Terrain-Induced Local Weather Phenomena of Candlewood Lake

by

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Abstract

Candlewood Lake, located in Western Connecticut, is the largest lake in Connecticut at 21.76 square kilometers. Because it is bounded by an undulating topography, it is possible that the thermal, orographic, and frictional characteristics of the lake contribute to localized diversity in weather. In particular, this project characterized atmospheric variables around Candlewood Lake and investigated the potential for katabatic flow and thermally driven winds. Meteorological variables (horizontal wind vectors, temperature and relative humidity) are measured with automated *in-situ* weather stations at two different sites on the lake. It was found that the terrain surrounding Candlewood Lake does induce microscale differences in the flow, which in turn affect the atmospheric variables measured. By means of the Froude number, the flow was characterized as turbulent. Backward facing step analysis step was completed and each station was found to be within the recirculation zone of their respective flows. Temperature and relative humidity at each respective location is dependent on wind direction and speed. The warmer influence of the lake is most apparent on nights where radiational cooling conditions are present, as compared to DXR. Katabatic flows were not found in the experiment, however further investigation is suggested to better characterize this phenomenon.

1. Introduction

a) Overview

Residents living closest to Candlewood Lake have long believed there are meteorological differences from one side of the lake to the other. These differences include temperature, wind speed, and amount of precipitation. In order to test this hypothesis, an experiment was conducted adjacent to Candlewood Lake, which included establishing a weather station on each side of the lake. Preliminary tasks to support this experiment included: performing background research on Candlewood Lake, obtaining permission from land owners to establish weather stations on their property, acquiring new instrumentation, and performing bench top tests to ensure the scientific validity of the instruments. During the experiment, data collection and maintenance were conducted on a weekly basis at the two locations. The field experiment period was from 13 October 2007 to 20 December 2007.

b) Temperature

i) Radiational Cooling

Radiational cooling occurs on calm, clear nights, when the longwave radiation emission from the surface is not in balance with shortwave radiation, due to no shortwave radiation at night. Hence the net loss of energy results in cooling. The reason for researching this topic is to find the magnitude of the role the lake plays in the reduction or reversal of the effect of radiational cooling along the lakeshore given the time of year. In order to do so, comparison of lakeshore location data will be made with Danbury Airport's (KDXR) ASOS station (Wunderground), located approximately 5 km to the southwest of the lake and removed from any nearby water sources.

ii) Terrain Effects on Temperature

Advection will be influenced by topography. The steeper slope of the mountains surrounding the westside station protects it more than the eastside. Thus, the station on the westside is less influenced by the synoptic scale flow and less coupled to the atmospheric vertical temperature gradient. The nocturnal surface radiation temperature is more closely associated to terrain curvature than surface elevation over undulating terrain (Mahrt and Heald, 1983). It was found that the role of slope angle with respect to the topography was significant in the thermal effects of a valley location. A smaller magnitude of the thermal forcing at night creates a larger magnitude of terrestrial temperature gradient relative to daytime values. Weak downward nocturnal heat fluxes create greater along-slope variations of air temperature in comparison with the large heat fluxes during the day when both horizontal and vertical mixing are more significant.

There also exists the possibility of topographic shading at each shore side weather station. Topographic shading (Chow et al, 2006) can play a significant role in absorption of incoming solar radiation during sunrise and sunset, both reducing and enhancing temperature profiles at these times. This could play a role in the data obtained for this experiment.

iii) Lake as a Heat Source

Specific heat is a measure of the ability of a substance to store energy. In particular, it is the quantity of heat required to raise the temperature of a unit of mass of a substance by a unit change in temperature. The specific heat of water is 4.186 kJ kg^{-1} K^{-1} while the specific heat of soil is 0.80 kJ kg^{-1} K^{-1}. Since the energy storage capacity of water (lake) is greater than that of the ground, a smaller diurnal range of temperatures would be expected at the lakeside stations. The cases investigated included light to calm wind conditions and clear skies at night with the likelihood of radiational cooling. These conditions will be favorable to investigate lake as a heat source phenomenon.

Lakes can contribute significantly to the area-average surface fluxes at night when cooler air from the land flows over the warmer lake water. In contrast, nocturnal surfaces fluxes are lower from land surfaces. The advection of cold daytime air over the warmer water may amplify fluxes over the water during maximum heating time, which is when the sun is at its greatest zenith angle (Burba et al, 1999). Heikinheimo et al (1999) indicates the fluxes over smaller sheltered lakes (less than 1 km fetch) are less significant than those over large lakes. Determination of the role of the Candlewood Lake on the immediate surroundings' diurnal temperature range is considered.

c) Wind

i) Froude Number

The Froude number is a dimensionless number characterizing the relative importance of inertial and gravitational forces. Froude number is considered to determine the effects of topography on the approaching flow around the lake. Stratification effects on flow around topography are generally described in terms of a Froude number based on the characteristic height (H) or length scale (L) of the topographical feature in the direction of the flow.

$$Fr = \frac{U_0}{NH} \qquad (1)$$

Fr – Froude number
U_0- Characteristic velocity
N – Brunt-Vaisala frequency
H – Characteristic height

When Fr=1, the natural wavelength of the air is in resonance with the size of the hill and creates the most intense mountain waves.

For Fr<1, some of the low-altitude upstream air is blocked by the hill, short-wavelength waves separate from the top of the hill, and the remaining air at lower altitudes flow laterally around the hill.

For Fr>1, very long wavelengths form downwind of the hill, and can include a cavity of reverse flow just to the lee of the hill near the surface.

$$N = \left(-\frac{g}{\rho_0}\frac{\delta\rho}{\delta z}\right)^{1/2} = \left(\frac{g}{\Theta_0}\frac{\delta\Theta}{\delta z}\right)^{1/2} \qquad (2)$$

Where:

$$\frac{\delta\Theta}{\delta z} = \frac{\delta T}{\delta z} + \Gamma \qquad (3)$$

To calculate the Froude number, the Brunt-Vaisala number and mean wind speed (U_0) had to be calculated. The Brunt-Vaisala frequency is the natural frequency of internal gravity waves or lee waves. To determine *N*, equation 2 was used. The vertical temperature gradient was found using radiosonde data from Albany for the selected time periods (Govett, 2007).

ii) Backward-Facing Step

Turbulent flow over a backward facing step is considered when evaluating turbulence in the prediction of separated flow. Flow over a backward facing step provides a well-characterized, turbulent, decelerating flow useful for measure relative velocities and reattachment lengths. While the Froude number is useful in characterizing the flow on the windward slope of the mountain, the backward-facing step theory will characterize the flow on the lee of the mountain. In order to distinguish the flow as laminar or turbulent at the separation point, the Reynolds' number must be found. By determining a flow regime to be laminar or turbulent, specific constants and equations are used for the necessary flow regime. This is useful when determine the reattachment point of flow past the backward-facing step.

