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Tidally-generated internal waves in Southeast Hudson Bay

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ABSTRACT

The location of the amphidromic point of the M2 tide in Hudson Bay roughly coincides with Belcher Islands, a region where the surface mixed layer stays relatively fresh throughout summer and winter due to significant ice melt and river discharge. High-resolution satellite radar imagery for the ice-free season revealed that the coastal region in the south-east Belcher Islands is a hot spot for short-period internal wave activity. For a first investigation of tidal dynamics in the region, we took advantage of the sea ice platform to deploy an ice-tethered mooring consisting of nine conductivity and temperature sensors and an acoustic Doppler current profiler. The mooring was deployed at 65 m depth in January–March 2014 in a narrow channel between Broomfield and O′Leary islands located in the south-east tip of the Belcher Islands group in Hudson Bay (56°20′N, 79°30′W), northeast Canada. The surface mixed layer under the land-fast ice in this area stays relatively fresh through winter presumably because of significant winter river discharge in nearby James Bay. The mooring recorded oscillations of temperature and salinity throughout the whole water column, which were attributed to vertical displacement caused by internal tidal waves. The tidal harmonic analysis performed for the M_2 tidal constituent showed the dominance of the baroclinic tide with maximum velocity amplitudes at the surface and decreasing with depth. Vertical displacements of water parcels derived from both temperature and salinity were statistically similar and displayed the maximum values of 11.9 m at 35 m (instrument depth). The combination of winter hydrographic data and summer satellite observations confirmed that the observed internal waves were generated by the interaction of strong tides, typical for Hudson Bay, with highly variable bottom topography southeast of the Belcher Islands archipelago.

1. Introduction

Internal waves in Arctic regions have been of recent scientific interest due to their role in vertical mixing, and their influence on the heat budget of the upper ocean and ice cover (Morozov and Pisarev, 2002; Garrett and Kunze, 2007; Morozov et al., 2008, 2017; Guthrie et al., 2013; Rippeth et al., 2017). Several studies of internal waves were conducted in Arctic fjords during ice-free (Svendsen et al., 2002; Støylen and Fer, 2014) and ice covered (Parsmar and Stigebrandt, 1997; Marchenko et al., 2010; Støylen and Weber, 2010; Morozov and Marchenko, 2012) periods. During ice-free periods, internal waves in fjords are forced by changing winds and barotropic tides (Svendsen et al., 2002). During the ice-covered season, internal waves are formed through the interaction between the barotropic tide, bottom topography and the background stratification (Støylen and Weber, 2010; Luneva et al., 2015). In certain cases, the ice cover can act as a contributing factor towards internal tidal wave amplification (Dmitrenko et al., 2002, 2012). Internal waves can be generated below the land-fast ice due to the interaction of the tidal flow and glacier outlets (Kirillov et al., 2017).

Hudson Bay (Fig. 1) is a large (~ 831,000 km^2), seasonally-ice covered shelf sea, connected to the Arctic Ocean through the Canadian Archipelago and to the North Atlantic through Hudson Strait. Hudson Bay receives freshwater inputs from the largest watershed in Canada, which, together with sea ice-melt, results in strong seasonal stratification (cf., Ferland et al., 2011). The tide in Hudson Bay is mostly lunar semidiurnal (M_2) with an amplitude of about 3 m at the entrance to Hudson Bay from Hudson Strait (Prinsenberg and Freeman, 1986;

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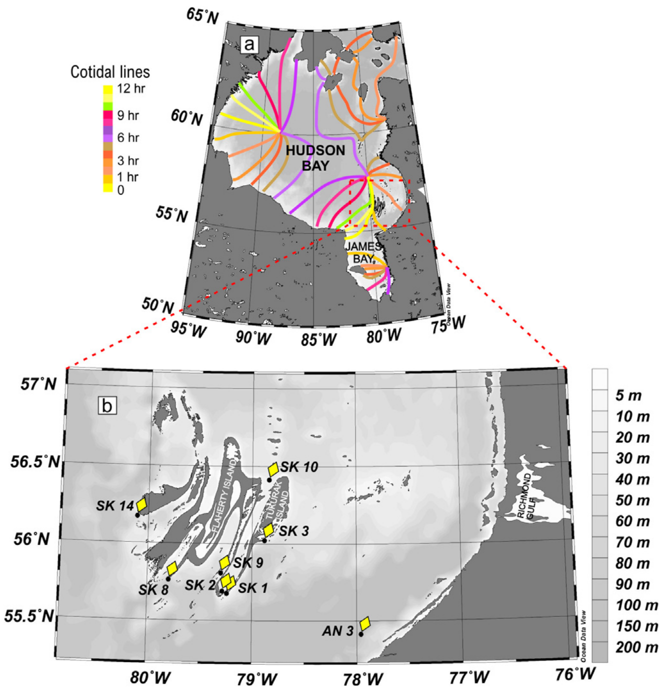

Fig. 1. (a) Hudson Bay and M $_2$ amphidromic points and hourly cotidal lines with phase intervals of ~ 30° (adapted from St-Laurent et al. 2008). (b) The bathymetric map of the Belcher Islands region and location of the 2014 sampling sites and ArcticNet 2003 mooring location (AN 3). Map data: Ocean Data View, GEBCO.

