Investigating the water movements around a shallow shipwreck in Big Tub Harbour of Lake Huron: implications for managing underwater shipwrecks.

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Abstract

The *Sweepstakes* in Fathom Five National Marine Park, is one of Ontario's more iconic shipwrecks. Continued exposure to water currents has directly and indirectly affected the integrity of the wreck and resulted in management interventions including efforts to stabilize the wreck and control vessel activity. An extensive series of field measurements were made during the peak tourist season in the summer of 2015 with the aim of differentiating between natural hydrological processes present at this site versus human-derived water movements. There is a high-degree of natural current variability from processes as diverse as wind-induced surface gravity waves, internal gravity waves, and diurnal flows due to differential heating. Our results show that circulation driven by internal gravity waves derived from upwelling is insignificant. While vessel induced currents were detectable at the shipwreck, they were no larger than the normal summer variability. There is evidence of scour around the shipwreck which likely comes from large wave events from winter storms. Monthly climatological significant wave heights for Lake Huron suggest that typical winter storms contain far higher wave heights than anything observed in summer 2015 and could be responsible for the sediment scouring around the shipwreck.

KEYWORDS: shallow shipwrecks, scouring, water movements, marine archeology, management

Introduction

Ships have long plied and risked the world's waters, with over 3 million voyages ending in wreck (UNESCO, 2013). Although lost from service, many shipwrecks continue to be recognized and valued for their cultural and historical significance, providing a tangible connection to the marine heritage of an area. In the Laurentian Great Lakes there are over 6,000 shipwrecks (Great Lakes Shipwreck Museum, 2019), with about a 1,000 within ready access of divers and boaters (e.g., Kohl, 2008) and several 100 conserved and presented within protected areas (e.g., NOAA and State of Michigan, 2009; Parker et al., 2017). While conserving a shipwreck in-situ is the preferred management approach (Maarleveld et al., 2013), such a context continues to expose the resource to environmental factors that can contribute to its deterioration (Bethencourt et al., 2018; Gregory et al., 2012; MacLeod and Binnie, 2011). Preservation and maintenance of the structural integrity of submerged cultural resources is affected by a variety of hydro- physical, chemical, and biological factors. Physical factors include waves, currents, temperature, depth as well as human impacts (Wheeler, 2002). Chemical factors include salinity, pH, and dissolved oxygen levels (Wheeler, 2002). Biological factors include bacteria, fungi and various other organisms including Dreissenid mussels (Watzin et al., 2001; Wheeler, 2002). All these factors interact in complex and non-linear ways, and can challenge the effectiveness of conservation efforts, which can be particularly concerning within those areas established and managed to protect such submerged cultural resources.

Fathom Five National Marine Park (FFNMP), Lake Huron, Canada is one such protected area facing this challenge (Fig. 1a). Fathom Five Provincial Park was established in 1971 and slowly transformed the small community of Tobermory (Fig. 1b) from a fishing village into one of Canada's premier recreational diving destinations, as well as tourist destination due to glass bottom tour boats (McClellan, 2001). The park was later transferred along with the local islands of Georgian Bay Islands National Park, and in 1988 FFNMP was formed and Parks Canada became the steward of its first site to be managed under the National Marine Conservation Area program (Canada, 2002; Wilkes, 2001). From the earliest days through today, a long-standing cultural resource management priority for Fathom Five has been the conservation and presentation of the Sweepstakes (Fig.1c-f). The hull of the wooden sailing vessel has rested upright and nearly intact within a few meters of the water surface since 1885 and is perhaps Ontario's most photographed and popular shipwreck, with over 100,000 tour boat visitors and divers/year. With the passage of time, this iconic shipwreck has required various management interventions, including physical stabilization, monitoring and restrictions on vessel activity, in order to maintain it in a safe and desirable state (e.g., Parks Canada, 1991; Parks Canada, 1992).

One notable observation around the Sweepstakes was lakebed scouring, particularly on the portside (see the faint ring, Fig. 1c) and associated concerns for vessel stability. To this end, an investigation by Boyce (1996) was undertaken in 1993-1994 to quantify water and sediment movements in the area. Boyce (1996) suggested four major sources of energy for the Sweepstakes that could be responsible for the scouring: wind-driven currents, gravity flows due to upwelling events, surface wave orbital velocities, and flows induced by the wakes of tour boats or divers. Based on the currents and temperature measurements, he concluded that bottom currents induced by wind driven circulation and differential heating was insignificant to account for erosion at the shipwreck. However, if the tour boats were operated aggressively using full power bursts and thrust, it could produce transient currents capable of eroding bottom sediments around the shipwreck. Further, he concluded that there is a possibility that surf-beats (Wunk, 1949) can produce oscillating current which may be capable of eroding bottom sediments. However, these surf-beats stirred up sediments in small patches rather widespread bottom scouring. This study proved to be exceptionally useful and directly supported Parks Canada's management policies at the time.

Several decades later the context has changed, in particular there has been a notable increase in vessel size (~40% larger) and frequency of use. Although the wreck will eventually collapse (Parks Canada, 1992), the need to differentiate natural versus human derived water movements will influence what options are considered to best conserve and manage the site today. Natural water movements around the Sweepstakes in Big Tub Harbour can be attributed to wind induced surface gravity waves, internal gravity waves, and gravity flows generated by differential heating. Previous studies of the thermal variability in FFNMP have shown that large-scale internal waves on the summer thermocline are ubiquitous and can have greatest temperature variability at depths of 10- 20 m with periods of oscillation between 12 to 24 h (Wells and Parker, 2010). Differential heating in an aquatic system with a sloping bottom can also create temperature (i.e. density) gradients that drive dense gravity currents flowing downslope (Wells and Sherman, 2001). Amplification of surf-beats has also been previously observed in certain embayments of FFNMP (Hlevca, Wells and Parker, 2015) which can lead to currents strong enough to erode sediment and change water quality. The major source of human derived water movements is thought to be the propeller wash from boats that could lead to turbulence and pressure perturbations in the water column. If the wash is strong enough, the water currents could potentially disturb the sediment resulting in re-suspension. Likewise, if the boats produce significant pressure perturbations in the water column, the structure of the shipwrecks could be moved. Additionally, recreational divers swimming near the underwater shipwreck are a possible source of human derived water movements.

In this manuscript, we aim to determine the relative magnitudes of natural and human derived water movements that could influence the structural integrity of the Sweepstakes shipwreck. We will use detailed field measurements acquired in the summer of 2015 the Big Tub Harbour. Specifically, we quantify and differentiate natural versus human derived water movements during the peak summer tourist season at the Sweepstakes and determine if there is any measurable increase in peak water currents. The field observations include water currents, pressure, and temperatures in the vicinity of the Sweepstakes, and video observations for biological activities and tour boat activities. Further we will use winds and wave heights from regional meteorological stations to estimate the wave heights during fall and winter storms, that could generate potentially higher erosion than anything that occurs during summer periods.

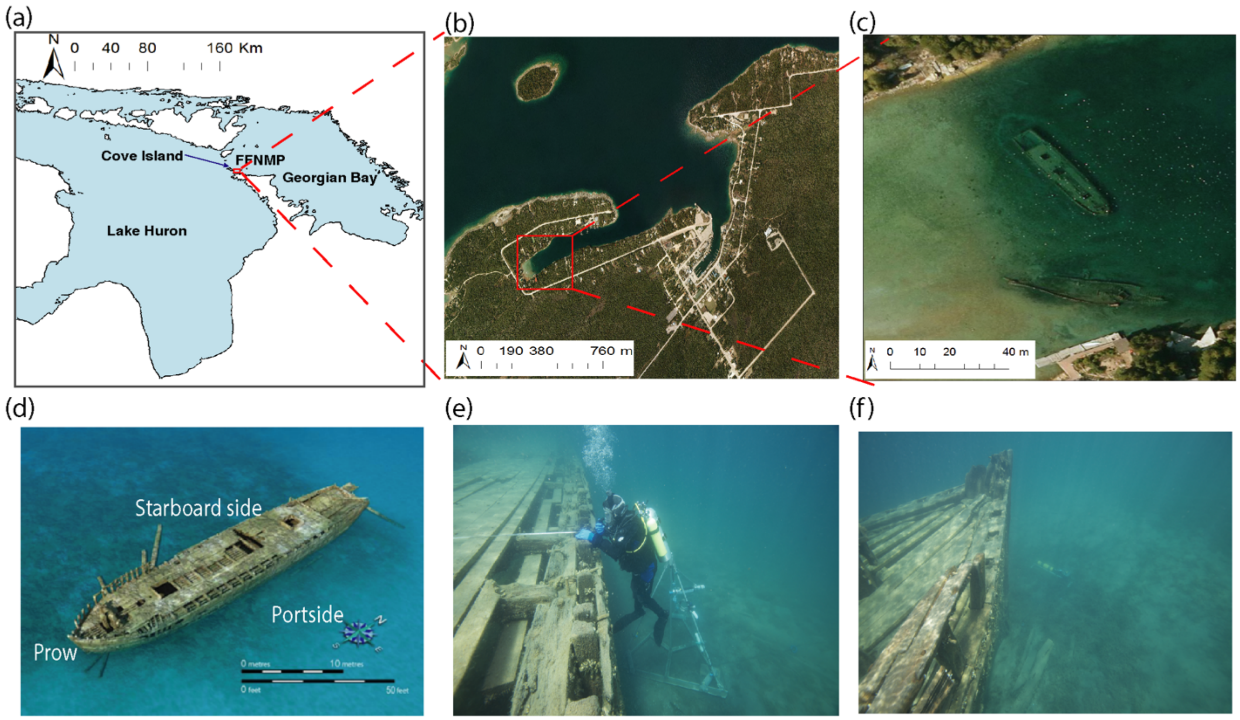

Fig. 1. The geographical location and the views of the Sweepstakes in the Big Tub Harbour of Fathom Five National Marine Park near Tobermory. (a) A map of Lake Huron and Georgian Bay. (b) Location of Big Tub Harbour and Tobermory. (c) Close up of western end of Big Tub Harbour, showing the two shipwrecks, namely, the Sweepstakes (1867-1885) and located to the south, the City of Grand Rapids (1879-1907). A ring of erosion is visible around the Sweepstake where no weed (*Chara sp.)* is growing and sand is exposed. While the Sweepstakes is a fully intact underwater shipwreck, the City of Grand Rapids has only the timbers from the bottom hull. (d) A sketch of the Sweepstakes. The prow faces south while the portside faces east towards Lake Huron. (e) An underwater photograph of portside of the Sweepstakes, with the tripod is visible behind diver. (f) An underwater photograph of the prow of the Sweepstakes, the yellow ADP is visible in background on the bed. Photograph credits: Parks Canada.