Characterizing the flow allows correct estimations of the backward-facing step equations.

The Reynolds' equation is:

$$Re = \frac{Vl}{v} \qquad (4)$$

Re - Reynolds' Number
V - Average velocity
l – characteristic length
v – kinematic viscosity

The Reynolds' number is a dimensionless number which gives a measure of the ratio of inertial forces to viscous forces, therefore it quantifies the relative importance of the two types of forces for the given flow conditions (Thangam and Speziale, 1992). Laminar flows are those described by Reynolds' values of Re<2000, thus Reynolds' values greater than 2000 are considered turbulent.

The backward-facing step effect may be realized at each location when there is any westerly flow for the New Fairfield station or easterly flow for the Brookfield station. Each station would be vulnerable to fall within the reattachment length of the backward facing step with the conditions described above.

In order to find the reattachment length of the flow, the following equation was used.

$$L = \frac{Xr}{H} \qquad (5)$$

L – Reattachment point
Xr - Axial distance from step
H - Backward-facing step height

Height of the backward-facing step at the west station is 139 m, while the east station is 12.19 m.

iii) Katabatic Flow

Katabatic flow is localized density/topography driven flow. With regard to Candlewood Lake, a downslope flow driven by cooling at the slope surface may be experienced during periods of light, larger-scale winds. Due to the relief of the hills surrounding Candlewood Lake, katabatic flows may exist. In fact, the greater topographical gradient surrounding the westside location may result in lower nighttime temperatures than for the eastside. This is due to steeper topography allowing for the possibility of greater momentum of katabatic flow. These decreases in temperature will be less than the decrease in temperature compared to KDXR.

There also exists the possibility of a funneling effect around the lake. Winds blowing against large hills tend to go around or over them. If a pass or a valley breaks the hill barrier, the air is forced through the break at a greater speed. When wind is forced through narrow valleys, it is known as the funnel effect and is explained by Bernoulli's Theorem. According to Bernoulli's Theorem, pressures are least where velocities are greatest (Funnel Effect).

The wind in the free-atmosphere is generally near-geostrophic. The experiment performed however took place in the atmospheric boundary layer (ABL) where the actual winds differ from the geostrophic winds because of the surface friction and a vertical transport of momentum.

d) Relative-Humidity

Relative humidity is the ratio of the air's water vapor content to its water vapor capacity. Flow is always turbulent in the ABL. The water vapor is efficiently transported away from the interfacial molecular sub layer by turbulent eddies. Eddy transport at the air-water interface and the strength of turbulent mixing depend on surface roughness, friction velocity, and thermal stratification. The evaporation rate would also be dependant on these variables.

As explained previously, due to

length of the wave created by the flow over the hill, a cavity of light turbulent mixing flow may occur immediately following the hill. RH values may be higher on the westside than the eastside because minimal advection occurred and therefore less evaporation due to lower wind velocities.

2. Pre-Deployment Rooftop Experiment

Experimentation began 04 October 2007 on the rooftop of the Science Building at Western Connecticut State University's Midtown Campus. The initial test was to verify the functionality of the individual instruments as well as the written code using PC208W, including desired sample rates and correct meteorological variables. Consideration was also taken to the set-up of station, placement of instruments on the tripod (including heights), and the ability to retrieve data.

The experiment ran for a total of eight days, finishing on 12 October 2007. After data retrieval, a short analysis was conducted against DXR to prove the validity of measurements taken.

3. The field experiment: siting, instrumentation and auxiliary data sources

a) Sites

Two locations with approximately the same latitude were chosen on the east and west shores (Fig 1). The eastside location was situated in the town of Brookfield (41° 28.59' N, 73° 26.66' W) and the westside location was positioned in New Fairfield (41° 27.45' N, 73° 27.5' W). Observation of the surrounding landscape suggests there might be a significant local topography influence in wind direction and speed measurements at the two locations. The steep topography and forested nature of the lake shore would have to be considered during data analysis.

As indicated, the field experiment period was from 13 October 2007 to 20 December 2007. The Brookfield station was established on 13 October; the New Fairfield was established on 9 November.

b) Instruments

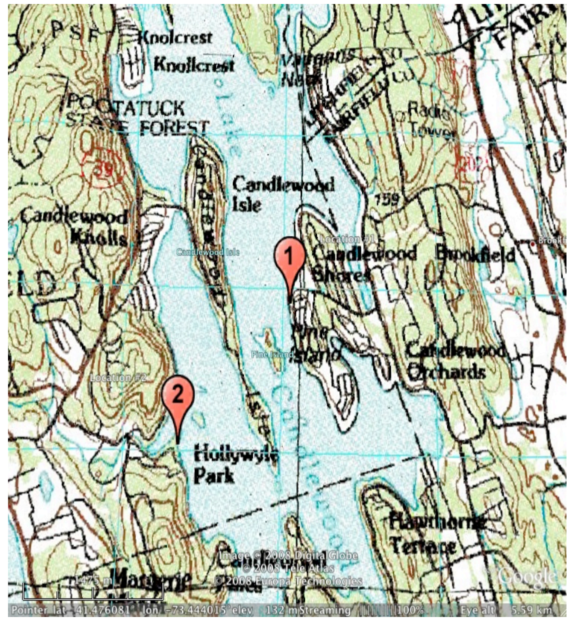

Fig 1. Topographic Map of Candlewood Lake. Site locations are depicted by 1 (eastside) and 2 (westside).

i) WCSU Platforms

Each weather station consisted of a tripod, mast, temperature/RH probe, anemometer, solar panel, rain gauge, and datalogger (Table 1). The original plan was to include precipitation data; however there was only one working rain gauge, so it was decided to exclude that variable from the experiment.

