The Chesapeake Bay Interpretive Buoy System and the Winter of 2015:

Problems and Solutions

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Abstract**—***The NOAA Chesapeake Bay Interpretive Buoy System (CBIBS) is a network of observational platforms managed by the NOAA Chesapeake Bay Office (NCBO) that provides continuous real-time environmental data from the Chesapeake Bay to a wide variety of users. The ten buoys deployed throughout the Bay also support the National Park Service's Captain John Smith Chesapeake National Historical Trail and provide the observational backbone for educational tools used in research and classrooms. Standard buoys are AXYS Watchkeeper platforms equipped with sensors measuring wind, weather, water quality parameters, current profiles, waves, and underwater acoustic animal tracking telemetry. Through a partnership with MARACOOS, CBIBS applies U.S. Integrated Ocean Observing System QARTOD standards to quality control the data, and delivers the real-time data broadly: online via a dedicated interpretive web portal (buoybay.noaa.gov); through dedicated mobile apps; to other data services such as MARACOOS, National Data Buoy Center, and WeatherFlow; and by phone service (877-BUOYBAY).*

Since the deployment of the system beginning in 2007, only the three northernmost buoys in the system (Susquehanna, Upper Potomac, and Patapsco) have been regularly removed for winter, while the others remain in the water and unharmed. The severe winter of 2015 was an anomalous year in weather and water conditions that caused significant damage to many of the buoys. Several strong, relatively late season cold air outbreaks (e.g., February 14 – 17, 2015) accompanied by gale force winds were followed by sustained low temperatures. The cold winds led to significant events of freezing spray, which accumulated and remained on the buoy superstructures. The iced buoy's righting moments decreased until they were horizontal, and several froze into the surface ice in that position for extended periods of time. The poor weather, rapid thickening of surface ice, and lack of available ice-capable service vessels precluded expedient recovery, and further damage from ice and water ensued. Several buoys were lifted off station and were subjected to significant hull and structural damage.

In consideration of the significant loses of equipment and observing down time, NCBO and partners MARACOOS and AXYS are considering preventive actions that can monitor conditions and prevent and mitigate damage when exposed to similar future conditions. Possible actions include:

- *Estimating ice accumulation potential from forecast and measured wind, temperature, and wave conditions; modeling buoy righting moment changes due to ice accumulation; using those to monitor and forecast likelihood of buoy capsize.*
- *We have successfully deployed low surface area spar 'ice buoys' on the northernmost moorings in past winters; instrumenting those buoys to provide basic overwinter air and water quality measurements would enhance the winter observing network and make us more likely to remove fully instrumented, more expensive buoys.*
- *Modify the existing buoy structure to minimize ice accumulations*
- *Identify water intrusion locations (seen in Watchkeeper buoy hulls and battery wells, Watchman controller enclosures, and TriAXYS wave modules) and make appropriate design changes*
- *Include sensors to monitor buoy orientation (mean pitch/roll, horizon and hull imaging) in order to identify and address righting moment problems early*
- *Change winter maintenance schedules and vessel availability to respond quickly to developing situations.*

The winter of 2015 was an anomalous year that has motivated us to improve the buoy and observing system design by implementing one or some of these engineering solutions that will help prevent water intrusion, ice damage, and resulting system down time in the future. This paper will describe the anomalous conditions, the resulting damage to the CBIBS system, explore the causes, and suggest proposed solutions

Keywords—buoy; icing; Chesapeake Bay; NOAA; AXYS

I. Introduction

The NOAA Chesapeake Bay Interpretive Buoy System (CBIBS) is a network of observational platforms managed by the NOAA Chesapeake Bay Office (NCBO) that provides continuous real-time environmental data from the Chesapeake Bay to a wide variety of users. Currently, CBIBS comprises ten buoys deployed throughout the tidal regions of the Bay that support and interpret points along the National Park Service's Captain John Smith Chesapeake National Historical Trail (Fig. 1). The standard buoys are AXYS Watchkeeper platforms equipped with sensors measuring wind, weather, water quality parameters, current profiles, waves, and underwater acoustic animal tracking telemetry. Through a partnership with MARACOOS, the "smart buoys" apply U.S. Integrated Ocean Observing System QARTOD standards to quality control the

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data, and delivers the real-time data broadly: online via a dedicated interpretive web portal (buoybay.noaa.gov); through dedicated mobile apps; to other data services such as MARACOOS, National Data Buoy Center, and WeatherFlow; and by phone service (877-BUOYBAY). The buoys provide boaters with local conditions before leaving the harbor, the observational backbone for educational tools used in research and classrooms, and data and information needed for policy and management decisions to protect and restore the Bay.

