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Movement of drift ice as a vector for transport of sediment and invertebrates on intertidal mudflats of the Bay of Fundy

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During winter, intertidal mudflats of the upper Bay of Fundy are affected by large numbers of blocks of drift ice that get stranded during periods of emersion. We evaluated the potential for ice blocks (>1 m^3) to transport sediment and invertebrates. We first measured the sediment load of ice blocks, and found an average of 34.5 ± 38.3 (SD) g of sediment per litre of melted ice, which translates to 20.2 ± 20.1 (SD) kg of sediment per block (average volume of blocks was 8.0 ± 7.9 (SD) m^3). We then looked for invertebrates in the melted ice samples and found a total of 123 individuals (out of the samples from 27 blocks) belonging to 7 different taxa, 44 % of which were still alive and vigorous. To evaluate potential distances over which ice blocks might carry sediment and animals, we performed a mark-recapture experiment. Most ice blocks moved little, but on specific occasions they moved hundreds of metres and even left the mudflat completely. Given the abundance of ice blocks that are carrying invertebrates, we concluded that ice-mediated between-mudflat migration is possible and may play a role in the population dynamics of mudflat invertebrates in the upper Bay of Fundy.

1. Introduction

During winter in temperate marine environments, different types of ice can form in the intertidal zone. Shore-fast ice forms between the high and low high-water mark (Gutt, 2001) and crust ice forms at the surface of the substrate (Gordon and Desplanque, 1983). Also, pieces of drift ice can pass over the intertidal zone during periods of immersion and can sometimes get stranded (Gordon and Desplanque, 1983). Movement of drift ice can cause scouring of the substrate, dislodging plants and animals (Barnes, 1999) and also accumulate and transport material (Dionne, 1984).

The upper Bay of Fundy, eastern Canada, experiences some of the highest tides in the world (Desplanque and Mossman, 2004) and the intertidal zone contains several intertidal mudflats, some of which can cover an area of ~20 km^2. These mudflats bear a diverse and abundant community of invertebrates including crustaceans (amphipods, copepods and ostracods), molluscs (bivalves and gastropods) and polychaetes (Hicklin et al., 1980). Mudflats are important foraging grounds for vertebrates, including commercially exploited fish (McCurdy et al., 2005) and different species of migratory shorebirds (Hicklin and Smith, 1979). During winter, large amounts of drift ice accumulate over the mudflats and may cause important mortality of invertebrates through scouring (Wilson, 1991). Drift ice accumulates large amounts of sediment as shown by a sampling of blocks found in salt marshes in the area, and ice-rafting contributes significantly to the transport of sediments from the mudflats to the high marshes (Ollerhead et al., 1999). Direct associations between unattached marine ice and benthic invertebrates have been reported in Medcof and Thomas (1974) and Dayton (1970), where a number of invertebrates (some still alive) were brought to the surface after being trapped in anchor ice. To our knowledge, whether ice blocks can also trap and carry intertidal mudflat animals and contribute to the redistribution of infaunal invertebrates has not yet been examined.

The objective of this study was to evaluate the potential for blocks of drift ice to serve as a vector of transport for sediment and invertebrates within and between mudflats in the upper Bay of Fundy. We measured the sediment load of blocks of drift ice stranded on a focal intertidal mudflat and evaluated if blocks also contained invertebrates during the winter of 2010-2011. As well, to determine if ice blocks can be involved in the dispersal of animals, we evaluated survival of animals trapped in ice. Finally, to determine how far ice blocks could potentially transport invertebrates, we performed a mark-recapture experiment with ice blocks.

2. Methods

2.1 Study site

The work was conducted on the Grande Anse mudflat located in Shepody Bay (western branch of Chignecto Bay; Fig. 1) between January and March 2011. The mudflat is approximately 6 km wide along shore and the intertidal zone extends over 2.5 km across shore. The sediment is mostly composed of silt and clay (T. Gerwing, unpublished data) with a layer of unconsolidated sediment typically 10 cm deep (but can reach up to 40 cm). The mudflat faces west and dominant westerly winds push drift ice towards shore, usually resulting in a densely packed ice zone near shore and a relatively ice-free zone far from shore. Depending on the total amount of ice on the mudflat on a given day, the ice zone can extend from about 100 to 1500 m from shore. Sampling and experiments were done on 3 transects running perpendicular to the line of low water, hereafter referred to as north, central and south transects (Fig. 1).

