Investigating the Benefits of a Chesapeake Bay Lighthouse Subnetwork

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Table of Contents

Abstract

The Chesapeake Bay plays a critical role in shaping regional weather patterns, supporting coastal infrastructure, and sustaining economic and recreational activity in Maryland and Virginia. To improve understanding of the Bay's environmental impacts and associated hazards, the Maryland Mesonet proposes a lighthouse-based observation subnetwork in partnership with The Lighthouse Centers. Meteorological and ozone instruments will be installed at the Hooper Island Lighthouse and Craighill Channel Lower Range Front Light using existing infrastructure. These in-situ sensors will provide near real-time data to support hazard identification and coastal resilience planning. The data will also offer valuable insight into offshore air and water quality.

Chapter 1. Introduction

1.1 Chesapeake Bay

The Chesapeake Bay is the largest estuary in the United States, located in the Mid-Atlantic region and extending approximately 320 kilometers from Havre de Grace, Maryland, to Norfolk, Virginia (NOAA 2010). The bay's width varies significantly across this span, from about 6.5 kilometers near Aberdeen, Maryland, to nearly 48 kilometers near Cape Charles, Virginia (Chesapeake Bay Program n.d.). This spatial variability contributes to diverse meteorological and ecological characteristics throughout the region. The Chesapeake Bay watershed is home to a diverse ecosystem with more than 3,600 species of plants and animals recorded (Chesapeake Bay Program n.d.). Approximately 18 million people live within the watershed, relying on the bay for freshwater resources, fisheries, transportation, and recreation.

Economically, the bay supports multiple sectors including maritime trade, commercial fishing, aquaculture, and tourism. According to the National Oceanic and Atmospheric Administration's Fisheries One Stop Shop (FOSS), Maryland accounted for $82,107,678 in 2023 for commercial fishing (NOAA Fisheries n.d.). A study run by the Maryland Office of Tourism Department reported that in 2021, the Chesapeake Bay region had 8.9 million visitors that resulted in a $3.2 billion in total economic impact (MOTD 2023). Additionally, the bay hosts 2 out of the 5 major North Atlantic ports, further emphasizing its national economic importance (Chesapeake Bay Program n.d.).

1.2 Meteorological and Environmental Hazards

Despite the Chesapeake Bay's ecological and economic significance, the region remains vulnerable to many meteorological and environmental hazards. These risks are not yet fully understood due to limitations in observational data and monitoring (Riggin & Davenport 2025; Skeeter 2022). These hazards influence the environment, atmosphere, and those who live near or visit the bay.

Meteorological phenomena and hydrodynamic conditions contribute to the classification of hazardous waters. According to the Maryland Department of Natural Resources Police, hazardous waters were the fourth leading cause of boating accidents in

Maryland in 24, accounting for 16% of all recorded incidents (Maryland Department of Natural Resources 2025). In addition to these meteorological events, other hazards in the region can be linked to air quality and water quality. The interactions among the physical, atmospheric, and anthropogenic variables will be examined in this chapter.

The Chesapeake Bay is situated in a topographically complex region, with the Appalachian Mountains to the west and the Atlantic Ocean to the east. These three topographic features result in complexities for forecasting meteorological conditions for the land positioned between these features and the maritime conditions over the bay (Boyer et al. 2025, Flood 2004, Hawbecker & Knievel 2022, Letkewicz & Parker 2010, Riggin & Davenport 2025, Skeeter 2022). Along with these topographical conditions, seasonal convective properties from the bay contribute to a complex meteorological environment (Hawbecker & Knievel 2022, Hurlbut & Cohen 2014, Letkewicz & Parker 2010, Riggin & Davenport 2025, Skeeter 2022).

One of the more consistent mesoscale meteorological events that occur from the Chesapeake is bay breeze, or more generally known as water-body breezes (Segal & Pielke 1985, Sikora et al. 2010). These breezes are caused by differential heating between local surface-level low pressure (Warm land) and local surface-level high pressure (cooler water), initiating a mesoscale circulation between the waterbody and land, as seen in Figure 1. As the moist air from the water flows into the surface low pressure, the air rises, resulting in the development of fair-weather cumulus clouds along the shoreline. The heating differential can also be enhanced through the warming effect of urban development which is present on the western side of the bay, further supporting cloud development (Eastin et al. 2018; Hawbecker & Knievel 2022; Skeeter 2022).