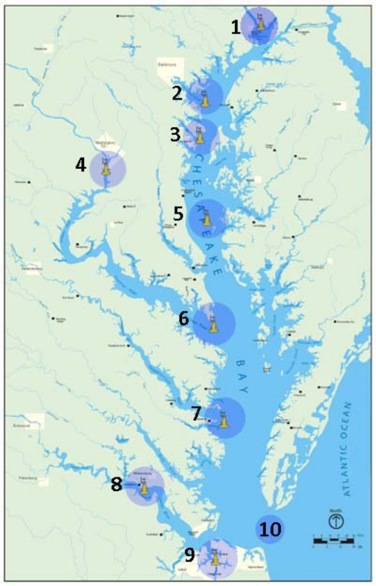

Fig. 1 *Map showing current distribution of CBIBS array. The numbers correspond to the following buoys: Susquehanna, Patapsco, Annapolis, Upper Potomac, Gooses Reef, Point Lookout, Stingray Point, Jamestown, Norfolk and First Landing, respectively.*

The AXYS Watchkeeper platforms are rotationally molded, 1.75-m-diameter, polyethylene buoys. The body of the buoy is a SB-138P Sentinel designed and built by Tideland Signal Corporation and includes a hull and two-part superstructure. The seamless hull is 9.5 mm thick and features an internal, stainless steel bracing system that links the concrete internal ballast to the lifting and mooring eye. The lower section of the hull is filled with cement, and the upper section is filled with closed-cell polystyrene foam that prevents the ingress of water and provides reserve buoyancy if the hull's outer skin is damaged. Plastic tubes that are 25.4 cm in diameter and called "moonpools" house the subsurface instrumentation allowing for easy top-side access for maintenance and are installed through the hull. A central cavity in the hull houses a sealed aluminum battery well that accommodates four 12-volt, 100-ampere, solar-powered batteries and a water level sensor that provides an early warning of potential flooding of the battery well. The two-part superstructure comprises (1) a middle compartment (mid-section) that houses the TriAXYS Directional Wave Sensor and comes equipped with several Dom Nylon Stuffing tubes allowing for passing of cables through the buoy to the subsurface sensors, and (2) the "navaid" tower, which supports four, 20-watt solar panels; a payload compartment (drawer allowing access to sensor equipment); a navigation lamp; an internal radar reflector (10-m2 cross section, X-band); GPS receiver/transmitter; and meteorological sensors. A perforated polyethylene handling ring or "skirt" installed around the top of the mid-section protects the solar panels from collision damage and provides handles for manipulating the buoy during in-water service. The top portion of the superstructure is a hollow, polyethylene, rectangular prism with a circular base that mates with the mid-section. The superstructure is encased in a stainless steel, four-panel scaffold frame that is powder-coated. The fully assembled and equipped buoy stands approximately 4.27 m tall; in the water, the buoy stands roughly 3.05 m above the waterline. Each CBIBS buoy is moored to the bottom of the bay by way of a 1-in. mooring chain connected to a ~2000 lb. sinker. The mooring chain is attached to the buoy at two points (mooring eyes) via the bridle. The total length of the mooring chain is approximately 2.5 times the water depth at the buoys' location.

Since the start of the system in 2007, the three northern buoys (Susquehanna, Patapsco and Upper Potomac) are removed for the winter to avoid ice damage. However, the severe winter of 2015 was an anomalous year in weather and water conditions that caused significant damage to many of the buoys in the mid and lower Bay, including the Annapolis, Gooses Reef, Point Lookout and Jamestown buoys. Several strong, relatively late season cold air outbreaks (February 14 – 17, 2015) accompanied by gale force winds were followed by sustained low temperatures. The freezing temperatures with sustained high winds and increased wave heights led to significant events of freezing spray and splash, which accumulated and remained on the buoy superstructures. The iced buoy's righting moments decreased until they were horizontal, and several froze into the surface ice in that position for extended periods of time (Fig. 2).

Fig. 2. *Annapolis buoy on February 18, 2015. Photo credit: NOAA LTJG Philip J. Klavon.*

II. February 2015 Conditions

As of February 18, 2015, 90% of the northern Bay was covered in ice with significant coverage in the mid-Bay and hugging the Eastern Shore. The majority of ice was thin (<10.2 cm), but several areas had ice thickness reports that exceeded 0.3 m [1]. Several buoys were lifted off station and were subjected to significant hull and structural damage likely due to surface ice flows. The poor weather, rapid thickening of surface ice, and lack of available ice-capable service vessels precluded expedient recovery, and further damage from ice and water ensued.

The Annapolis, Gooses Reef and Jamestown buoys measured surface water temperatures that dropped below the calculated seawater freezing point (Fig. 3), which was the first time in CBIBS history this has been recorded and observed. Annapolis, Gooses Reef and Point Lookout buoys had sustained, high wind gusts (~20 m/s, Fig. 3) and all four buoys experienced increased significant wave height.

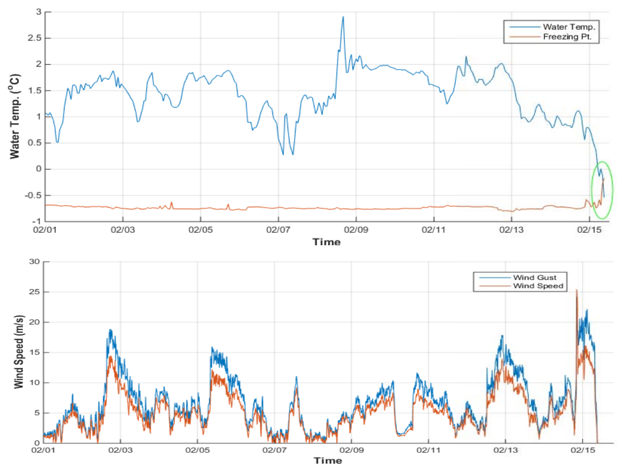

Fig.3 *February 2015 Annapolis buoy seawater temperature & freezing point (°C, top) and wind speed & gust (m/s, bottom) observations. The green circle indicates where the water temperature dips below freezing point.*

Under high wind speeds (>~20 m/s), sea spray is generated by water shearing from the crest of the waves and in cold temperatures this can cause significant ice accretion on structures [2]. Ice accumulation can also occur at lower wind speeds due to waves running up the side of the structure and freezing at the height of the splash, where the water content is decreased [2].