2.2 Sampling of ice blocks

Blocks of drift ice were sampled to obtain information on (1) their size distribution, (2) sediment load and (3) presence of trapped invertebrates. Sampling was done on the 3 transects during 3 periods in winter 2011: (1) immediately after ice blocks appeared, 31 January to 12 February, (2) in the middle of the ice season, 13-27 February, and (3) immediately before all ice blocks disappeared, 28 February to 3 March. For each day of sampling and on each transect, the distance from shore to which the ice zone extended was measured and this distance was used as the transect length. Each transect was then sampled using a stratified random design by subdividing it into 3 equal-length zones, and 4 ice blocks (bigger than 1 m^3) were randomly selected within each zone. We thus recorded information for 36 ice blocks during each sampling period (4 blocks x 3 distance zones x 3 transects). Each block was measured along 3 axes (height, along shore and across shore) and volume was estimated by multiplying the 3 measurements.

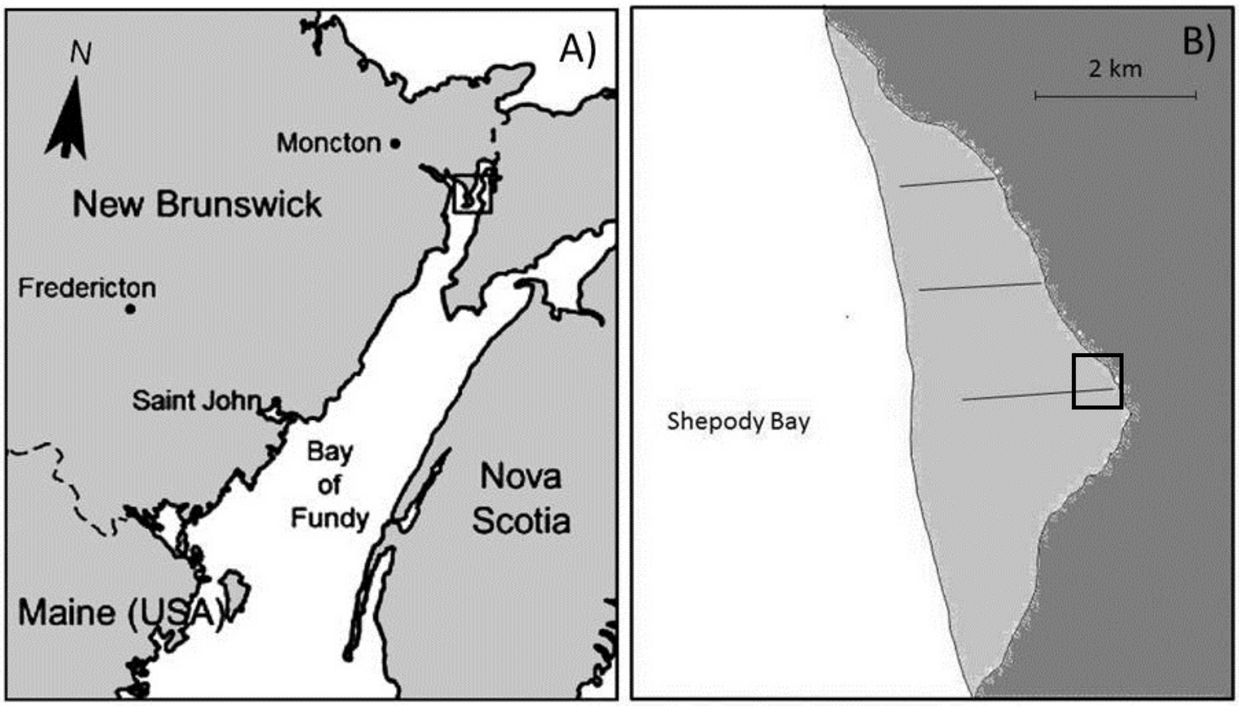

Figure 1. Maps of A) the Bay of Fundy in Eastern Canada; square shows the general location of the study site and B) the Grande Anse mudflat with the approximate location of the 3 transects (solid lines); square shows zone magnified in Figure 5.

