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A comparison of the motions of surface drifters with offshore wind properties in the Gulf of Finland, the Baltic Sea

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ABSTRACT

We analyse the interconnections of wind forcing and trajectories of in-situ surface drifters deployed in the Gulf of Finland in different seasons of the years 2011 and 2013. The water masses of this brackish water body are usually strongly stratified, resulting in a layered system. The drifters were designed to follow the uppermost layer of the sea with a thickness of about 2 m. The drifter speed was 2.9–6.3% of the wind speed in 2011 when the drifters were more strongly impacted by the wind, and 1.9–2.9% in 2013 after the drifters had been modified to reduce the wind impact. The trajectories of drifters varied, in many instances the drift was almost aligned with the direction towards which the wind was blowing. In some cases the motion of drifters was systematically to the left of the wind vector apparently owing to boundary effects in the gulf. While on most occasions the drift was mostly along the gulf, on several occurrences rapid across-gulf transport was observed on time scales of 6–12 days. These observations suggest that the motions in the upper layer of the Gulf of Finland (and in similar environments) are intermittently driven by two drivers: the wind impact (including the accompanying Ekman drift) under moderate and strong winds and by underlying synoptic- and basin-scale circulation patterns in weak wind conditions.

1. Introduction

Patterns of ocean surface currents may assist tremendously in our understanding of the transport of pollution and debris (Korotenko et al., 2004, 2010), or marine organisms (Korajkic et al., 2009). This knowledge is often used, e.g., for estimates of exposure of various sea areas to current-driven impacts (Ciappa and Costabile, 2014; Otero et al., 2014) and for planning of shipping routes (Soomere and Quak, 2007; Viikmäe et al., 2011; Soomere et al., 2014). Even though there are several driving forces that influence the entire three-dimensional (3D) ocean circulation (such as large-scale currents, atmospheric pressure fluctuations, winds, tides, Earth's rotation), the short term variability of surface currents is often influenced primarily by the winds (Vandenbulcke et al., 2009). This property is especially pronounced in strongly stratified water bodies such as the Baltic Sea Proper (Lehmann et al., 2012) or the Gulf of Finland (Soomere et al., 2011a).

Due to the largely chaotic, often strongly turbulent and sometimes inaccessible (for direct measurements) nature of the surface layer, recent studies have relied greatly on the numerical ocean models to assist in understanding this layer (Kantha and Clayson, 2000). Whilst 3D models are quite successful in predicting the general circulation on a variety of scales from local (Meier, 2007) over regional (Beuvier et al., 2010) to global scales (Maltrud and McClean, 2005), they often fail to capture small-scale or rapidly changing processes (Griffa et al., 2004; Gräwe et al., 2012). For studies of wind dominated surface currents it is therefore particularly important to carry out field experiments in addition to numerical studies, to obtain data for scales not covered by models, and if possible to verify model results.

Most numerical ocean models are formulated in terms of the Eulerian specification of the flow field, where the velocity vector field is represented as a function of space and time (Haidvogel and Beckmann, 1999; Cushman-Roisin and Beckers, 2011). The Eulerian frame of reference is convenient for describing flow dynamics at selected locations, and can therefore be used to specify the flow on a fixed grid (Döös et al., 2013), however it does not preserve information about individual fluid parcels passing through the grid

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Tracking of individual fluid parcels is important when studying the transport of substances carried with the flow. Such problems are more conveniently formulated in terms of the Lagrangian specification of the flow field, where the flow is described by the displacement of individual fluid parcels as a function of time. Lagrangian flow properties can be measured using autonomous devices that are free to move with the flow. Surface drifters (restricted by buoyancy to remain at the sea surface) are a subset of such devices.

Although transport of floating substances on ocean surface is mostly confined to the essentially 2D surface layer, their motion can still be remarkably complex. The surface layer is directly affected by wind and waves. In numerical ocean models the impact of these drivers on the surface current is normally represented by fairly realistic but still largely simplified parameterisations (Ardhuin et al., 2009). Even though we may posses knowledge of the main driving forces and ocean models can predict the mean circulation pattern fairly well, the local features of surface currents and especially the Lagrangian transport of water (including pollution parcels or various items carried with the water), are often not captured properly even by the best models (Vandenbulcke et al., 2009). The circulation pattern is only infrequently governed by large-scale jet like flows (such as the Gulf Stream and the Kuroshio Current). More often the driving forces may be interacting with each other and the temporal scale that some of the important processes occur at can be quite short (1–2 weeks and intermittent at times). Thus some of rapidly varying features are difficult to capture and reconstruct from numerical models. The situation is even more complicated in strongly stratified water bodies (such as the Baltic Sea) and estuaries where the interaction between wind and wave drag and the impact of subsurface water masses may lead to extremely complicated behaviour of the 1–3 m thick surface layer (Gästgifvars et al., 2006).

