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Formation, collapse and composition of ice banks in a macrotidal channel of the Bay of Fundy

CarolAnne Black*, Paul S. Hill, Laura deGelleke

Dalhousie University, Department of Oceanography, Halifax, Nova Scotia B3H 4R2, Canada

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ABSTRACT

Large ice blocks containing enough sediment to be denser than sea water form in the Minas Basin of the Bay of Fundy, Canada. Ice block composition and the timing of ice block formation were monitored to improve understanding of the potential threat to tidal power generators posed by collision with ice blocks. Field studies were carried out in 2012 and 2013 in the Kennetcook River, which is a tributary of the Minas Basin of the Bay of Fundy. In 2012, the cross-sectional area of the channel at the study site decreased by 21% due to the formation of ice walls. In 2013, it decreased by 24%. Large ice blocks separated from the ice walls during spring tides following a time lag of the minimum air temperature. The time lag was 20 days in 2012 and 21 days in 2013. Eleven percent of samples from ice blocks were denser than sea water.

1. Introduction

During winter in the Minas Basin of the Bay of Fundy (Fig. 1), a remarkable change occurs in the morphology of the channels of tidal tributaries. Ice freezes to the banks and flats of tidal channels connected to the Basin, and vertical ice walls up to 5 m high form (Desplanque and Mossman, 2004). This morphology lasts until the end of winter, when the ice walls become unstable and collapse, releasing large ice blocks into tidal channels (Knight and Dalrymple, 1976). Approximate volume of individual ice blocks can exceed fifty cubic meters based on rough field measurements of vertical and horizontal dimensions (Fig. 2). These ice blocks contain sediment and may be as dense as or denser than sea water (Sanderson and Redden, 2015).

Interest in large, sediment-laden ice blocks and the ice cliffs that spawn them waxes and wanes with plans for large infrastructure projects in the Bay of Fundy. Hind (1875) was the first to describe ice in the upper basins of the Bay. His study of the ice addressed its effects on a proposed navigational canal between the upper Bay of Fundy and the Northumberland Strait. Since then, others have described the ice to improve understanding of the challenges posed to tidal energy generation with installations such as tidal barrages (Desplanque and Bray, 1986; Gordon and Desplanque, 1981; Sweet, 1968). Others have discussed large sediment-laden ice blocks as part of wider efforts to understand general ice conditions in the Bay (Desplanque, 1967; Gordon and Desplanque, 1983). Some studies have focussed on the ecological effects in relation to sediment transport and disturbance caused by ice blocks interacting with the channel bed. (Bancroft, 1905; Gordon and Desplanque, 1981; Gordon and Desplanque, 1983; Knight and Dalrymple, 1976; Ollerhead et al., 1999; van Proosdij et al., 2006). More recently, interest in ice blocks has grown because bottom-anchored tidal energy generators may be deployed in Minas Basin to extract tidal energy. Such generators may be damaged by neutrally or negatively buoyant sediment-laden ice blocks (Sanders et al., 2008; Sanderson and Redden, 2015). The overall motivation for this work is to increase understanding of the threat posed by sediment-laden ice blocks.

The specific goal of this work was to conduct regular surveys of the geometry of a tidal channel to clarify the timing of formation and release of ice blocks into the Bay. Additionally, because of the possible threat to bottom-anchored tidal energy generators posed by neutrally or negatively buoyant ice blocks, density and composition of samples of ice blocks also were measured.

1.1. Seasonal ice cycle in tidal channels

What follows is an observational overview of the formation of ice in tidal channels in the Minas Basin (Fig. 3). For more detailed definitions of types of Minas Basin ice, see Gordon and Desplanque (1981).

In early winter, tiny fragments of ice, called frazil ice, form in abundance throughout the super-cooled water column over the Minas Basin mudflats. The ice particles float to the surface and agglomerate with one another and with suspended sediment, creating a brown

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* Corresponding author.
E-mail address: carolanne.black@dal.ca (C. Black).

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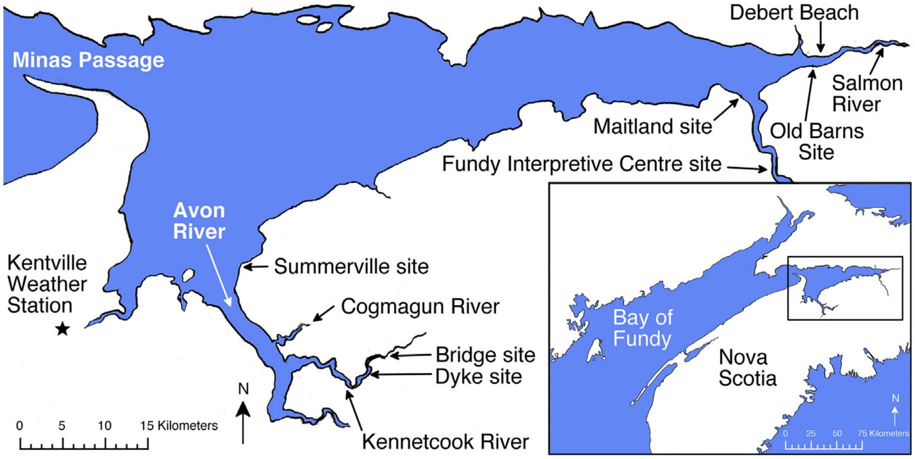

Fig. 1. Map of Minas Basin, Bay of Fundy. Field sites are indicated for Summerville; the Kennetcook River Bridge and Dyke; Maitland and Fundy Interpretive Centre, along the Shubenacadie River; and Debert Beach and Old Barns, along the Salmon River. The inset is of the greater Bay of Fundy region and indicated within it is the location of Minas Basin. The location of the Kentville weather station is also indicated.