We analyzed the sediment and invertebrate content of one randomly selected ice block within each transect x zone combination (9 blocks per sampling period). A ~ 30 cm x 30 cm x 30 cm chunk was taken from each of the top, middle and bottom third of each block, brought back to the laboratory and left to melt in a plastic container for 48 h. Note that we were careful not to collect ice that was in direct contact with the substrate to avoid artificially inflating sediment load. To collect any invertebrate contained in the melted ice, the water was passed through a 250-µm sieve (Crewe et al., 2001), and the sieve was rinsed with the original water until all the sediment went through. We retained all water and sediment from the original sample for further measurements of water volume and sediment load. Contents of the sieve were examined under a dissecting microscope. Invertebrates were counted, identified to various taxonomic levels and assessed as dead or alive. The rest of the melted ice (water and fine sediment) was left to settle for 3 days, after which we carefully decanted and separated the water and the sediment. We measured the volume of water in a graduated beaker. We placed the wet sediment in a pre-weighed aluminum dish, weighed it, dried it at ~ 100 °C for 48 h and reweighed it to calculate sediment weight and water loss during drying. The volume of water lost was then added to the volume of water collected earlier. From there, we calculated sediment concentration (g L^{-1}) for each sample. Also, using the volume of the ice block measured in the field, it was possible to estimate the total sediment load of each ice block. This was done by calculating the average concentration of sediment in the bottom, middle and top third of each block and dividing this value by the estimated proportion of a chunk of ice sampled (0.027 m^3 (30 x 30 x 30 cm) divided by the estimated total volume of the block). We evaluated the temporal and spatial variation in sediment concentration (g L^{-1}) for each block (average for the 3 layers) by conducting a two-way factorial ANOVA with the fixed factors Time (the 3 sampling rounds) and Transect (south, central and north). Concentrations were $\log_{10}$-transformed to correct for heterogeneity of variances.

2.3 Tracking of ice blocks

To determine if blocks of drift ice that are stranded on the mudflat are mobile and evaluate how far blocks can go, we performed a mark-recapture experiment on the South and North transects (Fig. 1). We used both visual marking and radio transmitters, and deployed markings on 10-11 February and 2 March 2011. The visual marking of blocks was done by (1) drilling a 2.5-cm diameter hole (30 cm deep) in each of the 4 sides of the block, (2) placing a 2.2-cm diameter piece of wood dowelling (9 cm long and attached to a long piece of flagging tape) in each hole, and (3) plugging each hole with snow and ice and splashing with water. The flagging tape (with identification markings) extended 20-30 cm outside the block's side surfaces. For the blocks that were also tagged using radio-transmitters (on 10-11 February), a fifth hole on the block's side was drilled as described above, a radio-transmitter was inserted (BD-2 transmitter; Holohil Systems Ltd), and the hole covered as above. The antenna extended ~10 cm outside the block's side. For the first deployment, 6 blocks were visually marked on each transect, with 3 blocks tagged close to shore (30-50 m from the shore-fast ice) and 3 further from shore (100-150 m). Within each transect x distance zone combination, we placed a radio transmitter on one block. For the second deployment, one block was visually tagged in each transect x distance zone combination. After the blocks were marked, their position was recorded with a handheld GPS unit (Garmin eTrex H, typical accuracy of 3-5 m). On the following days, blocks were relocated using a thorough visual search of the mudflat and a radio receiver (R1000; Communications Specialists Inc) for radio-tagged ice blocks. The new position of the blocks was recorded. For the first deployment, this was done 1, 2, 3, 6 and 7 days after the initial marking on the South transect, and after 1, 2, 5 and 6 days on the North transect. For the second deployment, recapture was done 1, 2 and 3 days after the marking on the South transect and after 1 and 2 days on the North transect. From the coordinates of the blocks, we measured the daily net displacement.

3. Results

3.1 Sampling of ice blocks

The average volume of the 108 ice blocks measured was 6.8 m^3 (SD = 6.8; Fig. 2), with many small blocks (1-5 m^3) and a few larger blocks (maximum volume of 41.8 m^3). The 27 ice blocks sampled had an average of 34.5 g of sediment per L of water collected (SD = 38.3; Fig. 3). Sediment concentration in ice blocks did not vary significantly with Time (ANOVA: $F_{2,18}$ = 1.10, p = 0.36) or Transect ($F_{2,18}$ = 0.68, p = 0.52), and there was no interaction between the two factors ($F_{4,18}$ = 0.61, p = 0.66). Most blocks had a low sediment concentration (< 20 g L^{-1}) although some blocks had a very high concentration (maximum of 160 g L^{-1}). When the total sediment load was estimated, we obtained an average of 20.2 kg of sediment (SD = 20.1; Fig. 4) per block. Most blocks had less than 10 kg of sediment, but the maximum value recorded was over 80 kg.

