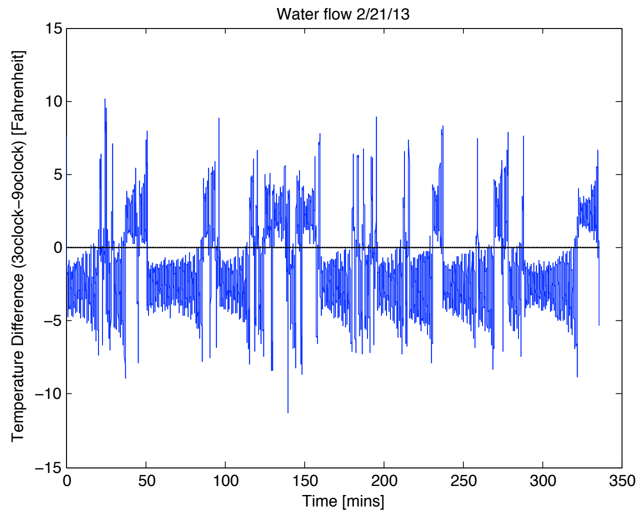


Figure 4: 2/21/13 Timeseries Segment

Water flow in the first new thermosyphon. Negative numbers correspond to a clockwise flow, and positive numbers correspond to a counterclockwise flow. The further from the x-axis, the faster the flow.

After adjusting the bottom half's heating so it was more even, the water flow spent 58.2% of the time going clockwise and 41.8% of the time going counterclockwise over a five and a half hour trial (Figure 5).

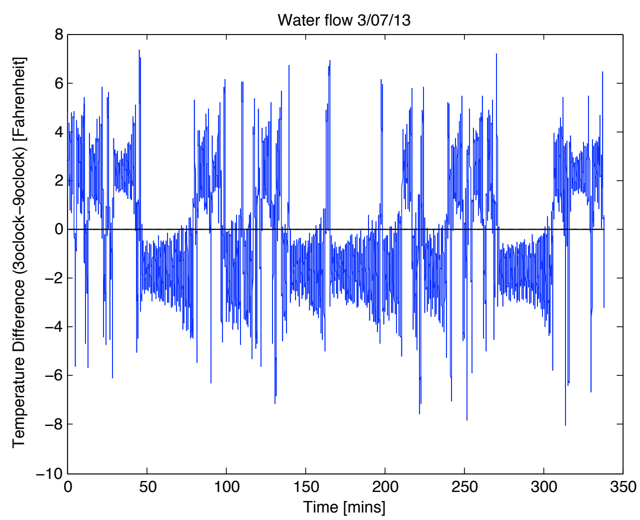


Figure 5: 3/07/13 Timeseries Segment

Water flow in the first new thermosyphon. Negative numbers correspond to a clockwise flow, and positive numbers correspond to a counterclockwise flow. The further from the x-axis, the faster the flow.

A final 9 hour trial was conducted (Figure 6). The water flow spent 70.1% of the time going clockwise and 29.9% of the time going counterclockwise.

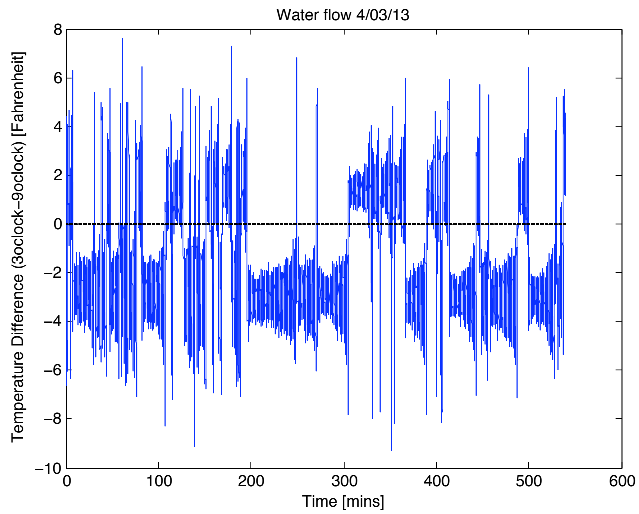


Figure 6: 4/03/13 Timeseries Segment
Water flow in the first new thermosyphon. Negative numbers correspond to a clockwise flow, and positive numbers correspond to a counterclockwise flow. The further from the x-axis, the faster the flow.

