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Circulation Patterns in the Gulf of Finland Applied to Environmental Management of Marine Protected Areas

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for a doctoral or an equivalent academic degree.

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NICOLE DELPECHE-ELLMANN

TTÜ KIRJASTUS

Contents

List of publications constituting the thesis

The thesis is based on four academic publications which are referred to in the text as Paper A, Paper B, Paper C and Paper D. Papers A to D are indexed by the ISI Web of Science:

Paper A Soomere T., **Delpeche N.,** Viikmäe B., Quak E., Meier H.E.M., Döös K. 2011. Patterns of current-induced transport in the surface layer of the Gulf of Finland. *Boreal Environment Research*, 16(Suppl. A), 49–63.

Paper B Soomere T., Viikmäe B., **Delpeche N.,** Myrberg K. 2010. Towards identification of areas of reduced risk in the Gulf of Finland, the Baltic Sea. *Proceedings of the Estonian Academy of Sciences*, 59(2), 156–165.

Paper C **Delpeche-Ellmann N.,** Soomere T. 2013. Investigating the Marine Protected Areas most at risk of current-driven pollution in the Gulf of Finland, the Baltic Sea, using a Lagrangian transport model. *Marine Pollution Bulletin*, 67(1–2), 121–129.

Paper D **Delpeche-Ellmann N.,** Soomere T. 2013. Using Lagrangian models to assist in maritime management of Coastal and Marine Protected Areas. *Journal of Coastal Research*, Special Issue 65(1), 36–41.

Author's contribution

Paper	Contribution of the author
A, B	Data extraction, processing, implementing some of the necessary algorithms, visualisation of some results and writing several parts.
C, D	Data extraction, processing, implementing some of the necessary algorithms, visualisation and writing the paper.

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Introduction

The transport of substances in seas and oceans occurs ubiquitously in the environment at immensely different scales, both spatially and temporally. For instance, at planetary and temporal scales of many years, in the Atlantic Ocean, the Gulf Stream transports not only water masses but also heat and marine organisms from the tropics to poleward regions (Frankignoul et al., 2001; Lee et al., 1991). However, at microscales plankton in the upper layers of the ocean are known to utilise the local vertical motions (turbulent mixing, double-diffusion) of water parcels that take place from daily scales down to seconds (Lewis et al., 1984; Schmitt, 1994; Serra et al., 2007; Sommer et al., 2013). Similar scales of transport are also known to occur in the atmosphere (Frankignoul et al., 2001; Schepanski et al., 2009).

These examples of transport in the natural environment may not always be apparent to us. However, when a disaster occurs, such as an oil spill that may travel over great distances and pollute the marine environment, the need for a better understanding of the transport process becomes of utmost importance because it is essential to quickly predict the path substances may follow, to save the environment and funds. This ability has been stressed by accidents that took place in the Gulf of Mexico, U.S.A, with *Deepwater Horizon* 2010 oil spill (Figure 1)

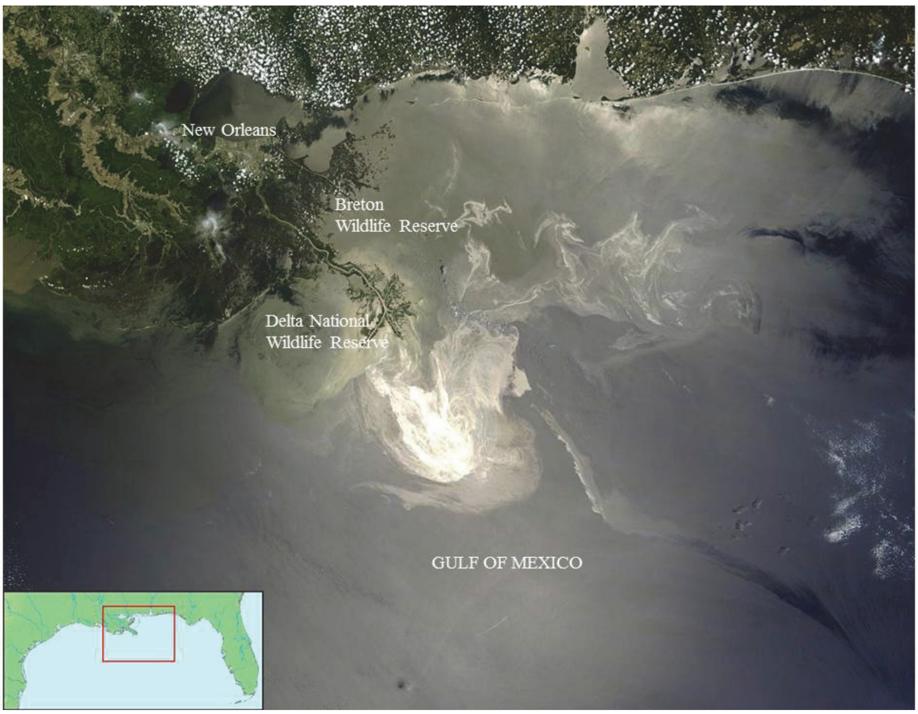

Figure 1. Deep Horizon oil spill and the location of wildlife reserves (Marine Protected Areas). Map by NASA TERRA satellite (May 2010).

(Klemas, 2010; Liu et al., 2011) or with the *Prestige* oil spill in Spain, 2002 (Vieites et al., 2004).

The shipping industry is one of the major sources of ocean pollution (Burgherr, 2007), especially in major industrial areas and along main navigational routes such as the Baltic, Barents, or North Sea, English Channel and seas surrounding China (Kirby and Law, 2010). Accidents do occur and they often bring large quantities of potentially toxic substances into the marine environment as instantaneous, locally defined events. Combined with the steady flow of (plastic) debris, litter and garbage into the water environment (Pichel et al., 2007), the resulting marine pollution is of great danger for the ecological state of the World Ocean and especially for particularly sensitive domains such as the Baltic Sea (HELCOM, 2009).

In order to manage maritime pollution, two major methods are often used (Paper C). The first is to develop quick remedial action plans in the event of an accident (e.g., Keramitsoglou et al., 2003; Kostianoy et al., 2008). These include a variety of activities, rescue and clean-up operations that require pollution simulations, methods for detecting pollution at sea, and are often referred to as post-incident actions. Generally speaking, any activity of this approach is only implemented after an accident has already occurred.

Another, rapidly developing approach is the preventive maritime planning strategy. It considers the effect that a pollution accident would incur before it actually happens. This may include the optimisation of the shipping routes (Schwehr and McGillivary, 2007), designation of Marine Protected Areas (MPAs) and assisting with possible policies and regulations (Ko and Chang, 2010; Hassler, 2011; Rusli, 2012). Its distinguishing feature is a forward look, to make plans in advance to avoid an accident or minimise the pollution.

Both these approaches rely on our understanding of the transport patterns that exist in the marine environment. These patterns and their detailed properties are usually extremely complicated to understand and reconstruct (Figure 2). The transport in the water column and on the sea surface is usually highly turbulent and

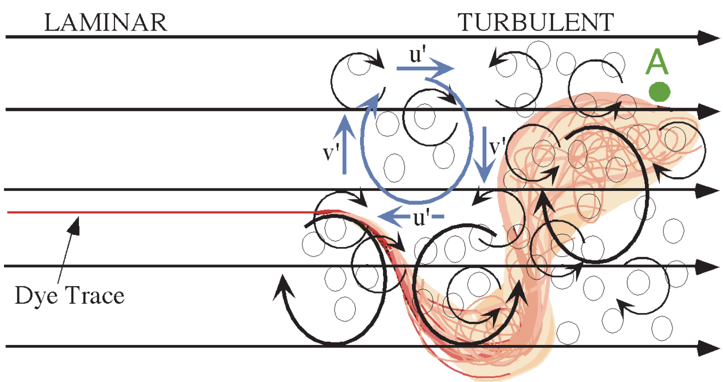

Figure 2. Tracer transport in laminar and turbulent flow structure. Source: Massachusetts Institute of Technology (Open Courseware).

may not always follow velocity streamlines or be separated into single eddies. These features can be easily identified in large-scale jet-like flows such as the Gulf Stream and Kuroshio Current. Even in the particular case of the surface layer of the ocean, the two-dimensional (2D) flow is accurately predictable only within a very limited time interval (Vandenbulcke et al., 2009).

However, there often exists a certain concealed order and/or important transport pattern within all the seeming disorder even if snapshots of instantaneous current velocity data may look quite noisy. For example, pollutants or debris when released into the ocean are known to after some time collect mainly in particular areas (Samuelsen et al., 2012; Eriksen et al., 2013).

A widely used modern concept is that more data with a higher resolution, allow more accurate modelling of the environment (Reverdin et al., 2003; Kirtman et al., 2012). The increase in the data volume or implementation of higher-resolution simulations do not necessarily indicate that the understanding of the environment has improved. The improvement is primarily limited because of the nature of three-dimensional (3D) hydro- and aerodynamics for which long-term exact forecast of the flow may be in principle impossible (Bertozzi and Majda, 2002).

The underlying idea of the research in this thesis is that this fundamental restriction can be to some extent circumvented by means of using statistical methods (Chapter 3) to identify some of the frequently repeating patterns of transport properties (on specific temporal and spatial scales) that may assist us to better understand the typical pathways of pollution. This approach does not contradict the large uncertainties with the forecast of motions of single pollution parcels owing to the turbulent nature of surface flow in the ocean (Viikmäe et al., 2013). Such way of thinking is employed to highlight transport patterns in the surface layer of the Gulf of Finland, Baltic Sea (Paper A). The properties of transport are indirectly used to identify the MPAs of high and low risk of pollution in Papers C and D.

Patterns in current-driven transport and their persistency

The main driving forces for the relocation of a substance in the ocean are currents, wind and waves (Vandenbulcke et al., 2009). With the advancement in computer technology and progress in fundamentals of physics and hydrodynamics, marine science has only recently reached the state where it is possible to address the transport of a substance in a reliable way. The direct impact of wind and waves on the propagation of pollution and different objects in the upper layer of the sea has been relatively well understood. The resolving of this impact requires additionally to the determination (measuring or modelling) of the wind and wave fields also some elements of the current fields such as the Ekman and Stokes drift (Ardhuin et al., 2009; Röhrs et al., 2012). These elements can be determined from the wind and wave properties in a relatively direct manner (Leppäranta and Myrberg, 2009; Cushman-Roisin and Beckers, 2011).

The situation for current-induced transport is fundamentally different and the quantification of its impact on pollution transport tends to be the most challenging (Soomere and Quak, 2013). The reason is that the currents are usually forced as a joint impact of numerous drivers that extensively interact with each other. Even though these forces can be predicted by deterministic models to some extent, there is not yet a deterministic method to combine them in order to accurately reproduce the floating object transport (Vandenbulcke et al., 2009). The common opinion is that inadequate representation of current patterns is one of the main reasons why the forecast of current-induced transport is much less reliable than the description of wind- and wave-induced transport (Soomere and Quak, 2013).

The well-known examples of relatively persistent current patterns are the Gulf Stream and Kuroshio in the northern hemisphere, the East Australian Current in the sub-tropical and the Agulhas current in the boreal southern hemisphere. Although the flow in these systems is not exactly regular, an easily identifiable intense persistent transport of water masses is observed for some of their journey and these systems act as a quick transport hub. These examples of persistent currents are not very common. Circulation patterns in many other sea areas (including the Baltic Sea, Paper A) are highly complicated and jet-like patterns are rare. Even for jet-like streams such as the Northern Current in the Gulf of Lions, the Mediterranean Sea, the transport patterns are often hidden due to the meandering of the current (e.g., Petrenko, 2003).

For the Baltic Sea Proper[1] and for sub-basins of this sea the traditional viewpoint is that jet currents are not common and the circulation pattern mainly consists of a large number of meso-scale features and circulation cells with greatly varying spatio-temporal scales (Leppäranta and Myrberg, 2009). However, many studies have revealed in some areas semi-persistent current patterns, with a typical lifetime from weeks up to a few months (Lehmann et al., 2002; Andrejev et al., 2004b; Meier, 2007; Osiński and Piechura, 2009; Osiński et al., 2010). The existence of such patterns eventually has a high potential for the rapid and systematic transport of both water masses and adverse impacts such as nutrients, toxic substances, or oil pollution (Soomere and Quak, 2007) between the specific sea areas as discussed in more detail in Paper A and Chapter 2.

One of the most difficult tasks for predicting current-induced transport lies in determining the spatial and temporal scales at which the most important processes occur (e.g., meso-scale eddies) and which need to be properly resolved. The ability of numerical simulations to replicate many of these processes substantially depends on many factors such as the resolution of bathymetry being used (Broström et al., 2011), the spatio-temporal resolution of the initial and forcing data (Griffa et al., 2004) and the accuracy of the numerical methods (Gräwe et al., 2012). It is common that small variations in the model parameters or input can lead to large variations in the simulation results (Griffa et al., 2004). This feature can be partially overcome by using statistical methods. Namely, several core statistical

[1] I use here Baltic Proper to denote the open part of the Baltic Sea, consisting of the Northern Gotland Basin, Eastern Gotland Basin, Bornholm Basin and Gdańsk Bay (Leppäranta and Myrberg, 2009).

properties of current-driven transport are practically invariant with respect to major changes in the model setup (Viikmäe et al., 2013).

The uppermost layer of the sea has usually the largest water velocities of the water column (Leppäranta and Myrberg, 2009) and is often responsible for the most intense transport of various substances. The identification of frequently occurring surface flow patterns has the largest practical importance as they substantially contribute to the course of large-scale disasters related to oil spills (Broström et al., 2011). For this reason the calculations for this study were made for the surface layer covering depths of 0–3 m in the Gulf of Finland, including its entrance area adjacent to the northern Baltic Proper, for the period of 1987–1991. The choice of this time frame and the surface layer allows matching the results presented in this thesis with the outcome of earlier high-resolution simulations of the dynamics of the Gulf of Finland for the upper surface layer (depths 0–2.5 m) (Andrejev et al., 2004a, 2004b) and efforts towards environmental optimisation of fairways in the Gulf of Finland (Andrejev et al., 2011; Soomere et al., 2011a; Viikmäe, 2014).

Approaches to environmental engineering and management

Due to the highly complicated nature of surface currents, statistical methods are often used for the quantification of the transport properties (Abascal et al., 2010; Paper A, Paper B). Since most of the transport occurs in a Lagrangian framework (discussed in Chapter 2), a reasonable method is to use the current-driven trajectories of pollution parcels as single realisations of pollution pathways (Ohlmann and Mitarai, 2010; Chang et al., 2011; Soomere et al., 2011a).

The basic idea is that through modelling the Lagrangian transport driven by currents it is possible to simulate both semi-persistent patterns of currents (Paper A) and the statistical properties of the paths of possible pollutants (Paper B). Identifying such patterns also allows us to better understand the processes and mechanisms that are involved in their development.

Approaches combining these two constituents are becoming increasingly popular in studies related to the transport of different objects and substances in the marine environment, from fish eggs and larvae up to toxic algae, oil pollution and marine litter (Korotenko et al., 2004, 2010; Korajkic et al., 2009; Gräwe and Wolff, 2010; Havens et al., 2010; Monzon-Argullo et al., 2010; Yoon et al., 2010).

Studies addressing the path of a substance or a specific parcel normally utilise a global ocean circulation model (to obtain the velocity field) combined with a Lagrangian particle tracking model. A widely used relevant technique (Döös et al., 2013) is discussed in Chapter 2. This approach is often used for plastic marine debris (Lebreton et al., 2012), fish larvae (Mariani et al., 2010) and oil pollution (Chrastansky and Callies, 2009; Chang et al., 2011) by employing different types of ocean models and particle tracking models. The majority of these studies were targeted to predicting the path of a substance after it has been released into the marine environment and were thus geared more towards a post-incident action.

An increasing number of studies have focused on preventive optimisation of the consequences of potential accidents, in terms of current-driven hits of pollution to vulnerable domains. The first known attempts of this type addressed the possibilities of the dynamic relocation of tugboats along the Norwegian coasts. The goal was to ensure their minimum distance to a ship that might need assistance (Eide et al., 2007; Schwehr and McGillivary, 2007).

More recent studies (an early example of which is Paper B) used high-resolution 3D circulation models specifically tuned to the conditions of the target area, different models to simulate the current-driven path of the possible pollutants and statistical analysis to quantify the potential of the offshore areas to serve as the starting point of the pollution that may drift to some vulnerable area. The analysis of this type was performed for the south-western Baltic Sea (Lu et al., 2012), the Baltic Proper (Viikmäe et al., 2011; Höglund and Meier, 2012; Lehmann et al., 2014) and the Gulf of Finland (Andrejev et al., 2011; Soomere et al., 2011a) using both Lagrangian (Soomere et al., 2011b) and Eulerian transport approach (Höglund and Meier, 2012; Meier and Höglund, 2013).

The results have been combined with models for optimisation of ship routes (Murawski and Woge Nielsen, 2013) and used to determine the areas that are statistically safer to travel in terms of risk of coastal pollution (Andrejev et al., 2011; Soomere et al., 2011a) and to specify the (equiprobability) line that would equally divide the costs of pollution of opposite coasts (Paper B, Soomere et al., 2011b; Viikmäe et al., 2011). Similar methods have recently been applied to the Mediterranean Sea (Ciappa and Costabile, 2014) and to the nearshore of Portugal (Otero et al., 2014).

Most of the listed studies assumed that (i) the nearshore was the most vulnerable area and (ii) the "value" of all nearshore areas was equal. These approximations are not particularly realistic for in most marine areas some offshore and coastal regions are more sensitive than others. For example, some areas may be under larger environmental stress, other areas may contain diverse and valuable ecosystems, or be of specific cultural importance or economic value.

One of the methods, used to highlight and protect these sensitive regions or environments, is the delimitation of MPAs. Since the designation of the oldest MPA (Royal National Park, New South Wales, Australia) in 1879 (Anonymous, 2002a), many countries have identified MPAs for sea areas that need extra protection. A description of the major MPAs in the study area (the Gulf of Finland) is presented in Section 1.4 and in Papers C and D. As most MPAs consist of specific nearshore and offshore areas, the patterns of hits to the MPAs may considerably differ from similar patterns of hits to the entire nearshore (cf. Viikmäe et al., 2013; Viikmäe and Soomere, 2014).

Globally few studies have investigated the path of substances to a MPA. Such an application was suggested in Mitarai et al. (2009) using Lagrangian probability density functions based on numerical solutions for the coastal circulation of the Southern California Bight. Ciappa and Costabile (2014) investigated from a reverse perspective (backwards in time) a Lagrangian method for the identification of risk areas in the Egadi MPA, Meditteranean Sea.

Several studies have been performed in the Baltic Sea to determine how pollution may affect specifically the MPAs (Paper C). Aps et al. (2009a) considered the MPAs at the southern coast of the Gulf of Finland, using a Bayesian network and from the perspective of the species that would be affected the most by pollution. A geographic information system database combined with Bayesian networks was used to select the best available oil spill response and to evaluate the overall environmental impact (Aps et al., 2009b; Lecklin et al., 2011). Corell and Döös (2013) investigated how the properties of particle transport vary in different coastal areas. These studies mostly suggest remedial actions after the accidents have actually occurred.

Following Andrejev et al. (2011) and Soomere et al. (2011a), the main emphasis of this thesis is on the properties of current-driven transport in the uppermost layer. Strictly speaking, the presented results are directly applicable only to persistent neutrally buoyant substances that are dissolved in strongly stratified environments under calm conditions. In such conditions the contaminants (e.g., dissolved radioactive substances) largely remain in the uppermost layer and are mostly carried by surface currents (e.g., Periáñez, 2004). The setup used in the thesis is only conditionally valid for oil pollution as it does not consider other metocean drivers, chemical process, buoyancy effects, etc. (Soomere and Quak, 2013). These aspects are extensively discussed in Paper C.

The use of the field of surface currents to simulate the drift of oil pollution is most applicable 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) and also during the presence of ice cover (up to six months in some years; Sooäär and Jaagus, 2007). In such conditions surface currents are almost totally disconnected from the direct atmospheric influence. An overview of the possible influence of the direct impact of wind on the solution and seasonal variations in the solutions obtained under this assumption is presented in Murawski and Woge Nielsen (2013).

Objective and outline of the thesis

In this study the focus is on scenarios of current-driven pollution transport in the environment where the "value" of different nearshore or offshore areas may be different. The emphasis is on risks associated with ship traffic and especially its potential for large-scale oil pollution (Montewka et al., 2011, 2013) that is one of the largest challenges in environmental engineering in the entire Gulf of Finland (Soomere and Quak, 2013) as well as for the management of MPAs in the gulf. The perspective is on preventive optimisation of the costs before an accident actually occurs and on establishing whether any realistic ways may exist to reduce the level of danger to an existing or planned MPA.

I make an attempt to find a first-order engineering solution, to mitigate risks to MPAs created by pollution from ship traffic, by means of preventively adjusting the location of possible accidents. The goal is to provide both a scientific basis and quantitatively justified recommendations for environmental management of this potential source of stress and damage to these most sensitive marine areas. The intention is to develop an engineering approach that can assist in the preventive maritime planning worldwide.

The main objectives in this thesis are as follows:

- To explore the current-driven patterns that may exist in the surface layer of the Gulf of Finland, Baltic Sea, using the outcome of a state-of-the art ocean model, a Lagrangian trajectory model, a specific approach to select out the motions at scales that are important for MPAs and common methods of statistical analysis;
- To utilise the current-driven circulation patterns in a maritime management approach that assists in identifying the MPAs that are at high/low risk of pollution, quantifying the related risks and providing feasible solutions to mitigate these risks.

The general idea is to design the relevant measures before an accident occurs. To accomplish this focus, it is first necessary to evaluate the properties of current-driven patterns for the propagation of potential pollution that are present in the particular sea region. As described in Chapter 1, this is usually a challenge for the complicated interrelations, superpositions and interactions of the forces that drive the circulation both spatially and temporally in a highly unpredictable manner. The study area – the Gulf of Finland in the Baltic Sea – is in no way an exception as it hosts extremely complicated field of motions. Emphasis is referred towards the existing knowledge about various semi-persistent or repeated circulation patterns. This is complemented by a brief overview of the marine policies that exist for the MPAs.

The understanding of the ocean circulation and processes has been greatly advanced in recent years by the joint advancement in computer technology and associated numerical methods. As the relevant information is scattered over a large number of publications, Chapter 2 gives a brief overview of the main features and limitations of the circulation and trajectory models that are used to generate the background information about Eulerian velocities for this study and to convert this information into properties of Lagrangian motions. The Eulerian velocity fields used in this thesis are produced by the Rossby Centre Ocean model RCO (Meier et al., 2003; Meier and Höglund, 2013) and provided in the framework of the BONUS BalticWay cooperation. From the model output, only velocity data for the surface layer (0–3 m) of the Gulf of Finland are used. These are converted into Lagrangian trajectories using the TRACMASS model (Döös et al., 2013) and utilised to obtain transport trajectories of water and pollution parcels. Using these trajectories the basic transport parameters are calculated such as net and bulk transport and their ratio. The intention is to extract from these patterns information that is not directly available from the analysis of Eulerian velocity fields.

Chapter 3 (Papers A and B) presents results about the long-term average of Eulerian flow fields and often repeating Lagrangian transport patterns. Such patterns exist even in the seemingly most chaotic area of the Gulf of Finland. The results *inter alia* allow to some extent verification that the Eulerian velocity data used were reliable and also make it possible to identify a number of interesting features of the Lagrangian transport.

The propagation of various adverse impacts and pollution parcels mostly obeys Lagrangian rules. Chapter 4 (Papers C and D) presents the results of an attempt to use the Eulerian velocity data combined with tracking the Lagrangian motion of passive current-driven parcels and classical statistical methods. The properties of Lagrangian transport are applied to assist in understanding the path of substances in the surface layer and to provide meaningful engineering solutions. The aim is to establish the MPAs that would have the largest chances to be hit by current-driven pollution and to identify which sections of the existing major fairway offer the greatest danger to the existing MPAs.

Chapter 4 first provides a new insight into the current-driven risk to MPAs and then quantifies this risk to single MPAs and examines the MPAs most prone to pollution and suggests means to quantify this risk. Further on, this approach is applied to identify the source areas of pollution. This analysis provides core information for managing and possibly mitigating of these risks, including identifying the areas of refuge for ships in distress and the effect that changing the design of the fairways would have on the amount of pollution to the MPAs. This information is directly applicable in marine environmental management and maritime spatial planning when designing fairways or deciding on limits of MPA or on possible policies.

Approbation of the results

The basic results described in this thesis have been presented at the following international conferences:

Delpeche-Ellmann N., Soomere T. Using current-driven patterns in the surface layer of the Gulf of Finland to predict the Marine Protected Areas at risk of pollution. Oral presentation and poster at the *IUTAM Symposium on Complexity of Nonlinear Waves* (8–12 September 2014, Tallinn).

Delpeche-Ellmann N., Soomere T. Using Lagrangian models to assist in maritime management of coastal and Marine Protected Areas. Oral presentation at the *International Coastal Symposium 2013* (8–12 April 2013, Plymouth, UK; presented by T. Soomere).

Viikmäe B., Soomere T., **Delpeche-Ellmann N.** Optimizing fairways to reduce environmental risks in the Baltic Sea. Oral presentation at the *8th Baltic Sea Science Congress* (22–26 August 2011, St. Petersburg, Russian Federation; presented by B. Viikmäe).

Viikmäe B., Soomere T., **Delpeche N.** Using Lagrangian trajectories to find areas of reduced risk of coastal pollution in the Gulf of Finland. Oral presentation at the *5th International Student Conference on "Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region"* (06–08 October 2010, Palanga, Lithuania, presented by B. Viikmäe).

Viikmäe B., Soomere T., **Delpeche N.** Potential of using Lagrangian trajectories for environmental management in the Gulf of Finland. Oral presentation at the *10th International Marine Geological Conference* (24–28 August 2010, St. Petersburg, Russian Federation, presented by B. Viikmäe).

Delpeche N., Soomere T., Viikmäe B. Towards a quantification of areas of high and low risk of pollution in the Gulf of Finland, with the application to ecologically sensitive areas. Poster presentation at the *6th Study Conference on BALTEX* (14–18 June 2010, Międzyzdroje, Island of Wolin, Poland).

Viikmäe B., Soomere T., **Delpeche N.,** Meier H.E.M, Döös K. Utilizing Lagrangian trajectories for reducing environmental risks. Oral presentation at the *6th Study Conference on BALTEX* (14–18 June 2010, Międzyzdroje, Island of Wolin, Poland, presented by B. Viikmäe).

Soomere T., **Delpeche N.,** Viikmäe B. The use of current-induced transport for coastal protection in the Gulf of Finland, the Baltic Sea. Poster presentation at the *European Geosciences Union General Assembly* (2–7 May 2010, Vienna, Austria).

Soomere T., **Delpeche N.,** Viikmäe B. Semi-persistent patterns of transport in surface layers of the Gulf of Finland. Oral presentation at the *Joint Baltic Sea Research Programme BONUS Annual Conference* (19–21 January 2010, Vilnius, Lithuania, presented by T. Soomere).

Isotamm R., Viikmäe B., **Delpeche N.** An empirical method to determine a low-risk fairway in the Gulf of Finland. Oral presentation at the conference *Coping with Uncertainty: A Multidisciplinary Research Conference on Risk Governance in the Baltic Sea Region* (15–17 November 2009, Sigtuna, Sweden).

Delpeche N., Isotamm R., Viikmäe B., Soomere T. Application of a trajectory model to select areas of high risk of pollution. Oral presentation at the conference *Coping with Uncertainty: A Multidisciplinary Research Conference on Risk Governance in the Baltic Sea Region* (15–17 November 2009, Sigtuna, Sweden).

1. Physical background of the Baltic Sea dynamics

This thesis focuses on surface transport in a sub-basin of a major semi-enclosed sea. The fundamentals of the functioning of such basins depend on a large pool of geographical conditions and forcing factors. Similar to the Black Sea and different from the Mediterranean Sea, the Baltic Sea and the Gulf of Finland belong to the family of positive estuaries (also called dilution-type basins, Stanev and Lu, 2013), for which the net budget of water (precipitation plus river inflow minus evaporation) is in excess (Pritchard, 1955; Cameron and Pritchard, 1963). In many other crucial aspects the (open part of the) Baltic Sea and the Gulf of Finland are greatly different from other estuarine-type basins. As their specific features are only very shortly explained in Papers A–D, I present in this chapter a short overview of their core properties that substantially affect the surface circulation and transport of pollution.

1.1. The Baltic Sea

The Baltic Sea (Figure 3) located in Northern Europe is the Earth's second largest estuarine water mass and largest brackish water body, with a total surface area of about 390 000 km^2. It is also relatively shallow with an average depth of 54 m (Leppäranta and Myrberg, 2009). The water exchange between the Baltic Sea and North Sea is limited due to the shallow and narrow Danish straits that lie between the Kattegat and the interior of the Baltic Sea. This environment habitats quite a diverse and unique marine life, similar to many other estuarine environments such as the Elbe River estuary in Germany, Chesapeake Bay in the USA or St. John River estuary, Canada.

The Baltic Sea is a young basin unveiled from beneath the Fennoscandian ice sheet at the end of the Weichselian glaciation about 9 000–13 500 years ago (Leppäranta and Myrberg, 2009). Its major parts are probably very old depressions in the bedrock. It has historically been through different freshwater and brackish water phases, influenced by glacier melting, land uplift and eustatic changes in global sealevel (Leppäranta and Myrberg, 2009). These phases eventually led to the current interesting physical and ecological state of the Baltic Sea.

At present the sea consists of a series of (sub-)basins which are divided based on sills and geometrical features. Most of the sub-basins of the Baltic Sea are only slightly inter-connected with each other and can generally be treated as separate entities (Lehmann and Hinrichsen, 2000). The largest basin is the Gotland Sea (consisting of three sections in Figure 3) which contains almost half of the Baltic Sea water (area of 151 920 km^2 or 39% of the total area of the Baltic Sea and mean depth of 71 m). The second largest is the Gulf of Bothnia (with a volume of 6369 km^3, area of 115 516 km^2 and mean depth of 55 m). The Bornholm Basin (area of 38 942 km^2, volume of 1780 km^3 and mean depth of 46 m) and the Gulf of Finland (area of 29 498 km^2, volume of 1098 km^3 and mean depth of 37 m) are much smaller. The Danish straits, the Arkona Basin and the Gulf of Riga have relatively small volumes (Leppäranta and Myrberg, 2009).

The highly dynamic interplay of lighter water in the surface layer (largely stemming from powerful river runoff and precipitation) overlying saline dense water (supplied by intermittent salt water inflow from the North Sea) in the bottom layer results in almost permanent two-layer structure. The layers are separated by a sharp halocline. Due to such a vertical structure the direct impact of atmospheric forcing mainly affects the upper layer which has a thickness of about 40–80 m. Motions in the bottom layer are mostly controlled by advection and mixing processes. The vertical structure may also contain a third layer in some seasons. A well-mixed surface layer with a typical thickness of 15–20 m is formed on the top of the upper layer due to summer-time heating. This layer is separated from the rest of water masses by a sharp thermocline. This thermocline vanishes during autumn due to thermal convection and mixing (Myrberg and Lehmann, 2013).

The commonly accepted understanding is that currents in the Baltic Sea are mainly driven by four factors: the wind stress at the sea surface, the surface pressure gradient, the thermohaline horizontal gradient of density and tidal forces. The currents are steered furthermore by the Coriolis acceleration, topography and friction (Myrberg and Lehmann, 2013) that together should form a general cyclonic circulation.

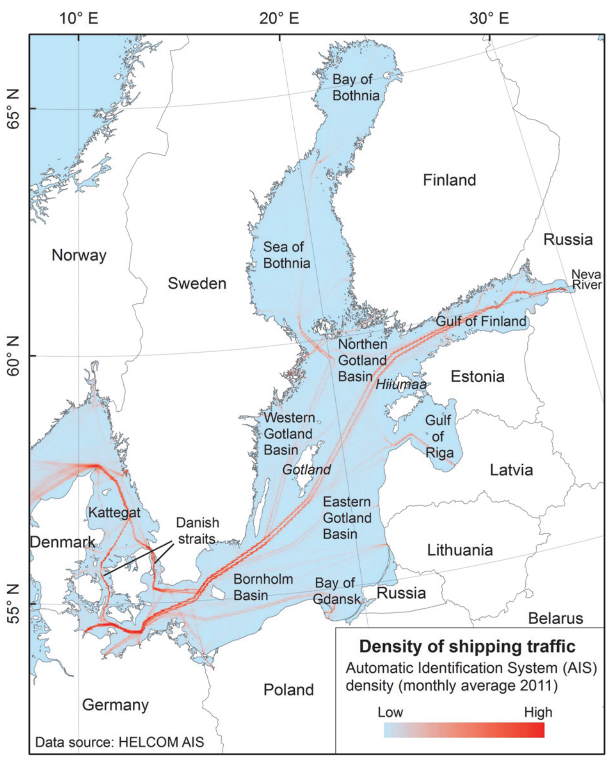

Figure 3. Main fairways in the Baltic Sea. Map by M. Viška.

