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Type of Project: Partners

Project Title: A Cold Pool Microscale Effect Resulting from Nocturnal Winter Season Radiational Cooling

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Section 1: Summary of Project Objectives

This study was initiated after an episode of extreme cooling occurred at KART (January 14, 2009), where the minimum temperature reached -23.1^{o}F. The minimum temperature was not the main issue brought up by the meteorological community; rather what brought notice to this cooling event was the rapid drop of temperatures that occurred between 05:56 and 06:56 hours (a cooling rate of 0.23^{o}/min). While this type of extreme cooling episode at Watertown (KART) is described in the meteorological community as happening "all the time" under winter radiational cooling conditions, a number of hypothesis have been proposed to explain it.

Aside from radiational cooling, one hypothesis presented by the meteorological community is that the rapid drop in temperatures at KART may be associated with the location of the ASOS thermometer within a topographic depression (hereafter referred to as the 'bowl' hypothesis). The bowl hypothesis is described as follows: very cold surface air will flow to the lowest point of the depression. As the cold air continues to flow into the depression, the cold air layer deepens. At some point, the cold air layer reaches the height of the ASOS thermometer, and the recorded temperature suddenly plummets. Other hypotheses include some form of cold air drainage, whether local or initiated from Tug Hill.

The objective of this study is to characterize the extreme cooling episodes, explore reasons for the rapid cooling during these episodes, and to suggest a possible 'patch' to improve the minimum forecasts during extreme cooling episodes.

Section 2: Project Accomplishments and Findings:

Temperature Profiles

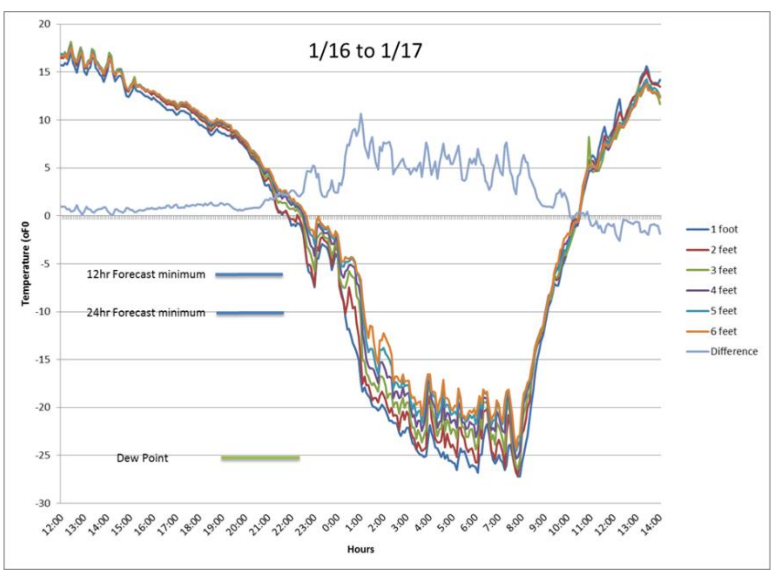
A number of extreme cooling events (radiational cooling) were recorded in 2010-2011, exceeding our original expectations. A snow pack existed for all ten episodes. Ten of these events were examined in detail – examining temperatures at six heights (meteorological tower), along with sky and wind conditions (obtained from KART). Of the ten events, eight were subzero events, of which four recorded minimum temperatures below -20^{o}F (extreme events comparable to the January 14, 2009 event that initiated this study).

The graphs associated for each extreme cooling episode show air temperature heights at six levels (from 1-foot to 6-foot above the surface. The 'Difference' plot refers to air temperature differences between the 6-foot and 1-foot data loggers (6-foot temperature subtracted from the 1-foot temperature). A positive value indicates warmer temperatures with height, and a negative value indicates cooling temperatures with height.

The 6-foot temperatures measured from the meteorological tower compared best with KART temperatures. A comparison of minimum values is shown in Table 1.

Table 1. Comparison of minimum temperatures between the 6-foot height data logger on the meteorological tower (this study) and ASOS air temperature measurements (KART).

