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Spatial pattern of current-driven hits to the nearshore from a major marine fairway in the Gulf of Finland

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ABSTRACT

The spatial pattern of hits to the nearshore by tracers originating in a major fairway in the Gulf of Finland and transported by surface currents is analysed based on Lagrangian trajectories of water parcels reconstructed using the TRACMASS model from three-dimensional velocity fields by the Rossby Centre circulation model RCO for 1987–1996. The probabilities for a hit to different parts of the nearshore and the ability of different sections of the fairway to serve as starting points of tracers (equivalently, certain type of nearshore pollution) have extensive seasonal variability. The potential of the fairway to impact the nearshore in this manner is roughly inversely proportional to its distance from the nearest coast. A short section of the fairway to the south of Vyborg and a segment to the west of Tallinn are the most probable starting points of tracers. The most frequently hit nearshore areas are short fragments between Hanko and Helsinki, the north-eastern coast of the gulf to the south of Vyborg, and longer segments from Tallinn to Hiiumaa on the southern coast of the gulf.

1. Introduction

The Baltic Sea hosts one of the heaviest ship traffics in the world. Although relatively small in size, still up to 15% of the world's ship cargo is transported along its numerous fairways. The number and the size of ships have grown in recent years. The largest threat to the environment is oil transportation, which increased by more than a factor of two in 2000–2008 and a 40% increase is expected by the year 2015 (HELCOM, 2009). One of the major marine highways in the European waters enters the Baltic Sea through the Danish Straits, crosses the Baltic Proper and stretches through the Gulf of Finland (Fig. 1) to Saint Petersburg, the largest population and industrial centre in this area, and to a number of new harbours in its vicinity.

Sustainable management of this traffic flow is a major challenge in the Baltic Sea, which is designated as a Particularly Sensitive Sea Area (PSSA) by the International Maritime Organisation. When an area is approved as a PSSA, specific measures can be used to control the maritime activities in it (IMO, 2007; Kachel, 2008). The problems of detection, modelling and forecasting of the fate of oil spills in the Baltic Sea have been addressed in numerous publications since the mid-1990s (Ambjörn, 2000; Johannessen et al., 2006; Kostianoy et al., 2005; Lavrova et al., 2006; Tufte et al., 2004; Uiboupin et al., 2008); also the relevant econometric issues (Aps et al., 2009; Elofsson, 2010; Gottinger, 2001), statistical models of collision and grounding probability (Gucma, 2008), optimum allocation of the available monitoring resources (Deissenberg et al., 2001) and propagation of pollution under ice cover (Alhimenko et al., 1997; Wang et al., 2007) have been treated. The official HELCOM oil spill forecast system Seatrack Web, launched at the turn of the millennium (Ambjörn, 2000; Gästgifvars et al., 2002) and regularly updated (Ambjörn, 2007), has become an important constituent of operational oceanography in the region (Ambjörn, 2008; Kostianoy et al., 2005, 2008; Lavrova et al., 2006; Uiboupin et al., 2008).

Apart from oil pollution, a variety of adverse impacts, (chemical) substances and objects, carrying a certain danger, can be potentially released from ships. They may be carried to substantial distances by the complex interaction of different metocean drivers (currents, waves, direct impact of wind) and may be modified by a number of physical and chemical processes (e.g. weathering of the oil pollution, dispersion of chemicals, and change in the radioactivity level of nuclear wastes). The number of drivers is quite large and even the very best models of the propagation and fate of adverse impacts of different kinds still suffer from some limitations that result in imperfect predictions (e.g., Ambjörn, 2007) and can be quite demanding computationally.

The direct impact of wind and waves on the propagation of pollution and different objects in the upper layer of the sea is relatively well understood (Ardhuin et al., 2009; Breivik et al., 2011) and relevant parameterisations were implemented into operational models decades ago. The situation with current-driven transport is much less satisfactory. Although there exist attempts to replicate the three-dimensional (3D) propagation of oil spills (Chang et al., 2011), the tracking of pathways of even single drifters (or pollution parcels) and the regions of their

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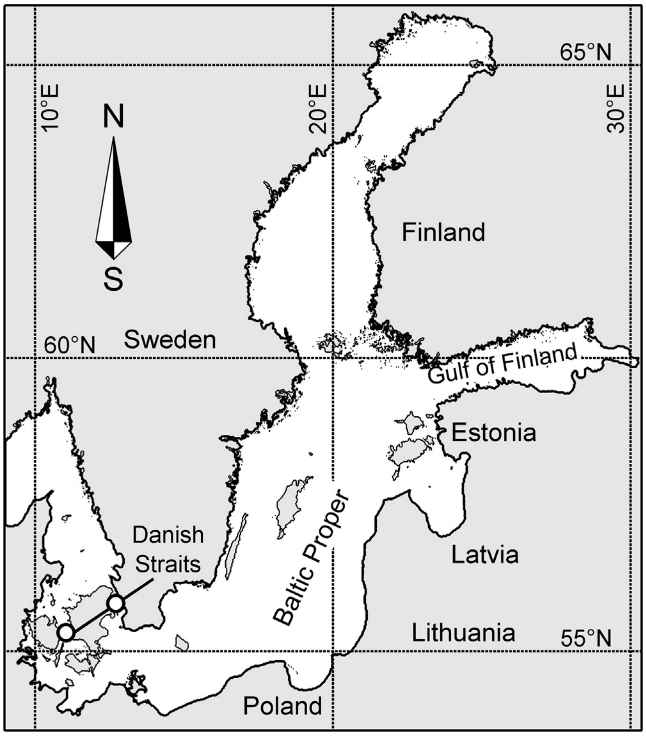

Fig. 1. Scheme of the Baltic Sea and the Gulf of Finland.

impact is extremely complicated also for small sea domains, the very best ocean models and their ensembles (Fingas, 2011; Vandenbulcke et al., 2009). The situation is by no means better in the Baltic Sea (Kjellsson and Döös, 2013; Verjovkina et al., 2010).