The internal (baroclinic) Rossby radius largely defines the typical size of meso-scale circulation cells (meso-scale or synoptic eddies) and eventually also a part of the parameters of other semi-persistent patterns. This radius is about 10 km in the Baltic Proper (Fennel et al., 1991), that is, much less than in the open ocean (e.g., Cushman-Roisin and Beckers, 2011). This property is one of the key reasons for the complexity of motions of the water masses of the Baltic Sea that is often called a small ocean (Leppäranta and Myrberg, 2009). As a result, circulation in this water body largely functions via a series of relatively small eddies and other meso-scale features, statistical average of which gives rise to an overall cyclonic circulation scheme. A similar scheme is present in all large sub-basins of the Baltic Sea separately, with less transport between them (Lehmann et al., 2002; Andrejev et al., 2004a, 2004b). The smallness of the internal Rossby radius substantially complicates the modelling of the dynamics of the Baltic Sea because a proper numerical description of meso-scale eddies usually requires that the model grid size should not exceed ½ of this radius (Myrberg and Soomere, 2013).

The reaction of surface currents to different forcing factors depends on the typical time scale of these factors. For longer time scales (from several months to years) the baroclinic circulation is largely independent of short-term variations in the wind properties. In shorter time scales (1–10 days) the currents extensively react to the variations in wind stress. Due to large variability of the winds, the mean circulation is weak and transient currents exceed the average ones by one order of magnitude (Myrberg and Lehmann, 2013).

The combination of strong stratification, frequent strong winds and relatively short and steep waves suggests that the uppermost layer of the sea is under particularly strong influence of the atmospheric forces. This impact leads to Ekman transport often occurring in the surface layer. Frequent south-western winds give rise to substantial anisotropy of the areas of coastal up- and downwellings (Lehmann et al., 2012) and of the probability of the drift of passively advected pollution parcels to the eastern and western nearshore (Lehmann et al., 2014).

The winds when strong enough and from a particular direction can reverse the typical estuarine circulation or intensify the existing one in the Baltic Sea and/or its subbasins (Elken et al., 2003, 2014; Lehmann et al., 2012). This fact hints that the dynamics of surface layers of the sub-basins of the Baltic Sea may be quite similar. Even relatively modest but persistent westerly winds over the Danish straits with speeds of only 2–5 m/s can stop the surface-layer outflow of brackish water (Lehmann et al., 2012). Due to freshwater surplus (Leppäranta and Myrberg, 2009), the water volume in the Baltic Sea will increase although no direct inflow is forced, and this may have remote impact on all sub-basins of the sea, especially on the Gulf of Finland that is widely open to the Baltic Proper.

The properties of atmospheric forcing of the Baltic Sea and the Gulf of Finland vary remarkably depending on the exact location of the polar front and the strength of the westerlies. Large-scale variations in the forcing can to some extent be characterised using the North Atlantic Oscillation (NAO) index (Hurrell et al., 2003), which simply parameterises the intensity of the westerlies. Also the Baltic

Sea index is often used, which has a close similarity to the NAO index (Lehmann et al., 2002). The NAO index is positive when there is 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 NAO index is negative the winds tend to blow from mostly northerly and easterly directions and mean wintertime temperatures are lower than normal (Lehmann et al., 2002; Leppäranta and Myrberg, 2009).

The large-scale phenomena characterised by the NAO index evidently have pronounced impact on several aspects of the functioning of seas and oceans that are not essential to this study such as the direction and magnitude of currents (Luo et al., 2013), the height of waves (Feng et al., 2014), wind mixing, the stability of the water column and associated changes to the ecosystem (Henson et al., 2009). For practical applications it is important to recognise which type of forcing occurred during the time frame of calculations 1987–1991 presented in the thesis.

Positive values of the NAO index indicate stronger than average westerlies over the mid-latitudes. Since 1980 the NAO index has been in a highly positive phase, with the winters of 1983, 1989 and 1990 marked by its highest positive values recorded since 1864 (Lehmann et al., 2002). This index was large and negative in 1987 (–1.41) and large and positive in 1989 (2.72) and 1990 (2.56). The time interval 1987–1991 thus contained a large negative NAO index but most of the time this index was positive. This interval also contained two of the highest positive NAO index values since 1980. Thus it may be expected that the presented five-year average results properly characterise the “climatologically valid” solution of the problem.

The winds over the Baltic Sea have also a strong seasonal pattern. The winds are usually strongest between October and February and weakest between April and June. Maximum wind speeds are observed in wintertime. On average the mean wintertime wind speed was 8–10 m/s (Niros et al., 2002). In spring (March–May) wind speeds are 6 m/s with predominately southerly and western directions. In summer (June–August) cyclonic activity is weakest and winds blow on average from the west and north-west with a speed of 5–6 m/s. In autumn (September–November) wind speeds increase, the average values are 7–8 m/s and the predominant direction is between the south and the west. The variability gives rise to remarkably different patterns of semi-persistent surface transport (Paper A). Its impact on the long-term transport processes is analysed in Andrejev et al. (2011). It usually takes 3–4 years of integration to reach a good approximation of the long-term average.

The most frequently occurring wind directions in the north-western Baltic Proper are south-west and north-north-west (Soomere and Keevallik, 2003). The directions of the strongest winds do not necessarily coincide with the most frequent wind directions because of the mismatch of the geometry of the basin and the direction of predominant winds.

Thus the atmospheric forcing in the Baltic Sea generally has a major influence not only on the surface circulation but also on the formation of wave fields and may substantially contribute to the drift of substances floating on the sea surface. Its partially ephemeral nature together with a long reaction time of the system of currents substantially complicates reliable detecting of the associated seasonal patterns of current-driven transport. Myrberg and Lehmann (2013) concluded that the long-term mean surface circulation in the Baltic Sea is created by a non-linear combination of wind-independent baroclinic mean circulation and the mean wind-driven circulation. Murawski and Woge Nielsen (2013) showed that under some circumstances the optimum solutions for the fairway design may have completely different appearance for different seasons in the Gulf of Finland.

1.2. Dynamics of the Gulf of Finland

The focus of this thesis is on the Gulf of Finland, a moderate-size sub-basin located at the extreme eastern end of the Baltic Sea. This gulf has an elongated configuration, with a length of ~400 km and width of 48–125 km. Its mean depth is around 37 m (maximum depth 123 m). Its maximum cross-sectional depth decreases almost monotonically from 80–100 m at the entrance to 20–30 m in the eastern part of the gulf (Alenius et al., 1998; Soomere et al., 2008). Differently from the Gulf of Bothnia or the Gulf of Riga, the western part of the Gulf of Finland is widely open to the Baltic Proper, whereas there is no sill between these basins. Moreover, the main oceanographic driving forces behind the dynamics of the open Baltic Sea are largely the same for the Gulf of Finland (Myrberg and Soomere, 2013). As most of the analysis in this thesis addresses motions in the uppermost layer, well above the halocline, some of the above-discussed four forces (e.g., tidal forces, Lilover et al., 2014) only weakly impact the current-driven transport patterns.

The described features result *inter alia* in intense water exchange with the Northern Gotland Basin (Andrejev et al., 2004a, 2004b), complicated interplay of the estuarine and wind-driven processes (Elken et al., 2003, 2014) and frequent penetration of storm waves generated in the Baltic Proper into the Gulf of Finland (Soomere et al., 2008). The impact of saltier water from the entrance area, combined with a large amount of freshwater input into the eastern part of the gulf due to the Neva (the biggest contribution of fresh water to the whole Baltic Sea, Bergström and Carlsson, 1994), Narva and Kymijoki rivers causes a large spatio-temporal variability in salinity and temperature both in vertical and horizontal directions, creating a true estuarine environment (Figure 4).

Sea surface salinity[2] decreases from 6–6.5 g/kg in the western part to 0 g/kg in the easternmost part of the Gulf of Finland. In the bottom layers of the western gulf

[2] Historically, the salinity of sea water has been expressed in units ‰ (per mill). The new international standard TEOS-10 uses absolute salinity values in g/kg (Millero et al., 2008) and it is also customary to skip the unit in modern oceanographic literature.

(where an almost permanent strong halocline exists) the salinity can be 7–9 g/kg (occasionally 10 g/kg). There is no permanent halocline in the eastern part where salinity increases approximately linearly with depth and can be 0–5 g/kg at the bottom (Alenius et al., 1998). Salinity and stratification tend to undergo strong seasonal variations (Haapala and Alenius, 1994; Elken et al., 2003, 2014). The seasonal changes in the sea surface temperature are also pronounced due to large variations in solar radiation. A seasonal thermocline starts to develop in May. The surface mixed layer reaches a maximum depth of 15–20 m by mid-summer and erosion of the thermocline starts in later August due to wind mixing and thermal convection (Alenius et al., 1998; Myrberg and Soomere, 2013).

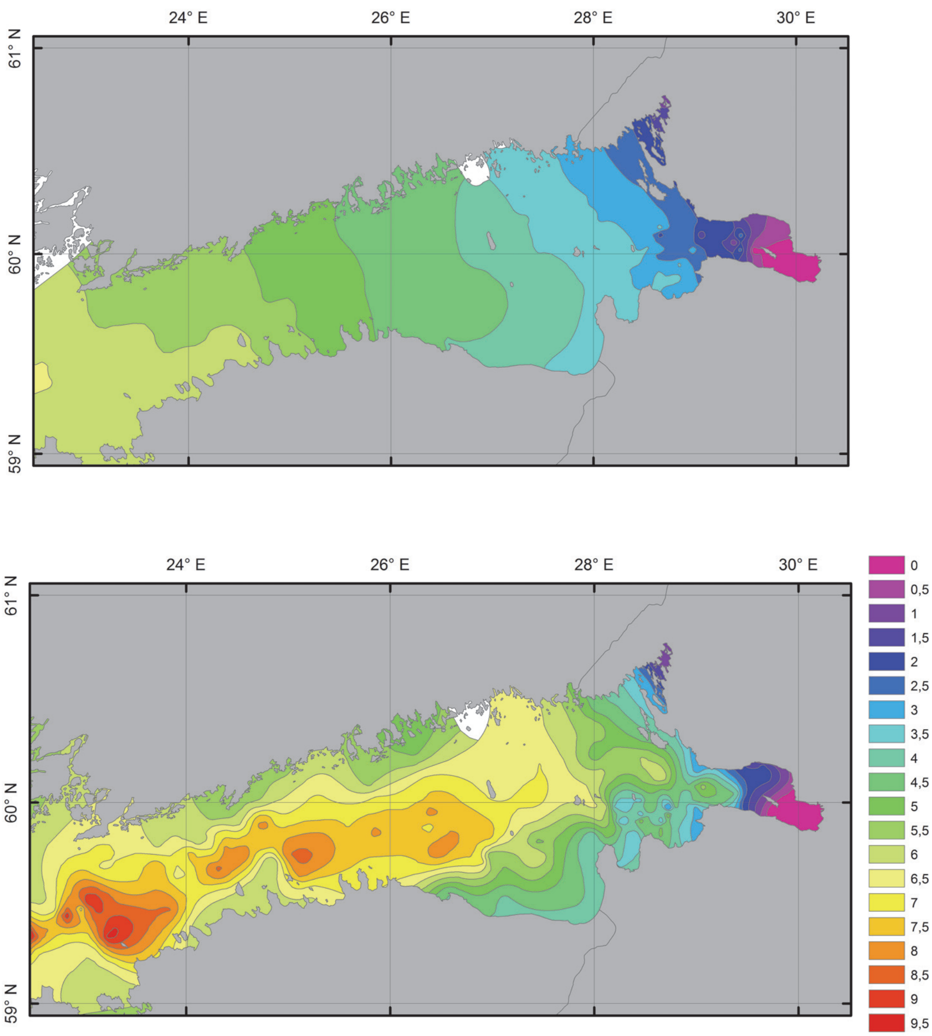

Figure 4. Salinity distribution on the surface and bottom layer of the Gulf of Finland from 1 June to 1 September 1996 (Myrberg et al., 2010, cited after Soomere and Quak, 2013).

The overall pattern of flows in the Gulf of Finland only partially matches the classical cyclonic circulation pattern in water bodies on the northern hemisphere (Myrberg and Soomere, 2013). The major player here is the strong halocline. It not only prevents vertical mixing in the western and middle parts of the gulf but also provides a waveguide for the propagation of internal waves into the gulf (Kurkina et al., 2011). The presence of strong stratification leads to the situation in which motions in the deeper waters below the halocline are – similarly to the above-described situation in the Baltic Proper – to a large extent decoupled from the direct atmospheric forcing. As mixing through the halocline is limited, the renewal of the deep waters in the western part of the gulf mostly occurs via the water exchange with the Northern Gotland Basin.

Similarly to the Baltic Proper, buoyancy-driven currents together with wind-driven circulation and motions induced by sea level gradient play an important role in the circulation of the gulf (Alenius et al., 1998; Soomere et al., 2008). Thus, variations in the main forcing factors are expected to be reflected not only in the seasonal but also in the interannual and decadal-scale oceanographic conditions. For instance, a major Baltic inflow (which occasionally brings saltier water from the North Sea to the Baltic Sea, Schinke and Matthäus, 1998; BACC, 2008) often results in a stronger and shallower halocline in the Baltic Proper.

This process, with a certain delay (Meier, 2007), leads to more saline water being transported into the bottom layers of the Gulf of Finland, thus increasing the strength of stratification. Contrariwise, a decrease in the intensity or frequency of such inflows leads to an overall weakening of stratification in the Gulf of Finland. During the years 1987–1991 there were no major Baltic inflow (BACC, 2008; Matthäus et al., 2008; Nausch et al., 2013). Consequently, it is likely that the stratification was relatively weak and, similarly to the Baltic Proper (Väli et al., 2013), the major pycnocline was located relatively deep during this time interval. This conjecture is confirmed by data from 1965–2000 (Laine et al., 2007) that show a decrease in salinity and a weakening of stratification until the early 1990s and a slight increase afterwards.

The contact area of the Gulf of Finland and the Northern Gotland Basin contains probably the most intense dynamics (Andrejev et al., 2004a, 2004b). Additionally to the presence of a highly persistent front system (Kononen et al., 1996) at the entrance to the gulf, a number of meso-scale cyclonic features with a characteristic size of about 60 km have been observed and hindcast in this area. It is very likely that substantial water masses may visit the gulf for a brief period without affecting the general hydrography of the central and eastern parts (Andrejev et al., 2004a, 2004b).

Whilst the standard estuarine circulation apparently exists for most of the wind directions in the Gulf of Finland, in some discrete occasions the deeper layer violently reacts to surface forcing. Long-lasting, strong (south-)western winds may push a large amount of fresher surface water into the gulf. The excess volume of water increases the hydrostatic pressure and may lead to a gradual export of the deeper water mass (the salt wedge) in the bottom layer of the gulf (Elken et al., 2006). Such a phenomenon, called reversal, may occur if mean south-westerly wind speed exceed as low a threshold as 4–5.5 m/s (Elken et al., 2003, 2014). This process is a particular realisation of the well-known property that the standard estuarine circulation could be reversed by appropriate winds that cause landward flow in the surface layer and seaward flow in the lower layer (Alvarez-Salgado et al., 2000; Gibbs et al., 2000). In many estuarine environments this reverse occurs under the influence of the tides and low water discharge, for instance in the Hudson River estuary, USA (Blumberg and Hellweger, 2006) and in the Saint John River estuary, Canada (Delpeche, 2006).

The classical picture of the depth-averaged mean circulation of the Gulf of Finland is an overall cyclonic circulation pattern (Alenius et al., 1998), complemented by an average surface water import along the Estonian coast and an export along the northern Finnish coast. This concept is recommended to be considered as an idealised view (Myrberg and Soomere, 2013). Several studies have indicated that this concept may not always be realistic (especially for single layers in the water column), although the overall circulation down to about 45 m shows the classical cyclonic features (Andrejev et al., 2004b). In particular, in Paper A and in Section 3.1 it is demonstrated that even an anticyclonic gyre may be present in the surface layer of the central Gulf of Finland. The overall cyclonic circulation pattern is, however, reflected in the salinity patterns (Figure 4) whereby the northern part of the gulf has fresher water than the southern coast (Andrejev et al., 2004a, 2004b).

Owing to the overall small values of the internal Rossby radius in the Gulf of Finland, the circulation pattern is believed to contain numerous meso-scale circulation cells (Andrejev et al., 2004a; Myrberg and Soomere, 2013). The local values of the internal Rossby radius considerably vary over seasons. In the spring and summer they are around 2.5 km, whilst in the autumn they reduce to about 1.3 km (Alenius et al., 2003). This difference is connected with the seasonal changes in stratification (Alenius et al., 1998, 2003) and evidently affects the flow dynamics in different seasons.

1.3. Motions in the surface layers of the Gulf of Finland

Many of the circulation pattern studies performed for the Gulf of Finland have been based on using various types of averages of Eulerian currents which were simulated by numerical ocean models (Andrejev et al., 2004a, 2004b; Myrberg et al., 2010; the relevant overviews are available in Soomere et al., 2008; Myrberg and Soomere, 2013). The existing numerical simulations have shown that the circulation pattern may be radically different in different layers of this gulf (Andrejev et al., 2004a, 2004b).

From the viewpoint of this thesis, the most important is the circulation in the uppermost layer. This layer (0–2.5 m) is mainly wind-driven, has typical current velocities from 5 to 10 cm/s and contains frequent up- and downwellings along the coast (Andrejev et al., 2004a, 2004b). The currents tend to be deflected to the right from the wind direction owing to Coriolis force and often form Ekman-like drift. The inflow from the Baltic Proper into the gulf, partially driven by predominant south-westerly winds, is most intense on the southern (Estonian) side. The compensating outflow (that is enhanced by the voluminous river runoff) adjacent to the northern coast of the gulf often shows a meandering structure. The eastern part of the central Gulf of Finland is mainly characterised by small-scale eddies. The Neva River runoff becomes visible as a strong westward-directed, highly persistent flow in Neva Bight (Figure 5).

As discussed in Section 1.2, the mean circulation that is acquired for the Gulf of Finland represents a statistical property rather than a permanent feature (Alenius et al., 1998). Only recently it has been shown that a more or less permanent residual flow exists at least in some parts of the gulf (Pitkänen et al., 1993; Myrberg and Soomere, 2013). This observation exemplifies one of the fundamental probems and challenges in averaging various geophysical fields, namely, that sometimes the patterns that we are exploring for may be lost and fake patterns or trends may become evident in the averaging process. Most circulation studies require some degree of averaging to highlight the mean or residual flow and frequently repeating patterns.

This problem is further exemplified in terms of attempts to quantify a simple but rich in content measure of the current's variability – its directional persistency. Its measure *R* was introduced for the Gulf of Finland by E. Palmén at the beginning of the 20th century (Leppäranta and Myrberg, 2009) as the ratio

$$R = \frac{\left|\langle \mathbf{U} \rangle\right|}{\langle U \rangle} \times 100\% . \tag{1}$$

Here $\mathbf{U}$ is the current velocity[3], $\left|\langle \mathbf{U} \rangle\right|$ is the length of a vector consisting of mean values of the velocity components and $\langle U \rangle$ is the mean current speed. If the

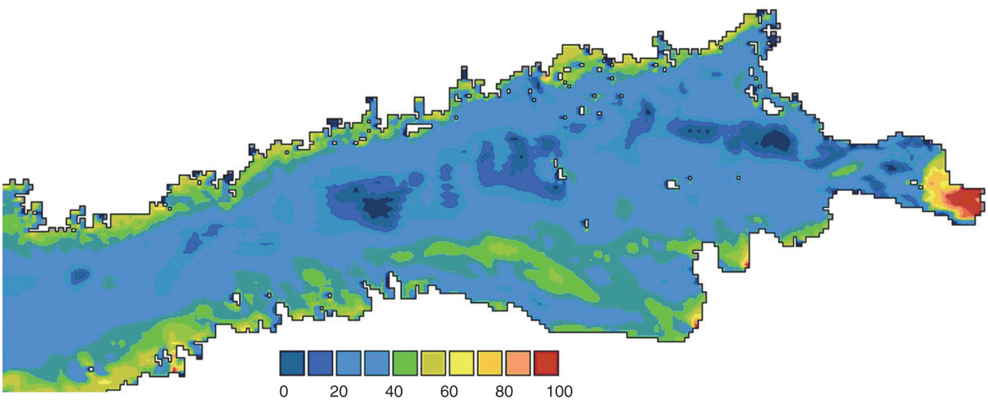

Figure 5. Persistency of the circulation in the surface layer of the Gulf of Finland (Andrejev et al., 2004b).

[3] Below I interpret velocity as a vector and speed as its length (scalar).

direction of the current is constant, the persistency is 100%. Thus the persistency gives us a measure of how stable in terms of directions the current-driven transport is.

The long-term persistency of surface currents in the Gulf of Finland was found to be between 6% and 26% (Leppäranta and Myrberg, 2009), whereas it was much larger during some seasons. Andrejev et al. (2004a) found that in the uppermost layer (0–2.5 m) the persistency was highest in coastal areas with values up to 50%, whereas the values near the axis of the gulf are around 15–20% (Figure 5). The motions were much more persistent in the subsurface layer (2.5–7.5 m): north of the axis the persistency was 50–60%, whilst adjacent to the Estonian coast it was only 15% (Andrejev et al., 2004a). In both layers the highest persistency was found near the mouth of the Neva River with the values or R reaching 90–100% (Figure 5).

These results suggest that in the surface layer (0–2.5 m) the effect of the wind drift is of great importance. The motion in the layer immediately below (2.5–7.5 m) is mostly dominated by the large-scale circulation system. Below these layers (<7.5 m) the numerically simulated current system was found to be more or less homogenous. Its persistency ranged from 50 to 80%. It contained strong inflow adjacent to the Estonian coast and strong outflow on the northern side of the gulf. This structure persisted down to 45 m depth. Although at deeper levels the effect of bottom topography becomes evident in the form of small vortices, in some regions on the eastern side of the gulf $R > 50\%$ throughout the entire water column. This indicates the presence of areas where smaller-scale internal circulation is quasi-stationary. All significant meso-scale eddies identified in Andrejev et al. (2004a) were cyclonic and located south of the outflowing waters. These vortices extended to the bottom. The flow persistency in the lower layer (from 12.5–17.5 m to the bottom) was 35–60%.

Therefore the circulation pattern in the Gulf of Finland is fairly complicated. Its persistency in the coastal areas is evidently relatively high, thus the patterns observed in this region (strong inflow at the entrance or frequent upwellings and downwellings, Myrberg and Andrejev, 2003; Lehmann et al., 2012) are basically reliable. The most ordered flow apparently exists in the sub-surface layer of the gulf at depths of 2.5–7.5 m.

The overall small values of the quantity R suggest that, statistically, the surface-layer flow is fairly chaotic, particularly in the central part of the gulf where most of ship traffic is concentrated. This does not exclude the occurrence of structured and/or regularly occurring flow features at certain time scales. The most important time scale from the viewpoint of current-driven propagation of oil spills in the Gulf of Finland seems to be the weekly scale (Anonymous, 2002b). This scale in the Gulf of Finland is intermediate to the synoptic scale (typical turnover time of meso-scale eddies) and the seasonal scales. These two scales almost overlap for the open ocean (Cushman-Roisin and Beckers, 2011).

This hypothesis, tested in Paper A and described in Section 3.1, is supported by the presence of current patterns with a life-time from a few weeks up to a few months in the Baltic Proper (Lehmann et al., 2002; Andrejev et al., 2004b; Meier, 2007; Osiński and Piechura, 2009). The existence of such patterns eventually has a high potential for the rapid and systematic transport of both water masses and adverse impacts such as nutrients, toxic substances, or oil pollution between the specific sea areas, and may be used for various offshore engineering purposes.

Similarly to the entire Baltic Sea, the differences in seasonal wind velocities may substantially influence both the dynamical processes and long-term circulation patterns. It is likely that in the windy season (autumn and winter) the atmospheric conditions, the Ekman drift and bottom topography may have a greater effect on the currents (Krauss and Brügge, 1991), whilst for the calm seasons (spring and early summer) the circulation is mostly determined by basin-scale drivers (Lehmann and Hinrichsen, 2000). An evidence of this seasonality is the variation in the average velocity (Paper A). Soomere and Quak (2007) express the opinion that the seasonality also becomes evident in how the underlying circulation (that is driven mainly by the basin-scale factors) impacts the local motions in the relatively thin uppermost layer. It is likely that the uppermost layer largely follows the dynamics in the rest of the water column when the wind is weak (i.e., during calm conditions) and under ice cover that shelters the water masses from the direct impact of wind.

1.4. Marine Protected Areas of the Gulf of Finland

The Baltic Sea is quite unique not only due to its geographic and oceanographic characteristics depicted in the previous sections. The complexity of implementing engineering and management solutions here severely depends on the need for finding suitable administrative agreements between countries and avoiding transboundary impacts. The sea, similarly to the Mediterraean Sea, is surrounded by several countries having different life standards and political systems, and with different perceptions of the assets associated with benefits from the sea and its ecosystem services (Uggla, 2007). Due to the high activity of the existing ports influenced by the economic growth of the surrounding countries and increased oil export from Russia (Knudsen, 2010), it is one of the busiest shipping domains in the world (Rytkönen et al., 2002). Today as much as about 15% of the entire world's international maritime cargo is transported over the Baltic Sea (HELCOM, 2009). Due to the sensitivity of this marine environment combined with extreme anthropogenic pressure (HELCOM, 2010), it has been classified as being within top ten most threatened waters in the world (Uggla, 2007).

One of the pillars of administrative and environmental management of the Baltic Sea is the United Nations Convention on the Law of the Sea (UNCLOS) that has been ratified by all countries surrounding the Baltic Sea. The UNCLOS basically defines boundaries of sea zones (for example territorial waters, contiguous zone, exclusive economic zone, high seas zones) with specific rules and rights to the boundaries (Figure 6). In other words, the UNCLOS delimits the sea area that each country may use for economic and political purposes. It also defines the international waters that may be used by all countries.

Even though the UNCLOS assigns particular rights for the surrounding countries, certain sea areas still need further protection environmentally. The high vulnerability of the marine ecosystem of the Baltic Sea with respect to the anthropogenic influences, especially caused by shipping activities, has been signalled in the designation of the almost entire Baltic Sea (except the Russian territorial waters) by the International Marine Organisation (IMO) as a Particularly Sensitive Sea Area (PSSA). This indicates that specific measures (such as ship routing, strict requirements to vessels, etc.) can and should be used to control the maritime activities in this area to protect coastal states, flag state and the environmental and shipping community (Kachel, 2008). Even though the PSSA regulation does not provide specific protection, it provides international recognition of the special significance of a sea area and informs mariners of the importance of taking extra care when navigating in that sea area (Kuronen and Tapaninen, 2009).

The countries surrounding the Gulf of Finland have designated several MPAs in the gulf and at its entrance (thus within the PSSA) (Figure 6). Due to ecological, social or scientific characteristics, these areas are either more vulnerable and/or of greater importance than other areas. Similarly to many other domains of the World Ocean (Boersma and Parrish, 1999), most of the MPAs in the Baltic Sea are located along shipping lanes or nearby centres of human activity, and thus the chance of chemical and biological pollution of the MPAs is also high.

Even though there are measures in place to protect the marine environment, accidents do occur in the maritime shipping industry. The consequences frequently endanger the PSSAs and MPAs (Dalton and Jin, 2010). Such disasters have several

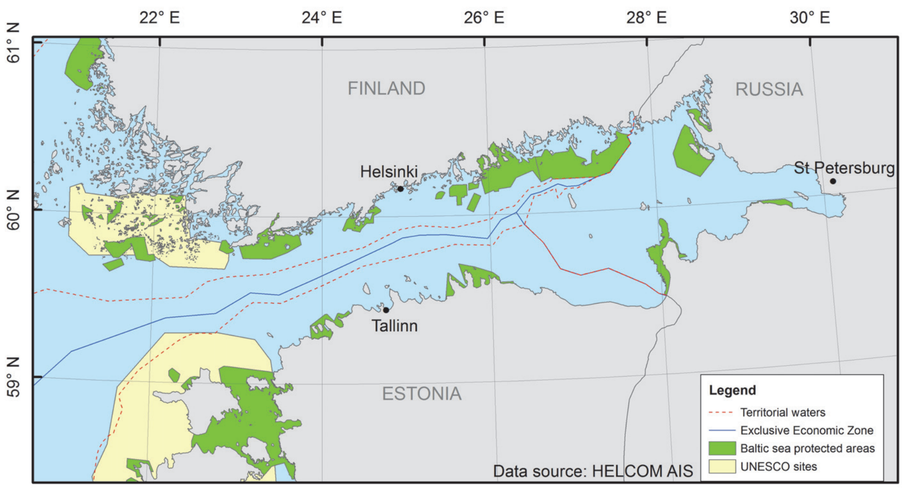

Figure 6. Map of the Gulf of Finland showing the MPAs, international and territorial waters for the surrounding countries. Map by M. Viška.

times occurred in the Baltic Sea basin or with ships carrying cargo from the Baltic Sea ports (Paper C). For example, the *Full City* accident led to the release of estimated 300 tonnes of oil into the Skagerrak next to the Baltic Sea in 2009 (Broström et al., 2011). Several dozen tonnes of oil were released to the Gulf of Finland in two accidents in 2006 (Soomere and Quak, 2007). In 2003 the Polish cargo ship *Gdansk* collided with the Chinese bulk ship *Fu Shan Hai* and extensive resources were mobilised to restrict the oil leakage (HELCOM, 2009). The most drastic was the case of MV *Prestige* (Vieites et al., 2004) that set sail from Saint Petersburg, Russia. On reaching Galicia, Spain, she leaked 63 000 tonnes of heavy fuel oil in 2002. Several more recent cases of grounding or other accidents have occurred in Estonian waters (Filippov, 2010), which fortunately have not led to major consequences.

Even though an area is designated as an MPA, it is not immune with respect to maritime accidents. According to HELCOM (2013), the most frequently reported threats to MPAs in the Baltic Sea are eutrophication and general pollution. However, the largest potential threat is pollution from shipping which includes oil spills and invasion of alien species. As of 2013, 65% of the MPAs have a management plan in force, 26% have such a plan in preparation and 9% have no management plan at all. Most areas with no plan or a plan in preparation are located in the eastern and southern Baltic Sea. This set involves several MPAs in the Gulf of Finland. Even though shipping is reported as one of the main threats to the MPAs, no efforts towards regulating shipping activities are foreseen in their management plans.

2. Circulation and trajectory models

The method used in this thesis (Figure 7) relies on the outcome of contemporary ocean circulation and current-driven Lagrangian transport models. The starting point is the three-dimensional (3D) velocity data for the Gulf of Finland. Accurate modelling of the processes in this basin requires a sophisticated model that is able to couple turbulence, sea ice models and atmospheric forcing of high quality to perform realistic multi-year hindcasts. These data are mostly analysed using a Lagrangian trajectory model. Common statistical methods are used next to acquire the patterns of currents (Papers A and B). The obtained patterns serve as a clue to quantify the current-driven risk to the MPAs and identify which ones are at high and low risk of pollution as described in Papers C and D and in Chapters 3 and 4. This quantification, similarly to the parallel work (Viikmäe, 2014), makes it possible to determine, for example, places of refuge that a vessel in distress can travel to (Maddern and Knight, 2003). The presented climatologically valid solutions are evidently not perfect for each particular accident or critical situation. Their major advantage in the marine environmental engineering and managing in ship transport is their fast availability for decision-making, while sophisticated model runs may take days and require large amounts of initial data.

2.1. Eulerian and Lagrangian approaches

The velocity fields in a particular sea area can be characterised using either the Eulerian or Lagrangian viewpoint (Figure 8). In the Eulerian framework the flow is

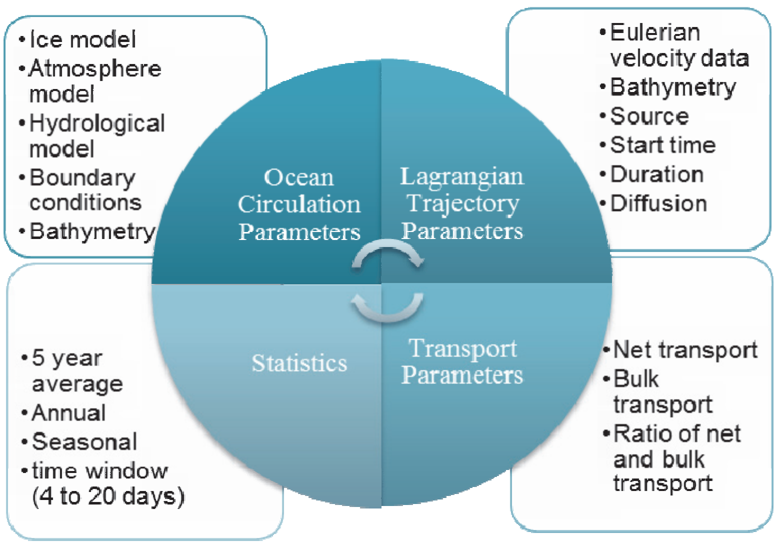

Figure 7. Flow chart showing the method used to investigate the current-driven transport patterns and to identify the MPAs of high and low risk of pollution.

viewed from a fixed point in space over a period of time. The Lagrangian technique[4] is based on the perspective of parcels carried by the flow. To calculate the Lagrangian currents or current-driven paths of pollution parcels, it is necessary to know the velocity at each point of the path at the time instant when the parcel is located at this point. If the goal is to calculate paths of many water or pollution parcels, it is generally necessary to employ the information about Eulerian velocities in the entire water body and during the entire propagation time interval (Figure 8).