Instrument height was measured with a Sonic Laser Tape (Straight-Line). Both anemometers were mounted on the tripod mast 3.2 m from ground level while the temperature/RH probe was set up at 1.83 m. The National Weather Service instruction manual for the Automated Surface Observing Systems (ASOS) station recommends the temperature/RH probe be installed between the heights of two to three meters. The standard height for the wind sensor is 10 m with a minimum of 6.1 m (Magnus, 1999). Due to the relatively small size of our mast

Table 1	Westside Location	
Instruments	Company	SN
Datalogger	Campbell	46256
Temp./RH	Vaisala	C2730119
Anemometer	RM Young Wind Monitor	81460
Solar Panel	BP Energy	C10207152159061
	Eastside Location	
Instruments	Company	SN
Datalogger	Campbell	45301
Temp./RH	Vaisala	A1750018
Anemometer	RM Young Wind Monitor	71497
Solar Panel	BP Energy	11010321

Table 1. Instrumentation used and location

and issues with the overhead tree canopy, 3.2 m was the tallest height attainable for our instrument.

The Vaisala Temperature/RH humidity probe was used on both of the stations. The probe indirectly measures temperature with a 1000-Ohm platinum resistance thermometer (PRT) and relative humidity with a capacitance chip. The probe was placed in a Gill radiation shield.

Wind measurements were taken by RM Young Wind Monitors Marine version. The marine versions are specifically for offshore and marine applications. They have a waterproof bearing within the instrument as well as a small, heavy-duty cable that hooks directly into a longer cable attached to a datalogger. The anemometer is a propeller-type with a fuselage and a tail wind vane. The anemometer was leveled with an orthogonal bubble level. This ensures verticality of the tripod mast.

In order to prevent the battery from dying, a BP Energy 10 Watt Solar panel was attached to the station. The panel was facing the south at a 45° angle to ensure it received the most solar radiation possible. It is guaranteed to provide up to 10 W of power during the day, with a minimum of 9 W.

All of the previously mentioned instrumentation connected into a CR10x data logger for measurement and control as well as data storage. The data logger had a 2 Mbyte internal memory. This allowed the station to be unattended for longer periods of time. A data acquisition code was written to enable the data logger to collect wind speed and direction, temperature, and relative humidity. Sample rates of one minute were used, along with an hourly diagnostic update. A software program (LoggerNet, included in the purchase of a CR10x) was used to write the code.

Once both of the automated in-situ weather stations were established, they were visited frequently with a laptop to upload data from the storage module. In addition, instrument operation was checked and diagnostic testing was performed. This included inspection of battery voltage and the temperature of the data logger (by use of an internal thermocouple).

A rain gauge was originally connected to the platform. Due to technical difficulties on numerous occasions and the inability to have comparable data at both the Brookfield and New Fairfield stations, rainfall information is not included in this paper.

Fig 2. Eastside location on 13 October 2007

(ii) KDXR ASOS station

Throughout the data analysis process, data obtained from KDXR's ASOS station was used. ASOS stations are comprised of many sensors and probes (Appendix, Fig 1). The instruments include a ceilometer, visibility sensor, precipitation identification sensor, freezing rain potential, lightning sensor, pressure sensor, ambient/ dew point temperature sensor, anemometer with direction and speed, and a precipitation accumulation sensor (Magnus, 1999). For this experiment, only the wind and temperature data was used.

The thermometer uses a platinum wire Resistive Temperature Device (RTD) to measure ambient temperature. The RTD operates on the idea of electrical resistance in a wire varies with temperature. The RTD is located in a stream of air entering the sensing unit and assumes the ambient air temperature. The sample rate is once per minute. The average accuracy is 0.2°C in temperature and 2% in relative humidity.

The anemometer that is described in ASOS user manual describes the instrument as a cup and vane anemometer. However, after visiting DXR and researching further, an upgrade was made to the system and it now uses a sonic anemometer as of 2005 (G. Conte, personal phone conversation, 2008). ASOS stations now use Vaisala 425NWS Ice Free ultrasonic wind sensor. This is an array of three equally spaced transducers which radiate and receive ultrasonic pulses in a horizontal plane. The sensor measures transit times in both directions for each of the three transducer pairs. The wind speed and direction are then derived from the six transit time measurements. The instrument takes 24 five-second averages to determine the two-minute average wind speed and direction. The highest three-second running average speed is stored for gust and peak wind processing (NOAA NWS Focus, 2005). The accuracy of the sonic anemometer is 3% or ± .26 knots (Vaisala, 2003).

(iii) Lake Temperature reference

Lake surface temperature is an important variable to utilize in reference to the air temperature. Because bodies of water have a higher energy storage capacity compared to land, it is reasonable to assume that Candlewood Lake surface temperature would affect its immediate surroundings. Lake temperature was measured by Jim Pski, owner of Pski's Angling Adventures. Jim took two different measurements of the lake using two different depth finders. One of the models he used was a Lowrance X50 DS Dual-Search Fishfinder. Because it is an in situ device, it only measures the first three centimeters of the lake surface temperature. The other depth finder was a Lowrance LMS-527C with Internal GPS. Careful consideration was used in determining validity of the data. Jim calibrated each instrument against the other one and was within ~.1ºC of each other (J. Pski, personal phone conversation, 2008). This consistency was important as it provided a strong support to the data analysis concerning wind anomalies and temperatures differences.

4. Analysis

After collecting all the data, processing and quality control began. This consisted of identifying data that was corrupted or generally bad in some way. Examples include disregarding the tipping bucket rain gauge due to its ineffectiveness and missing data points. Because data collection occurred many times over a two-month period, many files had to be combined to create readable data sets for analysis. Matlab code was created to analyze the data.

The data analysis considered evaluation of a topographical map of the area to consider whether orographic effects influenced temperature and air flow around the lake. Historical surface maps and hourly observations from KDXR were also considered. Integrated atmospheric moisture equations to calculate microscale surface fluctuations were also used.

a) Post-Deployment Bench Intercomparison Experiment

While analyzing and comparing relative humidities of both locations, a large difference was noted. The westside location was, on average, roughly 4% greater than that of the eastside. Many theories were hypothesized as to the reason for the difference. A bench top test was performed to determine whether the difference was due to an instrumentation bias or if it was an actual physical phenomenon.

A bench top experiment began on 17 Oct 2008. The temperature probes were connected to the same platforms as they were in the field experiment and placed next to one another (Fig 3).

Fig 3. Temp./RH probes during bench top testing on 17 Oct 2008

Data was collected for four days, ending 21 October.

Several things were noted in the data. First, there was a bias between the west RH probe and east RH probe, however not at the 4% initially thought. As seen in Fig 4, the instruments were well correlated. The mean bias was 0.7272%, nearly 3% less than in the field experiment. Therefore, the bias in the field experiment was an actual physical bias. The calibration bias of .7272% was rightfully taken into account and adjusted for the eastside station.