It was observed that when the water flow stays in a regime for a long time, the temperature difference (and velocity) of the water oscillates (Figures 4-6). The size of the oscillation grows until it is able to switch regimes, as first seen by Welander (Welander 1967).

The microspheres allowed visual observations not only of the direction of the large scale circulation but also of the smaller-scale currents within the thermosyphon (Figure 7). One of the most interesting behaviors was a back flow between 10 and 11 o'clock when the current was circulating clockwise, and between 1 and 2 o'clock when it was circulating counterclockwise. This only occurred when the flow spent a long time in a single regime. It can be viewed online at http://www.youtube.com/watch?v=Vbni-7veJ-c. One explanation for this phenomenon is that the water closest to the tubing wall is cooled the most. The cooler water is denser and less buoyant, so it can create a small sub current that descends down the wall. This happens even if the water at the center of the tube is going in the opposite direction.

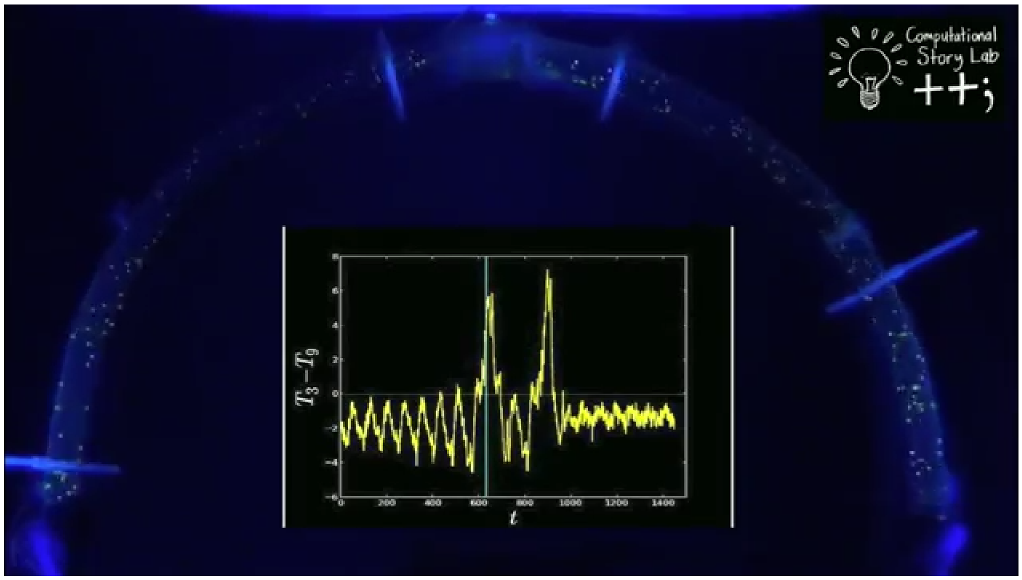


Figure 7: Youtube Still

Still of Youtube Video of an operating thermosyphon. The thermosyphon is under black light, causing the microspheres to glow. It is overlaid with the simultaneously collected data on the temperature difference between 3 o'clock and 9 o'clock.

4 Analysis

4.1 Existing UVM Thermosyphon

The first two attempts to take data from the prebuilt metal thermosyphon confirmed that we were taking temperature measurements of the water baths and not the circulating water of the thermosyphon. The thermosyphon had been built to contain both the water baths and the separate circulating water. The thermocouple sensor had to pass through the water bath without proper thermal insulation to reach the circulating water. Since the thermocouples were metal, they conducted too much heat to the point where the bath temperature was being measured. This made it impossible to 'see' what was actually happening inside the metal thermosyphon.