Although Lagrangian velocities are calculated similarly to the Eulerian ones using the simple formula speed = distance/time, they do not necessarily coincide. An overview of the theoretical aspects of the Lagrangian viewpoint in the context of this thesis in presented in Döös et al. (2013). Examples of Eulerian velocity fields can be either simulated numerically (see, e.g., Torsvik et al., 2013 for an overview) or measured from fixed-location surface velocity sensors (e.g., stationary moorings, Acoustic Doppler Current Profilers). Examples of the Lagrangian viewpoint and/or velocities are provided by floating drifters (e.g., ARGOS drifters or studies using various tracers, Döös et al., 2013).

The Eulerian framework considers the instanteneous velocity of water parcels that flow through a fixed location. The Lagrangian technique, even though it is often used to represent the velocity at a particular location, more represents the transport features of the water parcel as its speed and direction are calculated based on how it moves from one location to the next. Importantly, the (Lagrangian)

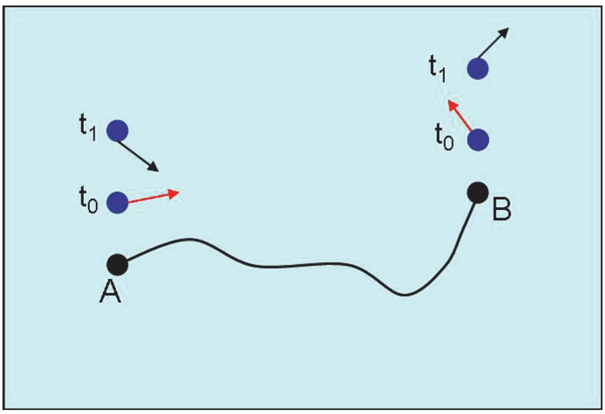

Figure 8. Eulerian vs Lagrangian flow: The meandering line (A to B) represents a Lagrangian trajectory during the time period t_0 to t_1. At the points A and B shows the flow at time t_0 and t_1.

[4] Kristofer Döös brings the following illustration (Döös et al., 2013, p. 226): “This can be illustrated by a cyclist, who passes an immobile traffic jam. In this case the static car driver sees the moving cyclist from an Eulerian perspective, while the moving cyclist observes the static traffic jam from a Lagrangian perspective. The zigzagging path of the cyclist between the cars constitutes a Lagrangian trajectory.”

velocity of the parcel may change when it moves from one location to another. Often very weak currents at the location of the origin of pollution parcels relocate the pollution after some time into strong currents along its path.

Most analytical and numerical models in fluid dynamics are implemented in an Eulerian framework (Torsvik et al., 2013) for it is more straightforward to describe the motion as a function of position and time on a fixed grid (Döös et al., 2013). The common ocean circulation models have the equations of motion discretised with finite differences on a fixed grid. The motion of the water and various hydrophysical fields such as salinity and temperature are described from the Eulerian perspective with values specified in each grid box, even if the vertical discretisation often has a time-dependent component related to the motion of the fluid (Döös et al., 2013).

2.2. Numerical ocean models

Accurate and reliable modelling of the ocean circulation and the spatio-temporal distributions of various hydrophysical, chemical and biological fields is important in virtually all aspects of ocean science and management, from long-term climate studies, pollution control or management of fisheries down to everyday operations. Historically, the understanding of the oceans was mainly based on in-situ measurements which were sparse, expensive and time-consuming. The 20th century has been empowered with advancement and improvements in computer technology, sophisticated remote sensing capacities and improved fundamental knowledge of the seas and oceans. These and many more improvements have greatly assisted in our understanding of the ocean in the 21st century. Numerical ocean models that are run on high-performance computers, both in a standalone mode and in combination with observed data, have radically increased the ability to simulate and comprehend oceanic processes, monitor the current state of the oceans and to a limited extent even predict their future state (Kantha and Clayson, 2000).

All numerical models of circulation of seas and oceans (called ocean models below) solve certain governing equations for oceanic motions. These equations for processes that are important for the studies in this thesis usually assume that the sea water is incompressible isotropic Newtonian fluid. They represent the first principles such as the conservation of mass (a continuity equation) and momentum (the Navier–Stokes equations or their analogues). They are complemented by certain thermodynamical equation(s). An ocean model also includes a budget equation for salinity and an equation of state relating water density with temperature, salinity and pressure (Cushman-Roisin and Beckers, 2011). A detailed description of the model, results of which are used in this study, is presented in Meier and Höglund (2013).

A large number of numerical ocean models have been developed and implemented over the past decades (e.g., Haidvogel and Beckmann, 1999; Torsvik, 2013). This variety is largely due to different choices in the model construction, e.g., discretisation techniques, horizontal and vertical grid configurations, turbulence schemes, parameterisation of subgrid-scale and boundary layer processes and boundary conditions. The particular design usually depends on the intended use of the model, for instance, whether it is designed for global- or regional-scale simulations, or used in a short-term forecast system, long-term climate study or intermediate-duration (multi-)seasonal study.

Even though the ocean models in some cases can reasonably well predict the general circulation and dynamics, they are never perfect. Major uncertainties include the handling of model parameters near open boundaries at which flow conditions are not known (e.g., Nycander and Döös, 2003 and references therein). The presence of complicated stratification increases demands on computer resources to adequately reproduce the vertical structure of water masses. There is much room for improving the parameterisation of the impact of surface waves or for an acceptable reproduction of internal waves (Reissmann et al., 2009). The horizontal resolution of models used to reconstruct Lagrangian trajectories should be able to reproduce the basic meso-scale features such as synoptic eddies. On top of that, the resolution of atmospheric forcings should also be adequate (Kantha and Clayson, 2000; Myrberg et al., 2010).

Contemporary ocean models implemented for regional purposes typically have a horizontal resolution of 5–20 km (Griffa et al., 2004). They employ various closure schemes to account for sub-grid effects (motions with typical scales smaller than the horizontal or vertical grid step). The relevant approaches are, in essence, certain smoothing operators that fail to capture many complex and oceanic processes at the submeso-scale and small scale (Griffa et al., 2004). For example, near Florida coast a high-resolution Doppler radar device measured strong eddies of 1–3 km diameter (Shay et al., 2002). Most global and regional ocean models employ the hydrostatic approximation which is only conditionally applicable at a horizontal resolution of less than several kilometres even if the computations are feasible (Kantha and Clayson, 2000).

The resulting truncating below the typical grid spacing in ocean models is likely to impact the simulation of Lagrangian trajectories (Kjellsson and Döös, 2012). Repercussions of this feature were analysed for the Gulf of Finland by Viikmäe et al. (2013) by means of including artificial effects of subgrid-scale motions into the calculations of Lagrangian trajectories. The appearance of single trajectories and the spreading of initially closely located trajectories radically changed. Several core statistical features of the transport such as the frequency of drift of pollution parcels to the nearshore, the time it took for the parcels to drift from the offshore to the nearshore regions and the spatial patterns of locations reached by the parcels remained practically unchanged. This experience suggests that certain major features of statistics of current-driven Lagrangian transport are almost invariant with respect to the particular way of reproduction of subgrid-scale processes.

Several regional models have been developed or adjusted specifically for the Baltic Sea and the Gulf of Finland. The High Resolution Oceanographic Model of the Baltic Sea (HIROMB; Funkquist, 2001; Funkquist and Kleine, 2007) belongs to the family of DMI/BSHcmod circulation models (Kleine, 1994; Dick et al., 2001 (both cited after Viikmäe, 2014); Myrberg, 2010). This family was originally developed in Bundesamt für Seeschifffahrt and Hydrographie (The Federal Maritime and Hydrographic Agency, Germany) and further improved in the Danish Meteorological Institute (Stanev and Lu, 2013). The HIROMB model is currently used for operational sea forecast in Estonia (Lagemaa et al., 2011).

The Rossby Centre Ocean (RCO) model (Meier, 1999; Meier et al., 2003), the results from which are largely used in this thesis, has been designed for long-term climate studies and has a moderate spatial resolution. The OAAS model (Andrejev and Sokolov, 1989, 1990; Andrejev et al., 2004a, 2004b, 2010) has been specifically designed for the Gulf of Finland conditions. Other models such as MIKE 3 (DHI Water and Environment, 2000) are also occasionally used in the Baltic Sea basin (Myrberg et al., 2010).

The comparison by Myrberg et al. (2010) showed that in general the listed models reproduced the major hydrodynamic features of the Gulf of Finland fairly well. However, none of the models were able to accurately simulate the vertical profiles of temperature and salinity. Their performance was better in the western section of the gulf than in the eastern section. The key requirement in the evaluation of current-driven transport is that the model resolution (first of all the horizontal grid size) should ideally be small enough to resolve the major features of meso-scale motions. The results presented in Andrejev et al. (2011) suggest that that the underlying ocean model should capture at least the main features of meso-scale motions. The typical scale of such motions is governed by the internal Rossby radius (Section 1.2). As stratification is sometimes very strong in the Gulf of Finland, a detailed vertical resolution is necessary in order to resolve its complex dynamics and topography.

2.3. Rossby Centre Ocean model

The results presented in this study largely rely on the 3D Eulerian velocity fields that were computed using the RCO model for the entire Baltic Sea and provided by the Swedish Meteorological and Hydrological Institute (SMHI) in the framework of the BONUS+ BalticWay cooperation (Soomere et al., 2014). These Eulerian velocity fields were then used in a Lagrangian trajectory model that evaluated the transport paths of water (and pollution) particles in the surface layer (Figure 8).

The RCO model is a 3D coupled ice-ocean model of the Baltic Sea. It was developed to simulate physical processes on time-scales of hours to decades, with the main goal of studying the past and future climate variability of the Baltic Sea (Meier, 1999; Meier et al., 2003). This designation and appropriate performance for the Gulf of Finland (Myrberg et al., 2010) suggest that it takes properly into account the main factors affecting the physical processes in the Baltic Sea, their driving forces (atmospheric conditions, external forcing from the North Sea and river discharge), underlying bathymetry and also appreciably resolves the main hydrodynamic processes in the sea.

The RCO model is extensively described and validated in the international literature (see Myrberg et al., 2010 and references therein about its use in the Gulf of Finland conditions and Meier and Höglund, 2013 about its detailed set-up). For this reason I only shortly depict its main features following the presentation in Paper A. The RCO model is, in essence, a variation of the Bryan–Cox–Semtner free-surface general circulation model following Webb et al. (1997) and Killworth et al. (1991). It is based on primitive equations and employs the Boussinesq and hydrostatic approximations. The model equations are solved using a regular rectangular grid in the horizontal direction and *z*-coordinates in the vertical direction. The horizontal resolution (2 nautical miles (nm)) is considered acceptable with regard to mesoscale dynamics in the open part of the Baltic Sea (Meier et al., 2003; Meier, 2007).

The model has open boundary conditions (Stevens, 1991) in the northern Kattegat (North Sea, Figure 3). In case of outflow, a modified Orlanski radiation condition is utilised (Orlanski, 1976). In case of inflow, temperature and salinity values at the boundaries are nudged towards observed climatologically profiles. Sea level elevation at the boundary is prescribed from hourly tide gauge data. The monthly river runoff data have been taken from Baltic Sea Experiment (BALTEX) hydrological Data Centre (BHDC) at SMHI (Bergström and Carlsson, 1994).

The model depths are based on so-called Warnemünde bottom topography (Seifert et al., 2001). The model uses up to 41 vertical levels (depending on the local water depth), the thickness of which varies between 3 m close to the surface and 12 m at 250 m depth. The uppermost layer, used in the analysis below, corresponds to depths of 0–3 m. Subgrid-scale mixing is parameterised using a turbulence closure scheme of the k–ε type with flux boundary conditions to include the effect of a turbulence-enhanced layer due to breaking surface gravity waves (Meier, 2001). A flux-corrected, monotonicity-preserving transport scheme following Gerdes et al. (1991) is embedded. No explicit horizontal diffusion is applied. A time step splitting scheme is used, with 150 s for the baroclinic and 15 s for the barotropic timestep. The output is stored once in six hours.

The atmospheric forcing used was developed at the SMHI (Meier and Döscher, 2003). It was based on 3-hourly gridded observations of sea level pressure, geostrophic wind components, 2 m air temperature, 2 m relative humidity, precipitation and sea level pressure fields. The relevant data were constructed from the ERA-40 re-analysis (Uppala et al., 2005) over Europe using a regional atmosphere model with a horizontal resolution of 25 km (Höglund et al., 2009; Samuelsson et al., 2011). Data from all available synoptic stations (about 700 to 800) covering the entire Baltic Sea drainage basin were interpolated on a regular horizontal grid. A boundary layer parameterisation was utilised to calculate wind speeds at 10 m height above sea level from the geostrophic wind data (Bumke et al., 1998). As the atmospheric model tends to underestimate wind speed extremes, the wind is adjusted using simulated gustiness to improve the wind statistics (Höglund et al., 2009).

The circulation model is coupled to a Hibler-type sea ice model (Hibler, 1979) with elastic-viscous-plastic rheology (Hunke and Dukowicz, 1997) and thus appreciably replicates the presence of ice cover and its impact on the dynamics of currents in the entire water column. Standard bulk formulae are used to calculate the air-sea fluxes over open water and over sea ice (see Meier and Höglund, 2013). The model thus apparently resolves the major part of the reaction of water masses to realistic atmospheric and lateral forcing, including the ice season. However, the model does not account for the roughness of the lower surface of the ice (e.g., ridging).

As any gridded representation of reality, the RCO model does not exactly replicate the processes in the Gulf of Finland (Myrberg et al., 2010). As discussed above, high vertical and horizontal resolution with a corresponding short time step is essential to resolve the bottom topography (Figure 9) and small-scale processes with impact on the large scale (Meier and Döscher, 2003). The largest sources of uncertainties and biases are inexact parameterisations of subgrid-scale processes, a modest horizontal and vertical resolution and inaccuracies of forcing fields.

A large part of deviations from reality occur for the fields in the interior of the water masses. The modelled main halocline is often located higher than the real one (Meier, 2007), mixing during salt water inflows is not correctly replicated (Meier et al., 2003) and sea surface temperature occasionally contains unrealistic numerical noise (Löptien and Meier, 2011). The simulated vertical stratification in the Gulf of Finland tends to be stronger than in reality (Meier, 2007). These shortcomings seem to be characteristic of all contemporary circulation models of the Baltic Sea (Lagemaa et al., 2011).

The most serious limitation of the RCO model for its use in the Gulf of Finland is its modest horizontal resolution (about 3.7 km). This resolution implies that the model is, at best, eddy-permitting in this water body where the typical values of the

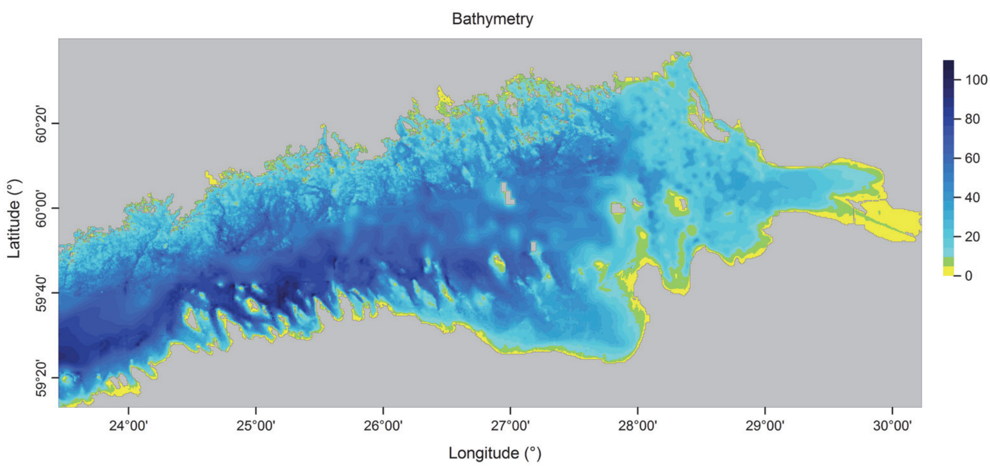

Figure 9. Bathymetry and geometry of the Gulf of Finland with a resolution of ¼ nautical mile (about 470 m) (Andrejev et al., 2010).

internal Rossby radius are 2–4 km (Alenius et al., 2003). Although an accurate representation of meso-scale eddies cannot be expected, it is likely that the model replicates the larger eddies and their contribution to current-driven transport as described in Paper A. It is also natural to assume that it replicates the major statistical properties of Lagrangian transport, as the impact of meso-scale motions is to some extent accounted for via parameterisation of subgrid processes. Although the RCO model has quite a large bias for several Lagrangian properties of passive tracers (Kjellsson and Döös, 2012), many important statistical properties of current-driven transport have been shown to be almost invariant with respect to the particular choice of the model resolution (Andrejev et al., 2011; Viikmäe et al., 2013).

2.4. The path of a substance: Lagrangian trajectory model TRACMASS

Obtaining the 3D Eulerian velocity field is usually the first step in the evaluation of the path of a substance in a water body. To reconstruct or predict such a path, it is often necessary to utilise a Lagrangian framework. Technically, it is possible to use a pool of Lagrangian particle data to predict the trajectories of other particles (Özgökmen et al., 2000, 2001). A much more widely used method for trajectory calculations is based on the knowledge of the underlying Eulerian velocity field. This information may stem either from high-resolution surface velocity data (e.g., from remote sensing) and/or from ocean models such as the RCO model.

The moderate resolution of the RCO model and especially its inability to exactly replicate the meso-scale structures implies that application of methods based on the dynamical system theory is not feasible. For better replications of the flow structure such methods can provide a way of assessing and quantifying the effects of organised or coherent structures in a flow of transport (Poje and Haller, 1999; Wiggins, 2005).

In this thesis, similarly to the parallel work (Viikmäe, 2014), it is assumed that particles are passively advected with the flow. I used the classical approach in which the trajectories of Lagrangian particles are calculated from the gridded Eulerian velocities (Lu et al., 2012; Viikmäe and Soomere, 2014). The necessary Eulerian velocity data were extracted from the output of the RCO model.

Regardless of the particular method for the replication of Lagrangian motions, there still are problems. For example, small errors in the estimation of Eulerian ocean currents can drastically change particle trajectories and greatly reduce the predictability of Lagrangian motions. Common sources of errors include uncertainties in forcing functions, bathymetry, coastlines, stratification and details of model numerics (Griffa et al., 2004). Based on the discussion of the invariance of the statistics of Lagrangian trajectories on several key properties of the ocean model (Section 2.2, Viikmäe et al., 2013), it is likely that these errors may considerably affect single trajectories but apparently do not substantially impact the major statistical features of the transport.

The trajectories can be calculated either "on-line" (which entails the simulations produced simultaneously with the integration of the ocean model) or "off-line" (i.e., after the ocean model has been run for some time and the velocity fields have been stored). The main difference is whether the trajectories are evolving together with the velocity field or are reconstructed later (Soomere, 2013). The on-line approach makes use of velocity data at each internal integration time step of the ocean model, hence the trajectories can be evaluated with a much higher temporal resolution than for off-line calculations. However, the off-line method is more efficient if there is a need to re-run experiments with different sets of parcels, e.g., when simulating the effect of different properties of substances, or when the time, place and amount of parcels to be selected are not prescribed at the time of running the ocean model.

Both methods have been used in studies of pollution propagation in the Baltic Sea. The on-line approach has been used for Eulerian tracers in the entire Baltic Sea (Höglund and Meier, 2012; Meier and Höglund, 2013) and in high-resolution simulations for the Gulf of Finland (Andrejev et al., 2011). The off-line approach has been more common. It has been applied in a series of studies of B. Viikmäe and co-authors for the Gulf of Finland and the northern Baltic Proper, in Lu et al. (2012) for the south-western Baltic Sea and in Lehmann et al. (2014) for the entire Baltic Sea. Murawski and Woge Nielsen (2013) employed a combined method of calculating oil spill propagation under joint impact of waves and surface currents.

In this thesis the trajectories are calculated using the off-line Lagrangian trajectory TRACMASS model (Döös, 1995; de Vries and Döös, 2001). The off-line mode is preferable because of the necessity of re-running many realisations with the velocity data for different partially overlapping time intervals in order to derive a large enough set of samples for the statistical approach. The TRACMASS code has been used successfully in many global (Döös and Coward, 1997; Döös et al., 2008) and regional studies for the Mediterranean Sea and the Baltic Sea (Döös et al., 2004; Engqvist et al., 2006; Soomere et al., 2011b), as well as in studies of large-scale atmospheric circulation (Kjellsson and Döös, 2012; Kjellsson et al., 2013).

The trajectories are calculated based on linear interpolation of the velocity field at each point of a particular grid cell. This is described in detail in Paper A. Linear interpolation is necessary in order to convert the RCO model output into the format required by the TRACMASS code. The RCO velocities are stored using the so-called Arakawa B-grid cell staggering technique (at the corners of each cell, see, e.g., Torsvik, 2013; Döös et al., 2013). They are recalculated for a C-grid (at the walls of each grid cell) for the use in TRACMASS by simple linear interpolation.

The TRACMASS code solves the trajectory path through each grid cell using an analytical solution of a differential equation which depends on the velocities on the grid box walls (Döös et al., 2013). The zonal and meridional displacement of the trajectory inside each grid box and the time it takes for it to reach the wall of the neighbouring cell are thus calculated exactly from the velocity fields. The smallest transit time in either direction indicates at which wall of the grid box the trajectory will exit (de Vries and Döös, 2001). This procedure of building a trajectory has an adjustable temporal resolution that can be made basically equivalent to that of the input velocity data. The process is repeated in each subsequent cell and/or time instant.

The trajectories calculated by the TRACMASS model depend to some extent on the temporal resolution of the circulation data and of the trajectory calculation scheme. It is generally expected that the resulting errors will lead to a certain divergence of initially close trajectories. The experience with the TRACMASS code reveals that the spreading of the calculated trajectories is usually much smaller than the spreading of real drifters. In other words, initially close trajectories have an overly tendency to stay close (Kjellsson and Döös, 2012; Kjellsson et al., 2013). This issue largely reflects the ignoring of sub-grid turbulence. Although artificial inclusion of the impact of sub-grid motions obviously affects the shape of single trajectories, it likely does not impact the core statistical features of transport patterns (Viikmäe et al., 2013). This stability of the overall patterns of transport and the locations where the pollution parcels reach the nearshore implicitly suggests that the potential impact of the time step of saving the circulation data or the similar effect of the choice of the temporal resolution in trajectory reconstruction are minor.

3. Patterns of surface currents in the Gulf of Finland

The flow in the surface layer of seas and oceans is often referred to as a turbulent motion that is commonly interpreted as chaotic and disordered. This disorder still possibly contains important and systematically occurring circulation and transport patterns. For instance, children's toys lost from transoceanic container ships in the North Pacific have been reported to show up ten months later on the beaches of Stika, Alaska (Ebbesmeyer and Ingraham, 1994). Floating plastic fragments released from sea- and land-based sources appear in sub-tropical gyres ("garbage patches") of the northern and southern hemispheres (Pichel et al., 2007; Eriksen et al., 2013).

In many occasions interesting and intriguing patterns may be extracted by means of properly averaging the Eulerian velocity fields. Doing so has led to a description of semi-persistent current patterns in the subsurface layer of the Gulf of Finland at depths of 2.5–7.5 m (Andrejev et al., 2004a, 2004b) (Section 1.2). A similar analysis in Section 3.1 has led to an observation that an anticyclonic gyre may exist in the surface layer of the eastern Gulf of Finland (Paper A).

Extracting and discovering of more complicated and normally concealed patterns require extending the analysis beyond the classical (Eulerian) features of the velocity fields. This approach is evidently necessary in the Gulf of Finland where the surface layer circulation is substantially impacted by rapidly changing atmospheric forcing and relatively persistent currents are rare. The method of Lagrangian trajectories, presented in Section 3.2 and based on Paper B, is applied in Paper A to establish the main parameters of the net and bulk Lagrangian transport in semi-persistent patterns of currents (Sections 3.3 and 3.4). The information about these patterns is particularly useful for interpreting the results of the quantification of the risk of current-driven pollution to the MPAs in the Gulf of Finland in Chapter 4.

3.1. Eulerian average velocities

The results of the analysis of Eulerian velocity fields produced by the RCO model by means of simple averaging (Paper A) correspond reasonably well with the existing knowledge for the Gulf of Finland. The 5-year average of the zonal (east–west) and meridional (north–south) components of velocities at the sea surface (0.02–0.07 m/s, Figure 10) match both the measured and numerically simulated average values (Alenius et al., 1998; Andrejev et al., 2004a, 2004b). The highest velocities (0.027–0.056 m/s) occur in the windy season (Table 1 of Paper A). In the calm season the velocities are much smaller, usually 0.01–0.02 m/s. During windy seasons the average surface flow is predominantly to the east, whereas during calm seasons it is mostly to the west. The meridional and zonal flow speeds are uncorrelated. The differences that occur in the seasonal velocities are expected, as

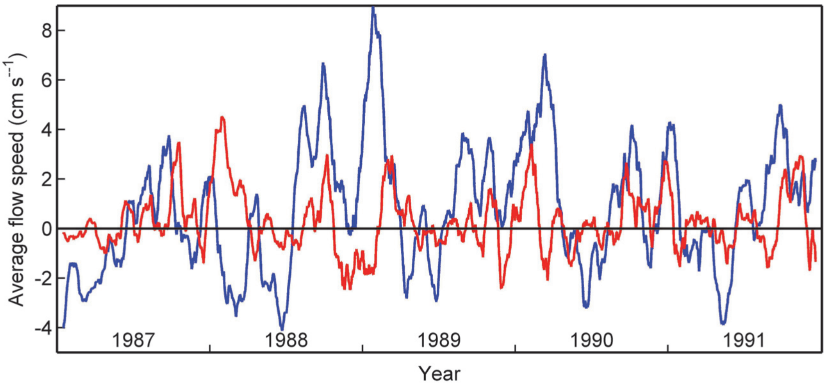

Figure 10. Time series of the running average over 30 days of velocity components (blue: east–west component, positive to the east, red: north–south component, positive to the north) averaged over all sea grid points of the interior of the Gulf of Finland (eastwards from the latitude 24°E) (Paper A).

discussed in Section 1.3, for the windy season has the strongest winds, thus the strongest velocities.

The map of vectors consisting of pointwise averaged zonal and meridional components over the 5 years in question (Figure 11) also shows several well-known features of the circulation. This operation of averaging highlights the long-term average direction and speed of relocation of water parcels at each location, similarly to properties of air flow in meteorological applications.

A relatively intense inflow occurs, on average, at both the northern and southern coasts at the entrance to the Gulf of Finland. This pattern has been a constant

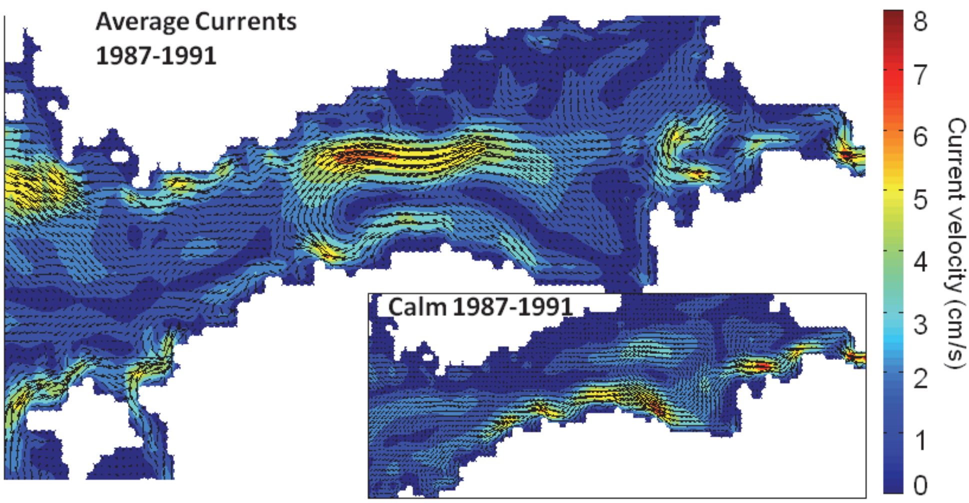

Figure 11. Average velocity field over the entire period of 1987–1991 (main image) and during calm seasons (May–August, inset) over the same interval in the Gulf of Finland. Both the colour code and lengths of vectors show current velocity in cm/s (Paper A).

feature in previous studies (Andrejev et al., 2004a). It is likely that this flow is a fingerprint of a long-term average of velocities and therefore represents a statistical feature rather than a jet-like formation. It nevertheless hints that a pollutant, if released near any coast of the entrance to the Gulf of Finland, may be transported into the gulf interior.

This analysis also leads to some unexpected properties of the 5-year average pattern of currents. The most interesting feature is a large elongated (in the east–west direction) anticyclonic gyre in the central area of the Gulf of Finland (Figure 11). The study area is situated in the northern hemisphere where long-term average circulation patterns tend to be cyclonic. Previous studies of the residual circulation in the Gulf of Finland have also found that the long-term circulation is cyclonic (Alenius et al., 1998; Andrejev et al., 2004a).

Such anticyclonic patterns are, however valid solutions of the underlying equations for single layers. Their presence is a well-known feature in wide (width larger than the internal Rossby radius) stratified estuaries that receive large freshwater input. In such situations the joint impact of the Earth's rotation and the classical estuarine circulation may drive an anticyclonic gyre at the estuary head (Fujiwara et al., 1997). It is natural for this phenomenon to appear in the easternmost Gulf of Finland where the Rossby radii are fairly small (Nekrasov and Lebedeva, 2002). Similar anticyclonic gyres were found to exist in other basins of the Baltic Sea, for instance in the Kattegat (Nielsen, 2005), the Bornholm Basin, Gdańsk Bay, north of the Gotland Basin (Lehmann et al., 2002) and recently in the Gulf of Riga (Soosaar et al., 2014) in a basin that is generally less favourable for this phenomenon to occur. They have been also identified in the Great Lakes (Beletsky et al., 2006).

This anticyclonic gyre apparently dominates when the upper mixed layer is very thin. It only becomes evident when the velocity field is averaged over the 5-year interval. It is not present every year and does not necessarily reflect transport patters over a few weeks or months. This feature once more underlines the importance of choosing a proper averaging procedure and time interval for highlighting subtle features of the circulations patterns.

Figure 11 also indicates relatively large and ordered average transport velocities in the central part of the gulf where previous studies (Section 1.3) have found very low persistencies (Alenius et al., 1998; Andrejev et al., 2004a). This discrepancy signals that the anticyclonic gyre is a statistical feature rather than an ordered flow during some seasons or other time intervals.

Another difference of the 5-year average patterns from the classical concept of the Gulf of Finland circulation is highlighted in Paper A for the averaged east–west and north–south components of the velocity field. The eastward current dominates in the almost entire northern part of the gulf (except for some small areas in the widest part of the gulf), whereas the current is directed to the west only in a narrow band at the southern coast. As a result, an overall domination of surface-layer transport to the east is likely as suggested by Andrejev et al. (2004a, 2004b).

The explanation for this discrepancy may be linked to the atmospheric conditions. The NAO index (Section 1.1) has been positive since 1980, which means that stronger than average westerly winds may cause the surface circulation to have a larger component to the east. Also, the selected time period contains several extreme values of the NAO index for the years 1979–1998 (Lehmann et al., 2002). The winters of 1989 (the highest overall) and 1990 had very high positive NAO index values and in 1987 its lowest negative value for the two decades. Lehmann et al. (2002) also noted that the variability of the NAO index on a monthly scale is rather high and changes from NAO positive to negative phases can happen within one month.

The presented discrepancies from the traditional concept of cyclonic mean circulation of the Gulf of Finland (Section 1.2) can be explained in a straightforward manner by noting that the classical scheme applies to the average conditions over the entire water column (at least for the layer above the main halocline). The situation in the uppermost layer involving only the first 2.5–3 m may easily be different from that in the lower layers. This viewpoint is not new and, in essence, has been proved by showing that the decoupling of the uppermost layer takes place frequently enough to create radically different directional persistency of the motion in the uppermost and subsurface layers (Andrejev et al., 2004a, 2004b).

Paper A also provides a discussion of the physical drivers of the described phenomena. Part of the described decoupling is evidently caused by the impact of predominant moderate and strong winds from the south-west (Soomere and Keevallik, 2001, 2003). These winds create Ekman transport to the (south-)east and also force the nearshore surface current to the east near the Finnish coast as demonstrated in Figure 11.

The average of the north–south component of the surface currents is to the south at the entrance to the gulf and at the longitudes of Narva Bay where the average flow has clear similarity with the one calculated by Andrejev et al. (2004a). A key consequence of this property is that, on average, the north-western coast of Estonia and the coasts of Narva Bay are expected to be more frequently hit by adverse impacts transported by surface currents than other sections of the southern coast of the gulf (Paper A). The listed features are modulated by extensive interannual variation in the prevailing transport direction on monthly and seasonal scales. This variability is larger for the average meridional flow component. The flow is, on average, usually to the south in windy seasons with relatively intense currents such as 1988/89 or 1989/90, whereas in seasons with low currents (such as 1987 or 1990–1991, Table 1 of Paper A) the motion is directed to the north.

Thus it can be concluded that the pool of Eulerian velocity fields produced by the RCO model, even if it does not perfectly represent the reality, contains a number of interesting and counter-intuitive but still easily explainable and apparently correct features. It not only replicates the well-known basic features of the Gulf of Finland circulation but also highlights the particular role of the atmospheric forces influencing the circulation at different times. The presented results also signal that many normally concealed features of currents and current-driven transport may be identified by means of using advanced methods and a proper choice of the averaging time interval.

