

**Sediment–Laden Ice Measurements and Observations, and Implications
for Potential Interactions of Ice and Large Woody Debris with
Tidal Turbines in Minas Passage**

Final Report submitted to the OEER/OETR

by

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The Ice Phenomena of the Bay of Fundy

Within an hour or so of the flood tide the estuary is seen to be full of masses of floating ice, mud-stained and some times, but not often, loaded with earth, stones, or pieces of marsh.

Henry Y. Hind, 1875.

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1 Synopsis

1. Floating ice cakes are commonly observed in February and March. Infrequently surface ice-jams form in Minas Passage, where bathymetry causes convergence as floating material is advected into the channel on the outgoing tide. Floating ice imposes a recognized constraint upon the deployment and maintenance of turbines in the tidal stream.
2. Ice cakes are produced in Minas Basin at locations that are relatively shallow, subject to snow accumulation, and have low salinity due to catchment discharge.
3. Large sediment-laden ice cakes were sectioned and samples cut from layers, top to bottom. Density and porosity were measured. Porosity of samples was highly variable but tended to increase going from the base of the ice cake to its top. Most samples were buoyant. Negatively buoyant samples were sometimes found at the base of the ice cake when frozen sediment (or gravel) had become attached.
4. Frozen sediment samples had densities of about 1600-1800 kg/m³. Sediment has a soft red surface-layer that is easy to suspend. The dark sediment beneath is much more stable to mechanical disturbance.
5. Often, ice cakes are greatly discoloured by sediment loading and yet they were observed to remain very buoyant. Furthermore, all portions of these ice cakes were both greatly discoloured and were very buoyant.
6. Sediment stained ice cakes are not a concern for the operations of subsurface turbines deployed in Minas Passage.
7. Sediment staining reduces the albedo of ice cakes and has been observed to promote melting of stranded ice cakes, even when the air temperature is below freezing.
8. Limited observations (of floating ice) indicate that sediment is washed out of stained ice cakes when they are eroded by melting.
9. Ice cakes can freeze to bottom substrate (sediment, gravel, or rock) when the receding tide leaves them stranded for sufficient time in freezing weather. Such ice cakes will:
 - (a) Remain anchored to the bottom when the tide rises, in which case they are of no concern for the operations of subsurface turbines deployed in Minas Passage.

(b) Become detached from the bottom substrate as they are lifted by buoyancy forces on the rising tide. Again, this does not cause them to be of any concern for the operations of subsurface turbines deployed in Minas Passage.

(c) Incorporate a layer (or portion) of frozen bottom sediment as buoyancy forces tear it from the bottom. This creates an ice cake with overall positive buoyancy but consisting of large portions that are negatively buoyant — quite different from staining. Samples cut from such ice cakes were observed to have higher porosity in the top layers. Samples more dense than seawater were usually only found near the base of the ice cake. Such ice cakes may:

- i. Melt or fracture so as to drop the dense material. Observations of rafted material are consistent with this happening. The rafted material was too dense to suspend into the water column.
- ii. Melt or fracture so as to become near neutral buoyancy. By calculating the balance of drag and buoyancy forces we infer that ice cakes can have a range of densities (around neutral buoyancy) consistent with it being entrained into the water column by turbulent flow. The density range (Table 10) decreases as the size of the ice cake increases. Thus the probability of a large ice cake impacting a subsurface turbine is low. We did not observe any ice cakes that might pose a danger to subsurface turbines. Most were far too buoyant to be a danger. One mudflat stranded ice cake was too dense to become suspended into the water column, and barely moved in a strong tidal current. To the best of our knowledge, there has never been a reliable observation of large subsurface ice cakes drifting in Minas Basin or Minas Passage. Such ice cakes are uncommon because their production requires that they are composed of just the right ratio of constituent parts, one part (sediment-stained ice) being far too buoyant, the other part (frozen sediment torn from the bottom) being far too dense.

10. Water-soaked logs and other wood debris has been suggested as a potential danger to subsurface turbines in Minas Passage. The abundance of waterlogged wood debris is not expected to be exceptional because:

(a) Much of the coastal area within Minas Basin has been stripped of trees due to farming

and other human activity.

- (b) Softwood tree species are common and most can be expected to be strongly buoyant. Surface floating drifters have been tracked and they tend to be either stranded nearshore or quickly washed through the Minas Passage and beyond. It is unlikely that a drifting log would remain within the critical area for the relatively long period required for it to become waterlogged.

11. The danger posed, to a subsurface turbine, by large subsurface objects (water-soaked wood debris or sediment-laden ice) will scale as the cube of current speed. The power that a subsurface turbine can generate will also scale as the cube of current speed. Thus, **the risk of damage scales in proportion to the potential for power production.**

12. We advise that:

- (a) Subsurface ice cakes and water-soaked wood debris may still pose a risk to any subsurface turbines being tested in Minas Passage.
 - i. Nonetheless, there are many other ways in which turbines might fail during trial deployments. It would be excessive to forestall turbine deployment on account of the low risk of collision with subsurface ice or wood debris.
 - ii. It would be expensive and difficult to monitor cross-sections of Minas Passage in order to reliably detect and identify subsurface ice cakes and wood debris in a sufficiently comprehensive manner so as to derive the probability of collisions with a subsurface turbine.
 - iii. It would be practicable and desirable to mount monitoring equipment to the turbine and/or its support structure in order to:
 - A. Measure current flow near the turbine.
 - B. Detect and identify objects moving near the turbine. We suggest use of both acoustic and photographic/video technologies.
 - C. Detect vibrations of the turbine and its support structure that might be associated with collisions (or machine-current interaction, or machine performance).
 - D. Once cable technologies are in place, such data may be transmitted to shore for near real-time monitoring and analysis.

Turbine engineers and environmental scientists should be free to jointly and individually study all measurements. Risks can be identified and quantified, machines improved, and operating procedures developed to mitigate risks of collisions.

- (b) The entrainment of slightly buoyant objects into the water column at the turbine test area should be measured. This is a low-cost activity.
- (c) The strength of samples cut from ice cakes should be measured and compared to measurements of porosity and density. This is a low-cost activity. Strength of the ice is fundamental to understanding damage that may result from collisions.
- (d) The lower portion of the intertidal zone (in Minas Basin) be surveyed at low tide. This is where one is most likely to be able to unambiguously observe ice cakes and wood debris that have near-neutral buoyancy. This is a low-cost activity.
- (e) Near-shore areas in the Minas Passage region, where wood debris are commonly observed to be washed ashore, should be surveyed and densities of wood samples measured. Determine how many logs move onto and off the shore over a period of time. This is a low-cost activity.

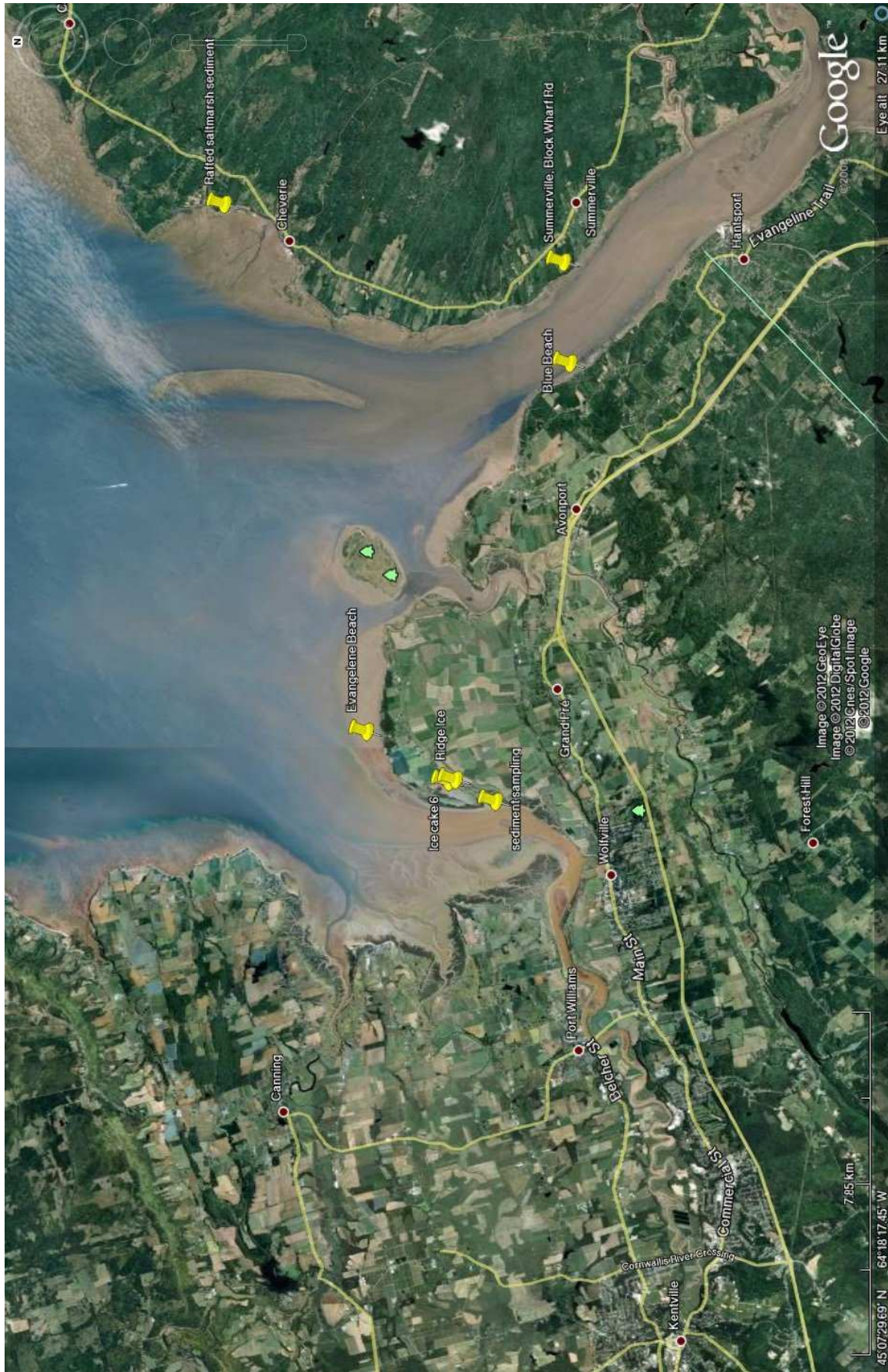


Figure 1: Locations referred to in this study.

2 Introduction

The Minas Passage and Minas Basin are sometimes subject to surface ice in winter (Sanders and Baddour 2006,2007) so in-stream tidal turbines and their support structures must either be engineered to withstand surface ice flows or submerged beneath those ice flows. Sanders et al (2008) flag other possible dangers associated with sub-surface sediment-laden ice, waterlogged wood and large marine vertebrates. The distributions and abundances of sub-surface ice and water-soaked wood have not been assessed in either Minas Basin or Minas Passage. Large marine vertebrates are sometimes seen in the area but they are capable of detecting and evading obstructions, abilities which place them in an entirely different category from sub-surface ice and wood. Tollit et al (2011) address the detection of marine mammals in the Minas Passage.

In the following work, we use the more general term ‘water-soaked wood’ rather than ‘waterlogged trees’. Other researchers may prefer ‘ice block’ or some other term rather than ‘ice cake’ and we do not disagree. Presently we use ‘ice cake’ in order to conform with Sanders et al (2008).

The following are anecdotes about submerged ice in the Bay of Fundy.