Materials and Methods

Study site

Big Tub Harbour (81°40'38.67"W, 45°15'22.21"N) is located within the Fathom National Marine Park on Georgian Bay (area of 15,000 km^2), Lake Huron (area of 44,000 km^2) (Bennett, 1988). It is a sheltered harbour with a rectangular shape, approximately 700 m long and 100 m wide with a mean depth of 12 m (Fig. 2 and 3). Slightly to the east is the small town of Tobermory, located around the commercial port of Little Tub Harbour. The bed of Big Tub Harbour is composed of spatially discrete patches of silt, silty-sand, and sand and the harbour walls are dolomite bedrock. At the head of Big Tub Harbour rest two shipwrecks, The Sweepstakes and the City of Grand Rapids. The Sweepstakes (1867-1885) was a 36 m long two-masted wooden schooner and on the evening of 23 August 1885, she struck a rock off Cove Island (located 3 km to the north) and sank stern first in shallow water. Weeks later she was salvaged and towed to Big

Tub Harbour and eventually laid up and abandoned in approximately 7 m of water where her nearly intact hull remains today (Ringer and Folkes, 1991). Also lying in the sand at the head of the harbour just south of the Sweepstakes is the broken, fire–gutted remains of the Steamer City of Grand Rapids (1879-1907). She caught fire while docked in Little Tub and was towed towards the open lake. Once cut loose she slowly drifted in Big Tub Harbour where she remains (Ringer and Folkes, 1991).

Big Tub Harbour bed sediment and vegetation structure

The lakebed composition was mapped by classifying data from a 2007 multi-beam backscatter survey of the harbour (Fig. 2). The analysis was trained using Ponar grab and video samples of the harbour bed. The classification provides a coarse sediment structure and general distribution of submerged aquatic vegetation. Silty sand dominates near the shipwreck site, which (Boyce, 1996) found to be in the range of 125-200 microns. The major forms of benthic vegetation are *Chara sp.* and *Macrophytes* (e.g. *Myriophyllum, Potamogeton sp.*). *Chara sp.* is visible in the background of photographs in Figs. 1e and f.

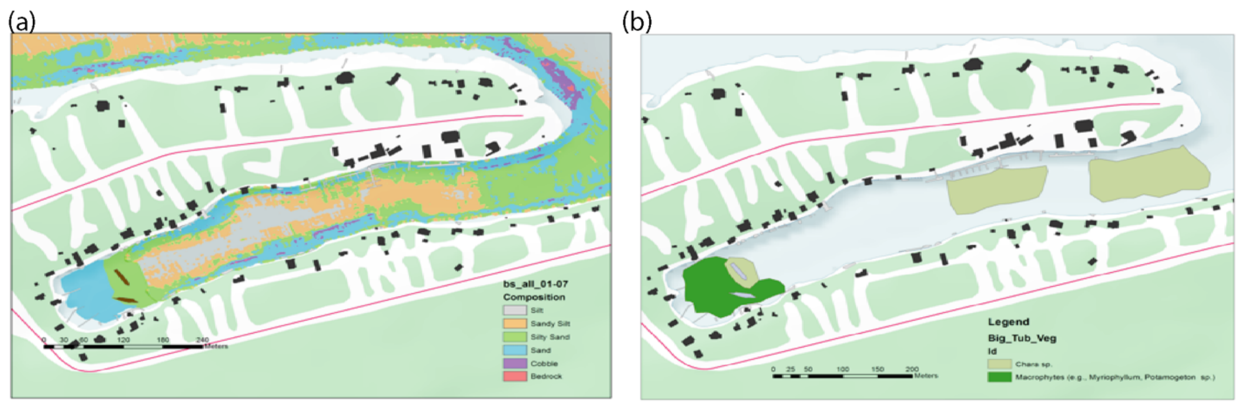

Fig. 2. Composition of bottom (a) sediments (b) aquatic vegetation in Big Tub Harbour. The presence of nearby houses and roads are drawn, along with the two shipwrecks. The classification provides a coarse sediment structure on the harbour bed and general distribution of submerged aquatic vegetation. Around the two shipwrecks at the head of Big Tub Harbour, the bed is dominated by silty sand and *Chara sp.* vegetation. Figures credit: Parks Canada.

Field measurements

The field data collection campaign at the Big Tub Harbour ran from 05 May 2015– 13 October 2015, and was jointly undertaken by Parks Canada, Environment Canada and the University of Toronto. The purpose of the monitoring was to study summer water movements and differentiate natural movements (e.g., gravity currents, waves, and seiches) from the motions forced by the vessels around the Sweepstakes. The locations of the instruments relative to the Sweepstakes wreck are given in Fig. 3 and a summary of instruments used are presented in Table 1.

Table 1: Summery of instruments deployed in Big Tub Harbour.

Position on Map	Instrument Name	Measured property	Sampling interval /Frequency	Depth and other information
1	Float 1	Temperature	5 mins	One logger at 0.5 m above the harbour bed.
2	Float 3	Temperature	5 mins	Two loggers at 0.5, 1 m above the harbour bed.
3	Float 4	Temperature	5 mins	Two loggers at 0.5, 1 m above the harbour bed.
4	Float 5	Temperature	5 mins	Two loggers at 0.5, 1 m above the harbour bed.
5	MOB chain	Temperature	5 mins	13 loggers at 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 m above the harbour bed.
6	HR-ADCP	Currents, pressure	1024 sample per 5 min burst interval	Down looking and 1.5 m above the harbour bed.
7	AWAC	Currents	1024 samples per 20 min burst interval	Upward looking and 6.5 m of from the surface water.
8	ADP	Currents, camera for biological activities	One sample per 2 min burst interval	ADP is Upward looking and 5.5 m of from the surface. The camera is downwards angle away from the wreck and installed 6.5 m of from the surface.
9	Surface Camera	Tour boat visitation times	continuous	On shore

To measure the water column temperature, we used HOBO Tidbit v2, UTBI-001 thermistors. Three arrays (floats 1, 3, and 4) were deployed around the Sweepstakes (locations given as 1, 2 and 3 in Fig. 3) and one array (float 5) was deployed a few meters east from the Sweepstakes (location 4 in Fig. 3). Three arrays (floats 3, 4, and 5) contained two thermistors where one was installed at 0.5 m above the water bed while the other was at 1.0 m above the harbour bed. The remaining array (float 1) only contained a single thermistor such that it is installed 0.5 m above the harbour bed. The loggers were deployed at approximately 08:00 EST, June 12, 2015 and retrieved at approximately 12:00 EST August 26, 2015. Another large array (Marine Operations Base-MOB chain) of thirteen HOBO Tidbit v2, UTBI-001 thermistors was placed near the mouth of the harbour (given as locations 5 in Fig. 3) to record the temporal fluctuations of the harbour's water column temperature. The array was deployed from May 05, 2015 – May 22, 2015. The data record started again, at approximately 12:00 EST, May 23, 2015 and retrieved at approximately 10:30 EST September 17, 2015. The thermistors recorded the water temperature every 5 minutes with a resolution of 0.02 ^{0}C and an accuracy of ± 0.21 ^{0}C.

One acoustic Doppler profiler (SonTek ADP, S/N M945) was installed in 5.5 m water depth approximately 5 m off the prow of the Sweepstakes, pointing upwards (location 8 in Fig. 3, also visible in Figure 1f). The ADP, with 1500 kHz frequency, was programmed to ping as rapidly as possible and record the 30-seconds average current velocity in all three directions in every 2-minutes. This allows the ADP to gain 30-seconds of measuring followed by 90-seconds of inactivity in each 120-seconds. The ADP had a blanking distance of 0.4 m. The ADP recorded the readings for seven 0.5 m bins where it recorded the average currents over half metre intervals from 0.8 m to 4.3 m above harbour bed. The ADP was deployed on June 24, 2015 at around 10:30 EST and retrieved on August 21, 2015 at approximately 16:30 EST. Another acoustic wave and current profiler (Nortek AWAC, 600 kHz) with acoustic surface tracking (AST) was installed approximately 5 m off the starboard side (east) of Sweepstakes (location 7 in Fig. 3). It was placed in an upward facing configuration in approximately 6.5 m of water. In 20-minute intervals, it sampled at 1 Hz for 17.06-minutes (i.e. 1024 samples per burst). The AWAC started recording on June 23, 2015 at 16:00 EST and ran until July 08, 2015 at 23:00 EST. Current velocities were measured in 0.5 m bins. The AWAC has a blanking distance of 0.5 m. The AWAC has an accuracy of 1% of the measured value ± 0.5 cm/s. The AST feature allows for accurate measurements, 0.1% of full scale, of the water surface elevation in order to measure surface waves or wakes. The third high resolution ADCP (Nortek Aquadopp HR) is closely located (location 6 in Fig. 3) on the starboard side of the shipwreck. This is a downward looking ADCP that was mounted on a tripod, which is visible in Figure 1e. The tripod is mounted 1.5 m above the harbour bed and has a blanking distance of 0.10 m. The burst interval is 300-seconds such that instrument samples 1024 per burst. The cell size was 0.03 m and contains 48 cells. The velocity range is 0.19 m/s in the horizontal and 0.08 m/s in the vertical. The instrument was deployed on June 23, 2015 at 12:00 EST and the last measurement was recorded on October 13, 2015 at 11:03 EST.

