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# Changes in the dynamics/energetics of surface and internal tides in the White Sea on the coexistence of shore-fast and drifting ice covers

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ABSTRACT

The results of modeling for $M_2$ surface and internal tides in the White Sea are discussed. These results are obtained for the case when shore-fast and drifting ice covers are present concurrently. It is assumed that the interface between ice covers is of non-tidal origin (i.e., it is pre-assigned) and that ice rheology is viscous-elastic, representative of the low temperatures typical of winter conditions. Emphasis is placed on tidal energetics and, in particular, on the averaged (over a tidal cycle) values of the density and the dissipation rate of barotropic/baroclinic tidal energy. It is shown that in the White Sea, unlike in other marginal seas, the averaged (over a tidal cycle) and depth-integrated density of baroclinic tidal energy for the combined ice cover is much less than the same defined density of barotropic tidal energy. Similarly, the averaged and integrated (over the volume of the White Sea) rate of baroclinic tidal energy dissipation is much less than the same defined rate of barotropic tidal energy dissipation. The latter, in turn, is greater than for the shore-fast ice cover, but is smaller than for the drifting ice cover.



## 1. Introduction

Ice-induced changes in the dynamics and energetics for $M_2$ surface and internal tides in the White Sea were the subject of investigation in Kagan and Timofeev (2006a, b). These changes are due to shore-fast and drifting ice covers. Observations show that during winter time the White Sea is covered with a combination of shore-fast and drifting sea ice. Shore-fast ice forms primarily at headlands and in the eastern parts of the Kandalaksha, Onega, Dvina, and Mezen bays. The remaining regions of the White Sea are covered with drifting ice. The maximum shore-fast ice occurs during midwinter (Fig. 1).

The present study addresses the questions of how the coexistence of shore-fast and drifting ice affects surface and internal tides in the White Sea, and how different the tides for the case of combined ice are from predictions in the limiting cases of fixed (shore-fast) and drifting ice covers.

The above issues are interesting, among other things, from a cognitive standpoint. Indeed, for progressive waves (all other factors being equal), that is, at idealized conditions, the ice cover is responsible for decreasing tidal amplitudes and increasing tidal phases. Whereas, opposite changes can be detected at realistic conditions. That such is the case is illustrated by the example of the White Sea.

The paper is organized as follows: Following the introduction in Section 1, Section 2 then offers a brief description of the model and assumptions used. In Section 3, we present and compare the modeling results for the cases of shore-fast, drifting, and combined ice covers, followed by Section 4, where we summarize the study and draw conclusions.

## 2. The model

A modified version of the three-dimensional (3D) finite-element hydrothermodynamic model QUODDY-4 was used for the investigation. The only modification to the original model was the inclusion of a module for the simulation of tidal ice drift with viscous-elastic ice rheology (Kagan and Timofeev, 2006b).

At this point it is worth recalling that the rheological properties of sea ice depend strongly on temperature (Shapiro, 1983); namely, at low temperatures sea ice behaves as an elastic material

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while at temperatures close to the freezing point it behaves as a plastic material. It is therefore apparent that the choice of ice rheology is equivalent to specifying temperature. In our case, the assumption of ice rheology to be viscous-elastic corresponds to temperatures typical of midwinter in the White Sea. Other assumptions are, based on Kagan and Timofeev (2006a, b), that shore-fast ice is fixed in the horizontal but moveable in the vertical, following tidal sea surface level elevations, and that the interface between shore-fast and drifting ice covers is of non-tidal origin and determined by taking into account influencing factors like the presence of a neighboring continent, wind-driven currents, and topography. In other words, the interface is pre-assigned (see Hydrometeorological Conditions, 1989).

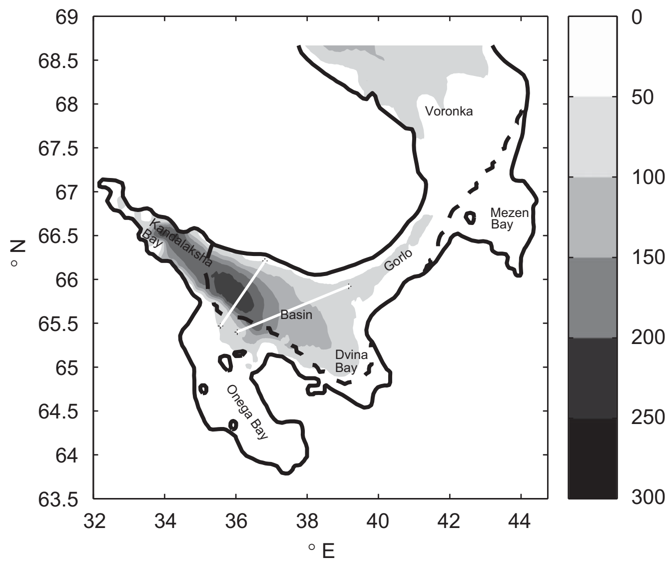


**Fig. 1.** Location of the shore-fast ice edge (dotted) in midwinter, bottom topography (in m) in the White Sea, the geographic locations referred to in the text and the sites where the internal tidal waves are generated (straight lines).