3.2. Method for the calculation of trajectories and transport parameters

The presented material has vividly demonstrated that the system of surface currents in the Gulf of Finland is extremely complicated, has extensive monthly, seasonal and interannual variability and is hardly predictable in the dynamical sense. The material also suggests that there definitely is a certain order in this system. This order becomes evident in different forms, from regularly occurring coastal currents (with possibly alternating directions) up to flow patterns in the central gulf that can be highlighted via a carefully chosen averaging procedure.

Papers A and B concentrate on the identification and utilisation of semi-persistent and frequently occurring patterns of motions that persist during certain relatively short time intervals, from a few days up to a few weeks. As discussed in Section 1.3, such patterns have been identified for different domains of the Baltic Sea both numerically (Lehmann et al., 2002; Meier, 2007; Lu et al., 2012) and experimentally (Osiński and Piechura, 2009). Their typical lifetime (from a few days to weeks up to a few months) frequently lies between the time scale of meso-scale (synoptic) motions and the scale of seasonal changes. Figure 11 suggests that often (even if irregularly) occurring current fields may provide a joint effect similar to that of jet currents even in a system that seemingly is almost chaotic. In long-term run they may cause systematic transport of pollution and thus provide increased risk for vulnerable regions and MPAs. Even if it is not yet possible to impact the dynamics of such transport, it is important to highlight such patterns and to take their presence into account.

Identification of such motions is a multi-parameter problem, an approximate solution method to which is presented in Paper B. The method aims at highlighting the impact of motions with a particular time scale. It is implemented via calculation

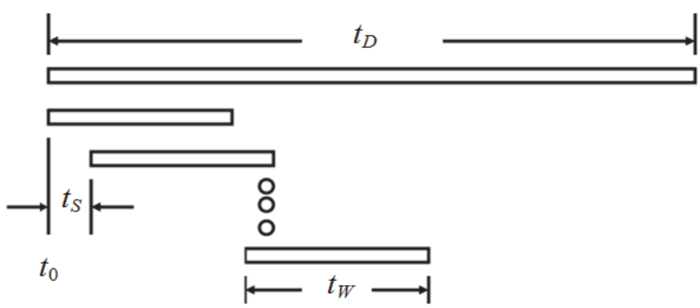

Figure 12. The scheme of splitting trajectory calculations into single time windows for highlighting semi-persistent transport patterns (Paper B).

of the trajectories of large pools of selected water parcels using the TRACMASS code. The method is such that a particular time period t_D is divided into time windows t_W of fixed length. The windows may overlap with each other, the lag between the overlap is the time step t_S (Figure 12). The properties of transport are then calculated from the properties of these trajectories.

The average over many parcels for a fixed t_W characterises the flow persistency in terms of Lagrangian velocity during all time intervals of this length. By varying the length of the time window, shifting the initial location of parcels over the sea area and the starting instant of calculations within the years in question (1987–1991) it is possible to identify patterns persisting in different regions and over different time intervals. A detailed analysis of the suitable range of its major parameters is presented in Viikmäe et al. (2011). Comparison of the average net and bulk transport calculated over certain time windows t_W allows, for example, identifying the areas that frequently host strong flow that persists over time intervals $\geq t_W$ even if the flow direction varies over longer time intervals (Paper A). The knowledge of such patterns is a precondition for various ways towards the reduction of anthropogenic impact on vulnerable areas and MPAs

An example of application of this method is presented in Paper B to identify a local optimum for potentially dangerous activities for an elongated basin, the coastline of which is divided into two opposite parts. The same method is applied in a number of studies into possibilities of preventive protection of the coastal environment (Viikmäe et al., 2010; Viikmäe, 2014; Soomere et al., 2011a).

The key parameters for current-driven relocation of adverse substances and pollution, considered in this thesis, are (Lagrangian) net and bulk transport, and their ratio (Paper A). The net transport after travelling along a trajectory is defined as the distance between the start and end positions of a trajectory and the bulk transport reflects the total length of the trajectory (Figure 13). The analysis of trajectories of different duration allows the identification and visualisation of several properties of surface currents that cannot be extracted directly from the (Eulerian properties of) current fields.

Single trajectories in this scheme were calculated using the output of the RCO model (the Eulerian velocity data, Section 2.3) as the input for the TRACMASS model (Section 2.4). The user of this scheme is required to define the initial positions of parcels used in the simulation and the starting time and duration of

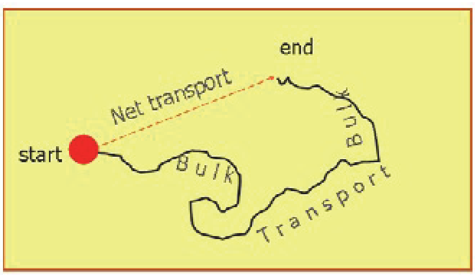

Figure 13. Net and bulk transport along a Lagrangian trajectory.

each simulation time window. For simulations in Paper A one parcel was inserted to the centroid of each grid cell of the RCO model located in the Gulf of Finland. The first calculation was launched at 00:00 on 01 January 1987. The calculations were repeated with the same position of the parcels but with a time lag t_S of 6 h, 12 h, 18 h, etc., until the end of 1991.

The scheme produces a pool of trajectories that have the same start position but different shapes for different start instants. As the focus was in what happens over several days, the coordinates of the instantaneous trajectory points are saved once in 6 h. It is assumed that doing so does not significantly affect the calculated statistical values, although it may cause some side-effects such as trajectories seemingly crossing some peninsula or islands. Most of calculations in Paper A were performed for $t_W = 4$ days. The options of varying time windows are discussed in Viikmäe et al. (2010) This length was thought to represent the turnover time of a considerable part of synoptic eddies in the Gulf of Finland and is about a half of the typical time of hitting the coast by tracers released in the surface layer of this water body (Paper B).

The average net transport and its velocity for each sea point were then calculated as an average over the entire pool of the results for 4-day sections. The results characterise the flow persistency in terms of Lagrangian velocity during the given time window. The spatial patterns of the resulting maps of net and bulk transport and their ratio represent the ability of the surface flow in the Gulf of Finland to transport potential adverse impacts over such 4-day sections. They first highlight the areas where the flow (in terms of Lagrangian transport) may be fast or slow on average. Elongated areas of fast net transport evidently indicate pathways of fast movements of water masses and associated tracers.

3.3. Lagrangian transport parameters: net and bulk transport

The averaged Eulerian velocities described above basically showed maps of long-term properties of water flow at particular grid points in the Gulf of Finland. These maps do represent some important features of the flow patterns but ignore all their smaller-scale properties. In particular, they are not able to indicate the path a substance may take within a few days or weeks, which we are interested in for this study. The calculation scheme presented in Section 3.2 provides a possibility of averaging over a large number of examples of Lagrangian transport over a fixed time interval.

The properties of the average net transport for the period 1987–1991 (Paper A) revealed to some extent similarities with the averaged Eulerian velocities. The net transport also indicates the presence of a persistent inflow at the northern coast of the gulf. This inflow merges with the above-discussed anticyclonic gyre in the middle of the gulf. The properties of Lagrangian net transport and the average Eulerian velocities also had a number of differences. For example, the maps of net transport indicate a clear band of inflow along the north-western coast of Estonia (Paper A), whereas this feature is very weak in the average current field.

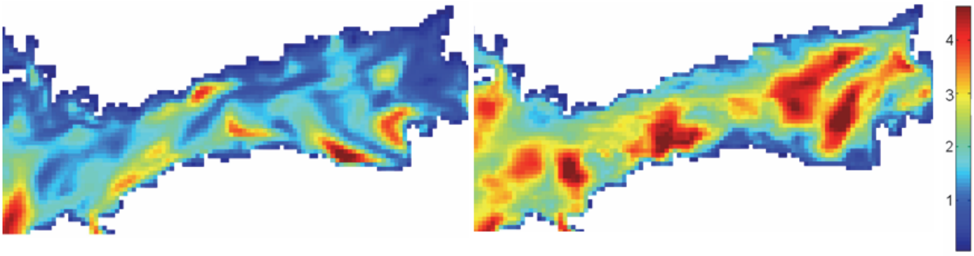

Figure 14. The average *y*-component of net transport velocity (cm/s) for spring transitional season of 1987 (March–May, left panel) and autumn transitional season of 1988 (August–October, right panel) for the Gulf of Finland (Paper A).

An interesting feature that was somewhat expected based on the Eulerian velocity patterns was the presence of relatively fast transport across the Gulf of Finland (Figure 14). This feature is not noticeable in the yearly averages but more so in the averages for the spring and autumn transitional seasons (March–May and August–October). This suggests that rapid pathways of meridional transport (that is, across the gulf) of surface water may frequently exist during these seasons. The transport direction may be variable. For example, in 1987 it was mostly to the north, whilst in 1988 it was to the south. This alternation may be linked to the atmospheric conditions at the time, in particular to the NAO index which influenced the wind direction.

Such areas of intense cross-basin transport, calculated using the time window of 4 days, evidently mirror the presence of certain mesoscale features that result in a relatively rapid transport on a weekly scale. The elongated areas of intense net transport that are largely aligned along the gulf may reflect regions where the coastal current often separates from the coastal slope. Larger patches of intense north–south net transport in Figure 14 may reflect either the position of frequent contact areas between slowly drifting meso-scale eddies or the typical locations of upwelling filaments (Paper A).

3.4. Ratio of net to bulk transport

The presented material so far shows that the surface-layer circulation of the Gulf of Finland contains, along with strong coastal currents, also relatively intense cross-gulf transport of possibly varying direction. As an alternative to the directional persistency, the ratio of net to bulk transport is a useful parameter that allows us to determine if the flow may be almost unidirectional (hinting at strong flows) or if it may be meandering or regularly changing its direction (hinting at eddies). This parameter to some extent hints if a pollutant may eventually hit a coastal area or if it may remain in the open sea for a longer time interval.

The five-year mean ratio of the net to bulk transport (Figure 15) has the qualitative distribution similar to that of the flow persistency in Andrejev et al. (2004b). The map reveals two bands of moderate and relatively high values of this

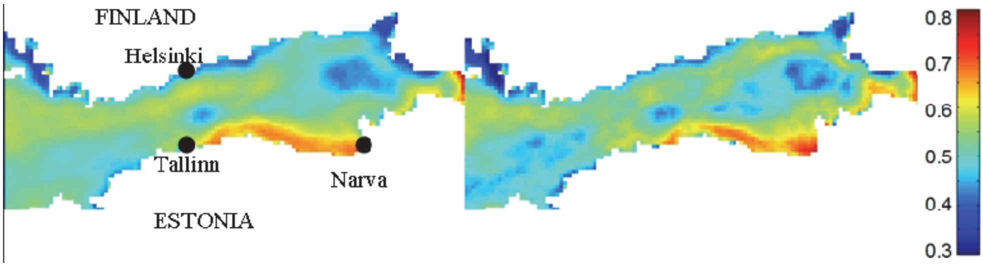

Figure 15. The ratio of net to bulk transport averaged for the years 1987–1991 (left) and for 1991 (right) for the time window length of 15 days for the Gulf of Finland (Paper A).

ratio, more or less corresponding to areas with relatively high flow persistency. The largest values (in a range between 0.4 and 0.7) occur along the south-eastern coast of the gulf from Tallinn to Narva Bay. This feature suggests the presence of a relatively persistent coastal current along the north-eastern coast of Estonia. Large values of this ratio in the area close to Neva Bight are evidently associated with the voluminous runoff of the Neva River.

Similarly to the net transport, the annual average values of the ratio in question had very little interannual variability. Its spatial distribution showed limited, mostly qualitative similarity with the average Eulerian velocity. Therefore, Lagrangian transport patterns not necessarily match the average of Eulerian currents.

The ratio of net to bulk transport exhibits substantial spatial variations during different seasons. The maps of this ratio for windy and calm periods qualitatively resemble the similar map for the 5-year average of this quantity but show somewhat larger contrasts. The area of high values of this ratio in calm seasons (Figure 16) matches the location of the area of overall high persistency of motions

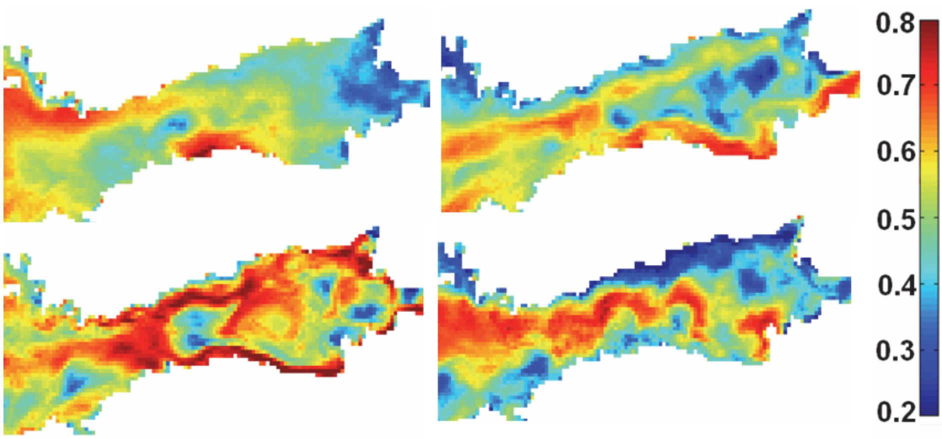

Figure 16. The ratio of average net to bulk transport during the windy season of 1988/89 (upper left panel), calm season in 1990 (upper right panel), spring transitional season in 1988 (lower left panel) and autumn transitional season in 1989 (lower right panel) for the Gulf of Finland (Paper A).

in the subsurface layer (Andrejev et al., 2004a). This feature can be interpreted as suggesting that in low wind conditions the subsurface dynamics predominates also in the surface layer.

An interesting feature is that small values of the ratio in question occur for Neva Bight during windy seasons and large values during calm seasons. A persistent area of low values of this ratio exists to the east of the Tallinn–Helsinki line. The area with maximum values of this ratio for transitional seasons (Figure 16) has strong interannual variation and rich internal structure. During these two-month intervals several areas of high values of this quantity of stretching across the gulf axis are evident in the central and eastern parts of the gulf. In Paper A it is suggested that they may represent typical locations of long upwelling filaments or zones of large meridional velocities of basin-scale seasonal circulation patterns. Their nature, however, needs further research.

An interesting, although somewhat speculative interpretation may be provided for the dependence of the variations in the long-term ratio of net to bulk transport over the entire Gulf of Finland on the length of time window (Paper A). Figure 17 suggests that there is a bending point of this ratio at the length of the time window of about 5–6 days. This point may indicate the turnover time of the larger synoptic eddies in the Gulf of Finland that are replicated by the RCO model. The average speed of currents in the surface layer of the gulf is 0.033 m/s (Paper A). The maximum speed in the eddy cores is usually much larger, roughly about twice as high as the average speed. The perimeter of the core of such eddies that make a full turn in 5–6 days is about 30 km. Their radius (understood as the distance from their centres to the area with the largest velocities) is about 5–6 km. This rough approximation matches well the estimates of the internal Rossby radius for different areas of the Gulf of Finland (2–5 km, Alenius et al., 2003). This interpretation supports the assertion that the RCO model resolves the larger examples of mesoscale eddies.

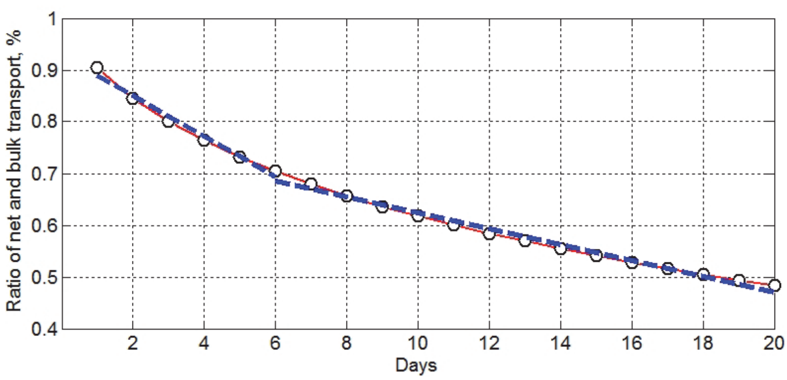

Figure 17. Dependence of the average ratio of net to bulk transport on the length of the time window (days) for 1992 over the entire Gulf of Finland (3131 grid points, one tracer released into each grid centre; the calculations restarted after each 6 h). Dashed lines show linear trends for days 1–5 and 6–30 (Paper A).

4. Marine Protected Areas of high and low risk of pollution

The features of Eulerian velocities and Lagrangian transport in the surface layer of the Gulf of Finland highlighted in Papers A and B may greatly affect the path of various substances. For example, the presence of an anticyclonic gyre may increase the chances of the north-eastern nearshore of the gulf to be hit by current-driven pollution released along the major fairway. This chapter depicts several attempts to utilise these transport patterns for environmental management, to determine the MPAs that may be of high and low risk of pollution and to recognise simple engineering solutions to reduce this risk. The presentation mostly follows Papers C and D.

Section 4.1 presents an extension of the method used for the quantification of the potential of offshore areas to serve as the starting point of current-driven transport of pollution that after some time reaches a vulnerable region. This method has been applied to the coastal areas in Paper B and in a number of parallel studies (e.g., Soomere et al., 2011a, 2011b; Viikmäe et al., 2011). Here the emphasis is on the MPAs that may extend far offshore and that cover only a part of the nearshore.

Section 4.2 provides an example of a possible quantification of the vulnerability of the existing MPAs in the Gulf of Finland in terms of current-driven propagation of pollution from the existing major fairway. An associated examination of the ability of different fairway sections to serve as starting points of pollution that is transported by surface currents to MPAs is provided in Section 4.3.

One of the main objectives of this thesis is to assist in the environmental management before an accident occurs. Sections 4.2 and 4.3 mostly address this perspective based on the present situation in the Gulf of Finland without adjusting the existing assets (MPAs) and infrastructure (fairways). Section 4.4 continues in this direction by depicting places of refuge for vessels in distress and by presenting some indications about how adjusting the location of the fairway would change the exposure of MPAs to the risks of current-driven pollution.

4.1. Method for determining MPAs most at risk

To identify the MPAs of high and low risk of pollution, I employ a method similar to that used in Paper B and further developed in a series of studies (e.g., Andrejev et al., 2011; Soomere et al., 2011a, 2011b; Lu et al., 2012, among others). This method, originally targeted at the optimisation of the fairways, consists of four steps (Andrejev et al., 2011). Firstly, a 3D velocity field of the sea area is calculated using an ocean model. Secondly, these data are employed to calculate Lagrangian trajectories of a large pool of parcels that are assumed to imitate the pollution. Thirdly, a statistical analysis of these trajectories is performed to determine if any particular patterns of risk (or areas providing increased levels or risk) exist. Finally, further analysis of these results is employed to determine the possible management options (e.g., to choose the best route that may limit the amount of pollution to the MPAs).

The major difference of this research from previous studies is that the coastal areas are no longer assumed to have a constant value. Instead, it is assumed that the MPAs are particularly valuable and the target is to investigate options that reduce pollution to the MPAs. Differently from the goal in many previous studies (e.g., Soomere et al., 2011a, 2011b; Höglund and Meier, 2012; Lehmann et al., 2014) to quantify the entire offshore, the analysis in this Chapter is limited to the pollution stemming from the major fairway and possibly transported to the vicinity of the MPAs similarly to Chrastansky and Callies (2009) and Chrastansky et al. (2009).

This position is justified by the practical impossibility for large shifts of the existing major fairway in the Gulf of Finland. Therefore, instead of seeding parcels over the entire gulf (as was done in Paper A and Paper B), the initial locations of parcels in Paper C and Paper D are chosen along the major fairway from the Baltic Proper to Saint Petersburg (Figure 18). The fairway is represented as a belt of a width of 3 RCO model grid cells similarly to Viikmäe et al. (2013) and Viikmäe

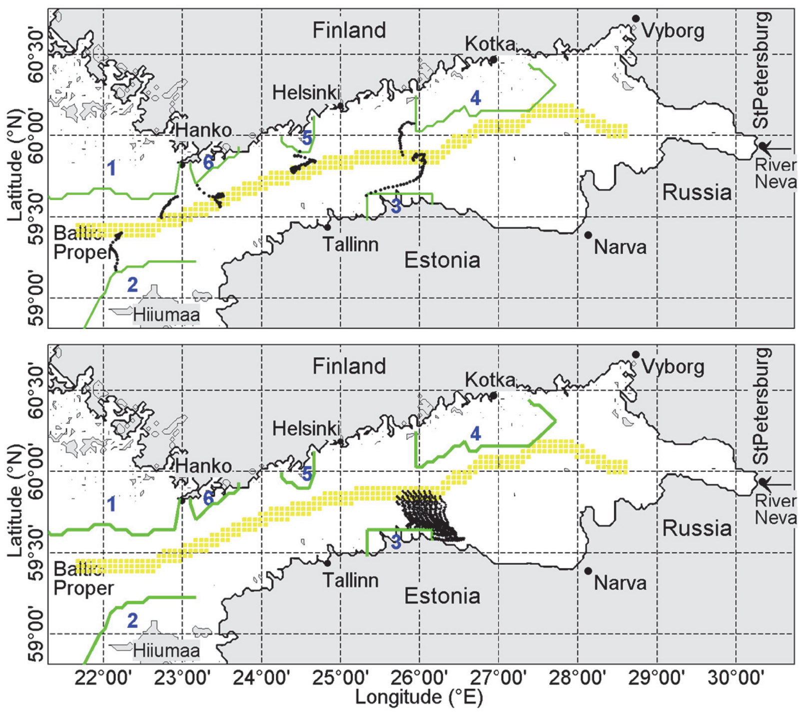

Figure 18. Examples of the starting points (cells along the yellow line) and shapes (black dotted lines) of trajectories from the fairway to the MPA (upper panel); the set of trajectories that hit MPA 3 during 20 days in July 1988 (lower panel). MPA 1 is the Southern Archipelago Sea, MPA 2 – the Western Estonian Archipelago Biosphere Reserve, MPA 3 – Lahemaa National Park, MPA 4 – the Eastern Gulf of Finland, MPA 5 – the Kirkkonummi Archipelago, MPA 6 – the Tammisaari Archipelago (Paper C).

and Soomere (2014). Although pollution may also be released in other domains of the sea, placing its major sources exclusively along the fairway is a valid first approximation to reality because the Baltic Sea is known as one of the busiest shipping domains in the world (HELCOM, 2009).

The calculations were organised as described in Section 3.2. To create a large enough pool of independent trajectories, the period of interest was divided into 20-day-long partially overlapping time windows (Figure 12). The calculations started at 00:00 on 01.01.1987 and were performed until 24:00 on 20.01.1987. The coordinates of the instantaneous trajectory points were saved once in six hours. The new set of calculations started after 10 days at 00:00 on 10.01.1987 and was again performed for 20 days. The process was repeated for the rest of the years of interest and resulted in a set of 180 trajectories for each grid cell. Estimates provided in Viikmäe et al. (2010) suggest that this choice of parameters of calculations allows for acceptably resolving the spatial distribution of the probability of hits to the MPAs and the time it takes for the pollution to reach the MPAs. As hits to the offshore parts of the MPAs are apparently much more frequent than hits to the nearshore (there is no boundary-effect redirecting the motion near the marine border of the MPAs; see Viikmäe et al., 2010), this selection is suitable for our purposes.

As the focus is on the role of relatively large-scale current-driven transport, no artificial means to replicate the impact of subgrid turbulence are used. Such means may improve the formal properties of spreading of initially closely located parcels or tracers (Andrejev et al., 2011; Kjellsson et al., 2013; Viikmäe et al., 2013) and/or affect the rate of hitting the nearshore (Broström et al., 2011) but they apparently do not improve the statistics of current-driven transport of pollution to the nearshore domains (Viikmäe et al., 2013).

The location of the six MPAs in the Gulf of Finland (Designated Baltic Sea protected areas and UNESCO sites, Figure 6) was obtained from the HELCOM Map and Data service (maps.helcom.fi/website/mapservice/index.html). The size and shape of the MPAs have been subject to minor changes over the years (HELCOM, 2010). The configuration in Figure 18 reflects an approximation of the existing MPAs in the resolution of the RCO model.

The model fairway (Figure 18) follows the most frequently used sailing lines (Figure 3). It is located almost at the centreline of the gulf and deviates a little bit to the south in the central part of the gulf. In the widest (western) part of the gulf it deviates to the north due to the presence of islands. The most remote from the fairway is MPA 3 (Lahemaa, Figure 18) whereas the fairway practically touches the south-eastern border of MPA 4 (Eastern Gulf of Finland). The MPAs at the entrance of the gulf (1 and 2) are located more or less symmetrically with respect to the model fairway. The four MPAs in the gulf interior are shifted with respect to each other in the east-west direction. This configuration is basically favourable for locally relocating the sections of the fairway that provide the greatest danger to the MPAs.

Similarly to the studies that aimed at fairway optimisation in the Gulf of Finland (Andrejev et al., 2011; Soomere et al., 2011a, 2011b), from the above-described pool of trajectories it was identified how many released parcels and from which fairway points were transported to each of the MPAs. A hit was counted when a trajectory for the first time entered the MPA. The further behaviour of this trajectory was ignored. The parcels that left the Gulf of Finland into the northern Baltic Proper were ignored (Paper D).

4.2. Marine Protected Areas most at risk

It is not surprising that the MPAs that are closest to the fairway had the most hits (Table 1 in Paper C). Thus MPA 4 (situated in the north-eastern section of the Gulf of Finland in the vicinity of Kotka) was most frequently affected by pollution (Figure 19). An additional reason for frequent hits to this MPA may be the slow anticyclonic gyre (Section 3.1, Paper A) that causes (statistically) frequent current-driven transport from the fairway to the north, with a subsequent hit to this MPA.

An approximate linear relationship

$$N(x) \approx -1.3x + 36.7 \quad (2)$$

was found to occur between the number of hits N and the shortest distance x (km) of a particular MPA from the fairway. The relevant correlation coefficient –0.985 indicates a strong relationship that may allow one to quantify the level of risks and to predict a reasonable distance for the fairway from a particular MPA.

Both Eulerian and Lagrangian patterns of transport discussed in Chapter 3 seem to affect the distribution of the probability of curren-driven hits to some of the MPAs. Marine Protected Areas 1 and 2, located in the western part of the Gulf of Finland, had the second highest rate of hits. This feature may reflect strong meso-scale activity in the entrance area of the gulf (Andrejev et al., 2004) and intense net transport along the southern coast of this area. It was also noted in Paper B that the western side of MPA 2 apparently was a high risk area.

The smallest MPA 5 is located between Helsinki and Hanko at relatively large distance from the fairway. Somewhat surprisingly, it had a comparatively high number of hits. Similarly to MPA 1, a probable reason may be the above-discussed anticyclonic gyre that may bring pollution from the fairway region to the nearshore of Finland. Another reflection of this feature is a possible strong strain in this region associated with meridional currents that at times extend from coast to coast (Viikmäe et al., 2012).

Marine Protected Area 3 had the lowest amount of hits. However, when a hit occurred, it took on average only 5 days (by about 2 days less time than for other MPAs) to reach this MPA (Figure 19). This feature is consistent with the occasional presence of semi-persistent currents that rapidly carry surface water almost across the gulf during certain seasons (Paper A). This conjecture is also consistent with the wide range of the sources of hits along the fairway. As no strong relationship seems to exist between the hits and properties of wind for the time interval in question, it is likely that particular (e.g., upwelling) events largely govern the current-driven transport to MPA 3.

The relatively small standard deviation of the number of hits for different years (Figure 19) indicates a small level of interannual variability of the transport patterns and strengthens the conjecture that the estimate in Paper D for the frequency of the hits for the MPAs by pollution stemming from the fairway is generally reliable. The largest but still reasonable interannual variation is seen for MPA 4. The count of hits and their standard deviation are almost the same for MPAs 2, 5 and 6 located in the northern nearshore of the gulf. The standard deviation was relatively low for MPAs 1 and 3 located in the southern nearshore.

Both the wind speed and current patterns vary substantially over different seasons in the study area (Lehmann et al., 2002; Andrejev et al., 2011). This suggests that both the probability for a hit and the time it takes should also vary. To make the results comparable with the above material (Paper A), the windy season was associated with October–February and the calm season with May–July. The largest number of hits generally occurred during the windy months. Only for

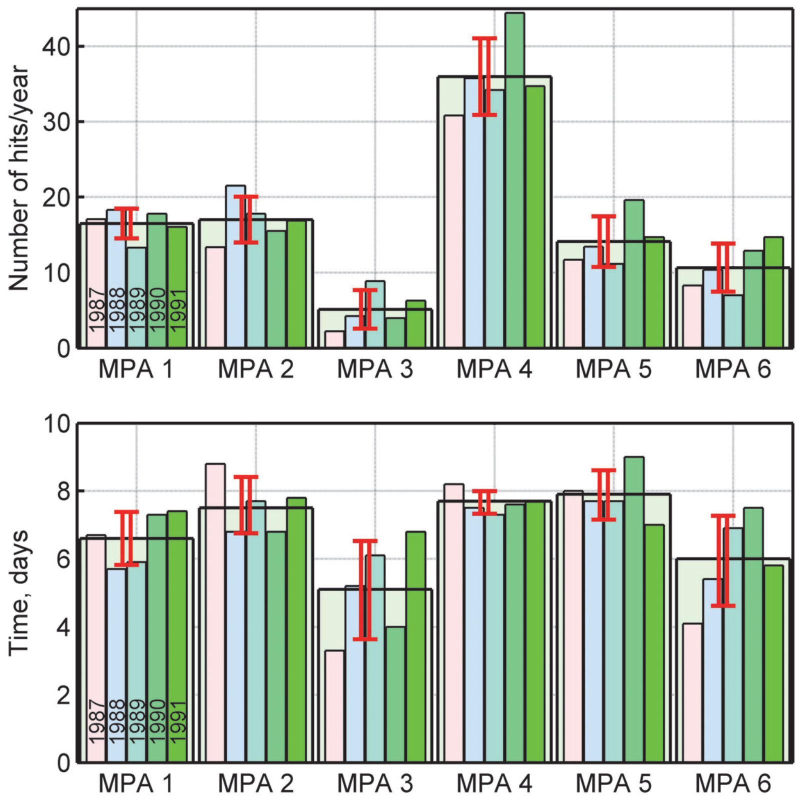

Figure 19. Probabilities of parcels hitting the coast (%, upper panel) and particle age (days, lower panel) for the years 1987–1991 calculated with the time window of 20 days (Paper C). The vertical lines indicate the standard deviation for the number of hits in different years.

MPA 3 in 1988 and in MPA 1 in 1989 the largest count of hits occurred during transitional months. The number of hits was smallest in the calm season for most of the MPAs. Similar features were obtained in Paper B for the hits to the nearshore where the average time for a hit was also about 10 days and the largest frequency of hits occurred in the windy season. However, in Paper B high variability of hits was found not only on a seasonal level but also of a few days to a few weeks.

4.3. The locations of sources of hits from fairways

The material presented in Section 4.2 makes it possible to quantify the present exposure of MPAs with respect to the risk of current-driven pollution. It is equally important to identify the possible sources of pollution. Solving this problem gives essential information for improvement of the fairway design from the environmental viewpoint. The linear relationship between the average number of hits and the distance from the fairway given in Section 4.2 implicitly suggests that the starting points of the pollution parcels that have hit the MPA would be in the sections of the fairways in close proximity of this MPA. Interestingly, this is not the case for the MPAs in the Gulf of Finland (Figure 20). Even though many of the hits came from the sections located close to a particular MPA, a substantial number of hits arrived to all MPAs from quite remote sections of the model fairway (Paper D).

This aspect has large implications on the policy of preventive protection of the MPAs. It is generally natural to expect that the greater the quantity of pollution, the greater are the consequences of this pollution to MPAs. However, the vulnerability of different MPAs with respect to different pollution types may vary considerably. In some cases a small amount of pollution located in pristine places can have

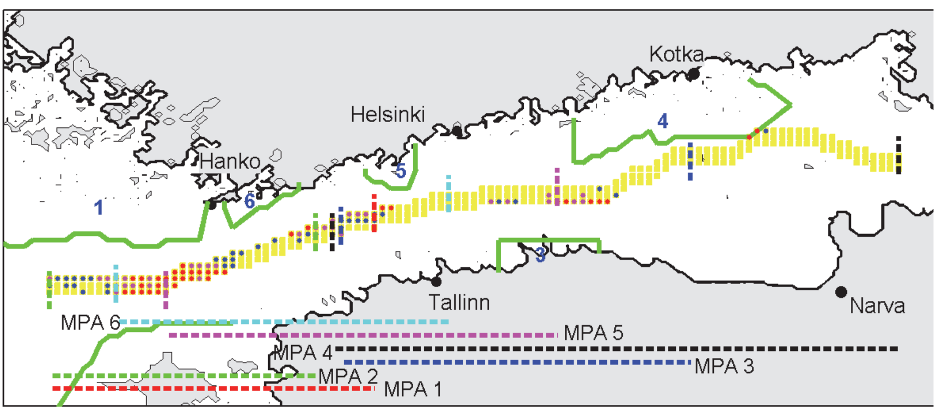

Figure 20. The sections along the fairway where the hits were sourced from for each of the MPAs. MPA 1 – red, MPA 2 – green, MPA 3 – blue, MPA 4 – black, MPA 5 – magenta, MPA 6 – cyan (Paper D).

substantial negative impact on a MPA. Such a situation took place in the Galapagos Islands when the vessel *Jessica* sank (Wikelski et al., 2002 (cited after Vieites et al., 2004)).