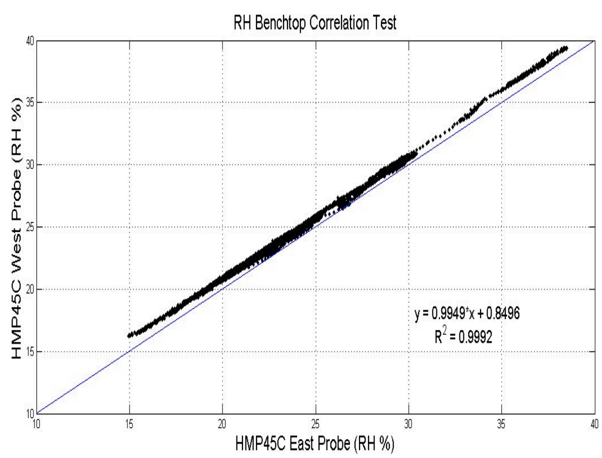

Fig 4. Correlation plot for East vs. West RH probes during bench top experiment

b) Froude Number Analysis

Flow around the lake appears to be affected by topography. One hill in particular, Sweet Cake Mountain, is located to the north west of the Westside station. The elevation of Sweet Cake Mountain (Fig 1, located NNW of Point 2) is 264.87m and has a steep incline on the south and east facing slopes.

This mountain appears to play a significant role in the microscale weather of the westside station. Therefore, stratification effects were calculated in this experiment by determining the Froude number for flow at this mountain. Three separate cases were chosen based on light, moderate, or strong wind events.

The wind speed from the surface at DXR was used to determine U_0.

To determine *H*, Google contour maps were used. A point to the NNW of Sweet Cake Mountain is found to be 207.3 m above sea level. This height was subtracted from the mountain height, leaving the height above the upstream valley height as *H*. The calculated height of the mountain above the lower surface was determined to be 57.5 m.

All cases chosen had a northwesterly component; key to understanding the flow around Sweet Cake Mountain and its effects on the west station.

i) Light Winds

Day 328 00z was chosen for the light wind. During this case, winds were at 3.1 m s^{-1} out of the north-northwest. The estimated Froude number was 1.92. Since Fr>1, stratification is not considered to be strong. An important aspect of stably stratified flows over and around three-dimensional topographical features is the increasing tendency of fluid parcels to go around rather than over the topography with increased stratification (or decreasing Froude number). This is because such fluid parcels do not possess sufficient kinetic energy to overcome the potential energy required for lifting the parcel through a strong, stable density gradient. Whether a given parcel in the approach flow would go over or around the mountain depends on the height of the flow relative to the mountain height. Therefore, flow will continue over the mountain.

As a result, there is a cavity present during this weak flow at the surface. When static stability is weak and winds are greater, flow obtains a lesser frequency and its wave amplitude is weak.

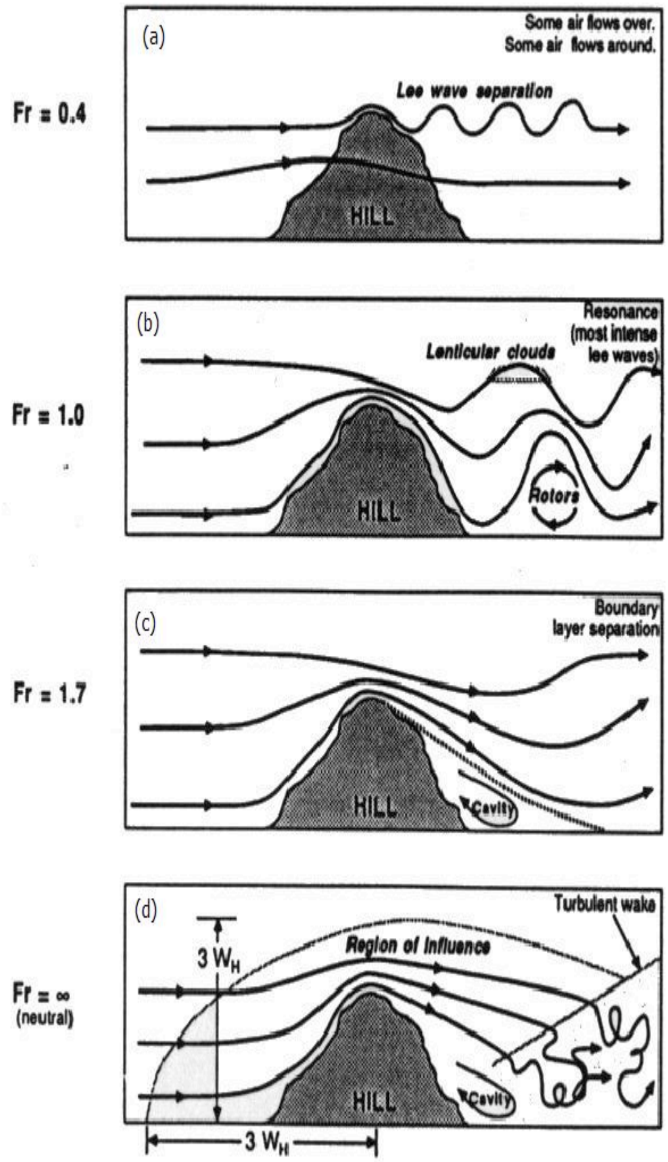

Fig 5. Idealized flow over an isolated flow. Different regimes

This scenario (Fig 6) would likely fall into the category of a backward-facing step. This situation would include separated flow, recirculation zone and reattached flow at some downstream point.

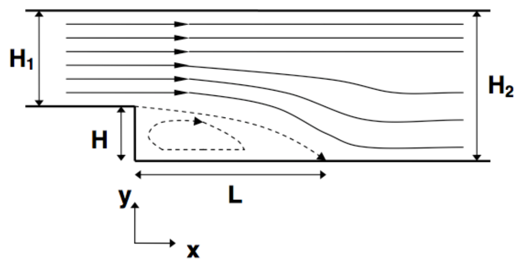

Fig 6. Schematic of flow over a backward-facing step

In many scholarly papers (Kim et al)(Thagnam and Speziale), the ratio (H_2/L) is experimentally determined to be approximately 7.0 ± 1. These values seem to be universal when flows are turbulent at separation or when the transition to turbulence occurs very close to separation. Reynolds' numbers were computed to be 1.73 $x10^8$, which is well above the transition point characterizing flow. For *Re*<2000, flow is said to be laminar and any number above 2000 is turbulent. Therefore, the flow is turbulent and Kim's experimental reattachment length of 7.0 is used.