An underwater camera was installed on the same tripod as the ADP, on the port side (east) of the Sweepstakes in 6.5 m of water (location 8 in Fig. 3). The camera was oriented to look at a downwards angle away from the wreck. Video footage was recorded, with a few gaps, on June 29, 2015 and then fairly continuously from July 3, 2015 until July 14, 2015. Due to poor visibility at night, it was only possible to analyze video taken during the day resulting in a total of about 100 usable hours of underwater footage. A second camera (Plotwatcher Pro, Model TLC-200-C) was placed on shore from June 25, 2015 – July 03, 2015 looking over the Sweepstakes wreck site, in order to make a record of exactly when tour and other boats were present above the shipwrecks (location 9 in Fig. 3). The underwater video camera footage allowed us to capture any sediment re-suspension events and corresponding possible causes happened in the water column. For instance, we captured biological activities such as round gobies (*Neogobius melanostomus*) digging in the sediments causing localized re-suspension that would not be observable in the water temperature and current records.

A pressure logger was mounted on HR-ADCP frame (at 7.0 m from the surface, 45°15.316’N 081° 40.849’W, mounted 0.75 m above the bottom, location 6 in Fig. 3). It continuously sampled at 2 Hz from June 23rd, 2015 at 16:00 EST and ran until September 12, 2015 at 02:50 EST. Hourly mean wind speeds and direction were obtained from Environment Canada’s Tobermory Airport Weather Station (Tobermory RCS, WMO ID 71767). The station is located at 45°14'00.000" N and 81°38'00.000" W. The monthly climatological significant wave heights and winds were extracted from the meteorological buoy located in the southern Georgian Bay (44.945 N, 80.627 W, and Buoy ID C45143). The data runs from May 2007 through November 2017.

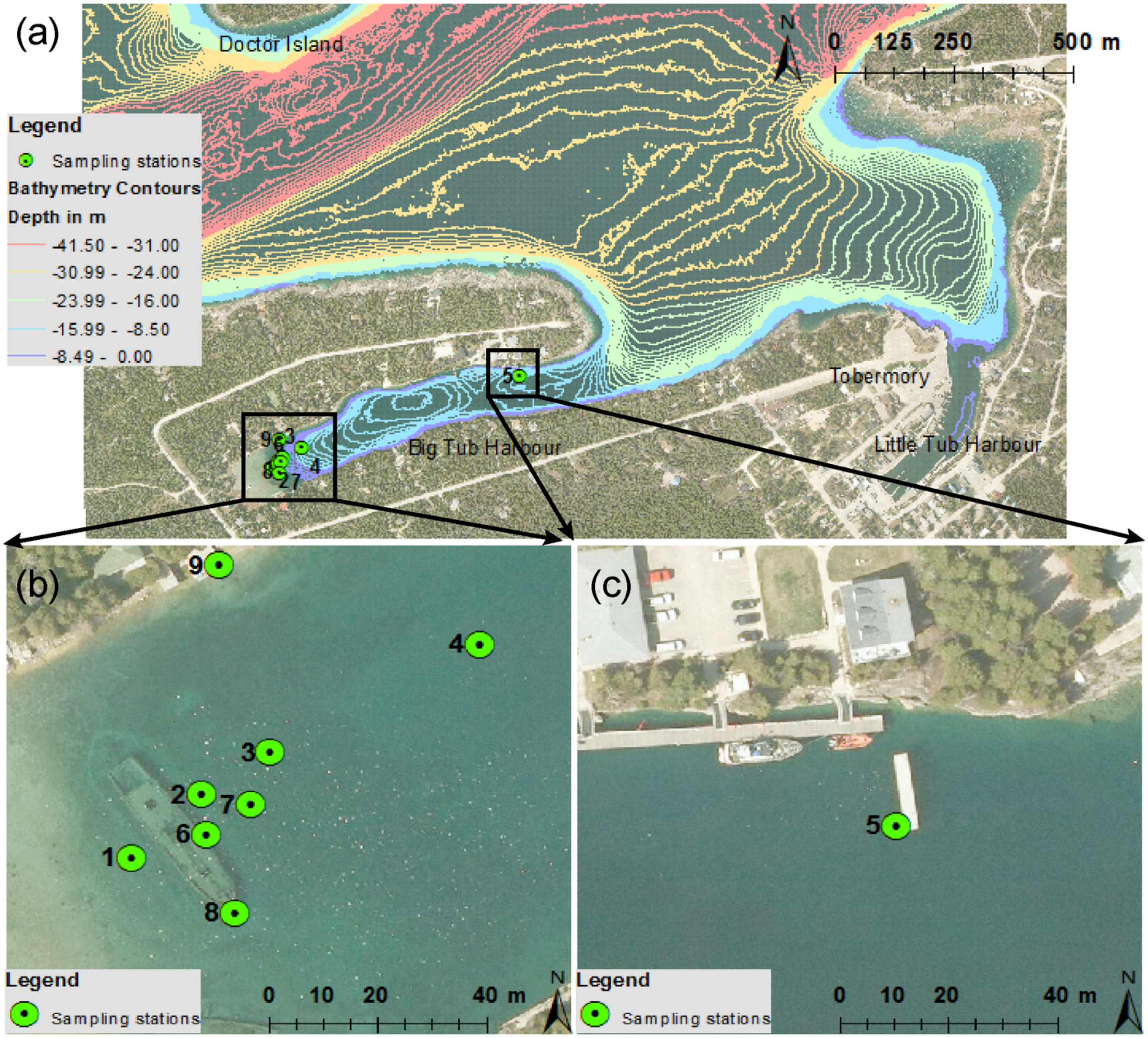

Fig. 3. Bathymetry of Big Tub Harbour and geographical locations of the field instruments relative to the Sweepstakes. The Sweepstakes wreck is visible in (b) with the prow pointing to the south. The numbers correspond to individual instruments as follows: 1: Float 1 (one thermistor), 2: Float 3 (two thermistor loggers), 3: Float 4 (two thermistor loggers), 4: Float 5 (two thermistor loggers), 5: Marine Operations Base (MOB) chain (13 thermistor loggers), 6: HR-ADCP 7: AWAC (also a pressure sensor) 8: ADP and downward looking camera), 9: On shore surface camera.

Data processing

To evaluate the major sources of energy – natural or human derived water movements – that could be responsible for scouring around the Sweepstakes, we use time series plots of temperature and bottom currents. We estimate how much current variability is due to natural physical processes such as wind-induced surface gravity waves, internal gravity waves, and diurnal flows due to differential heating. We extract water currents driven by human interaction as a function of prop-wash induced currents. Then we compare the bottom currents with respect to natural variability and human interactions to identify the major sources of energy responsible for scouring.

We examine the current measurements acquired at the prow and the starboard side of the Sweepstakes to quantify the magnitude of the near-bed currents that could potentially result in scour and erosion. We divide our velocity data processing into few steps. First, we plot the time series of the east-west and north-south velocities of acquired at all acoustic current meters located in the vicinity of the shipwreck to visually identify the bottom currents. The HR-ADCP records data up to 1.5 m from the harbour bed. Hence, for comparison purposes we only consider the currents variability in the depths up to 1.5 m from the harbour bed. If the bottom currents show a barotropic variability such that no vertical velocity gradient, we can average the velocity bins up to 1.5 m from the harbour bed. Then, we use Fast Fourier Transform (FFT) analysis to identify the dominant periods of the bottom currents in the vicinity of the shipwreck. The dominant periods reveal relevant peaks of natural forces. In this analysis, we de-trend the speed data and then, use Welch (1967) algorithm where the power spectrum is estimated by dividing stationary data into segments. The number of segments depend on the length of the time series. Thus, we find the modified periodigram for each segment that expresses the uncorrelated estimates of the spectra. To obtain the average of the modified periodograms, the segments are multiplied by a window function, Hanning window, with a 50% overlapping technique to reduce the variance of the periodogram. To evaluate the currents induced by the propeller wash from the tour boats, we divide data in to two windows; times that the boats were present and the times when the tour boats were absent. Then we plot the histogram of the current speeds with respect to the time windows selected. In order to compare the results, we use probability of speed occurrences which varies between 0 and 1. We hypothesize that if the bottom currents show an increased variability during the boats were present, then the propeller wash induced currents contribute to scouring in the sediment and thus, might compromise the structural integrity of the Sweepstakes.