- Mark Taylor, fisherman, reports ‘*catching*’ ice in a scallop dredge during early spring in the Minas Passage (Sanders et al 2008). No observation was reported whether this ice floated or sank upon being emptied from the scallop dredge.
- Professor Graham Daborn (Acadia University) retrieved a small (10 cm long) piece of ice from a plankton net that was dragged through a portion of the water column beneath the Port Williams Bridge (Personal Communication).
- Ice cakes on mud flats become frozen to the frozen bottom-sediment when the tide is out. After the tide rises, buoyancy forces sometimes break ice free from the bottom. In such circumstances, it is common place to observe (both see and hear) ice bursting to the surface (Desplanque and Mossman 1998, Personal Observations and Communicated Observations by others).

Sanders et al (2008) quote measurements of sediment concentrations in ice cakes from two studies (Atlantic Tidal Power Engineering and Management Committee 1969, and Knight and Dalrymple 1976). Sanders infers that 3 out of the 10 ice cakes might have been negatively buoyant, based upon their sediment content. No consideration is given to air bubbles trapped within the ice and no measurement was made to determine whether these ice cakes did actually float.

Ollerhead et al (1999) measured sediment concentrations in 25 ice cakes, each at least a metre in size. Most ice cakes had little sediment but a small minority contained substantial sediment. Only one ice cake contained sufficient sediment that it may have been negatively buoyant according to the criteria used by Sanders et al (2008). Again, there is no evidence that it was negatively buoyant nor were there any measures of air space contained within the ice. Indeed, the premise for the measurements made by Ollerhead et al (1999) was that sediment was being rafted onto the marsh by positively buoyant sediment-laden ice cakes.

Smith et al (2009) attempted to measure density of 83 samples of ice cakes from 34 locations around Minas Basin during the period March to early April 2009. Their method was to place a sample in a plastic bag and convey the sample to the laboratory where the volume of the bagged sample was measured according to water displaced. Each sample was subsequently processed to determine the amount of water, salinity, dissolved solids, and dry weight of sediment. Such information is difficult to obtain and is insufficient to determine whether or not freshly cut samples would float when placed in seawater (without being bagged). The major difficulty is that no proper account is taken for air spaces, either those that would be infiltrated upon placing the sample in seawater or those that would remain as isolated bubbles.

Density is the variable of primary interest for determining the risk of ice cakes drifting at sufficient depth to collide with sub-surface turbines. It is far easier to simply measure ice density than to measure sediment concentration and all the other quantities required in order to calculate ice density (if this is even possible). The following work will, therefore, be mostly concerned with the direct measurement of the density of ice cakes.

3 Sediment Density

What actually gets incorporated into ice is wet sediment that becomes frozen (not dry sediment). We have therefore measured the density of frozen sediment samples. The samples were collected with minimal disturbance at the location marked in Figure 2 on 4 December 2010. (The top 1-2 cm of sediment is red and easy to disturb but beneath the sediment is black and firm.) The samples were frozen and their densities were determined using Archimedes Principle.

- The sediment sample from the unvegetated (lower) site had density $1805 \pm 25 \text{ kg/m}^3$.
- The sediment sample from the more elevated, vegetated site had density $1657 \pm 20 \text{ kg/m}^3$.

The vegetated site had lower sediment density, probably due to the inclusion of saltmarsh roots and perhaps other less obvious organic material.



Figure 2: Location of sediment sampling sites at Grand Pre is shown with the yellow thumb tack. One sample was obtained at a level that was largely clear of marsh grass. The other sample was obtained at approximately 1 m higher elevation where marsh grass was ubiquitous.

The standard paradigm is that a buoyant ice cake settles on sediment during the falling tide. Freezing weather causes the ice cake to attach to the frozen sediment beneath. Upon the rising tide, buoyancy forces lift the ice cake, perhaps with some of the frozen sediment attached. The following calculation shows how the density of the ice cake would be changed.

Let the initial density of the ice cake be ρ_i and its initial volume V_i . This initial volume is the volume of water that is displaced when the ice cake is submerged (ie, not including porous spaces). If an additional volume of sediment V_s is attached to the bottom when the ice cake is torn from the bottom by buoyancy forces then the ice cake will have volume $V_i + V_s$ and new density

$$\rho_{\text{new}} = \frac{\rho_i V_i + \rho_s V_s}{V_i + V_s}$$

assuming no other mechanisms apply in the interim. Interestingly, the ice cake must have density less than the seawater in which it is immersed $\rho_{\text{new}} < \rho_{\text{seawater}}$ or the necessary buoyant force could not exist.

Assuming geometric similarity, large ice cakes will have a greater ratio of volume to surface area than will small ice cakes. Smaller ice cakes will, therefore, be less able to tear up frozen bottom sediment when inundated by the tide. Perhaps such intertidal sediment-attached ice cakes might be ‘caught’ as a scallop dredge is dragged along the bottom? Large ice cakes are more able to tear large portions of sediment (or rock) from the frozen bottom substrate. Desplanque and Mossman (1998) report that it is easier for ice cakes to tear free from a gravel substrate than from clay or silt substrate. Conceivably, it is large ice cakes that might, through subsequent melting or fracturing, result in smaller chunks of submerged ice that are sufficiently big to be potentially dangerous to turbines in tidal streams.

4 Measurements of Ice Density and Porosity

The volume of an ice cake is not simple to describe using Euclidean geometry. Ice cakes have cavities with many scales so there is no clear separation into macroscopic surface that encloses an ice cake volume and smaller scale cavities that can be separately considered as porous spaces. The Hausdorff metric geometry (Mandelbrot 1982, Barnsley 1988) may provide a better mathematical foundation but requires making more detailed measurements than are practicable within the constraints of the present project.

Ice cakes are usually too massive to manually manipulate and directly measure using inexpensive, portable tools. For this reason, ice cakes were sectioned vertically in the field and divided into layers (from top to bottom). Three to five ice samples were cut from each layer and separately measured. Ice samples had a typical size of about $30 \times 30 \times 20 \text{ cm}^3$. Figure 3 shows an ice cake that has been sectioned and later sampled following the obvious layering.



Figure 3: An ice cake has been sectioned. The axe is 83.5 cm long. Samples of ice were cut from each layer in order to measure their density and porosity. This photograph was taken at 14:15 on 18 February 2011 from the beach at Block Wharf Road, Summerville. The background view looks across the ice rafts on the Avon River towards the Hantsport - Blue Beach coastline.

Immediately we can determine whether or not the ice sample will float by placing it in a container containing local seawater. The salinity and temperature of the seawater was measured so that the seawater density ρ_{seawater} could be calculated using the UNESCO equation of state (Gill 1982).

The practical-mass of a floating ice sample can be determined from the volume V_f of water that it displaces while freely floating. Thus the practical-mass is $\rho_{\text{seawater}} V_f$. We shall define the practical-volume of an ice sample as the volume of seawater V_s that it displaces when it is fully submerged within a container of seawater for a short time. Thus, the practical-density (henceforth density) of a floating ice sample is

$$\rho_{\text{sample}} = \rho_{\text{seawater}} \frac{V_f}{V_s} \quad (1)$$

In the instances when the ice sample did not float, the ice sample was placed on top of styrofoam

so the joint styrofoam-ice volume and density could be measured as above and the ice density backed out from the known mass and volume of the styrofoam.

The practical-porosity (henceforth porosity) was arrived at by considering the volume of water V_r removed from the container when the submerged ice cake is removed from the container in a smooth, deliberate, repeatable motion. Thus, the porosity is

$$P_{\text{porosity}} = \frac{V_r}{V_s + V_r} \quad (2)$$

Obviously, if the ice cake is lifted out of the water and held above the container to drain then the measurement of porosity would be less. For this reason, the same person (Brian Sanderson) conducted all measurements in as consistent fashion as was biomechanically possible.

Throughout this report we tabulate densities and porosities to 3 or 4 significant figures. Measurement accuracy could only justify 2 significant figures. The additional figures are kept to preserve the arithmetic consistency between the calculated numbers and the raw data, in order to facilitate future cross-checking and analyses.

4.1 Measurements on 16 February 2011

Density and porosity of ice samples were measured at Evangeline Beach and Blue Beach. The densities and porosities are illustrated in Figure 4. Generally, there is a trend for porosity to be higher near the top (layer 1) of an ice cake. All samples floated in the local seawater which had density 1023.5 kg/m^3 at Evangeline Beach and 1022.3 kg/m^3 at Blue Beach. Further details are presented in the following three subsections.

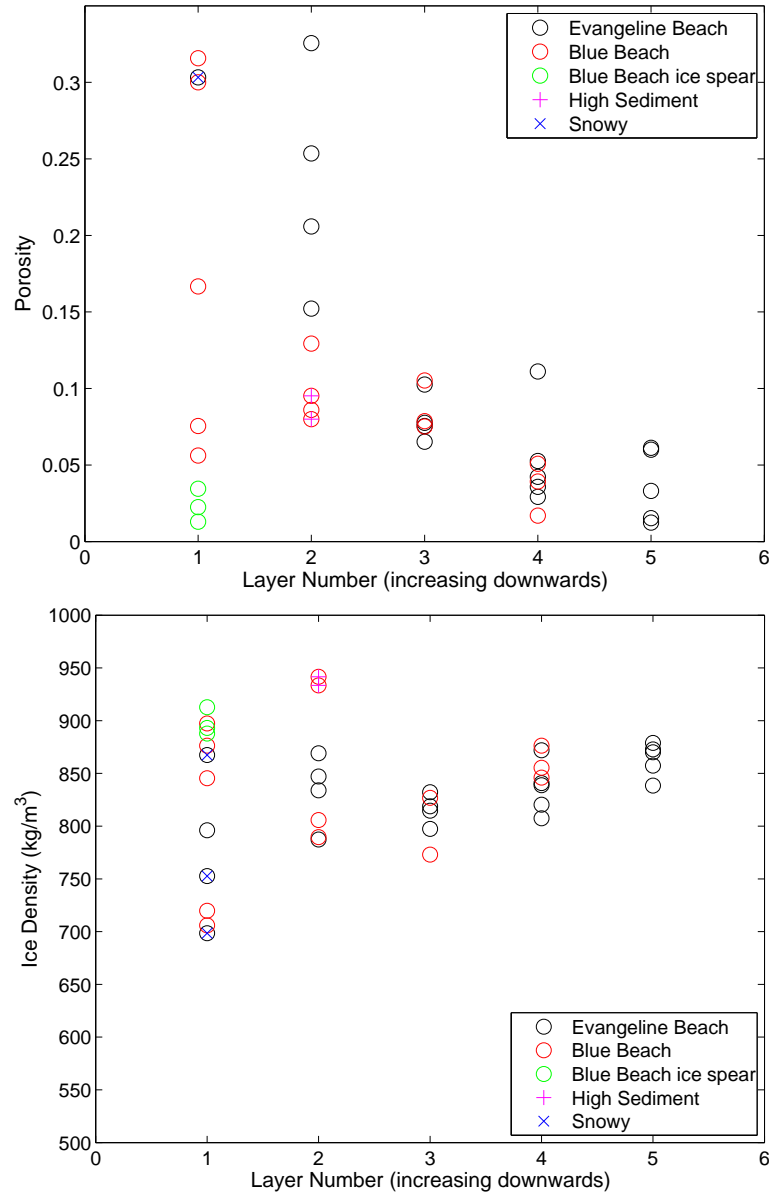


Figure 4: Densities and porosities measured on 16 February 2011. Black circles pertain to ice cake 1 at Evangeline Beach. Red circles pertain to ice cake 2 at Blue Beach. The green circles show results for an ice spear which does not have a layered structure.

4.1.1 Ice Cake 1, Evangeline Beach, 16 February 2011

One ice cake (Figure 5) was sectioned at Evangeline Beach (45.13834° N, 64.31901° W) and porosity and density determined for ice samples taken from 5 levels (level 1 being at the top and level 5 at the base of the ice cake). Results are reported in Table 1.