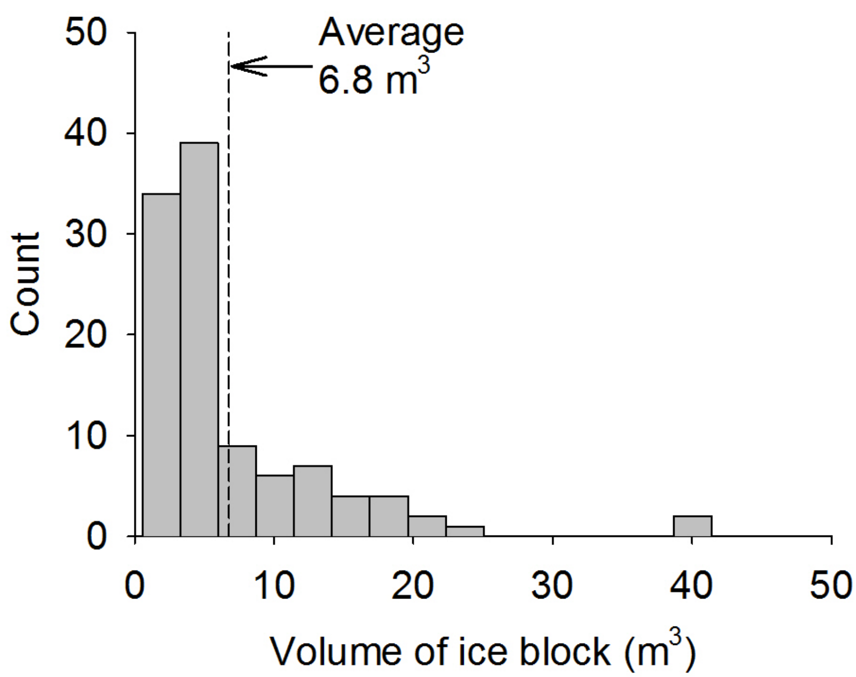

Figure 2. Frequency distribution of volume of the 108 ice blocks measured on the Grande Anse mudflat during winter 2011.

We found 123 invertebrates from 7 taxa in the melted ice samples. The main taxa identified were amphipods (all were *Corophium volutator*, except 1 that was a *Marinogammarus*), copepods, ostracods, nematodes, polychaetes, molluscs and turbellarian (Table 1). The most commonly found group was copepod with 86 individuals in total. Between 25 and 60 % of individuals (for taxa from which we found more than 1 individual) were still alive and swimming vigorously (Table 1).

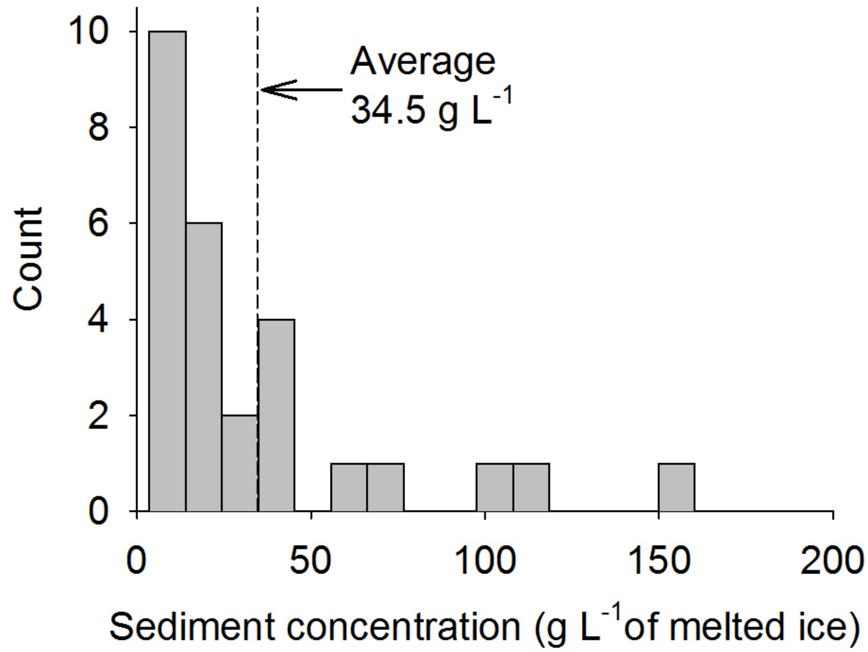

Figure 3. Frequency distribution of sediment concentration found in 27 ice blocks on the Grande Anse mudflat during winter 2011.