4.2 Simulated Data

In preparation for the experimental data deluge, computational fluid dynamics simulated data from William F Louisos (Louisos, Hitt, and Danforth 2013) was analyzed. His time series was recreated (Figure 8) and new time delayed attractors (Figure 9) and Lyapunov exponent curves (Figure 10) were plotted when gravity was taken to be $9.8m/s^2$. The positive and negative heat fluxes from the neutral system were $100W/m^2$. The value of gravity was used as a dial as opposed to temperature difference because it was easier for the computer program (Louisos, Hitt, and Danforth 2013).

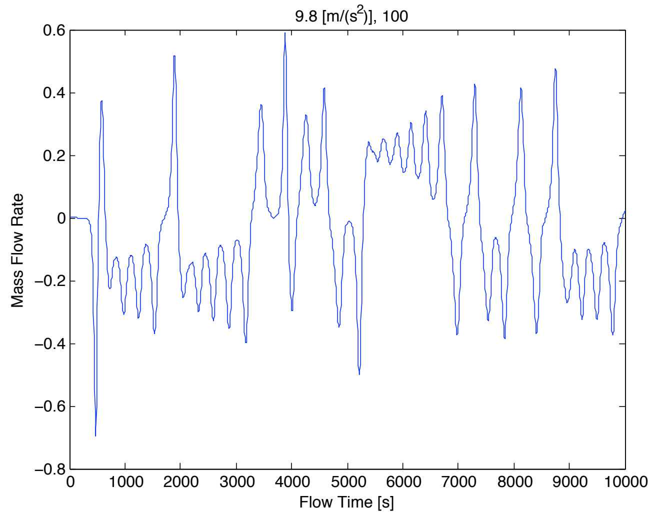


Figure 8: Simulated Time Series
The simulated data was created by Louisos. This was a recreation of his time series. This run was when g=9.8m/s^2 and the heat flux was 100W/m^2 (Louisos, Hitt, and Danforth 2013)

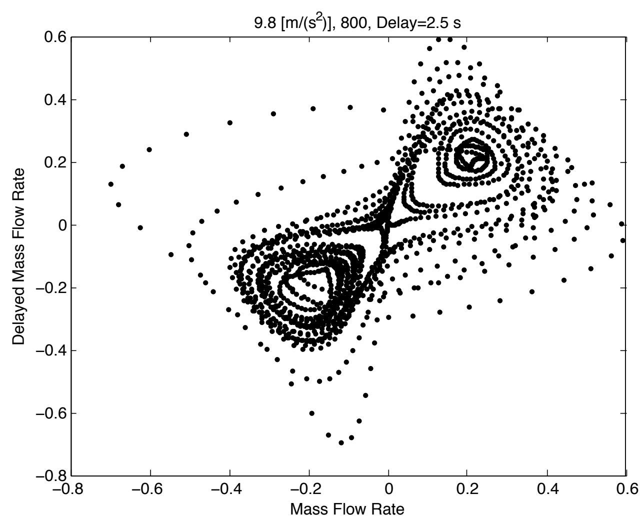


Figure 9: Simulated Data Delayed Attractor
The simulated data was created by Louisos. This was a new plot of the delated attractor. This run was when g=9.8m/s^2 and the heat flux was 100W/m^2 (Louisos, Hitt, and Danforth 2013)

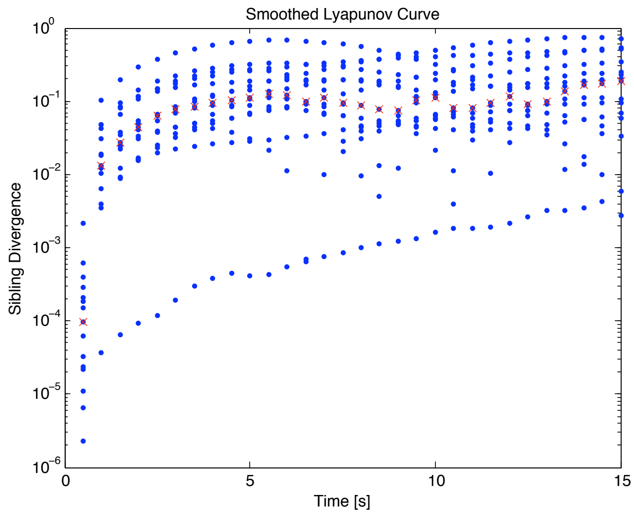


Figure 10: Simulated Data Lyapunov Curve

The simulated data was created by Louisos. This was a new plot of the Lyapunov exponetial curve. This run was when g=9.8m/s^2 *and the heat flux was* 100W/m^2 *(Louisos, Hitt, and Danforth 2013)*