Figure 5: Photograph of ice cake 1 at Evangeline Beach (45.13834° N, 64.31901° W) on 16 February 2011. The tide has yet to recede to the base of the ice cake. A preliminary sectioning cut is being made.

Table 1: Density and porosity of samples from layers of an ice cake sectioned at Evangeline Beach (45.13834° N, 64.31901° W) on 16 February 2011

Evangeline Beach, ice cake 1	Layer	Porosity	density (kg/m ³)
	1	—	796
	1	—	867
	1	—	753
	1	0.3033	698
	2	0.1522	787
	2	0.2059	834
	2	0.3256	847
	2	0.2535	869
	3	0.1026	819
	3	0.0755	815
	3	0.0652	797
	3	0.0776	832
	4	0.0357	872
	4	0.0526	807
	4	0.0423	820
	4	0.1111	841
	4	0.0292	839
	5	0.0331	857
	5	0.0612	879
	5	0.0153	872
	5	0.0600	838
	5	0.0123	870

4.1.2 Ice Cake 2, Blue Beach, 16 February 2011

Ice cake 2 (Figure 6) was sectioned at Blue Beach (45.09667° N, 64.21221° W) and porosity and density determined for ice samples taken from 4 levels (level 1 being at the top and level 4 at the base of the ice cake). Results are reported in Table 2.



Figure 6: Photograph of ice cake 2 at Blue Beach (45.09667° N, 64.21221° W) on 16 February 2011. Preliminary sampling cuts have been made. The length of the axe is 83.5 m. The ice spear is visible in the upper left corner of the photograph.

Table 2: Density and porosity of samples from layers of an ice cake sectioned at Blue Beach (45.09667° N, 64.21221° W) on 16 February 2011

Blue Beach, ice cake 2	Layer	Porosity	density (kg/m ³)
	1	0.3000	876
	1	0.0562	706
	1	0.1667	897
	1	0.0755	720
	1	0.3158	845
	2	0.0860	806
	2	0.0952	942
	2	0.0800	933
	2	0.1293	790
	3	0.0752	773
	3	0.0787	773
	3	0.1053	827
	4	0.0508	876
	4	0.0392	855
	4	0.0169	846

Table 3: Density and porosity of samples from an ice spear sectioned at Blue Beach (45.09667° N, 64.21221° W) on 16 February 2011

Blue Beach, ice spear	Layer	Porosity	density (kg/m ³)
	1	0.0345	913
	1	0.0225	893
	1	0.0130	888

4.1.3 Ice Spear, Blue Beach, 16 February 2011

An ice spear (Figure 7) was cut into three pieces at Blue Beach (45.09667° N, 64.21221° W) and porosity and density determined. Results are reported in Table 3. It is doubtful that this ice spear formed in the marine environment. It looks like the ice spears that can be seen hanging from down-pipes at highway overpasses.



Figure 7: Photograph of ice spear at Blue Beach (45.09667° N, 64.21221° W) on 16 February 2011. The length of the axe is 83.5 m.

4.2 Measurements on 18 February 2011

One ice cake was measured at Summerville, Block Wharf Rd (45.09813° N, 64.18271° W). Figure 8 shows the ice cake prior to sectioning. Figure 3 shows a different view after the ice cake has been sectioned. Porosity and density determined for ice samples taken from 5 levels (level 1 being at the top and level 5 at the base of the ice cake). Results are reported in Table 4 and plotted with black circles in Figure 10. Porosity is much higher near the top of the ice cake but density does not vary systematically from top to bottom layers. None of these samples were more dense than seawater.

We also searched the beach for dense-looking, sediment-laden ice and results from these are shown in Table 5 and plotted with red circles in Figure 10. None of these samples were more dense than seawater.

Finally, we found an ice cake that had become frozen into the gravel substrate. We cut a block out of it (Figure 9) and measured its density to be 1470 kg/m^3 . This gravel-laden ice-block was taken back to the lab and allowed to melt. The melt-water had salinity 4.3 ppt.



Figure 8: Ice cake 3 at Summerville, Block Wharf Rd, 18 February 2011.

Table 4: Density and porosity of samples from ice cake 3 sectioned at Summerville, Block Wharf Rd (45.09813° N, 64.18271° W) on 18 February 2011

Summerville, ice cake 3	Layer	Porosity	density (kg/m ³)
	1	0.3824	901
	1	0.2826	898
	2	0.2075	852
	2	0.0541	876
	2	0.2118	885
	2	0.2466	855
	3	0.1690	866
	3	0.2323	860
	3	0.2111	864
	4	0.1765	912
	4	0.1852	883
	5	0.0500	874
	5	0.0385	900
	5	0.0192	862

Table 5: Density and porosity of dense-looking, sediment-laden ice at Summerville, Block Wharf Rd (45.09813° N, 64.18271° W) on 18 February 2011

Summerville, ice with a dense appearance	Porosity	density (kg/m ³)
	0.1067	946
	0.0784	870
	0.0092	871
	0.0179	874
	0.0317	888



Figure 9: Summerville, Block Wharf Rd, 18 February 2011. A dense gravel-laden block of ice. The axe head has dimension 18 cm.

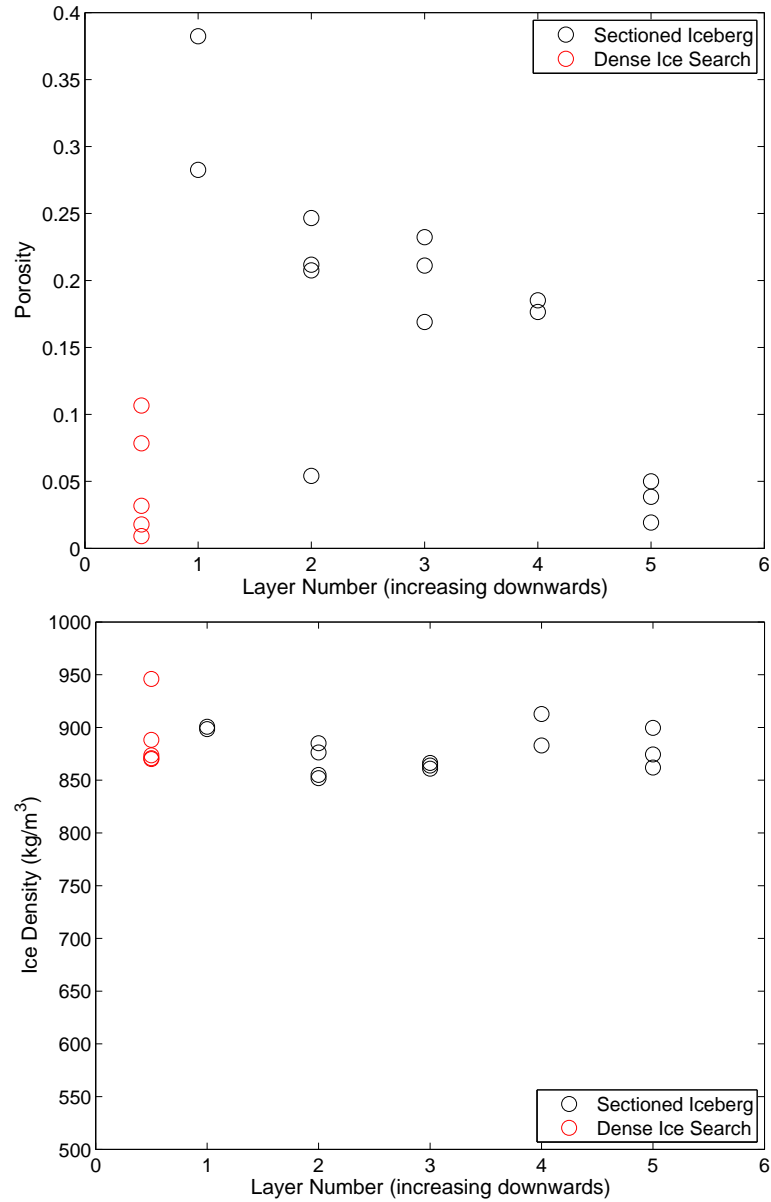


Figure 10: Densities and porosities measured on 18 February 2011 at Summerville, Block Wharf Rd. Black circles show results for ice samples from ice cake 3. Red circles show results for samples collected in a deliberate effort to find dense pieces of sediment-laden ice.

4.3 Measurements on 22 February 2011

By 22 February 2011 most of the ice cakes had drifted from the beach at Summerville, Block Wharf Rd (Figure 11). The spring tide had a maximum height of 14.69 m on 19 February and was 14.41 m on 21 February, making many floatable ice cakes vulnerable to offshore wind and tide. Winds were generally from the west-north-west, although they were strong and more northerly around the time of the 20 February high tide (14:00 hours AST) — so this may have been when many ice cakes were washed offshore. One expects that some of those ice cakes that have been left behind are stranded because they are more dense than seawater or too high up the beach to be floated on the tide. A dense ice cake (number 4) was found and sampled at Summerville, Block Wharf Rd on 22 February 2011 (Figure 12).

Figure 13 shows density and porosity of samples. The usual sectioning and layer sampling strategy was not applicable for ice cake 4. Ice cake 4 can be considered to have a broad, thin base with weakly attached top layers. Samples from the lower part of the base were all more dense than the local seawater. The weakly attached “cake” on top had density much less than that of the local seawater. The upper portions of the base were also less dense than the local seawater. Table 6 records density of the various samples taken from ice cake 4.

The less dense top cake was removed during sampling, leaving behind a base that we expect to be marginally more dense than the local seawater. The adjacent Avon River had salinity 26.3 ppt and temperature $-0.8\text{ }^{\circ}\text{C}$ which corresponds to a density of 1021.1 kg/m^3 . Unsurprisingly, ice cake 4 did not move more than a few metres (Figure 25) even though it was subsequently washed by strong tidal currents because its location is at a coastal prominence where tidal current is strong. A sample obtained from ice cake 4 on 23 Feb 2011 had density 1122 kg/m^3 .

Table 6: Density and porosity of ice cake 4 at Summerville, Block Wharf Rd (45.09811° N, 64.18322° W) on 22 February 2011

Ice cake 4	density (kg/m ³)	Porosity
Bottom of Base	1172	
	1112	
	1062	
	1169	
	1073	
	1060	
Cake sitting on top of the base	789	0.0638
	801	0.1096
	817	0.0678
	832	0.0000
Top layer of base	873	0.0159
	856	0.0312
	823	0.0270
	891	0.0351
Vertical section of base	964	
	992	
	983	
Top/bottom vert. sect. of base	941	0.0377
	917	0.0167
	1074	
	1174	



Figure 11: Views from Block Wharf Rd, Summerville. **Top:** Stranded ice covers the beach on 18 February 2011. **Bottom:** Tides and wind have removed most ice from the beach by 22 February 2011.



Figure 12: Ice cake 4 at Summerville, Block Wharf Rd, on 22 February 2011. Ice cake 4 has a negatively buoyant base (high sediment) with positively buoyant sediment-laden ice above. The top levels of ice were weakly attached and they broke off as we worked on them. The base had equivalent dimensions of about 1.9 m \times 2.3 m \times 0.3 m. The weakly attached top snowy part had equivalent dimensions of about 1.6 m \times 0.75 m \times 0.4 m. Location, GPS: 45.09811° N, 64.18322° W.