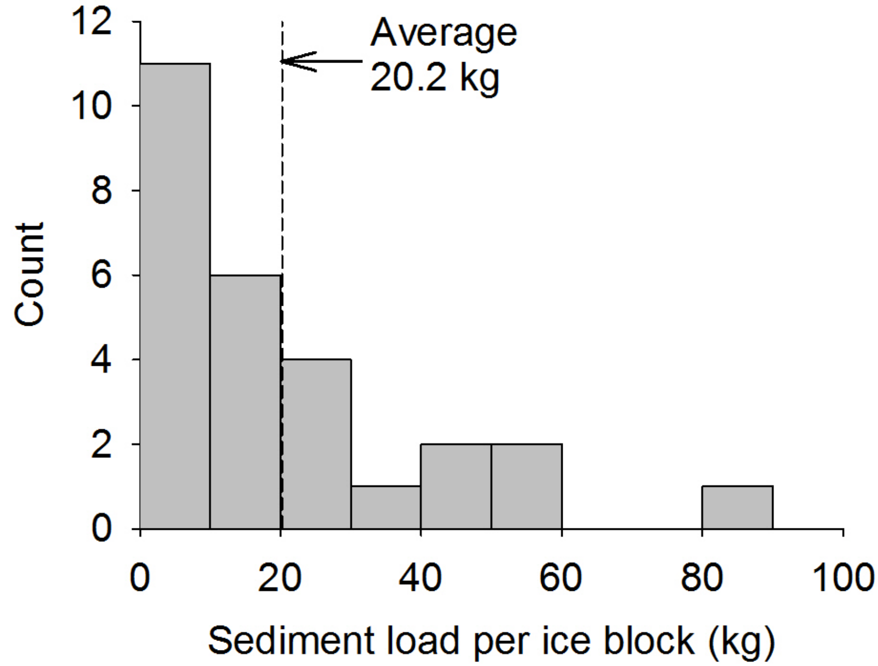

Figure 4. Frequency distribution of total sediment load of 27 ice blocks (volume of 1-39 m^3) sampled on the Grande Anse mudflat during winter 2011.

Table 1. Number of live and dead invertebrates of different taxa found in blocks (n = 27) on the Grande Anse mudflat in the upper Bay of Fundy during winter 2011.

Taxon	Alive	Dead	Percentage alive
Amphipod	7	8	47
Copepod	36	50	42
Ostracod	2	6	25
Nematode	4	3	57
Polychaete	3	2	60
Mollusc (*Macoma)*	1	0	100
Turbellarian	1	0	100

3.2 Tracking of ice blocks

Of the 7 ice blocks marked close to shore (3-50 m from the shore) all of them were re-sighted at least once, whereas we only re-observed 3 of the 9 blocks marked further away from shore. A typical path (Fig. 5) consisted of several days with little to no movement, followed by long jumps. The average daily displacement was 13.3 m (SD = 23.4) with most blocks moving very little (<5 m) and one block moving a minimum of 113 m within 24 h (Fig. 6). However, on one occasion, an ice block equipped with a radio-transmitter (and flagging tape) disappeared from the mudflat as its signal could not be picked up at all and it was not visible.

4. Discussion

In this study, we evaluated the potential for blocks of drift ice to act as vectors for transport of sediment and invertebrates on a mudflat of the upper Bay of Fundy. Several conditions were required for this possibility to be realistic. First, significant amounts of sediment must be found within the ice blocks for them to have a notable impact on sediment budget. Second, invertebrates must be present within the ice, and still be alive to allow successful settlement and contribution to the population dynamics of their new location. Third, the ice blocks, picking up sediment while stranded on the mudflats at low tide, need to move.

Large amounts of sediment were indeed present in the blocks of ice. We found on average 38.5 g of sediment per litre of melted ice, which translated into 20.2 kg of sediment per block. Ice blocks can pick up sediment by different means. They can incorporate suspended sediment from the water or the substrate during the freezing process (in salt marshes or along the sides of drainage channels; Argow et al., 2011), or collect sediment while settling at the surface of the mudflat or while being dragged over the surface of the mud during ebb or flood tide (Gordon and Desplanque, 1983). Our estimates of sediment concentration are within the range obtained by previous studies focussing on salt marshes; Ollerhead et al. (1999) found an average of 48 g L^{-1} in the same general area (Chignecto Bay) and Argow et al. (2011) found an average of 19 g L^{-1} in New England, with a latitudinal gradient (less sediment further south). Note that our estimates of mass of sediment per ice block may be slight overestimates because we simplistically assumed an ice block was a rectangular prism (we calculated volume by multiplying the length of the block on three axes). On most occasions this assumption seemed