This problem leads to the question of identifying the areas (among those from where the pollution may theoretically reach the MPA) that most frequently serve as a starting point of the propagation of current-driven pollution (Figure 21). These "hot spots" were found to be largely in the vicinity of the relevant MPAs. Therefore, even though some of the pollution parcels may have travelled from great distances along the fairway, the majority of current-driven parcels still stem from the fairway section close to the MPA. There is, however, a clear structure of the distribution of these "hot spots" along larger MPAs such as MPA 4 (Figure 21). Also, the majority of areas that may often serve as starting points of the current-driven hits to MPAs are located in the western section of the gulf, indicating that this segment of the fairway may provide an extensive level of risk of current-driven pollution to the MPAs and thus requires particulary careful environmental management.

On average it took about 5–8 days for a parcel to arrive to the MPAs (Figure 19). Some of the trajectories travelled long distances before arriving at an MPA (Paper D). This variability mirrors the complexity of the transport driven by surface currents in the gulf. The ratio of net to bulk transport (Paper A, Figure 15) is relatively small (ranging from 0.4 to 0.5) along the model fairway in the centre of the gulf). Also, low persistencies were established in this area (Andrejev et al., 2004a) (Figure 5). These features suggest that eddies may frequently occur in this region and their presence normally slows down the extension of net transport of pollution particles along the gulf.

The presented results are consistent with those in Paper B about hits to the coastal areas. In some months coastal hits may occur within the first day and in other months a hit would not occur until after the ninth day (Viikmäe et al., 2011).

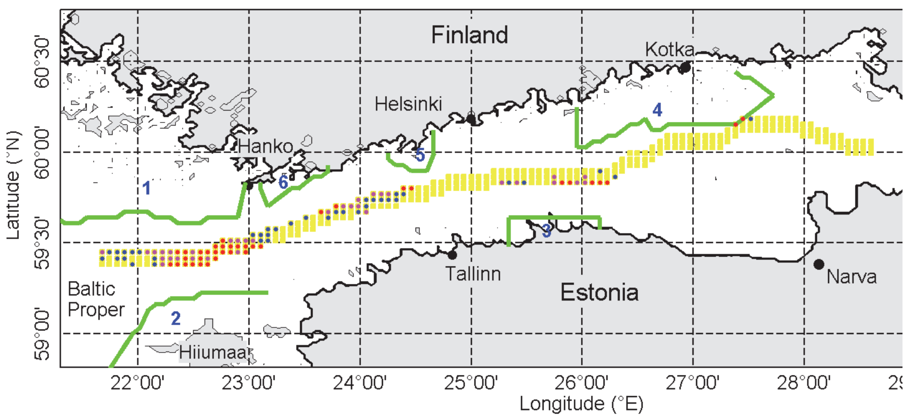

Figure 21. Locations along the fairway where >70% of the hits were sourced from for each of the MPA for the period 1987–1991. Red identifies >90%, magenta 90–80%, blue 80–70% (Paper D).

The mutual location of the MPAs and most frequent starting points of current-driven pollution for these MPAs in Figure 21 is also consistent with the patterns of net and bulk transport discussed above and in Paper A. For particular seasons the ratio of net to bulk transport also shows strong variability but may reach quite large values along the axis of the gulf (Figure 16). Thus, the transport of pollution along the gulf axis may be almost unidirectional and quite rapid at times.

4.4. Engineering applications: refuge places and shifting the fairway

In many cases of maritime accidents a forewarning of distress is notified. A well-known example of this type is the *Prestige* accident in 2002 (Vieites et al., 2004). It is commonly not easy to convince a port to host a problematic ship. Such a situation occurred when Spanish and Portuguese authorities argued over whose responsibility *Prestige* accident was. As a result, *Prestige* was not able to make a port call or find safety in a place of refuge. The resulting accident led to major pollution of vital marine and coastal areas (Maddern and Knight, 2003).

The described accident stresses the need to foresee and offer for vessels in distress already in the early stages of difficulties an offshore area where the potential consequences of an accident to the environment would be minimised. There exists no legally binding instrument that a ship in need of assistance should follow and ships are under the jurisdiction of their flag country. At present most of the measures in place to protect the environment are not regulations but basically guidelines that vessel and countries should follow. An International Marine Organisation (IMO) guideline states how to prepare for rendering timely assistance to ships in distress. A popular method is the pre-selection of potential places of refuge (so-called pre-selection model). These places are identified on the basis of generic assessments. When an accident occurs, an event assessment is carried out for that particular place, e.g., in Spain and Denmark (Bradarić and Kostelac, 2009).

Such an application is particularly necessary for the ecologically sensitive Gulf of Finland due to high marine traffic present, narrowness of its geometry and the occurrence of areas that need specific protection. This problem was addressed in Viikmäe and Soomere (2014) from the viewpoint of the entire nearshore. Also, it was established in Paper B that the eastern part of the Gulf of Finland may serve as an area of reduced risk in terms of overall coastal pollution. However, the proximity of this area to the MPAs requires more detailed consideration how the MPAs could be affected.

The analysis presented in Papers C and D shows that the source of hits to any of the MPAs can stretch over a long span of the fairway. The problem of possible refuge sections can be to a first approximation addressed using the maps of the entire source areas for each MPAs and the "hot spots" of pollution (Figure 21). In general, for a vessel in distress in the middle of the gulf, the location around the Tallinn–Helsinki area would be the least dangerous for the MPAs from the viewpoint of current-driven pollution. In the eastern section the safest area in this respect would be the extreme eastern end of the fairway.

These results are partially counter-intuitive and do not match the outcome of a similar analysis from the viewpoint of the entire nearshore (Viikmäe and Soomere, 2014). The main reason for a substantial difference of the results presented here from those of Viikmäe and Soomere (2014) is the highly different specification of the vulnerable areas. However, in both studies the spatial distribution of hits to the nearshore or to the MPAs is largely governed by specific features of the modelled surface circulation. According to the classical cyclonic circulation scheme in the Gulf of Finland, pollution released in the eastern end of the gulf should drift towards MPA 4. This is definitely not the case in the presented analysis, the results of which mirror the presence of the slow anticyclonic gyre detected in Paper A. The results thus once more confirm that the dynamics of the surface layer (0–3 m) and the associated transport of pollution not necessarily follow the traditional averaged circulation conditions of the gulf.

These results also indicate that it is possible to identify for a vessel in distress and in aid of quick action a location along the fairway that minimises the amount of pollution to a single MPA. Doing so may adversely impact other MPAs. Another projection of the possible sources presented in Paper D makes it possible to identify the areas along the fairway that affect several of the MPAs. Although these recommendations may decrease the probability of hits to the MPA designed before 2010, the coastal areas and new MPAs (effective since 2010) may still be affected.

The material presented above has examined the ways of quantification of the risk to the MPAs and the potential of the MPAs being polluted based on the present configuration of the major variables (incl. the location of the major fairway and the MPAs) involved in the problem. The above discussion of the location of a refuge place for ships in distress was also limited to the relocation of the ship along the existing fariway. The results have revealed that the risk of being polluted substantially depends on the proximity of a particular MPA to the fairway. It is also unlikely to locate an ideal place of refuge on the western section of the fairway that would not affect any of the MPAs.

Paper D undertakes an attempt to expand this analysis towards changing one of the background variables, namely, to evaluate the effect that adjusting the entire fairway location laterally (across the Gulf of Finland) would have on the probability of pollution transport to the MPAs. This research is, in essence, an extension of the analysis performed in Paper B, which considered determining the areas in which the consequences of accidents would be equally divided between the opposite coasts of the Gulf of Finland. The relevant solution was the equiprobability line (Soomere et al., 2011b; Viikmäe et al., 2011).

Figure 22 demonstrates that shifting the fairway by as little as 2 nm to the south from its present location may decrease the number of hits to MPA 4 by about 50%. Such an impact was not unexpected as the present fairway is located at the southern border of this MPA. The other MPAs and the origin of sources of their hits were almost not affected by this shift.

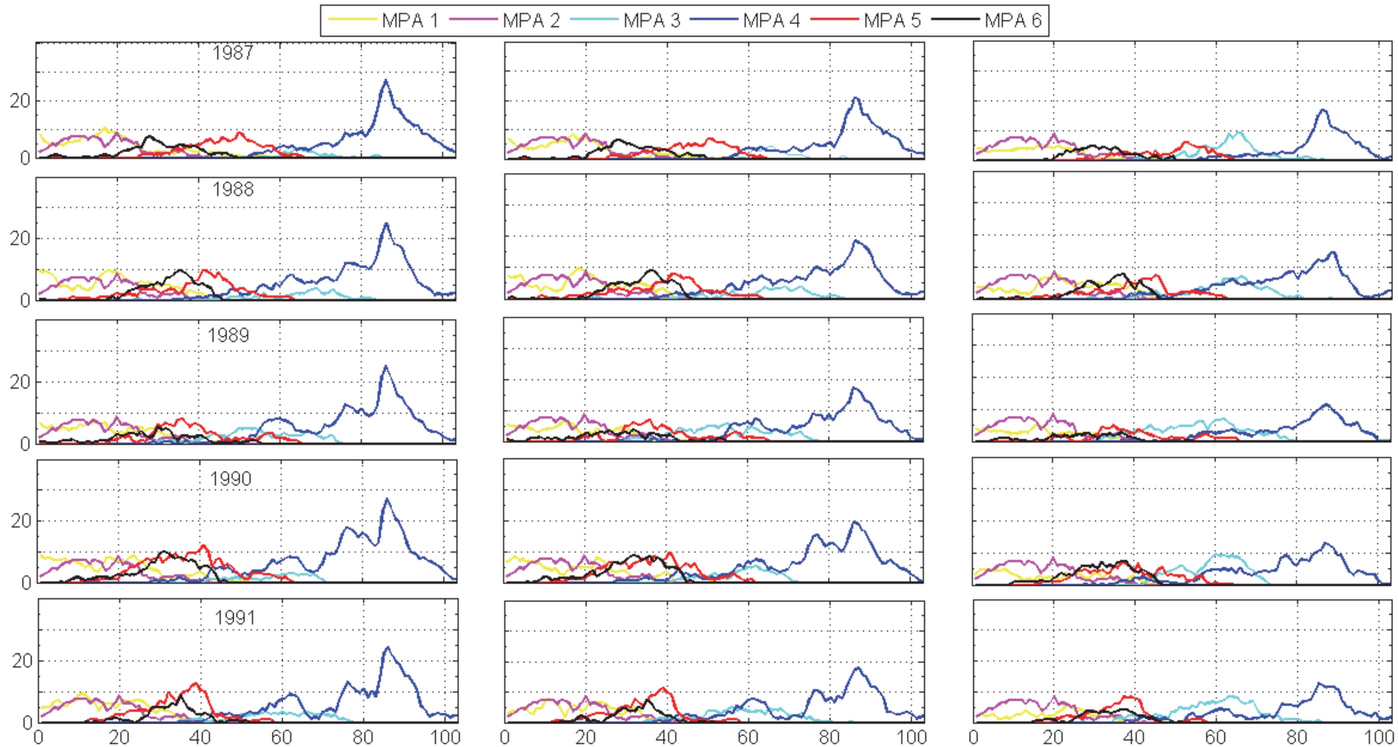

Figure 22. The number of hits averaged by similar longitude (vertical axes) in 1987–1991 for the original fairway (left column), sources shifted by 2 nm to the south (central column) and by 6 nm to the south (right column). The horizontal axes indicate the sequential number of the RCO grid cells along the fairway from west to east for the Gulf of Finland (Paper D).

A shift by 6 nm southwards would adversely impact the probability of current-driven transport to different MPAs. Whilst it may decrease the amount of hits on the northern MPAs 1 and 4–6, the amount of hits on the southern MPAs 2 and 3 would clearly increase. A viable option would be to shift only certain portions of the fairway. For MPA 4 already a shift by 2 nm would make a big difference, whilst for MPA 5 and 6 a shift by at least 6 nm would make a difference.

The performed analysis thus indicates that there exists no ideal solution for all parts of the gulf and different parts of the fairway should be handled differently. Also, it is generally necessary to take into account that in the case of determining areas of refuge for ships in distress or shifting some parts of the fairway to protect the MPAs, other coastal or vulnerable areas may be adversely impacted.

Conclusions

Summary of the results

Very often in marine applications the role of the surface layer in the transport of various objects and substances is underestimated or oversighted due to the complexity of its circulation. The results presented in this thesis show that the combined use of modelling Lagrangian transport and classical methods of statistics makes it possible to extract semi-persistent current-driven transport patterns from the seemingly disordered surface layer velocity fields. The outcome of this analysis is utilised to develop a maritime engineering approach that quantifies and mitigates risks to Marine Protected Areas (MPAs), created by pollution from shipping in the Gulf of Finland, the Baltic Sea.

The main objectives were to (i) explore the current-driven patterns that may exist in the surface layer of the Gulf of Finland, both spatially and temporally, and (ii) utilise these patterns in maritime management and environmental engineering for quantification of risks to MPAs. The perspective is on preventive optimisation of the location of an accident or a ship in distress, before an accident actually occurs. The wider goal was to provide a generic way towards quantitatively justified recommendations for environmental management of this potential source of stress and damage to the most sensitive marine areas.

The analysis of current-driven patterns in the surface layer (0–3 m) of the Gulf of Finland was performed by using Eulerian velocity data from the Rossby Centre Ocean (RCO) model for 1987–1991 and with a horizontal resolution of 2×2 nautical miles. Although the RCO model is barely eddy-permitting in the Gulf of Finland, the hindcast Eulerian velocities reproduced well the known basic features of the dynamics of the surface layer. The prevailing direction of the long-term average surface flow to the east is most likely influenced by the fact that the North Atlantic Oscillation index was positive during the period studied. An intriguing feature, not evident in earlier studies of the Gulf of Finland, is the presence of an anticyclonic gyre in the relatively wide eastern part of the gulf in an area that is traditionally believed to have a cyclonic pattern. The gyre does not occur every year and apparently is present when the upper mixed layer is thin. This result supports the concept that strong persistent westerly winds play a major role in the surface circulation of the Gulf of Finland and decouple the surface layer from the underlying layers.

A technique combining Eulerian velocity data, Lagrangian trajectory model TRACMASS and classical statistical methods was developed for the identification and visualisation of the key parameters and semi-persistent spatial patterns of surface transport and its temporal variability. The properties and statistics of net and bulk Lagrangian transport were evaluated using trajectories of passively advected water parcels locked in the surface layer.

Both the net and bulk transport show limited interannual variability but possess substantial seasonal variations. Similarly to the outcome of the direct analysis of

Eulerian velocity fields, semi-persistent patterns of net Lagrangian transport are mainly aligned along the coasts of the Gulf of Finland. A clear inflow is present on the north-western coast of Estonia. Analysis of monthly and seasonal patterns of transport revealed that in some seasons (mostly in transitional spring and autumn months) relatively intense cross-gulf net transport may exist on a weekly scale. This feature is of major importance for the identification of areas of high risk in terms of coastal pollution. The ratio of net to bulk transport exhibits substantial spatial variations during different seasons.

The level of risk of current-driven pollution to reach the existing MPAs in the Gulf of Finland was quantified by analysing Lagrangian trajectories of persistent pollution parcels locked in the surface layer and released in the vicinity of the major fairway along the axis of this gulf. The results show that the MPAs located at the entrance of the gulf and in its easternmost section are the most at risk of being polluted. It takes on average 5–8 days for possible contaminants to arrive. The vulnerability of particular MPAs to be hit by current-driven adverse impacts correlates well with the established features of average Eulerian velocities and net Lagrangian transport patterns. The MPA at the easternmost Gulf of Finland received the most hits evidently due to its size and close proximity to the fairway. No evident correlation exists between the size of a MPA and its probability of being hit by current-driven adverse impacts from the fairway. An almost linear relationship exists between the minimum distance from the fairway of a particular MPA and the number of hits to this MPA stemming from the fairway.

Equally important is the knowledge on where the main sources of pollution may be from. Potential sources of hits for the three largest MPAs ranged from very long sections that covered 31–56% of the total length of the fairway in the Gulf of Finland. A substantial number of hits arrived to all MPAs from quite remote sections of the model fairway. This feature makes questionable the possibility of the preventive relocating of accidents and raises the question about sensibility of designating new MPAs or new habitat areas for sensitive species.

The method implemented and the maps produced were used to identify reasonable places of refuge along the existing fairway that minimise the amount of pollution that would travel to the MPA from a ship in distress. The western section of the fairway at the entrance to the Gulf of Finland that hosts very intense traffic also serves as the most probable source of pollution for several MPAs. If a pollution accident was to occur in this region, the best scenario would be for the vessel to proceed out of the gulf. The easternmost section of the fairway would be a feasible alternative for ships in distress. No reasonable offshore refuge place seems to exist in the central part of the gulf.

A viable option to decrease the chances for MPAs to be hit by pollution is to shift only certain portions of the fairway. For the MPA in the north-eastern part of the gulf already a shift by a few kilometres southwards would make a big difference, whilst for the MPAs in the north-western part of the gulf a shift by at least 10 km would make a difference. No ideal solution exists for all parts of the gulf.

Main conclusions proposed to defend

1. The results of the analysis of various averaged features of Eulerian velocity data simulated by the RCO model for 1987–1991 correspond well with previous studies. Long-term averaging reveals that surface transport is predominantly to the east and a slow anticyclonic gyre exists in the wide eastern part of the Gulf of Finland.
2. A technique combining Eulerian velocity data, Lagrangian trajectory model TRACMASS and classical statistical methods has been developed for the identification and visualisation of semi-persistent patterns of surface transport on weekly scales.
3. Using this method, the key parameters, spatial patterns and the temporal variability of net and bulk transport and their ratio have been established for the Gulf of Finland.
4. Semi-persistent patterns of net transport are mainly aligned along the coasts of the Gulf of Finland but in some seasons (mostly in transitional spring and autumn months) intense cross-gulf transport may exist.
5. The level of risk to the MPAs in the Gulf of Finland has been quantified with respect to the current-driven pollution from the major fairway.
6. A linear relationship has been established between the number of hits to the MPA and the distance of this MPA from the fairway.
7. For the Gulf of Finland the sections of the fairway where most of hits to a particular MPA stem from and possible places of refuge for vessels in need of assistance have been determined.
8. The effect that shifting the fairway would have on the MPA has been quantified. It has been shown is that no perfect solution to the entire system of MPAs exists but several MPAs may largely benefit from a shift of certain segments of the fairway.

Recommendations for further work

The presented results support the viewpoint that the circulation pattern of the surface layer is often almost decoupled from the motions in the sub-surface layer (Andrejev et al., 2004a) and substantially linked with the atmospheric conditions, first of all with wind speed and direction (Lehmann et al., 2002). Thus greatly different patterns may occcur during different seasons. This observation leads to several perspectives for future research:

1. It is important to include the direct wind impact and the influence of waves on the transport in the surface layer similar to the analysis of Murawski and Woge Nielsen (2013).
2. It is necessary to have very accurate and high-resolution atmospheric data. The RCO model run, the data from which were used in this thesis, was forced with the atmospheric data constructed at the SMHI from the ERA-40 re-analysis (Uppala et al., 2005) over Europe using a regional atmosphere model with a horizontal resolution of 25 km (Höglund et al., 2009; Samuelsson et al., 2011) and based on a temporal resolution of 3 h. Geostrophic wind field was utilised with a boundary layer parameterisation to calculate wind speeds at the standard height of 10 m above sea surface (Meier et al., 2003). As the realistic near-surface wind fields in the Baltic Sea often substantially deviate from such reconstructed winds (Keevallik and Soomere, 2010), more realistic atmospheric wind data with a better spatio-temporal resolution may lead to much more accurate and reliable results.
3. Many interesting and often repeating features of surface-layer transport become evident within specific seasons. This property is consistent with the analysis of Murawski and Woge Nielsen (2013) and suggests that it is important to build "climatology" of different features of the transport on seasonal scales on which the contribution of sea currents and direct atmospheric impact may either cancel or amplify each other. Moreover, it may be necessary to apply engineering solutions based on environmental consideration only during specific seasons.
4. Since the subsurface layer and surface layer may have similar or dissimilar transport patterns for different seasons, it will be interesting to perform similar calculations for the subsurface layer to establish the properties of transport of substances and objects (e.g., dissolved substances in a thicker mixed layer or ships without propulsion) that is impacted by the joint dynamics of both layers.

The horizontal resolution of the RCO model (2 nautical miles or 3.7 km) is barely eddy-permitting in the conditions of the Gulf of Finland. This model evidently does not resolve many important features present in the Gulf of Finland where the typical values of the baroclinic Rossby radius are 2–4 km. Using a higher-resolution model may allow much better replications of the meso-scale circulation and its impact on the transport patterns. Of particular interest would be to compare the results with the outcome of similar analysis based on a non-hydrostatic model of the Baltic Sea (which is supposed to much more reliably resolve the dynamics of the Gulf of Finland) or on the fields of surface velocity derived from satellite altimetry.

The presented results reflect a short time interval of five years and thus give only a conditional understanding of the stability and persistence of the extracted features. For example, the anticyclonic gyre in the eastern Gulf of Finland is not present every year. Moreover, it is located in an area of low persistency of surface flow velocities (Andrejev et al., 2004a). This raises the question whether the described features are universal for the dynamics of the upper layer of the Gulf of Finland or whether they are statistical artefacts partially caused by a specific resolution (and bathymetry), choice of atmospheric forcing, or model-specific parameterisations.

The analysis is based on simulations using the Lagrangian trajectory model TRACMASS. Although it is likely that the major sources of uncertainties are asscociated with the numerically reconstructed Eulerian velocities, it will be interesting to verify the presented results against simulations using different ways of evaluation of Lagrangian transport. It would also be very interesting to compare the results with actual data sets from Lagrangian surface drifters released along the major fairway, in particular for different seasons to compare the difference between model and field measurements.

More generally, implementation of engineering solutions, a first-order guess to which has been proposed in the thesis, requires cooperation of several institutions in different countries. This first applies to particular mitigation solutions such as determining a safe place of refuge for a vessel in distress or a shift of a fairway to reduce the amount of pollution. These solutions need cross-boundary cooperation in order to create a science-based marine management plan. The particular solutions have to consider, along with environmental quantification discussed in this thesis, also a number of various factors such as depth of water, shelter from weather, good holding ground and national jurisdiction rights.

Thus the legal rights and responsibilities of surrounding countries and the legality of some of the regulations and concepts presently being used should also be considered as important items in the decision-making process. One solution is to incorporate all relevant data (that include our results amongst others), using a geographic information system to reach scientifically valid, environmentally acceptable and realistic decisions concerning marine environmental management.

Bibliography

Abascal A.J., Castanedo S., Medina R., Liste M. 2010. Analysis of the reliability of a statistical oil spill response model. *Marine Pollution Bulletin*, 60, 2099–2110.

Alenius P., Myrberg K., Nekrasov A. 1998. Physical oceanography of the Gulf of Finland: a review. *Boreal Environment Research*, 3, 97–125.

Alenius P., Nekrasov A., Myrberg K. 2003. The baroclinic Rossby-radius in the Gulf of Finland. *Continental Shelf Research*, 23, 563–573.

Alvarez-Salgado X.A., Gago J., Miguez B.M., Gilcoto M., Perez F.F. 2000. Surface waters of the NW Iberian margin: upwelling on the shelf versus outwelling of upwelled waters from the Rias Baixas. *Estuarine, Coastal and Shelf Science*, 51, 821–837.

Andrejev O., Sokolov A. 1989. Numerical modelling of the water dynamics and passive pollutant transport in the Neva inlet. *Meteorology and Hydrology*, 12, 75–85 (in Russian).

Andrejev O., Sokolov A. 1990. 3D baroclinic hydrodynamic model and its applications to Skagerrak circulation modeling. In: *Proceedings of the 17th Conference of Baltic Oceanographers (Norrköping, Sweden)*, pp. 38–46.

Andrejev O., Myrberg K., Alenius P., Lundberg P.A. 2004a. Mean circulation and water exchange in the Gulf of Finland – a study based on three-dimensional modeling. *Boreal Environment Research*, 9, 1–16.

Andrejev O., Myrberg K., Lundberg P.A. 2004b. Age and renewal time of water masses in a semi-enclosed basin – Application to the Gulf of Finland. *Tellus A*, 56, 548–558.

Andrejev O., Sokolov A., Soomere T., Värv R., Viikmäe B. 2010. The use of high-resolution bathymetry for circulation modelling in the Gulf of Finland. *Estonian Journal of Engineering*, 16, 187–210.

Andrejev O., Soomere T., Sokolov A., Myrberg K. 2011. The role of spatial resolution of a three-dimensional hydrodynamic model for marine transport risk assessment. *Oceanologia*, 53, 309–334.

Anonymous 2002a. Results from the reader challenge: which MPA is the oldest? *MPA News*, 3, 6.

Anonymous 2002b. An Updated Assessment of the Risk for Oil Spills in the Baltic Sea Area. Presented as a Status report on risk analyses for use in response to oil pollution in the Baltic Sea by Dr S. Ovsienko, Fifth meeting of the Sea-based Pollution Group HELCOM SEA, Turku, Finland, 13–17 May 2002. Helsinki Commission, Helsinki, 77 pp., www.helcom.fi/stc/files/shipping/RiskforOilSpillsReport2002.pdf

Aps R., Fetissov M., Herkül K., Kotta J., Leiger R., Mander Ü., Suursaar Ü. 2009a. Bayesian inference for predicting potential oil spill related ecological risk. In: Guarascio M., Brebbia C.A., Garzia F. (eds.), *Safety and Security Engineering III*. WIT Transactions on the Built Environment, 108, pp. 149–159.

Aps R., Herkül K., Kotta J., Kotta I., Kopti R., Leiger R., Mander Ü., Suursaar Ü. 2009b. Bayesian inference for oil spill related Net Environmental Benefit Analysis. In: Brebbia C.A., Benassai B., Rodriguez G.R. (eds.), *Coastal Processes*. WIT Transactions on Ecology and Environment, 126, pp. 235–246.

Ardhuin F., Mariė L., Rascale N., Forget P. 2009. Observation and estimation of Lagrangian, Stokes and Eulerian currents induced by wind and waves at the sea surface. *Journal of Physical Oceanography*, 39, 2820–2838.

BACC Author Team 2008. *Assessment of Climate Change for the Baltic Sea Basin*. Springer, Berlin, 473 pp.

Beletsky D., Schwab D., McCormick M. 2006. Modeling the 1998–2003 summer circulation and thermal structure in Lake Michigan. *Journal of Geophysical Research: Oceans*, 111(C10), Art. No. C10010.

Bergström S., Carlsson B. 1994. River runoff to the Baltic Sea: 1950–1990. *Ambio*, 23, 280–287.

Bertozzi A., Majda A. 2002. *Vorticity and Incompressible Flows*. Cambridge University. Press, Cambridge, 545 pp.

Blumberg A.F., Hellweger F.L. 2006. Hydrodynamics of the Hudson River Estuary. *American Fisheries Society Symposium*, 51, 9–28.

Boersma P.D., Parrish J.K. 1999. Limiting abuse: marine protected areas, a limited solution. *Ecological Economics*, 31, 287–304.

Bradarić Z., Kostelac M.M. 2009. Place of refuge for ships in need of assistance – methodological approach and Croatian concept. In: *OCEANS 2009, Bremen, Germany, May 11–14, 2009*. OCEANS-IEEE, 1451–1455.

Broström G., Carrasco A., Hole L.R., Dick S., Janssen F., Mattsson J., Berger S. 2011. Usefulness of high resolution coastal models for operational oil spill forecast: the Full City accident. *Ocean Science*, 7, 805–820.

Bumke K., Karger U., Hasse L., Niekamp K. 1998. Evaporation over the Baltic Sea as an example of a semi-enclosed sea. *Contributions to Atmospheric Physics*, 71 (2), 249–261.

Burgherr P. 2007. In-depth analysis of accidental oil spills from tankers in the context of global spill trends from all sources. *Journal of Hazardous Materials*, 140, 245–256.

Cameron W.M., Pritchard D.W. 1963. Estuaries. In *The Sea*, John Wiley and Sons New York, pp. 306–324.

Chang Y.L., Oey L., Xu F.H., Lu H.F., Fujisaki A. 2011. 2010 oil spill: trajectory projections based on ensemble drifter analyses. *Ocean Dynamics*, 61, 829–839.

Chrastansky A., Callies U. 2009. Model-based long-term reconstruction of weather-driven variations in chronic oil pollution along the German North Sea coast. *Marine Pollution Bulletin*, 58, 967–975.

Chrastansky A., Callies U., Fleet D.M. 2009. Estimation of the impact of prevailing weather conditions on the occurrence of oil-contaminated dead birds on the German North Sea coast. *Environmental Pollution*, 157, 194–198.

Ciappa A., Costabile S. 2014. Oil spill hazard assessment using a reverse trajectory method for the Egadi marine protected area (Central Mediterranean Sea). *Marine Pollution Bulletin*, 84, 44–55.

Corell H., Döös K. 2013. Difference in particle transport between two coastal areas in the Baltic Sea investigated with high-resolution trajectory modeling. *Ambio*, 42, 455–463.

Cushman-Roisin B.J., Beckers J.-M. 2011. *Introduction to Geophysical Fluid Dynamics: Physical and Numerical Aspects.* Elsevier/Academic Press, Amsterdam, San Diego, 828 pp.

Dalton T., Jin D., 2010. Extent and frequency of vessel oil spills in US marine protected areas. *Marine Pollution Bulletin*, 60, 1939–1945.

de Vries P., Döös K. 2001. Calculating Lagrangian trajectories using time-dependent velocity fields. *Journal of Atmospheric and Oceanic Technology*, 18, 1092–1101.

Delpeche N. 2006. *Observation of Advection and Turbulent Interfacial Mixing in the Saint John River Estuary, New Brunswick Canada*. MSc thesis. Department of Geodesy and Geomatics, University of New Brunswick, Canada, 287 pp.

Dick S., Kleine E., Müller-Navarra S. 2001. *The Operational Circulation Model of BSH (BSH cmod). Model Description and Validation*. Berichte des Bundesamtes für Seeschifffahrt und Hydrographie 29/2001. Hamburg, Germany, 48 pp.

Döös K. 1995. Inter-ocean exchange of water masses. *Journal of Geophysical Research: Oceans*, 100(C7), 13499–13514.

Döös K., Coward A.C. 1997. The Southern Ocean as the major upwelling zone of the North Atlantic Deep Water. *WOCE Newsletter*, 27, 3–17.

Döös K., Meier H.E.M., Döscher R. 2004. The Baltic haline conveyor belt or the overturning circulation and mixing in the Baltic. *Ambio*, 33, 261–266.

Döös K., Nycander J., Coward A.C. 2008. Lagrangian decomposition of the Deacon Cell. *Journal of Geophysical Research: Oceans*, 113, Art.no. C07028.

Döös K., Kjellsson J., Jönsson B. 2013. TRACMASS–A Lagrangian trajectory model. In: Soomere T., Quak E. (eds.), *Preventive Methods for Coastal Protection*. Springer, Cham, Heidelberg, pp. 225–249.

Ebbesmeyer C., Ingraham W. 1994. Pacific toy spill fuels ocean current pathways research. *EOS: Transactions of the American Geophysical Union*, 75, 37.

Eide M.S., Endresen Ø., Brett P.E., Ervik J.L., Røang K. 2007. Intelligent ship traffic monitoring for oil spill prevention: risk based decision support building on AIS. *Marine Pollution Bulletin*, 54, 145–148.

Elken J., Raudsepp U., Lips U. 2003. On the estuarine transport reversal in deep layers of the Gulf of Finland. *Journal of Sea Research*, 49, 267–274.

Elken J., Mälkki P., Alenius P., Stipa T. 2006. Large halocline variations in the northern Baltic Proper and associated meso- and basin-scale processes. *Oceanologia*, 48(S), 91–117.

Elken J., Raudsepp U., Laanemets J., Passenko J., Maljutenko I., Pärn O., Keevallik S. 2014. Increased frequency of wintertime stratification collapse events in the Gulf of Finland since the 1990s. *Journal of Marine Systems*, 129, 47–55.

Engqvist A., Döös K., Andrejev O. 2006. Modelling water exchange and contaminant transport through a Baltic coastal region. *Ambio*, 35, 435–447.

Eriksen M., Maximenko N., Thiel M., Cummins A., Lattin G., Wilson S., Hafner J., Zellers A., Rifman S. 2013. Plastic pollution in the South Pacific subtropical gyre. *Marine Pollution Bulletin*, 68, 71–76.

Feng X., Tsimplis M.N., Yelland M.J., Quartly G.D. 2014. Changes in significant and maximum wave heights in the Norwegian Sea. *Global and Planetary Change*, 113, 68–76.

Fennel W., Seifert T., Kayser B. 1991. Rossby radii and phase speeds in the Baltic Sea. *Continental Shelf Research*, 11, 23–36.

Filippov M. 2010. Tankeriõnnetuse põhjustas ilmselt inimlik eksimus (The tanker accident was evidently caused by a human error), *Postimees*, 05.01.2010, http://www.postimees.ee/207725/tankerionnetuse-pohjustas-ilmselt-inimlik-eksimus

Frankignoul C., de Coëtlogon G., Joyce T.M., Dong S. 2001. Gulf Stream variability and ocean–atmosphere interactions. *Journal of Physical Oceanography*, 31, 3516–3529.

Fujiwara T., Sanford L.P., Nakatsuji K., Sugiyama Y. 1997. Anticyclonic circulation driven by the estuarine circulation in a gulf type ROFI. *Journal of Marine Systems*, 12, 83–99.