In order to determine the role the winds versus waves played in contributing to the icing seen on the buoys, the wave run-up and splash height was calculated following [2] & [3]. Using the buoy observed wave period and significant height throughout February 2015, the run up and splash height was calculated using (1), where g is acceleration due to gravity, m is a run-up and splash parameter and u is the water particle velocity at the height of the wave crest η_{max} given by second order Stokes theory.

$$R = n_{max} + m\frac{u^2}{2g} \qquad (1)$$

Over the course of February 2015, the maximum run up and splash height at Annapolis occurred on February 15, 2015, which is the day the buoy was found to be heeled over and stopped reporting. The mean run up and splash height for the month at Annapolis was 0.238 and 0.539 m, respectively, and the buoy sits about 3.048 m above the waterline. Thus, the icing seen on the top of the anemometer (Fig. 1), was most likely not due to wave action and instead can be attributed to the sustained wind gusts at approx. 20 m/s. Similarly, Point Lookout and Gooses Reef experienced high, sustained winds, however at Jamestown, the winds stayed below 15 m/s. Therefore, the wave action at Jamestown may have played a larger role than the winds in the ice accumulation than at the other three buoys.

III. Ice Accumulation Forecast

In consideration of the significant loses of equipment and observing down time, NCBO and partners MARACOOS and AXYS are considering preventive actions that can monitor conditions and prevent and mitigate damage when exposed to similar future conditions. One possible action includes estimating ice accumulation potential from forecast and measured wind, temperature, and wave conditions.

NOAA's National Data Buoy Center uses an algorithm developed by Overland and Pease in the mid-1980s to predict ice accumulation on vessels. For vessels, ice accretion primarily is due to wave-generated spray produced by the impact of waves against the hull [4, 5, 6, 7]. The volume of water available for freezing on vessels is ten times greater for a wind speed of 20 m/s than 10 m/s [7]. Extreme icing on vessels was found when water temperatures dropped below 2°C and a decreasing icing rate with increasing SST up to 6 °C [4, 8, 9, 10, 11]. Overland's algorithm for sea spray icing prediction (PPR) for mid-size (20 – 75 m in length) vessels is a function of wind speed (Va), freezing point of seawater (Tf), air temperature (Ta) and seawater temperature (Tw):

$$PPR = \frac{V_a(T_f - T_a)}{1+0.3(T_w - T_f)^2} \qquad (2)$$

The *PPR* is characterized by the associated icing class (none, light, moderate, heavy and extreme) and rate (0, <0.7, 0.7 - 2.0, 2.0 – 4.0, > 4.0 cm/hr.) and thus, can be helpful in predicting future icing conditions on vessels using atmospheric predictions from the weather forecast. However, because vessels mainly generate sea spray from wave action while cruising, using this equation for moored buoys may require the wind speeds to play more of a dominant role in order to generate enough volume of water for icing. To test whether this algorithm would be applicable for buoys without modification, we used the Annapolis buoy observed daily average conditions over the month of February 2015 and calculated the PPR. Throughout the month, light icing was projected for three days (2/3, 2/6 and 2/14), moderate icing on 2/13 and heavy icing on 2/15, which is reasonable to what was observed over the month.

Because wind speeds are a critical factor in ice accumulation on offshore structures [2] (and vessels [4]) in order to determine what wind speeds would be necessary to cause the various levels of icing, the Annapolis average daily conditions on 2/15/15 were used to calculate V_a, where Tf = -0.61, T_a = -7.02, T_w = 0.35, *PPR* = -0.01, 0, 22.4, 53.3, 83, 83.1 (Table I).

TABLE I. V_A Threshold Values

PPR	*Class*	*V_a (m/s)*
<0	None	0
0 – 22.4	Light	0 – 4.50
22.4 – 53.3	Moderate	4.50 – 10.71
53.3 – 83	Heavy	10.71 – 16.68
>83	Extreme	>16.68

Although the average daily wind speed was below 12 m/s, the maximum daily gust was above 16.68 on 2/13, 2/14 and 2/15, which could theoretically create extreme icing events (with all other variables equal) if the gusts were sustained. What needs to be developed further is how long the winds need to remain above these calculated thresholds in Table I in order to generate enough sea spray to parallel the wave driven sea spray from vessels and thus, be able to use the *PPR* algorithm with confidence to predict icing events on the buoys.

