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Transient upwelling in the central Baltic Sea

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ABSTRACT

The paper presents a theoretical study to explain the regular occurrence of a cold water upwelling cell at the southern east coast of the Gotland island in the central Baltic Sea. While for a circular island up- and downwelling patterns would rotate around the island, the responses around the elongated Gotland island with narrow tips at its southern and northern ends are different. The study uses the example of the response of a coastal ocean to a wind band to develop an understanding of important aspects of generation of Kelvin waves and how the waves change the response patterns.

The basic idea is that Kelvin waves starting from the northern tip diminish the upwelling along a portion of the east coast, while the export of upwelling around the southern tip is hindered by a slow phase speed due to shallower waters and coastal curvatures. This results in the generation of the upwelling cell at the southern east coast.

For a proof of the suggested mechanism and to provide a more realistic quantitative analysis, we use a numerical circulation model of the Baltic Sea (MOM4) with a horizontal grid scale of one nautical mile.

The findings provide some insight, which can be applied to other systems with variable alongshore bathymetry.

1. Introduction

In oceanography the term 'upwelling' is generally related to processes near the eastern boundaries of the oceans or the equator, where the divergence of the Ekman transport results in upward motion of the water below the thermocline into the upper layer. Upwelling usually implies a high biological productivity, because cold, nutrient rich water from below the oceanic thermocline is transported into the euphotic layer and fuels the primary production (e.g. Richards, 1981; Chavez and Messi, 2009). The phytoplankton signal is then passed along the food web via zooplankton up to fish. The upwelling regions at the eastern boundaries belong to the most important fishing grounds. In these regions, the wind-forcing is relatively persistent, apart from some seasonal or interannual variations.

The Baltic Sea is also a relatively productive area with substantial fish catches (e.g. Köster et al., 2003). But the productivity of this marginal sea is sustained largely by nutrient supplies from several rivers that gather nutrients from a large catchment area, and inputs from the atmosphere (Mörth et al., 2007). After the spring bloom, when the upper layer is nutrient depleted, upwelling events can support pulses of nutrient fluxes into the upper layer and trigger additional phytoplankton blooms. Upwelling events are an important part of the mesoscale dynamics, they contribute to the effective vertical diffusion of nutrients from the deeper waters to the surface layer and support horizontal entrainment of coastal waters into the central basins. Since the wind forcing over the Baltic is highly variable, coastal upwelling occurs only intermittently for time periods of a few days to a few weeks. From spring to fall a seasonal thermocline exists that separates warm surface water from cold waters below. During this period, upwelling can be detected by changes of the sea surface temperatures, SST.

The Baltic can be considered as a model-system to study upwelling events in response to wind pulses. A review was recently given by Lehmann and Myrberg (2008). The processes involved in the responses of a coastal ocean to wind forcing include generation of coastal jets, vertical current components due to divergence of the cross-shore currents, and coastally trapped waves excited by spatial structure of time-varying wind fields. In particular, the role of these waves can be studied in highly variable systems like the Baltic. An attempt to show the existence of coastally trapped waves with data from an array of moorings was published by Pizarro and Shaffer (1998). A combination of analytical theory and numerical modeling was used to explain the effect of Kelvin waves on shaping coastal upwelling in the western Baltic in Fennel and Seifert (1995).

The focus of this paper is on the responses of the central Baltic Sea to upwelling favorable winds near the Gotland island. The location of the island in the Baltic Sea and the surrounding bathymetry is shown in Fig. 1. SST satellite images show that during south wind episodes a relatively small upwelling cell, indicated by cold water, develops near the southernmost part of

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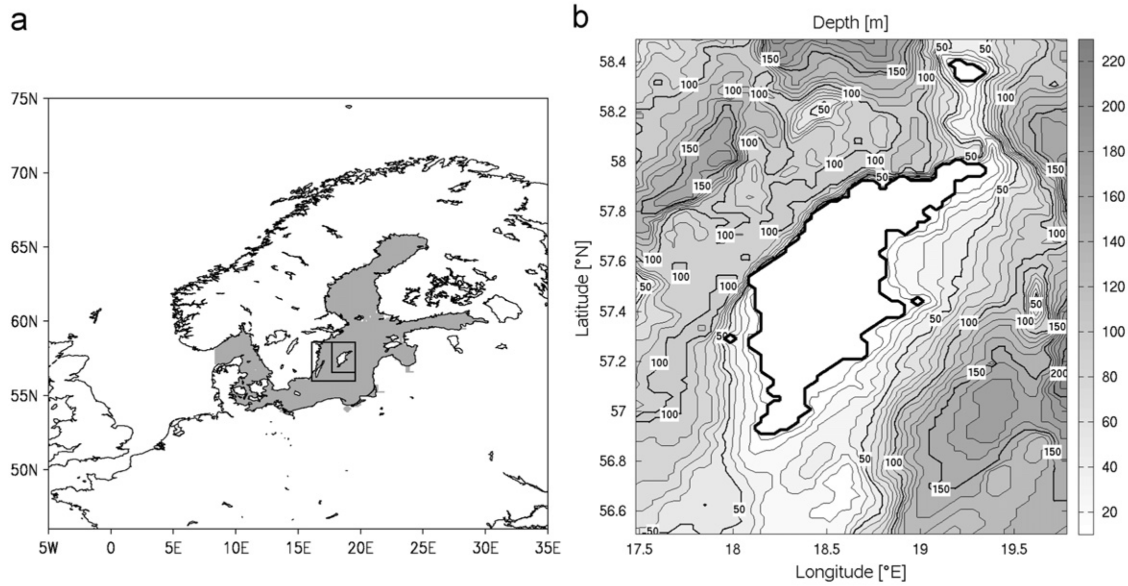