We compare the temperature time series acquired in the direct vicinity of the Sweepstakes and at the mouth of the harbour to see that there are any intrusive cold gravity flows in the Big Tub Harbour induced by the upwelling of cold waters in Lake Huron. The upwelling events are identified as a drop-in water temperature by 5-8 ^{0}C in the space of few hours. Often, these cold-water upwelling events are driven by strong local winds or by internal gravity waves induced by distant wind events (Wells and Parker, 2010). Thus, we first plot the time series of the temperature measurements acquired by the temperature loggers located in the vicinity of the shipwreck and located near the mouth of the Big Tub Harbour to visualize the spatial and temporal variability of the temperatures at different depths. Then we adapt Continuous Wavelet Transform (CWT) method (Grinsted et al., 2004) to determine the times that upwelling is significant. CWT expands the time series in to time-frequency domain. Next, we use the same spectral analysis described above to understand the dominant periods related to temperature variability. To evaluate the importance of episodic upwelling events on bottom currents driven by internal gravity waves that can scour the bottom sediments around the shipwreck, the time window is split in to the times that upwelling occurs and it was not. Then we compare the histogram of horizontal bottom currents at the times corresponds to upwelling. For the comparison purpose, the frequency in the histogram was normalized. If the bottom currents show a significant increase in variability during the identified upwelling events, one could assume that the circulation is driven by the gravity flows induced by upwelling. In addition, there could be standing surface waves, or seiches in the harbour, similar to those seen at nearby sites in FFNMP that were visually observed to lead to significant water currents (Hlevca, Wells and Parker, 2015).

To account for the discussion of propeller–wash induced forcing, we apply the spectral analysis obtained from the FFT - described above - on the pressure measurements acquired from sensor that was attached to the HR-ADCP. The FFT results will be used to examine the dominant frequency of any seiche induced oscillations.

Estimation of seiche periods in harbour

Big Tub Harbour is a shallow, open-mouth, long, and narrow basin with a rectangular shape and potentially could support standing wave oscillations. The frequency of these waves can be made by assuming the depth of the harbour is approximately a constant and there are vertical walls on the side. Thus, periods of the eigen (natural) modes of the standing oscillations in such an open basin can be described using the classic Merian formula (Rabinovich, 2010).

$$T_n = \frac{4L}{(2n+1)\sqrt{gH}} \tag{1}$$

where, T is the period, n is the modes of the oscillations, g is the gravitational acceleration (~ 9.8 m/s^2), and H is the water depth. The first mode $(n = 0)$ is known as the Helmholtz resonance mode such that, Eq. (1) becomes

$$T_0 = \frac{4L}{\sqrt{gH}} \tag{2}$$

For instance, in the Big Tub Harbour, the length (L) is ~ 690 m and H is 12 m. Thus, the Helmholtz resonance period (T_0) is computed as 4.2-minutes (Eq. 2).

Calculating high frequency pressure perturbations

In order to determine the pressure perturbations generated by the high frequency waves near the Sweepstakes, the measurements have a high pass filter applied at 4-minutes. The high pass filter at 4-minutes removes any variability caused by natural modes of oscillations in the harbour and retain only high frequency events. The high pass filtered amplitude of the pressure perturbation variability caused by the water level fluctuations (such as from high frequency waves) will then be compared with the times that the boats were present and absent. The pressure perturbation is defined as

$$P' = P_{total} - P_{hydrostatic}, \tag{3}$$

where, P' is the pressure perturbation, P_{total} is the high pass filtered total pressure measured by the pressure sensor attached to the HR-ADCP located at the starboard side of the Sweepstakes, $P_{hydrostatic}$ is the hydrostatic pressure $(= \rho g H)$, ρ is the water density (~1000 kg/m^3), g is the gravity (~ 9.8 m/s^2), and H is the total water column depth. As ρ and g are constant over short periods, the pressure perturbation P' is usually reported as an equivalent depth of water in metres. The time-series of high pass filtered amplitude of the pressure perturbation is then compared with the time-series of wind speeds with direction as a proxy for when surface waves would likely have been large.

Data and Results

Our goal of the field campaign was to differentiate between the natural hydrological processes versus human-made water movements present at the vicinity of the Sweepstakes shipwreck site. The analysis identifies natural currents variability from processes such as wind-induced surface gravity waves, internal gravity waves, and diurnal flows due to differential heating. However, there is a detectable variability caused by tour boats. Thus, we will further compare the effect of propeller-wash induced bottom currents with respect to that caused by natural variability.

Thermal structure

Water temperature time series extracted at Floats 1, 3, 4, 5 located near the Sweepstakes and MOB chains located off of the Parks Canada dock (toward the mouth of the harbour) shows the spatial and temporal evolution of the thermal structure in the Big Tub Harbour (Fig. 4). During the deployment period the surface waters in Big Tub Harbour (Fig. 4a) gradually warm from 10 ^{0}C and reaches to a maximum temperature of 20 ^{0}C by the August (~ DOY 213-230). A similar warming was observed in the bottom temperatures in the direct vicinity of the Sweepstakes (Figs 4b-e). For instance, on a sample day- DOY 176 (June 25, 2015), the temperature loggers at 1 m from the harbour bed in the direct vicinity of the Sweepstakes (Floats 1, 3, and 4) show an average temperature of 9.3 °C and rose to 20.7 °C by DOY 233 (August 21, 2015). This corresponds to an average warming trend of ~0.2 °C per day (Figs 4c, d, and e). The mean depth of the summer mixed layer is approximately 8 m. Big Tub Harbour (with a mean depth of 12 m) is shallower than the depths where temperature variability is greatest in the FFNMP i.e. the depth at which the summer thermocline lies. In FFNMP, the maximum temperature variability was observed at 20 m depth (Wells and Parker, 2010).

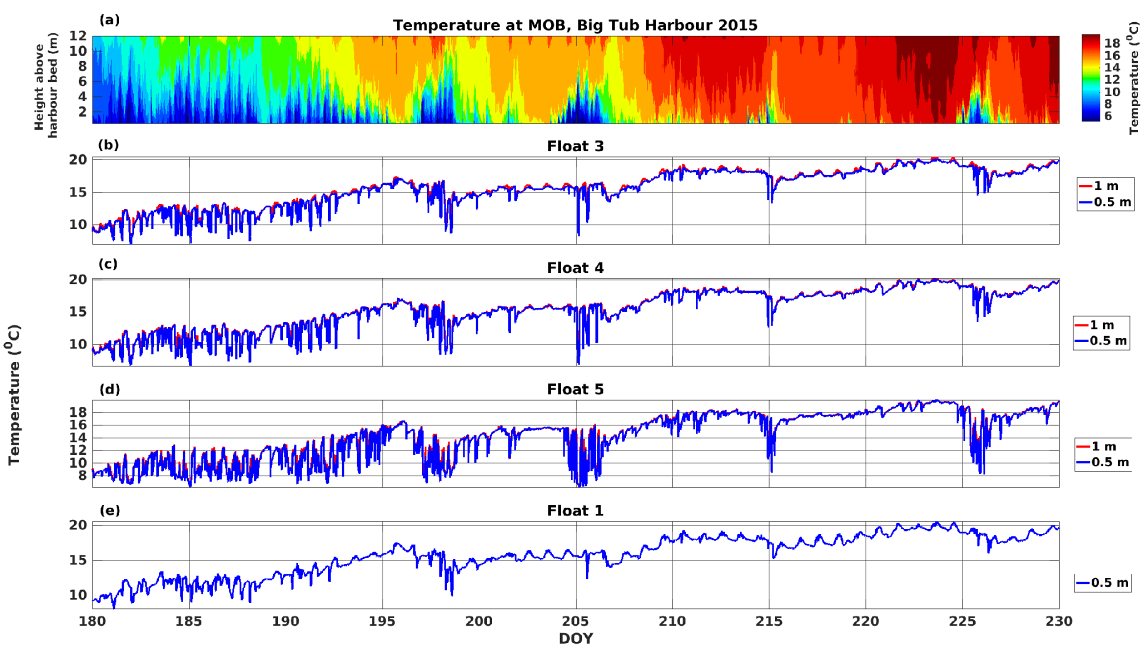

Fig. 4. Water temperature and wind stress time series. (a) Contour plot of water temperature variations with height above the harbour bed and time. Note that the strong upwelling signals in the deeper water, the strong daily warming signal near the surface, and the general warming trend as time progresses. (b) Temperature measurements at Float 3 (closest chain at the east of Sweepstakes). (c) Temperature measurements at Float 4. (d) Temperature measurements at Float 5 (e) Temperature measurements at Float 1. Note that the larger fluctuations in temperature at the lower thermistor (at 0.5 m from the harbour bed) are observed in all floats due to cold water upwelling.

The power spectrum of the temperature measurements at the 0.5 m from the harbour bed acquired at temperature loggers in the vicinity of the shipwreck shows a strong semi-diurnal signal (Fig. 5) which could be a result from gravity flows induced by differential heating. Another distinct mode was identified at 6.15 h and this may be related to the cold-water intrusions at the bottom (upwelling). Further, the above calculated period of 6.15 h is close to the H1 seiche mode (Lake Huron mode 1) documented in Schwab et al. (1977) which is about 6.6 h. Thus, upwelling events in the temperature records may be driven by the free modes of oscillations attributed to Lake Huron seiches.