Funkquist L. 2001. HIROMB, an operational eddy-resolving model for the Baltic Sea. *Bulletin of Marine Institute Gdańsk*, 28, 7–16.

Funkquist L., Kleine E. 2007. *An Introduction to HIROMB, an Operational Baroclinic Model for the Baltic Sea*. Technical report, SMHI, Norrköping, Sweden, 48 pp.

Gerdes R., Köberle C., Willebrand J. 1991. The influence of numerical advection schemes on the results of ocean general circulation models. *Climate Dynamics*, 5, 211–226.

Gibbs M.T., Bowman M.J., Dietrich D.E. 2000. Maintenance of near-surface stratification in Doubtful Sound, a New Zealand fjord. *Estuarine, Coastal and Shelf Science*, 51, 683–704.

Gräwe U., Wolff J.-O. 2010. Suspended particulate matter dynamics in a particle framework. *Environmental Fluid Mechanics*, 10, 21–39.

Gräwe U., Deleersnijder E, Shah S.H.A.M., Heemink A.W. 2012. Why the Euler scheme in particle tracking is not enough: the shallow-sea pycnocline test case. *Ocean Dynamics*, 62, 501–514.

Griffa A., Piterbarg L.I., Özgökmen T. 2004. Predictability of Lagrangian particle trajectories: effects of smoothing of the underlying Eulerian flow. *Journal of Marine Research*, 62, 1–35.

Haapala J., Alenius P. 1994. Temperature and salinity statistics for the northern Baltic Sea 1961–1990. *Finnish Marine Research*, 262, 51–121.

Haidvogel D.B. Beckmann A. 1999. *Numerical Ocean Circulation Modeling*. Imperial College Press, London, 344 pp.

Henson S.A., Dunne J.P., Sarmiento J.L. 2009. Decadal variability in North Atlantic phytoplankton blooms. *Journal of Geophysical Research: Oceans*, 114(C4), Art. no. C04013.

Hurrell J.W., Kushnir Y., Ottersen G., Visbeck M. (eds.) 2003. *The North Atlantic Oscillation: Climate Significance and Environmental Impact.* American Geophysical Union, Geophysical Monograph Series, 134, 279 pp.

Hassler B. 2011. Accidental versus operational oil spills from shipping in the Baltic Sea: risk governance and management strategies. *Ambio*, 40, 170–178.

Havens H., Luther M.E., Meyers S.D., Heil C.A. 2010. Lagrangian particle tracking of a toxic dinoflagellate bloom within the Tampa Bay estuary. *Marine Pollution Bulletin*, 60, 2233–2241.

HELCOM 2009. *Ensuring Safe Shipping in the Baltic.* Stankiewicz M., Vlasov N. (eds.), Helsinki Commission, Helsinki, 18 pp.

HELCOM 2010. *Towards an Ecologically Coherent Network of Well-managed Marine Protected Areas*. Implementation report on the status and ecological coherence of the HELCOM BSPA network. Baltic Sea Environment Proceedings No. 124B, 143 pp.

HELCOM 2013. *Overview of the Status of the Network of Baltic Sea Marine Protected Areas*. Borg J., Ekebom J., Blankett P. Helsinki Commission, Helsinki, 31 pp.

Hibler W.D. 1979. A dynamic thermodynamic sea ice model. *Journal of Physical Oceanography*, 9, 815–846.

Höglund A., Meier H.E.M., Broman B., Kriezi E. 2009. *Validation and Correction of Regionalised ERA-40 Wind Fields over the Baltic Sea Using the Rossby Centre Atmosphere Model RCA3.0.* Rapport Oceanografi No 97, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden, 29 pp.

Höglund A., Meier H.E.M. 2012. Environmentally safe areas and routes in the Baltic Proper using Eulerian tracers. *Marine Pollution Bulletin*, 64, 1375–1385.

Hunke E.C., Dukowicz J.K. 1997. An elastic–viscous–plastic model for sea ice dynamics. *Journal of Physical Oceanography*, 27, 1849–1867.

Jönsson B., Lundberg P., Döös K. 2004. Baltic sub-basin turnover times examined using the Rossby Centre Ocean model. *Ambio*, 23, 257–260.

Kachel M.J. 2008. *Particularly Sensitive Sea Areas*. Hamburg Studies on Maritime Affairs, 13, Springer, Berlin, 376 pp.

Kantha L.H., Clayson C.A. 2000. *Small Scale Processes in Geophysical Fluid Flows*. Academic Press, 888 pp.

Keevallik, S., Soomere T. 2010. Towards quantifying variations in wind parameters across the Gulf of Finland. *Estonian Journal of Earth Sciences,* 59, 288–297.

Keramitsoglou I., Cartalis C., Kassomenos P. 2003. Decision support system for managing oil spill events. *Environmental Management*, 32, 290–298.

Killworth P., Stainforth D., Webb D., Paterson S. 1991. The development of a free-surface Bryan–Cox–Semtner ocean model. *Journal of Physical Oceanography*, 21, 1333–1348.

Kirby M., Law R.J. 2010. Accidental spills at sea – Risk, impact, mitigation and the need for co-ordinated post-incident monitoring. *Marine Pollution Bulletin*, 60, 797–803.

Kirtman B.P., Bitz C., Bryan F., Collins W., Dennis J., Hearn N., Kinter J.L., Loft R., Rousset C., Siqueira L., Stan C., Tomas R., Vertenstein M. 2012. Impact of ocean model resolution on CCSM climate simulations. *Climate Dynamics*, 39(6), 1303–1328.

Kjellsson J., Döös K. 2012. Surface drifters and model trajectories in the Baltic Sea. *Boreal Environment Research*, 17(6), 447–459.

Kjellsson J., Döös K., Soomere T. 2013. Evaluation and tuning of model trajectories and spreading rates in the Baltic Sea using surface drifter observations. In: Soomere T., Quak E. (eds.), *Preventive Methods for Coastal Protection*. Springer, Cham, Heidelberg, pp. 251–282.

Kleine E. 1994. *Das Operationelle Modell des BSH für Nordsee und Ostsee, Konzeption und Übersicht*. Bundesamt für Seeschifffart und Hydrographie, 126 pp. (in German).

Klemas V. 2010. Tracking oil spill and predicting their trajectories using remote sensors and models: case studies of the Sea Princess and Deepwater Horizon oil spills. *Journal of Coastal Research*, 26, 789–797.

Knudsen O.F. 2010. Transport interests and environmental regimes: the Baltic Sea transit of Russian oil exports. *Energy Policy*, 38, 151–160.

Ko T.T., Chang Y.-C. 2010. Integrated marine pollution management: a new model of marine pollution prevention and control in Kaohsiung, Taiwan. *Ocean & Coastal Management*, 53, 624–635.

Kononen K., Kuparinen J., Mäkelä K., Laanemets J., Pavelson J., Nõmmann S. 1996. Initiation of cyanobacterial blooms in a frontal region at the entrance to the Gulf of Finland, Baltic Sea. *Limnology, Oceanography*, 41, 98–112.

Korajkic A., Badgley B.D., Brownell M.J., Harwood V.J. 2009. Application of microbial source tracking methods in a Gulf of Mexico field setting. *Journal of Applied Microbiology*, 107, 1518–1527.

Korotenko K.A., Mamedov R.M., Kontar A.E., Korotenko L.A. 2004. Particle tracking method in the approach for prediction of oil slick transport in the sea:

modeling oil pollution resulting from river input. *Journal of Marine Systems*, 48, 159–170.

Korotenko K.A., Bowman M.J., Dietrich D.E. 2010. High-resolution numerical model for predicting the transport and dispersal of oil spilled in the Black Sea. *Terrestrial, Atmospheric and Ocean Sciences*, 21, 123–136.

Kostianoy A.G., Ambjörn C., Soloviev D.M. 2008. Seatrack Web: a numerical tool to protect the Baltic Sea marine protected areas. In: *IEEE/OES US/EU-Baltic International Symposium, Tallinn, Estonia, May 27–29, 2008*. IEEE Press, New York, pp. 7–12.

Krauss W., Brügge B. 1991. Wind-produced water exchange between the deep basins of the Baltic Sea. *Journal of Physical Oceanography*, 21, 373–384.

Kurkina O., Pelinovsky E., Talipova T., Soomere T. 2011. Mapping the internal wave field in the Baltic Sea in the context of sediment transport in shallow water. *Journal of Coastal Research*, Special Issue 64, vol. II, 2042–2047.

Kuronen J., Tapaninen U. 2009. *Maritime Safety in the Gulf of Finland: Review on Policy Instruments*. Publications from the Centre for Maritime Studies University of Turku, A 49, 90 pp.

Lagemaa P., Elken J., Kõuts T. 2011. Operational sea level forecasting in Estonia. *Estonian Journal of Engineering*, 17, 301–331.

Laine A.O., Andersun A., Leiniö S., Alain Z.F. 2007. Stratification-induced hypoxia as a structuring factor of macrozoobenthos in the open Gulf of Finland (Baltic Sea). *Journal of Sea Research*, 57, 65–77.

Lecklin T., Ryoma R., Kuikka S. 2011. A Bayesian network for analyzing biological acute and long-term impacts of an oil spill in the Gulf of Finland. *Marine Pollution Bulletin*, 62, 2822–2835.

Lee T.N., Yoder J.A., Atkinson L.P. 1991. Gulf Stream frontal eddy influence on productivity of the south east U.S. continental shelf. *Journal of Geophysical Research: Oceans*, 96, 22191–22205.

Lehmann A., Hinrichsen H.-H. 2000. On the thermohaline variability of the Baltic Sea. *Journal of Marine Systems*, 25, 333–357.

Lehmann A., Krauss W., Hinrichsen H.-H. 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. *Tellus A*, 54, 299–316.

Lehmann A., Myrberg K., Höflich K. 2012. A statistical approach to coastal upwelling in the Baltic Sea based on the analysis of satellite data for 1990–2009. *Oceanologia*, 54, 369–393.

Lehmann A., Hinrichsen H.-H., Getzlaff K. 2014. Identifying potentially high risk areas for environmental pollution in the Baltic Sea. *Boreal Environment Research*, 19, 140–152.

Leppäranta M., Myrberg K. 2009. *Physical Oceanography of the Baltic Sea.* Springer Praxis, Berlin, 378 pp.

Lewis M.R., Cullen J.J., Platt T. 1984. Relationships between vertical mixing and photoadaption of phytoplankton: similarity criteria. *Marine Ecology*, 15, 141–149.

Lilover M.-J., Pavelson J., Kõuts T. 2014. On the nature of low-frequency currents over a shallow area of the southern coast of the Gulf of Finland. *Journal of Marine Systems*, 129, 66–75.

Liu Y., Weisberg R.H., Hu C., Zheng L. 2011. Tracking the Deepwater Horizon oil spill: A modeling perspective. *EOS Transactions*, 92 (6), 45–46.

Löptien U., Meier H.E.M. 2011. The influence of increasing water turbidity on the sea surface temperature in the Baltic Sea: a model sensitivity study. *Journal of Marine Systems*, 88, 323–331.

Lu X., Soomere T., Stanev E.V., Murawski J. 2012. Identification of the environmentally safe fairway in the South-Western Baltic Sea and Kattegat. *Ocean Dynamics*, 62, 815–829.

Luo Y., Rothstein L., Liu Q., Zhang S. 2013. Climatic variability of the circulation in the Rhode Island Sound: a modeling study. *Journal of Geophysical Research: Oceans*, 118, 4072–4091.

Maddern D., Knight S. 2003. Refuge for ships in distress: International developments and the Australian position. *Australian and New Zealand Maritime Law Journal*, 17, 101–118.

Mariani P., MacKenzie B.R., Iudicone D., Bozec A. 2010. Modelling retention and dispersion mechanisms of bluefin tuna eggs and larvae in the northwest Mediterranean Sea. *Progress in Oceanography*, 86, 45–58.

Matthäus W., Nehring D., Feistel R., Nausch G., Mohrholz V., Lass H.-U. 2008. The inflow of highly saline water into the Baltic Sea. In: *State and Evolution of the Baltic Sea, 1952–2005*. Wiley, Hoboken, New Jersey, pp. 265–309.

Meier H.E.M. 2001. On the parameterization of mixing in three-dimensional Baltic Sea models. *Journal of Geophysical Research: Oceans*, 106(C12), 30,997–31,016.

Meier H.E.M. 1999. *First Results of Multi-Year Simulations Using a 3D Baltic Sea Model.* SMHI Reports Oceanography, No 27, Norrköping, Sweden, 48 pp.

Meier H.E.M. 2007. Modeling the pathways and ages of inflowing salt- and freshwater in the Baltic Sea. *Estuarine, Coastal and Shelf Science,* 74, 610–627.

Meier H.E.M., Höglund A. 2013. Studying the Baltic Sea circulation with Eulerian tracers. In: Soomere T., Quak E. (eds.), *Preventive Methods for Coastal Protection*. Springer, Cham, Heidelberg, pp. 101–130.

Meier H.E.M., Döscher R., Faxén T. 2003. A multiprocessor coupled ice-ocean model for the Baltic Sea: application to salt inflow. *Journal of Geophysical Research-Oceans*, 108(C8), 32–73.

Mietus M. (co-ordinator) 1998. *The Climate of the Baltic Sea Basin, Marine Meteorology and Related Oceanographic Activities*. Report No. 41, World Meteorological Organisation, Geneva, 64 pp.

Millero F.J., Feistel R., Wright D.G., McDougall T.J. 2008. The composition of standard seawater and the definition of the reference-composition salinity scale. *Deep-Sea Research* I, 55, 50–72.

Mitarai S., Siegel D.A., Watson J.R., Dong C., McWilliams J.C. 2009. Quantifying connectivity in the coastal ocean with application to the Southern California Bight. *Journal of Geophysical Research: Oceans*, 114, Art. no. C10026.

Montewka J., Krata P., Goerlandt F., Mazaheri A., Kujala P. 2011. Marine traffic risk modelling – an innovative approach and a case study. *Proceedings of the Institution of Mechanical Engineering. Part O. Journal of Risk and Reliability*, 225, 307–322.

Montewka J., Weckström M., Kujala P. 2013. A probabilistic model estimating oil spill clean-up costs – A case study for the Gulf of Finland. *Marine Pollution Bulletin*, 76, 61–71.

Monzon-Argullo C., Lopez-Jurado L.F., Rico C., Marco A., Lopez P., Hays G.C., Lee P.L.M. 2010. Evidence from genetic and Lagrangian drifter data for transatlantic transport of small juvenile green turtles. *Journal of Biogeography*, 37, 1752–1766.

Murawski J., Woge Nielsen J. 2013. Applications of an oil drift and fate model for fairway design. In: Soomere T., Quak E. (eds.), *Preventive Methods for Coastal Protection*. Springer, Cham, Heidelberg, pp. 376–415.

Myrberg K., Andrejev O. 2003. Main upwelling regions in the Baltic Sea – a statistical analysis based on three-dimensional modelling. *Boreal Environment Research*, 8, 97–112.

Myrberg K., Lehmann A. 2013. Topography, Hydrography, Circulation and Modelling of the Baltic Sea. In: Soomere T., Quak E. (eds.), *Preventive Methods for Coastal Protection*. Springer, Cham, Heidelberg, pp. 31–64.

Myrberg K.., Soomere T. 2013. The Gulf of Finland, its hydrography and circulation dynamics. In: Soomere T., Quak E. (eds.), *Preventive Methods for Coastal Protection*. Springer, Cham, Heidelberg, pp. 181–222.

Myrberg K., Ryabchenko V., Isaev A., Vankevich R., Andrejev O., Bendtsen J., Erichsen A., Funkquist L., Inkala A., Neelov I., Rasmus K., Rodriguez M.M., Raudsepp U., Passenko J., Söderkvist J., Sokolov A., Kuosa H., Anderson T.R., Lehmann A., Skogen M.D. 2010. Validation of three-dimensional hydrodynamic models in the Gulf of Finland based on a statistical analysis of a six-model ensemble. *Boreal Environment Research*, 15, 453–479.

Nausch G., Feistel R., Umlauf L., Mohrholz V., Siegel H. 2013. *Hydrographisch-hydrochemische Zustandseinschätzung der Ostsee 2012*. Meereswissenschaftliche Berichte (Marine Science Reports, in German), 91, 109 pp.

Nekrasov A.V., Lebedeva I.K. 2002. Estimation of baroclinic Rossby radii in Luga–Koporye region. *BFU Research Bulletin*, 4–5, 89–93.

Nielsen M.H. 2005. The baroclinic surface currents in the Kattegat. *Journal of Marine Systems*, 55, 97–121.

Niros A., Vihma T., Launiainen J. 2002. Marine meteorological conditions and air-sea exchange processes over the northern Baltic Sea in 1990. *Geophysica*, 38(1/2), 59-87.

Nycander J., Döös K. 2003. Open boundary conditions for barotropic waves. *Journal of Geophysical Research: Oceans*, 108(C5), Art. no. 3168.

Ohlmann J.C., Mitarai S. 2010. Lagrangian assessment of simulated surface current dispersion in the coastal ocean. *Geophysical Research Letters*, 37, Art. No. L17602.

Orlanski I. 1976. A simple boundary condition for unbounded hyperbolic flows. *Journal of Computational Physics*, 21, 251–26x.

Osiński R., Piechura J. 2009. Latest findings about circulation of upper layer in the Baltic Proper. In *BSSC 2009 Abstract Book, August 17–21, 2009*. Tallinn, 103.

Osiński R., Rak D., Walczowski W., Piechura J. 2010. Baroclinic Rossby radius of deformation in the southern Baltic Sea. *Oceanologia*, 52, 417–429.

Otero P., Ruiz-Villarreal M., Allen-Perkins S., Vila B., Cabanas J.M. 2014. Coastal exposure to oil spill impacts from the Finisterre Traffic Separation Scheme. *Marine Pollution Bulletin*, 85, 67–77, doi: 10.1016/j.marpolbul.2014.06.020.

Özgökmen T.M., Griffa A., Piterbarg L.I., Mariano A.J. 2000. On the predictability of Lagrangian trajectories in the ocean. *Journal of Atmospheric and Oceanic Technology*, 17(3), 366–383.

Özgökmen T.M., Piterbarg L.I., Mariano A.J. 2001. Predictability of drifter trajctories in the tropical Pacific Ocean. *Journal Physical Oceanography*, 31, 2691–2720.

Petrenko A. 2003. Variability of circulation features in the Gulf of Lion NW Mediterranean Sea. Importance of inertial currents. *Oceanologica Acta*, 26, 323–338.

Periáñez R. 2004. A particle-tracking model for simulating pollutant dispersion in the Strait of Gibraltar. *Marine Pollution Bulletin*, 49, 613–623.

Pichel W.G., Churnside J.H., Veenstra T.S., Foley D.G., Friedman K.S., Brainard R.E., Nicoll J.B., Zheng Q., Clemente-Colon P. 2007. Marine debris collects within the North Pacific Subtropical convergence zone. *Marine Pollution Bulletin*, 54, 1207–1211.

Pitkänen H., Tamminen T., Kangas P., Huttula T., Kivi K., Kuosa H., Sarkkula J., Eloheimo K., Kauppila P., Skakalsky B. 1993. Late summer trophic conditions in the north-eastern Gulf of Finland and the river Neva estuary, Baltic Sea. *Estuarine Coastal and Shelf Science*, 37, 453–474.

Poje A.C., Haller G. 1999. Geometry of cross-stream mixing in a double-gyre ocean model. *Journal of Physical Oceanography*, 29, 1649–1665.

Pritchard D.W. 1955. Estuarine circulation patterns. *Proceedings of the American Society of Civil Engineers*, 81(717), 1–11.

Reissmann J.H., Burchard H., Feistel R., Hagen E., Lass H.U., Mohrholz V., Nausch G., Umlauf L., Wieczorek G. 2009. Vertical mixing in the Baltic Sea and consequences for eutrophication – A review. *Progress in Oceanography*, 82, 47–80.

Reverdin G., Niiler P.O., Valdimarsson H. 2003. North Atlantic Ocean surface currents. *Journal of Geophysical Research: Oceans*, 108(C1), 2-1–2-21.

Röhrs J., Christensen K.H., Hole L.R., Broström G., Drivdal M., Sundby S. 2012. Observation-based evaluation of surface wave effects on currents and trajectory forecasts. *Ocean Dynamics*, 62, 1519–1533.

Rusli M.H.B. 2012. Protecting vital sea lines of communication: a study of the proposed designation of the Straits of Malacca and Singapore as a particularly sensitive sea area. *Ocean & Coastal Management*, 57, 79–94.

Rytkonen J., Siitonen L., Riippi T., Sassi J., Sukselainen J., 2002. *Statistical Analysis of the Baltic Maritime Traffic*. VTT Research Report VAL34-012344, 108 pp., www.helcom.fi/stc/files/shipping/VTTreport.pdf.

Samuelsen A., Hjøllo S.S., Johannessen J.A., Patel R. 2012. Particle aggregation at the edges of anticyclonic eddies and implications for distribution of biomass. *Ocean Science*, 8, 389–400.

Samuelsson P., Jones C.G., Willén U., Ullerstig A., Gollvik S., Hansson U., Jansson C., Kjellström E., Nikulin G., Wyser K. 2011. The Rossby centre regional climate model RCA3: model description and performance. *Tellus A*, 63, 4–23.

Schepanski K., Tegen I., Macke A. 2009. Saharan dust transport and deposition towards the tropical northern Atlantic. *Atmospheric Chemistry and Physics*, 9, 1173–1189.

Schinke H., Matthäus W. 1998. On the causes of major Baltic inflows – an analysis of long time series. *Continental Shelf Research*, 18, 67–97.

Schmitt R.W. 1994. Double diffusion in oceanography. *Annual Review Fluid Mechanics*, 26, 255–285.

Schwehr K.D., McGillivary P.A. 2007. Marine ship Automatic Identification System (AIS) for enhanced coastal security capabilities: an oil spill tracking application. In: *Proceedings of the 2007 OCEANS Conference, Vancouver, Canada, September 29–October 04, 2007*. IEEE Press, New York, pp. 1131–1139.

Seifert T., Tauber F., Kayser B. 2001. A high resolution spherical grid topography of the Baltic Sea, revised edition. In: *Baltic Sea Science Congress, 25–29 November 2001*, Poster #147, Stockholm, www.iowarnemuende.de/iowtopo resampling.html.

Serra T., Vidal J., Casamtijana X., Soler M., Colomer J. 2007. The role of surface vertical mixing in phytoplankton distribution in a stratified reservoir. *Limnology and Oceanography*, 52, 620–634.

Shay L.K., Cook T.M., Peters H., Arthur M.J., Weisberg R., Edgar An P., Alexander S., Luther M. 2002. Very high-frequency radar mapping of surface currents. *IEEE Journal of Oceanic Engineering*, 27, 155–169.

Sommer T., Carpenter J.R., Schmid M., Lueck R.G., Schurter M., Wüest A. 2013. Interface structure and flux laws in a natural double-diffusive layering. *Journal of Geophysical Research: Oceans*, 118, 6092–6106.

Sooäär J., Jaagus J. 2007. Long-term variability and changes in the sea ice regime in the Baltic Sea near the Estonian coast. *Proceedings of the Estonian Academy of Sciences. Engineering*, 13, 189–200.

Soomere T., Keevallik S. 2001. Anisotropy of moderate and strong winds in the Baltic Proper. *Proceedings of the Estonian Academy of Sciences. Engineering*, **7**, 35–49.

Soomere T., Keevallik S. 2003. Directional and extreme wind properties in the Gulf of Finland. *Proceedings of the Estonian Academy of Sciences. Engineering*, 9, 73–90.

Soomere T., Quak E. 2007. On the potential of reducing coastal pollution by a proper choice of the fairway. *Journal of Coastal Research*, Special Issue 50, 678–682.

Soomere T., Quak E. (eds.) 2013. *Preventive Methods for Coastal Protection: Towards the Use of Ocean Dynamics for Pollution Control*. Springer, Cham, Heidelberg, 442 pp.

Soomere T., Myrberg K., Leppäranta M., Nekrasov A. 2008. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia*, 50, 287–362.

Soomere T., Andrejev O., Myrberg K., Sokolov A. 2011a. The use of Lagrangian trajectories for the identification of the environmentally safe fairways. *Marine Pollution Bulletin*, 62, 1410–1420.

Soomere T., Berezovski M., Quak E., Viikmäe B. 2011b. Modelling environmentally friendly fairways using Lagrangian trajectories: a case study for the Gulf of Finland, the Baltic Sea. *Ocean Dynamics*, 61, 1669–1680.

Soomere T., Döös K., Lehmann A., Meier H.E.M, Murawski J., Myrberg K., Stanev E. 2014. The potential of current- and wind-driven transport for environmental management of the Baltic Sea. *Ambio*, 43, 94–104.

Soosaar E., Maljutenko I., Raudsepp U., Elken J. 2014. An investigation of anticyclonic circulation in the southern Gulf of Riga during the spring period. *Continental Shelf Research*, 78, 75–84.

Stanev E.V., Lu X. 2013. European semi-enclosed seas: Basic physical processes and their numerical modelling. In: Soomere T., Quak E. (eds.), *Preventive Methods for Coastal Protection*. Springer, Cham, Heidelberg, pp. 131–179.

Stevens D.P. 1991. The open boundary condition in the United Kingdom Fine-Resolution Antarctic Model. *Journal of Physical Oceanography*, 21, 1494–1499.

Torsvik T. 2013. Introduction to computational fluid dynamics and ocean modelling. In: Soomere T., Quak E. (eds.), *Preventive Methods for Coastal Protection*. Springer, Cham, Heidelberg, pp. 65–100.

Uggla Y. 2007. Environmental protection and the freedom of the high seas: the Baltic Sea as a PSSA from a Swedish perspective. *Marine Policy*, 31, 251–257.

Uppala S.M., Kållberg P.W., Simmons A.J., Andrae U., da Costa B.V., Fiorino M., Gibson J.K., Haseler J., Hernandez A., Kelly G.A., Li X., Onogi K., Saarinen S., Sokka N., Allan R.P., Andersson E., Arpe K., Balmaseda M.A., Beljaars A.C.M., van de Berg L., Bidlot J., Bormann N., Caires S., Chevallier F., Dethof A., Dragosavac M., Fisher M., Fuentes M., Hagemann S., Hólm E., Hoskins B.J., Isaksen L., Janssen P.A.E.M., Jenne R., McNally A.P., Mahfouf J.-F., Morcrette J.-J., Rayner N.A., Saunders R.W., Simon P., Sterl A., Trenberth K.E., Untch A., Vasiljevic D., Viterbo P., Woollen J. 2005. The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society*, 131, 2961–3012.

Väli G., Meier H.E.M., Elken J. 2013. Simulated halocline variability in the Baltic Sea and its impact on hypoxia during 1961–2007 *Journal of Geophysical Research: Oceans*, 118, 6982–7000.

Vandenbulcke L., Beckers J.-M., Lenartz F., Barth A., Poulain P.-M., Aidonidis M., Meyrat J., Ardhuin F., Tonani M., Fratianni C., Torrisi L., Pallela D., Chiggiato J., Tudor M., Book J.W., Martin P., Peggion G., Rixen M. 2009. Super-ensemble techniques: application to surface drift prediction. *Progress in Oceanography*, 82, 149–167.

Vieites D.R., Nieto-Rom S., Palanca A., Ferrer X., Vences M. 2004. European Atlantic: the hottest oil spill hotspot worldwide. *Naturwissenschaften*, 91, 535–538.

Viikmäe B. 2014. *Optimising Fairways in the Gulf of Finland Using Patterns of Surface Currents*. PhD thesis. Tallinn University of Technology, 196 pp.

Viikmäe B., Soomere T. 2014. Spatial pattern of current-driven hits to the nearshore from a major marine highway in the Gulf of Finland. *Journal of Marine Systems*, 129, 106–117.

Viikmäe B., Soomere T., Viidebaum M., Berezovski A. 2010. Temporal scales for transport patterns in the Gulf of Finland. *Estonian Journal of Engineering*, 16, 211–227.

Viikmäe B., Soomere T., Parnell K.E., Delpeche N. 2011. Spatial planning of shipping and offshore activities in the Baltic Sea using Lagrangian trajectories. *Journal of Coastal Research*, Special Issue 64, 956–960.

Viikmäe B., Torsvik T., Soomere T. 2012. Analysis of the structure of currents in the Gulf of Finland using Okubo–Weiss parameter. In: *Proc. IEEE/OES Baltic 2012 International Symposium "Ocean: Past, Present and Future. Climate Change Research, Ocean Observation & Advanced Technologies for Regional Sustainability,"* May 8–11, 2012, Klaipėda, Lithuania, IEEE, 7 pp. doi 10.1109/BALTIC.2012.6249184.

Viikmäe B., Torsvik T., Soomere T. 2013. Impact of horizontal eddy-diffusivity on Lagrangian statistics for coastal pollution from a major marine fairway. *Ocean Dynamics*, 63, 589–597.

Yoon J.-H., Kawano S., Igawa S. 2010. Modeling of marine litter drift and beaching in the Japan Sea. *Marine Pollution Bulletin*, 60, 448–463.

Webb D.J., Coward A.C., de Cuevas B.A., William G.S. 1997. A multiprocessor ocean circulation model using message passing. *Journal of Atmospheric and Oceanic Technology*, 14, 175–183.

Wiggins S. 2005. The dynamical systems approach to Lagrangian transport in oceanic flows. *Fluid Mechanics*, 37, 295–328.

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* * *

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Abstract

The main goal of this thesis is to develop an engineering approach to mitigate risks to Marine Protected Areas (MPAs), created by pollution from ship traffic, by means of preventively adjusting the location of possible accidents. This is achieved by demonstrating that (i) various normally concealed semi-persistent transport patterns in the surface layer (at various spatial and temporal scales) of the Gulf of Finland, the Baltic Sea, can be identified with the combined use of a Lagrangian trajectory model and classical statistical methods and (ii) these patterns can be utilised to quantify threats through current-driven transport of pollution from a major fairway to the MPAs.

The analysis relies on the Eulerian velocity data for the surface layer (0–3 m) with a horizontal resolution of 2 nautical miles, obtained from the Rossby Centre Ocean model (RCO) for the period 1987–1991. Analysis of the Eulerian transport patterns is performed by simple averaging of the RCO data, whilst patterns of the net and bulk Lagrangian transport are evaluated using the trajectory model TRACMASS.

The results of various average features of Eulerian velocities, such as average flow speed or persistent coastal currents, match well with the outcome of previous studies. Surface transport is predominantly to the east. A slow anticyclonic gyre in the wide eastern part of the Gulf of Finland is present in the five-year average but not necessarily in single years.

A technique combining the Lagrangian trajectory model TRACMASS and classical statistical methods is developed for the identification and visualisation of semi-persistent patterns of surface transport on weekly scales. The key parameters and spatial patterns of net and bulk transport and their ratio have been established for the Gulf of Finland using trajectories with a length of about a week. Semi-persistent patterns of net transport are mainly aligned along the coasts of the Gulf of Finland but in some seasons (mostly in transitional spring and autumn months) intense cross-gulf transport may exist.

The level of risk to the MPAs in the Gulf of Finland is quantified with respect to the current-driven pollution from the major fairway using 20 days long trajectories. The MPAs located in the eastern and western sections of the gulf are the most vulnerable for pollution. It takes on average 5–8 days for pollution to reach the MPAs. A linear relationship is established between the number of hits to a MPA and the distance of this MPA from the fairway. For the Gulf of Finland the sections of the fairway where most of hits to a particular MPA stem from and possible places of refuge for vessels in need of assistance have been determined. The sources of pollution to MPAs cover 31–56% of the entire length of the fairway in the Gulf of Finland. The effect that shifting the fairway would have on the level of the risk of discussed type to the MPAs is quantified. It is shown that no perfect solution exists to the entire system of MPAs. However, several MPAs may largely benefit from a shift of certain segments of the fairway.

Resümee

Doktoritöö peamine eesmärk on välja töötada laevateede lähistel paiknevate merekaitsealade haldamiseks ja neile mõjuvate riskide preventiivseks maandamiseks sobivate võtete alused. Riskiallika näitena vaadeldakse laevaliiklusega seonduvat merereostust ning meetmena võimalike õnnetuste asukoha optimeerimist liikluse ümbersuunamise kaudu. Oluliste sammudena demonstreeritakse, et (i) Soome lahe pinnakihi poolpüsivaid hoovuste mustreid saab tuvastada veeosakeste Lagrange'i trajektooride statistilise analüüsi kaudu ning et (ii) nende mustrite poolt põhjustatud Lagrange'i transpordi omaduste alusel saab adekvaatselt kvantifitseerida hoovustega edasi kantavaid riske.

Analüüs põhineb peamiselt RCO (Rossby Centre Ocean model) tsirkulatsioonimudeli abil rekonstrueeritud kiirusväljadel. Mere pinnakihi (0–3 m) kiiruste andmestikku sammuga 2 meremiili aastate 1987–1991 jaoks) kasutatakse nii tsirkulatsiooniskeemi analüüsiks kui ka Lagrange'i trajektooride leidmiseks TRACMASS tarkvara abil. Tsirkulatsiooniskeemi analüüsi peamised tulemused (veemasside ümberpaiknemise keskmine kiirus, püsivate rannalähedaste hoovuste eksisteerimine) kinnitavad varasemate uuringute seisukohti. Uute aspektidena selgus, et Soome lahe pinnakihis domineerib idasuunaline liikumine ning et lahe kõige laiemas osas ilmneb paljuaastase keskmisena päripäeva suunatud aeglane tsirkulatsioon (mis aga ei pruugi esineda üksikutel aastatel).