There are many forecasting models and products available (such as the National Weather Service's and the SPIA Index) that can be used in predicting an oncoming storm and icing event. We can use those products in combination with algorithms such as Overland's icing predictor or the simple freezing rain ice accretion model [12] that we would modify for moored buoys. In an attempt to avoid similar damaging icing events, we will continually analyze real-time buoy conditions during future winters and compare those observations with trends we saw in February 2015. Specifically, we will be looking for decreasing air and water temperatures combined with projected high, sustained winds.

If we predicted the onset of a storm that may have comparable conditions to those experienced in February 2015, we would need to take immediate action to remove the buoys and/or sensors in order to prevent similar ice damage that we experienced this past winter. Ideally, we will implement a protocol for icing events and have an alert system in place so that we allow ourselves a bit of reaction time, which will depend on the rate of the onset of the storm or change in conditions. It will also depend on the Bay conditions (i.e. is the Bay showing surface ice like last winter) and vessel availability and proximity. The icing event predictor tools, ample reaction time and established protocol plan for our response are all critical in our effort to prevent future ice damage.

IV. Buoy Hydrodynamic Stability Analysis

In order to better understand the conditions that caused the buoys to capsize last winter, the buoy hydrodynamic stability and response was modeled as a function of ice thickness and heel angle.

A. Method

We calculated the buoy surface area available for ice accumulation and assumed ice thickness to vary between 10 and 170 mm and the buoy heeling angle to range between 0 and ~140°. The added mass of ice is a function of ice thickness and was calculated by multiplying the surface area with the thickness and the density of ice. The origin is defined as the lowest point on the vertical axis of the buoy. For each added mass element, its corresponding distance from the origin was calculated. In this simulation it is assumed that the mooring chain is always in a vertical position with a constant length, no matter the heeling angle of the buoy. This means that the center of mass of the buoy-chain system moves in a two dimensional plane at different heeling angles. The equations used for the center of mass as a function of heeling angle and ice thickness are the following, where $\vec{x}$ and $\vec{y}$ are distances (mm) from the origin:

$$\vec{x}_{(\delta\varphi, ice\ thickness)} = \frac{1}{M_{Total(ice\ thickness)}}\left(m_{chain}x_{chain(\delta\varphi)}\right) \quad (3)$$

$$\vec{y}_{(\delta\varphi, ice\ thickness)} = \frac{1}{M_{Total(ice\ thickness)}}\left(m_{buoy}y_{buoy} + m_{total\ ice\ (ice\ thickness)}y_{total\ ice\ (ice\ thickness)} + m_{chain}y_{chain(\delta\varphi)}\right) \quad (4)$$

In order to calculate the new waterline that results from the addition of mass due to ice, the approximate volume of water displaced by the buoy was needed. The added mass is equal to the change in mass of water displaced and thus, the following relationship must be true, where each side of the equation is equivalent to the change in volume calculated in different ways.

$$A_{cross\ section}\, h_{ice\ thickness} = \frac{m_{added}}{\rho_{water}} \quad (5)$$

Solving for h, we get the vertical distance (mm) between the initial and end waterlines, where h is a function of the different masses of ice (m_{added}) corresponding to the array of possible ice thicknesses. Using h, the new waterline can be computed from the following equation:

$$Waterline_{new} = Waterline_{free\ floating} + h_{ice\ thickness} \quad (6)$$

The center of buoyancy is the center of mass of displaced water, so it can be calculated in a similar way to how the buoy's center of mass was found. At 0° heel, the center of buoyancy only has a vertical component:

$$\vec{B}_{(ice\ thickness)} = \frac{\left(m_{water\ free\ floating}\vec{B}_{free\ floating} + m_{water\ added}\vec{B}_{water\ added}\right)}{m_{water\ free\ floating} + m_{water\ added}} \quad (7)$$

$$m_{water\ added} = A_{section} * h_{(ice\ thickness)} * \rho_{water} \quad (8)$$

$$\vec{B}_{water\ added} = Waterline_{free\ floating} + \frac{h_{(ice\ thickness)}}{2} \quad (9)$$

Due to symmetry, the centroid of the submerged buoy cross sectional area is the center of mass. Thus, as a result of added mass and heel, the new center of buoyancy (B_1) has the exact coordinates as the centroid of that area. Using the Matlab function POLYGEOM [13] the centroid of the cross sectional area of the submerged buoy, was found for an array of waterlines and heeling angles. Starting from the horizontal waterline with its corresponding center of buoyancy on the vertical axis and moving counterclockwise, we tracked the center of buoyancy movement in two dimensions (Fig. 4).

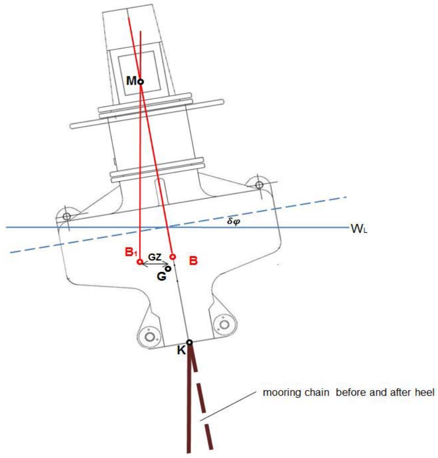

Fig. 4. *The Watchkeeper AXYS buoy with waterline (W_L) at a heel angle ($\delta\varphi$), the center of buoyancy before heel (B), the center of buoyancy after heel (B_1), the center of mass (G), the metacenter (M), the keel (K) and the righting arm ($\overrightarrow{GZ}$). Since the mooring chain always has to be vertical to ground, it forces (G) to have an x axis component which is a function of $\delta\varphi$.*