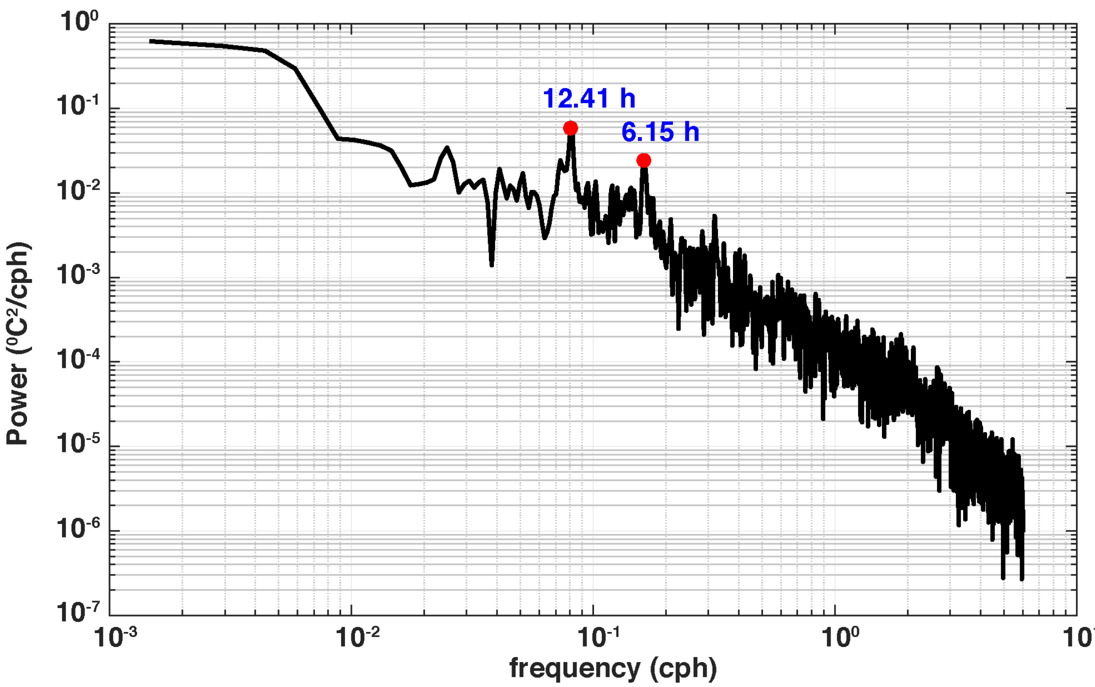

Fig. 5. A sample power spectrum for the de-trended bottom temperature (0.5 m from the harbour bed) acquired at the float 3. The record shows significant periods at 12.41 h (semidiurnal) and at 6.15 h. A similar behaviour is seen in all floats in the vicinity of the Sweepstakes shipwreck.

Based on the Continuous Wavelet Transform (CWT) of the bottom (0.5 m above the harbour bed) temperature records show four distinct upwelling events given on DOYs 226, 215, 205, and 198 (Fig. 6). During these cold - water intrusion events at the bottom, the water temperature quickly drops and rises again by 5-8 ^{0}C over few hours (Fig. 4a). Similarly, the comparison of the temperatures at 0.5 m from the bottom, located near the Sweepstakes, show a strong variability compared to those observed at 1 m depth from the harbour bed (Figs 4b–e) suggesting a frequent upwelling events near the Sweepstakes. These episodic upwelling events, which extend all the way to the end of the harbour, suggest that the waters of Big Tub Harbour are frequently exchanged with waters from Lake Huron (Fig. 4a).

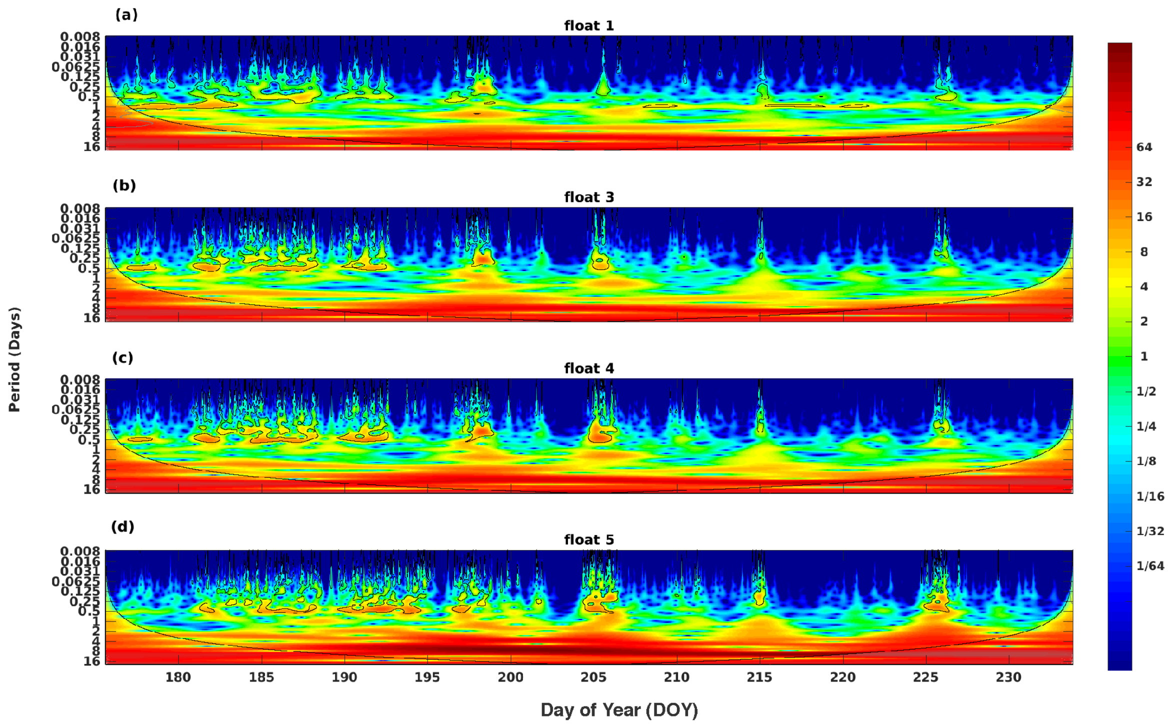

Fig. 6. Continuous Wavelet Transform (CWT) of the temperatures obtained at the bottom thermistor (0.5 m above the harbour bed) from (a) float 1, (b) float 3, (c) float 4, and (d) float 5. CWT expands the time series in to time-frequency space. The record shows four distinct upwelling events on DOYs 226, 215, 205, and 198 on all temperature records.

Effect of upwelling on water circulation

The variability of bottom currents during four distinct upwelling events that was identified in the temperature time series (Fig. 6) are compared with the variability during at times where there is no visible upwelling (Fig. 7). Times except upwelling days are noted as non-upwelling events. The comparison will quantify the strength of the flows driven by the internal gravity waves in the Big Tub Harbour. If the bottom currents show increased variability during upwelling events this could suggests that gravity currents driven by combination of differential heating and internal-seiches in the Lake Huron might contribute to scouring around the shipwreck. However, if the variability or maximum velocities do not change, then the effect of internal gravity waves on the flows is minimal. For the comparison purpose, the distribution is normalized (Fig. 7) to give the probability of speed occurrences. As in Figure 7, the probability distribution suggest that the bottom currents do not show an increased variability during upwelling events to account for the circulation driven by internal gravity waves. Hence, the frequent upwelling events do not contribute to strong currents in the direct vicinity of the shipwreck that could stir the bottom sediments and scouring.

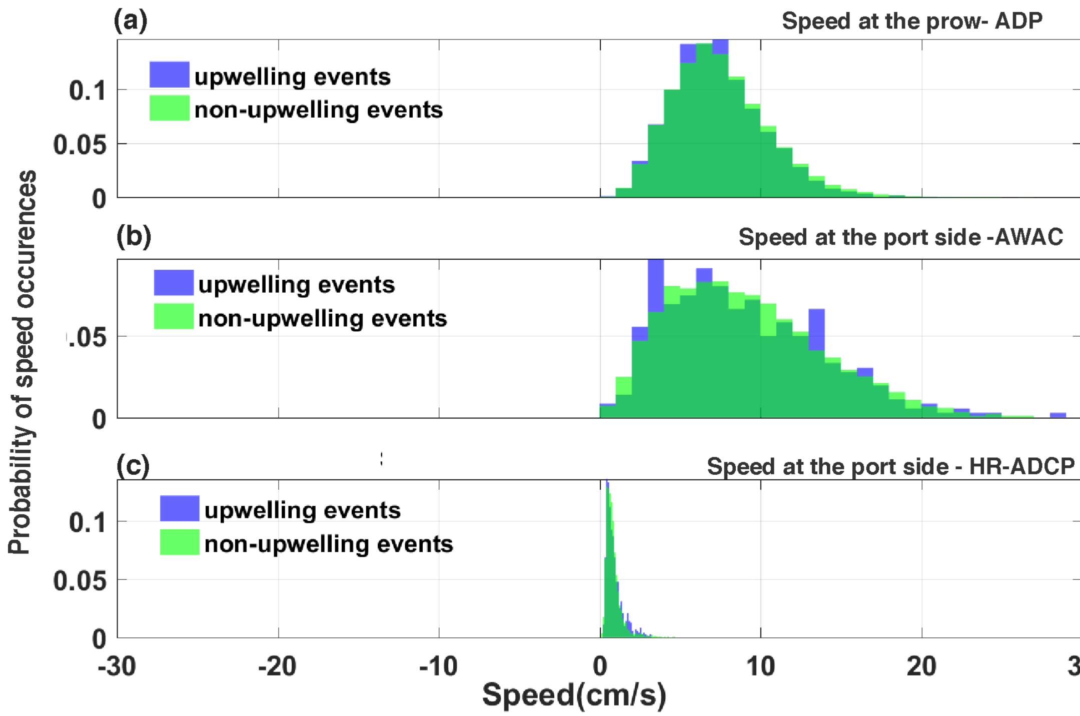

Fig. 7. Histogram analysis of bottom currents with the presence and absence of upwelling events. The y-axis value is the probability of the speed occurrences. The histogram of currents speeds at (a) ADP located at the prow (b) AWAC located at the portside of the shipwreck, and (c) HR-ADCP located at the portside of the shipwreck. While blue color denotes the bottom speeds during upwelling events the green color represents the speeds of the bottom water currents during non-upwelling times. The upwelling events are observed in DOYs 226, 215, 205, and 197 (See Figs. 4 and 6 for visualization of upwelling events).