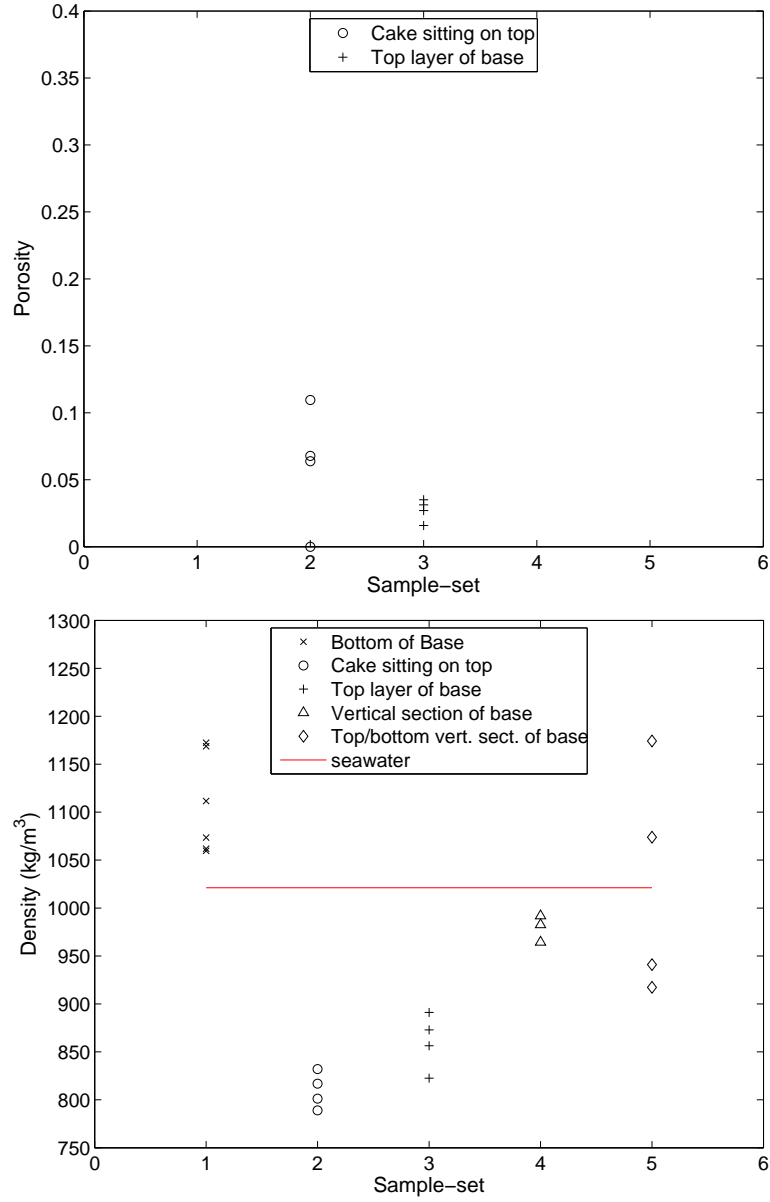


Figure 13: Densities and porosities measured on 22 February 2011 at Summerville, Block Wharf Rd. We did not measure the porosity of negatively buoyant samples. The horizontal-axis and symbols indicate samples obtained from different locations within ice cake 4.

4.4 Measurements on 23 February 2011

Measurements were made at Summerville, Block Wharf Rd, on 23 February 2011. Water temperature was $-0.8\text{ }^{\circ}\text{C}$ and salinity was 25.3 ppt in the Avon River. Mean air temperature at Kentville on 23 February 2011 was $-6.4\text{ }^{\circ}\text{C}$ (max $-2.0\text{ }^{\circ}\text{C}$, min $-11.4\text{ }^{\circ}\text{C}$). We recorded air temperatures of -4 and $-8\text{ }^{\circ}\text{C}$ at the study site. It was sunny and a brisk northerly wind blew alongshore (towards upriver). Figure 14 shows the sunny and shaded sides of ice cake 5. Air temperature was below zero but the dark sediment decreases albedo so the ice melts on the sunny side. The meltwater does not absorb radiation and so it freezes in the cold wind, forming long icicles. Sediment is left behind as little muddy nodules which wash off ice samples when they are immersed to measure density and porosity — volumes of muddy nodules are not sufficient to significantly corrupt the determination of density.

Ice cake 5 is substantially eroded revealing an extremely complex topography when sectioned (photograph not presently presented) — as would be expected from the appearance of the intact ice cake (Figure 14). Porosity shows the usual features, being highly variable and generally decreasing towards the base of the ice cake. Most of the samples were less dense than the local seawater, except for the bottom-most layer. Ice cake 5 was probably stranded by virtue of being high on the beach because it is unlikely that its overall buoyancy was negative — although it is clearly less buoyant than ice cakes 1-3.

Table 7: Density and porosity of ice cake 5 at Summerville, Block Wharf Rd (45.09811° N, 64.18322° W) on 23 February 2011

Ice cake 5	Layer	Porosity	density (kg/m ³)
	1	0.2022	862
	1	—	1051
	1	0.0227	997
	2	0.2826	928
	2	0.2500	918
	3	0.1000	983
	3	0.0759	1006
	3	0.1127	939
	4	0.0820	966
	4	0.0118	972
	5	0.0882	987
	5	0.0392	958
	5	0.0390	938
	5	0.0704	974
	6	—	1042
	6	—	1080
	6	—	1347
	6	—	1080
	6	—	1117



Figure 14: Ice cake 5 at Summerville, Block Wharf Rd, on 23 February 2011. **Top:** view of the shaded side. **Bottom:** the sunny side. Average air temperature was -6.4°C at Kentville.

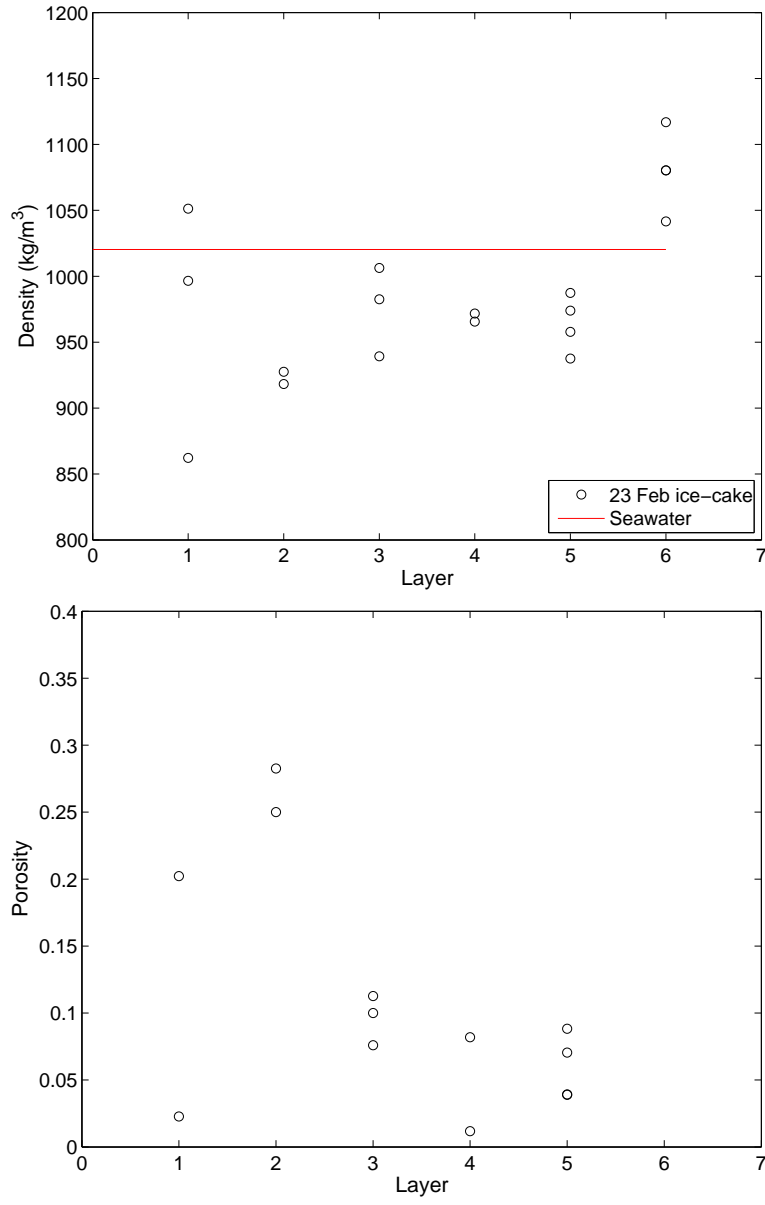


Figure 15: Density and porosity of ice cake 5 at Summerville, Block Wharf Rd, on 23 February 2011.

4.5 Measurements on 7 March 2011

Ice density and porosity measurements were made on the saltmarsh at Grand Pre, West Long Island Rd, on 7 March 2011. Two sets of measurements were made. The first was of ice cake 6 (Figure 16). The second was of samples of ice cut from the ice ridge (Figure 17) that typically crests the top-edge of channels running through marshland. Desplanque and Mossman (1998) use the term “ice wall” but we consider “ice ridge” to be more descriptive of the sites that we studied. Figure 2 shows the approximate location of ice cake 6 and the ice ridge using the red symbols A and B.

We measured an air temperature of 10.4 °C. Water was collected from the channel running through the saltmarsh. It had salinity 0.5 ppt and temperature 2.6 °C at 1231h (at which time the water level was about 3 m higher than that shown in Figure 16). High tide was 13.30 m at 1418h so the channel water was collected after about 4 hours of incoming tide. This explains the low salinity in the channel as being farmland drainage through the aboiteau that had accumulated in the channel ahead of the incoming tide.

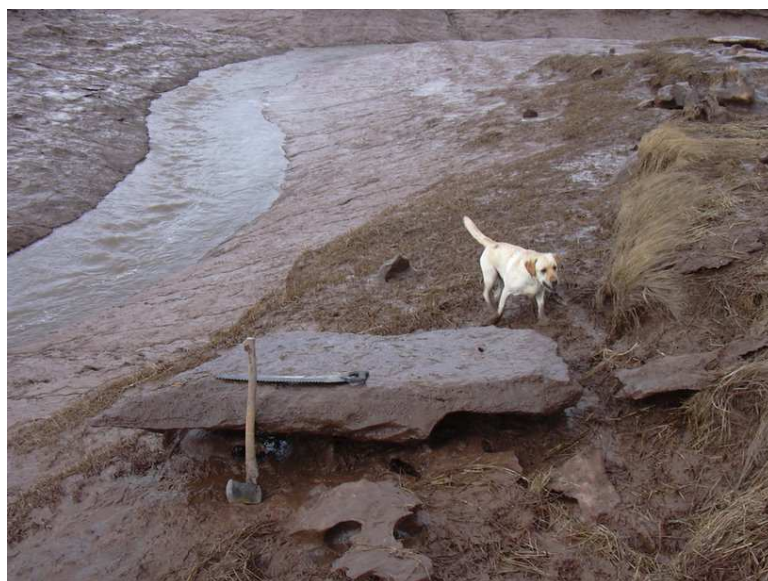


Figure 16: Ice cake 6 at Grand Pre, West Long Island Rd, on 7 March 2011. GPS 45.12154° N, 64.33353° W. This ice block is located at the upper part of the channel. The water flowing in the channel is freshwater flowing out of the aboiteau. Salinity 0.5 ppt and temperature 2.6 °C of channel water were measured at 12:31 pm when the tide had risen about 3 m from the level shown in this photograph.

Ice cake 6 (Figure 16) is heavily stained by sediment which is typical for ice cakes on saltmarsh

Table 8: Density and porosity of ice cake 6 (45.12154° N, 64.33353° W) and ridge ice (45.12016° N, 64.33297° N), Grand Pre, West Long Island Rd. Measured on 7 March 2011

	Porosity	density (kg/m ³)
ice cake 6	0	871
	0.015	857
	0.010	830
	0	845
	0	842
	0.020	830
ridge ice	0.007	827
	0	811
	0	797
	0	831
	0	822

at this late stage of the ice season. It takes very little sediment to greatly modify the appearance and albedo of ice cakes so it is not surprising that all samples from ice cake 6 were quite buoyant (Figure 18, Table 8). Ollerhead et al (1999) quantify the amount of sediment in ice cakes and show photographs of the small layer of sediment that a large ice cake leaves behind after it has melted. We photographed similar features on the saltmarsh at Grand Pre. Sediment obviously increases the rate of melting by increasing the absorption of solar radiation. Porosity was low for all samples.