Using eqn 5, *Xr* is found to be approximately 970 m, spanning slightly over half the lake. This places the New Fairfield station within the recirculation zone and cut off from the main flow. The recirculation zone is a zone of much lighter winds and generally flows in the opposite direction of the mean flow. Given the latitude of Candlewood Lake (~41° 28 N), the lake would fall in the region of westerly, synoptic-scale winds. With this in mind, the east lakeshore received greater wind velocities than the west lakeshore, as expected by the Froude and backward-facing step analysis.

Furthermore, the Brookfield station would be influenced by westerly flow becoming reattached to the mean flow over the lake surface. This would result in lower humidity, higher temperatures, and greater wind speed.

ii) Moderate Winds

Day 352 00z was chosen for the moderate winds. During this case, winds were at 6.2 m s^{-1} out of the west-northwest. The estimated Froude number using these variables is 4.16. Similar to light winds, this case shows that a turbulent wake will set up, given these conditions.

In this case, the likelihood of a cavity on the lee side of the mountain would be found. Once again, the west station falls into the recirculation zone while the east station continues to be influenced by the synoptic mean flow. As mentioned by Ting and Prakash (2005), the reattachment length, *L*, is a function of the Reynolds' number. As the Reynolds' number increases, so does the reattachment length. For the moderate wind case, the Reynolds' number was determined to $3.46x10^8$. Even with the higher Reynolds' number, the flow will still reattach over the lake prior to reaching land, even with Kim's accuracy of ± 1 of *L*. The flow would reattach at 1,112 m, still over the lake surface.

iii) Strong Winds

Day 320 12z was chosen for the strong wind. During this case, winds were at 10.8m s^{-1} out of the northwest. The Froude number was calculated to be F>>1, at 10.5. In this flow, wave amplitude would be even weaker and provide larger and more turbulent wakes across the lake. For this situation, a turbulent wake will often form downwind of the mountain, sometimes with a cavity of reverse flow near the ground.

The backward-facing step would also again come in to play, but the reattachment point would be very difficult, if not impossible, to obtain given the turbulent wake downstream of the recirculation zone (Fig 5 [d]).

For the strong wind case, the Reynolds' number was determined to 6.03×10^8.

iv) East Side Backward-Facing Step

When analyzing the wind data from the Brookfield station, it is noticed that there was no component of easterly wind measured. Upon further investigation of the topography, it is noted that there is a steep decline from street (South Lake Shore Dr) to the lake. It is a total relief of 12.19 m towards the lake over a distance of 60 m. It is hypothesized that this steep incline would provide the necessary step height to form a recirculation zone that the station would be affected by.

Flow is found to be turbulent by Reynolds' number calculation of 1.22×10^7 with light winds. The Reynolds' number would continue to increase as the wind speed increased.

The backward-facing step theory was applied to the east station using equation 5. The reattachment length was found to be 85.33 m, which is means the station is located within with the recirculation zone of the flow. This theory supports the data, which shows no easterly flow at the eastside station, regardless of the magnitude wind speed.

c.) West Side Wind Anomalies

Throughout the experiment, the east side station measured wind velocities greater than that of the west side just about all the time. As a matter of fact, the west side rarely measured wind speeds in excess of 5 m s^{-1}, which are attributed to the results of the Froude number, backward-facing step and other topographic blocking (Lin and Hubbard, 2000). There were two cases investigated where the west side wind velocities were greater for a period of more than six hours. These two anomalies were analyzed in great detail along with the

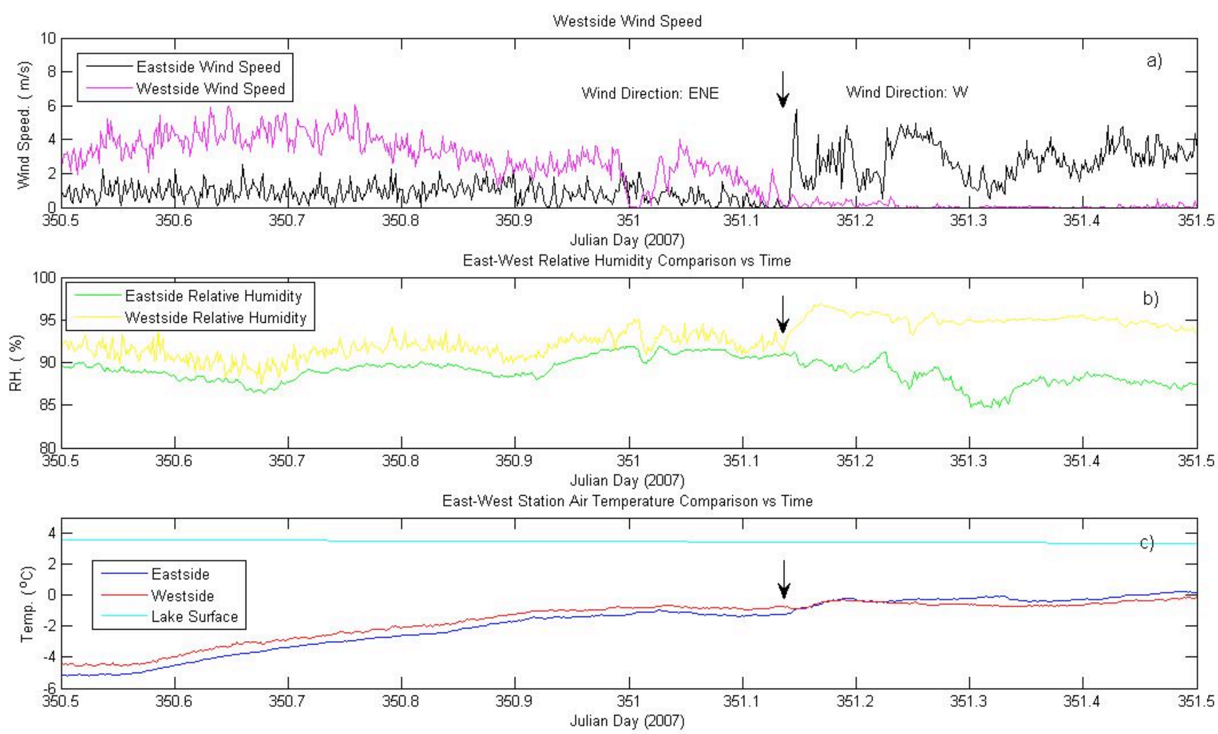

Fig 7. Wind speed [panel (a)] and the effects on relative humidity [panel (b)] and temperature [panel (c)]. Arrows indicate time of wind shift from east-northeast to west.

supporting information of the synoptic scale weather conditions, DXR weather observations, and the east and west side station variables.

i.) Case 1: 17Z 350 to 17Z 351

The synoptic weather conditions for this time period involved a strong area of low pressure moving northeast off the Atlantic seaboard. A Nor'easter supplied the area with a constant ENE flow for some time until it moved north of the area and the winds shifted to the west. DXR also confirmed this shift in their hourly observations.