Date	This Study (oF)	KART (oF)
12/09/10 - 12/10/10	-2.8	-4.0
12/24/10 - 12/25/10	7.3	7.0
01/05/11 – 01/06/11	0.2	0.0
01/10/11 - 01/11/11	-4.2	-4.0
01/13/11 - 01/14/11	-6.2	-7.0
01/16/11 - 01/17/11	-24.3	-24.0
01/21/11 - 01/22/11	-12.5	-13.0
01/22/11 - 01/23/11	-23.6	-25.0
01/23/11 - 01/24/11	-30.0	-30.0
01/30/11 - 01/31/11	-23.0	-23.0



Example

Figure 1. The January 16-17, 2011 extreme cooling episode. Forecasted minimum temperatures and the dew point temperature associated with the observed minimum are shown.

Local Land Survey

The survey results (Figure 2) do not show a well-formed bowl shape, but rather a gentle grade (0.7%), sloping downward from the northeast to southwest. The highest elevation difference (about 40 inches higher in relation to the tower) actually occurs along the runway, and it is the runways height in relation to the foot of the tower which gives the appearance of a semi-bowl shape. Additional surveys were conducted after snowfalls events (12/03/2010, 01/14/2011, and 02/14/2011) to determine if the surface topography changed with accumulated snow pack. The results show little change in the shape of the landscape. What changes that did take place due to the snow pack tended to smooth out the differences in elevation.

The local land survey (using surveying equipment) was extended to Black Creek Bay by examining contours from a topographic map. A study of the map reveals that the gentle slope, as measured at KART, continues at a 0.6% grade down to Black River Bay.

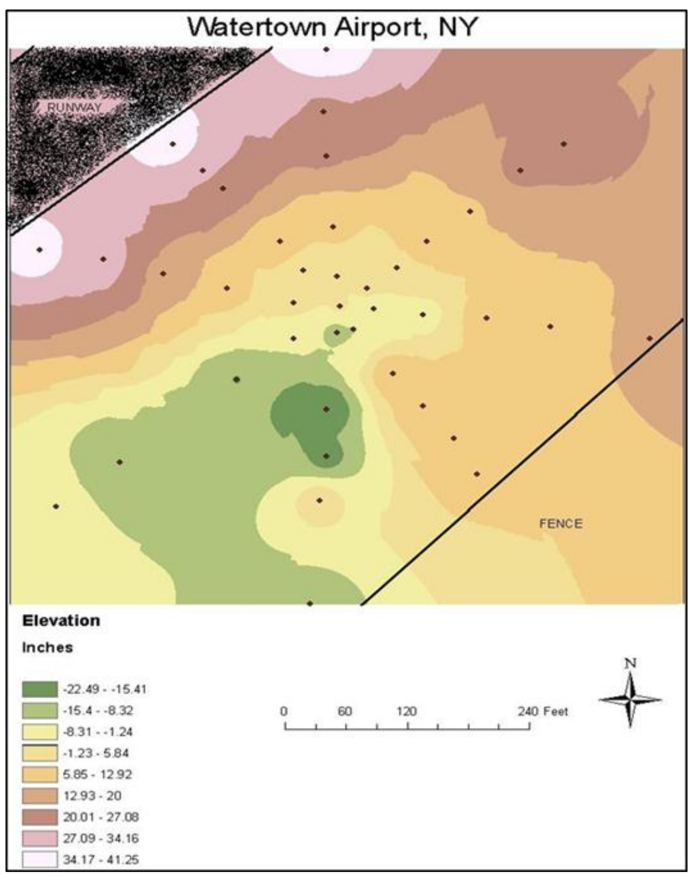


Figure 2. Instrumental survey results. Differences in height are measured relative to the center point (location of meteorological tower).

Two-Stage Cooling Process

An examination of the 10 cooling events, as captured in this study, illustrate a two-stage cooling processes at KART. The initial stage is classic boundary layer meteorology. A ground-based temperature inversion quickly establishes itself after sunset when sky conditions are clear and winds are calm, or later in the evening if sky conditions and winds are not suitable at sunset. The initial rate of cooling is rapid - greatest at the lower heights - but levels out at all levels as the air temperature approaches the dew point temperature. Rates of cooling typically were 0.14 to 0.2^{o}/min at the 6-foot height, and 0.2 to 0.5^{o}/min at the 1-foot height. It is often at this point that the temperature difference between the 6-foot and 1-foot height are at their greatest (often greater than 10^{o}F).

During the second stage the temperatures at all levels cool slowly through the night. It is during this second step that the minimum temperature is usually realized (just a few degrees above dew point). A well-established temperature gradient (between the 1-foot and 6-foot height) usually remains throughout the cooling period. Eventually sunrise and/or changing sky and wind conditions warm the air (diabatic warming) and eventually break up the ground-based inversion.

