How Lake Superior Shapes Air Quality and Atmospheric Patterns on the Keweenaw Peninsula

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Abstract

The Keweenaw Peninsula of Michigan, characterized by large changes in elevation and proximity to a large body of water, presents a unique setting for studying how the lake breeze phenomenon affects local meteorology and aerosol concentrations. Lake breezes influence the transport and trapping of air pollutants, having impacts on local communities like L'Anse, MI. The village of L'Anse, situated at the southeast shore of the peninsula, is a site of particular interest due to its proximity to the lake and the biomass-burning plant located in the area. The previous work of Wagner (2022) examined concentration levels of aerosols associated with lake breezes. Our study (a piece of the larger Lake-Induced Trapping of Emissions along the Superior Coast (LITESC) project) aims to build a more comprehensive profile of wind patterns and pollutant distributions, building on Wagner's work. This is done through measurements from Atmospheric Emitted Radiance Interferometer (AERI), High Spectral Resolution Lidar (HSRL), Doppler LiDAR (LiDAR), PurpleAir sensors, and weather station tripods. These measurements were taken at multiple sites with differing elevations, distances to the lake, and orientations relative to the lake. The results demonstrate that, in the absence of larger synoptic winds, inversions can be observed inland and aerosol concentration is correlated with wind direction, showing evidence of lake breeze-facilitated changes to local meteorology.

1. Introduction

Understanding lake breezes is essential because they impact the distribution of pollutants and influence weather systems and climate conditions in coastal areas. Lake breezes form due to the difference in specific heat between water and earth, indicating that the former is more resistant to changes in temperature. During the daytime, the sun heats the lake at a slower rate than the land surrounding it, eventually resulting in the land becoming significantly warmer. The land thus heats the air above it more quickly, causing it to rise and be replaced by the cooler air above the lake; this movement of air creates a breeze. Until it is cooled, the upper layer of warm air floats on top of the denser displaced cooler air in a phenomenon known as a temperature inversion. This has the potential to trap pollutants under the warm air layer, as such particles are too dense to rise above it.

Air quality is a critical concern as it directly affects human health, ecosystems, and the economy. Air pollution from industrial activities, transportation, and agriculture leads to health problems such as respiratory diseases, cardiovascular issues, and other chronic conditions. Local air quality is influenced by wind conditions, which disperse or concentrate pollutants depending on wind direction and speed. In regions close to lakes, lake breezes have a significant impact on the local wind conditions and temperature inversions. Studying how lake breezes modulate air quality provides insight into the interplay between local weather phenomena and pollution dispersion, which is essential for understanding and mitigating air quality issues in regions like the Upper Peninsula of Michigan.

This study focuses on the Keweenaw Peninsula, a unique region where the proximity to Lake Superior, a large freshwater lake, significantly influences the climate, resulting in warmer weather that persists later into the fall season. Despite its distinctive characteristics, research and data in this region remain limited due to its remote location and sparse weather station coverage. The peninsula's geography creates an environment conducive to the development of lake breezes, as the relatively warm land temperatures contrast with the cooler lake. This study goes beyond simply examining lake breezes and temperature inversions but also addresses the effects of the local climate on air quality, offering a broader perspective on the region's meteorological and environmental dynamics.

Given these uncertainties, we focused on studying how lake and atmospheric temperature variations influence the formation of inversions, lake breezes, and air quality on the Keweenaw Peninsula. To address this, we explored two primary research questions. Our first hypothesis proposed that a 6-10°C temperature gradient between the land and lake surface promotes lake breezes, and events such as diurnal fluctuations and lake overturning events enhance these phenomena. Additionally, we hypothesized that shallow boundary layer temperature inversions correlate with higher concentrations of aerosols, trapping pollutants near the surface. To test these hypotheses, we utilized advanced instrumentation, including but not limited to radiosondes, windsondes, drones, air quality sensors, the High Spectral Resolution lidar (HSRL), and the

Atmospheric Emitted Radiance Interferometer (AERI) to collect vertical profiles, surface data, and particulate concentrations.

2. Methods

2.1 Setting

Our field campaign took place on the Keweenaw Peninsula in Michigan's Upper Peninsula, a region renowned for its proximity to Lake Superior and its dynamic weather patterns. The study sites were divided into two areas: the McLain sites closer to the lake (McLain, Lily Pond, and Swedetown) as shown in Figure 1, and the L'Anse sites further inland (L'Anse, Second Sand Beach, and Baraga Cliffs) as shown in Figure 2. These were carefully selected to capture variations in meteorology and aerosol concentrations. Each site included three stations positioned to reflect differences in elevation, distance from the shoreline, and orientation relative to Lake Superior. The first station was deployed close to the shoreline to measure immediate lake-atmosphere interactions. The second station, located 200 to 500 meters inland, provided insights into conditions slightly removed from the lake's direct influence. The third station was situated roughly 6 kilometers inland at a significantly higher elevation (at least 50 meters) to observe the effects of elevation changes on meteorology and aerosol transport.

The observation period highlighted changing weather patterns over the campaign. Early on 12 October, calm conditions prevailed as an upper-level shortwave approached the region, bringing easterly winds by evening. A surface low-pressure system developed near the Wisconsin-Michigan border, resulting in precipitation on 13 October that dissipated by the afternoon. By 14-15 October, winds shifted to a northerly direction, with cooler surface and upper-level temperatures contributing to lake-effect precipitation.

A map of the study sites is provided at the bottom of this section in Figures 1 and 2 which highlights the spatial distribution of the McLain and L'Anse site clusters within the Keweenaw Peninsula.

2.2 Experimental Design

This experiment has two main focuses: the evolution of a lake breeze and interactions between 2.5-micron particulate matter (PM2.5) and atmospheric conditions. Respectively, the main site locations were decided based on focus, where the boundary layer dynamics of lake breezes were studied at the McLain sites, and the atmospheric implications of PM2.5 pollution were analyzed at the L'Anse sites. The field campaign was divided into two days (12-13 October 2024) at the McLain sites and two days (14-15 October 2024) at the L'Anse sites. The SSEC's Portable Atmospheric Research Center (SPARC), which housed an Atmospheric Emitted Radiance Interferometer (AERI), High Spectral Resolution Lidar (HSRL), and a Doppler

LiDAR, moved between the McLain and L'Anse sites after two days. The instrumentation locations are detailed in Table 1.

2.3 Observations

To test for the development of a lake breeze, we deployed Honest Observer By Onset (HOBO) weather station tripods to gather data on how wind, humidity, and temperature are modified as lake breeze development moves inland, sampling data every minute. Specifically, the tripods measured temperature, humidity, wind speed, wind direction, and pressure. Kestrel tripods were deployed as HOBO alternatives, sampling data every minute. Differences in accuracy between the Kestrel Weather Meter and HOBO Weather Station are detailed in Table 2. It is important to note that Kestrels do not have a solar shield, so solar radiation could have influenced the temperature further.