The timing of the wind shift, which is represented by the arrow in Fig 7, was determined by taking an average of the measured wind shift times at each station.

It is evident that there is a strong correlation between the change in wind direction and the temperature of the two stations. Prior to the wind change, the east side station is upwind of the flow/lake which results in a small influence due to the recirculation zone by the lake and a lower ambient temperature. The west side station is downwind during this period and experiences a warmer ambient temperature as the flow is influenced by heat fluxes from the warmer lake water. Temperatures quickly respond to the wind shift after this period as the east side station now becomes downwind of the flow and warms up. The opposite effect is seen as the west side becomes upwind of the lake.

The measured relative humidity is also dependent on wind speed and direction. Although the humidities never intersect like in the temperature graph, it is clear that with an easterly fetch, the two stations' relative humidity values become closer to one another. Following the wind shift, the humidities move apart drastically at values approaching 10%. As the west side station cools due to the lack heat transfer from the lake, the dew point depression decreases and therefore the humidity rises. The east side station sees an opposite effect with a warming westerly flow that is influenced by the warmer lake, which leads to a greater dew point depression and lower humidity. It is believed that the moisture content in the air (dew point) is generally constant across the lake given topography driven turbulence and mixing of air.

The wind speed across the Candlewood Lake also effects the temperature and humidity of the station that is downwind of the flow. Preceding the wind shift, the prevailing ENE wind is generally steady until 351.0, as seen on Fig 7, where the winds are lighter. At this moment in time, the humidities at the east and west side stations are at their closest. The concept is that the slower the "air mass" moves from one side of the lake to the other, the more time for the heat to transfer from the lake to warm it. Further evidence supports this theory after the wind shift including and especially right after 351.3. The mean wind speed decreases during this time and it is clear that the east side temperature increases in response to an "air mass" which has had more time to be influenced by the warmer lake. The humidity also decreases in response to a larger dew point depression and the largest separation of the two station's humidities for the period may be found here.

ii.) Case 2: 05Z 322 to 17Z 323

The synoptic weather conditions over this time period include an area of high pressure north of the Great Lakes strengthening and providing an on-shore flow to New England as the high tracks the to north. Prior to this, a weak pressure gradient created light winds at the lakeside stations.

The arrow in Fig 8 shows the timing of the wind shift at DXR from south to east. Again, it is evident that the wind is directly responsible for the increase of the west station's temperature, with flow over the lake

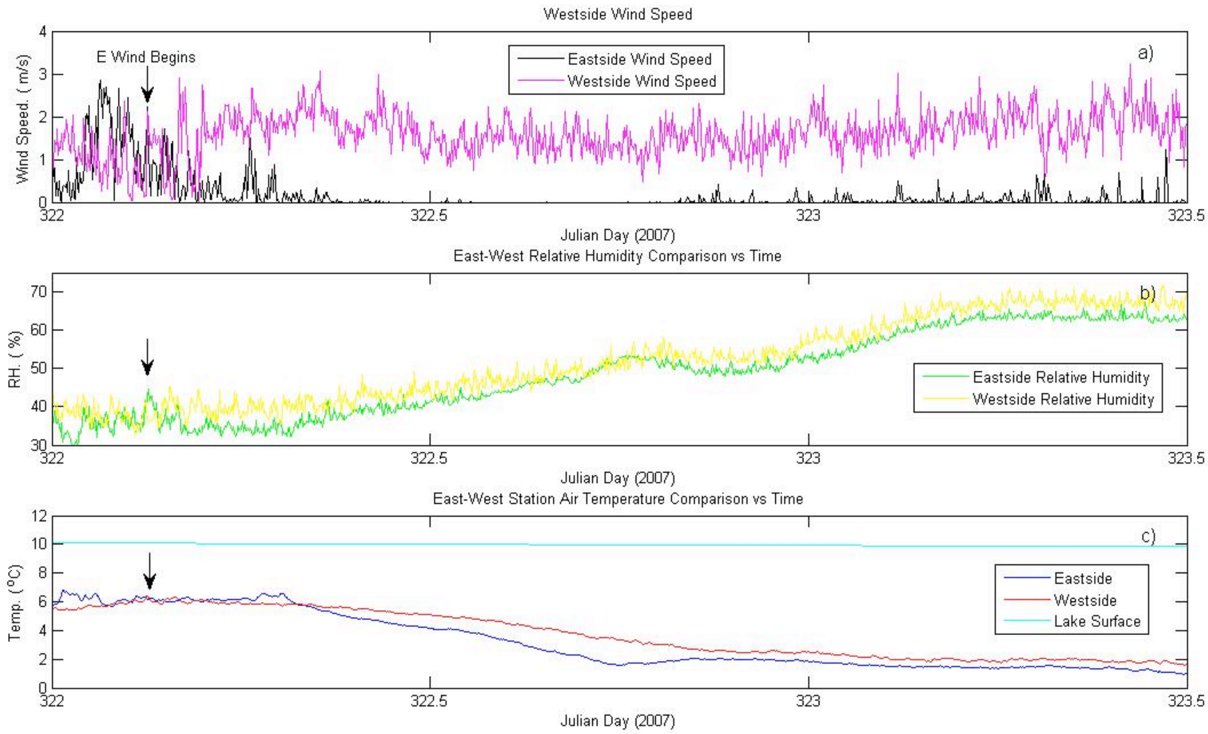

Fig 8. Wind speed [panel (a)] and the effects on relative humidity [panel (b)] and temperature [panel (c)]. Arrow indicate time of wind shift from south to east.

and turbulent mixing available.