4.3 First New Thermosyphon

Taking temperature data at the 3 and 9 o'clock positions while the thermosyphon heated up, transitions between the different states. At first conduction gives way to convection (Figure 11). Then convection gives rise to a small widow of chaotic motion when the temperature of the bottom half is 100°F greater than room temperature (Danforth 2011). If the thermosyphon is heated up too much, then the chaotic state reverts back to convection.

Since the water flow is going clockwise 58.2% of the time on 3/7/13 and clockwise 70.1% of the time on 4/3/13, it can be assumed that the left side of the thermosyphon is still being heated slightly more than the right side. One way to fix this is to slowly rotate the thermosyphon counterclockwise and see how that affects the flow. This should cause more of the right side to be heated and more evenly distribute the time the water flows clockwise and counterclockwise. If there is no new position that improves the water flow, then a more precise method of wrapping the heating rope will need to be devised. Despite the uneven time spent in each regime, chaotic behavior was still observed in the thermosyphon.

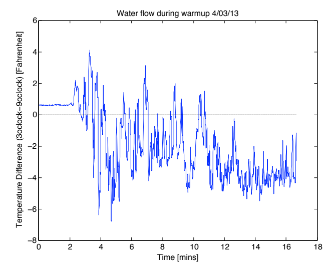


Figure 11: Stable to Unstable Convection
Stable Convection (identified by the initial steady temperature difference) in the Thermosyphon gives way to unstable convection (identified by the highly variable temperature difference) at about 2 minutes.

The raw temperature difference data was sampled twice a second and has two scales of variability, large scale fluctuations on the order of minutes and superimposed small scale fluctuations on the order of seconds. The large scale fluctuations are due to the main circulating current. The small scale fluctuation are due to small sub-currents and small temperature variations within a water pocket. To improve the analysis and reduce outliers caused by the small scale fluctuations, the curve was smoothed (Figure 12). To make the curves smoother, each temperature difference plotted was the running average of the 10 differences before and after it in the time series. The smoothed data was used in all analyses.

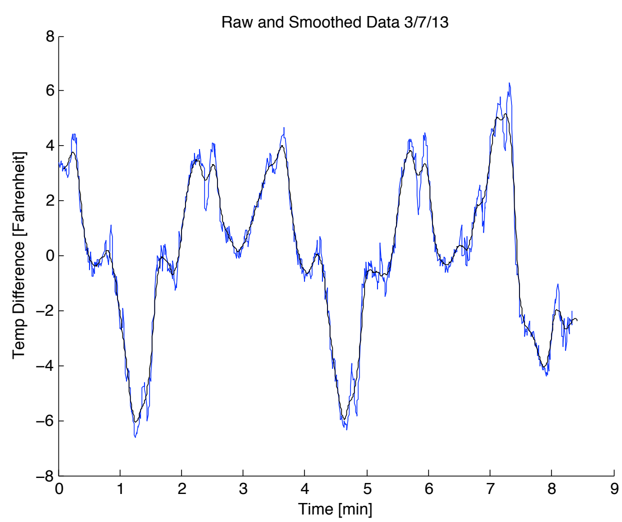
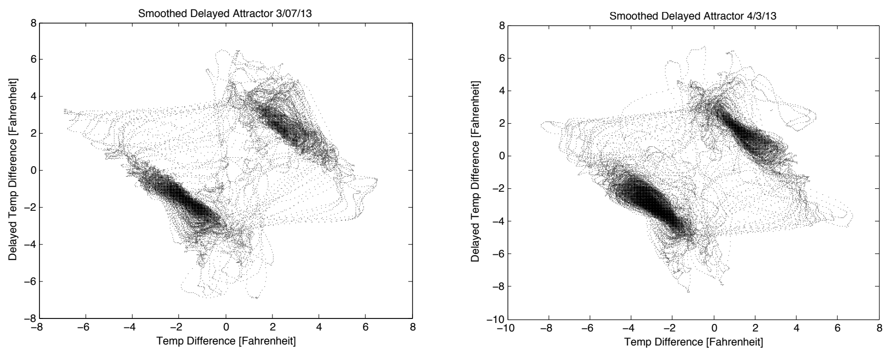