Bottom currents in the vicinity of the shipwreck

In order to understand the variability in water movements, we have compare the current speed data at the prow measured by the ADP (location 8 in Fig. 3), and on the starboard side of the shipwreck measured by two different ADCPs, namely, AWAC (location 7 in Fig. 3) and HR-ADCP (location 6 in Fig. 3). The HR-ADCP is the closest to the starboard side of the shipwreck while AWAC is few meters away (towards the Open Harbour) from HR-ADCP (Fig. 3). The velocity time series shows an oscillatory motion at 1.5 m from the harbour bed (Fig. 8). The oscillatory motion can be defined as a barotropic flow such that there is no vertical velocity gradient in the water column. The FFT analysis shows significant peaks at 23.75 h (~diurnal), and at 12.0 h (~semi-diurnal) for the mean bottom current speeds (i.e. 1.5 m from the harbour bed). Because of the barotropic motion, we averaged the bins within 1.5 m from the bottom of harbor (Fig. 9). The currents at 1.5 m from the harbour bottom but at the prow of the shipwreck extracted from ADP show a mean speed of ~7.5 cm/s, minimum of ~0.2 cm/s, a maximum of ~33 cm/s, and a range of ~33 cm/s (Fig. 9b). The speed calculated from velocity measurements acquired from AWAC shows a mean speed of ~9 cm/s (Fig. 9c). The minimum, maximum, and the range are ~0.1 cm/s, ~31 cm/s, and ~31 cm/s, respectively. The currents measured by HR ADCP show a mean speed of less than 1 cm/s but show some very brief periods (10 s) of high speeds (Fig. 9d).

The maximum and the minimum speeds recorded during the observation period are ~0.2 cm/s and ~5 cm/s, respectively. The observed speed range measured by the HR-ADCP is ~4.5 cm/s. It is clear that the flow speed is order of magnitude larger at the prow (Fig. 9b) compared to the starboard side of the shipwreck (Fig. 9c).

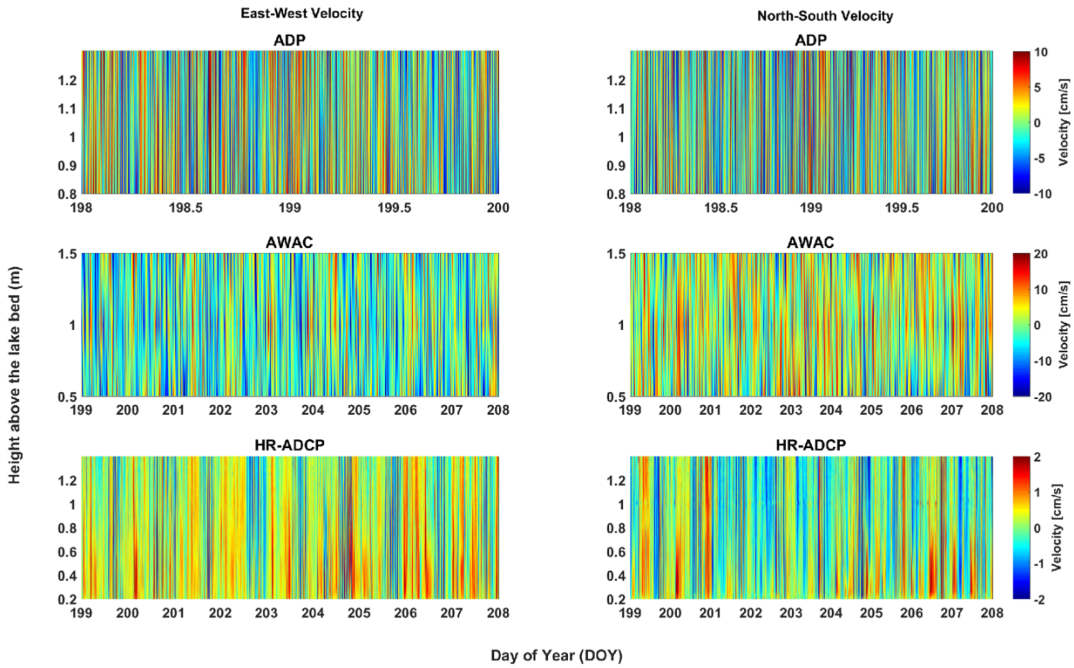

Fig. 8. The east-west and north-south velocities up to 1.5m from the bottom (harbour bed). (a) The east-west velocities extracted by ADP which is located at the prow, (b) The north-south velocities extracted by ADP (c) The east-west velocities extracted by AWAC on the side, and (d) The north-south velocities extracted by AWAC (e) The east-west velocities extracted by HR – ADCP located closest to the side of the shipwreck. (f) The north-south velocities extracted by HR – ADCP. The oscillatory motion in velocity distribution shows a barotropic flow (almost no vertical velocity gradients) in the bottom water column.

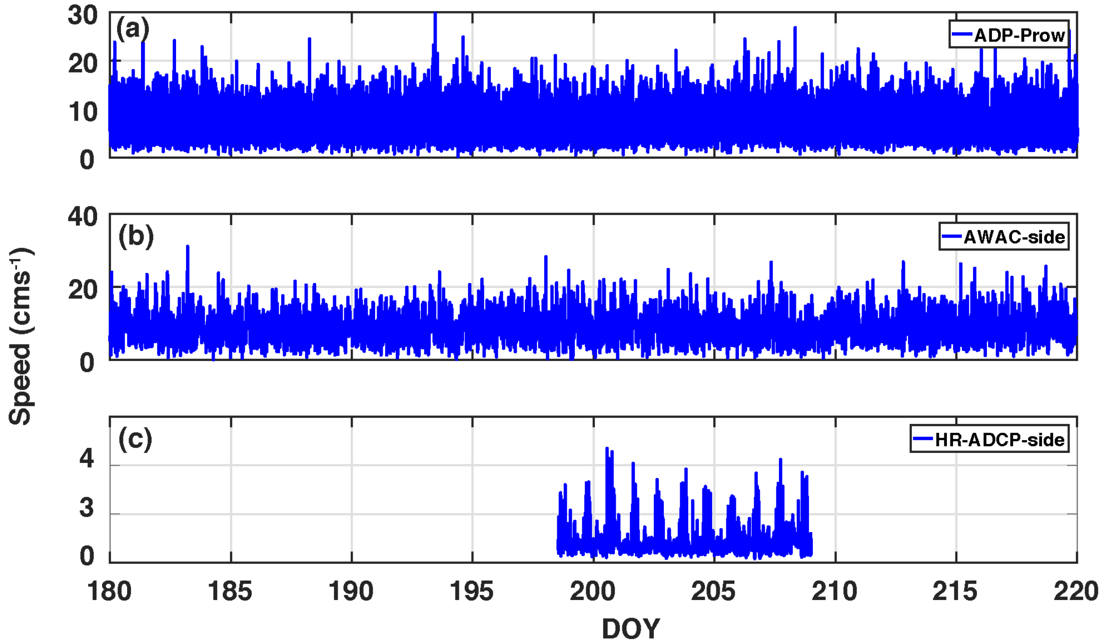

Fig. 9. The depth averaged velocities up to 1.5m from the bottom. The currents are measured by (a) ADP which is located at the prow, (b) AWAC on the side, and (c) HR – ADCP located closest to the side of the shipwreck (note the different scale on y-axis). The mean speed nearest to the shipwreck but located on the side ~1 cm/s while, at the prow is ~8 cm/s. However, the measured mean speed at AWAC location is ~10 cm/s.

Effect of tour boat propeller wash on water currents

The effect of tour boat propeller wash on water currents was evaluated by comparing the bottom water currents in the immediate vicinity of Sweepstakes when boats were present and when they were not (as based on video footage). We hypothesize that if the bottom water currents that are significantly faster, or if there is significantly more turbulence in the water column when boats are present then there should be a correlation between boat activity and water velocity around the shipwreck. If, however, there is no statistical difference in water current and turbulence properties between times when boats are and are not present, it would imply that the tour boats do not significantly disturb the water more than natural variability does. Aided by onshore cameras and commercial tour boat schedules, the water current profile time series was split into two parts: times when commercial tour boats are present above and in the vicinity of the Sweepstakes, and when they are absent. Additionally, the data set when boats were not present was truncated to only cover the days for which boat presence data was available which is 9:00 EST to 16:00 EST from June 16, 2015 to September 03, 2015. The histogram of the velocities when boats were present and absent show an insignificant variability in the flow during the times that tour boats were present compared to those observed during the times when tour boats were absent (Fig. 10).