Fig. 2. Sediment-laden ice block, of about 3 m by 4 m by 4 m in size, at Debert Beach on February 24, 2011.

slushy layer of unconsolidated ice, called *grease ice*. (Desplanque and Bray, 1986) Over time, grease ice freezes together into pieces of flat and plate-like *pan ice*. The ice is transported with the tides around the Basin and into tidal channels. During ebb tides, large volumes of ice become stranded on the exposed sections of the mudflats and channel banks. Stranded ice, open to freezing air temperatures at low tide, freezes to surrounding ice or to the substrate. Larger conglomerations of ice form as pan ice is rafted over, and deposited onto, pieces of pan ice that are already temporarily stranded on mudflats. Additional thickening occurs by deposition and accumulation of snow and freezing rain. Pieces of ice that grow nearly as thick as they are wide are called *cake ice*. (Gordon and Desplanque, 1981) Some of the ice is re-floated as water returns on flood tides, but some freezes so solidly that it does not re-float. Ice that is frozen to the substrate is called *shorefast ice*.

Ice walls are one form of shorefast ice (Desplanque and Mossman, 1998; Gordon and Desplanque, 1981; Gordon and Desplanque, 1983). In the narrow parts of tidal channels, which have trapezoidal cross-sections in the summer, the accumulation of ice results in the formation of vertical *ice walls* (Figs. 4 and 5) that make the cross-sectional shape rectangular in the winter (Desplanque, 1967; Gordon and Desplanque, 1981). Ice-wall height depends on tidal range in the host channel (Fig. 5). The tops reach the high water level, and the bases occur close to the low water level (Gordon and Desplanque, 1983) because ice strands and freezes to the bed most easily on substrate that is exposed to the air during part of the tidal cycle. (Sanderson and Redden, 2015)

During the spring melt, ice walls fracture and large pieces of ice slump and fall into channels (Gordon and Desplanque, 1981). The density of these large blocks can increase by two mechanisms. First, as an ice block melts, it preferentially releases water, but retains sediment, which increases its density by *differential release* (Fig. 6a). Alternatively, Sanderson and Redden (2015) observed that melting can soften sediment in blocks, which allows currents to remove it from blocks as they are inundated. This process reduces the density of blocks. Second, stranded ice can freeze to the substrate and incorporate a significant amount of sediment into its base, *plucking* it away with the re-floated block (Desplanque, 1967; Desplanque and Bray, 1986; Desplanque and Mossman, 1998; Hind, 1875; Knight and Dalrymple, 1976; Gordon and Desplanque, 1981; Sanders et al., 2008; Sanderson and Redden, 2015). Indications of plucking are layers of sediment and grass in blocks and indentations in the sediment substrate (Fig. 6b and c).

The first objective of this study was to explore the relationship between air temperature and timing of ice wall formation and collapse. The second objective was to collect data on the density and composition of sediment-laden ice by measuring the masses and volumes of samples of sediment-laden ice blocks and the sediment mass contained within the same samples.

2. Methods

2.1. Field sites

The primary field site was at a bridge along a narrow section of the Kennetcook River, near Scotch Village, Nova Scotia (Figs. 1, 4a, b, 5, 7, 8). The bridge span is greater than the width of the channel, so that the ends of the bridge do not interact with the channel, and the channel banks have not been altered to become part of the bridge structure, i.e., there is no cement or other kind of armouring of the banks. There is one bridge footing, in the centre of the channel. The tides in the region are semi-diurnal, and the tidal range at the bridge is about 5 m. The primary field site was observed weekly to biweekly from October 2011 to May 2012, and approximately weekly from January to April 2013. Ice walls were monitored with photography, the channel profile was measured, and sediment samples were collected (in 2011–2012 only). Attempts were made to collect ice cores directly from the ice walls, but the upper surfaces of the ice walls had large air pockets and regions of poorly consolidated ice. These physical properties made it impossible to estimate the volume of the cores accurately, so the composition and density of the ice walls were not measured directly in this study. Ice blocks that either had rafted onto, or calved off of, the ice walls, however, were sampled and characterized.

At five other sites, ice blocks were routinely sampled and photographed. One site was at Summerville, along tidal flats near the mouth of the Avon River. Two sites were along the Shubenacadie River, close to Maitland, along Highway 215: one was at the Fundy Tidal Interpretive Centre in South Maitland, where rock cliffs wall the river and a small tributary connects to it; the other was farther north along Highway 215, in Maitland, at the mouth of the Shubenacadie River,