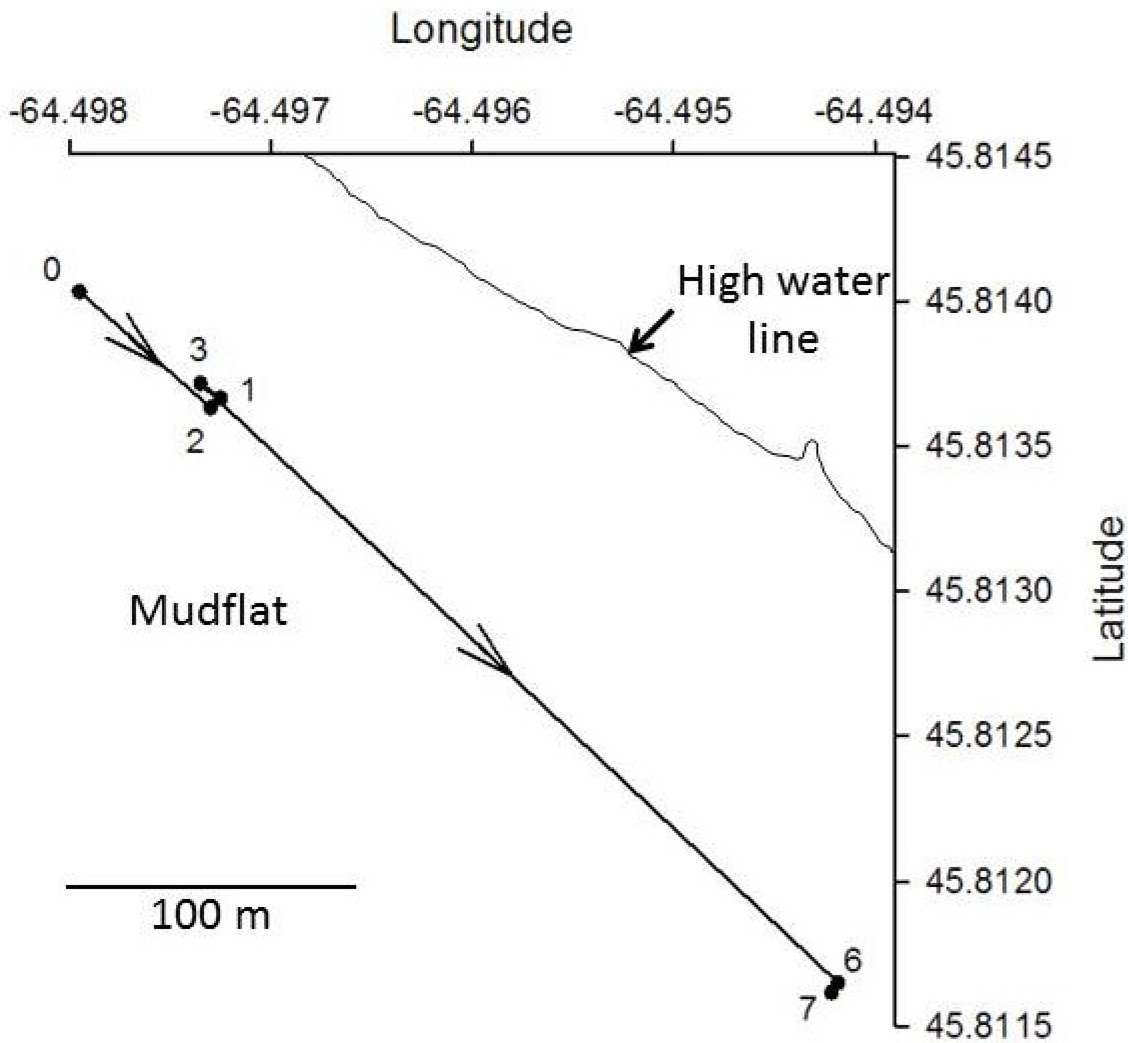

Figure 5. Map showing a representative path of a tagged ice block on the Grande Anse mudflat. See Figure 1 for specific location on the mudflat. Each dot represents the position of the ice block on a specific day following the initial marking (numbers beside dots; block was tagged on day 0).

reasonable given the general shape of the blocks, but in other cases the blocks seemed more ellipsoidal. Also, for practical reasons, we only collected chunks of ice from the periphery of the blocks. We were careful not to sample ice in direct contact with the mud, but observations showed that blocks can flip during periods of immersion. Given sediment is partially collected by direct contact with the substrate, the outside is where we would expect the highest concentration, so again this may have caused an overestimation.

