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High resolution tidal model of Canadian Arctic Archipelago, Baffin and Hudson Bay

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ABSTRACT

Ice induced variability of tides in the Canadian Arctic Archipelago, including Baffin Bay and Hudson Strait/Hudson Bay system, was studied by means of a new high resolution tidal model. Here we show that the seasonal variations of the tidal constants are significant in the major part of the domain. Month to month changes of the tidal phases can reach 180 degrees due to changes in the number and positions of the amphidromic points, whereas the amplitude variations are especially large in the near resonant basins. We also show that the tidal seasonality has undergone dramatic changes in the past decades due the decaying extent of the Arctic sea ice. These seasonal/decadal scale changes not only vary tidal dissipation on the shelf, but also impact tides in the adjacent open ocean and, therefore, cannot be neglected.

1. Introduction

The Canadian Arctic Archipelago, shown in Fig. 1, is a collection of islands located on the northern North American continental shelf. It is known to be an important gateway for water, ice and tidal energy exchange between the Arctic Ocean and North Atlantic. Changes in the circulation of freshened seawater and ice through its narrow passages have the potential to influence both regional and global climate. It can significantly affect the distribution of sea-ice in the Arctic, recirculation of the surface waters and freshwater fluxes around Greenland as well as the strength of ocean circulation in the Atlantic, (Joyce and Proshutinsky, 2007).

Accurate tide prediction is crucial for many purposes such as investigating the variability of the sea surface currents and eddy activities. Tidal motion influences the turbulent mixing and heat anomalies required for polynya formation and, therefore, affects sea ice properties and distribution, (Wang et al., 2003; Makinson et al., 2011). Furevik and Foldvik (1996) have shown that near critical latitude the boundary layer thickens and it encompasses the entire water column at critical latitude. The thickened boundary layer imparts vertical shears in the horizontal velocities to more of the water column and can lead to mixing. As a result of the increased baroclinicity of the water column due to internal tides, enhanced mixing, resonant effects with the inertial frequency, even weak tidal regimes play a significant role in ice-shelf melting when they are subject to critical latitude effects, (Robertson, 2013).

While global ocean tide models improved dramatically in the recent years due to combination of data assimilation based on satellite altimetry analysis with sophisticated hydrodynamic/assimilation modeling, the accurate representation of shallow-water (depth < 1000 m) and high-latitude (polewards from $\pm 66^{\circ}$) tides still remain a challenge, (Cheng and Andersen, 2011; Stammer et al., 2014). The model limitations in polar regions arise from a poorly known bathymetry and relatively sparse and poor quality data for model validation and assimilation. Another source of errors is the ice induced seasonal variability of the tidal constituents, which is insufficiently studied.

The existing tidal models represent an annual mean state of the tidal constants. The presence of ice cover and its effects are often ignored completely or represented via imposing a stationary mean ice concentration field. The rationale behind this is that the ice induced changes do not exceed the model errors. This conclusion is, however, drawn based only on a few tide gauge records along the White Sea coastline, off the Siberian continental shelf and in the Canadian Arctic, (Henry and Foreman, 1977; Murty and Polavarapu, 1979; Godin and Barber, 1980; Murty, 1985; Prinsenberg, 1988; St-Laurent et al., 2008). There is no data and there are only a few numerical studies dedicated to the temporal variability of tidal constants on a larger scale, (Kowalik, 1981; Saucier et al., 2004; Kagan and Romanenkov, 2007; Kagan et al., 2007; Kagan and Sofina, 2010; Müller et al., 2014). The majority of the mentioned studies only compare winter and summer (January vs September) regimes. None of them show monthly variations of the tidal constituents and cover the complete area considered here.

In this paper a new tidal model of the Canadian Arctic Archipelago including Baffin Bay, Hudson Strait and Hudson Bay is developed and

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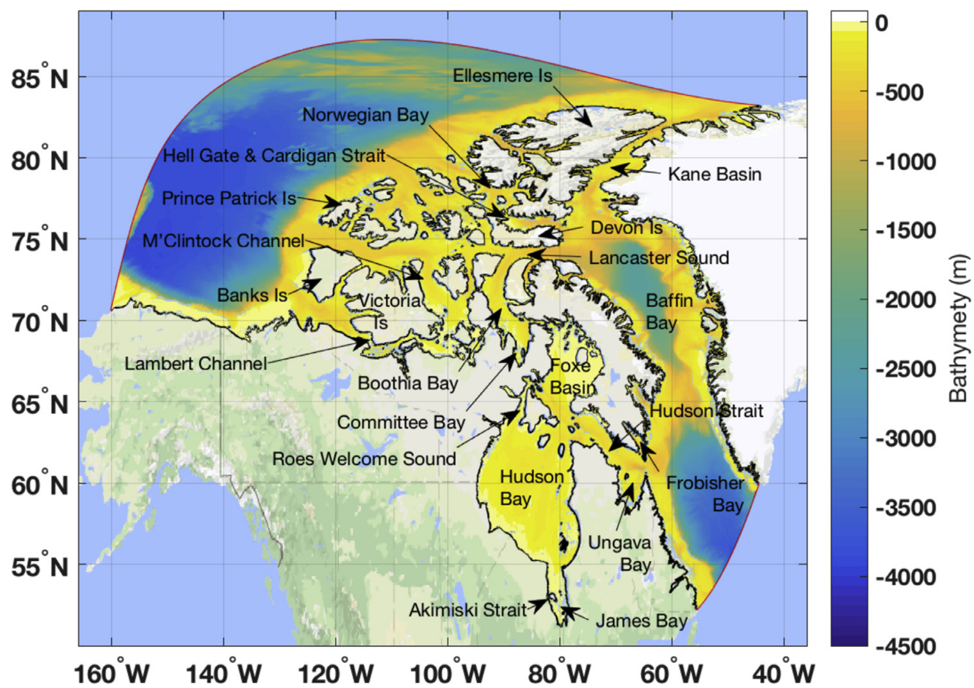