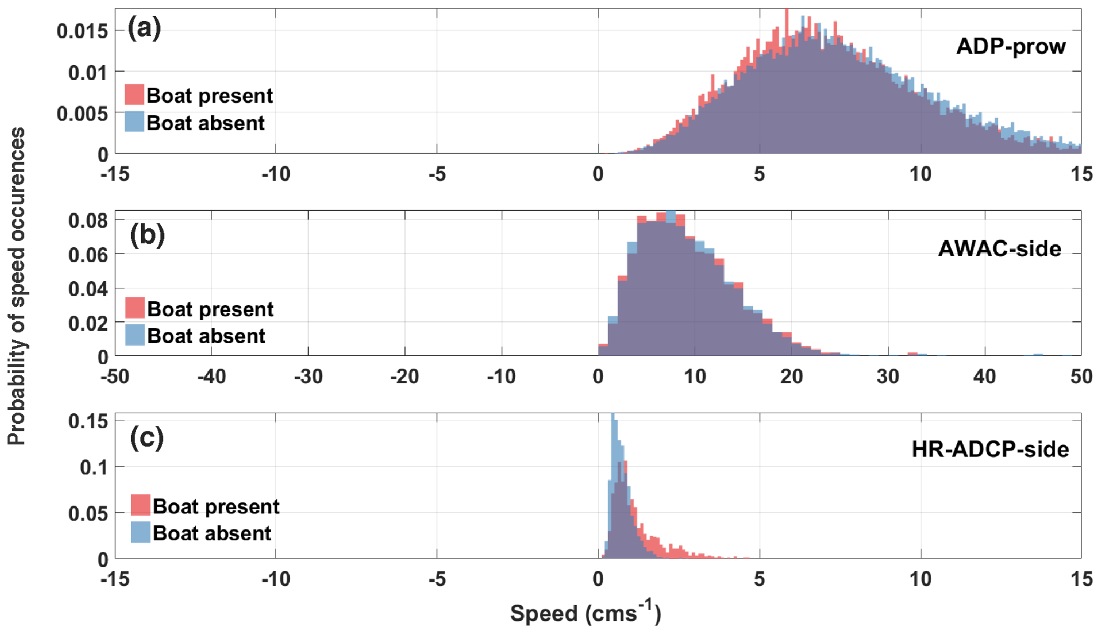

Fig. 10. Histogram analysis of currents with the presence and absence of boats. Normalized frequency on the y-axis is the probability of occurrences which varies between 0-1. (a) The locations of the current measurements. The histogram of currents speeds at (b) ADP located at the prow (c) AWAC located at the side of the shipwreck, and (d) HR-ADCP located at the side of the shipwreck. The blue color denotes the velocities at the times that the tour boats were not present while red color represents the water currents at the times that the boats were present. The tour boats were allowed from 9:00 EST to 16:00 EST from 16th of June 2015 to 03rd of September 2015.

Effect of tour boats on water pressure

A pressure sensor attached to the bottom-mounted, HR-ADCP is programmed to record high frequency water pressure and water surface elevation. The spectrum analysis of the pressure perturbation, given in Eq. (3), near the Sweepstakes shows a distinct 4.2-minute period (Fig. 11) which corresponds well to the harbour's resonant frequency (Eq. 2).

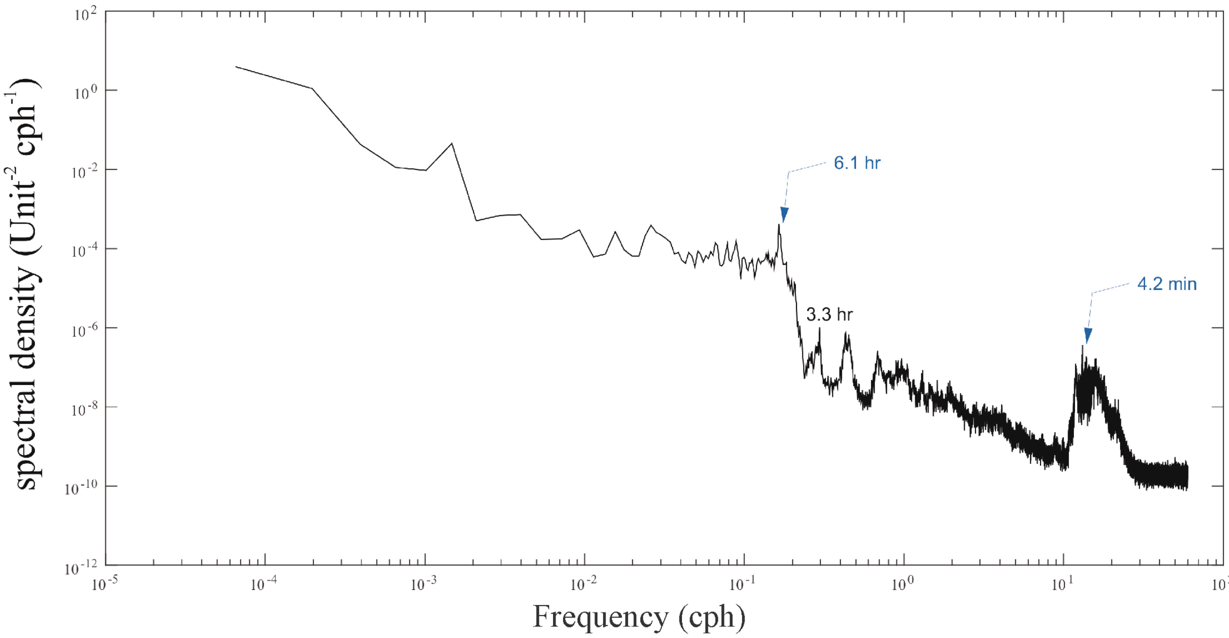

Fig. 11. Spectral density diagram for water pressure perturbations. Note that the 4.2-minute period corresponds to the resonant frequency of the harbour.

The maximum amplitude of pressure perturbation near the Sweepstakes were generally greatest during the day often followed by relatively inactive periods during the night. These maxima in pressure fluctuations generally correspond with both peaks in the wind speed data (Fig. 12a), and the presence of tour boats (green bands in Fig. 12b). Although the maxima of pressure fluctuations show a good correlation with the time that tour boats were present, the magnitude of fluctuations are in the order of ~5 mm -10 mm. For context this magnitude of pressure perturbations is comparable to a wave with a height of 5 mm -10 mm. Hence, we can assume that those high frequency pressure perturbations that may be caused by the waves generated by the tour boats are small and do not reach to the bottom to stir the sediments around Sweepstakes.

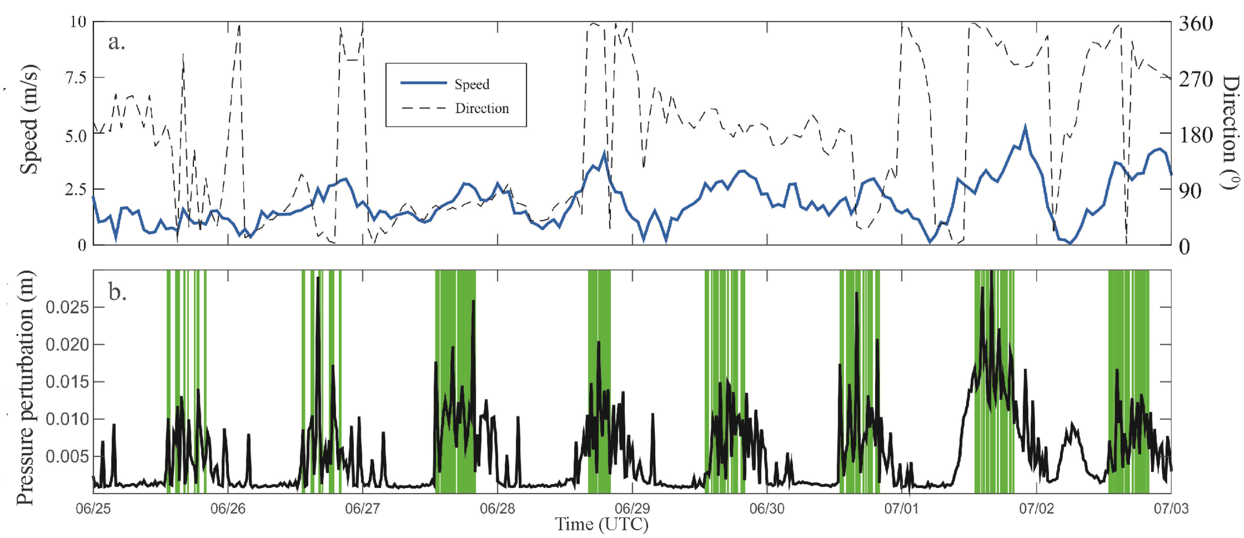

Fig. 12. Comparison of the amplitude of pressure perturbations with wind. Of 2015 (June 25 to July 03) time series of (a) wind velocity and direction (in azimuthal direction, 0 is north) at Tobermory Airport Weather Station Hourly Data. (b) Maximum of observed pressure perturbations (obtained using high pass filtered at 4 minutes). In panel (b), the green background areas indicate the presence of boats (based on the camera recorded data).

Video observations of Biological activities around the shipwreck

A careful analysis of the 100+ hours underwater video camera footage revealed that there were no significant sediment resuspension events during the field experiment (See highlights at https://youtu.be/3i0ORJ_EUS4). A byproduct of watching the video was that the fish activity was typically seen to greatest in the evening hours (after approximately 17:00 EST) and was fairly consistently less in the morning and afternoon hours. Further, round gobies were by far the most numerous fish species present, being almost ubiquitous. Round gobies are known to eat native benthic fishes such as sculpins and darters (Parks Canada, 2010) such that they can cause some bioturbation and sediment resuspension. An average of 10.1 and 14.5 goby fish were observed (in the camera window) per second when tour boats are permitted and not permitted, respectively. One possible explanation for this could be that fish activity naturally increases in the evenings, which coincides with times when boats are not present. Other species were also seen, to a lesser degree, including lake and rainbow trout, freshwater drum, common carp, shiner, brook stickleback and a couple of cormorants (birds).

Discussion

For over 130 years the hull of the Sweepstakes has rested upright, nearly intact at the head of Big Tub Harbour. As the wood decomposes and metal corrodes, the vulnerability of the wreck to collapse and further deterioration only increases with time. Understanding the nature and source of the forces that could potentially impact the integrity of the site helps to inform and guide possible management actions. Hence, we studied to differentiate the summer and fall water movements around the Sweepstakes to quantify the effect of natural and human derived water movements using spatial and temporal observations of temperatures and currents. The underwater shipwrecks increase flow velocity and the turbulent intensity such that, resulting scouring can ultimately lead to failure and collapse of the structure (Quinn, 2006). Boyce (1996) proposed that the scouring around the Sweepstakes can be attributed to one or combination of wind-driven currents, gravity flows due to upwelling events, surface wave orbital velocities, and flows induced by the wakes of tour boats or skin divers. Hence, to rule out the possible forcing that may cause scouring in Sweepstakes, we studied the individual forcing using high frequency temperature and currents observed at the immediate vicinity of the shipwreck and at the mouth of the Big Tub Harbour.