The mechanisms for formation of ice ridges (also called “ice walls”) along the top edge of channels are outlined by Desplanque and Mossman (1998). Presently it is of interest that this ridge ice has relatively low density (Figure 18 and Table 8) so buoyancy forces will cause lifting forces at high tide which act against any attachment to the frozen sediment beneath. However the ridge ice is observed to remain in place, perhaps because it is topologically molded to the curved surface of the crest of the channel and this might increase its mechanical stability.



Figure 17: **Top:** Looking at the ice ridge that forms along the top-edge of the channel (down stream about 150 m from ice cake 6). **Bottom:** A section cut through the ice ridge. Ice samples were taken from the sides of this cut to measure density and porosity. GPS: 45.12016° N, 64.33297° W, date: 7 March 2011.

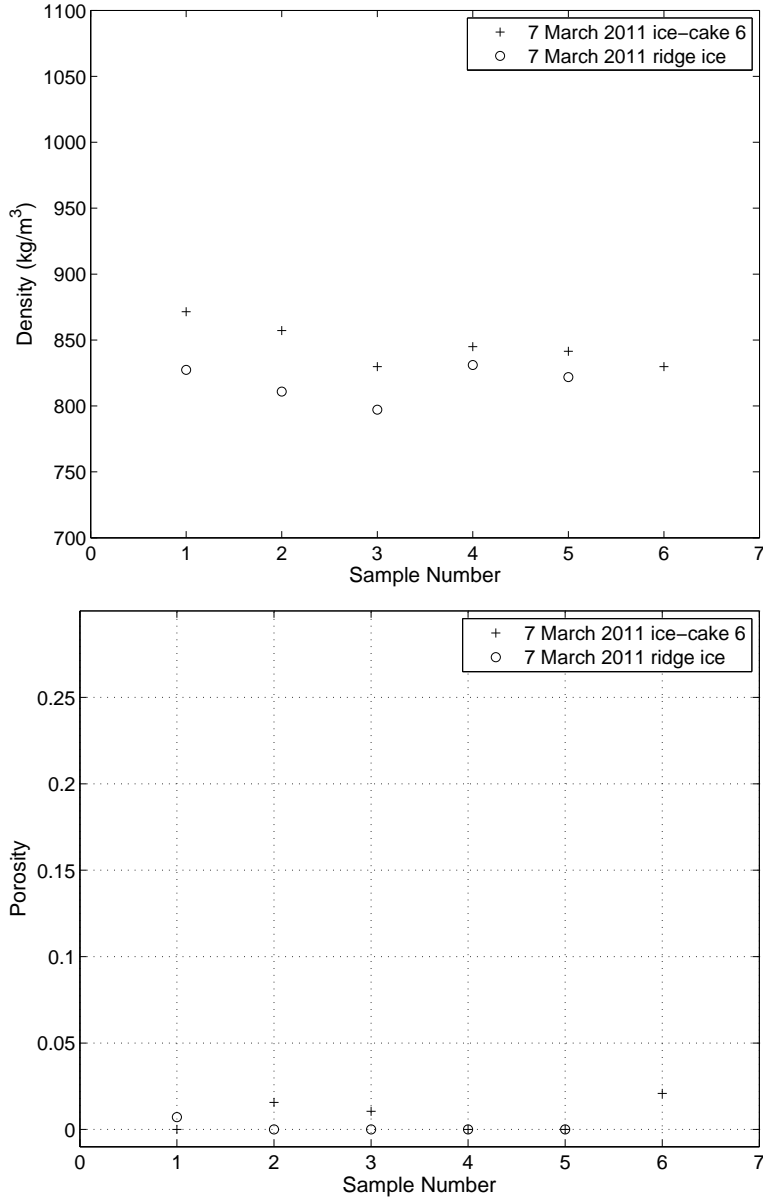


Figure 18: Density and porosity of ice-cake 6 and ridge ice at Grand Pre saltmarsh, West Long Island Rd, 7 March 2011.

4.6 Measurements on 8 March 2011

Measurements were made at Summerville, Block Wharf Rd on 8 March 2011. Two hours after low tide we waded into the channel to a depth of about 1 m and measured salinity of 12.6 ppt and temperature 0.7 °C. Nearer to shore, in water about 10 cm deep, salinity was 11.1 ppt and temperature was 2.2 °C. Note, temperature is increased as water rises over the sun-warmed sediment. It was sunny at the time of measurements (about 1100 h) so the solar heating can be expected to raise surface-sediment temperature significantly above the -1 °C air temperature.

At 1320 hours the tide had risen substantially so further temperature and salinity measurements were made at three distances from the shoreline that correspond to increasing water depth: 23.4 ppt and 2.4 °C at 0.1 m depth, 23.8 ppt and 1.5 °C at 0.5 m depth, 25.3 ppt and 0.5 °C at 1 m depth. This seems to confirm that water is heated as it rises over the solar-warmed sediment. The on-offshore salinity gradient results from horizontal shear in the incoming tidal current and the along-thalweg salinity gradient. Salinities are higher than at the earlier low tide measurements, consistent with salinity being less towards the head of the Avon River. Baroclinicity results in some vertical salinity structure. Salinity and temperature structure influences ice formation and melting.

There was very little ice on the inter-tidal flat but there were ice cakes high on the beach. Tides were near spring (high tide on 8 March being 13.08 m). What little ice remained in the channel was highly eroded and melted (Figure 19). The ice has a skeletal look about it, being more holes than ice. Notably, sediment seemed to have been washed out, leaving a skeleton of clear ice. Such skeletal ice cakes might be characterized as more water than ice and obviously have far less ice mass and strength than solid ice with the same overall length scales. Given the large amount of surface area for a relatively small volume of ice, it is conceivable (but has not been observed) that skeletal ice cakes could be prone to being dragged to depth in roiling currents — even though they are clearly buoyant.

Higher up the beach we found two ice cakes (Figures 20 and 21) that were subsequently sampled to measure density and porosity. Densities and porosities of samples from these ice cakes are plotted in Figure 22 and recorded in Table 9. Ice cake 7 was sectioned into 3 layers and all samples were buoyant except for one sample from the lower layer that contained a great deal of gravel, frozen into the base from the local substrate. Ice cake 8 was sectioned into 4 layers and only one negatively buoyant sample was obtained from its base (layer 4). Porosity was highly



Figure 19: The skeletal remains of an ice cake, Summerville, Block Wharf Rd, 8 March 2011. There is no sediment in or on that portion of the ice cake that is washed by waves.

variable but clearly diminishes nearer the base of both ice cakes.



Figure 20: This is ice cake 7 which we sampled for density and porosity measurements. Samples from this ice-block were less dense than the sea water except for one sample from the bottom layer. The GPS location was 45.09785° N, 64.18295° W.



Figure 21: **Top:** This is ice cake 8 and its position is 45.09810° N, 64.18295° W. The axe is 83.5 cm long and the axe head has max dimension 18 cm. Most of this ice block is less dense than seawater. But it has settled on frozen gravel and sand which has become attached to the bottom layer. We can see that buoyancy forces seem to have ripped it away from the underlying sand (see bottom photograph) so that the bottom of the ice-block consists of a layer of frozen gravel and sand. **Bottom:** A thin layer of frozen sediment (sand and gravel) has been removed to the left of ice cake 8. The removed material has dimension and shape consistent with the base of ice cake 8.

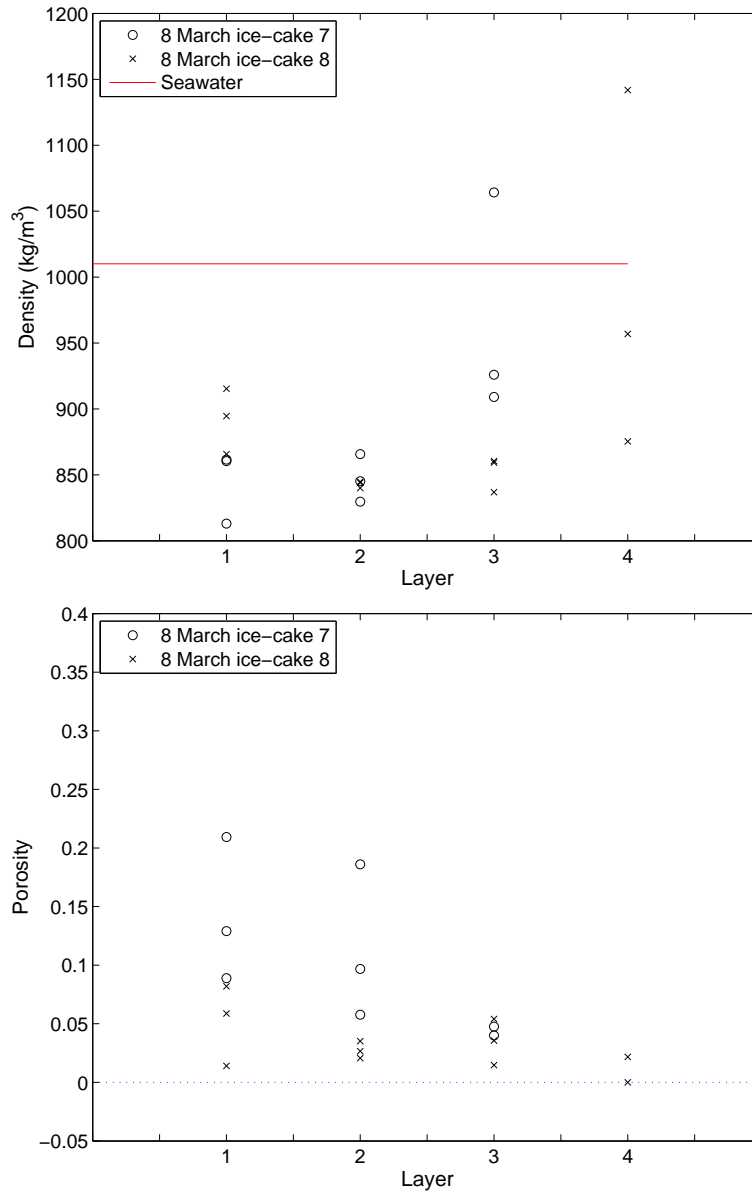


Figure 22: Density and porosity of ice-cakes 7 and 8, at Summerville, Block Wharf Rd, March 2011.

Table 9: Density and porosity of ice cakes 7 and 8, at Summerville, Block Wharf Rd on 8 March 2011

	Layer	Porosity	density (kg/m ³)
ice cake 7	1	0.2093	862
	1	0.1290	860
	1	0.0889	813
	2	0.1860	866
	2	0.0577	845
	2	0.0968	830
	3	0.0476	909
	3	0.0400	926
	3	—	1064
ice cake 8	1	0.0588	915
	1	0.0820	866
	1	0.0141	895
	2	0.0206	840
	2	0.0267	844
	2	0.0351	845
	3	0.0147	859
	3	0.0541	837
	3	0.0357	860
	4	0	957
	4	0.0217	875
	4	—	1142

5 Ice Formation

Water with salinity S (ppt) freezes at a temperature T ($^{\circ}\text{C}$) of approximately

$$T_{\text{freeze}} = -0.003 - 0.0527S - 0.00004S^2 \quad (3)$$

whereas the temperature at which water achieves maximum density is approximately

$$T_{\rho_{\text{max}}} = 3.95 - 0.200S - 0.0011S^2 \quad (4)$$

(Neumann and Pierson 1966). Obviously $T_{\rho_{\text{max}}}$ falls more quickly than T_{freeze} as salinity S is increased. At a salinity of 24.7 ppt both temperatures are the same, $T_{\rho_{\text{max}}} = T_{\text{freeze}} = -1.33$ $^{\circ}\text{C}$.