Figure 12: Raw vs Smoothed Data
The raw (blue) and smoothed (black) temperature differences for the first 8 minutes of the 3/7/13 run. The smoothed curve is an average of the temperature differences 5 seconds in the past and future.

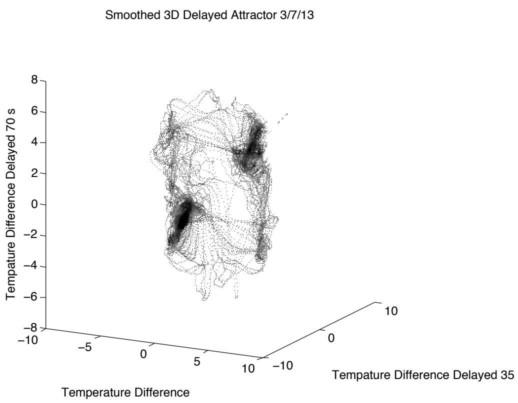
A time-delay reconstructed attractor was created by plotting the smooth temperature difference time series versus the smooth temperature time series delayed by 35 seconds (Figure 13). This resulted in a bound state with two attractors. The shape of this graph is typical of a chaotic system (Alligood, Sauer, and Yorke 1996) .



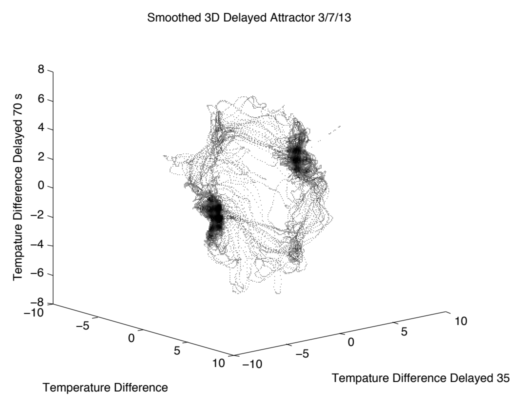
(a) 3/07/13 Five and A Half Hour Run (b) 4/03/13 Nine Hour Run

Figure 13: Delayed Attractors
Smoothed Delayed Attractor both with a 35 second time delay.

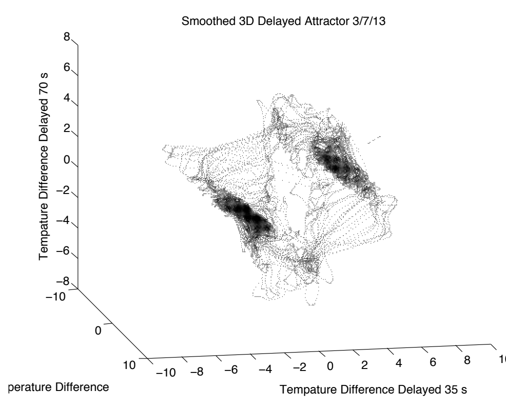
A 3D Lorenz attractor was constructed using three snapshots of the smoothed time series. The data from the first snapshot started at the beginning of the original time series and ended 70 seconds before the end. The second snapshot started 35 seconds after the original time series and ended 35 seconds before the end. Finally, the third snapshot started 70 seconds after the original time series and ended at the end of the original time series. These 3 new time series were plotted against each other in a 3D delay reconstruction plot. This system is dependent on more than 3 variables, which accounts for the attractor's shape (Figure 14 & Figure 15). In Figure 15 , the third attractor that appears next to one of the two main attractors may be due to the uneven amount of time spent in each regime.