In addition, AERI data and periodical windsonds provided information regarding the evolution of the boundary layer. Additional wind data was gathered by a Doppler LiDAR. AERI and Doppler LiDAR observations were sampled every 20 seconds. HOBOs were deployed near SPARC and at two other inland locations based on topography. Windsonds were launched twice daily at each site. The Purple Air PM2.5 sensor recorded air quality data. From this, measurements were made in Air Quality Index (AQI) units rather than $\mu g\ m^{-3}$. Conversions are detailed in Table S.1 for reference.

2.4 Analyses

The data is plotted by site. A 20-minute rolling mean was implemented for the atmospheric data with averages. An hourly mean was implemented for the Purple Air data.

3. Results

3.1 Basic overview of the climate/weather of the week

The early morning hours on the 12th featured relatively benign conditions antecedent to an upper-level shortwave and subsequent surface low pressure. Winds turned due easterly by the evening of the 12th, and by the 13th the low was located just along the Wisconsin-Michigan border. The resultant precipitation lasted through the morning hours and began to wane by 17 UTC.

The previously banal shortwave rapidly intensified in response to a baroclinic sharpening of the height field, and positive vorticity advection shifted the optimal region for upper-level divergence to the Pennsylvania-Ohio border. This made quick work in dissipating the Wisconsin-Michigan low, and as its energy redeveloped, winds quickly shifted more northerly by late into the 14th and early into the 15th. Surface temperatures dropped, but upper-level temperatures dropped even faster, and in the wake of the system lake effect precipitation broke out in response to near-dry adiabatic low-level lapse rates. On these days, convective precipitation development and gusty winds were observed (Figures 5-6).

3.2 Analysis of near-shore and inland temperature and wind at the surface and in boundary-layer

Given the strong synoptic-scale forcing throughout the duration of the observation period, lots of the data collected generally adheres to the broader atmospheric regime. One notable exception is the 12th, where Figure 3 illustrates the passage of some smaller scale boundaries through the observation sites, noting an increase in relative humidity, decrease in temperature, and change in wind direction. Otherwise, Figure 4 depicts the 14th and 15th, where winds and temperature generally adhered to forcing from the strong upper-level low.

3.3 Analysis of near-shore and inland aerosol gradients

The average PM2.5 concentrations recorded across the various locations on October 14th and October 15th provide distinct spatial and temporal patterns influenced by the proximity to the power plant and other meteorological factors as shown in Figure 7. On October 14th, the PM2.5 concentrations were the second-highest near the power plant which suggests it is a significant source of emissions shown in Figure 7a. Interestingly, the Shrine exhibited the most intense odor with the highest recorded PM2.5 emissions. In contrast, sites further from the power plant, such as L'Anse and Second Sands, showed significantly lower PM2.5 levels which indicates a dispersion gradient away from the source. Data collected on October 15th revealed a different pattern as shown in Figure 7b. The Meadowbrook site displayed the highest PM2.5 concentrations, with insufficient data at the other sites. The isolated result may be due to various meteorological factors such as local wind patterns and aerosol dynamics.

The variation in PM2.5 concentrations between October 14th and 15th highlights the potential role of wind and atmospheric conditions in transporting and dispersing aerosols. The correlation between odor and pollutant concentrations at the Shrine location is particularly noteworthy and suggests further investigation.

3.4 Relationship of aerosol gradients and temperature/wind gradients to lake-land breezes, inversions, etc.

Wind direction and speed at L'anse stayed fairly stagnant throughout the 14th, with wind direction remaining approximately easterly for the duration of the day. On this day, the locations west of the plant, such as the Baraga Shrine, experienced elevated PM2.5 levels. This is likely due to the westward winds of the day, which may have carried PM2.5 from the power plant across the area. On the 15th, winds in L'anse were more variable, shifting direction and magnitude throughout the day. Many locations where PM2.5 was sampled had concentrations that were too low to register, indicating that the shifting winds likely prevented the buildup of pollutants in any one location.

4. Discussion

4.1 Lake Breeze Development and Inland Penetration

While the study answered the questions to some extent, the results were strongly influenced by the prevailing weather conditions during the observation period. For lake breeze development, an indication of a smaller scale boundary was observed on October 12th with changes in wind direction, temperature, and humidity near the shoreline. However, precipitation and strong northerly winds on the following days limited the ability to confirm how lake breezes penetrate inland and affect local meteorology.

It is suggested by the temperature measurements (from HOBO & buoy stations) that the overall meteorological conditions were not very favorable for lake breeze formation over the Upper Peninsula of Michigan during the field experiments (from Oct 12 to 15, 2024). A positive temperature gradient from the lake to inland (i.e., the temperature over land is significantly higher than the temperature over the lake) is crucial for the development of a lake breeze (Lyons, 1972). This temperature gradient will induce strong baroclinicity between the land and lake (i.e., the constant-pressure contours are no longer parallel to the constant-density contours), which, according to the Bjerknes circulation theorem, will force changes in the circulation pattern and result in a lake breeze (Wagner et al., 2022). However, very small differences between the temperature from HOBO weather stations (land) and that from BUOY stations (lake) were observed on site (less than 2K), which served as a significant discouragement for lake breezes. From the perspective of climatology, while the regional temperature consistently decreases in October as the winter is approaching, the decrease of lake temperature is milder than that of land temperature (because the water body of the deep lake has a higher heat capacity and serves as a larger heat reservoir to buffer temperature changes), which would undermine the positive land-lake temperature difference on-site to discourage lake breezes (as the land cooled climatologically faster than the lake). In addition, as the strong onshore temperature gradient is meteorologically attributed to the differential diurnal heating (i.e., the land heats diurnally faster than the lake, due to the similar mechanism suggested in the climatological section), a calm atmosphere with few synoptic disturbances and non-convective clouds will be a favorable environment with sufficient diurnal radiation for the development of temperature gradient and lake breezes (Lyons, 1972). Therefore, from the perspective of meteorology, the synoptic conditions on site were also unfavorable for lake breezes because, since October 13, a low-pressure system entered the study region and thus brought considerable cloudiness and precipitation to disrupt the diurnal heating, leading to weak temperature gradients that discourage lake breezes (even if a weak breeze got formed, the strong synoptic winds would easily disrupt and weaken the circulation cell, making it almost undetectable).

For instance, the measurements on Oct 13 (Figure 4) suggested that the land temperature was consistently lower than the lake temperature (negative land-lake difference) due to the heavy precipitation on that day, and thus the overall circulation pattern simply followed the synoptic one with no abrupt changes. On Oct 14 & 15, although the synoptic activities became weaker, considerable cloud cover and localized precipitation events were still prevailing around the study area, undermining the efficiency of diurnal heating. The measurements of the two days (Figures 5 & 6) suggested that the land and lake temperature curves closely followed each other with small differences (less than 1K), which could hardly support onshore temperature gradients and related lake breezes. Additionally, while there were indeed some abrupt changes in circulation on Oct 14 & 15 (e.g., the wind direction shift from westerly to easterly on Oct 14), these changes seemed to be disconnected from the thermal contrast between land and lake (i.e., when the wind direction shift happened, the land temperatures were still slightly lower than the lake temperatures, and no abrupt temperature shift was observed to accompany the wind shift) and thus should still be primarily caused by synoptic activities rather than mesoscale lake breezes. As the three HOBO stations are distributed around the bay distant from each other on the two days (Figure 2), one mesoscale circulation cell of lake breeze could hardly be captured by all the stations, which further confirmed these relatively uniform changes across stations have a synoptic origin instead of a mesoscale one.