- Most of the Minas Basin has salinity more than 24.7 ppt so convective adjustment requires that the entire water column be cooled to freezing temperature before ice is formed in the water column. Nova Scotia winters are not sufficiently severe for this to happen. *Envirosphere* (2009a) and *Oceans* (2009) measured salinities close to 31 ppt in Minas Passage.
- Salinities less than 24.7 ppt might be found nearshore and certainly up-river where there is freshwater discharge from the catchment. By way of example, on 7 March 2011 we measured salinities of: 0.5 ppt in the aboiteau channel at West Long Island Rd Grand Pre, and 19-21.8 ppt in Cornwallis River at Port Williams Bridge. About 2 hours after low tide on 8 March 2011 we measured salinities 11.1 ppt in the Avon River at Summerville. At such locations (and further up-river) ice can form on the surface while the water beneath is warmer and more dense, as is seen to happen in freshwater lakes.

Ice cake 1 was measured on a cold day with fresh onshore winds forming frazil in the shallow waters adjacent Evangeline Beach on 16 February 2011, see Figure 5. Kentville meteorological station recorded an average air temperature of -9.3 $^{\circ}\text{C}$ with a range from -14 to -3 $^{\circ}\text{C}$. Wind-waves were quickly attenuated as they propagated into the frazil adjacent the shoreline. Dipping a YSI probe into the frazil-laden seawater gave a salinity reading of 29.3 ppt and temperature -1.5 $^{\circ}\text{C}$. A sieve was used to collect a sample of frazil which had a salinity of 20.5 ppt when it was melted. The 29.3 ppt salinity is higher than 24.7 ppt but given the shallow water and high frazil content it seems likely that ice formation was in progress. The freezing point temperature of 29.3 ppt seawater is -1.58 $^{\circ}\text{C}$ which is not significantly different to our measurement, given instrument uncertainty and the fact that seawater salinity would have been lower prior to the frazil formation. When the tide

falls, the onshore winds ensure that a 2-3 inch layer of clean-white frazil is left behind, coating the beach, rock, and ice cakes (Figure 23). The freshly deposited frazil ice is soft and slushy but can harden if cold conditions persist.



Figure 23: The tide has fallen on Evangeline Beach and ice cake 1 is shown in a sectioned view after samples had been cut out of it. Beyond the work area, the beach has been covered with a fresh white layer of soft frazil-ice, left behind by the combination of falling tide and onshore wind.

Snowfall contributes directly to the mass of frozen material on a saltmarsh (van Proosdij 2005). We have observed wind-driven currents and waves to cause large accumulations of frazil, snow and small ice-bits upon saltmarsh during the rising tide and to add to the frozen mass of stranded ice cakes after the tide has fallen. Such mechanisms will increase the buoyancy of ice cakes.



Figure 24: **Top:** Frazil driven ashore on a high tide. Photograph taken shortly after high tide on Sunday 22 Jan 2012. The tide was about 0.5 m below its highest level (14.19 m). **Bottom:** Ice coated with freshly deposited frazil after the tide falls. Photograph taken after 4 hours of falling tide. The frazil is soft when the tide first recedes but hardens with continued exposure to the cold weather. Note, all ice has been washed off the distant saltmarsh. Long Island Point is visible at the top-right of both photographs.

6 Observations Regarding a Negatively Buoyant Ice Cake

Ice cake 4 was first observed on 22 February 2011 (Figure 12). Samples taken from the ice cake (Table 6) indicated that what remained might be negatively buoyant. We watched the ice cake as the tide rose over it. The ice cake appeared, briefly, to move with the tide. Tidal currents were strong at this location and the water was highly turbid with suspended sediment. The incoming tide also transported many floating ice cakes so it was difficult to be certain whether or not ice cake 4 was moved or remained anchored to the bottom. We returned to the site at several times when the tide was low and obtained GPS coordinates for ice cake 4. Positions are plotted in Figure 25. Positions on 23, 24, 25 February are the same to within the accuracy of the GPS. Nevertheless, between 22 and 23 of February ice cake 4 did move a short distance. The direction of motion was up-estuary and down the beach slope so this movement is consistent with our brief observation of apparent motion with the incoming tide on the afternoon of 22 February 2011.

It is notable that the most dense material in an ice cake is typically distributed in a thin bottom layer as must be expected since **large masses of dense material can only be accumulated by a large ice cake lifting sediment from the bottom** (the bottom usually being fairly flat on the scale of an ice cake). Thus ice cake 4 had a flattened shape, which is probably a common feature of ice cakes that have lost positive buoyancy. Such flattened shapes are favourable for hugging a flat seabed in tidal currents.

On 25 February 2011, ice cake 4 was melting (Figure 26) and by 8 March 2011 it was entirely gone. Radiative heating is mostly responsible for the melting, which is far greater on the side exposed to the sun. Any ice cakes that might have made it as far as Minas Passage would be exposed to relatively warm water compared to the Avon River, given measurements at Scots Bay gave salinity 32 ppt and water temperature of 2.5 °C at 1344 hours on 25 February 2011.

There is some evidence for rafting of clumps of saltmarsh, as shown in Figures 27 and 28.

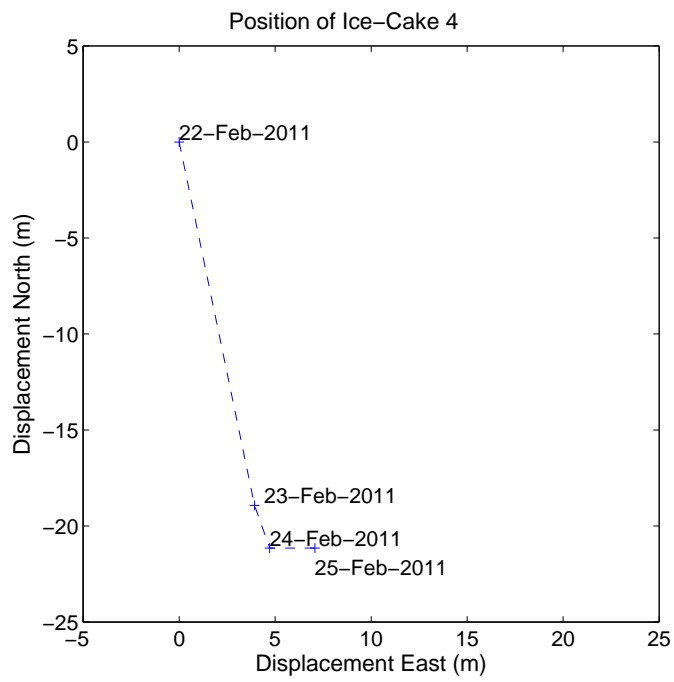


Figure 25: Positions of the negatively buoyant ice cake 4.



Figure 26: Ice cake 4 was melting on 25 February 2011. **Top:** the side most exposed to the sun. **Bottom:** the side least exposed to the sun.



Figure 27: Photograph taken on February 23, 2011 at Cheverie, Shipyard Road. GPS location: 45.16736° N, 64.16587° W. This large frozen chunk of *Spartina* and saltmarsh sediment may have been rafted from a nearby saltmarsh.



Figure 28: A clump of saltmarsh that has been rafted to Summerville, Block Wharf Road, on 25 February 2011. The clump was not present on the previous day. The GPS coordinates are: 45.09792° N, 64.18286° W.

7 Formation of Near-Neutral Buoyancy Ice Cakes

We have measured the distribution of density (and porosity) in ice cakes. The general tendency is for ice cakes to become more dense and less porous at their base. Sometimes samples from the bottom layer were negatively buoyant where they had frozen sediment or gravel into their base. The ice cakes that we sampled cannot be considered to be representative of the total population of ice cakes. Generally, we were sampling at locations and times that are expected to be biased towards finding dense ice cakes, or ice cakes that contain some dense material. Ice cake 4 is a particular example of extreme sample bias. This ice cake was found at a time and place where a great many floating ice cakes had recently been removed by wind and tide. But for this fact, we may never have sampled ice cake 4 because it would have been hidden amongst numerous buoyant ice cakes.

Ice cakes are formed in shallows adjacent the coast. To incorporate dense material, an ice cake must freeze onto the sediment and then break a portion of the sediment free from the bottom. The only way this can be done is through buoyancy forces which scale proportional to the volume of the ice cake. Thus, to incorporate a large amount of sedimentary material, an ice cake must be both large and have high buoyancy. In order to obtain a near neutrally-buoyant ice cake in offshore waters, it is necessary for:

1. A much larger buoyant ice cake to form in the intertidal zone,
2. Incorporate a large mass of dense, frozen sedimentary material,
3. Still be buoyant,
4. Be washed offshore,
5. While offshore, it must differentially melt or fracture, so less dense ice is lost preferentially to negatively buoyant sedimentary ice.
6. Achieve an overall density that falls within a narrow range in order that turbulence can move it vertically through the water column.

This sequence of events is plausible. Steps 1-3 happened for ice cake 4. But then ice cake 4 achieved negative buoyancy in shallow water where it remained trapped. (Also, our sampling strategy may have contributed to ice cake 4 becoming negatively buoyant.) In part, ice cake 4 may have been

stable to strong tidal flows because of its low profile, being broad and flat, hugging the bottom. Given the mechanism for incorporating dense material into ice cakes, one might expect a broad, flat shape to be common for ice cakes that are both large and not strongly buoyant.

It is difficult to assess a probability for each of steps 1 to 6 above. The preferential melting of less dense ice, leaving sediment-laden ice, is not evident in Figure 19. Cleaner ice cakes are seldom seen. The chance of forming an ice cake dangerous to tidal turbines is a multiplicative process, equal to the product of probabilities of processes in steps 1 to 6. This joint probability is akin to the “Drake Equation” (Brin 1983) and is similarly confounded by poorly known constituent probabilities and the lack of a single observation of the sought-after entity.

The frequency distribution of density for ice samples is somewhat binormal (Figure 29), or at least has a long tail on the high-density end of the distribution. This must be expected if the material derives from two sources: (1) low-density frozen water, (2) high-density sediment. Furthermore, the mechanics of incorporating large quantities of bottom-sediment requires that this should happen as a two-dimensional feature at the base of a large ice cake. As previously noted, our sampling strategy is biased towards dense ice. Thus, drifting ice (eg Figure 30) is undersampled and we expect the low-density peak in Figure 29 would be larger (relative to the number of higher-density samples) for a frequency distribution that was generally representative of all ice cakes in Minas Basin.

It is notable that the density of ice is substantially less than the density of seawater at Minas Passage whereas the density of frozen bottom sediment is very much higher. Similarly, samples from within ice cakes are either much more or much less dense than the seawater at Minas Passage (Figure 29). Obviously, it is *possible* for inhomogeneous buoyant ice cakes to drift offshore and become near neutrally-buoyant by mechanisms indicated in step 5 above. Even if this happens, near neutral buoyancy is not expected to be commonly achieved and when it is achieved it may not be for long.