(a) First View



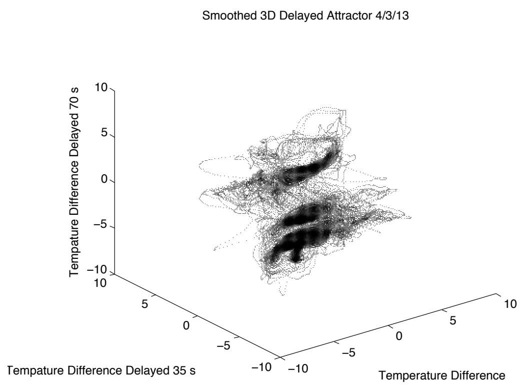
(b) Second View



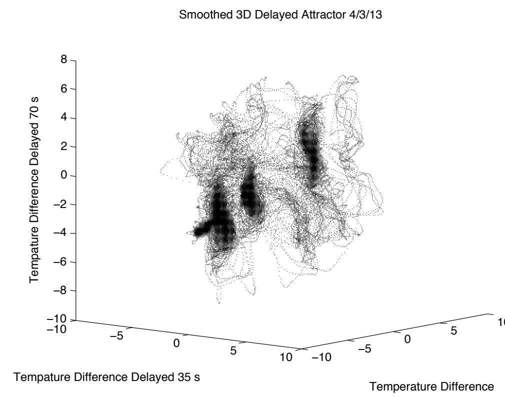
(c) Third View

Figure 14: 3/07/13 3-D Delayed Attractor

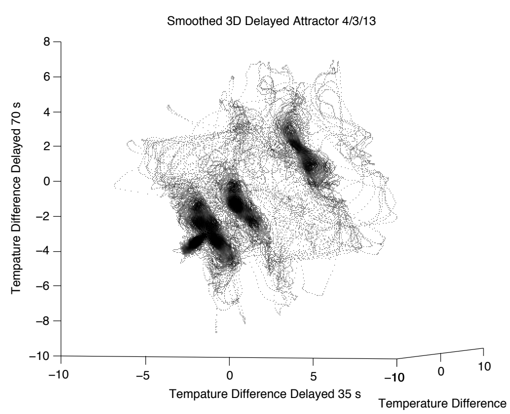
Three views of the smoothed 3-D delayed attractor. The time delay between the first and second time series was 35 seconds, and the time delay between the first and third time series was 70 seconds.



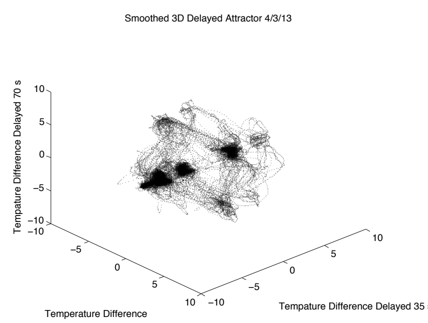
(a) First View



(b) Second View



(c) Third View

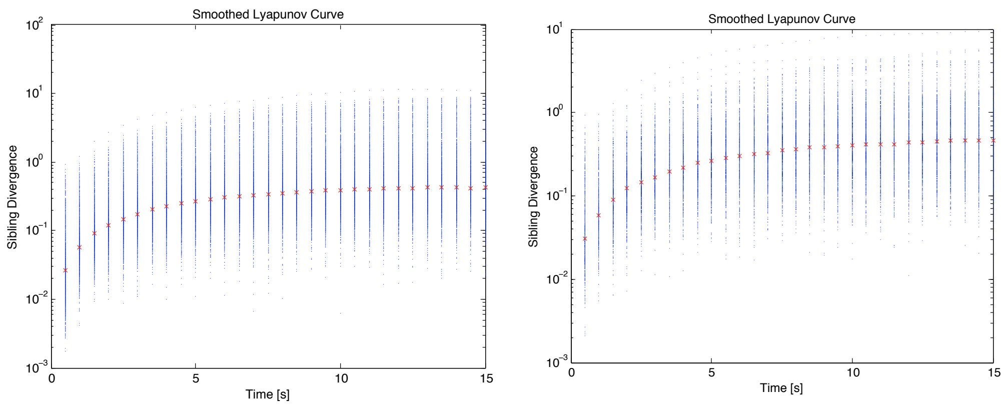


(d) Forth View

Figure 15: 3/07/13 3-D Delayed Attractor

Three views of the smoothed 3-D delayed attractor. The time delay between the first and second time series was 35 seconds, and the time delay between the first and third time series was 70 seconds.