However, October 12 had a relatively calm synoptic condition before the arrival of the low-pressure system and thus did show some anomalous changes in the circulation pattern related to lake breezes (Figure 3). Because of the differential diurnal heating between land and lake, the land air temperature increased steadily while the lake air temperature remained almost constant at about 12.5 °C. The Lily Pond site (in red), for example, warmed up to about 14.5 °C in this process to gain a 2 °C land-lake temperature difference (which is also the largest observed difference on site). While this temperature difference was not as significant as it is expected in the hypothesis (6 to 10 °C), it was still able to induce some lake breezes. Specifically, after the maximum temperature (and the maximum land-lake temperature difference) was reached, a much more rapid temperature decrease occurred until the land temperature returned to be similar to the lake temperature. At the same time, there was also a sharp increase in relative humidity and wind speed, as well as a counterclockwise shift in wind direction, suggesting a consistent shift in circulation induced by the lake breeze. If an onshore temperature gradient gets built up, a lake breeze will be formed to advect the cold air onshore from lake to land over the surface (with a returning offshore flow at higher altitudes) to eliminate the baroclinicity by closing the land-lake temperature difference (i.e., the observed rapid cooling of land to the same level of the lake). During this cold air advection, the primary direction of winds will get reorientated with usually a strengthened wind speed, and, as the moist air over the lake is advected to land(with decreased temperature), there will also be an increase in the relative humidity over land. Similar circulation shifts were also observed for the other two stations (McLain & Swedetown) but at different times with different magnitudes. As the stations are distributed in a way to test the inland penetration of lake breezes (Figure 1), the difference in measurements between stations should tell something about the inland propagation of the lake breeze. Specifically, the McLain site (in green), which is the one closest to the shoreline, experienced the earliest change in circulation at about 17:00 UTC (after the maximum temperature reached about 13.4 °C), the Lily Pond site (in red), which has a medium distance to the shoreline, experienced the shift a little bit later at about 17:40 UTC (Tmax reached about 14.5 °C), and the Swedetown site, the most inland site, experienced the latest shift at about 18:00 UTC (Tmax reached about 13.5 °C). This pattern demonstrates that the lake breeze (over the surface) originated from the lake and moved gradually towards the land like a mesoscale front so the more inland sites would experience the influence of the lake breeze later in time (in this case, it took about 1 hour for the lake breeze to propagate 7 km inland from McLain to Swedetown).

The specific magnitudes of the changes in circulation also varied between sites. While the relative humidity had a uniform increase of about 10% for all the sites upon the arrival of the lake breeze, the land-lake thermal contrast was largest at the Lily Pond site (2 °C) while the other two had lower contrasts (1 °C for both). The McLain site could be explained by its close distance to the lake (i.e., as the positive temperature gradient was landward due to the differential heating, the temperature right at the shore would be lower than that of the more inland sites), and, for the Swedetown site, it could be explained by its high elevation (i.e., the cooling with height would counteract the diurnal heating). In addition, while the Lily Pond site and the McLain site both experienced a distinct shift in wind direction after the lake breeze, the Swedetown site (the most inland site with significant topographic uplift) experienced "oscillations" in wind direction as, instead of completely changing the direction, the wind there seemed to frequently oscillate between the original synoptic direction (westerly) and the new direction induced by the lake breeze (northerly). This suggests that, when the lake breeze reached the Swedetown site, its strength had been significantly weakened so its impact could not completely override the prevailing synoptic conditions. Furthermore, it is also notable that all the stations experienced a strengthening of wind speed after the lake breeze, but the Lily Pond site experienced a very rapid wind acceleration within a relatively short time while the other two experienced more gradual increases in wind speed (and the Swedetown site experienced the weakest acceleration in magnitude as the impact of the lake breeze was weakest there).

In short, while the specific mechanisms of these variations have not been well understood yet, the results on October 12 do suggest that the influence of a lake breeze will vary with the locations as it penetrates inland. Lake breezes act like a mesoscale front to march landward from the lake (so the sites closer to the shoreline will experience the lake breeze first) and will be considerably weakened by far inland penetration combined with topographic uplift (so it can hardly override the synoptic conditions of the highly inland site at high elevation). In addition, it is also found that the lake breeze tends to cause more significant changes in the circulation pattern for the site that is some distance away from the shoreline than the site right on the shore, which is an interesting phenomenon worth further investigation.

4.2 Lake Breeze Development and Temperature Inversion

As the surface flow of the lake breeze over the lake usually has a very limited vertical extent, the advected cold air from the lake will form a shallow cold layer beneath the original warmer air over the land, leading to a layer of high static stability (i.e., temperature increases with height) within the boundary layer (Wagner et al., 2022). The atmospheric soundings retrieved from windsonde on October 12 when a potential lake breeze was identified (Figure 9) suggested that the overall boundary layer was well mixed across sites as the potential temperature generally decreased with height (i.e., being super-adiabatic to allow the air to move freely and get mixed in the boundary layer). However, after the lake breeze developed and went through all the site during noon (around 18:00 UTC), the atmospheric soundings retrieved in the afternoon did indicate some development of shallow temperature inversion as an increase in potential temperature with height (while the soundings retrieved in the morning served as a control group without the impact of lake breeze). At the McLain site (Figure 9-A), while the morning retrieval got a consistently decreasing potential temperature with height in the boundary layer, the afternoon one (after the lake breeze) had small inversions between 995 and 990 hPa. These inversions were not well organized and small in their magnitudes, which might be attributed to its close distance to the lake and the late time of retrieval (as the overall afternoon temperature had cooled to the same level as the morning one while the other two had the afternoon temperature significantly higher than the morning one). At the Lily Pond site (Figure 9-B), the morning sounding had an insignificant potential temperature increase with height between 995 and 985 hPa, which was too large in its vertical extension and too weak in its strength to be considered as a temperature inversion. In the afternoon, a more significant temperature inversion developed between 995 and 990 hPa, with a shallow extension and strong magnitude, which was more likely to be induced by the lake breeze. At the Swedetown site (Figure 9-C), a shallow inversion was also observed closer to the surface in the afternoon (but at a higher pressure level: 975 hPa). Since October 13 (until 15), in contrast, there was little temperature inversion observed in the retrieved atmospheric soundings (as suggested in Figure 8), which agreed with the lack of lake breeze found in the previous section. In short, it was observed on October 12 that the passing of a lake breeze is related to the development of shallow temperature inversion (which is of high static stability to trap the air and influence the dispersal of the aerosol within the air). In addition, the observations suggested that the inversions tended to occur higher in the atmosphere than the expectations where the inversion should develop shallowly right at the surface (except the Swedetown site at high elevation), which needs to be resolved in future research.

4.3 Lake Breeze Development and Aerosol Concentration

The results answered part of our question on aerosols, as we were able to see how the interaction of breezes off the lake affects aerosol concentration. We were able to see that wind direction plays a big role in air quality since during our measurements we observed relatively clean air when the wind was flowing northeasterly off the lake. Later, lower air quality was observed when winds were southerly, transporting less clean and warmer city air from the south. However, we did not get to answer the question of whether a temperature inversion affects air quality, as we simply did not observe a temperature inversion during our time in the field.

