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Surface and internal semidiurnal tides and tidally induced diapycnal diffusion in the Barents Sea: a numerical study

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ABSTRACT

The simulation results for the surface and internal semidiurnal tides in the Barents Sea are presented. A modified version of the finite-element hydrostatic model QUODDY-4 is taken as a basis. The simulated surface tide agrees in a qualitative sense with the results obtained previously by other authors, but quantitative discrepancies are significant. The predicted internal tide belongs to the family of trapped waves. Their generation sites are located in regions of frequent internal tidal wave (ITW) detection by remote sensing. Here, the maximum baroclinic tidal velocities have a clear expressed mode-one (corresponding to the first baroclinic mode) vertical structure. This is also true for the averaged (over a tidal cycle) local density of baroclinic tidal energy. For the no-ice case, the averaged (over a tidal cycle) local rate of baroclinic tidal energy dissipation is enhanced as the bottom is approached. A comparison of the predicted tidally induced values of the depth-averaged diapycnal diffusivity with typical estimates of the combined vertical eddy diffusivity in oceans of mid- and lower latitudes, determined by the wind and thermohaline forcings, indicates that they either have the same order of magnitude or these values are larger than the latter. It follows that the contribution of tides is not negligible for the Barents Sea climate.

1. Introduction

Unlike the surface tides in the Barents Sea, which have been the subject of numerous publications [Sgibneva, 1964, Schwiderski, 1986, Gjevik and Straume, 1989, Harms, 1992, Gjevik et al., 1994, Kowalik and Proshutinsky, 1994, Padman and Erofeeva, 2004] providing useful insights into their spatial structure, much remains to be learned about the internal tides (alternatively, internal tidal waves (ITWs)) in this basin. Only two systematic investigations are known at present that deal with the spatial structure of the ITWs in the Barents Sea, namely, those carried out by Morozov et al. (2002) and Kozlov et al. (2010).

The first investigation is based on the results obtained in the frame of a 2D (in a vertical plane) model of ITW generation. The ITWs are considered plane and propagating at right angles to bottom topography irregularities. Thereby, the ITW-induced variability in the direction normal to the bottom irregularities is assumed to be well in excess of that tangent to them. Being true to a large extent, the need for simulations of the 3D ITW structure is not eliminated. Moreover, there is evidence (see Craig, 1988, Holloway, 1996, 2001, Cummins and Oey, 1997, Katsumata, 2006) that the horizontal wave flux of baroclinic tidal energy, determining, among other factors, the budget of baroclinic tidal energy, depends on the dimensionality of the model (whether the model is 2D or 3D).

Inaccuracies in the ITW 2D model simulations can arise due to the non-monotonic depth increase in the seaward direction: depths as shallow as 50 m occur in the southeastern and north-western parts of the sea, while near the coastal areas, the depths range up to 100–200 m at a distance of several dozen kilometers. There is an impression that inevitable restrictions related to fixing the direction of the ITW propagation can manifest themselves in the resulting field of their amplitudes. This consideration should be kept in mind when analyzing the modelling results presented in Morozov et al. (2002). According to these results, the extreme ITW amplitudes in the Barents Sea amounting to approximately 50 m are found in the Kara Gate Strait (see Fig. 1). Significant amplitudes (up to 10 m) occur along the northern coast of the Kola Peninsula, between the Kola and Kanin Peninsulas and along the western coast of Novaya Zemlya. In other parts of the Barents Sea, the ITW amplitudes remain a matter of few meters.

A different distribution of the ITW amplitudes is provided by satellite synthetic aperture radar (SAR) data (Kozlov et al., 2010). They show that most of the ITWs were detected near the Franz

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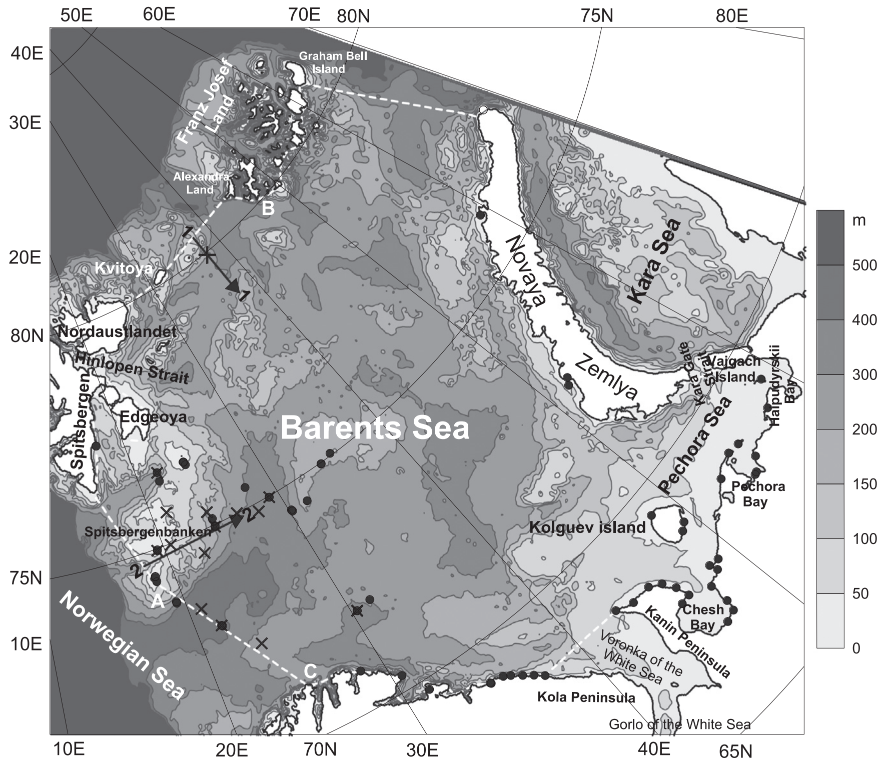