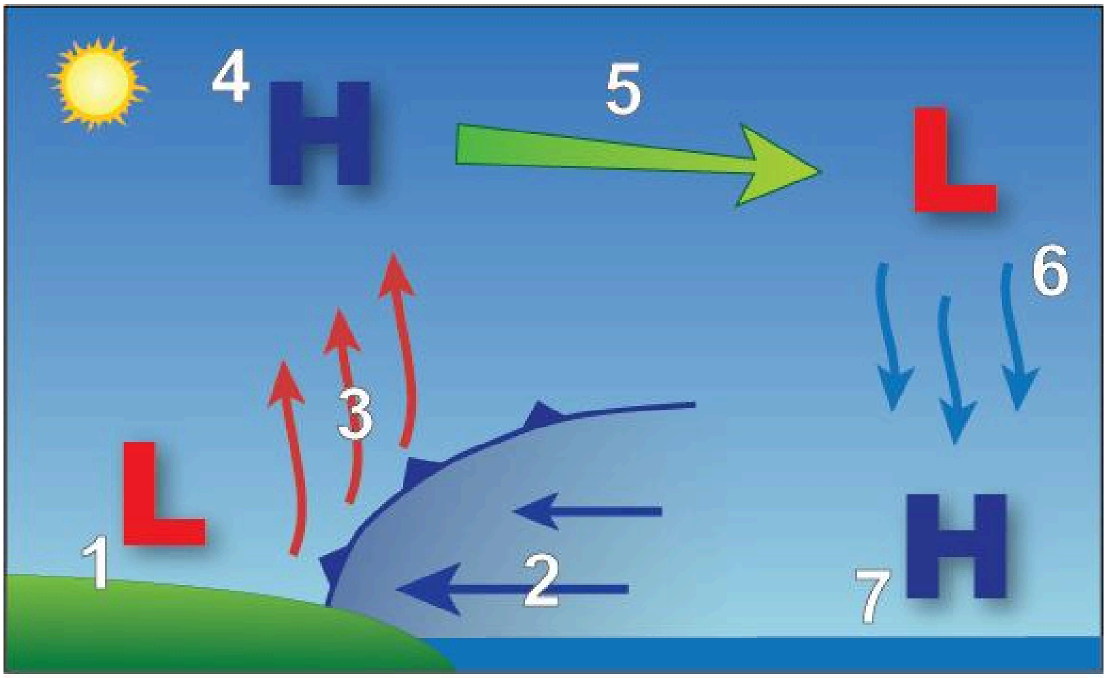

Figure 1. (NOAA 2023). Graphic illustrates the circulation of water-body breeze where the cold air from the water flows to the low pressure over land, resulting in rising air. This can initiate convection and cloud development.

This solenoidal circulation or lack of circulation has a direct effect on convective initiation and cloud development for the region and can modulate pre-existing systems (Kingsmill 1995; Loughner et al. 2014; Skeeter 2022). A case study done on the mesoscale environment during the April 28th, 2002 severe storm outbreak over Maryland found that the water-body breeze circulations of the Potomac River and Chesapeake Bay were unlikely during the events (Rogowski & Zubrick 2004). The weakening of the circulations is believed to help increase the stability of the storms and contribute to the severity.

Bay breeze influences local wind events, modulates precipitation, and modulates storm stability while the breeze can be influenced by the temperature differences of surfaces and frontal systems (Hawbecker & Knievel 2022; Riggin & Davenport 2025; Skeeter 2022). The direct effects it has on meteorological events also has indirect effects on air quality and water quality in the Chesapeake Bay area.