4.4 Relationship to previous research on this topic

The scientific questions in this study are motivated by past research, in particular the Wagner et al. 2022 field campaign on the shores of Lake Michigan. In this study, AERI, Doppler lidar, and HSRL devices were deployed at multiple sites on the shore to measure lake breeze penetration and its impact on moisture and aerosol content. It was found that the lake breezes were primarily southeasterly and penetrated deeper in unstable environments with weak pre-existing flow. It was also found that there were larger concentrations of aerosols after lake breeze passages (Wagner et al. 2022). We were motivated by this work to ask similar questions about lake breeze events and air quality implications at various sites on the shores of Lake Superior in the upper peninsula of Michigan. In particular, we were motivated to ask similar questions in the context of how it may affect the community of L'anse, Michigan.

4.5 Limitations in this work

Throughout this study, we encountered several limitations. First, the temporal scope of the measurements, especially the data collected from HOBO as our main data source, was limited to daytime hours, typically between 10 a.m. and 4 p.m. local time. The observation period was also quite short, which limited observed patterns of lake breezes and inversions in the Keweenaw Peninsula. Additionally, the tools and measurements had their limitations. The Kestrel devices were useful because they could be deployed at multiple locations, but the data they provided were limited and not always reliable. AERI and Doppler lidar provided more reliable information, but they were limited to a single location, which resulted in limited spatial and temporal resolution.

Weather conditions during the observation period were another factor beyond our control. Strong synoptic-scale winds, precipitation on October 13th, and the presence of a surface low-pressure system may have created conditions that were unfavorable for the development of inversions. Strong northerly flow also kept aerosol concentrations low for the entire length of our study. This set some limitations on what we could see with respect to aerosols, however, we were still able to identify air quality patterns due to the biomass-burning plant and wind direction.

4.6 Implications of findings for general motivation, ideas for future work

This study provides insights into the interaction between Lake Superior, air quality, and atmospheric patterns on the Keweenaw Peninsula. However, additional observations at other locations and over longer periods will be helpful to better understand the occurrence of inversions over the lake and their impact on air quality. Integrating numerical modeling with observational data for future research could also provide a more detailed understanding of the factors driving lake breeze formation, temperature inversions, and aerosol dispersion.

For future aerosol studies, it would be of interest to get more drone data at the different sites near L'anse for aerosol concentration. It could be that the majority of the PM2.5 aerosols produced by the biomass-burning plant were suspended high in the atmosphere, and a drone sounding could get those concentrations higher up. This work motivates the study to track suspended aerosols from the biomass plant to track their impact on other further away communities.

5. Conclusion

This investigation into the impacts of inversion strength and timing and pollution distribution has broad implications for atmospheric science and small communities like L'Anse, MI. The position of the Keweenaw Peninsula on Lake Superior is unique, but numerous communities experience similar combinations of industry and lake-atmosphere interactions. While our procedure focused on a limited spatial area, our understanding of how local characteristics can influence pollutant and wind conditions impacts the daily lives and health of the people who live in L'Anse. Our times of most measurements were limited by our experimenter's schedules; data was typically collected between 10 am and 4 pm on days when weather conditions were not hazardous. Measurements over a 24-hour period, throughout the year, or at a greater spatial distribution on the Keweenaw Peninsula could further broaden our understanding of the development of inversions and their influence on pollutant dispersion in the area.

We came to several conclusions after analyzing the data collected. For aerosol concentration, wind direction is imperative for observed surface level PM2.5. The northeasterly flow pattern keeps the L'Anse area with relatively clean surface level air according to our measurements, while we did still see a gradient in air quality downwind of the biomass-burning plant. There is also a chance that the main concentration of aerosols was suspended higher up, as physical signs of air quality issues, including odor, were present even when readings of PM2.5 were still relatively low. For inversions and breezes, large-scale synoptic forcings largely prevented the formation of inversions and breezes during our period of study, aside from anomalous conditions on the 12th. Evidence exists from our MTU peers' data that inversions developed later in when synoptic forcings were limited.

Acknowledgments

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Open Software and Data Statement

During our field campaign, a large amount of data was collected and is made publicly available at the link at the end of this section. Raw data from HOBO tripods and Windsond launches is in CSV files and data from the set of SPARC instruments is in NetCDF files. Processing of the data was done using both Python and R. Raw data files and processing scripts can be found at the github here: https://github.com/peanutbutter3/LITESC-Field-Campaign