The Lyapunov curve is a way to express how quickly two initially close states diverge. This was done by looking at each point in Figure 14 or Figure 15, finding its closest neighbor, and seeing how quickly their subsequent trajectories diverge in time. The smoothed 3/7/13 and 4/03/13 temperature difference data was used to find the Lyapunov curve for the thermosyphon (Figure 16. The starting conditions for the Lyapunov were that a selected data point and the next closest data point in Figure 14 or Figure 15 could not be within 5 time steps (2.5 seconds) or 0.5°F temperature difference. From there, the 2-norm vector difference between the two points as they both went forward in time. After roughly 7.5 seconds the two points generally stopped having any correlation. This means that two, nearly indistinguishable points in Figure 14 and Figure 15 greater than 2.5 seconds apart were completely unrelated after only 7.5 seconds. Data was excluded if the 'closest point' was too far away, defined here as a greater than 0.5 difference between there norms (meaning that the original data point was an outlier). This was done for every 100th data point.



(a) 3/07/13 Five and A Half Hour Run

(b) 4/03/13 Nine Hour Run

Figure 16: Lyapunov Curves

Smoothed Lyapunov Curve. One point out of every 100 points was plotted. 'Too close' along the time series was 2.5seconds F, 'too far' between two points so they were not longer indistinguishable was 0.5.

The correlations indicate this simple model of the atmospheric circulation can provide complex chaotic data. Two nearly indistinguishable points will diverge within 7.5 seconds. This thermosyphon has already provided a test bed where mathematical descriptions and computer generations of chaotic behavior can be studied in the lab.

5 Discussion

It is inconclusive if Harris's mathematical prediction (Harris, Ridouane, Hitt, and Danforth 2012) of non-Lorenzian behavior can be seen in this system. Figure 1 is his plot of residency time vs. oscillation amplitude, which can be compared to Figures 17 and 18 for the working thermosyphon. A purely Lorenzian system would only have a positive slope. Harris's data clearly had a Lorenzian system for oscillation amplitudes under 14.5 non-dementional velocity units. and a non-Lorenzian system for oscillation amplitude above 14.5 non-dementional velocity units.

The 3/7/13 and 4/3/13 runs' data were used to reproduce Figure 1. A switch in regime occurs when two adjacent temperature differences had different signs and the average of the 50 temperature differences before the two points and the average of the 50 temperature differences after the two points had different signs. The time when this occurs is called the reversal time. The greatest amplitude before the reversals was taken to be the largest absolute value between the maximum and minimum values between two reversal times.

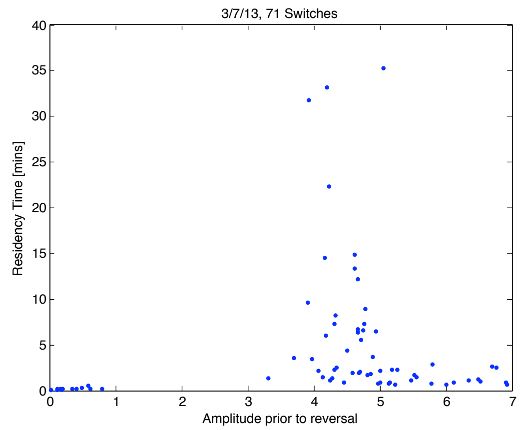


Figure 17: 3/07/13 Residency Time vs Oscillation Amplitude
71 reversals in a five and a half hour timeseries