Our field temperature observations show that gradual warming in the water column reaching to maximum of 20 ^{0}C in the water column. This is persistent throughout the water column and found everywhere in the Big Tub Harbour. Due to wind setup in Lake Huron and Georgian Bay, internal waves can form at the thermocline and propagate through the lake. When the amplitude of these internal waves is large enough, they can propagate into Big Tub Harbour. The resulting internal waves are identified as episodic upwelling events in the temperature records (Fig. 4). As the internal wave runs up the harbour bed shoaling and wave breaking could occur, imparting energy and turbulence into the system which could assist in re-suspension of bottom sediment (Cossu and Wells, 2013; Chowdhury, Wells and Howell, 2016). These upwelling events can clearly be seen in the temperature data sets for all the thermistors located in Big Tub Harbour (Figs 4 and 6). However, the comparison of bottom currents during episodic upwelling events (Fig. 7) and when it was not showed a similar variability suggesting insignificant internal gravity flows induced by the cold-water intrusions.

Field observations of currents show a barotropic motion at the bottom (1.5 m from the harbor bed) with the significant peaks at diurnal and semidiurnal periods. Thus, to study the currents variability at the bottom near Sweepstakes, we use depth averaged speeds. The analysis of depth averaged bottom currents shows that the mean speeds of 10 cm/s at the prow of the shipwreck while less than 1 cm/s speeds at the starboard side of the shipwreck (Fig. 9). The increase in flow velocity at the prow is due to the conservation of mass as flow of water goes in and out of the harbour (Quinn, 2006). Similarly, the much lower velocities at the side of the boat could represent a stagnation point of water trying to go around the boat. Analysis of bottom currents that might be potentially induced by propeller wash (Fig. 10) showed there was similar variability for when boats were present to when they were absent. This suggests that the propeller wash induced currents do not lead account for the increased intensity of turbulence and scouring around the shipwreck. However, Boyce (1996) suggested that if the boats used full power bursts and thrust, they can produce transient currents where, it will induce turbulence in the water column. Hence, the turbulence caused by transient currents increases the possibility of erosion in the bottom sediments around the shipwreck. Scouring associated with these transient currents (usually generate within few seconds) are localized and cannot contribute to widespread scouring observed in the vicinity of the Sweepstakes (Boyce, 1996). Based on our real-time observations, none of the boats were operated at such a maximum thrust. In order to account for the high frequency oscillations caused by the tour boasts, the natural modes of oscillations were removed from the pressure perturbations (reader may refer to the Fig. 8). The power spectrum showed that the resonant frequency (Helmholtz frequency) of the Big Tub Harbour is 4.2-minutes. Thus, we applied a high pass filter at 4-minutes only to account for the short-term fluctuations caused by the tour boats. The presence of boats and the wind showed a good correlation with the variability in the amplitudes of the high-pass filtered pressure perturbations (reader may refer to the Fig. 10). However, mean amplitude is in the order of 5 mm such that the transient currents are small to account for the erosion of bottom sediments.

As water flows over the bottom, it exerts a stress on the bottom sediments. This phenomenon results in transport of material as suspended load modes or as bedload transport (Signell and Butman, 1991). However, suspended transport caused by fine sediment particles is much faster and farther compared to bedload transport by the coarse sediment materials. The shear stress (τ) can be calculated as $\tau = \rho_w c_h u^2$, where, ρ_w is the density of water, c_h is the drag coefficient, u is the measured bottom currents. The fined grain silty sand in the vicinity of the Sweepstakes (See Fig. 2) is in the range of 125-200 micron (0.12 - 0.2 mm) (Boyce, 1996). Butman (1987) suggests that for resuspension of find sand (~0.125 mm) needs a near bed bottom current (u) is ~80 cm/s. For medium sand (~0.25 mm), the near bed bottom current (u) is ~200 cm/s. With respect to our observations, we see that the maximum currents occur at 30 cm/s, while maintaining the mean currents at 10 cm/s. Therefore, sediment resuspension due to bottom currents observed during deployment is insignificant, as observed in the underwater video record. Although there were essentially no waves during our deployment in the Big Tub Harbour, it is well known that there are significant waves due to winter storms in Lake Huron (Scott Parker, personal communication). These increased wave heights in fall and winter are seen in the monthly wave climatology extracted from hourly characteristic significant wave heights observed at the buoy located in the southern Georgian Bay (44.945 N, 80.627 W, Buoy ID: C45143). This data shows an increase in significant wave heights with respect to the climatological winds (Fig. 13). Signell and Butman (1991) suggested that if there are significant waves due to storm events, the stress at the bottom is increased by the unsteady wave currents. Therefore, fall and winter storms are likely the main cause for scouring observed near the Sweepstakes.

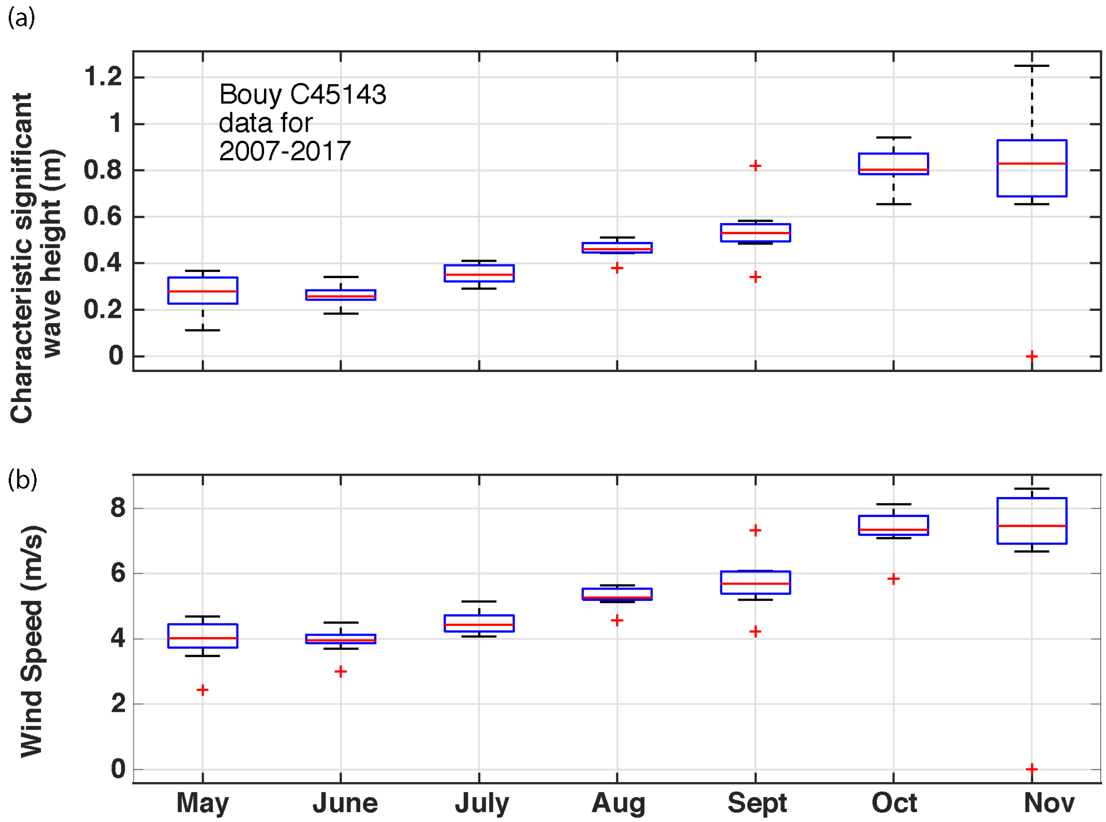

Fig. 13. Monthly climatological (a) characteristics significant wave heights and (b) winds. The data was observed at the meteorological buoy located in the southern Georgian Bay (44.945 N, 80.627 W, and Buoy ID: C45143). The data runs from 2007 May through 2017 November.

Conclusion

Quantifying and differentiating natural and human derived water movements around the wreck of the Sweepstakes is important for informing and guiding management actions. Naturally there would be some different options for managing human derived forces such as tour boat activity at the site. However, as observed, there does not appear to be a difference in water currents between when tour boats are present or absent. New and high frequency observations used in this study greatly supports the conclusions made in the previous study by Boyce (1996). Field observations suggest that the circulation induced by internal gravity waves derived from upwelling is insignificant. The analysis of normalized frequency histogram on bottom current variability during presence of tour boats and when it was not show insignificant effect of propeller wash induced bottom current to cause scouring in the vicinity of the Sweepstakes. Although there is a significant pressure perturbation generated by the tour boats, we see that insignificant current near the harbour bed. On the other hand, observed monthly climatological winds and significant wave heights in the Georgian Bay suggest that increased winter storm activities. The resulting significant wave heights are few orders of magnitude larger than the wave amplitudes derived from high frequency oscillations. These large winter storms can produce energy from order of magnitude large amplitude waves such that scouring is possible. While a study such as this, provides an opportunity to understand some of the forces at play, it is also helps to inform future management discussions and actions. What actions are tenable, possible and desirable in the long-term has yet to be confirmed for this valued submerged cultural resource.

Acknowledgement

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