It is notable that we found invertebrates incorporated into the ice blocks. This probably occurred by direct contact between the ice and the substrate, either while resting or while being dragged over the mudflat. All of the common groups of infaunal invertebrates found in core samples during the summer months were found in ice. Of the total number of animals found, ~44

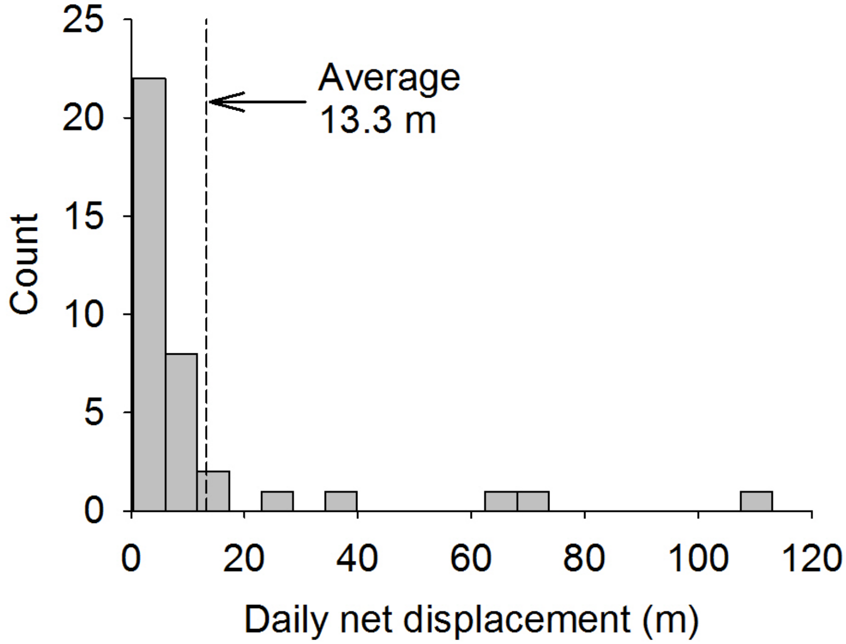

Figure 6. Frequency distribution of daily net displacement of ice blocks tagged on the Grande Anse mudflat during winter 2011.

% were still alive and many seemed fully healthy, swimming vigorously in the container while the ice chunks were melting. Many intertidal invertebrates are well adapted to extreme cold conditions and are known to be able to survive freezing (Loomis, 1995). However, given the fairly low survival measured, we believed survival time might be short. To our knowledge this is the first record of live mudflat invertebrates embedded in pieces of drift ice.

Ice blocks that were stranded on the mudflat at low tide were occasionally moved during a period of immersion. Typically, a block would remain fairly stationary for a few days and then jump over longer distances. This resulted in a highly skewed distribution of the daily displacement distances (Fig. 6). Note that most of the small distances measured (first histogram bar on Fig. 6), were smaller than the accuracy of the GPS unit used (normally 3-5 m), thus they may not have moved at all. Dominant westerly winds in the area (Gordon and Desplanque, 1983) typically result in a dense aggregation of ice blocks close to shore on the Grande Anse mudflat. Those tightly packed ice blocks may only be affected by currents in specific conditions, for example when the wind shifts, whereas ice blocks not surrounded by many others may move more freely. This may explain the lower re-sighting probability of blocks marked further from shore where block density was lower. Presumably these blocks moved too far to be re-sighted using the visual method. This is also supported by the fact that we lost one block that was equipped with a radio transmitter, suggesting the ice block left the range of the antenna (6 km) and probably the mudflat. In addition, blocks stranded lower in the intertidal zone might move more due to longer periods of immersion, higher wave action or stronger currents. Overall, blocks of drift ice stranded on the mudflat are often stationary but under specific conditions can move long distances and even leave a mudflat.