A mechanism that can be influenced by bay breeze, among other factors, is precipitation. For a healthy Chesapeake Bay, lower intensity precipitation is important (Swartwood 2022; Vargas-Nguyen et al. 2024). Increased convection creates potential for higher intensity rains, while a breakdown of the bay breeze reduces winds (Segal & Pielke 1985; Sikora et al. 2010). It is important for the bay to maintain balanced salinity and clarity. Intense precipitation creates runoff from land that picks up nutrients to feed algal blooms. When the algal blooms decompose, they remove oxygen from the water, creating dead zones for marine life (Swartwood 2022). Additionally, added precipitation will reduce the salinity balance of the brackish water of the bay. As more regions become urbanized, runoff will increase and will throw off the salinity balance at a higher frequency (Swartwood 2022; Vargas-Nguyen et al. 2024). Clarity becomes worse in high precipitation events due to the stirring of sediments and coastal erosion. As clarity decreases, underwater grasses lose access to sunlight. Death of these grasses then affect the habitats in the bay since it is a primary food source for marine life (Swartwood 2022). All of these factors contribute to low grades for the Chesapeake Bay Watershed (Vargas-Nguyen et al. 2024).

Air quality over the Chesapeake Bay region cannot be overlooked. Greenhouse gases and other pollutants impact both marine and human health. Studies have shown that bay breeze impacts the daily totals of tropospheric ozone, a secondary pollutant that results in respiratory ailments (Caicedo et al., 2021; Caicedo et al., 2019; Dreessen et al., 2023; Goldberg et al., 2014; Loughner et al., 2014; Mazzuca et al. 2019; Yang et al., 2022)). Studies have shown that on days where bay breeze events occur, mean ozone concentrations are higher in polluted air. This concept has been supported through observations (Mazzuca et al. 2019; Stauffer et al., 2015)) and modeling (Yang et al. 2022).

From these examples, it is clear that monitoring the meteorological conditions of the bay are critical for predicting and understanding human health (Mazzuca et al. 2019; Yang et al. 2022) and bay health (Swartwood 2022; Vargas-Nguyen et al. 2024), while being able to protect life and property in hazardous weather situations on land and in the bay (Caicedo et al., 2021; Caicedo et al., 2019; Dreessen et al., 2023; Goldberg et al., 2014; Kingsmill 1995; Loughner et al., 2014; Rogowski & Zubrick 2004; Skeeter 2022; Yang et al., 2022). There are very few real-time observations in the Chesapeake Bay which limits the ability to track real time hazardous situations over the water and along the shoreline (National Data Buoy Center n.d.). There is a need to help fill this knowledge gap by creating a robust monitoring system within the bay. A solution is discussed in Chapter 2.

Chapter 2. Methodology

2.1 Maryland Mesonet

University of Maryland (UMD) partnered with the Maryland Department of Emergency Management (MDEM) in 2022 to develop a mesoscale weather monitoring network or better known as a mesonet (Maryland Mesonet 2024a). The purpose of the Maryland Mesonet is to monitor mesoscale meteorological events in near-real time. The spatial resolution for this statewide network is expected to be 16 – 26 kilometers apart once fully built out (Koehler & Hyde 2024). At the time of this paper, 25 of the anticipated 75 stations are in operation.

Each station in the network consists of ten-meter towers equipped with instrumentation ranging from ten meters above the surface, to soil instrumentation one meter below the surface (Maryland Mesonet 2024b). Table 1 lists all instrumentation, measurements, and measurement heights per station.

Maryland Mesonet Instrumentation		
Measurement	**Instrument**	**Height AGL**
Horizontal wind speed and direction	Propeller anemometer	10 m
Global solar radiation	Pyranometer	2.0 m
Snow depth	Digital snow depth detector	2.0 m

Temperature + relative humidity probe	Air temperature and relative humidity	2.0 m
Atmospheric pressure	Digital Barometer	1.3 m
Rainfall intensity and derived precipitation accumulation	Tipping bucket rain gauge	~0.3-0.5 m
Soil permittivity, electrical conductivity, temperature, and water content	Water content reflectometer	0.05m, 0.1m, 0.2m, 0.5m, 1.0m below the surface

Table 1 (Maryland Mesonet 2024b) – Maryland Mesonet instruments, measurement parameters, and heights of measurement

Measurements are made every 3 seconds and are reported every minute. This data immediately goes through quality control and assessment before being transmitted to the Meteorological Assimilated Data Ingest System (MADIS) (NOAA 2022). Once reported to MADIS, the National Weather Service (NWS) and MDEM receive access to the data (Koehler & Hyde 2024; NOAA 2022). This immediate data transmission assists in emergency and early warning decisions for the Maryland region.