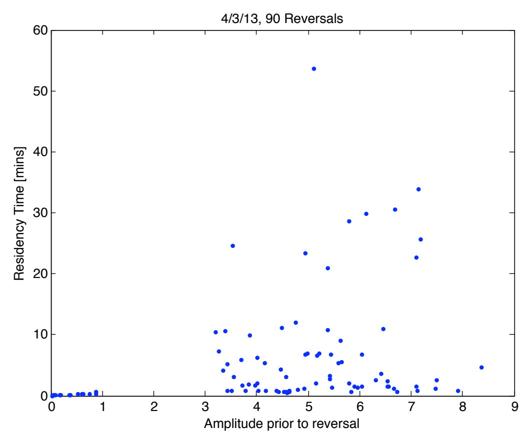


Figure 18: 4/03/13 Residency Time vs Oscillation Amplitude
90 reversals in a nine hour timeseries

There are some bands without any reversals (such as residency times between 15 and 20 minutes) and it is currently unclear if this is systematic or if the experiment was not allowed to run long enough. Only 71 and 90 reversals for the thermosyphon's two runs were recorded. Harris observed over 1,796 reversals in the CFD simulation. The reversals with amplitudes under 1 degree Fahrenheit and low residency times are thought to be the small switches between two large regime changes (Figure 17 and Figure 18). These quick switches (Figure 19) in temperature difference are not the big regime changes the study is looking for. A multi-day data collection run will have to be conducted in order to draw concrete conclusions about the viability of the simulated data Harris used (Harris, Ridouane, Hitt, and Danforth 2012) .

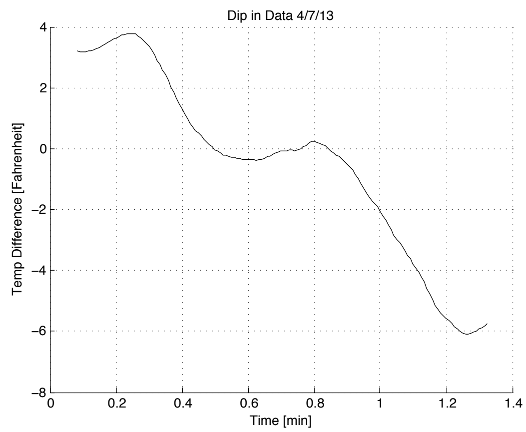


Figure 19: Switches During Reversals

Small switches can be seen between .5 and .7 minutes and between .7 and .85 minutes. From 4/03/13

References

Alligood, K., T. Sauer, and J. Yorke (1996). *Chaos an Introduction to Dynamical Systems*, pp. 359–392. New York: Springer.

Danforth, C. M. (2001, March). Why the Weather is Unpredictable, an Experimental and Theoretical Study of the Lorenz Equations. Undergraduate honors thesis, Bates College.

Danforth, C. M. (2011). Chaotic convection in a toy climate. www.mathaware.org.

Ehrhard, P. and U. Müller (1990, 7). Dynamical Behaviour of Natural Convection in a Single-Phase Loop. *Journal of Fluid Mechanics 217*, 487–518.

Harris, K. D. (2009, April). Predicting Climate Regime Change in Chaotic Convection. Undergraduate honors thesis, University of Vermont.

Harris, K. D., E. H. Ridouane, D. Hitt, and C. Danforth (2012). Predicting Flow Reversals in Chaotic Natural Convection Using Data Assimilation. *Tellus A 64*(0).

Lorenz, E. N. (1963). Deterministic Nonperiodic Flow. *Journal of Atmospheric Sciences 20*(2), 130–140.

Louisos, W. F., D. L. Hitt, and C. M. Danforth (2013). "Chaotic Flow in a 2D Natural Convection Loop With Heat Flux Boundaries". *International Journal of Heat and Mass Transfer 61*.

McKhann, A. (2011, April). Odes Modeling Chaotic Convection: Data vs. Physics. Undergraduate honors thesis, University of Vermont.

Vilmont, F. (2013, January). The Construction of a Thermosyphon. Lecture.

Welander, P. (1967, 6). On the Oscillatory Instability of a Differentially Heated Fluid Loop. *Journal of Fluid Mechanics*, 17–30.