With the light winds at both stations early in the period, temperatures were highly correlated and relative humidity values, although different, remained relatively unchanged. When the winds at the east side drop to zero, the temperature begins to decrease more rapidly than with a light wind. This is because the station loses its influence of the lake heat via lack of heat transfer from flow across the lake and turbulent mixing.

d) Katabatic Flow Investigation

i) Case 1: 24 Nov 2007

The synoptic weather conditions for 24 Nov 2007 (Julian Day 328) included an area of high pressure (1034 hPa) sliding from the Ohio River Valley into the Mid-Atlantic states by 12Z. High pressure overnight set the stage for calm winds and clear skies, which are conducive to radiational cooling.

There is also the possibility of micro-scale katabatic flows to exist in the area of the stations and DXR given the surrounding hills. The combination of radiational cooling and katabatic flows serve to characterize the differences in minimum temperature between all three stations.

As seen in panel (a) of figure 9 , during the late morning hours of JD 327.4, temperatures at east and west lake stations are highly correlated and roughly 2°C warmer than DXR. This is likely due to the proximity of the warmer water to the lakeside stations.

As the sun sets and shortwave radiation approaches zero, temperatures begin to fall. It is likely that topographic shading was the major contributor to the west side station temperature falling prior to the eastside temperature. The result of the low sun angle in the southwest would ultimately be blocked given the topography of the west side and cause a lower amount of solar radiation to be absorbed than that of the eastside. The temperatures initially begin to fall at the relatively the same rate (though initialized at different temperatures), however around JD 327.67 (1630 local), the slopes of the descending temperatures start differentiating at a larger rate. On average, DXR fell roughly 1.4°C per hour, while the west side lakeshore temperature reported a drop of .25°C per hour. The east side reported half the drop of west side, at roughly .13°C per hour. Given these calculations, temperatures fall at DXR to a minimum of -7.8°C, which is 9.5°C colder than the east location and 8.1°C than the west location. With generally a calm or light west wind present, a slower drop of the eastside temperature would be expected.

Likely determinants in the temperature difference are radiational cooling and lake surface temperature. Radiational cooling is the main factor in DXR dramatic decrease. Over a short distance (DXR to lake ~ 5km), one would expect similar radiational cooling rates of temperature decrease to occur. However, due to the much warmer lake temperature (9°C), temperatures at the lakeshore stay relatively constant with a small average hourly decrease.

ii) Case 2: 17-18 Dec 2007

Case two (panel b) also shows the same type of situation but twenty-four days later. The lake surface temperature is at 4°C; the lowest it can be before the lake completely freezes. As water cools, it condenses and becomes more dense and heavy until 4°C. Then, as the temperature drops towards the freezing point, it starts to expand and become lighter. It causes a complete circulation or overturning at least twice each year; once in the spring and once in late autumn. The minimum temperature recorded at DXR was -13.3°C, while the minimums at westside and eastside were -6.8°C and -6.3°C, respectively. The temperature differences between DXR and each station were 6.5°C and 7.0°C.

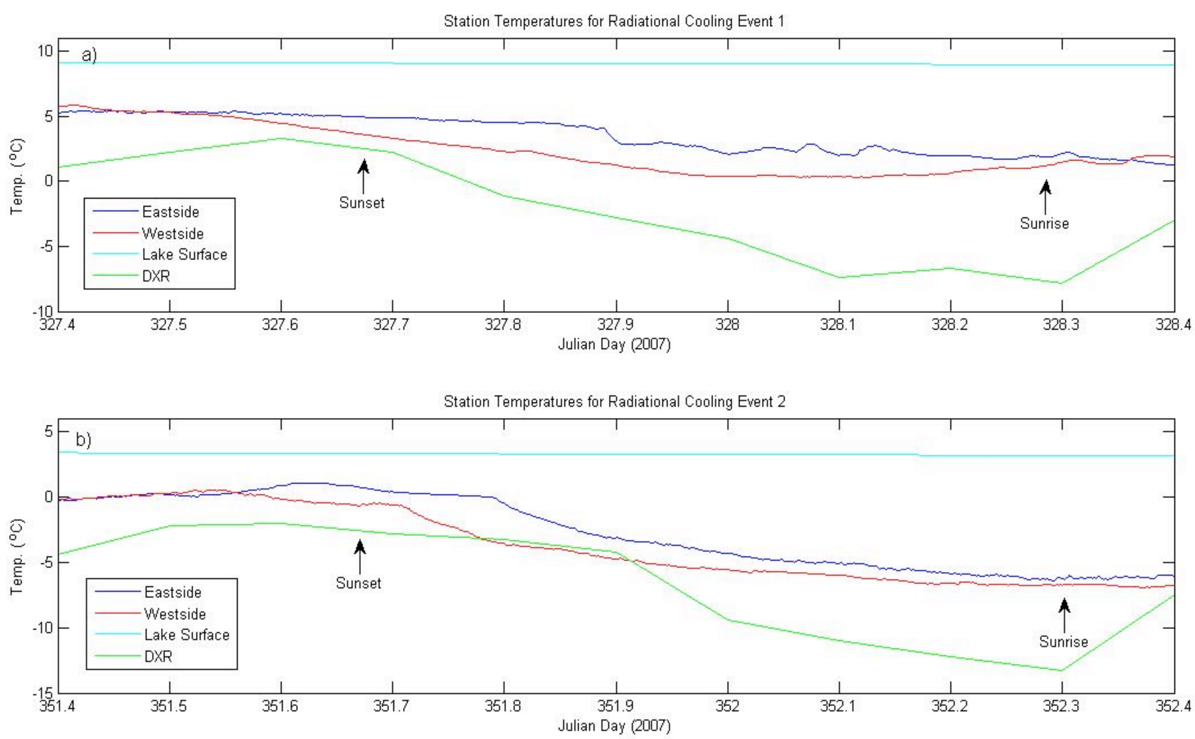

Fig 9. Candlewood Lake station temperatures evaluated against Danbury Aiport (KDXR) temperature time series from 17Z to 10Z for days 23-24 Nov 2007 [panel (a)] and 17-18 Dec 2007 [panel (b)]. Lake temperature included for reference purposes

Wind analysis does not support katabatic flow at the shore side locations. Given the small height of the hill, it may be that the velocity of the katabatic flow is less than that of the minimum threshold of the station anemometers to measure. The minimum wind speed for the instrument is 1.0 m s^{-1}. The cold, dense air of katabatic flow may also reside lower than height the instrument.