2.2 The Lighthouse Centers

The Chesapeake Bay has a longstanding history of lighthouse infrastructure. Over the course of the development as a critical commercial and nautical route, a total of 30 lighthouses were installed in the bay and its surrounding tributaries (Krikstan 2014). While some remain operational, many have been decommissioned, and few have been made available through public auction for preservation or private use. Three of these lighthouses were purchased by The Lighthouse Centers: the Hooper Island Lighthouse and the Craighill Channel Lower Range Front Light in Maryland, and the Wolf Trap Lighthouse in Virginia (TLC n.d., Viviano 2022). The organization aims to restore the historic infrastructure while promoting the conservation of the surrounding marine ecosystems (TLC n.d.). These lighthouses are geographically distributed across different subregions of the bay, providing opportunities to study a range of distinct conditions and environments. The spatial distribution of the three lighthouses is illustrated in Figure 2, in reference to the Chesapeake Bay region.

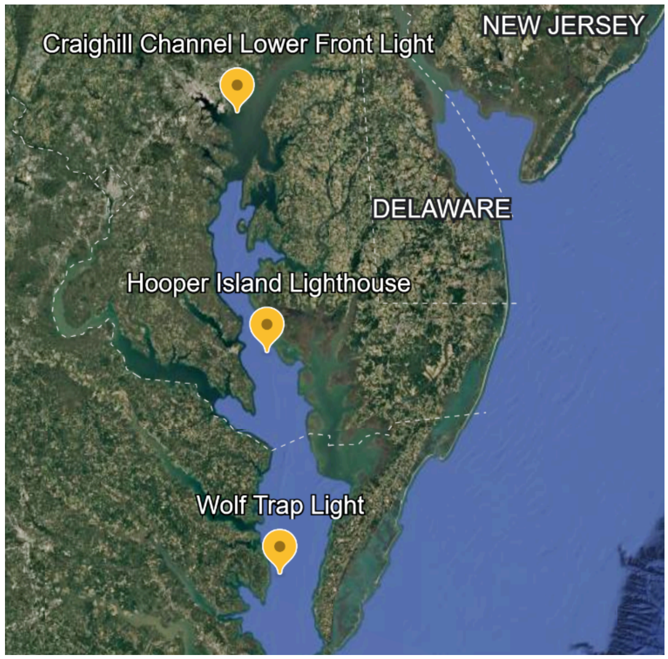

Figure 2, Locations of the three Lighthouses owned by The Lighthouse Centers taken from Google Earth Imagery

In 2023, preliminary discussions were initiated regarding a potential collaboration between The Lighthouse Centers and the Maryland Mesonet to establish a lighthouse observation subnetwork. The intention is to equip the restored lighthouses with a suite of meteorological and environmental instruments. Once equipped, the lighthouse stations will be integrated into the Maryland Mesonet system. These locations will offer unique vantage points for environmental monitoring, particularly over the open water and along the coast.

Hooper Island Lighthouse is the first structure to undergo full restoration and will therefore serve as a prototype site for this subnetwork. By adding these locations into the network, it will help provide data in critical areas that can give insight into the Chesapeake Bay hazards that were discussed in section 1.2 of this paper.

Section 2.3 will provide a detailed overview of the instrumentation upgrades specific to the Hooper Island Lighthouse, including schematic of the structure and sensor configurations.

2.3 Hooper Island Sensors and Schematics

The Hooper Island Lighthouse is located near the longitudinal midpoint of the bay and is situated roughly 5 kilometers west of the Hooper Islands shoreline (Chesapeake Chapter of the United States Lighthouse Society 2019; Viviano 2022). This offshore placement makes it an ideal platform for observing open-water meteorological and marine conditions that cannot be observed from structures along the shoreline. One of the notable features of this lighthouse is the dual-deck design. The lower-level deck is located 18 feet above the mean sea level making observations on this platform comparable to surface level data (Chesapeake Chapter of the United States Lighthouse Society 2019). The upper deck is located just below the focal point which is located 63 feet above the mean sea level (Chesapeake Chapter of the United States Lighthouse Society 2019). This structure is illustrated in Figure 3 in its pre-restoration condition.

