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Examining Lagrangian surface transport during a coastal upwelling in the Gulf of Finland, Baltic Sea

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ABSTRACT

We employ in-situ surface drifters and satellite derived sea surface temperature data to examine the impact that an upwelling event may have on mixing and Lagrangian transport of surrounding surface waters. The test area is located near the southern coast of the Gulf of Finland where easterly winds are known to trigger intense coastal upwellings. The analysis is based on the comparison of motions of three drifters that follow the currents in the uppermost layer with a thickness of 2 m with MODIS-based sea surface temperature data and high-quality open sea wind time series. The presence of an upwelling event superseded the classic Ekman-type drift of the surface layer and considerably slowed down the average speed of surface currents in the region affected by the upwelled cold water jet and its filaments. The drifters tended to stay amidst the surrounding surface waters. The properties of mixing were evaluated using the daily rate of temperature change along several transects. The upwelled cooler water largely kept its identity during almost the entire duration of the upwelling event. Intense mixing started at a later stage of the upwelling and continued after the end of the event when the winds that have driven the entire process began to subside.

1. Introduction

Wind induced coastal upwellings occur quite commonly worldwide (Smith, 1981; Myrberg and Andrejev, 2003). The upwelling process is first of all an efficient mechanism that brings nutrient-rich cooler water to the surface layer that is often otherwise depleted of nutrients (Bakun, 1990; Fonselius, 1996; Finni et al., 2001). It also contributes into mixing of water masses (Capet et al., 2008; Zhurbas et al., 2008; Piedracoba et al., 2008) and into generation of frontal areas (Kahru et al., 1995; Carbonel, 2003; Ryan et al., 2010).

The process usually encompasses two phases. During the active phase persistent winds blowing parallel to the coast induce an offshore Ekman transport of surface waters. This in turn generates the motion of dense and usually cooler water from deeper layers towards the surface (Bakun, 1990). If the wind blows long enough, cooler water reaches certain parts of the sea surface. The temperature may drop by >10 °C and temperature gradients often reach values of 1–5 °C/km (e.g., Leppäranta and Myrberg, 2009). The water masses are mainly forced by the external driving factors (mostly wind for coastal upwellings) and their relocation follows relatively simple dynamics during this phase.

This is followed by the relaxation phase when the wind has decreased but strong temperature and/or density gradients persist (Zhurbas et al., 2008; Gurova et al., 2013). The band of upwelled water or the associated longshore baroclinic upwelling jet (Zhurbas et al., 2008) normally becomes unstable after some time. The upwelled waters develop and/or are involved into various (sub)mesoscale phenomena (jets, meanders, filaments, eddies, fronts; often named differently by different scientists). Satellite images of sea surface temperature (SST) and chlorophyll patterns often reveal large variety of signatures of these phenomena (Van Camp et al., 1991; Abraham and Bowen, 2002). Their interplay usually leads to extremely complicated processes of drift, interleaving and mixing of upwelled waters and the 'original' (called surrounding below) water and substances in the surface layer. In this phase the most intense mixing is thought to occur (Zhurbas et al., 2008). The course and appearance of each upwelling event and its effect can vary from regions and also with time (Miranda et al., 2013; Tim et al., 2015; Wang et al., 2015). Variations in wind properties during an upwelling may lead to multi-stage events that contain recession and resumption phases (Suursaar and Aps, 2007).

Semi-enclosed water bodies such as the Baltic Sea (Fig. 1) are particularly prone to coastal upwelling (Lehmann et al., 2012; Omstedt et al., 2014). It is a key process along long stretches of their nearshore areas in the summer and autumn months. Numerous studies of this phenomenon in the Baltic Sea have employed remote sensing methods (Kahru

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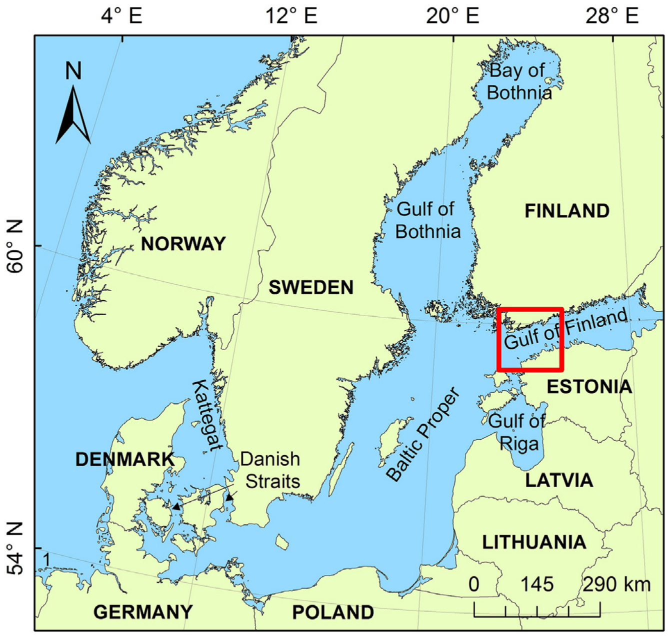

Fig. 1. Location scheme of the Baltic Sea and the study area (red box) near the entrance of the Gulf of Finland. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 1995; Uiboupin and Laanemets, 2008), models (Myrberg and Andrejev, 2003; Zhurbas et al., 2008; Laanemets et al., 2009; Väli et al., 2011) and field observations (Haapala, 1994; Suursaar and Aps, 2007; Kuvaldina et al., 2010; Kikas and Lips, 2015).