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Figures

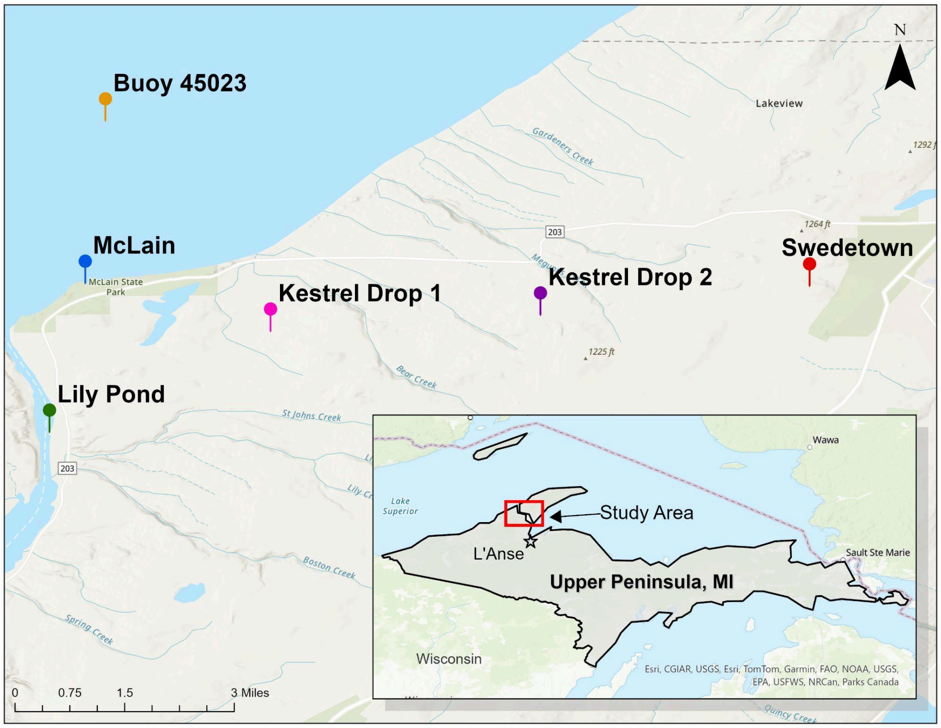


Figure 1. Map of Mclain Sites October 12-13th

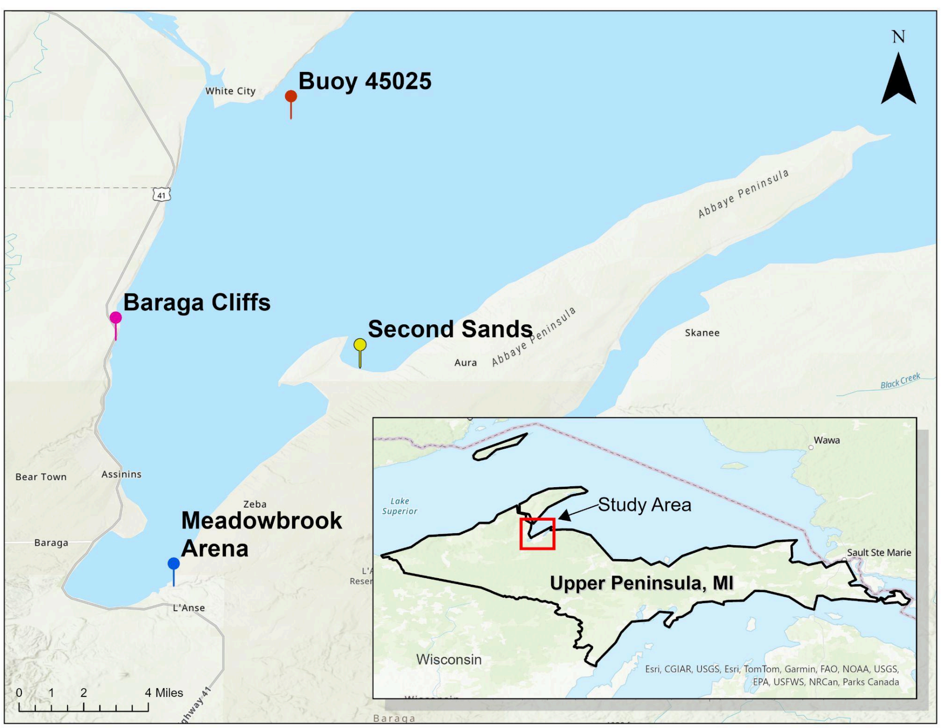


Figure 2. Map of L'Anse Sites October 14-15th.

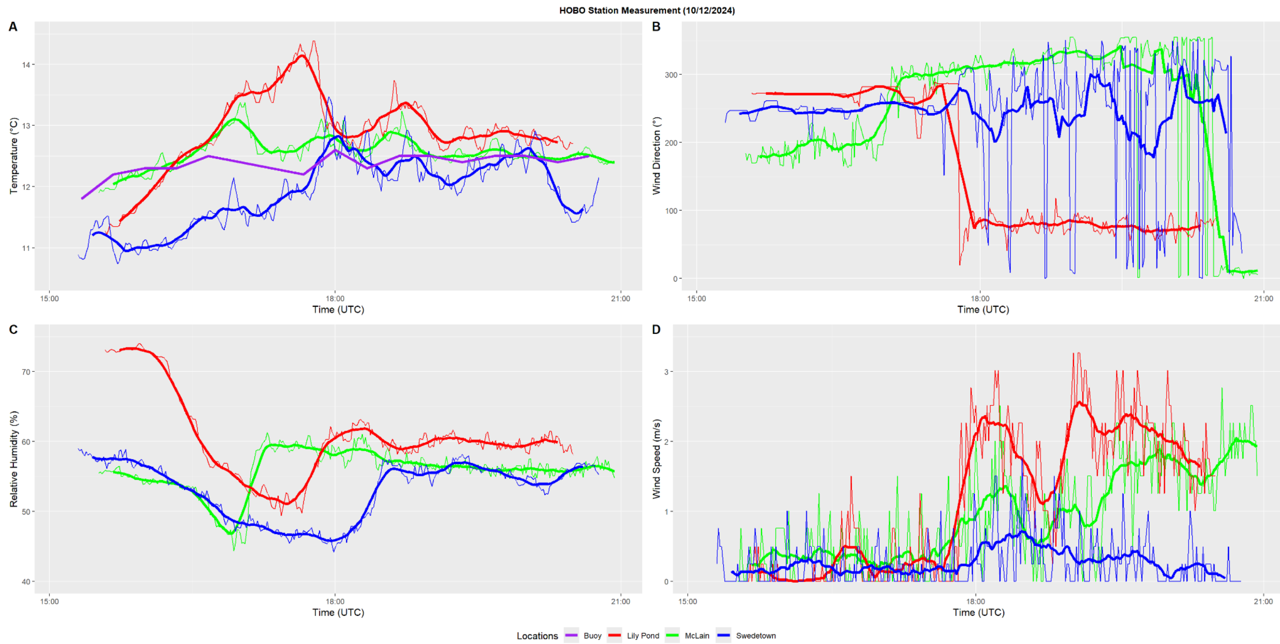


Figure 3. The four-panel plot for the measurement of HOBO Weather Stations on October 12th, 2024 at 3 locations: Lily Pond (Red), McLain (Green), and Swedetown (Blue). Panel A is temperature in °C, Panel B is wind direction in °, Panel C is relative humidity in %, and Panel D is wind speed in m/s. The air temperature measured by buoy station 45023 (Purple, to the north of McLain in the lake) is also plotted in Panel A for reference.

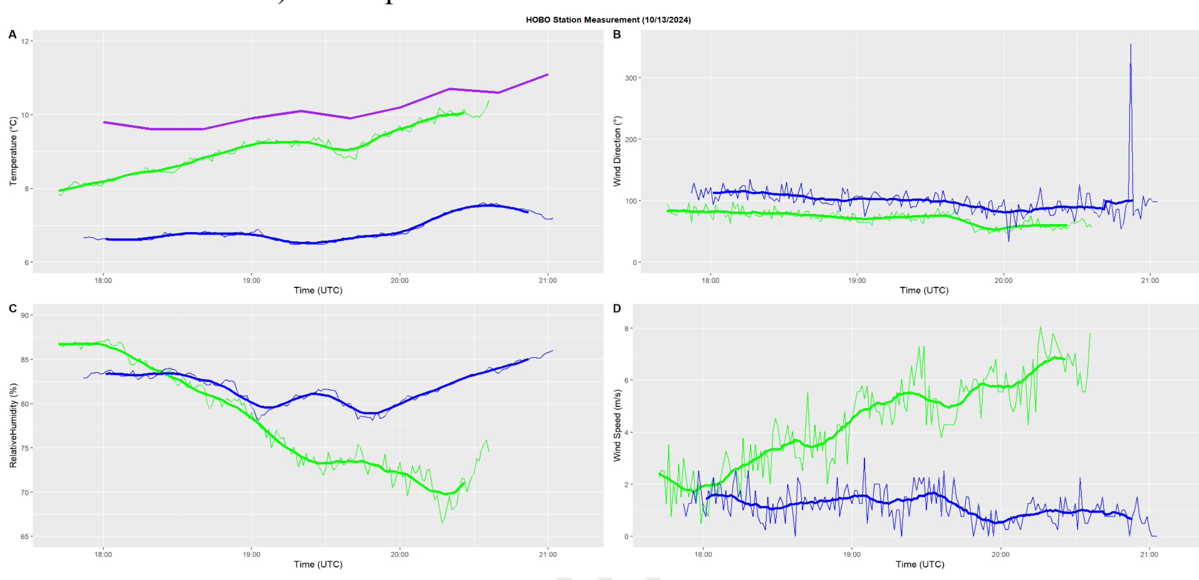


Figure 4. The four-panel plot for the measurement of HOBO Weather Stations on October 13th, 2024 at 2 locations: McLain (Green), and Swedetown (Blue) [No available data for Lily Pond]. Panel A is temperature in °C, Panel B is wind direction in °, Panel C is relative humidity in %, and Panel D is wind speed in m/s. The air temperature measured by buoy station 45023 (Purple, to the north of McLain in the lake) is also plotted in Panel A for reference.

