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On the nature of low-frequency currents over a shallow area of the southern coast of the Gulf of Finland

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ABSTRACT

This study aims to explain those factors influencing low-frequency currents in a shallow unstratified sea with complex topography. Current velocity measurements using a bottom-mounted ADCP, deployed at 8 m depth on the slope of Naissaar Bank (northern entrance to the Tallinn Bay, Gulf of Finland), were performed over five weeks in late autumn 2008. A quasi-steady current from nine sub-periods (two weeks) was relatively well correlated with wind (mean correlation coefficient of 0.70). During moderate to fresh winds, the current is veered to the right relative to the wind direction, by angles in the range of 14–38°. The flow is directed to the left, relative to the wind direction in stronger wind conditions, indicating evidence of topographic forcing. The observed current was reasonably in accordance with the flow predicted by the classical Ekman model. The modelled current speeds (wind speeds < 11 m s^{-1}) appear to be overestimated by 3–6 cm s^{-1}, whilst the observed rotation angles were mostly less than those predicted by the model. Inclusion of barotropic forcing to the Ekman model improved its performance. The discrepancies between the model and observations are discussed in terms of topographic steering, baroclinic effect and surface wave induced forcing.

1. Introduction

The Gulf of Finland is the second largest sub-basin of the Baltic Sea after the Gulf of Bothnia. The gulf is an elongated estuary (length about 400 km, width from 48 to 135 km and a mean depth of only 37 m) with a complex coastline and no sill towards the Baltic Proper. The eastern end of the gulf receives the largest single fresh water inflow to the Baltic Sea from the discharge of the River Neva, which retains the permanent horizontal salinity gradient along the gulf. The variable wind forcing over the gulf promoted by the dominant atmospheric circulation pattern of cyclones generally moving eastwards, in conjunction with the River Neva inflow, together with the irregular coastline and bottom topography, generate a complex water motion of different scales. However, the long-time mean circulation pattern in the gulf is cyclonic, as shown by classical observations (e.g., Hela, 1952; Palmén, 1930) and following studies reviewed by Alenius et al. (1998), as well as from the simulations of numerical models (Andrejev et al., 2004; Elken et al., 2011). The currents induced by mesoscale processes (coastal upwelling/downwelling, eddies) have been increasingly studied in the last decade (e.g., Laanemets et al., 2005; Suursaar and Aps, 2007; Zhurbas et al., 2008). There are also a few studies of currents in the very shallow sea (depth ~10 m) along the southern coast of the gulf with reference mainly to the variations of wind and sea level (Lilover et al., 2011; Suursaar, 2010).

Recent developments in the renewable energy sector have increasingly moved wind power generation from land to the sea. Thus, there is an increasing focus on the shallow coastal sea by the energy companies, as the most suitable area for the installation of windmill farms. The assessment of the environmental impact of both the installation and operation of windmills in certain coastal sea areas is a key issue. The local hydrodynamic pattern is the main driver for the transport of substances and sediments but because of the variable coastline and bottom topography of the Gulf of Finland, the water dynamics vary significantly spatially and therefore detailed measurements from locations with different characteristics are required. The particular topic of interest of this paper is the extent to which direct wind forcing and/or topographic steering explain the surface currents in the shallow sea.

There exists a clear deficit of observational evidence regarding the concurrent effects of wind and bottom topography on the currents in the shallow sea. In the present study, we revisit current velocity data from an observation site on Naissaar Bank at the northern entrance to Tallinn Bay, analysed by Lilover et al. (2011). They showed that about 50% of the energy of low-frequency currents is wind forced in the subsurface layer (unstratified sea) and that during periods of steady wind, the percentage rose to 75%. In addition, oscillating currents (mainly due to seiches) embraced about 15% of the current variations and during approximately 25% of the whole observation period, the currents were found to be topographically steered. Such a distribution of the energetics of the local hydrodynamic pattern is very favourable for studying more thoroughly the direct influence of wind forcing on the subsurface currents. For this purpose, we use

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the classical Ekman model based on the balance of the frictional and Coriolis forces (Ekman, 1905). According to the Ekman theory, bottom friction in shallow seas affects the current velocity so that the velocity vector spiral cannot fully develop and therefore, the wind driven current at the sea surface is directed to the right from the wind direction (Northern Hemisphere) by less than 45°. This means that the effect of the Coriolis force is less important due to the effect of bottom friction and therefore, the current aligns more to the wind direction. However, the expected superposition of the surface and bottom layers, together with the contribution from the background geostrophic current and the influence of the underlying bottom topography, should strongly modify the current behaviour.

Descriptions of vertical spirals of the current velocity vector in the shallow coastal sea are in fair accordance with the Ekman model in the conditions of seasonal stratification and without topographic steering (e.g., Cosoli et al., 2008; Lass et al., 2001). Therefore, our aim is to show the extent to which the observed low-frequency currents in very shallow unstratified seas are consistent with the classical Ekman model. To estimate the barotropic forcing on the observed currents we also invoked the pressure gradient term (through the along-gulf and cross-gulf sea level gradients) in the model. The remaining discrepancies between the model and observations are explained in the light of topographic steering, baroclinic effect and surface wave-induced forcing.