Fig. 1. (a) Map of the Baltic Sea, with indications of the area around Gotland Island and of the area comprising both Öland Island and Gotland Island. (b) The bathymetry of the Baltic Proper around Gotland Island.

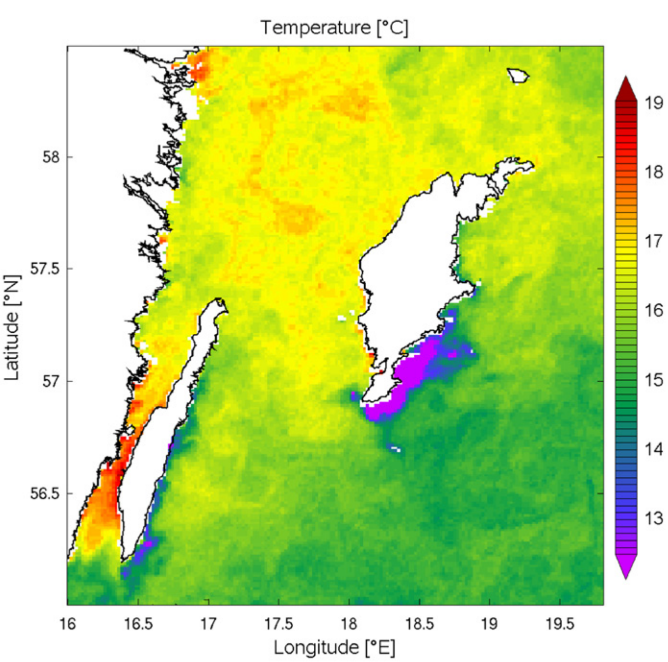

Fig. 2. Cold water cells near the southern east coasts of Öland and Gotland islands, as seen in a satellite image of the SST in the central Baltic at the 18 July 2007.

the east coast of Gotland island. An example is given in Fig. 2, which clearly shows longshore gradients in the SST-patterns for both Gotland and Öland islands. A similar upwelling pattern for these islands was discussed by Gidhagen (1987). Although these features of cold water upwelling signals are well known since the 1980s (Gidhagen, 1984), an explanation of why the cold water signal is restricted to a relatively small coastal portion was missing. Usually upwelling favorable southern winds act along the whole east coast. But only during an initial phase after the onset of the wind the cold water signature of upwelling occurs along the whole east coast. After the time period of one or two days the upwelling is usually shrank to a small southern cell.

In this study we will demonstrate that this phenomenon is related to coastally trapped waves. We consider a period of four weeks, from 5 July to 5 August 2007. The wind is characterized by a sequence of several southern (longshore) wind pulses of a duration of a few days, Fig. 3. In order to develop an understanding of the underlying mechanisms we use an advanced numerical model of the Baltic Sea in combination with an idealized analytical theory. This paper aims at elucidating theoretically the evolution of the localized upwelling cell.

The paper is organized as follows: in Section 2 we give a brief description of the analytical theory, which applies to the considered system. In Section 3 the simulation with the numerical model is described and compared with observations and the results are discussed in the light of the theory. The paper concludes with a discussion in Section 4.

2. Analytical theory

While near a circular island wind-driven up-and downwelling patterns rotate around the island, e.g. Wang (1982), the responses near elongated islands with narrow tips at its ends are different. To understand the evolution of the current patterns near the Gotland Island, it is helpful to consider the response of a coastal ocean to a band of upwelling favorable alongshore wind to study the adjustment processes, which reflect important aspects of the dynamics of the coastal sea off the east coast of Gotland. To this end, we describe theoretically the responses to the onset of wind.

In order to find analytical solutions, the model has to idealized. We choose a simple linear stratification, implying a constant Brunt–Väisälä frequency, a straight coast and a flat bottom. A realistic bathymetry and stratification is included in the numerical model, which is used in the next section. For the moment, the discussion is focused on the oceanic response to wind and the role of Kelvin waves, while we neglect how the response is modified by the realistic stratification and bottom topography.

We use the linear, hydrostatic Boussinesq equations for a flat bottomed ocean with a coast represented by a straight vertical wall, parallel to the y-axis,

$$\begin{aligned} &u_t - fv + p_x = X, \\ &v_t + fu + p_y = Y, \\ &u_x + v_y + w_z = 0, \end{aligned} \tag{1}$$