8 Locating Near-Neutral Buoyancy Ice Cakes and Wood Logs

Floating ice cakes (Figure 30) will move according to the wind and tide. Their motion is also influenced by baroclinicity. Up-estuary water is lower-salinity which enhances the down-estuary

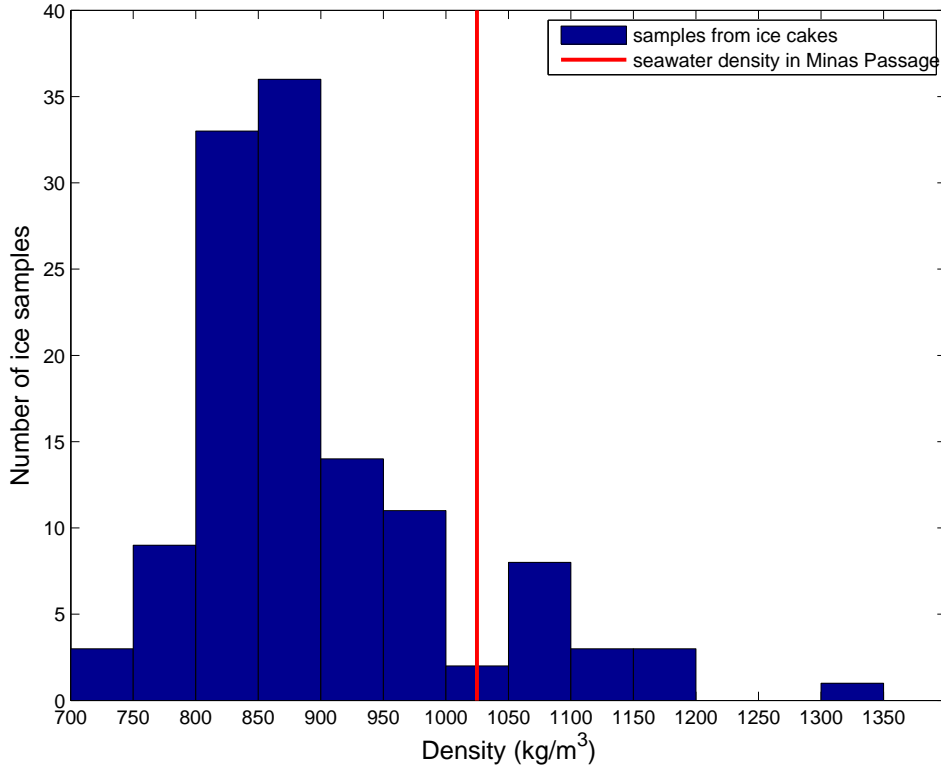


Figure 29: Histogram of density of samples from ice cakes, including samples from the ridge ice.

transport of floating ice cakes. While the large numbers of floating ice cakes are very evident in Figure 30, we have absolutely no direct observation of any ice cakes drifting at depth within the water column. It may be possible to use an echo sounder to search for sub-surface ice in the vicinity of such surface ice. Sub-surface ice is expected to be distributed more up-estuary than surface ice because baroclinic currents are up-estuary at depth and down-estuary near the surface. Thus, it is likely that any sub-surface ice may be located up-estuary from fields of surface ice like that shown in Figure 30.

Whereas an echo-sounding search might be practicable in constricted waterways (as shown in Figure 30), it may require an impractical amount of vessel time for the main body of Minas Basin or Minas Passage (6 km wide). Additionally, the water column is strongly stretched as the outgoing tide goes from the relatively shallow Minas Basin to the much deeper Minas Passage. Such stretching causes horizontal convergence of floating ice, impeding vessel operations when ice is abundant. Indeed, there is a report from 1809 that Ebenezer Bishop used a notched board to “walk” across the ice-jammed channel from Amethyst Cove to Parrsboro on 14 February 1809 (Black, 1965). One option would be to install a bottom-mounted acoustic device (perhaps an



Figure 30: High-floating ice cakes drifting with the outgoing tide in Avon River. Photograph was taken 16 February 2011, looking from Blue Beach to across the Avon River.

appropriately configured ADCP) to try to detect mid-water column objects moving in Minas Passage. (Alternatively, monitoring devices could be mounted to platforms used to retain turbines.) The difficulty would always be knowing what caused the reflected signal: ice, water-soaked wood, fish, marine mammals, etc. Concurrent image detection would be required.

There is another strategy that should reveal both near-neutrally buoyant ice cakes and near neutrally-buoyant logs — if such things exist in dangerous numbers. Consider the bathymetry of Minas Basin (Figure 31) where, for a 14 m tide, the area coloured yellow would be inundated at high tide but exposed at low tide. A simple calculation shows that about 63% of the water that was in Minas Basin at high tide would have flowed out of the basin by low tide. The outflowing currents are stronger near the surface than at depth. If there are near neutrally-buoyant ice cakes (or logs), that sometimes float within the water column, then the place where they are most likely to be visible is stranded at low tide in the deeper parts of the yellow zone of Minas Basin.

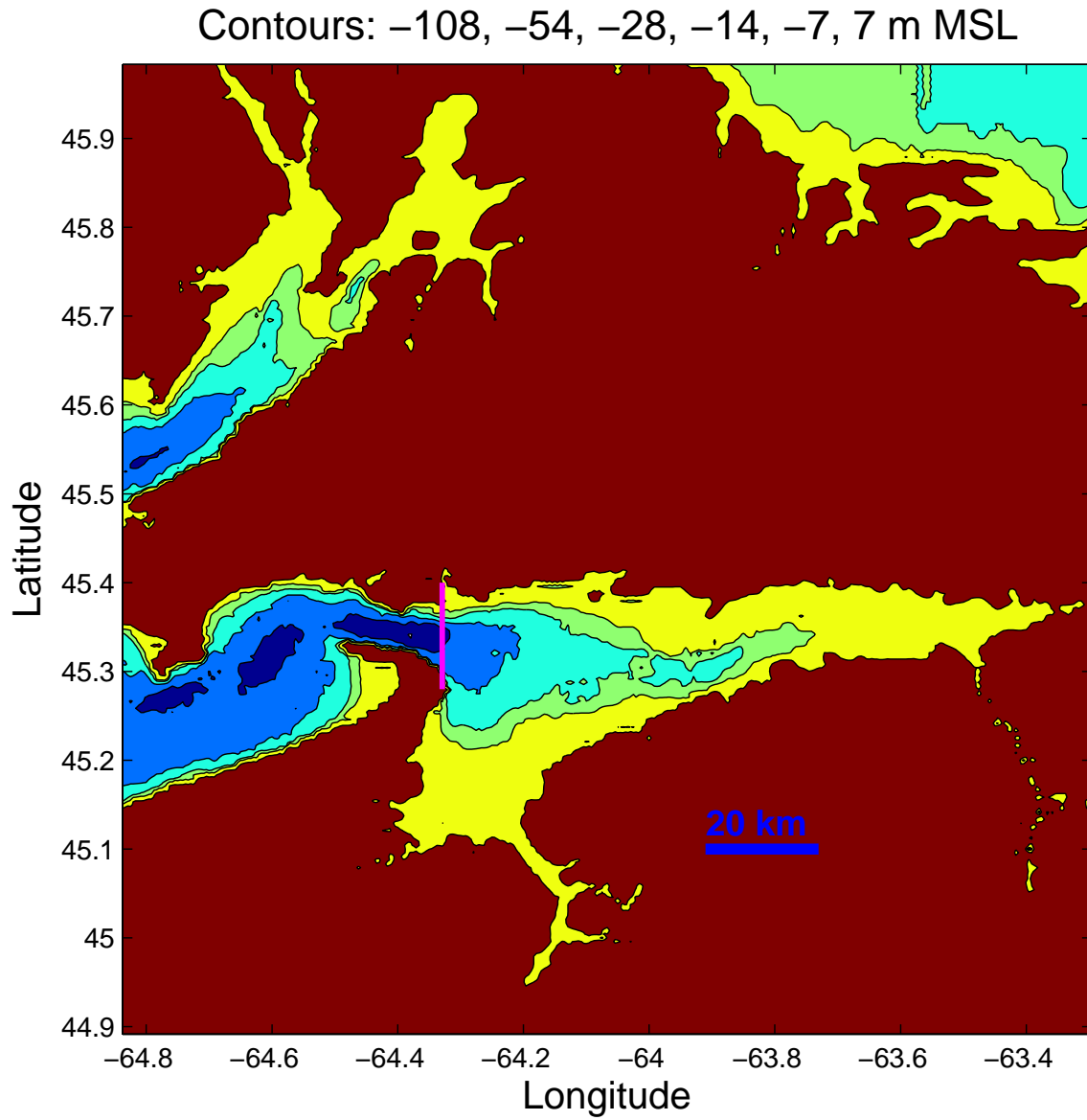


Figure 31: Bathymetric contours in Minas Basin and Minas Passage. Bathymetry is on a 15 arc-second grid and was obtained from: pubs.usgs.gov/of/1998/of98-801/bathy/. The vertical magenta line is used to demark a boundary between Minas Passage and Minas Basin.

9 Vertical Motion of Ice

There are breaking wind-waves in Minas Basin and Minas Passage which might push down small particles of buoyant ice. Tidal currents can be strong at some places in the Bay of Fundy, especially Minas Passage. Even in the Cornwallis River, the strongly flowing tide causes big rolling swirls (boils) where turbulent eddies roll from top to bottom. These boils cause vertical currents that can drag a particle with them even if that particle has density different from the water in which it is immersed.

Let's say that the vertical current speed is w . Denote the cross-sectional area of an ice cake as A , its volume as V , and density ρ . The drag force scales as $(1/2)C_d\rho_{\text{seawater}}Aw^2$ whereas the buoyancy force scales as $g(\rho_{\text{seawater}} - \rho)V$. Thus, there will be a critical current speed w_c at which these forces balance

$$\frac{1}{2}C_d\rho_{\text{seawater}}Aw_c^2 = g(\rho_{\text{seawater}} - \rho)V \quad (5)$$

A little algebra enables us to calculate the critical vertical current w_c that might drag a particle beneath the surface and deep into the water column.

$$w_c = \sqrt{\frac{2g|\rho_{\text{seawater}} - \rho|V}{C_d\rho_{\text{seawater}}A}} \quad (6)$$

Notice, this formula applies in both the upwards and downwards sense, depending upon whether a particle is more dense or less dense than the water in which it is immersed.

Presently, the key thing to realize is that w_c is proportional to $\sqrt{V/A}$ which is simply a length scale L for the ice. Obviously, all else being equal, small pieces of ice are relatively easy to entrain into the water column compared to large pieces of ice. Let's put some typical numbers into the problem, as they might pertain to the ice in plankton net observation made by Professor Daborn. Density of 30 ppt Cornwallis River water at -0.5°C is $\rho_{\text{seawater}} = 1024 \text{ kg/m}^3$ (Gill 1981, UNESCO equation of state). Density of 5 ppt ice containing neither bubbles nor sediment is $\rho = 930 \text{ kg/m}^3$ (Timco and Frederking, 1996). Let's give the piece of ice a length scale $L = V/A = 0.05 \text{ m}$. Consider a drag coefficient $C_d = 1$, and gravity $g = 9.81 \text{ m/s}^2$.

$$w_c = \sqrt{\frac{2 \times 9.81 \times |1024 - 930| \times 0.1}{1 \times 1024}} = 0.3 \text{ m/s} \quad (7)$$

In turbulent boundary-layer flows the characteristic velocity of the turbulence is typically $1/30$ of the mean current (Tennekes and Lumley 1972). If the horizontal tidal currents are about 3 m/s then one might expect turbulence to occasionally have vertical speeds as high as 0.3 m/s . This

is consistent with Professor Daborn's observation. A little bit of ice might be swept down into the water column by a swirling eddy, but typically it would be found at or near the surface. It is important to note that larger ice blocks with the same density will require larger currents to displace them downwards into the water column. A 16 ton ice block might be considered to have a length scale of 2.5 m in which case $w_c \approx 1.5$ m/s. The 90 ton denizens of the deep would require $w_c \approx 2$ m/s. The other point to note is that strong vertical currents tend to be very localized in the horizontal dimension. Thus, large buoyant particles are much less likely to be subject to large downward currents than are the small particles. **The take home message is, yes, we do expect to find small pieces of ice deep in the water column, but larger pieces will only be found at depth if their buoyancy is very close to that of the water in which they are immersed.**

There is another simple explanation for the observation by Professor Daborn. Ice can freeze to the bottom during low tide. After the tide has come in, defrosting and buoyancy forces can release it so that it floats upwards through the water column — perhaps becoming caught in a plankton net before reaching the surface. On the flood tide it is not uncommon to see a large buoyant block of ice emerge from the depths and bounce spectacularly at the surface, sometimes disappearing again as it gets trapped beneath the moving ice pack. **Such things should not be mistaken as evidence for large neutrally-buoyant ice cakes.**

It is important to realize that vertical current speed can be strongly influenced by bottom topography so the above theory requires site-specific calibration. Unfortunately it is difficult to measure vertical currents and any such measurements are very localized. Fundy Ocean Research Centre for Energy (FORCE) has commissioned deployment of several ADCPs near turbine berth sites and, when these data become available, these should enable some limited determination of vertical velocity.