2. Data and methods

Our study is based on the time series of current velocity measurements performed on Naissaar Bank, in the northern part of the Tallinn Bay in the central Gulf of Finland (Fig. 1), from 30 October to 6 December 2008. A bottom-mounted ADCP (307.2 kHz, RD Instruments) was deployed at 8 m depth near the northern tip (59°35.8′N, 24°35.8′ E) of the NNW–SSE oriented Naissaar Bank, which is about 4 km long, 1.5 km wide and in places only 5 m deep. The relatively deep trench along the isobaths of Naissaar Bank extending far into the bay is characteristic to Tallinn Bay (dimensions of about 10 × 15 km). The Uusmadal Bank is located north of the Naissaar Bank and forms a somewhat deeper NW–SE oriented channel between them.

The instrument was programmed to measure velocities over 0.5 m bins with a sampling interval of 10 min (average of 50 pings). The quality of current velocity data for each depth bin was checked using the procedure developed by Book et al. (2007) proceeding from the statistics of the ADCP's internal control parameters. Consequently, the data from the first and second bins under the surface were removed leaving the data from the depth range of 1.0 to 4.5 m for further analysis. Our earlier analysis with this ADCP data set revealed that at time scales shorter than 2 h the raw data are too noisy to be used (Lilover et al., 2011). Therefore, a low-pass Butterworth filter with a 2 h cut-off was performed to reduce measurement noise. To obtain the residual current free of submesoscale oscillations, e.g., tidal and seiche-related currents, the time series was filtered with a 36 h cut-off Butterworth filter and decimated in order to obtain hourly values.

We obtained high-resolution (5 min) wind data for the observation period from the meteorological station (Aanderaa Data Instruments) at the Tallinnamadal Lighthouse (59°42.7′N, 24°43.9′E) located 15 km NE from our measurement site. The wind data were measured at a height of 31 m and were later converted to the standard 10 m height level using a reduction factor of 0.91 (Launiainen and Laurila, 1984). To determine the role of barotropic currents, sea level data from the Tallinn, Sillamäe (170 km east of Tallinn) and Helsinki (80 km north of Tallinn) gauges were used in the model calculations. The wind and sea level data were low-pass filtered analogously to the current series. For the estimation of horizontal density gradients as a potential source of baroclinic currents in the vicinity of the ADCP site, the data from an autonomous Ferrybox system was used (Lips et al., 2008). The system installed aboard the passenger ferry travelling between Tallinn and Helsinki twice a day, measured seawater temperature and salinity taken from 4 m depth with horizontal resolution of 150 m. The ferry route is approximately 5 km to the east of the ADCP site (Fig. 1).

To evaluate the relationship between the current and wind vector time series, a complex correlation coefficient $\rho = R\ \exp(i\Phi)$, introduced to physical oceanography by Kundu (1976), was used. The magnitude of coefficient $0 \le R \le 1$ measures the overall correlation of the two series and the phase angle Φ, displays the average clockwise angle of the current vector series with respect to the wind vector series.

As the Ekman theory is applicable to a steady current and wind vector series, we calculated the stability factor (Palmén, 1930) to extract the quasi-steady sub-periods from both series. The stability factor is a measure of the directional stability of the flow (current or wind) and it is specified (over a whole series or sub-series) as a ratio of the vector mean speed and average flow speed (percentage). The flow direction is quasi-constant if the value of the stability factor is close to 100%.

3. The model

The low-frequency currents are explained within the framework of Ekman theory, where in addition to the frictional and Coriolis forces, the pressure gradient force is also included in the balance:

$$-fv = -\frac{1}{\rho_0}\frac{\partial p}{\partial x} + \nu\frac{\partial^2 u}{\partial z^2}, \tag{1}$$

$$fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial y} + \nu\frac{\partial^2 v}{\partial z^2}, \tag{2}$$

where: x, y, and z are coordinates of a right-hand Cartesian coordinate system with x pointing to the east and y to the north, u and v are the east and north current velocity components, f is the Coriolis parameter, ν the is eddy viscosity, ρ_0 is the reference density and p is the pressure.

We consider the solution of Eqs. (1) and (2) at a constant finite depth $z = -H$. The solution has to satisfy boundary conditions:

$$\nu\frac{\partial u}{\partial z} = \tau_x, \quad \nu\frac{\partial v}{\partial z} = \tau_y \quad \text{at } z = 0 \tag{3}$$

and

$$u = 0, \quad v = 0 \quad \text{at } z = -H, \tag{4}$$

where τ_x and τ_y are the wind stress components.

Using the complex representations for current velocities and wind stress components:

$$\chi = u + iv, \chi_g = u_g + iv_g, \sigma = \tau_x + i\tau_y,$$

where u_g and v_g are the eastward and northward velocity components of the geostrophic current, respectively, we obtain the complex solution for current velocity, which has wind stress and geostrophic forcing parts:

$$\chi = \frac{\sigma}{\nu\eta}\frac{\sinh\eta(z+H)}{\cosh\eta H} + \chi_g\left(1 - \frac{\cosh\eta z}{\cosh\eta H}\right), \tag{5}$$

where $\eta = \gamma(1+i) = \sqrt{\frac{f}{2\nu}}(1+i)$.