Detailed descriptions of the model equations and boundary conditions as well as the technique employed for numerical integration are presented in Ip and Lynch (1995), Lynch and Holboke (1997), and Kagan and Timofeev (2005). Note that the numerical constants, spatial resolution, and time step are used exactly as specified in Kagan and Timofeev (2006a, b). The depths are taken from database ETOPO-5 (Fig. 1); the $M_2$ tidal sea surface level elevations at the open boundary are obtained from interpolation of the observational data. Basic and trial functions, when the numerical solution is found in the studied domain, are discretized using simple prismatic finite elements. The horizontal grid resolution is assumed to be varying from <1 km near the coast and uplifts to 5.7 km in the deep sea (Fig. 2). The sea is divided into 20 layers of the non-uniform vertical span, determining the vertical resolution. The time step is 5.6 s for the surface tide and 2.8 s for the internal tide. The vertical profile of the Brant–Väisälä frequency (Fig. 3) is computed from the data on temperature and salinity which were measured in the beginning

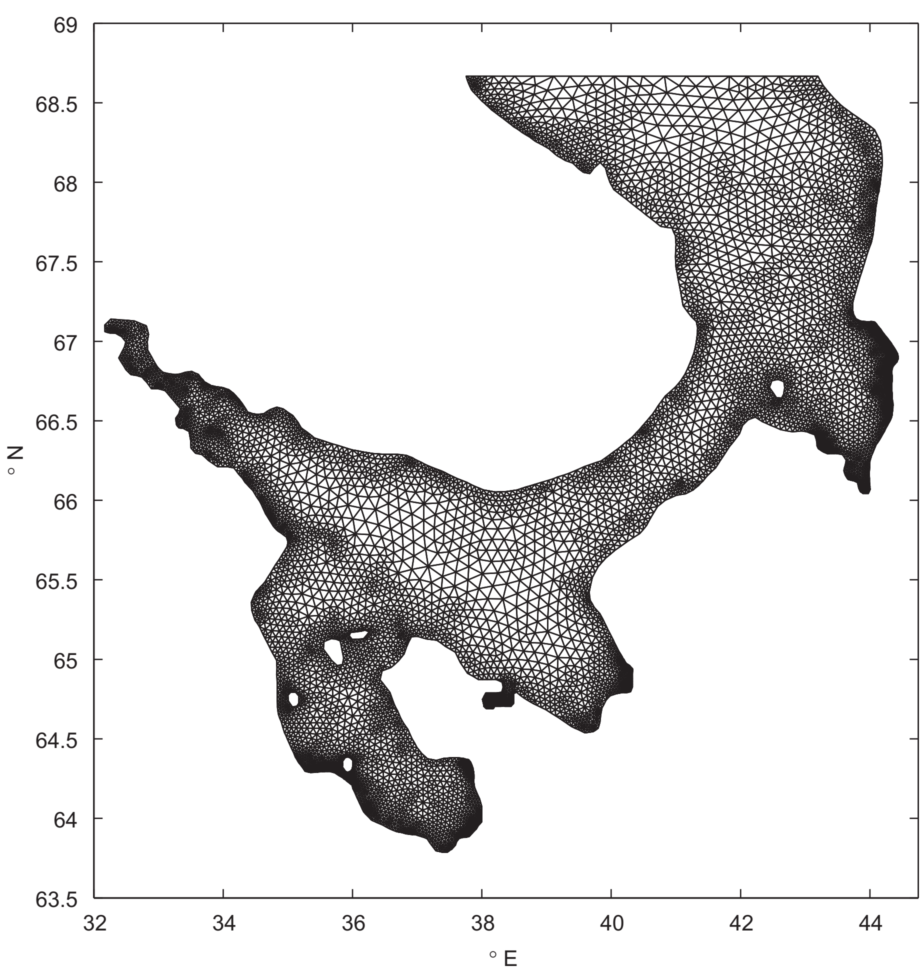


**Fig. 2.** Finite-element grid of the White Sea for the surface tide.