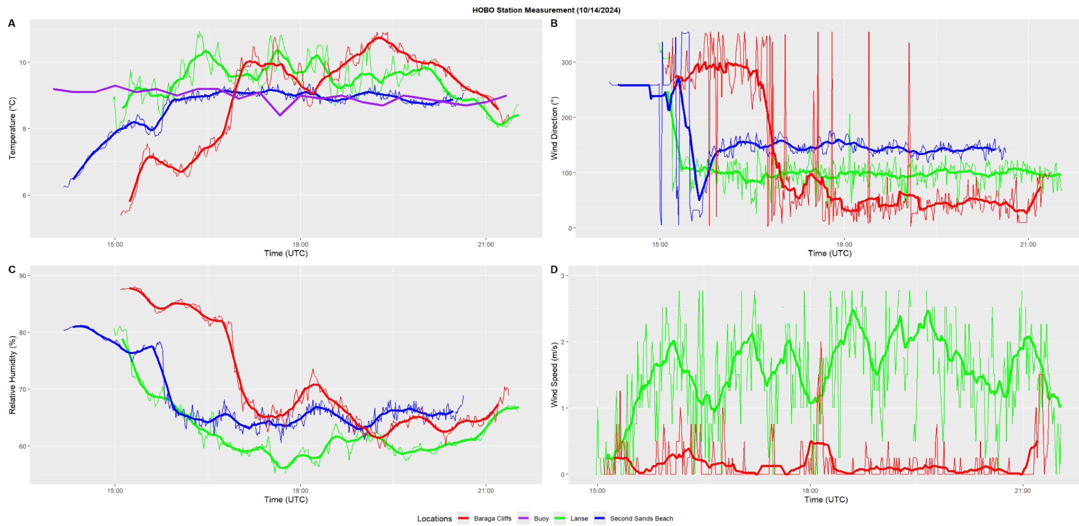


Figure 5. The four-panel plot for the measurement of HOBO Weather Stations on October 14th, 2024 at 3 locations: Baraga Cliffs (Red), Lanse (Green), and Second Sands Beach (Blue) [No available wind speed data for Second Sands Beach]. Panel A is temperature in °C, Panel B is wind direction in °, Panel C is relative humidity in %, and Panel D is wind speed in m/s. The air temperature measured by buoy station 45025 (Purple, to the north of the sites in Keweenaw Bay) is also plotted in Panel A for reference.

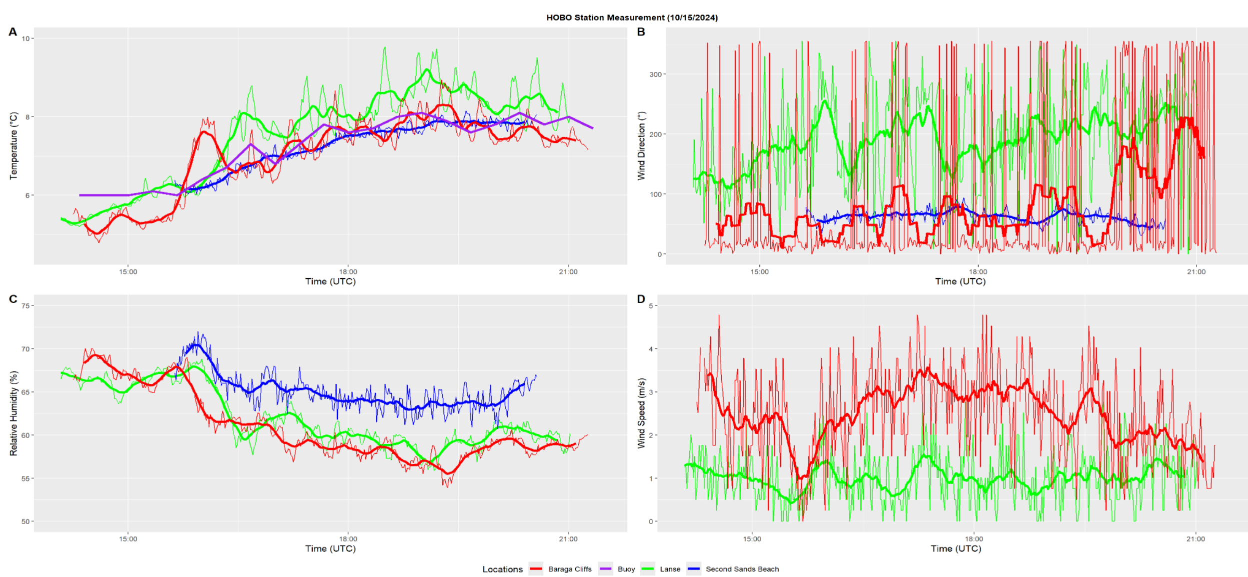
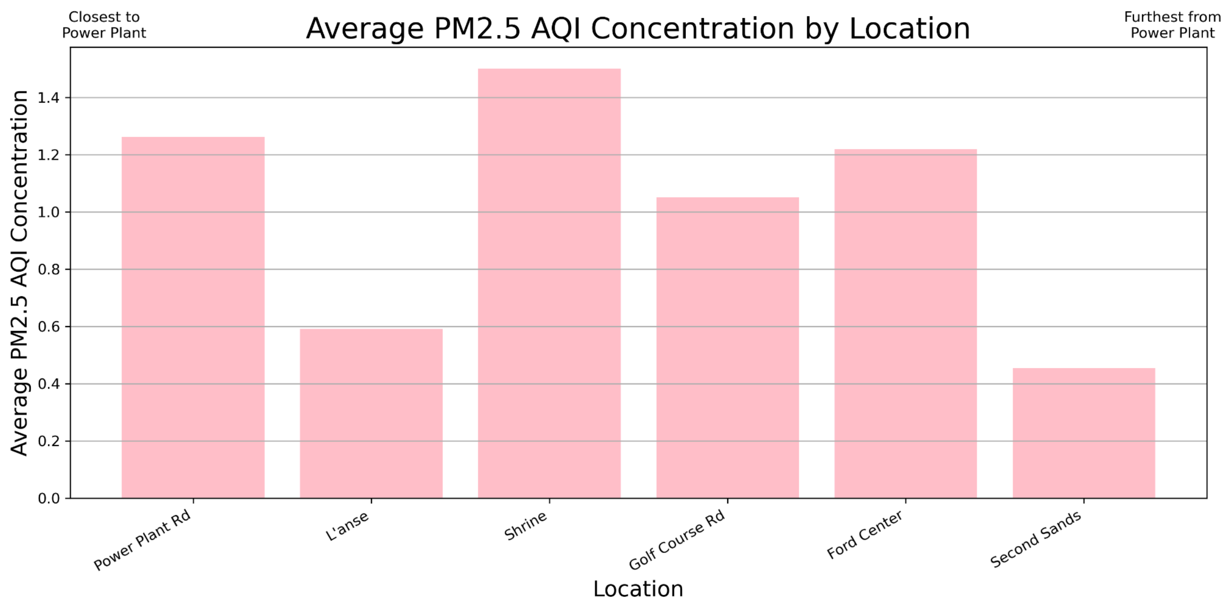