Building upon Lewis's approach of calculating the metacentric height $\overrightarrow{GM}$ for a vessel at small heel angles [15], we can estimate the vertical component, $\overrightarrow{\mathrm{GM}_y}$.

$$\overrightarrow{\mathrm{GM}_y} = \overrightarrow{\mathrm{KB}_y} + \overrightarrow{\mathrm{BM}_y} - \overrightarrow{\mathrm{KG}_y} \qquad (10)$$

Where $\overrightarrow{\mathrm{KB}}$ is the height of the center of buoyancy above the keel at equilibrium, $\overrightarrow{\mathrm{BM}}$ is the metacenter, and $\overrightarrow{KG}$ the height of the center of mass above the keel. We assumed that the keel (*K*) is at the very bottom of the buoy and it does not include any section of the mooring chain.

The righting arm ($\overrightarrow{\mathrm{GZ}}$) is the distance between the vertical forces of weight and buoyancy [14] and is calculated using:

$$\overline{GZ} = \overline{GMy}\sin(\delta\varphi) \qquad (11)$$

When $\overrightarrow{GZ}$ is positive, the buoy is in dynamic equilibrium and it will return to its upright position after some heel, $\delta\varphi$. If $\overrightarrow{GZ}$ is negative, the buoy is no longer stable and it will capsize. The plot of $\overrightarrow{GZ}$ vs $\delta\varphi$ is a very good indicator of the maximum angle at which the buoy can heel without capsizing. The intersection of the curve and the x axis is this threshold.

B. Results

We ran the model using various conditions (i.e. ice thickness and buoy surface area available for icing) to simulate the different buoy responses (i.e. buoy heeling angle). We plotted the righting arm as a function of heel angle (Fig. 5), where the total mass of ice added ranged from 75 to 1273 kg corresponding to a waterline ranging from 875 to 1956 mm from the bottom of the buoy. For reference, the mating surface between the buoy hull and tower is at 1496 mm from the bottom. It is significant to observe the dramatic change in curve pattern that starts at the 120 mm ice line (bright green). This occurs because with that thickness, the waterline exceeds the widest section of the buoy and any additional displacement has to come from the smaller volume above in the mid-section of the buoy.

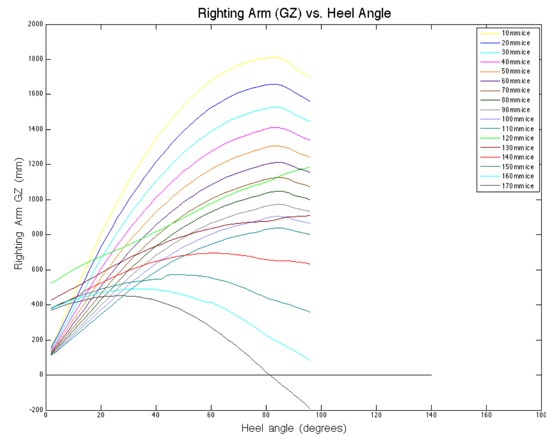

Fig. 5. *This shows the magnitude of the righting arm (mm) as a function of heel angle (°) for ice thicknesses ranging from 10 to 170 mm added to all five surfaces onto which ice was assumed to accumulate.*

Similarly, the magnitude of the righting arm vs. heel angle for ice thickness ranging from 120 to 150 mm was calculated (Fig. 6). Here, the meteorological mounting disk surface is quadrupled, simulating a top heavy buoy. The total mass of ice added ranged from 1132 to 1416 kg with the corresponding waterline ranging from 1527 to 2395mm. For the 130mm ice line (brown), the max heel angle before the buoy capsizes is 110°; for the 140mm ice line (red), it is 80°; and for the 150mm ice line (blue), it is 64°.

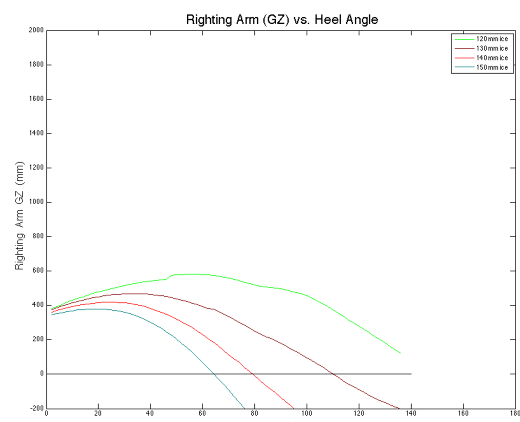

Fig. 6. *This shows the magnitude of the righting arm (mm) as a function of heel angle (°) for ice thicknesses ranging from 120 to 150 mm.*

The buoy handling ring ("skirt") was removed and the magnitude of the righting arm vs. heel angle for ice ranging in thickness from 120 to 150 mm was calculated for this reduced surface area condition (Fig. 7). Again, the meteorological mounting disk surface was quadrupled to simulate a top heavy buoy. The total mass of ice added ranges from 929 to 1161 kg with the corresponding waterline ranging from 902 to 1377 mm. For the 150 mm ice line (blue), the max heel angle before the buoy capsizes is 116°.