Apparent in this study, is the rapid cooling or warming that appears with changes in sky conditions and/or cloud cover during the night. A sudden clearing of the skies can result in rapid cooling, just as a sudden return to cloud cover can, with equal speed, break up an inversion and warm the air. This rapid temperature response to equally rapid changes in wind and sky conditions implies that cooling (or warming) occur in situ. The cooling of the upper layers of air appears to cool diabatically from the ground up, and warming occurs in reverse order. In these cases, radiational cooling would appear to dominate the cooling process, leaving insufficient time for cooling to be dominated by the piling of cold air from below (bowl hypothesis) or regionally-derived cold air drainage (e.g. off of Tug Hill). Furthermore, if the dominate cooling mechanism at the 6-foot height was due to the piling up of pooled cold air (bowl hypothesis), then the rate of cooling at the 6-foot level should exceed that of the lower levels, at least for a period of an hour or so during the time when the 6-foot level air temperatures drop dramatically. An examination of cooling rates for all 10 extreme cooling episodes shows that this is never the case.

There is evidence to suggest that local cold air drainage may play a lesser role in cooling air temperatures, especially during the second stage of cooling. During episodes of extreme cooling regional winds (often westerly) diminish to calm conditions interspersed with light winds from the NE. These light NE winds are likely a weak land breeze forming off the shoreline of Lake Ontario. In this scenario, the relatively warmer air over the lake rises up over the water, while drawing in a light breeze off of the land. The orientation of this breeze (NE to SW) is consistent with the gentle grade from KART to Black River Bay. Both the position of the airports runway and forest edge may help channel this breeze across the ASOS (and meteorological tower). Furthermore, temperature pulses are evident in some of the extreme cooling event temperature profiles. A ground-based temperature inversion is maintained during these pulses, thus they cannot be attributed to turbulent mixing of the air column. Rather, these pulses may be attributed to surges of alternating pooling and drainage of gently down sloping air.

An examination of land use around the Watertown Airport reveals a number of forested parcels (Figure 22) that may serve as barriers to air flow. Air moving down a gentle slope may pile up behind a barrier (a stand of trees), pooling cold air behind the barrier. Eventually the air will flow over the barrier, draining the pooled air. The effect of a deepening cold layer, building then draining over time, likely plays a minor role in explaining the extreme cold episodes at KART.

Forecasted Extreme Cold Episodes at KART

As discussed in the introduction, forecasted minimums (12 and 24 hour forecasts) during extreme cold episodes are often under predicted at KART. This under prediction can easily be attributed to a forecasting analysis package based on a 5 km square grid, which includes relatively warmer air bordering areas on the eastern shore of Lake Ontario. While an adjustment of a few degree is suitable for most minimums, during periods of extreme radiational cooling this adjustment is insufficient. A good rule of thumb or algorithm is not available to adjust temperatures down during extreme cooling episodes. A comparison of the minimum temperature forecasts and validations for the ten extreme cooling episodes show substantial forecasting errors (Table 2). It is interesting to note that the coldest observed minimum temperature was the one best forecasted.

Table 2. Comparison between forecasted and observed minimum temperatures at KART

Date	24hr forecast (oF)	12hr forecast (oF)	Verification (oF)
12/09/10 - 12/10/10	10	4	-4
12/24/10 - 12/25/10	22	22	7
01/05/11 - 01/06/11	17	9	0
01/10/11 - 01/11/11	3	7	-4
01/13/11 - 01/14/11	-1	7	-7
01/16/11 - 01/17/11	-10	-6	-24
01/21/11 - 01/22/11	3	2	-13
01/22/11 - 01/23/11	0	0	-25
01/23/11 - 01/24/11	-29	-33	-30
01/30/11 - 01/31/11	0	0	-23

While the minimum temperature forecasts are obviously off the mark, the minimum temperatures measured at KART are not atypical of the larger region (Table 3). What is typical is the variability in reported minimum temperatures, suggesting that microscale influences (location, location, location) dominate over mesoscale ones. An illustrative example is the relative warm temperatures reported at Cape Vincent (located along the Lake Ontario shoreline, #7), as compared to the much colder temperatures measured further inland and at a higher elevation at Constableville, NY (#4). It is interesting to note that the Watertown International Airport is located approximately the same distance from Lake Ontario as Cape Vincent, NY, but its minimum temperatures during the extreme cold episodes appear better aligned with the minimums at Constableville, NY.