It is conceptually easy to deploy slightly buoyant drifters in an area of interest and measure the extent to which they are dragged under. We plan to piggy-back with other projects (acoustic fish tracking and marine mammal monitoring) to obtain boat charter time in order to make such drifter measurements. Equipment has been constructed and preliminary methodologies formulated.

9.1 Density discrepancy, skeletons, and impact force

The observations by Professor Daborn and equation (5) enable preliminary calculations that contribute to an assessment of the probability that large ice cakes might collide with a submerged tidal turbine. Oceans (2009) measured tidal currents with values up to ~ 5 m/s in Minas Passage. Conservatively setting $w_c = 5/10 = 0.5$ m/s we can estimate the upper limit on density discrepancy from ambient $|\rho_{\text{seawater}} - \rho|$ that an ice cake with scale L can have and still conceivably be dragged to depths of a submerged tidal turbine. Table 10 shows that density of large ice cakes must be very close to seawater density if they are to be found at the depth of submerged tidal turbines. The main peak in Figure 29 has a density discrepancy from ambient seawater of about 200 kg/m^3 which is much greater than the density discrepancies required by a large ice cake in order for it to be potentially submerged. It seems improbable that just the right amount of much denser frozen sediment or rock will become attached in order that the ice cake can be dragged vertically through the water column by currents.

Given that ice cakes can achieve density discrepancies (of Table 10) by melting away excess buoyancy, and given observations that melting ice cakes have a skeletal structure, the nominal mass of the ice cake is made up of a good deal of liquid water filling gaps in an ice skeleton. The structural strength of such an ice cake would seem to be limited.

Submerged ice has very nearly the same density as seawater and so it has almost the same momentum as the water it displaces. The difference between the force of the flowing water on a turbine and the force of the ice on a turbine is attributable to the ice being less deformable. Thus, strength of an ice cake is a critical metric. We expect the strength of an ice cake to be related to its porosity (which is one reason for measuring porosity). An attempt was made to measure the strength of ice cakes using a penetrometer. This attempt failed, ice being inhomogeneous and having a complex texture. Nevertheless, ice cakes are easy to break up with simple hand tools and we have designs to make measurements pertaining to a ‘practical’ quantification of strength in future.

Table 10: An upper limit on density discrepancy $|\rho_{\text{seawater}} - \rho|$ of an ice cake with length scale L if that ice cake is to be dragged into mid water-column by turbulence resulting from 5 m/s tidal currents.

$ \rho_{\text{seawater}} - \rho $ (kg/m ³)	L (m)	nominal ice-cake mass (kg)
130	0.1	1
26	0.5	130
13	1.0	1000
8.7	1.5	3500
6.5	2.0	8200
5.2	2.5	16000
4.3	3.0	28000

10 The Danger of Subsurface Ice

We see that ice cake density has to fall within a very narrow range (Table 10) in order to pose a hazard to sub-surface tidal turbines. Samples from ice cakes are mostly outside of this range, the majority being of much lower density and a minority being of much higher density. **A large ice cake with near-neutral buoyancy and high structural strength can be achieved but only through a multiplicative sequence of physical mechanisms (see section 6), some of which seem unlikely, and jointly far more rare.**

Figure 32 is a copy of *photograph seven* which appears in Sanders et al (2008), along with commentary: *‘It is not known if the cake pictured in photograph seven was negatively or positively buoyant. If positively buoyant, it may have joined the surface ice that accumulates in the Headwaters of the Bay of Fundy [3,4]. If negatively buoyant, it may have rolled along the sea floor out of view from the surface.’* First, it may be misleading for Sanders et al (2008) to suggest that floating ice *‘accumulates in the Headwaters’* because estuarine circulation has a general tendency for near-surface flows to be out of the estuary with deep flows having a tendency for transport towards the head of the estuary. Second, we have sectioned and measured enough ice cakes to be reasonably confident that *photograph seven* shows a positively buoyant ice cake. Given the incorporated rock (lower right), a negatively buoyant sample might be cut out of this ice cake but almost all of the rest of this ice cake is made from positively buoyant ice.

Sanders et al (2008) make repeated reference to the discolouration of ice cakes. Photograph 2 of Sanders et al (2008) is described in its caption as: *‘Hundreds of lightly snow-covered, heavily sediment-stained ice cakes of unknown buoyancy grounded on Nova Scotia’s extensive intertidal mudflats. Spring tides, storm surges, offshore winds and impacts from adjacent mobile cakes can combine to return these grounded, sediment-laden ice cakes to the central sub-tidal channel.’* Few of those ice cakes were nearly so stained as the very buoyant ice cake shown in Figure 16. Measurements confirm that ice cakes can be very discoloured by silt and yet still be very buoyant. Observations regarding *‘visible amounts of ‘silt’* are of little relevance for assessing density.

Sanders et al (2008) report anecdotes of ice rafting *‘derelict motor vehicles’*. We have found patches of saltmarsh that appear to have been rafted by ice. Certainly rafting is a valid mechanism but this does not mean that submerged tidal turbines are in serious danger of being struck by neutrally-buoyant ice cakes carrying *‘derelict motor vehicles or farm equipment abandoned on the Fundy shore’*. Our observations are more consistent with ice cakes dropping rafted material, i.e.



Figure 32: Photograph seven from Sanders et al (2008).

splitting into two parts, one clearly buoyant the other clearly sinking to the bottom.

Sanders et al (2008) say ‘*We suspect that some of the cakes removed from intertidal mudflats are negatively buoyant.*’ We have studied one ice cake which samples indicated to be marginally, negatively buoyant. It moved only 20 m (Figure 25) even though it was located at a coastal prominence which concentrated strong tidal currents.

11 The Danger of Water-Soaked Wood

Figure 33 shows Photographs 13, 14 and 15 which have been adapted from Sanders et al (2008). Photograph 13 shows a portion of the Parrsboro shoreline with a tree tilting towards the ocean, presumably due to shoreline erosion. Photograph 14 shows forest extending to the edge of cliffs, high above the shoreline at Cape Split, Minas Passage. Photograph 15 shows very weathered logs high on the foreshore at some unspecified location, presumably near Parrsboro or at least in the vicinity of the Minas Passage. Our interpretation of these photographs is different from that of

Sanders et al (2008).

Strong tidal currents are well known to cause coastline erosion and trees tilting towards the sea, such as the one shown in Photograph 13, are not unusual in many parts of the world. Using Google Earth, one can scan the coastline of Minas Basin and Minas Passage and see that human activity has stripped trees from much of the coastal land. On the one hand, this might increase rates of erosion but on the other hand it diminishes the number of trees that might fall into the waterway because of coastal erosion.

Trees at the edge a high cliff (eg Cape Split) might eventually fall into the ocean. But the rate at which trees fall into the ocean is controlled by the rate at which the cliff face is moved inland. A great volume of rock and sediment must be eroded for such a high cliff to recede a short distance. It does not follow from Photograph 14 that this region represents a major source of trees falling into the tide.

Photographs 13, 14, and 15 indicate a predominance of softwood species. Many softwood species are relatively buoyant although they might become waterlogged if they remain in a wet environment for sufficient time. Smith et al (2009) fixed satellite transmitters to 9 ice cakes at various nearshore sites within Minas Basin. Trajectories of some of the transmitters were clearly influenced by grounding and some were lost before they could get out of rivers and into open waters. Three of the transmitters traversed Minas Passage and were retrieved west of Scots Bay. Surface currents tend to be out of the estuary. One expects surface floating objects, like logs and other wooden debris, to either be washed high onto the shoreline (eg Photograph 15) or to be quickly discharged from the area **before** becoming waterlogged.

Other sources of water-soaked wood include fish weirs and derelict wharves. The wood in these structures gets soaked, usually intermitently, over long periods.

There will be a narrow range of densities for which water-soaked wood can be suspended in the water column by turbulent currents. Table 10 can be considered to apply to water-soaked wood if the length scale L is re-interpreted to allow for the fact that trees are typically long and thin with a small cross-section. We have not made measurements of the frequency distribution for density of logs found in and around Minas. But there is no evidence of sinking wood in the 2500+ photographs and extensive video footage in the Minas Passage in and near the FORCE leased area (Envirosphere 2009b). This goes some distance towards suggesting a low risk that water-soaked wood have a density near the dangerous range.

It seems unlikely that '*waterlogged trees*' are more common in the Minas Passage than else-

where. It is an inevitable fact, however, that the number of particles crossing a particular area in a given time will scale in proportion to the tidal current. Similarly, impact forces increase as the square of current. The expectation of impact damage will scale as the cube of current (product of impact force with the distance traversed by particles drifting in the tide). The power that a turbine can generate will scale as the cube of current speed. Potential for power production scales proportional to the potential damage by unwanted collisions, for a given concentration of ice or woody debris drifting in the mid-water column. Waterlogged trees are not a disproportionate concern in Minas Passage.



Figure 33: Top to bottom shows: Photographs 13, 14, and 15 from Sanders et al (2008).

12 A Practical Response to Alarm

Sanders (2011) writes: *‘While I am aware of no proof (either of the existence or non-existence) of sub-surface ice in the tidal energy-rich waters of Nova Scotia’s Minas Passage, I feel there is adequate circumstantial evidence [Sanders et al., 2008] of its formation to require immediate direct monitoring for its presence.’* Specifically, Sanders recommends *‘that transects of sea-floor to water’s surface monitoring of sub-surface traffic be carried out at both the eastern and western boundaries of Minas Passage for at least a full calendar year.’* In order to be useful, such monitoring would require identification of the sub-surface objects, not an easy task.

To the best of our knowledge, there is no direct observation of ice cakes that are both: (1) near neutrally buoyant and (2) drifting near the middle of the Minas Passage water column. Lack of observation is not a proof on nonexistence unless one has made an infallible search. Several methods of searching have been outlined above but none of them can be considered to be comprehensive. But is a comprehensive search required?

Presently, the objective of the FORCE tidal turbine testing facility is to test in-stream tidal turbine technologies and to develop operational protocols. Fundamentally, this is challenging. There are a great many ways in which turbines could fail aside from the risk of collision with large inanimate objects like sub-surface ice or water-soaked wood.

Our measurements, and inference from known physics, leave us better informed as to the risks that ice cakes might present to sub-surface tidal turbines. Qualitatively, we think that near-neutral buoyancy ice cakes pose a small part of the total risk to tidal turbines installed for the purpose of testing. Testing of sub-surface tidal turbines in Minas Passage should be mindful of the ice-collision risk (albeit low) but not delayed or obviated by that risk.

Sanders (2011) proposes monitoring that would be expensive and still would not directly measure the frequency of collisions, or near collisions, with in-stream tidal turbines. It would be more cost-effective to equip turbines and their platforms with devices to measure currents and detect and identify any inanimate objects or marine life that passes nearby or collides with the installation. Other targeted methods to quantify sub-surface hazards may be worth funding, given some prospect that they might be cost-effective.

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