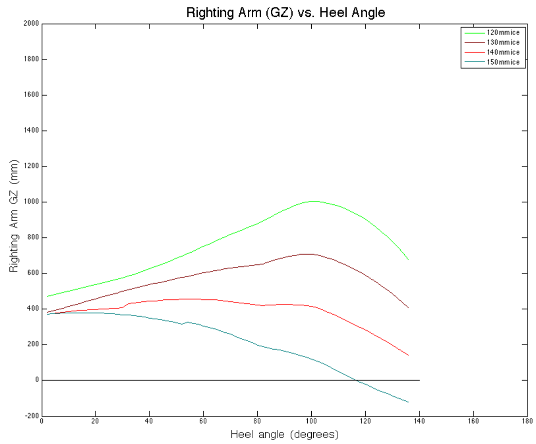

Fig. 7. *This shows the magnitude of the righting arm (mm) as a function of heel angle (°) for ice thicknesses ranging from 120 to 150 mm without the buoy skirt.*

C. Discussion

This model helped quantify the effects of ice surface area and thickness on the hydrodynamic stability of the buoy under several ice thickness accumulation scenarios.

Fig. 5 shows the transition through the critical waterline located at the top of the widest section of the hull. Once the hull of the buoy is completely submerged, the stability rapidly decreases with the righting arm (by 600 mm) and any additional mass has an increasingly destabilizing effect.

This shows that monitoring the waterline would be a valuable indicator of stability. A pressure sensor could be attached at the very bottom of the buoy transmitting the depth at any given time. A scaled alerting system could be set up sending out warnings when the waterline is near the critical level, above it, or even at the downflooding height at the junction of the buoy hull and tower.

Comparing Fig. 6 and 7, we can observe the large increase in stability by just removing the buoy skit. For an ice thickness of 150 mm, the maximum heel angle before the buoy capsizes increases by 52°. From an operational viewpoint it would make sense to remove the ring on all ice vurnerable buoys before the winter season. This is a task that can be accomplished in the field and has high retun compared to the effort required.

The primary assumption made in the model is that the buoy is completely watertight. From our experience, this is far from true having identified several locations of water ingress, discussed further in Section V. In terms of the model, this means that any additional mass of water within the buoy is not included in the calculation of the center of mass. Furthermore, the free surface effect of the water within the buoy would highly influence the x component of the center of mass. Another simplification is that the governing equations in the model are those of a vessel subject to small heeling angles and not of a moored floating structure. The equations used do not completely account for horizontal changes in the center of mass and cannot express the complexity of the buoy-chain-mooring system. Thus, possibly in the future we should use software designed more specifically to include mooring dynamics.

Additionally, this model does not account for the complexity and variability of the environment the buoys are in. For example, it is assumed that ice accumulation occurs evenly around the vertical axis. For example, it is assumed that ice accumulation occurs evenly around the vertical axis. However, in reality the rate in ice accumulation is a function of several environmental variables that together could cause a rapid change in the horizontal component of the center of mass causing the buoy to capsize. The influence of waves was not taken into consideration in our model, but as the mass on the buoy increases it would increase its natural period and potentially reach resonance. This might have contributed to buoy flooding experienced last winter, but was not verified. Lastly, the loss in stability and damage due to collisions and pressure exerted from flowing ice is not taken into consideration either. It would be extremely challenging to accurately model such a scenario.

V. WATCHKEEPER DESIGN MODIFICATIONS

A. Water Intrusion

The winter of 2015 was anomalous year that has motivated us to assess the buoy and observing system design and improve it by implementing one or some of the following engineering solutions that will help prevent water intrusion, ice damage, and resulting system down time in the future.

The Watchkeeper buoy structure is designed to be splash proof and not submergible. Therefore, there are several locations where water can seep between joints that are not fully waterproofed. The major locations of water intrusion include the joint connecting the hull and top structure of the buoy, the joints both on the top and bottom of the hull where the moonpools meet the hull, the Dorn Nylon Stuffing Tubes that allow the cables to run in and out of the buoys and the instrument panel drawer on the top of the buoy. Once water is inside the buoy, the water may seep into the battery well, TriAXYS wave sensor, modem and power controller boxes and Watchman controller if the lids are not properly sealed causing significant damage.

In order to minimize water intrusion through the joint between the hull and top structure, one suggestion would be to install an outer ring made of rubber (or some other water wicking material) either around the outside of the joint or on the inside that connects the hull and top structure, preventing water from reaching the battery well and internal buoy components. To reduce water ingress between the joint where the moonpools meet the hull, either thicker layers of Tam Tech Adhesive, which sticks to the polyethylene material, need to be applied or we could possibly work with AXYS on designing a hull that has the moonpools built in such that the hull and moonpools are one continuous structure versus having separate parts welded together as they currently are. To reduce water leakage through the stuffing tubes, closer attention to the size of the rubber piece with respect to the size of the cable is essential and sealant should be applied to minimize gaps where water could potentially seep through.