Poolpüsivate hoovuste ja nende poolt genereeritud Lagrange'i transpordi identifitseerimiseks ja visualiseerimiseks on välja töötatud meetod kindla ajamastaabiga transpordi arvutamiseks sobiva pikkusega Lagrange'i trajektooride statistilise analüüsi alusel. Meetodi abil on määratletud ligikaudu ühe nädala vältel toimuva veemasside ja reostuse bruto- ja netotranspordi ning nende suhte omadused. Poolpüsiv hoovustransport kannab veemasse edasi peamiselt rannaga paralleelselt. Kevadeti ja sügiseti võib esineda intensiivne lahe teljega risti suunatud transport.

Soome lahes asuvate merekaitsealade eksponeeritust rahvusvahelisele laevateele sattunud reostuse hoovustranspordi suhtes on analüüsitud 20 päeva pikkuste trajektooride abil. Kõige suurem reostusrisk on lahe suudmealal ja idaosas paiknevatel kaitsealadel. Reostus jõuab laevateelt kaitsealadele keskmiselt 5–8 päevaga. Konkreetsele kaitsealale jõudvate reostusosakeste arv on praktiliselt lineaarses sõltuvuses selle ala kaugusest laevateest. On määratletud laevatee lõigud, kust pärineb suurim osa hoovuste poolt merekaitsealadele kantavast reostusest, aga ka lõigud, kust reostus kaitsealadele jõuab harva ning mida saab kasutada probleemsete laevade ankrupaikadena. Konkreetsele kaitsealale võib reostus jõuda segmentidest, mis moodustavad 31–56% kogu laevatee pikkusest. Reostusallikate asukoha varieerimise abil on hinnatud, millist efekti annaks laevatee nihutamine kaitsealadele kanduva reostuse vähendamiseks. On näidatud, et laevatee kui terviku nihutamine ei pruugi anda parimat tulemust, kuid üksikute merekaitsealade eksponeeritust laevateelt lähtuvale reostusele saaks oluliselt vähendada laevatee teatavate segmentide nihutamise kaudu.

Appendix A: Curriculum Vitae

1. Personal data

Name	Nicole Delpeche-Ellmann
Date and place of birth	10.05.1978, Port of Spain, Trinidad
Address	Akadeemia tee 21, 12618 Tallinn
Phone	(+372) 620 4167
e-mail	nicole.delpeche@gmail.com

2. Education

Educational institution	Graduation year	Education (field of study / degree)
University of New Brunswick, Fredericton Canada	2006	Geodesy and Geomatics Engineering /MSc.E
University of the West Indies, Trinidad	2001	Surveying and Land Information /B.Sc.

3. Language competence/skills

Language	Level
English	native language
Estonian	average
Spanish	average

4. Special courses and further training

Period	Educational or other organisation
2009	*TRACMASS – A Lagrangian Trajectory code*, Tallinn University of Technology, Estonia
2005	Geophysical and Environmental Fluid Dynamics Summer school, Cambridge U.K.

5. Professional employment

Period	Organisation	Position
2008–to present	Institute of Cybernetics, Tallinn University of Technology	Researcher
2008–2010	FUGRO Netherlands	Hydrographic surveyor
2008–2010	GEO S.T Ltd, Estonia	Hydrographic surveyor

2007	University of the West Indies, Trinidad	Part-time lecturer Hydrographic surveying
2006–2008	Coastal Dynamics, Trinidad	Oceanographer /Hydrographic surveyor
2004–2006	University of New Brunswick, Canada	Researcher
2001–2004	FUGRO Trinidad, Trinidad	Hydrographic surveyor/Land surveyor
2000	CANE & Associates, Trinidad	Trainee hydrographic surveyor

6. Research activity

6.1. Publications

Articles indexed by the ISI Web of Science database (1.1)

Delpeche-Ellmann N., Soomere T. 2013. Investigating the Marine Protected Areas most at risk of currentdriven pollution in the Gulf of Finland, the Baltic Sea, using a Lagrangian transport model. *Marine Pollution Bulletin*, 67(1–2), 121–129.

Delpeche-Ellmann N., Soomere T. 2013. Using Lagrangian models to assist in maritime management of Coastal and Marine Protected Areas. *Journal of Coastal Research*, Special Issue 65(1), 36–41.

Soomere T., **Delpeche N**., Viikmäe B., Quak E., Meier H.E.M., Döös K. 2011. Patterns of current-induced transport in the surface layer of the Gulf of Finland. *Boreal Environment Research*, 16(Suppl. A), 49–63.

Viikmäe B., Soomere T., Parnell K.E., **Delpeche N**. 2011. Spatial planning of shipping and offshore activities in the Baltic Sea using Lagrangian trajectories. *Journal of Coastal Research*, Special Issue 64, Part I, 956–960.

Soomere T., Viikmäe B., **Delpeche N**., Myrberg K. 2010. Towards identification of areas of reduced risk in the Gulf of Finland, the Baltic Sea. *Proceedings of the Estonian Academy of Sciences*, 59(2), 156–165.

Kask A., Soomere T., Healy T., **Delpeche N**. 2009. Rapid estimates of sediment loss for “almost equilibrium” beaches. *Journal of Coastal Research*, Special Issue 56, Part II, 971–976.

Peer-reviewed articles in other international journals (1.2)

Delpeche N., Soomere T., Lilover M.J. 2010. Diapycnal mixing and internal waves in the Saint John River Estuary, New Brunswick, Canada with a discussion relative to the Baltic Sea. *Estonian Journal of Engineering*, 16(2), 157–175.

Parnell K.E., **Delpeche N**., Didenkulova I., Dolphin T., Erm A., Kask A., Kelpšaite L., Kurennoy D., Quak E., Räämet A., Soomere T., Terentjeva A., Torsvik T., Zaitseva-Pärnaste I. 2008. Far-field vessel wakes in Tallinn Bay. *Estonian Journal of Engineering*, 14(4), 273–302.

Master thesis (2.3)

Delpeche N. 2006. *Observations of Advection and Turbulent Interfacial Mixing in the Saint John River Estuary, New Brunswick, Canada*. MSc thesis, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, Brunswick, Canada. New Brunswick: University of New Brunswick, 287 pp.

Articles published in other conference proceedings (3.4)

Delpeche N., Soomere T., Viikmäe B. 2010. Towards a quantification of areas of high and low risk of pollution in the Gulf of Finland, with the application to ecologically sensitive areas. In: *6th Study Conference on BALTEX,* 14–18 June 2010, Międzyzdroje, Island of Wolin, Poland. Conference Proceeedings, Geesthacht, Germany. International BALTEX Secretariat Publication, 46, 138–139.

Viikmäe B., Soomere T., **Delpeche N**., Meier H.E.M., Döös K. 2010. Utilizing Lagrangian trajectories for reducing environmental risks. In: *6th Study Conference on BALTEX:* 14–18 June 2010, Międzyzdroje, Island of Wolin, Poland. Conference Proceeedings, Geesthacht, Germany. International BALTEX Secretariat Publication, 46, 159–160.

Abstracts of conference presentations (5.2)

Delpeche-Ellmann N., Soomere T. 2014. Using current-driven patterns in the surface layer of the Gulf of Finland to predict the Marine Protected Areas at risk of pollution. In: *IUTAM Symposium on Complexity of Nonlinear Waves*, 8–12 September, Tallinn 2014. Book of Abstracts. Salupere A., Maugin G.A., eds. Institute of Cybernetics at Tallinn University of Technology, 35–36.

Delpeche-Ellmann N., Soomere T. 2013. Using Lagrangian models to assist in maritime management of coastal and Marine Protected Areas. In: *ICS2013 International Coastal Symposium 2013. Book of Abstracts*, Plymouth University, 8–12 April 2013, Russell P.E., Masselink G., eds. CERF, 2013, 65.

Viikmäe B., Soomere T., **Delpeche-Ellmann N**. 2011. Optimizing fairways for environmental management in the Baltic Sea. In: *3rd International Workshop on Modeling the Ocean*, 06–09 June 2011, Qingdao, China, Book of Abstracts, 66.

Viikmäe B., Soomere T., **Delpeche-Ellmann N**. 2011. Technology for finding optimum fairways for environmental management in the Baltic Sea. In: *International Conference on Fundamentals, Experiments, Numeric and Applications "Particles in turbulence"*, 16–18 March 2011, University of Potsdam, Germany. Book of Abstracts, 78–79.

Viikmäe B., Soomere T., **Delpeche-Ellmann N**. 2011. Optimizing fairways to reduce environmental risks in the Baltic Sea. In: *8th Baltic Sea Science Congress*

[BSSC], 22–26 August 2011, Saint Petersburg, Russia. Book of Abstract. Saint Petersburg, RSHU, 88.

Soomere T., **Delpeche N.,** Viikmäe B. 2010. Semipersistent patterns of transport in surface layers of the Gulf of Finland. In: *Joint Baltic Sea Research Programme BONUS Annual Conference*, 19–21 January 2010, Vilnius, Lithuania. Programme and abstracts, 32.

Soomere T., **Delpeche N**., Viikmäe B. 2010. The use of current-induced transport for coastal protection in the Gulf of Finland, the Baltic Sea. *Geophysical Research Abstracts*, 12, EGU 2010-6056.

Viidebaum M., Viikmäe B., **Delpeche N**. 2010. Sensitivity study of the Lagrangian trajectory model TRACMASS. In: *5th International Student Conference [on] Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region: Conference Proceedings*, October 6–8, 2010, Palanga, Lithuania. Klaipeda, Klaipeda University, 104–105.

Viikmäe B., Soomere T., **Delpeche N**. 2010. Potential of using Lagrangian trajectories for environmental management in the Gulf of Finland. In: *The 10th International Marine Geological Conference The Baltic Sea Geology* – 10, 24–28 August 2010, VSEGEI, Saint Petersburg, Russia. Abstracts Volume, Saint Petersburg, VSEGEI Press, 148–149.

Viikmäe B., Soomere T., **Delpeche N.** 2010. The use of Lagrangian trajectories for minimization of the risk of coastal pollution. In: *Joint Numerical Modelling Group 15th Biennial Conference 2010*, 10–12 May 2010, Delft, The Netherlands. Programme and Book of Abstracts, 7.

Viikmäe B., Isotamm R., **Delpeche N.** 2010. An empirical method to determine patterns of the risk of coastal pollution in the Gulf of Finland. In: *15th Biennial Conference Joint Numerical Sea Modelling Group JONSMOD*, 10–12 May 2010, Delft, The Netherlands. Programme and Book of Abstracts, 6.

Viikmäe B., Soomere T., **Delpeche N**. 2010. Using Lagrangian trajectories to find areas of reduced risk of coastal pollution in the Gulf of Finland. In: *5th International Student Conference [on] Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region*, 6–8 October 2010, Palanga, Lithuania. Conference Proceedings, Klaipeda, Klaipeda University, 106–108.

Delpeche N., Hughes Clarke J., Haigh S. 2009. The generation and dissipation of a solitonic wave that travels in the reverse direction to the flow in the Saint John River Estuary, New Brunswick, Canada. In: *International Conference on Complexity of Nonlinear Waves*, 5–7 October 2009, Tallinn, Estonia. Book of Abstracts, Berezovski A., Soomere T., eds. Tallinn: Tallinn University of Technology, 12.

Delpeche N., Isotamm R., Viikmäe B., Soomere T. 2009. Application of a trajectory model to select areas of high risk of pollution. In: *Coping with Uncertainty: A Multidisciplinary Research Conference on Risk Governance in the*

Baltic Sea Region, 15–17 November 2009, Stockholm, Sigtuna. Book of Abstracts, Södertörn University, 29.

Delpeche N., Soomere T. 2009. Internal waves and interfacial mixing in stratified environments. In: *BSSC 2009 [7th Baltic Sea Science Congress 2009]*, 17–21 August 2009, Tallinn, Estonia. Abstract Book, Tallinn University of Technology, 120.

Isotamm R., Viikmäe B., **Delpeche N**. 2009. An empirical method to determine a low-risk fairway in the Gulf of Finland. In: *Coping with Uncertainty: A Multidisciplinary Research Conference on Risk Governance in the Baltic Sea Region*, 15–17 November 2009, Stockholm, Sigtuna. Book of Abstracts, Södertörn University, 31.

Delpeche N., Clarke J.H., Haigh S., Ellmann A. 2008. Observations of internal waves in the Saint John River Estuary New Brunswick Canada (*European Geosciences Union General Assembly 2008*, 13–18 April 2008, Vienna Austria.) *Geophysical Research Abstracts*, EGU2008-A-11649.

Delpeche N., Clarke J.H., Haigh S. 2007. Observations of advection and turbulent interfacial mixing in the Saint John River estuary. In: *XXIVth General Assembly of International Union of Geodesy and Geophysics (IUGG)*, 2–13 July 2007, Perugia, Italy. IAPSO(P) Abstracts, 5921.

Delpeche N., Clarke J.H., Haigh S. 2007. A soliton wave packet that flows in the opposite direction to the flow in the Saint John River estuary. In: *XXIVth General Assembly of International Union of Geodesy and Geophysics (IUGG)*, 2–13 July 2007, Perugia, Italy. IAPSO(P) Abstracts, 5926.

Delpeche N., Clarke J.H. 2005. Identification of instabilities in the Saint John River Estuary. In: *Atlantic Canada Coastal and Estuarine Society (ACCESS) Annual General Meeting*, 4–5 May 2005, DFO – Gulf Fisheries Center, Moncton, Canada. Minutes and abstracts, 1.

Appendix B: Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Nicole Delpeche-Ellmann
Sünniaeg ja -koht	10.05.1978, Port of Spain, Trinidad
Aadress	Akadeemia tee 21, 12618 Tallinn
Telefon	(+372) 620 4167
e-mail	nicole.delpeche@gmail.com

2. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala / kraad)
New Brunswick'i ülikool, Fredericton, Canada	2006	Geodesy and Geomatics Engineering (teadusmagister / MSc.E)
Lääne-India Ülikool (University of the West Indies), Trinidad	2001	Surveying and Land Information (bakalaureus, BSc)

3. Keelteoskus

inglise	emakeel
eesti	kesktase
hispaania	kesktase

4. Täiendõpe

Õppimise aeg	Täiendõppe läbiviija nimetus
2009	*TRACMASS – A Lagrangian Trajectory code*, Tallinna Tehnikaülikool, Eesti
2005	Suvekool *Geophysical and Environmental Fluid Dynamics*, Cambridge, Inglismaa

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2008–tänaseni	Tallinna Tehnikaülikool, Küberneetika Instituut	teadur
2008–2010	FUGRO Netherlands, Holland	hüdrograaf
2008–2010	GEO S.T. Ltd., Eesti	hüdrograaf
2007	University of the West Indies (Lääne-India Ülikool), Trinidad	lektor (hüdrograafia, osakoormusega)
2006–2008	Coastal Dynamics, Trinidad	okeanoloog-hüdrograaf
2001–2004	FUGRO Trinidad, Trinidad	hüdrograaf-geodeet
2000	CANE & Associates, Trinidad	hüdrograafia praktikant

6. Teadustegevus

Avaldatud teadusartiklite ja konverentsiteeside ning peetud konverentsiettekannete loetelu on toodud ingliskeelse CV juures.

Paper A

Soomere T., **Delpeche N.,** Viikmäe B., Quak E, Meier H.E.M., Döös K. 2011. Patterns of current-induced transport in the surface layer of the Gulf of Finland. *Boreal Environment Research*, 16(Suppl. A), 49–63.

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Patterns of current-induced transport in the surface layer of the Gulf of Finland

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The Lagrangian trajectory model TRACMASS based on an Eulerian field of velocities (calculated using the Rossby Centre Ocean Model), combined with relevant statistical analysis, is used for the identification of transport patterns in the surface layer of the Gulf of Finland from 1987–1991. The analysis of velocity fields and properties of net and bulk transport (the distance between the start and end positions of a trajectory, and the total length of the trajectory, respectively) shows the presence of semi-persistent (with a typical lifetime from a week to a few months) features of the surface-layer dynamics, a part of which evidently cannot be extracted directly from the velocity fields. The modelled surface dynamics mostly hosts an Ekman-type drift and, in yearly average, contains an anticyclonic gyre occupying the western part of the gulf. The prevailing transport directions to the east and slightly to the south match the direction of the Ekman surface drift created by predominant south-western winds. The spatial patterns of the net transport substantially vary over different seasons. The most intense net transport along the coasts occurs in the western and central parts of the gulf but contains relatively intense largely meridional transport pathways in some seasons.

Introduction

The movement of the marine surface layer and the accompanying drift of adverse impacts (e.g. oil spills, lost containers, or ships that cannot be steered anymore) in this layer are jointly governed by three factors: currents, wind and waves (Vandenbulcke *et al*. 2009). The transport induced by the latter two in semi-enclosed basins mostly (albeit not perfectly) mimics the behaviour of the wind patterns. The situation for the current-induced transport is fundamentally different. The instantaneous field of currents is an integral reaction of water masses to a variety of forcing factors mostly distributed over large sea areas but partially concentrated in river mouths. It is a highly nontrivial, anisotropic, inhomogeneous, non-stationary system with large spatial variation, even for practically stationary wind events. In semi-enclosed sea areas such as the Baltic Sea this system is frequently even in antiphase with wave- and wind-induced transport features (e.g. Andrejev *et al*. 2004a, Gästgifvars *et al*. 2006). For the above-mentioned reasons, drift prediction remains a very challenging task and even small errors in its estimates can drastically change the calculated particle trajectories (Griffa *et al*. 2004).

Marine science has only recently reached the situation where the development of mathematical models, the accuracy and reliability of circulation modelling, the computational facilities and the quality of information about forcing factors allow addressing the problem of drift prediction in a dependable way. Even though most of the contributions to such drift can be forecast by deterministic models to some extent, there is not yet a deterministic method to combine them in order to reproduce the floating object drift (Vandenbulcke *et al*. 2009). In particular, the inadequate representation of current patterns is one of the main reasons why the forecast of current-induced transport is much less reliable as compared with the description of wind- and wave-induced transport.

There are several ways to reduce the uncertainties in the current-induced drift patterns by means of statistical approaches such as the use of multiple runs of the same model or the use of model (super-)ensembles (Vandenbulcke *et al*. 2009). We focus here on a complementary technique to help lowering environmental risks in a marine environment, based on the optional presence of (statistically) semi-persistent current patterns. Such patterns, with a typical lifetime from a few weeks up to a few months have been recently identified for different areas of the Baltic Sea (Lehmann *et al*. 2002, Andrejev *et al*. 2004b, Meier 2007, Osinski and Piechura 2009). The existence of such patterns eventually has a high potential for the rapid and systematic transport of both water masses and adverse impacts such as nutrients, toxic substances, or oil pollution between specific sea areas. Their smart use can become one feasible way towards a reduction of anthropogenic impacts to vulnerable areas by placing human activities (such as marine traffic) in specific regions (areas of reduced risk), from which the transport of pollution to vulnerable or high-cost areas is unlikely (Soomere and Quak 2007).

When transporting dangerous goods on land by truck, there is typically an intricate system of permissions one has to obtain, following all sorts of regulations specifying when and especially on which route the transport has to be carried out to minimize risks in case of an accident. For marine transport rationales how to impose traffic routes to reduce environmental risks, for example of an oil spill reaching a vulnerable coastline, hardly exist at all. The Gulf of Finland is an area with extremely heavy ship traffic and thus a high risk of environmental damage caused by accidents. Consequently a careful investigation of drift patterns in this area can serve as a prime test case to develop an approach how to impose specific travel routes that minimize the risks to the coastlines. This does not mean to produce yet another operational model to assist rescue teams after an accident has happened but rather to identify beforehand regions where it is statistically safer to travel, by maximizing, for example, the time before a potential spill hits vulnerable coast, and thus reducing the impact.

Systematic identification of such areas generally presumes inverse tracking of the pollution propagation. A straightforward solution to this problem is not possible and no universal solution method exists. A feasible way to tackle it is to address the inverse problem with methods relying on the reanalysis of a large pool of numerically simulated transport patterns. Doing so eventually allows identifying the presence and basic (statistical) features of useful semi-persistent current patterns that may be used later for practical purposes.

Following this line of thinking, we focus on the analysis of the results of long-term, high-resolution simulations of the Baltic Sea circulation, with an emphasis on the Gulf of Finland. The main parameters of the models and the TRACMASS method, used for the extraction of information from the three-dimensional (3D) fields of currents, are described next, followed by discussion of the key properties of the current fields such as the average speed and long-term average Eulerian flow patterns. Finally, we analyse first results for semi-persistent Lagrangian transport patterns in the surface layer and certain implicitly obtained characteristics of the circulation such as an estimate for the typical size of the largest eddies, which implicitly characterize the ability of the model in use to represent the basic structure of currents in the area in question.

Circulation and trajectory models

The analysis below is mostly based upon a large ensemble of Lagrangian transport paths of water (and pollution) particles in a marine environment, for which velocity fields have been calculated based on the Eulerian approach. This study employs 3D current velocity calculated using the Rossby Centre Ocean circulation model (RCO) for the entire Baltic Sea. The horizontal resolution of the model grid is 2 × 2 nautical miles and the model uses 41 vertical levels in z-coordinates (Meier *et al*. 2003, Meier 2007). The thickness of the vertical layers varies between 3 m close to the surface and 12 m in 250 m depth. The uppermost layer, used in the analysis below, corresponds to water masses at depths 0–3 m. A time step splitting scheme is used in the RCO, with the choice of 150 s for the baroclinic and 15 s for the barotropic timestep. The output is stored once in six hours.

The RCO is a Bryan-Cox-Semtner primitive equation circulation model following Webb *et al*. (1997) with a free surface (Killworth *et al*. 1991) and open boundary conditions (Stevens 1991) in the northern Kattegat. It is coupled to a Hibler-type sea ice model (Hibler 1979) with elastic-viscous-plastic rheology (Hunke and Dukowicz 1997). Subgrid-scale mixing is parameterized using a turbulence closure scheme of the k-ε type with flux boundary conditions to include the effect of a turbulence-enhanced layer due to breaking surface gravity waves (Meier 2001). A flux-corrected, monotonicity-preserving transport (FCT) scheme following Gerdes *et al*. (1991) is embedded. No explicit horizontal diffusion is applied.

The model is forced with 10 m wind, 2 m air temperature, 2 m specific humidity, precipitation, total cloudiness and sea level pressure fields from a regionalization of the ERA-40 re-analysis over Europe using a regional atmosphere model with a horizontal resolution of 25 km during 1961–2007 (Samuelsson *et al*. 2011). The atmospheric forcing fields are extended beyond the ERA-40 period with analysis data from the operational ECMWF model (Anderson *et al*. 2006). As the atmospheric model tends to underestimate wind speed extremes, the wind is adjusted using simulated gustiness to improve the wind statistics (Samuelsson *et al*. 2011). Standard bulk formulae are used to calculate the air-sea fluxes over open water and over sea ice. For further details of the model set-up and an extensive validation of model output the reader is referred to (Meier 2001, Meier *et al*. 2003, Meier 2007).

From the variety of outputs of the RCO model, we only consider the velocity fields. The trajectories over different time intervals are computed with the TRACMASS model (Blanke and Raynard 1997, Döös 1995, de Vries and Döös 2001) from the RCO velocity fields off-line, i.e. after the circulation model has been integrated and the velocity fields have been stored. This approach has been applied to many different circulation models both for the ocean and the atmosphere (Fig. 1).

The trajectories are calculated based on a linear interpolation of the velocity field in each point of a particular grid cell with an adjustable temporal resolution that can be made basically equivalent to that of the RCO model. First the source point where the pollution may have been started (the initial position and depth of the trajectories) and the starting and ending time of propagation are specified. As we are specifically interested in what happens over several days, the coordinates of the instantaneous trajectory points are saved once in six hours. Doing so does not affect calculated statistics although it may cause some side-effects such as trajectories seemingly crossing some peninsula or islands (Fig. 2).

The resulting trajectories evidently will depend to some extent on the time interval of saving the circulation data and on the temporal resolution of the trajectory calculation scheme. In extreme cases, the resulting differences may lead to extremely large divergence of initially close trajectories. The experience with the TRACMASS code, however, reveals that the spreading of the calculated trajectories is normally much smaller than spreading of real drifters owing to the effect of sub-grid turbulence (Jönsson *et al*. 2004, Engqvist *et al*. 2006, Döös and Engqvist 2007, Döös *et al*. 2008). In other words, initially close trajectories have an overly tendency to stay close. This stability implicitly suggests that the potential impact of the time step of saving the circulation data or the similar effect of the choice of the temporal resolution

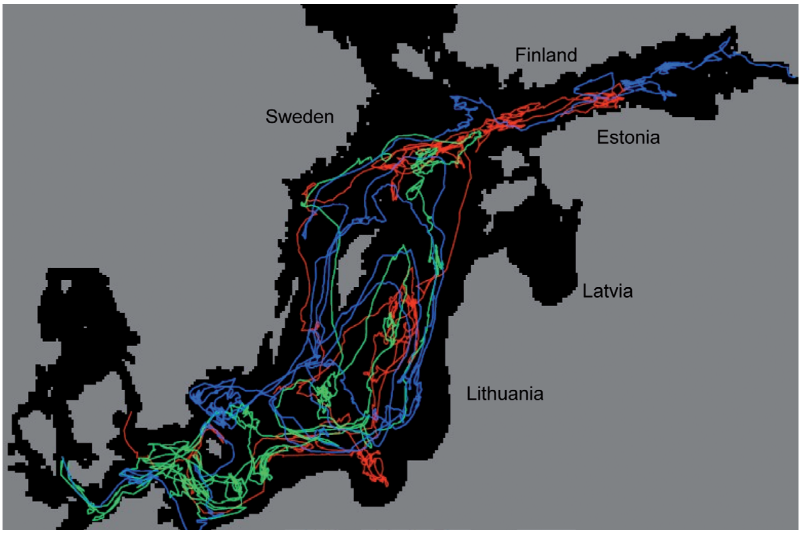

Fig. 1. The complexity of trajectories of water particles calculated using the TRACMASS code and the RCO model data in the Baltic Sea entering the sea through Öresund (red), Great Belt (green) and from River Neva through the Gulf of Finland (blue).

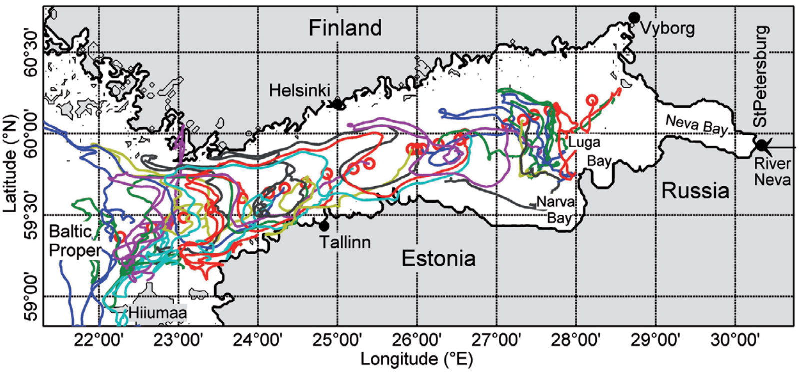

Fig. 2. The complexity of trajectories of water particles over 60 days calculated using the TRACMASS code and the RCO model data in the Gulf of Finland for 1987. Red circles show the starting points of the trajectories. The colours for trajectories are only used for distinguishing trajectories starting from different points.

in trajectory reconstruction is minor in terms of statistics of a large number of trajectories.

Properties of currents

The overall character of the average current field and its persistency are well known for the Gulf of Finland. A traditional but idealized view of the mean circulation of this basin, identified nearly a century ago, is that it is cyclonic with an average speed of a few cm s^{-1} (*see* Alenius *et al*. 1998, Soomere *et al*. 2008 and references therein). These features have been adequately reproduced in numerical models (for example, Lehmann *et al*. 2002) that have also indicated several non-trivial specific properties of the flow, such as the presence of numerous meso-scale eddies, the high persistency of the outflow in a subsurface layer and the predominance of the Ekman surface transport to the south-east (Andrejev *et al*. 2004a, 2004b).

For this study, using the current fields and large pools of trajectories calculated with the TRACMASS code, several parameters such as the average Eulerian velocities and circulation scheme, maps of the spatial distributions of Lagrangian net and bulk transport, and ratio of these two were estimated. The net transport is defined here as the distance between the start and end positions of a trajectory and the bulk transport reflects the total length of the trajectory. The analysis of trajectories allows the identification and visualization of several properties of surface currents that cannot be extracted directly from the current fields. Comparison of the average net transport calculated over certain time windows t_w with the average velocity fields allows, for example, identifying the areas that frequently host strong flow (the high values of velocity which frequently persist over time intervals ≥ t_w) even if the flow direction varies over longer time intervals.

Earlier attempts to identify semi-persistent current patterns in the Gulf of Finland have indicated their clear presence in the subsurface layer (depths 2.5–7.5 m, Andrejev *et al*. 2004a, 2004b). The persistence of currents in the uppermost layer, defined in terms of the conservation of the direction of the flow over five years, was found to be very small. This, however, does not exclude the existence of semi-persistent transport pathways in which the velocity vector undergoes variations of its direction (for example, coastal currents with alternating directions).

As the uppermost layer is usually responsible for the most intense transport of various substances and also possesses the largest velocities of the water column, the identification of such surface patterns has the largest practical importance. For this reason the calculations for this study were made for the surface layer covering depths of 0–3 m in the Gulf of Finland and the adjacent area of the northern Baltic Proper (Fig. 2) for the period of 1987–1991. The choice of this time window and the surface layer allows matching the outcome with similar results of the earlier high-resolution simulations of dynamics of the Gulf of Finland for the upper surface layer covering depths 0–2.5 m (Andrejev *et al*. 2004a, 2004b).

The overall purely kinematic properties of the current field such as long-term transport speed (defined as the length of the average velocity vector for each point) of 0.01–0.07 m s^{-1} (Fig. 3) match well both the measured and earlier numerically simulated average values (Alenius *et al*. 1998, Andrejev *et al*. 2004a, 2004b). The average speed of water particles for the five-year

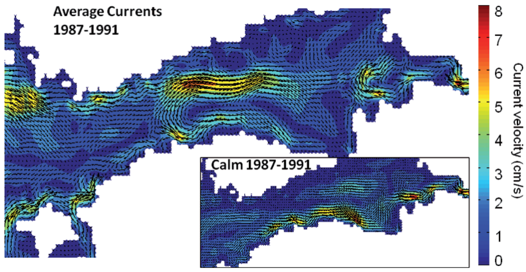

Fig. 3. Average velocity field over the entire period of 1987–1991 and during calm seasons (May–August, inserted panel) over the same interval in the Gulf of Finland. Both colour code and lengths of vectors show current velocity (cm s^{-1}).

period of 1987–1991 is 0.071 m s^{-1}. In order to account for the seasonality of the Baltic Sea dynamics, we divided the year into the following intervals: the calm period (May–August), the transition period from calm to windy (August–October), the windy period (October–March) and the transition period from windy to calm (March–May) (Räämet and Soomere, 2010). The highest speeds occur in the windy season when the average speed ranges from 0.074 to 0.097 m s^{-1} (Table 1). In the calm season the average speeds are much smaller (usually 0.03–0.05 m s^{-1}) but in some years may reach 0.08 m s^{-1}.

The circulation patterns averaged over the years 1987–1991 (Fig. 3) show that the flow in the surface layer of the Gulf of Finland has a limited similarity with the classical cyclonic circulation scheme of water masses in this basin. There is, on average, a relatively intense inflow at both the northern and southern coasts at the entrance to the Gulf of Finland (Fig. 3). Their presence (separated by an area with almost vanishing east-west velocity) is well known from simulations with different models (Andrejev *et al*. 2004a).

Table 1. Average transport speed and average speed of water particles (m s^{-1}) over the entire surface layer in the Gulf of Finland for calendar years and for the windy season (October–March of the subsequent year).

		1987	1988	1989	1990	1991
Transport speed	Annual mean	0.018	0.024	0.028	0.030	0.024
	Windy season	0.035	0.056	0.041	0.027	0.042
Average speed	Annual mean	0.056	0.074	0.075	0.080	0.068
	Windy season	0.074	0.097	0.082	0.080	0.084

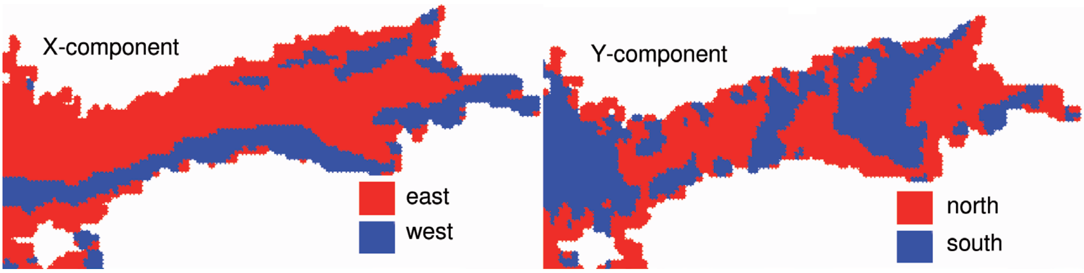

Fig. 4. The predominant directions of the *x*- and *y*-components for circulation of the Gulf of Finland for 1987–1991.