Fig. 1. Model domain: bathymetry and shore lines.

validated against available observations. The simulations were performed using ADCIRC unstructured model modified to account for the presence of an under-ice frictional layer. Unlike other existing models, the user defined ice concentration field used to calculate the ice-ocean drag coefficient is assumed to vary in time, Fig. 2. Since the majority of the available tide gauge records are too short to account for the tide seasonality, only a part of the simulated time series corresponding to the specific tidal record was used for comparison. After the initial model validation step, seasonality of the tidal constants in the entire domain was assessed by means of monthly harmonic analysis. The modelled variations were compared to the observations at a number of tide gauges with records spanning multiple years. The model behaviour in the Hudson Bay/Hudson Strait regions was also compared to the analytical model of the semi-diurnal response developed by Cummins et al. (2010). Although, the model does not account for a separate quarter-wavelength resonance exited at Leaf Basin in Ungava Bay, it gives a good indication of the range of semi-diurnal amplitude variation that can be expected in the resonant system due to the additional friction associated with the seasonal ice cover.

Estimates of M2 tidal energy dissipation from TOPEX/Poseidon altimeter data by Egbert and Ray (2001) has shown that the most important region of the world ocean for dissipating tidal energy is the area around Hudson Bay. High energy dissipation on a shelf is usually associated with tidal resonances. Indeed, results of Webb (2014) indicate that the Hudson Bay region has four significant resonances close to and straddling the semi-diurnal tidal band. Here we show that additional friction associated with the seasonally varying ice cover significantly influences tidal constants in the Hudson Bay region including Baffin Bay and Canadian Arctic straits. This, in turn, changes the amount of energy dissipated in the Hudson Bay and, thus, has potential to introduce seasonal variations of tides in the Northern Labrador Sea.

The paper is organized as follows: Section 2 gives a short description of ADCIRC including the implementation of the ice-ocean integration, design of the numerical experiment, observation data and error metrics used for the model validation. Model results are presented in Sections 3–5 and summarized in Section 6. Extended model validation results are given in Appendix.

2. Model description

2.1. Description of the numerical method

In this study we use a modified version of ADCIRC. ADCIRC (ADvanced CIRCulation), (Luettich and Westerink, 2004), a multi-scale, multi-physics coastal circulation model that is widely used for a range of modeling applications. The model runs on highly flexible, unstructured triangular meshes and is, therefore, highly scalable with linear performance scaling up to 16,000 cores, see e.g. Dietrich et al. (2012).

ADCIRC is a continuous-Galerkin, finite-element, shallow-water model, which utilizes the Generalized Wave Continuity Equation (GWCE) formulation to determine the water levels; velocities are obtained from the vertically integrated momentum equation. In order to account for the under-ice friction, a potential damping mechanism that dissipates tidal energy is the friction produced at the interface between the ice and the ocean, ADCIRC was modified as described below.

The ocean currents and sea ice interaction is usually represented through a simple quadratic stress proportional to the relative velocity between ice and water, (Pease et al., 1983). Dissipation of long-wave energy under drifting ice is negligible. However, during high ice concentration periods ice plates are confined by shorelines and their mobility is hampered. The relative velocity between the ice and the tidal current increases and the stress becomes significant.

A practical approach to simulate under-ice friction effect in a 2D model is combine the surface and bottom drag into a single friction parameter:

$$C_D = C_{D_{bot}} + C_{D_{surf}} \tag{1}$$

Similarly to Dunphy et al. (2005); Hannah et al. (2008) and Collins et al. (2011) the ice-ocean drag coefficient $C_{D_{surf}}$ is computed based on the fractional sea ice coverage as

$$C_{D_{surf}} = C_{D_{ice}}\, max\left(0,\, 2\left(A - \frac{1}{2}\right)\right) \tag{2}$$

where $C_{D_{ice}} = 1.8 \times 10^{-2}$ and A is the fractional sea ice coverage at the