If water does intrude into the buoy, the battery well, TriAXYS wave sensor, power controller and modem box and Watchman controller should be properly sealed in order to minimize water leakage and damage. Ideally, we would like these to be on par with the International Protection Rating of 68, which would be classified as “dust tight” and protected against submersion in water. The battery well, especially, can be a bit more permanently sealed as it never needs to be opened in the field versus the Watchman controller, which is opened for troubleshooting various issues.

B. Ice Accumulation

In order to prevent the damage due to ice that was experienced last winter, several buoy alterations can be implemented. As previously discussed, one suggestion would be to remove the buoy skirt in order to increase stability and prevent capsizing.

In the same idea of lowering surface area in order to minimize available structures for ice accumulation, the cell antennas that are currently used could possibly be replaced with a lower profile patch antenna. The buoys are close enough to the shoreline that they don’t require extensive range, but more research could be done to determine whether the smaller antennas would reach the minimum range requirements.

The anemometers that are currently used on nine of the ten buoys are the RM Young 05103 model, which has moving parts. First Landing is the one exception, which is equipped with a Gill WindSonic, which is a solid state anemometer that uses acoustics to measure wind speed and direction. A slightly different Gill model is the WindSonic M that has a heating system that toggles on and off depending on an internal thermistor control. The thermistor measures the outside ambient temperature and powers the heating unit when it drops to 5°C or below. The heater current peaks around 5.7 amps and has proven to continue to provide data in -40°C with winds above 60 m/s and several different states of precipitation. Although this would require more power to be drawn from the buoy, it may prevent icing on the anemometer in the future.

VI. WINTER ALTERNATIVE TO WATCHKEEPER BUOYS

Since the beginning of the system in 2007, the three northern buoys (Susquehanna, Patapsco and Upper Potomac) have been removed for the winter. Depending on the lifting capability of the vessel used, either the entire buoy and mooring system was removed, or just the Watchkeeper buoy and bridle were removed and replaced with a Tideland Signal SB-60 spar buoy to hold the mooring in place. Similar to the Watchkeeper, the SB60 is made of polyethylene and has a stainless steel mooring eye that is used to attach to the mooring chain. The cylindrical structure, thickness of the body (0.8 mm) and internal foam are all designs that allow the buoy to withstand collisions, making it ideal during surface ice conditions.

The major disadvantage with these spar buoys is that they are not designed to incorporate oceanographic or meteorological instrumentation. Thus, instrumenting those buoys to provide basic overwinter air and water quality measurements would enhance the winter observing network and make us more likely to remove fully instrumented, more expensive buoys in the upper and mid-Bay that may be susceptible to freezing.

The modifications shown in Fig. 8 are made with the following objectives in mind: using custom made parts and keeping required man hours to a minimum, while protecting the sensor from ice flow damage and minimizing the risk of water ingress; making the deployment preparations straightforward and fast; and incorporating materials and sensors we already have.

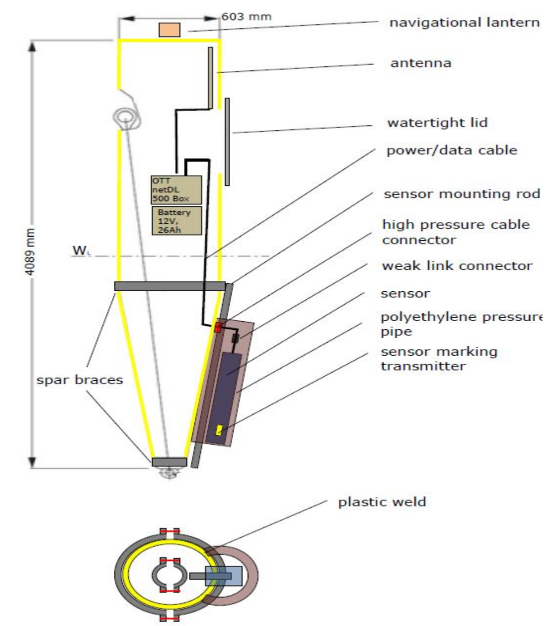

Fig. 8. *This diagram shows a profile (above) and top view (below) of the potential modifications to the Tideland Signal SB-60 spar buoy. Dimensions of added components are not in scale.*

Two detachable stainless steel braces located at the ends of the conical section of the buoy hold in place the mounting rod on which the sensor will attach. A polyethylene block will be fused onto the spar such that the top of the sensor will be at the same height as the block. A precision threaded hole will be opened through the block and the spar in order to install a high pressure cable connector. The protective tube, which the instrument will be inserted into, is a one meter long, 46 mm thick, high pressure polyethylene pipe that will be cut in half and welded onto the side of the buoy. A square opening approx. 920 mm above the waterline will be cut out and the expanded polystyrene foam will be carved out to precisely the outer dimensions of the battery and controller boxes. The perimeter of the square opening will be reinforced and on that section stainless bolts will be passed through, anchored from the inside with the threaded part towards the outside. Polyethylene strips will be welded around the cutoff adding the necessary sealing surface between the buoy and the lid. Holes will be opened on the lid and in alignment with the bolts allowing the two surfaces to merge.