Table 3. Comparison of minimum temperature between KART and 10 locations within a 40 mile radius. Values are in °F. Individual station elevation is shown.

Date	KART 325’	1 702’	2 860’	3 420’	4 1763’	5 1164’	6 755’	7 477’	8 297’	9 531’	10 580’
12/09/10 - 12/10/10	-4.0	1.8	10.0	5.0	-3.0	-3.5	-7.6	10.5	6.8	4.7	N/A
12/24/10 - 12/25/10	7.0	8.6	10.0	4.0	2.0	11.8	9.9	15.7	16.7	10.8	10.0
01/05/11 - 01/06/11	0.0	7.5	4.0	5.0	-10.0	6.6	-1.0	19.5	10.3	N/A	N/A
01/10/11 - 01/11/11	-4.0	3.3	N/A	N/A	-6.0	13.3	8.0	15.2	8.9	1.8	2.0
01/13/11 - 01/14/11	-7.0	3.4	-2.0	12.0	-11.0	2.8	-6.0	12.6	0.9	3.8	0.0
01/16/11 - 01/17/11	-24.0	-13.9	-18.0	-26.0	-30.0	-16.4	-24.7	-2.5	-13.9	-11.5	-13.0
01/21/11 - 01/22/11	-13.0	-4.0	-6.0	-7.0	-10.0	-1.5	-5.6	3.8	0.9	1.4	-4.0
01/22/11 - 01/23/11	-25.0	-21.3	-29.0	-7.0	-35.0	-21.8	-29.5	-9.9	-13.5	-18.8	-2.1
01/23/11 - 01/24/11	-30.0	-24.5	-29.0	-33.0	-34.0	-21.8	-33.2	-13.8	-18.0	-17.7	-26.0
01/30/11 - 01/31/11	-23.0	N/A	-7.0	-20.0	-13.0	-11.9	-16.9	N/A	-8.3	-5.0	-1.0

1. Great Bend, NY
2. Lowville, NY (COOP)
3. Gouveneur, NY (COOP)
4. Constableville, NY
5. Copenhagen, NY
6. Castorland, NY
7. Cape Vincent, NY
8. Clayton, NY
9. Adams, NY
10. Black River, NY

A Proposed Forecasting Algorithm

The 10 identified extreme cooling episodes (used as historical records) were used to develop a regression equation as a tool to predict minimum air temperatures during extreme radiational cooling episodes at KART. Air and dew point temperatures (KART data) were taken just prior to radiational cooling events (referred to as initial temperatures). In most cases, these initial temperatures were derived just after sunset, but in other cases, they occurred later in the evening when skies cleared or winds calmed. The minimum temperature was taken as the lowest recorded temperature during the cooling episode.

A good fit linear relationship appears to exist between initial air and dew point temperatures (R^2 = 0.80 and 0.90, respectively), when used as a predictor for minimum air temperatures during extreme cooling episodes (Figures 3 and 4). The initial dew point temperatures appear to provide a better prediction for minimum temperatures.