In this light, a better understanding of the properties of current-driven transport provides the largest unused potential towards more exact representation of the propagation of various adverse substances and dangerous, dubious or precious objects in the surface layer. This perception calls for us to seemingly take a step back, to intentionally ignore the direct impact of wind and waves on objects on top of water and substances in the uppermost layer of the sea, and to focus on the impact the surface currents may have on their pathways.

The resulting framework is directly applicable for persistent substances that are dissolved in strongly stratified environments under calm conditions when the contaminants (e.g. dissolved radioactive substances) largely remain in the uppermost layer and are mostly carried by surface currents (e.g., Periañez, 2004). This setup is only conditionally valid for oil pollution or the drift of floating objects extending over the sea surface or exposed to the wave action in most of the open ocean as it does not consider other metocean drivers, chemical processes, buoyancy effects, etc. Thus, it is not always justified from the viewpoint of practical applications. For example, the predominant driving force for oil advection at offshore locations of the Gulf of Finland (the test area in this paper) varies: it is the direct wind impact during stormy seasons and the system of currents during calm seasons (Murawski and Nielsen, 2013). There is no consensus about the exact magnitude of wind-driven drift of oil spills, estimates for which vary from 0.8% to 5.8% of the wind speed (Pahlke, 1985). A frequently used value estimated in offshore conditions is 3% (Reed and Aamo, 1994). This value may be overestimated for semi-enclosed regions like the Gulf of Finland where the wind-driven surface current speed is only about 1.4% of the wind speed (Hela, 1952). The interrelations between the wind- and current-induced drifts are even more complicated in the Baltic Sea basin where the wind direction frequently varies (Soomere, 2001). Wave effects (Stokes drift) are usually much smaller than the wind impact but they may in extreme cases become even larger. Similarly to the wind field, wave properties are highly variable in time in the Baltic Sea and the direct wave impact on the drift can be modelled to some extent as a random disturbance to the trajectories of pollutant parcels (Viikmäe et al., 2013). Spatial distributions of the long-term probability for a coastal hit of a realistic oil spill and the time it takes for the spill to reach a coast described in Murawski and Nielsen (2013) are qualitatively similar to the corresponding distributions of nearhsore hits and particle age in Andrejev et al. (2011). The impact of seasonally varying wind-induced drift, however, gives rise to substantially different appearances of these distributions for different seasons (Murawski and Nielsen, 2013).

The use of the field of currents to simulate the first approximation of the full drift of surface tracers in high-resolution models (Lončar et al., 2012; Meier and Höglund, 2012), is the best option in many occasions. For example, favourable conditions exist in the Gulf of Finland during a large part of the spring and early summer when the wind is fairly weak (below 5 m/s) (Mietus, 1998), surface waves are very low and a very thin uppermost mixed layer (with a depth of a few metres) stably overlies a sharp pycnocline (Leppäranta and Myrberg, 2009). This framework is also useful during the ice season (up to six months in some years in the Gulf of Finland; Sooäär and Jaagus, 2007) when the wave motion is absent and the wind impact only becomes evident through the ice drift. This setup is of clear value for improving the understanding of the possibilities of practical use of the intrinsic dynamics of currents to preventively reduce the costs of accidents at sea (Soomere and Quak, 2007). It also has an obvious potential for the quantification of the specific role of surface currents in the dynamics of any objects or substances in the surface layer, for example, for search-and-rescue purposes (e.g., Melsom et al., 2012), especially under low wind and old, smooth swells.

The commonly used approach to manage current-driven transport of pollution or important objects is to have ready quick remedial action plans (e.g., Keramitsoglou et al., 2003; Kostianoy et al., 2008, among many others). Another approach is to build a preventive maritime planning strategy; for instance, the optimisation of the shipping routes (Schwehr and McGillivary, 2007) to account for the effect that an accident or release of an object would incur before it actually happens. An area that is highly vulnerable to possible releases of adverse impacts from ship traffic is the nearshore, which usually has the greatest ecological value. While the probability of the hits of open ocean coasts by pollution released from a ship can be reduced by shifting shipping routes farther offshore, the problem for narrow bays, such as the Gulf of Finland, is how to minimise the probability of hitting any coast. A natural way to address this issue is by means of quantification of the offshore areas in terms of their ability to serve a danger to the coastal environment if pollution happened in these areas (Soomere et al., 2010, 2011a).

A convenient way to address this problem is to use statistical analysis of a large number of Lagrangian trajectories of test particles representing the potential pollution passively carried by surface currents. The use of Lagrangian trajectories for solving different environmental problems is becoming increasingly popular. This approach has been used, for example, in studies of current-driven transport of various substances such as water masses with specific properties (Meier, 2007), pollution (Soomere et al., 2011a), suspended matter (Segschneider and Sündermann, 1988), radioactive contamination (Periañez, 2004) and marine debris (Maximenko et al., 2011). Such analysis also allows identification and visualisation of several properties of currents that cannot be extracted directly from the current fields (Soomere et al., 2011c). The results obviously depend to a certain extent on the choice of the underlying velocity fields (Andrejev et al., 2011) as well as on the governing parameters for the trajectory calculations such as the initial location of test particles released into the sea, the duration of single trajectory simulations, and the number of trajectories involved for each calculation session (Viikmäe et al., 2010).

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