In summary, all the conditions required for ice blocks to act as vectors for sediment and invertebrate transport were met. Large amounts of sediment are embedded within the blocks, live invertebrates are present, and ice blocks can be highly mobile. Our data on movement of ice blocks are not detailed enough to evaluate the impact of drift ice on the net transport of sediment (i.e. resulting in accumulation or loss of sediment for a mudflat). To answer this question, an oceanographic modelling approach at broad spatial scales incorporating the tide and wind-driven currents would be more appropriate. The fact that we found live invertebrates in the ice supports the possibility of ice-mediated dispersal. Some invertebrates are probably carried around within a mudflat, but the impact on the overall within-mudflat distribution is probably negligible compared to the intense redistribution observed during the summer (e.g. Drolet and Barbeau, 2009). However, given the huge number of blocks that can be present on a mudflat, the length of the ice season (1-3 months), the number of invertebrates transported, and the potentially large distances travelled by ice blocks (see also Smith et al., 2009), ice-mediated between-mudflat dispersal seems plausible and could play a role in the population dynamics of infaunal mudflat invertebrates in the upper Bay of Fundy.

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References

Argow, B.A., Hughes, Z.J., and FitzGerald, D.M. (2011). Ice raft formation, sediment load, and theoretical potential for ice-rafted sediment influx on northern coastal wetlands. Continental Shelf Research, doi:10.1016/j.csr.2011.05.004

Barnes, D.K.A. (1999). The influence of ice on polar nearshore benthos. Journal of the Marine Biological Association of the United Kingdom, 79: 401-407.

Crewe, T.A., Hamilton, D.J. and Diamond, A.W. (2001). Effects of mesh size on sieved samples of *Corophium volutator*. Estuarine, Coastal and Shelf Science, 53: 151-154.

Dayton, P.K. (1970). Rafting of animals to the surface by ice. In: Holdgate, M.W. (ed.) Antarctic ecology, 1: 289-290.

Desplanque, C. and Mossman, D.J. (2004).Tides and their seminal impact on the geology, geography, history, and socio-economics of the Bay of Fundy, eastern Canada. Eastern Geology, 40: 1-130.

Dionne, J.C. (1984). An estimate of ice-drifted sediments based on mud content of the ice cover at Montmagny, Middle St. Lawrence Estuary. Marine Geology, 57: 149-166.

Drolet, D. and Barbeau, M.A. (2009). Diel and semi-lunar cycles in the swimming activity of the intertidal, benthic amphipod *Corophium volutator* in the upper Bay of Fundy, Canada. Journal of Crustacean Biology, 29: 51-56.

Gordon, D.C. and Desplanque, C. (1983). Dynamics and environmental effects of ice in the Cumberland Basin of the Bay of Fundy. Canadian Journal of Fisheries and Aquatic Sciences, 40: 1331-1342.

Gutt, J. (2001). On the direct impact of ice on marine benthic communities, a review. Polar Biology, 24: 553-564.

Hicklin, P.W. and Smith, P.C. (1979). Diets of five species of migrant shorebirds in the Bay of Fundy. Proceedings of Nova Scotia Institute of Science, 29: 483-488.

Hicklin, P.W., Linkletter, L.E. and Peer, P.L. (1980). Distribution and abundance of *Corophium volutator* (Pallas), *Macoma balthica* (L.) and *Heteromastus filiformis* (Claparède) in the intertidal zone of Cumberland Basin and Shepody Bay, Bay of Fundy. Canadian Technical Report of Fisheries and Aquatic Sciences 965: 56 pp.

Loomis, S.H. (1995). Freezing tolerance of marine invertebrates. Oceanography and Marine Biology Annual Review, 33: 337-350.

McCurdy, D.G., Forbes, M.R., Logan, S.P., Lancaster, D. and Mautner, S.I. (2005). Foraging and impacts by benthic fish on the intertidal amphipod *Corophium volutator*. Journal of Crustacean Biology, 25: 558-564.

Medcof, J.C. and Thomas, M.L.H. (1974). Surfacing on ice of frozen-in marine bottom materials. Journal of the Fisheries Research Board of Canada, 31: 1195-1200.

Ollerhead, J., van Proosdij, D. and Davidson-Arnott, R.G.D. (1999). Ice as a mechanism for contributing sediments to the surface of a macro-tidal saltmarsh, Bay of Fundy. Proceeding of the Canadian Coastal Conference: 345-358.

Smith, K., Woods, J., Long, A., MacDonald, W.B., Fader, G., Bishop, R., and Melrose, S. (2009). The characterization and tracking of sediment-laden ice in Minas Basin, Nova Scotia. Proceedings of the 8th BoFEP Bay of Fundy Science Workshop, 63-74.

Wilson, W.H. (1991). The importance of epibenthic predation and ice disturbance in a Bay of Fundy mudflat. Ophelia, supplement 5: 507-514.