Fig. 1. Bottom topography of the Barents Sea and the geographical names referred in the text. Bold circles are the stations where tide-gauge measurements are carried out, oblique crests are the locations where velocity measurements are taken, solid right lines are the sections going across the ITW-generation sites, arrows on these lines indicate the direction of increasing distance along the sections, a right crest is the point where consequences of varying the mean vertical profile of the buoyancy frequencies are assessed, and the dashed line is the open boundary. The white capital letters (A, B, and C) indicate Bear and Prince George Islands and Nordcap, respectively.

Josef Land archipelago, especially to the northwest from the Alexandra Land. ITWs were also detected (in decreasing number) within the Voronka of the White Sea, Spitsbergen bank, and the regions to the north and south of Novaya Zemlya and to the north of the Nordcap. The region to the south of Novaya Zemlya is where the differences between the modelled (in Morozov et. al., 2002) and SAR-observed (in Kozlov et al., 2010) ITWs are more evident. Judging from Kozlov et al. (2010), the ITW generation site in the Kara Gate Strait is not different from other ITW generation sites in the Barents Sea. Moreover, if the ETOPO-5 dataset used in the work of Morozov et al. (2002) is replaced by the International Bathymetric Chart of the Arctic Ocean (IBCAO) dataset (see IBCAO, 2008: http://www.ibcao.org/), the depths in this strait would be less than 50 m, and the ITW amplitude in the strait in principle cannot be identical to the amplitude reported in Morozov et. al. (2002).

It is worth noting that at present there exist three models (Baines, 1982; Hibiya, 1986; Nakamura et al., 2000) of internal wave (IW) generation (including the ITWs). According to Baines (1982), the most intense generation of the IWs or ITWs occurs when their characteristic slope coincides with the slope of the bottom topography (critical slope condition). If IW/ITW amplitudes are sufficiently large, these waves can disintegrate into large-amplitude solitary wave trains that, as surface waves, are subjected to diffraction and refraction on irregularities of bottom topography. Moving through the shallow waters, the IWs decrease in length and their amplitudes increase; so, they are disrupted.

Hibiya (1986) suggests that, for a relatively strong tidal flow over a sill, IWs with a horizontal scale approaching that of the sill are generated at each instant of an accelerating stage of the tidal cycle. By doing this, they propagate only upstream amplifying in the generation region if the internal Froude number, F_n, defined as the ratio of the near-bottom tidal velocity, U, to the phase velocity of n-th internal mode, c_n, equals unity, that is, when the condition $U/c_n = 1$ is fulfilled.

The influence of background currents and their associated Doppler shift of frequencies on the process of IW generation was discussed by Nakamura et al. (2000) and Nakamura and Awaji (2001). It was shown that for the case of a counter-flowing current, when $U<0$ and the frequencies of generated IWs are equal to $-kU$ (here, U is the barotropic tidal velocity; k is the IW horizontal wave number), waves with a horizontal scale smaller than that of the bank and called unsteady lee IWs exist while the nondimensional parameter kU_0/σ is much larger than unity. Here, U_0 is the amplitude of the barotropic tidal velocity, σ/k is the horizontal IW phase velocity, and σ is the tidal frequency. They, as the IWs considered by Hibiya (1986), can propagate only in one direction (upstream), being trapped in the region of generation and amplified due to the superposition with unsteady lee waves. By contrast, for $kU_0/\sigma << 1$, the ITWs are generated. They can propagate in both directions, and their frequencies remain almost invariable and are close to the tidal frequency. For kU_0/σ values close to unity, the IWs are generated with the frequencies of $-kU \pm \sigma$. Accordingly (depending on the direction of propagation), they have different phase velocities and are referred to as mixed tidal lee waves. Their properties are intermediate between those inherent in unsteady lee IWs and ITWs.

We will deal exclusively with the ITWs that can be separated from other IWs by the hydrostatic approximation. We stress that the use of this approximation predetermines the character of the predicted IWs or ITWs. They may be low-mode (large-scale) waves only. High-mode (short-scale) IWs / ITWs are not reproduced by any hydrostatic model. One additional remark should be done: while identifying large-scale IWs with low-mode waves and short-scale IWs with high-mode waves, it is necessary to remember of the conditionality of the mode description of the IWs near the critical latitude where tidal and inertial frequencies coincide with each other, that is, in the case when, strongly speaking, the equations that underlie this description are invalid.