Figure 6. The four-panel plot for the measurement of HOBO Weather Stations on October 15th, 2024 at 3 locations: Baraga Cliffs (Red), Lanse (Green), and Second Sands Beach (Blue) [No available wind speed data for Second Sands Beach]. Panel A is temperature in °C, Panel B is wind direction in °, Panel C is relative humidity in %, and Panel D is wind speed in m/s. The air temperature measured by buoy station 45025 (Purple, to the north of the sites in Keweenaw Bay) is also plotted in Panel A for reference.

(a) 10/14



(b) 10/15

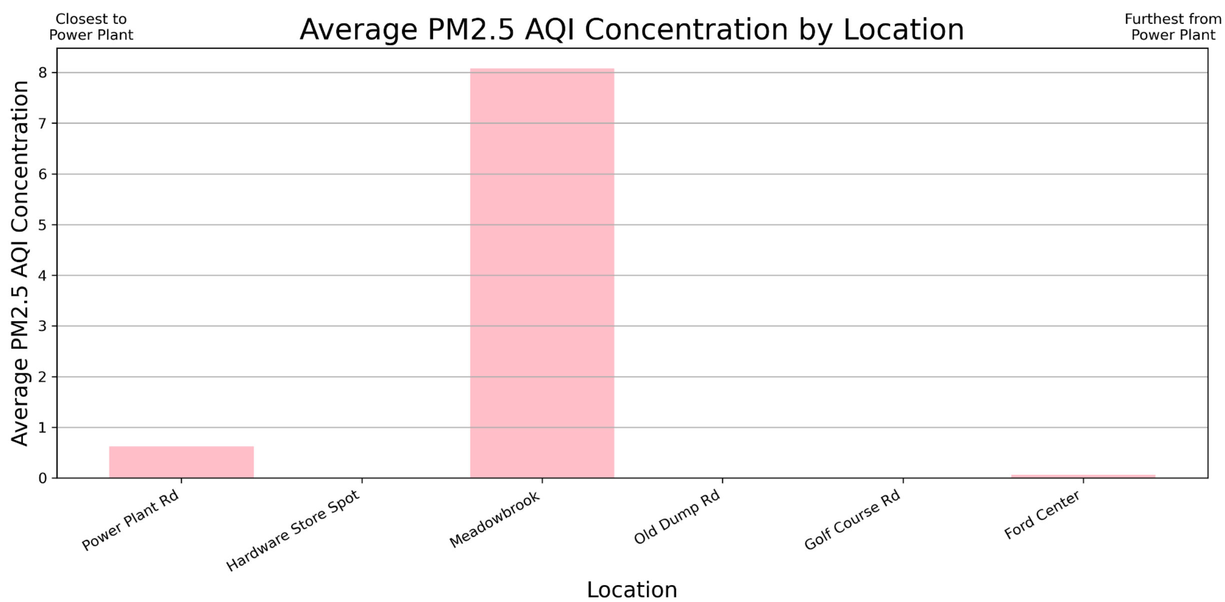


Figure 7. Two bar graph plots of the average PM 2.5 concentrations recorded by each location and ordered by distance from the power plant captured by Purple Air on October 14th (top) and October 15th (bottom). Created by Emma Hietpas. Group 5 Members: Emma Hietpas, Sam Kimball, Greta Schultz. The analysis code is called [purple_air_analysis.ipynb] and is located on the GitHub.

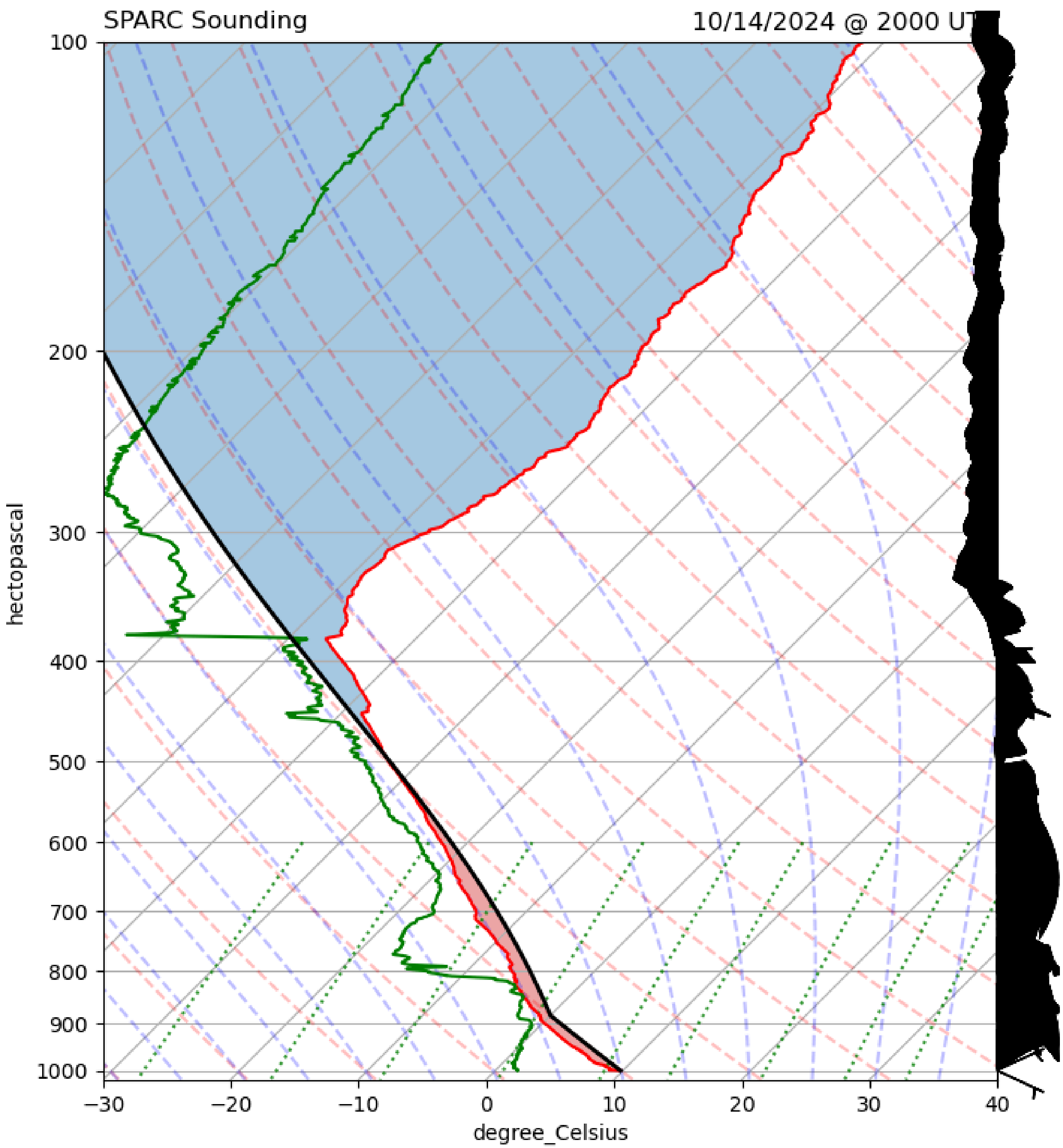


Figure 8. Vertical profile of temperature and dewpoint at L'anse at 20 UTC on October 14th.