Figure 3, photo provided by the Chesapeake Chapter of the U.S. Lighthouse Society of the Hooper Island Lighthouse.

The upper deck of the Hooper Island Lighthouse provides a high-elevation observation platform, making it suitable for wind profiling and atmospheric measurements that are not feasible with traditional buoy-based monitoring systems (National Data Buoy Center n.d.). Utilizing the upper deck will enable the collection of critical data in a region that is undersampled in the bay. To maximize observational potential and minimize structural interference, a telescoping rod will be mounted off the side of the upper deck to support multiple smaller sensors. This will increase exposure to natural air flow and reduce disturbances caused by the lighthouse (R.M. Young 2025a).

The most essential instruments to be installed at this level are two anemometers, tasked with measuring wind direction and speed. The two sensors will be an R.M. Young marine-grade propeller anemometer and a Lufft ultrasonic wind sensor. Although both instruments collect similar data, the use of two distinct sensor types offers several advantages.

The first benefit is redundancy. Deploying independent sensors ensures that, in the event of instrument failure or the anomalous readings, continuous wind observations can be maintained. Owing to the challenges of accessing the offshore lighthouse for maintenance, redundancy is critical for data continuity. The second benefit to having sensors is the diversity of measured parameters between the R.M. Young propeller anemometer and the Lufft ultrasonic wind sensor. The propeller anemometer strictly measures wind speed and direction whereas the ultrasonic wind sensor measures U and V vectors and is capable of also recording virtual temperature and barometric pressure (OTT HydroMet n.d.; R.M. Young 2025b). Propeller anemometers have a threshold and slower response. This reduces the need to install an additional barometer on the upper deck, thereby conserving space and power. The third benefit is improved detection of icing conditions. During icing events, propeller anemometers will either have a lower reading of wind speed or stop reporting wind speed altogether due to the ice coverage on the rotating propeller. Since the ultrasonic sensor lacks moving parts and incorporates a heating system, wind data will be measured unobstructed (Wang et al. 2021).

Additional sensors to be mounted to the rod will be a temperature and relative humidity sensor and a low-power draw ozone meter such as 2B Technologies Model 202. All of these sensors will be fed into the main cabinet where the data logger and communications are stored.

The lower deck will be equipped with all instrumentation that reflects Table 1. The only difference is the absence of soil sensors and a snow sensor since they are not beneficial in the marine environment. Two other sensors that are not listed in Table 1 are an additional ozone monitor and a water-level continuous flow bubbler, like the LevelVUE B10 (Campbell Scientific 2025) . The bubbler will be equipped below the deck into the water to measure sea level height based on barometric changes within the instrument (Campbell Scientific 2025). All of these instruments will report back to the data logger for transmission to the Maryland Mesonet servers.

This set up for a lighthouse weather monitoring station will be fully offgrid, powered by solar panels installed on the south facing side of the structure. Communications will be reliant upon a starlink antenna system (Starlink n.d.). This will allow for sustainable and reliable power in all weather conditions while providing real-time data to match the rest of the Maryland Mesonet network.

Chapter 3. Conclusions

The Chesapeake Bay, a complex environment, has little monitoring available; existing buoys reach only about 1 m above the surface and are not able to record measurements on a stable platform. Additionally, the monitors in the National Data Buoy Center transmit data at 6 and 12 minute intervals which leaves gaps in data (NOAA n.d.). Establishing a lighthouse subnetwork in partnership with the Maryland Mesonet and The Lighthouse Centers will provide environmental and meteorological data that has not yet been observed in the bay. The height of the lighthouses will provide information about inversions, boundary layer heights, data that is not usually found with surface level stations.

Lighthouse subnetwork data will be an asset to decision makers. The Maryland Department of Environment will be able to use the data to track air quality of polluted air along major shipping routes to activate better policies. The National Weather Service will finally be able to access observations to improve marine forecasts and forecasts for the state of Maryland. This will create a needed, safer environment for the whole region while providing insight on the mesoscale complexities.

The need for the lighthouse subnetwork has been made. The next step for this project is to obtain the instrumentation and install the prototype at Hooper Island Lighthouse. Once operational, the lighthouse will become an immediate asset to the entire region. If successful, more lighthouses can be added to the network to provide a denser observation network for the Chesapeake Bay.

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