The aim of this study is to shed some light on the interplay of direct atmospheric forcing (including surface waves) and the impact of subsurface water to the drift of the uppermost layer in a strongly stratified basin. The main sources of information are lightweight drifters that are designed to follow the motions in about 2 m thick uppermost layer. The main question is: how frequently (and to which extent of the distance covered) the motions in the surface layer are governed by the direct wind impact and how frequently they follow large-scale circulation patterns in the entire water column.

2. Study area, methods and data

The area of interest is the Gulf of Finland located in the easternmost end of the Baltic Sea (Fig. 1). The properties of its water masses are mainly created through a superposition of the limited water exchange with the open ocean from the North Atlantic via the Danish straits and by the voluminous river runoff from the surrounding countries. Almost the entire Baltic Sea is brackish, strongly stratified and with very thin layers (on the order of a few metres) that are separated by abrupt density changes during large parts of each year (Leppäranta and Myrberg, 2009).

The Gulf of Finland is an elongated water body located on the eastern end of the Baltic Sea, with a length of ~400 km, width of 48–125 km and mean depth of around 37 m (maximum depth 123 m). As there is no sill between this gulf and the rest of the Baltic Sea, many processes and features in the Baltic Sea Proper penetrate deep into this gulf. Its maximum cross-sectional depth decreases almost monotonically from 80 to 100 m at the entrance (where the impact of brackish and strongly stratified water masses predominates) to 20–30 m in the eastern part of the gulf. There exist three large rivers (Neva, Narva, and Kymi) that bring large volumes of fresh water into the gulf (Alenius et al., 1998; Andrejev et al., 2004a, 2004b; Soomere et al., 2008).

This interplay of different drivers creates basically estuarine conditions in this water body, but with substantial variations along the gulf. The highly dynamic interplay of lighter water in the surface layer (largely stemming from voluminous river runoff and precipitation) overlying saline dense water (supplied by intermittent salt water inflows from the North Sea into the Baltic Proper) results in almost permanent two-layer structure. The layers are separated by a sharp halocline especially in the western and middle sections of the gulf. Due to such a vertical structure the direct impact of atmospheric forcing is believed to mainly affect the upper layer (Myrberg and Soomere, 2013).

The wind regime of the gulf can to some extent be characterised using the North Atlantic Oscillation (NAO) index (Hurrell et al., 2003). This index simply parameterises the intensity of the westerlies. It is positive when there are high pressure anomalies in the south and low pressure anomalies in the north, at which time relatively strong westerly winds prevail in the Baltic Sea region and winters are typically much warmer than on average over most of Europe. When the NAO index is negative the winds tend to blow from mostly northerly and easterly directions and mean wintertime temperatures are lower than normal (Lehmann and Hinrichsen, 2002; Leppäranta and Myrberg, 2009). The interplay of positive and negative phases of this index gives rise to a characteristic two-peak structure of the directional distribution of winds in this region (Soomere and Keevallik, 2001).

In spring- and summertime the global winds are weaker and the local features (like land-sea breeze or winds along the elongated Gulf of Finland) often predominate (Myrberg and Soomere, 2013). As a result, the wind climate of the open part of the gulf contains frequent south-western and north-north-western winds (as in the open Baltic Sea) but also an appreciable number of western and eastern winds that blow along the axis of the gulf. South-easterly winds are infrequent and relatively weak (Soomere and Keevallik, 2003).

The wind climate of this region has a strong seasonal pattern. The winds are usually strongest (8–10 m/s on average, Niros et al., 2002) and usually blow from the south-west or west in autumn and winter, between October and February, and weakest (5–6 m/s on average) in spring and early summer (April–June). In summer (June–August) cyclonic activity is moderate and winds tend to blow from the west and north-west.

The classical view on the circulation in the Gulf of Finland has been developed in the first half of the 20th century based on conceptual models and on a limited amount of observations collected onboard lightships (Witting, 1912; Palmén, 1930; Hela, 1952). On average 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. This is generally due to the Ekman drift (Alenius et al., 1998; Leppäranta and Myrberg, 2009). The basin-scale circulation is thought to be cyclonic. Such mean flow, however, is very hard to detect (Myrberg and Soomere, 2013) and it only represents the long term average.

This concept was severely questioned in 3D numerical studies of the dynamics of the Gulf of Finland (Andrejev et al., 2004a, 2004b; Myrberg et al., 2010; with relevant overviews available in Soomere et al., 2008; Myrberg and Soomere, 2013). The circulation pattern may vary in different layers of the gulf (Andrejev et al., 2004a, 2004b). Whilst most of the water masses obey the overall cyclonic circulation similarly to the classic picture, the first few metres of the surface layer tend to be mainly influenced by the winds. The uppermost layer (0–2.5 m) is predominantly wind-driven with typical current velocities 5–10 cm/s. It is affected by