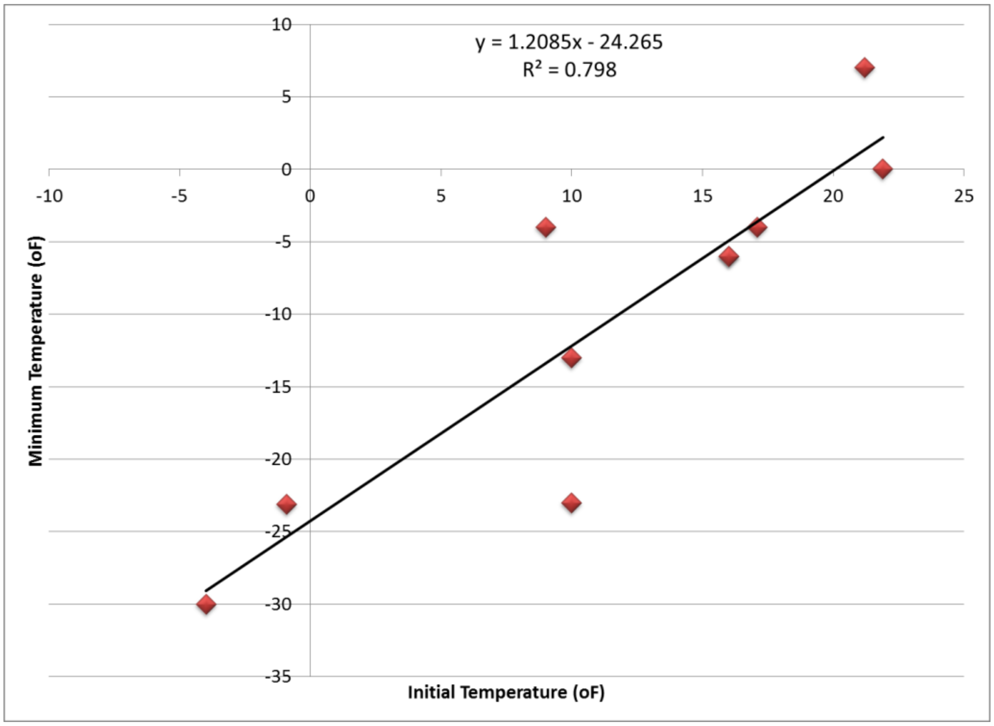


Figure 3. Comparison of initial air and minimum air temperatures.

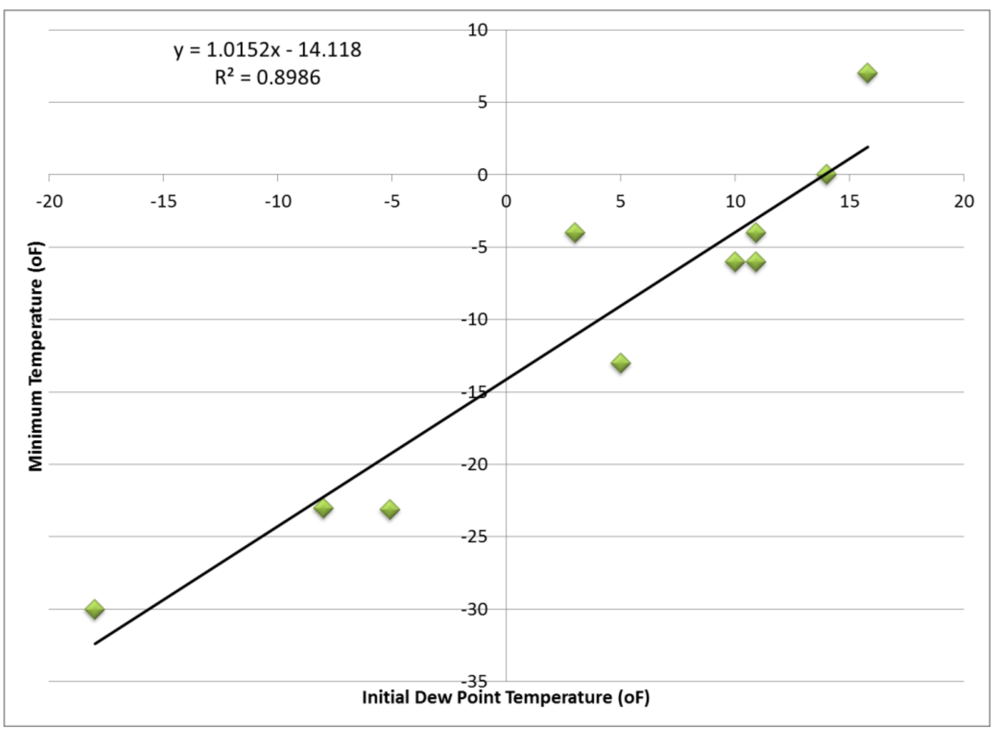


Figure 4. Comparison of initial dew point and minimum air temperatures.

The working forecast assumption is that it is reasonable to accurately forecast hourly air temperatures during non-radiational cooling events, even at 24- and 12- hours in advance. Thus, during hours when conditions (calm winds and/or clear skies) are forecasted which might result in radiational cooling (at sunset or at other times in the evening), the forecaster would apply the dew point derived regression equation to the forecasted initial air and dew point temperatures in order to calculate a minimum air temperature for the cooling episode.