(a) (b) (c)

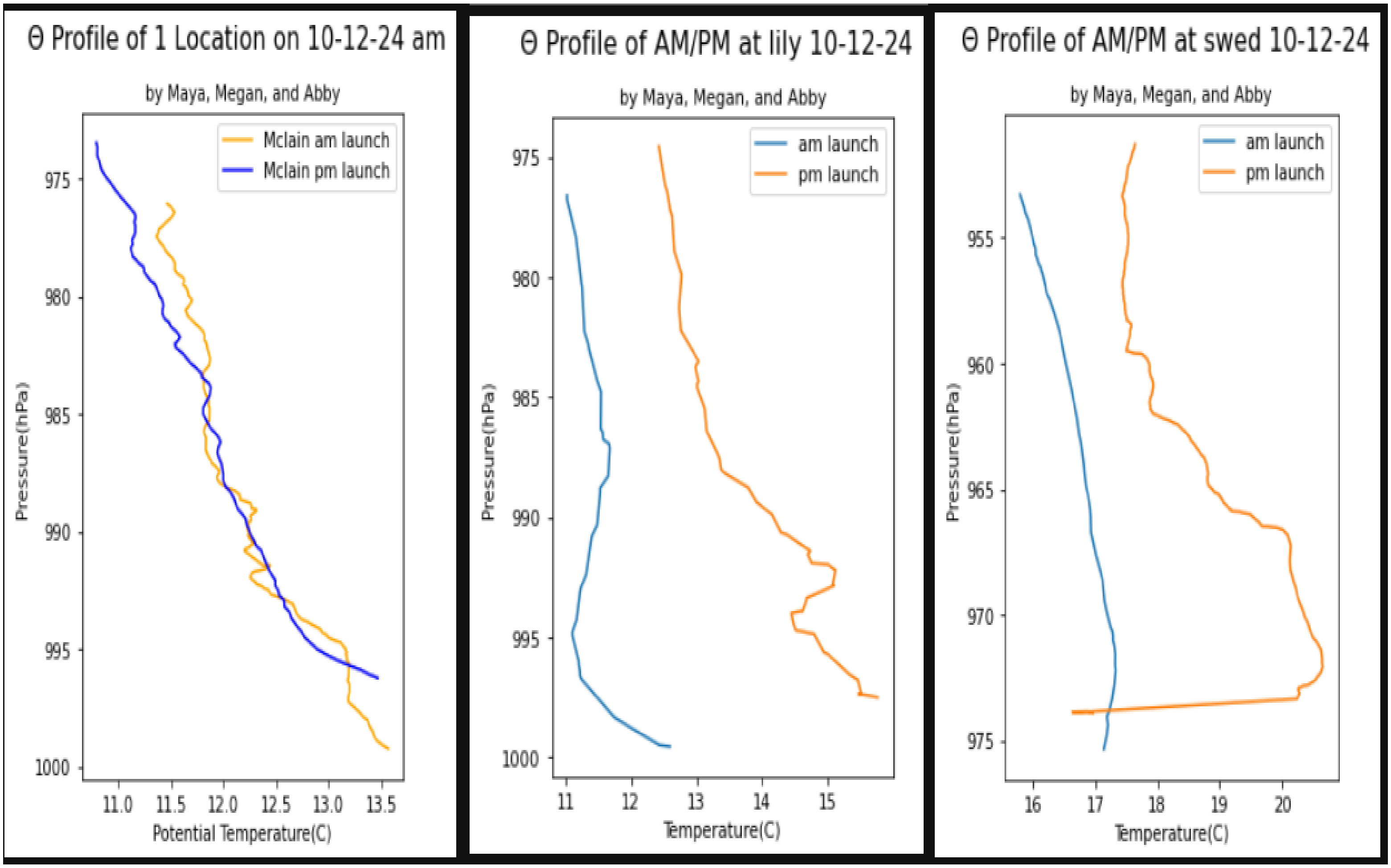


Figure 9. The vertical profile of potential temperature at McLain State Park (a), Lily Pond (b), and Swedetown (c) obtained by launching windsonde. The blue curve was launched before noon (before the lake breeze). The orange curve was launched after noon (after the lake breeze).

Tables

Table 1. Sites with equipment used in data collection. Note that the Purple Air sensor was mobile to multiple locations during the last two sites.

Date	Site	Temperature	Wind	Aerosol
12 Oct. 2024	McLain	HOBO Tripod AERI	HOBO Tripod Doppler LiDAR	Purple Air HSRL
	Lily Pond	HOBO Tripod	HOBO Tripod	NA
	Swedetown	HOBO Tripod	HOBO Tripod	NA
13 Oct. 2024	McLain	HOBO Tripod AERI	HOBO Tripod Doppler LiDAR	Purple Air HSRL
	Lily Pond	Kestrel Tripod	Kestrel Tripod	NA
	Swedetown	HOBO Tripod	HOBO Tripod	NA
14 Oct. 2024	L’Anse	HOBO Tripod AERI	HOBO Tripod Doppler LiDAR	HSRL
	Second Sand Beach	HOBO Tripod	HOBO Tripod	NA
	Baraga Cliffs	HOBO Tripod	HOBO Tripod	NA
15 Oct. 2024	L’Anse	HOBO Tripod AERI	HOBO Tripod Doppler LiDAR	HSRL
	Second Sand Beach	HOBO Tripod	Kestrel Tripod	NA
	Baraga Cliffs	HOBO Tripod	HOBO Tripod	NA

Table 2. Accuracy of atmospheric equipment used for data collection.

Equipment	Temp.	RH	Wind Speed	Wind Direction	Pressure
HOBO Weather Station	± 0.25°C	± 2.5%	± 1.1 m/s or 4% of reading, whichever is greater	± 5°	± 3.0 mb
Kestrel Weather Meter	± 1.0 °C	± 3.0%	± 3% or the least significant digit, whichever is greater	Unknown	± 1.5 mb

Supplemental Information

Table S.1. Conversions between AQI and μg m^{-3}, from NASA GSFC.

AQI Value	Concentration (μg m^{-3})	Air Quality Descriptor
0-50	0.0 - 15.4	Good
51-100	15.5 - 40.4	Moderate
101-150	40.5 - 65.4	Unhealthy for sensitive groups
151-200	65.5 - 150.4	Unhealthy
201-300	150.5 - 250.4	Very Unhealthy
301+	250.5 +	Hazardous