A cable will run from the battery and control boxes to the high pressure cable connector providing power and data transmission. Another cable will run from the high pressure connector to a waterproof weak link and out to the sensor. In the event that damaging tension is applied on the outboard cable, the weak link would part first, preventing damage to the sensor connector as well as the watertight connection on the spar.

Two sensors are considered: the Sea Bird Coastal HydroCAT which can measure conductivity, temperature, pressure (CTD) and optical dissolved oxygen (DO), and the WetLabs Water Quality Monitor (WQM), which is equipped with CTD, DO, chlorophyll and turbidity sensors. An advantage to using the WQM, would be that our laboratory already maintains an array of these instruments, with a calibration protocol in place and troubleshooting experience. The disadvantage being that an external battery source is required, which necessitates an opening to the buoy regardless of whether we transmit the data real-time or choose to log it and distribute the data after the deployment. On the contrary, the HydroCAT is not an instrument we already have, but is programmable for autonomous sampling and internal data logging which would eliminate the need for a controller, power supply, antenna, and most importantly, cutting through the buoy.

Even in extremely low water temperatures (T=2°C), the HydroCAT is able to sample at a rate of 6 samples/hours for over four months (130.6 days) just utilizing its internal batteries. Alternatively, the WQM does not have an internal battery, so it would draw power from the 12V 26Ah battery that will need to be installed in the buoy. For five minutes of sampling every hour, data can be acquired for 114 days which is approximately 3.7 months. Typically, the spar buoys are deployed from mid-December to mid-February, weather depending and thus, both sensors would sample the entire duration of deployment.

A cost estimate was completed and the cost of modifying the spar buoy to hold real-time transmitting WQM would be significantly less than installing the data logging HydroCAT ($3,415.50 vs. $13,438, respectively). Having the HydroCAT transmit real-time data increases the price about $2,000. This price differential is mainly due to the cost of buying a new HydroCAT sensor, which we do not have in house.

An independent equipment marker transmitter (pinger) can be secured on any of the two instruments used. In the unlikely event that the sensor detaches from the spar buoy, we would be able to locate and recover it from the seafloor. The transmitter also has the option of sensing tilt and could be programed to trigger an alarm if a tilt angle exceeds a preselected value. Receiving this information in real time would be critical buoy status information.

VII. CONCLUSION

CBIBS is a network of observational platforms managed by NCBO that provides continuous real-time environmental data from the Chesapeake Bay to a wide variety of users. The severe winter of 2015 was an anomalous year in weather and water conditions that caused significant damage to four of the buoys in the mid- and lower-Bay (Annapolis Gooses Reef, Point Lookout and Jamestown). The cold, high and sustained winds led to significant events of freezing spray, which accumulated and remained on the buoy superstructures. The iced buoy's righting moments decreased until they were horizontal, and several froze into the surface ice in that position for extended periods of time causing significant damage to the hull and sensors. Several buoys were lifted off station and were subjected to further damage.

The conditions of February 2015 were analyzed and for the first time in CBIBS history the surface water temperature dropped below the calculated seawater freezing point on several of the buoys. Three buoys (Annapolis, Gooses Reef and Point Lookout) had sustained wind gusts above 20 m/s, providing ample water volume to create freezing sea spray with the waves playing a secondary role in the icing events. Jamestown did not experience wind gusts above 20 m/s, thus the wave run up and splash might have generated more water volume for icing than winds. The Jamestown buoy and mooring system was moved about a quarter mile off station, most likely due to ice flows causing significant structural damage.

In order to prevent ice damage in the future, CBIBS will try to better forecast weather events using available products through the NWS and buoy-modified ice predictor formulas, while continuing to closely monitor the real-time conditions at the buoy in comparison with trends seen this past winter. If immediate response is required due to a predicted storm onset, the team will follow a winter emergency response protocol that will ideally allow enough reaction time to recover the buoy and/or the sensors in order to prevent damage.

The buoy stability was modeled in order to better understand the additional load capacity the buoy can withstand before capsizing. Several observations came from these calculations including the increased stability gained by removing the skirt and the importance of monitoring the waterline as an indicator of stability with the addition of a pressure sensor. Further investigation can be done regarding the implications of modeling the buoy stability regarding the influence of waves and once the buoy has taken on water.

In order to minimize water leakage, several Watchkeeper design suggestions were made. Ideally, we would like the buoys to be water proof and agreeable with IP-68 codes versus the current splash proof design. There are several modifications that can be implemented in order to prevent ice accumulation such as reduced surface area where possible and swapping instruments for ones that have alternative ice-preventing models, such as the heated Gill WindSonic.

The Tideland Signal SB60 buoy has been deployed in the past for the three northern buoys over the winter months to hold the mooring in place. The buoy design is ideal for withstanding ice and collisions, but currently does not hold any observational sensors. Modifications to this buoy could be implemented that would allow us to monitor water quality over the winter months. This would expand upon the CBIBS data set while also conserving more expensive buoys from possibly getting damaged over the harsh winter months.

The winter of 2015 was an anomalous year that has motivated us to improve the buoy and observing system design by implementing one or some of these engineering solutions that will help prevent water intrusion, ice damage, and resulting system down time in the future. Further development is required on several modification strategies along with the winter emergency response protocol prior to implementation.

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