Since the air has less ability to hold water vapor in it, it is reasonable to say that the transfer of heat energy into an 'air mass' would be less too. Therefore, the lake does not act as much as a heat source in the winter as it does in the autumn.

Included in the appendix are surface and upper air maps as well as vertical temperature profiles for each case.

5. Conclusions

We have shown that the terrain surrounding Candlewood Lake can induce microscale differences in the flow, which in turn affect temperature and relative humidity. Comparisons with DXR provided another reliable means of data source to further examine the atmospheric variables collected along the shore. By using historical surface and upper air charts, we were able to isolate specific cases when geographical influences would be maximized.

Our conclusions can be summarized as follows:

1) By calculating the Froude number during three separate cases of light, medium, and strong winds, we were able to determine the Froude number is greater than one for each case. Upon analyzing the Froude number, it became clear that flow over the mountains (specifically Sweet Cake Mountain) directly affected the wind measurements, or lack thereof. In fact, with Froude greater than one, cavities exist near the station on the lee side of the mountain. The flow around the station would then be characterized as vatriable, chaotic and turbulent. Because of this chaos, the wind speeds at the New Fairfield station were found to be about 60% that of the Brookfield station's wind speed on average during the experiment duration.

When using radiosonde data from Albany (~130 km from DXR), there exists real temperature bias that could not be rectified with data available. A few things were noted that gave credibility to our calculations. Given that northwest flow was investigated, Candlewood Lake is nearly directly downwind of Albany. During cases 1 and 2, synoptic flows in eastern New York had strong cold air advection aloft (meaning temperatures at Albany were being advected towards Candlewood Lake). In addition to the warmer lake water (supplying warmer surface temperature near the lake), the cold air advection would allow the vertical thermal gradient to be greater. Calculations were done with estimated thermal gradients, and the results were very comparable to those found in the Albany sounding calculations. Therefore these negligible differences verify that the Albany soundings may be used for computation of the Froude number.

While only Sweet Cake Mountain was investigated, there are many locations on the lakeshore that would be influenced by this phenomenon.

2) Given the step-like topography to the west of the New Fairfield station, the flow acts in a way that is characterized by the backward facing step. During synoptic scale westerly flow, we concluded the station is cut off from the flow and is in the wake region to the lee of the step.

Reynolds' number calculations allowed us to determine the flow to be turbulent. With this calculation, we were able to characterize the (H_2/L) ratio as 7.0 ± 1. The reattachment length was found to be approximately 970 m. Therefore the New Fairfield station was found to be in the recirculation zone, while the Brookfield station is located well downstream of the reattachment point.

Since the westside station falls within the recirculation zone, we found the station to be decoupled from the synoptic mean flow. This resulted in a large decrease of wind velocity. The wind velocity plays a large role in mixing in the turbulent boundary layer. These low velocities would not effectively advect water vapor away from the station, causing the values of relative humidity to be greater on the westside. Therefore, the 3% relative humidity bias is partially attributed to the backward-facing step, its position near weak recirculation zone winds, and no influence from the prevailing westerly flow.

Further investigations may be done on this region with the assistance of numerical modeling computers. These models could simulate the flow over the step and therefore characterize the strength and direction of the flow at the New Fairfield station. These models would allow a three-dimensional analysis of streamline flow as it encounters the backward-facing step as researched.

3) During the duration of the experiment, two cases of easterly flow were analyzed. Wind speeds at the west side were rarely found to be above 5 m s^{-1}. Only in cases of easterly flow did these measurements exceed 5 m s^{-1}. This not only solidifies our findings of the effect of the backward-facing step on the westside station for prevailing westerly flow, but also proves the existence of a backward-facing step at the eastside. Temperatures were highly correlated with the wind direction blowing over the warmer lake, which is to be expected. Further findings indicated that wind velocities also play a significant role.

Referring to Fig 8, the largest temperature differences are found when east winds decrease to zero, due to the proximity in the recirculation zone. The lack of mixing at the east side station allows for a considerable temperature decrease to occur. Also noted during these conditions was the east side relative humidity approaches and slightly surpasses that of the west side, one of the few times in the experiment this is seen. This strengthens our theory of stagnant air being present when in the recirculation zone of the backward-facing step. Little or no turbulence or mixing is found within the reattachment length.

4) Ideal radiational cooling conditions were analyzed from surface maps and observations for the experiment and two nights were isolated. The minimum temperature differences between DXR and the lake stations on days 328 and 352 were then probed.

At the beginning of each radiational cooling event when dusk approaches, topographic shading is identified (especially in Fig 9 [b]) as the main contributor for the earlier descent in temperature of the west side.

As noted by Lin and Hubbard (2000), there exist air temperature errors between the ASOS system and the Gill shield with an HMP 35C sensor. An increase in the airflow speed inside the shield will enhance the degree to which temperature sensor readings inside the shield represent the air temperature. Therefore, the largest errors are found during periods of calm winds, such as the radiational cooling event. With this consideration, future experiments may want to address these errors in more detail.

For JD 328, DXR measured a minimum temperature of -7.8°C, while the east and west locations measured 1.7°C and 0.3°C. For JD 352, the east and west recorded minimums of -6.3°C and -6.8°C and DXR's minimum was found to be -13.3°C. In the first case, the thermal differences were 9.5°C between DXR and Brookfield's station. A smaller difference was found during JD 352 of 7.0°C between DXR and Brookfield. Even with ideal conditions for radiational cooling, the stations on the lake will be heavily influenced by the warmer lake water. The degree of influence on the stations will decrease as lake water becomes cooler. Therefore, as the lake becomes frozen, it can be expect that the temperature differences between the lake stations and DXR will approach zero. Hence, the lake acting as a heat source during radiational cooling events is seasonally dependant.

5) Wind analysis of speed and direction does not support katabatic flow near the lake. Given the small size of the hill, katabatic flow may exist less than that of the minimum threshold for the instruments. If small scale katabatic flow were to exist, light wind would be directed off shore creating slightly cooler temperatures at the westside than the eastside due to no influence of the lake.

For future experiments, it is recommended that sonic anemometers be used at more than two locations at different heights. This would not only give the three-dimensions of the flow at lower speeds, but also provide many more data sets that will be useful in the understanding of streamline flow surrounding the lake and characterizing the possibility of katabatic flow.

6) Existing networks along the shore, including the Candlewood Lake Automated Weather (CLAW) Network, may provide an accurate portrayal of the weather at that station location, however it is neither reliable nor functional to use for any location away from the lake.

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