Most of the existing field studies of upwellings and their ecological implications in the Baltic Sea and similar basins have been performed in the Eulerian framework of currents (Vahtera et al., 2005; Laanemets et al., 2009; Lips et al., 2009; Kuvaldina et al., 2010, among others). Lagrangian studies of the upwelling phenomena are rare in the World Ocean. They mostly rely on remote sensing, numerical models and/or tracking of virtual parcels (e.g., Auger et al., 2015; Fabião et al., 2016; Taylor et al., 2016). A seminal field experiment involving several drifters was performed near northwest (NW) Iberia in 1998 (see Barton et al., 2001; Joint and Wassmann, 2001; Joint et al., 2001 and references therein). While there exist a large pool of research into the dynamics of upwelled waters and its filaments, very few studies have investigated the drift and entrainment of various substances and items that were located in the surrounding surface water during the upwelling process (see, e.g., Santana-Falcón et al., 2016).

The main aims of this study are to i) better quantify the different phases of the upwelling process, ii) examine the timing of intense mixing and iii) identify the impact of a strong upwelling event on the properties of Lagrangian transport of surrounding water in the Gulf of Finland (Fig. 1). To accomplish these aims we employ data from in-situ surface drifters, field measurements of winds and satellite derived SST data retrieved during a significant upwelling event in May–June 2013. The focus is on the relationship of the drifters and upwelled water masses.

We firstly quantify the spatial and temporal scales of this event and the timeline of temperature change in different parts of the area impacted by the upwelling. This analysis suggests that the classic division of an upwelling into an active and a relaxation phase may need modification to reckon a customary feature of Baltic Sea upwellings. Namely, offshore-directed jets often remain stable for a significant time interval, during which the cooler water is located within coherent jets and intense mixing occurs only in a relatively small part of the area impacted by the upwelling. Even though it is likely that lateral mixing is the main driver of observed changes in the properties of the cooler water, there may be other phenomena (vertical mixing, direct warming, restratification) that may contribute to this process. As the existing data set does not allow for the identification of the impact of single phenomena, we use the term 'mixing' to denote their joint effect.

This analysis is followed by exploring the course of mixing derived from the SST data along several transects and investigation of changes in the motion of in-situ Lagrangian drifters during the upwelling event. To our knowledge, this is the first detailed co-examination of dynamics of an upwelling using satellite SST information together with high-resolution information from in-situ drifters after experiments described in (Barton et al., 2001; Joint and Wassmann, 2001; Joint et al., 2001).

2. Study area, methods and data

2.1. Study area

The study area is located near the entrance of the Gulf of Finland (Fig. 1). This elongated bay in the eastern Baltic Sea, with a length of about 400 km and a width of generally <100 km, is regularly impacted by coastal upwellings (Leppäranta and Myrberg, 2009). It contains brackish, often strongly stratified water, the properties of which may strongly vary both horizontally and vertically (Alenius et al., 1998). Its uppermost mixed layer of relatively warm and fresh water may have a thickness of just a few meters for many weeks in spring and early summer. Also, the surface waters may contain strong velocity shear in large sections of the gulf (Andrejev et al., 2004a).

The traditional view on the basin-scale circulation in the Gulf of Finland interprets the overall motion of the water masses as mostly cyclonic (Alenius et al., 1998; Leppäranta and Myrberg, 2009). The relevant mean flow only represents the long term average and normally does not become evident in measurements (Myrberg and Soomere, 2013). The circulation pattern is thought to vary remarkably in different layers of this water body (Andrejev et al., 2004a, 2004b) owing to strong stratification of its water masses. Whilst bulk of the water possibly obeys the classic cyclonic circulation pattern, the motions within the first few meters of the surface layer are at times largely disconnected from the motions in the deeper layers (Soomere et al., 2011a).

The nature of motions in the surface layer of the Gulf of Finland seems to strongly rely on the wind speed. For moderate (6–10 m/s) and strong (>10 m/s) winds the Ekman drift pattern is formed. The local speed of surface currents is 2–3% of the wind speed and their direction is 20–30% to the right of the wind direction (Alenius et al., 1998; Leppäranta and Myrberg, 2009). For lower wind speeds the motions in the deeper layers eventually entrain the uppermost layer that starts to move almost independently of the wind properties (Gästgifvars et al., 2006; Delpeche-Ellmann et al., 2016).

Wind-driven upwellings may add another feature into this scheme as upwelling jets and filaments encompass and locally reveal momentum driven by the impact of wind over relatively large sea areas. The interleaving of a thin layer of cooler upwelled water with thicker masses of the surrounding surface water may modify both the described regimes. The impact of the upwelled water can be detected, e.g., from satellite-based SST images; however, its dynamics is largely unknown. In particular, the resulting surface currents may provide intense Lagrangian transport on weekly time scales in unexpected directions (e.g., across the gulf, Soomere et al., 2011a) and/or contribute to the drift of water (or pollution) parcels from different offshore areas to the nearshore (Andrejev et al., 2011).

The extent of the upwelling is often scaled by the internal Rossby radius that for the Baltic Sea is usually in the range of 2–10 km (Leppäranta and Myrberg, 2009). The width scale of upwellings (understood as their impact area from the shoreline to offshore) can vary from 5 to 20 km and the length scale (the alongshore extension of upwellings) between 30 and 150 km (Myrberg and Andrejev, 2003). Filaments of upwelled water at times spread several tens of kilometers out into the sea (Zhurbas et al., 2008; Laanemets et al., 2009).

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