Saucier et al., 2004). The M_2 tide in a form of a Kelvin wave propagates anticlockwise around Hudson Bay, partially entering James Bay at its southern end (Fig. 1) and partially proceeding along the east coast of Hudson Bay, before finally joining the incoming tide at Hudson Strait 25 h later (Prinsenberg and Freeman, 1986; Wang et al., 1994; Saucier et al., 2004; Chen et al., 2009). In the vicinity of the Belcher Islands, in south-east Hudson Bay, the maximum tidal heights reach 1.2 m. Hudson Bay has one of world highest M_2 tidal dissipation rates (Egbert and Ray, 2000). Two major M_2 amphidromic points (shown in Fig. 1a) are connected by a nodal line and located in the central and east-central parts of Hudson Bay (Freeman and Murty, 1976; St-Laurent et al., 2008; Webb, 2014). St-Laurent et al. (2008) in their model study showed the existence of two secondary M_2 amphidromic points: one located north-east of the latter major amphidrome and another one in the east-central part of James Bay (Fig. 1a). However, as pointed out by Chen et al. (2009), modeling of internal tides in Arctic and sub-Arctic regions including Hudson Bay, especially during the ice-covered period, is very difficult without having accurate information on water stratification and parameters (sea-ice velocity, deformation, and ice-ocean drag coefficient) of drifting and land-fast ice.

Until now observations of internal tidal waves in Hudson Bay have not been conducted. The Belcher Islands archipelago is an interesting region for internal wave observations due to its unique shoreline and bottom topography (Fig. 1b) and its location near an amphidromic point such that the M_2 tidal wave rotates counterclockwise around the islands. The sharp phase shift suggested by St-Laurent, see their Fig. 7) et al. (2008) drives currents through the narrow channels of Belcher Islands, creates many small latent heat polynyas, and could possibly influence internal wave development. Due to the large freshwater input to south-east Hudson Bay (Granskog et al., 2009b, 2011; Macdonald and Kuzyk, 2011), this region also has higher mean water column stratification compared to northeast Hudson Bay and Hudson Strait (Ferland et al., 2011).

The main objectives of our study are: (1) to describe and examine the water column structure and internal tidal waves recorded under land-fast ice in southeast Belcher Islands using temperature, salinity and current velocity data acquired in winter and (2) to describe the spatial patterns of short-period internal waves observed in satellite synthetic aperture radar (SAR) images of the study site during the ice-free season. The combination of winter under-ice in situ time-series measurements using land-fast sea ice as a stable measurement platform and the spatial information from satellite observations of ice-free areas provided a detailed picture of tidal dynamics in this Arctic region.

2. Material and Methods

2.1. Description of study area

The Belcher Islands archipelago is a group of about 1500 islands located in southeast Hudson Bay (ca) downstream of a large freshwater runoff input originating from James Bay. It is composed of a group of long and narrow islands and peninsulas separated by narrow channels and fjords oriented mostly in a northeast-southwest direction and with numerous scattered small islands and outcrops (Fig. 1b). This unusually intricate topography of the Belcher Islands, which belongs to the Churchill tectonic province, is a result of folding of unmetamorphosed Proterozoic strata into double plunging folds (Jackson, 1960). Ice-rafted material (> 20% of bottom sediment) additionally adds complexity to the seafloor that is mainly composed of silt or sand (Pelletier, 1968).

During winter a number of coastal polynyas are formed around the islands providing open water areas, which are crucial for marine habitat (Heath et al., 2006). Polynyas and ice formation with brine release affect salt balance during winter, while during summer, the coastal waters surrounding the Belcher Islands are affected by significant freshwater runoff from neighbouring James Bay (~ 350 km^3/yr) (Déry et al., 2011; Granskog et al., 2011). A number of major rivers, including the La Grande Rivière that discharges into James Bay, are now regulated as a result of hydroelectric development causing increased winter freshwater runoff (Déry et al., 2005, 2009, 2011) that help maintain surface stratification despite ice formation.

Hudson Bay is ice-covered for 8–9 months a year with ice formation typically starting in the north-west corner of the bay in late October (Hochheim and Barber, 2014). In places, there is a steady growth in ice thickness from January until April (Granskog et al., 2009a). The mean maximum ice thickness varies from 1.17 m in north-western Hudson Bay to 1.67 m in its eastern part, where the Belcher Islands are located (Landy et al., 2017). Around the Belcher Islands, the ice usually starts forming in December and breaks up in June (Hochheim and Barber, 2014; Eastwood, 2018).

In the winter of 2013–2014, sea ice started to form around the Belcher Islands in mid-December. The land-fast ice around the islands was formed by early January but large periodical opening and closing of leads up to 150 km long persisted throughout the winter both to the west and north of the islands (Figs. 2a and 2b). Besides these large leads, there were smaller polynyas close to the south-east tip of the islands and along the eastern shore (Fig. 2a). Such polynyas can significantly affect water circulation patterns in coastal areas, fjords and narrow channels (e.g., Dmitrenko et al., 2012, 2015). In coastal areas, a polynya produces frazil ice with associated brine release (Dmitrenko et al., 2010) and significant weakening of density stratification (Dmitrenko et al., 2012). When a polynya is present at the mouth of a fjord or a channel, brine release can enhance water circulation replenishing fjords' intermediate water layer with polynya generated water (Dmitrenko et al., 2015). This enhanced brine-related circulation also drives biological processes such as diel vertical migration of zooplankton (Petrusevich et al., 2016).

2.2. Mooring Setup

In our study, we deployed ice-tethered moorings and conducted CTD sampling below the sea-ice cover throughout the three winter