CONCLUSION

Ten extreme cooling episodes were examined during the winter of 2010-11 at the Watertown International Airport (KART). These extreme cooling episodes are dominated by radiational cooling, where a strong ground-based inversion sets up and maintains itself through the evening. The rapid cooling or warming that appears with changes in sky conditions and/or cloud cover during the night - a sudden clearing of the skies - implies that the cooling occurred in situ. The upper air layers appear to cool diabatically from the ground up. Radiational cooling appears to dominate the cooling process, leaving insufficient time for cooling to be dominated by the piling of cold air from below (bowl hypothesis) or regionally-derived cold air drainage (e.g. off of Tug Hill). A survey of the immediate area around the ASOS equipment reveals not a bowl shape, rather a gentle NE to SW slope toward Black Creek Bay.

Local cold air drainage may play a lesser role in cooling air temperatures. During episodes of extreme cooling regional winds (often westerly) diminish to calm conditions interspersed with light winds from the NE. These light NE winds are likely a weak land breeze forming off the shoreline of Lake Ontario. The orientation of this breeze (NE to SW) is consistent with the gentle grade from KART to Black River Bay. Temperature pulses are evident in some of the extreme cooling event profiles. A ground-based temperature inversion is maintained during these pulses, thus they cannot be attributed to turbulent mixing of the air column. Rather, these pulses may be attributed to surges of alternating pooling and drainage of gently down sloping air.

A regression equation is presented, derived from initial air and dew point temperatures prior to radiational cooling, as a means to forecast minimum temperatures during a cooling episode. Accurate hourly air temperatures, forecasted in advance, can be adjusted using the algorithm. Thus, minimum evening temperatures can be accurately forecasted whenever calm winds and/or clear skies) are forecasted.

A full report is available.

Section 3: Benefits and Lessons Learned: Operational Partner Perspective

The Buffalo Weather Forecast Office has long struggled with forecasting a low temperature for KART during nocturnal winter season radiational cooling events. This study shows clearly that the office has a warm bias, although during this study we forecasted for a 5-5km grid area and verified by a point. This project takes us closer to understanding why the rate of cooling is so strong for these events and gives us an excellent picture of the low level atmospheric profile. It is understood that microclimates are often the result of local variations in temperature, and KART is no exception. Our partner's land survey helped explain several subtleties that cannot be seen from casual observation, such as a gentle but persistent slope and no bowl. The survey also reminds us of the importance of nearby land usage (runway location and trees). The regression equation may be able to be integrated into our Graphical Forecast Editor (GFE), the tool used in creating our gridded forecasts. We will evaluate this possibility over the next year.

Section 4: Benefits and Lessons Learned: University Partner Perspective

This project provided for the purchase of monitoring equipment and the covering of travel expenses which was not available in an earlier attempt to understand the extreme cooling episodes at Watertown International Airport (KART). COMET funding allowed for a more detailed study of the problem. The COMET project benefitted two undergraduate students, providing a topic and funding to complete their undergraduate senior thesis, and it also allowed them to be a part of a larger research effort with ties to the Buffalo Weather Forecast Office. The research finding from this project have led to a better understanding of radiational cooling events at Watertown, NY, and have tested a number of proposed hypotheses for the extreme cooling. Furthermore, the research has provided the Buffalo Weather Forecast Office with an algorithm that may aid in the forecasting of minimum temperatures during extreme cooling episodes.

Section 5: Publications and Presentations

Miller, C. 2011. A Cold Pool Microscale Effect Resulting for Nocturnal Winter Season Radiational Cooling, Senior Undergraduate Thesis, Department of Geography and Planning, Buffalo State College, pp. 37.

Russell, A. 2011. Uncharacteristic Cooling Occurring Under Radiational Cooling Conditions at the NWS Station in Watertown, NY. Senior Undergraduate Thesis, Department of Geography and Planning, Buffalo State College, pp. 30.

Section 6: Summary of University/Operational Partner Interactions and Roles

The research proposal was developed and equipment installed by both of the partners. The University Partner coordinated the field sampling, as well as the two undergraduate students working on the project. Analysis of the collected data was the primary responsibility of the University Partner, although consultation was made with the Operational Partner on topics specific to forecasting concerns. Both partners reviewed the final report. In hind sight, more time and effort should have been spent on coordinating and consulting with the Operational Partner. This project was the first funded effort between the two institutions and partners; a relationship that hopefully will grow with time. While the COMET project has come to a close, the wealth of data collected and project recommendations - including validation of the forecasting algorithm – are areas for continued collaboration between the two partners.