Differently from the results of earlier studies, in the 5-year average velocity field a large elongated in the east-west direction *anticyclonic* gyre covers a large part of the central area of the gulf. The inflowing current at the northern coast deviates from the coastal area after passing the narrowest part of the gulf and merges with the northern branch of this cell. The resulting wide band of relatively intense flow to the west continues until Narva Bay. The southern branch of this gyre is a narrow band of eastward coastal current along the Estonian coast.

This circulation pattern, albeit intriguing in the Gulf of Finland conditions, is not unique in water bodies of similar size and similarly (obliquely) oriented with respect to predominant winds such as the Great Lakes. While large-scale circulation patterns in the Great Lakes tend to be more cyclonic when the thermocline deepens and density effects become more important, an anticyclonic gyre was identified, for example, in Lake Michigan, sometimes occupying the entire southern basin of this lake (Beletsky *et al*. 2006). This pattern apparently dominates when the upper mixed layer is very thin. It is somewhat surprising and interesting that it becomes a dominant feature in the Gulf of Finland for 1987–1991. It is also important to notice that this gyre only becomes evident when the velocity field is averaged over a very long time and thus not necessarily reflects transport patters over a few weeks or months as discussed below.

The average of the *x*-component of the surface current field is directed to the east in most of the gulf (Fig. 4). The eastward current dominates, on average, in almost the entire northern part of the gulf (except for some small areas in the widest part of the gulf), whereas the current is directed to the west only in a narrow band at the southern coast. As a result, an overall domination of transport to the east is likely as suggested by Andrejev *et al*. (2004a, 2004b). For the interior of the gulf (eastwards from the latitude 24°E), its average speed over 1987–1991 is 0.0078 m s^{-1}.

The comparison of this spatial pattern of surface currents with the above-discussed overall features of the Gulf of Finland dynamics suggests that the motions in the surface layer are, in average, largely decoupled from the dynamics of the underlying water masses in the sense that the long-term circulation patterns in the surface and subsurface layer are quite different. Although the vertical velocity shear may be quite limited for most of time, its regular presence may give rise to strong vertical velocity gradients between the average motions in the uppermost and the subsurface layer. Such a jump in velocity is clearly visible from the results of earlier numerical simulations (for example, Andrejev *et al*. 2004a: fig. 12).

The described decoupling is evidently caused by the impact of predominant moderate and strong winds from the south-west (Soomere and Keevallik 2001, 2003). These winds create Ekman transport to the (south-)east and also force the nearshore surface current to the east near the Finnish coast. The resulting transport is directed oppositely to the overall cyclonic circulation in the northern part of the gulf. The water masses forced to move to the east subsequently cause the counter-flow along the southern coast of the Gulf of Finland. As the majority of the surface flow appears to be directed towards an eastwardly direction, a compensating flow should exist either in the subsurface or in deeper layers (Andrejev *et al*. 2004a, 2004b).

The described feature is possibly connected with the phenomenon of the intense pumping

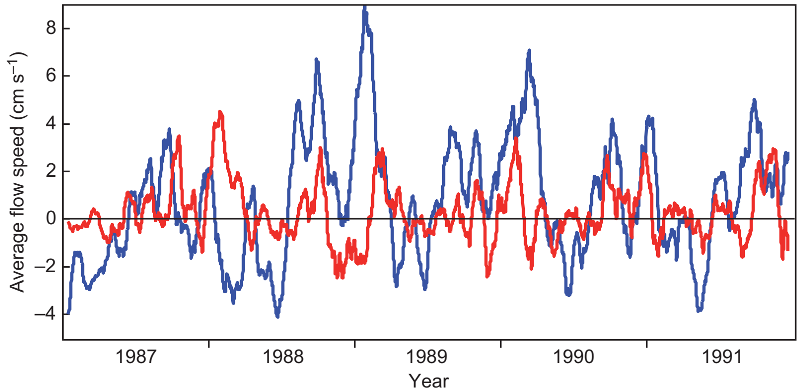

Fig. 5. Time series of the running average over 30 days of velocity components (blue: east–west component, positive to the east; red: north–south component, positive to the north) averaged over all sea grid points of the interior of the Gulf of Finland (eastwards from the latitude 24°E).

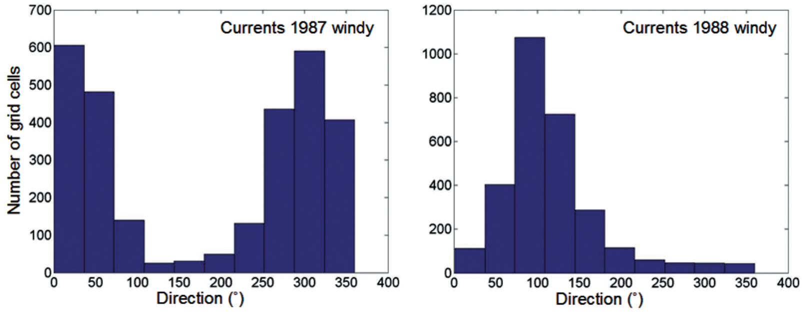

Fig. 6. The distribution of orientations of the average velocity vectors over the windy season in 1987 and 1988 in the sea grid points in the Gulf of Finland. Directions are counted clockwise from the north.

of water into the Gulf of Finland during strong westerly winds that may lead to the export of large volumes of saltier waters in the deeper layers of the gulf and to an almost entire loss of stratification at the gulf entrance (Elken *et al*. 2003). It is well known that the standard estuarine circulation could be reversed by appropriate winds, causing landward flow in the surface layer and seaward flow in the lower layer (Alvarez-Salgado *et al*. 2000, Gibbs *et al*. 2000). Whereas the standard circulation apparently exists for most of the wind directions in the Gulf of Finland, long-lasting, strong (south-)western winds may push a large amount of fresher surface water into the gulf. The excess volume of water increases the hydrostatic pressure in the gulf and may lead to a gradual export of the salt wedge in the bottom layer of the gulf (Elken *et al*. 2006). A reversal may occur if south-westerly wind speeds exceed as low a threshold for the mean wind speed as 4–5.5 m s^{-1} (Elken *et al*. 2003).

The spatial pattern of the average of the north-south component of the surface currents (Fig. 4) shows a predominant direction to the south at the entrance to the gulf and at the longitudes of Narva Bay where the average flow has clear similarity with the one calculated by (Andrejev *et al*. 2004a). A key consequence of this property is that, on average, the north-western coast of Estonia and the coasts of Narva Bay apparently are more frequently hit by adverse impacts transported by surface currents than other sections of the southern coast of the gulf.

An important feature is the large interannual variation of the prevailing transport direction within particular seasons. The typical monthly mean values of the average meridional flow component are generally of the same magnitude as the east–west component but show much more pronounced variability. The flow is, in average, usually to the south in windy seasons with relatively intense currents such as 1988/89 or 1989/1990, whereas in seasons with low currents (such as 1987 or 1990–1991, Table 1) the motion is directed to the north (Figs. 5 and 6). Although the overall average meridional flow component in the interior of the gulf is to the north, the average speed of this flow is very small, only 0.0026 m s^{-1}, and the simulations in

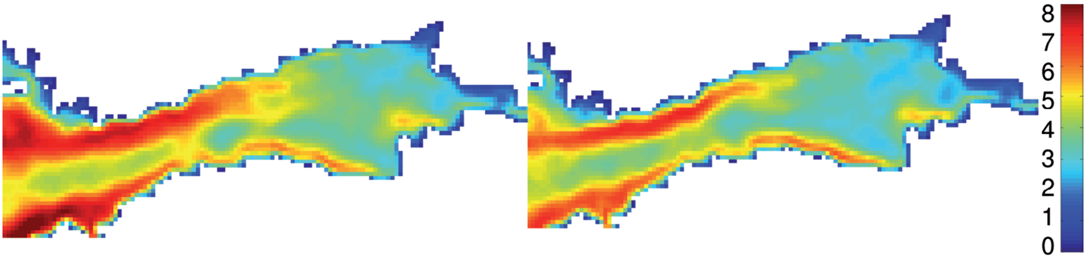

Fig. 7. Average net transport speed (cm s^{-1}) for 1987–1991 (left-hand side panel) and for 1987 (right-hand side panel).

question, thus, reveal no predominant direction of the meridional water transport. A substantial additional contribution to the southwards-directed transport may stem from the property of south-western winds to turn somewhat more to the west in the interior of the Gulf of Finland (Savijärvi *et al*. 2005, Keevallik and Soomere 2010). This feature apparently is not resolved in the forcing fields of the RCO model.

Patterns of net and bulk transport

A straightforward extension of the measure of the overall persistency of the flow used in (Andrejev *et al*. 2004a, 2004b) towards identification of flow patterns that persist over certain intermediate time scales consists in using the above-discussed definition of the net transport over certain time windows t_w. The net transport and its velocity within each window were calculated as the distance between the start and end positions of the trajectories simulated by the TRACMASS code. The result characterises the flow persistency in terms of Lagrangian velocity during the time window. In the limiting case t_w = 5 years it is equivalent to the persistency of (Andrejev *et al*. 2004a) in a Lagrangian framework. By varying the length of the time window and shifting it over the circulation data is it possible to identify patterns persisting over different time intervals and existing, for example, in different seasons.

In this study we mostly use a time window of 4 days that accounts for the internal circulation of most of the synoptic-scale eddies in the Gulf of Finland (*see* the relevant discussion below) and is about one half of the typical time of hitting the coast for tracers released in the surface layer of this water body (Soomere *et al*. 2010). One tracer was inserted in the centre of each grid cell. The first calculation was launched at 00:00 on 01 January 1987 for t_w = 4 days and was repeated with the same position of the tracers but with a time lag of 6 hours, 12 hours, 18 hours, etc., until the end of 1991. The average net transport and its velocity for each sea point were then calculated as an average over the entire pool of the results for 4-day sections and over selected time intervals (for example, over different seasons).

The spatial patterns of the resulting maps of the net and bulk transport speed and their ratio represent the ability of the surface flow in the Gulf of Finland to transport potential adverse impacts over such 4-day sections. They first highlight the areas where the flow (in terms of Lagrangian transport) may be fast or slow on average. Elongated areas of fast net transport evidently indicate pathways of fast movements of water masses and associated tracers. The map for the average net transport speed for the entire 5-year period from 1987–1991 (Fig. 7) shows that the fastest moving net flow on the surface layer occurs as a wide inflow band near the northern coast at the entrance and in the entire western part of the Gulf of Finland. There is also a limited area of eastwards flow near the southern coast of the gulf. The only more or less persistent net flow to the west exists as a coastal current along the north-eastern coast of Estonia.

These results mirror to some extent the above-discussed average circulation pattern: a persistent inflow at the northern coast of the gulf that merges with the northern branch of a large anticyclonic gyre in the interior of the gulf. It is characteristic that the match of the average (Eul-

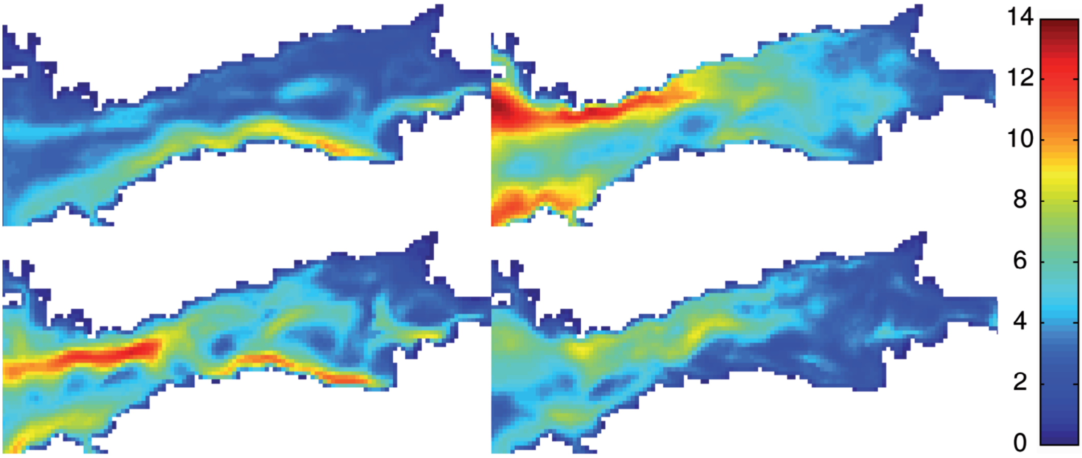

Fig. 8. Average net transport speed (cm s^{-1}) during the calm season of 1988 (upper left-hand side), windy period of 1988/1989 (upper right-hand side), windy to calm season of 1988 (lower left-hand side) and calm to windy season of 1989 (lower right-hand side).

erian) circulation and the intensity of (Lagrangian) net transport is only partial. For example, the maps of net transport speed indicate a clear band of inflow along the north-western coast of Estonia (Fig. 7), whereas this feature is very weak in the average current field (Fig. 3).

Differently from the above-discussed strong interannual variability of the average current patterns, the patterns for the average net transport speed are very similar to each other for all years in question. This feature suggests that the major pathways of fast Lagrangian transport are relatively stable although the patterns of Eulerian currents may vary. They all contain two bands of transport into the gulf in its western basin and characteristic areas of weak net transport in the very centre of the basin and in its easternmost part. A narrow band of westward transport near the southern coast of the gulf is only evident in selected years such as 1987 (Fig. 7).

An area of relatively intense net transport located to the west of the island of Hiiumaa apparently reflects the large-scale circulation of the northern Baltic Proper. It not necessarily enters the gulf but continues to the north from Hiiumaa and/or forms the famous semi-persistent front at the entrance to the gulf (Kononen *et al*. 1996).

The patterns of the average net transport speed for different seasons, especially for the windy and calm periods, are quite different. This feature may reflect the domination of subsurface currents over the impact of wind in low wind conditions as noted by (Gästgifvars *et al*. 2006). During calm seasons the band of intense net transport is usually located along the entire southern coast of the Gulf of Finland, whereas during windy seasons a similar band near the north-western coast is the most prominent. The transitional seasons frequently show combinations of fast transport bands near both north-western and south-eastern coasts of the gulf in spring, whereas relatively fast net transport is optionally observed also in the central area of the gulf during late summer and early autumn (Fig. 8).

The obvious differences in the spatial patterns of the largest average values for the Eulerian speed (Fig. 3) and for the net transport (Fig. 7) are the most pronounced in analogous patterns for the windy seasons, for which usually the most intense transport takes place.

A highly interesting feature of the net transport patterns is the presence of areas of relatively fast cross-gulf transport during a large number of transitional seasons (Fig. 9). The presence of such areas that are elongated in the meridional direction in both spring and autumn transitional seasons suggests that rapid pathways of meridional transport (that is, across the axis of the Gulf of Finland) of surface water masses frequently exist during these seasons. Comparison of such

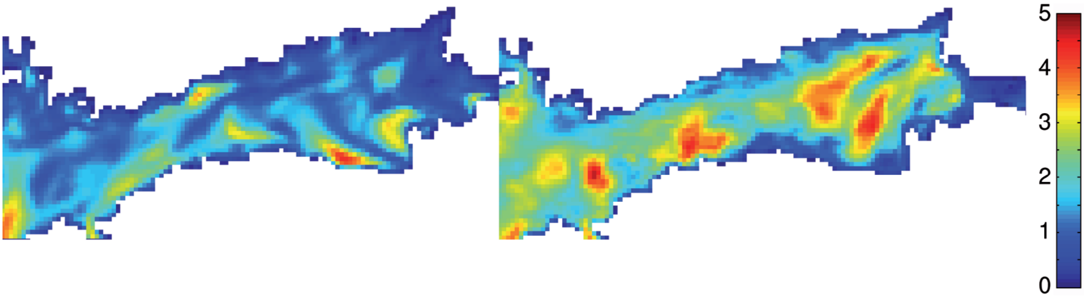

Fig. 9. The average *y*-component of net transport velocity (cm s^{-1}) for the windy to calm season of 1987 (left panel) and for calm to windy season of 1988 (right panel).

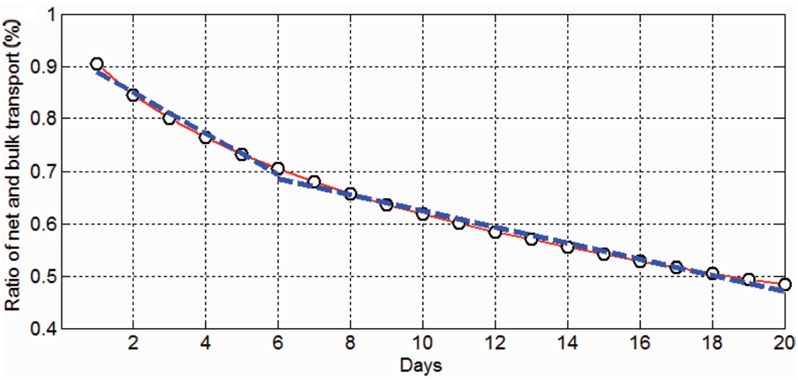

Fig. 10. Dependence of the average ratio of net to bulk transport on the length of the time window (days) for 1992 over the entire Gulf of Finland (3131 grid points, one tracer released into each grid centre; the calculations restarted after each 6 hours). Dashed lines show linear trends for days 1–5 and 6–30, respectively.

areas with the velocity data shows that the transport direction may be variable. For example, in 1987 it was mostly to the north whilst in 1988 it was to the south. The typical speed of net transport in such pathways is typically less than a half of the similar speed for meridional transport and reaches up to 0.05 m s^{-1}.

Such areas of relatively intense cross-basin transport evidently mirror the presence of certain well-known meso-scale features. The elongated areas that are largely aligned with the axis of the gulf may reflect regions where the coastal current usually separates from the coastal slope. Larger patches of intense north-south net transport may reflect either the position of frequent contact areas between slowly drifting meso-scale eddies or the typical positions of upwelling filaments.

The typical values of the net transport speed are close to average speed of water particles calculated componentwise over the entire Gulf of Finland and called transport speed (*see* Table 1). The average transport speed for the five-year period of 1987–1991 is 0.033 m s^{-1}, that is, about one half of the relevant average speed of water particles. The highest transport speeds occur, as expected, in the windy season when the average speed ranges from 0.027 to 0.056 m s^{-1} (Table 1). In the calm season the average transport speed is much smaller, usually 0.01–0.02 m s^{-1}.

The bulk transport was calculated as the total distance travelled by the water particle along the trajectory (that is, the length of the entire trajectory). The ratio of net to bulk transport in terms of distances is obviously close to 1 in the initial phase of propagation and decreases starting from the time instant when the trajectories start to bend (Fig. 10). Such bending may occur owing to a meandering of the currents, the presence of meso-scale (synoptic) vortices or inertial oscillations, etc. The temporal behaviour and the long-term limit of this quantity implicitly characterize the structure of the flow field. For example, for jet currents this quantity remains close to 1. It decreases infinitesimally for particles in the core of persistent eddies in a fixed location and tends to a certain limiting value for a field of gradually translating eddies.

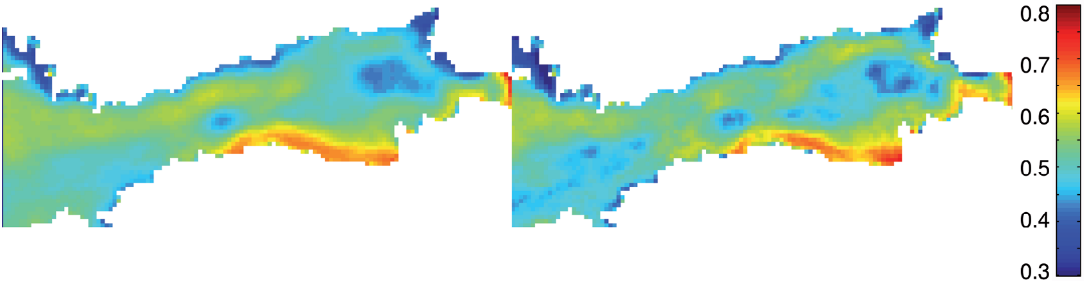

Fig. 11. Annual ratio of net to bulk transport for the five-year period of 1987–1991 (left-hand side panel) and for 1991 (right-hand side panel).

The analysis of this ratio allows to some extent to estimate the ability of the circulation model to reproduce the presence of meso-scale (synoptic-scale) eddies in the sea area in question and their impact on the structure of the surface transport. In sea areas where synoptic eddies play a minor role the average ratio of net/bulk transport is expected to decrease gradually at a slow pace. Although there are only a few direct measurements of such eddies in the Gulf of Finland (Soomere *et al*. 2008), they are generally thought to have an important (albeit not decisive) role in the system of currents. In such situations the average ratio of net and bulk transport is expected to decrease rapidly at first, within a few days, reflecting eddy rotation. After a certain time, however, the translation of eddies would play a role, and the rate of attenuation of this ratio should become much smaller. The bending point of the relevant time dependence roughly indicates the typical turnover time of the predominant synoptic-scale.

A relatively large change in the slope of the decrease of the ratio in question occurs for about 3–5 days in the Gulf of Finland (Fig. 10), possibly indicating the turnover time of the larger eddies. The average speed of currents in the surface layer of the gulf is 0.071 m s^{-1}. The maximum speed in the eddy cores is usually much larger, roughly about twice as high as the average speed, say, about 0.15–0.20 m s^{-1}. The perimeter of the core of such frequently occurring relatively large synoptic eddies in the Gulf of Finland, therefore, is about 20–30 km and their radius (understood as the distance from their centres to the area with the largest velocities) is about 4–6 km. This estimate matches well the estimates of the baroclinic Rossby radius for different areas of this water body (2–5 km, Alenius *et al*. 2003). This feature allows the conclusion that the RCO model represents the basic features of meso-scale dynamics of the Gulf of Finland correctly in the sense that it resolves the dynamics of the most typical examples of mesoscale eddies.

The spatial distribution of the ratio of net and bulk transport allows in addition distinguishing the areas where the current may be unidirectional from regions where it may have rapidly changing direction. Such distributions were calculated similarly to the distributions of net transport speed but only in terms of the relevant distances. As the time scale in which the role of bulk transport is properly resolved is a few turnover times of the typical mesoscale eddies, in this analysis we use time windows with the length of t_w = 15 days. The average ratio in question has a value between 0 and 1 and serves as a measure of the variability of the current direction for each sea point: it is close to 1 when the current is unidirectional and close to zero for eddy-dominated dynamics. Therefore, this quantity is also similar to the measure of persistency used in (Andrejev *et al*. 2004a, 2004b) but allowing the identification of Lagrangian transport patterns that persist over the length of the time window. Differently from the net transport (that does characterise rapid pathways but may include substantial excursions of the flow owing to, for example, inertial oscillations or mesoscale dynamics), the ratio of the net to bulk transport additionally shows how straight the motions of the tracer are.

The five-year mean ratio (Fig. 11) has a qualitative distribution similar to that of the flow persistency in (Andrejev *et al*. 2004b). Apart

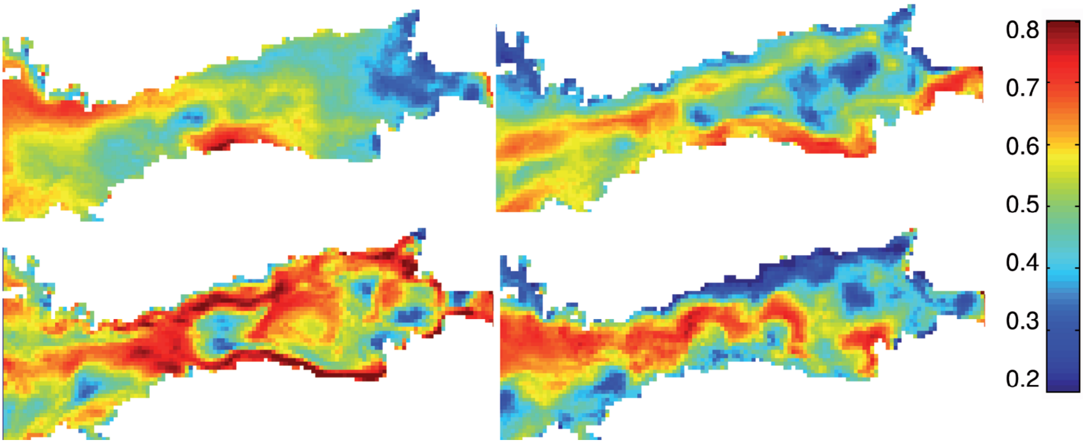

Fig. 12. Maps of the ratio of average net to bulk transport during the windy season of 1988/1989 (upper left-hand side), calm season in 1990 (upper right-hand side), windy to calm season in 1988 (lower left-hand side) and calm to windy season in 1989 (lower right-hand side).

from the obviously high values in Neva Bay evidently driven by the voluminous runoff of the River Neva, the map reveals two large bands of moderate and relatively high values of this ratio, more or less corresponding to areas with relatively high flow persistency. The largest values (in a range between 0.4 and 0.7) occur along the Estonian coast from Tallinn to Narva Bay. Somewhat smaller values, mostly below 0.5, occur in a wide band in the central and western Gulf of Finland slightly to the north from the axis of the gulf. The maps have features similar to the analogous distribution of the net transport (Fig. 6) but, for example, the area of rapid net transport at the southern coast of the entrance to the Gulf of Finland eventually contains a substantial amount of mesoscale oscillations.

The ratio in question shows, similarly to the net transport, very limited interannual variability in both the location of its maxima (Fig. 11) and the range of the largest values (0.7–0.8 for the area near the Estonian coast; about 0.6 near the Finnish coast in the western part of the gulf). Only in 1991 the area of relatively high values of the ratio (about 0.6) extends to Vyborg and Neva Bay along the northern coast of the gulf. The relatively poor similarity of maps in Fig. 11 with those of average velocities (Fig. 3) once more confirms that Lagrangian transport patterns not necessarily match the average of Eulerian currents.

Similarly to the net transport, the ratio of net and bulk transport exhibits substantial spatial variations during different seasons (Fig. 12). The maps of this ratio for windy and calm periods qualitatively resemble the similar map for the 5-year average of this quantity but show somewhat larger contrast of the underlying distributions. The area of high values in calm seasons (Fig. 12) matches the location of the area of overall high persistency of motions in the subsurface layer in (Andrejev *et al*. 2004a), suggesting that in low wind conditions the subsurface dynamics predominates also in the surface layer.

An interesting but also not completely unexpected feature is that small values occur for Neva Bay during windy seasons and large values during calm seasons. A somewhat surprising feature is the drastic interannual variation and the presence of rich internal structure of the area with maximum values of this ratio for different transitional seasons (Fig. 11). During these two-month sections several elongated across the gulf axis areas of high values of this quantity are evident in the central and eastern parts of the gulf. They may represent typical locations of long upwelling filaments or zones of large meridional velocities of basin-scale seasonal circulation patterns. Their nature, however, needs further research. It is also important to notice that there exists an extremely persistent area of low values of the ratio in question to the east of the Tallinn–Helsinki line.

Summary and discussion

The above analysis of the velocity fields and properties of transport created by the flow in the surface layer in the Gulf of Finland and a small adjacent section of the northern Baltic Proper has indicated the presence of several semi-persistent structures of the surface-layer dynamics in these water bodies, some of which evidently cannot be extracted from the straightforward analysis of the velocity fields. In order to visualize transport patterns and potential pathways, we have investigated the surface layer dynamics with the use of a pool of Lagrangian trajectories covering several years. The goal was to evaluate the basic parameters of current-driven transport such as the average net transport rate in different directions and the ratio of average net and bulk transport (equivalently, the ratio of the final displacement and the length of the trajectories). While several properties of the transport in question are intuitively obvious and/or can be consistently explained in terms of the existing knowledge, some features are counter-intuitive and further studies are necessary in order to understand their nature and role in the transport of adverse impact in the surface layer.

The model in use, although with a resolution somewhat lower than the one used in the most contemporary numerical simulations of the Gulf of Finland, reproduces well the basic features of the dynamics of the surface layer such as the average flow velocities, the spatial patterns of inflow and outflow through the entrance of the Gulf of Finland and the overall weak coupling of the surface dynamics with the flow in deeper layers (Lehmann *et al.* 2002, Andrejev *et al.* 2004a, 2004b). The prevailing direction to the east of the long-term average flow field in the Gulf of Finland suggests that extensive pumping of water into the gulf (and accompanying loss of stratification at its entrance) may happen quite frequently. An intriguing feature, not evident in earlier studies of the Gulf of Finland (but still noticed in similar studies into the Great Lakes circulation (Beletsky *et al.* 2006)) is the presence of a slow anticyclonic gyre in the relatively wide eastern part of the gulf.

The prevailing surface transport direction to the east and to the south over certain time intervals matches well the distribution of the frequency of upwellings in the Gulf of Finland (Myrberg and Andrejev 2003). It is intuitively clear that the relatively large probabilities of the occurrence of upwellings at the northern coast of the Gulf of Finland (compared with those for the southern coast) mean that strong Ekman transport frequently goes to the south-east. The consequences of this predominant transport direction and its role in the drift of oil spills or for search and rescue purposes, however, are not fully clear yet. It is obviously necessary to understand whether the described features are universal for the dynamics of the upper layer of the Gulf of Finland or whether are they partially caused by a specific resolution (and bathymetry), choice of atmospheric forcing, or by the scheme for resolving the vertical viscosity in the RCO model. The relevant analysis towards a comparison of the statistics of velocity fields and transport patterns with those obtained from the results of simulations by Andrejev *et al.* (2004a, 2004b) with a resolution of 1 mile and with an extension of their model to a resolution of 0.5 miles is currently in progress.

The spatial patterns of the net transport and the ratio of net and bulk transport show a very limited interannual but substantial seasonal variation. The large variability does not allow making definite conclusions about the possibilities of the forecast of the spatial distribution, persistency, relative strength or time scales of the formation of semi-persistent patterns with a lifetime between the typical time scale for mesoscale dynamics (a few days) and the length of a season (a few months).

Although the above has provided evidence about the existence of such patterns, the five-year period is definitely too short to create reliable statistics of their essential features or to establish their adequate correlation with the patterns of forcing factors. In particular, further analysis of such patterns evidently will make it possible to identify the areas where possibly mostly local eddy-driven circulation may exist and transport of adverse impacts to other sea areas is unlikely or very slow. These results will be particularly useful for identifying areas of low risk for the coasts.

An interesting feature is that in some seasons relatively intense mostly meridional transport pathways are present in the Gulf of Finland. Although they do not occur every year, their existence is of major importance with respect to the identification of areas of high risk in terms of coastal pollution. Their presence also suggests that between the typical turnover time of synoptic eddies (a week) and the length of a season (3–4 months) there may exist an intermediate time scale governing certain dynamical features.

In conclusion, the presented results of the use of a Lagrangian trajectory model based on Eulerian fields of velocities, combined with relevant statistical analysis, serve as a demonstration of the feasibility of this type of approach for the identification of semi-persistent transport patterns in the surface layer. The next step towards identification of areas of reduced risks consists in merging the detected patterns with the probability analysis of hitting vulnerable regions (such as the nearshore areas) by adverse impacts stemming from different sea areas.

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References

Alenius P., Myrberg K. & Nekrasov A. 1998. Physical oceanography of the Gulf of Finland: a review. *Boreal Env. Res*. 3: 97–125.

Alenius P., Nekrasov A. & Myrberg K. 2003. The baroclinic Rossby-radius in the Gulf of Finland. *Cont. Shelf Res*. 23: 563–573.

Alvarez-Salgado X.A., Gago J., Miguez B.M., Gilcoto M. & Perez F.F. 2000. Surface waters of the NW Iberian margin: upwelling on the shelf versus outwelling of upwelled waters from the Rias Baixas. *Estuar. Coast. Shelf Sci*. 51: 821–837.

Anderson D., Balmaseda M. & Vidard A. 2006. The ECMWF perspective. In: Chassignet E.P. & Verron J. (eds.), *Ocean weather forecasting: an integrated view of oceanography*, Springer, Dordrecht, pp. 361–379.

Andrejev O., Myrberg K., Alenius P. & Lundberg P.A. 2004a. Mean circulation and water exchange in the Gulf of Finland — a study based on three-dimensional modelling. *Boreal Env. Res*. 9: 1–16.

Andrejev O., Myrberg K. & Lundberg P.A. 2004b. Age and renewal time of water masses in a semi-enclosed basin – Application to the Gulf of Finland. *Tellus* 56A: 548–558.

Beletsky D., Schwab D. & McCormick M. 2006. Modeling the 1998–2003 summer circulation and thermal structure in Lake Michigan. *J. Geophys. Res*. 111(C10), C10010, doi: 10.1029/2005JC003222.

Blanke B. & Raynard S. 1997. Kinematics of the Pacific Equatorial Undercurrent: an Eulerian and Lagangian approach from GCM results. *J. Phys. Oceanogr*. 27: 1038–1053.

de Vries P. & Döös K. 2001. Calculating Lagrangian trajectories using time-dependent velocity fields. *J. Atmos. Oceanic Technol*. 18: 1092–1101.

Döös K. 1995. Inter-ocean exchange of water masses. *J. Geophys. Res*. 100(C7): 13499–13514.

Döös K. & Engqvist A. 2007. Assessment of water exchange between a discharge region and the open sea — a comparison of different methodological concepts. *Estuar. Coast. Shelf Sci*. 74: 585–597.

Döös K., Nycander J. & Coward A.C. 2008. Lagrangian decomposition of the Deacon Cell. *J. Geophys. Res*. 113(C7), C07028, doi: 10.1029/2007JC004351.

Elken J., Raudsepp U. & Lips U. 2003. On the estuarine transport reversal in deep layers of the Gulf of Finland. *J. Sea Res*. 49: 267–274.

Elken J., Mälkki P., Alenius P. & Stipa T. 2006. Large halocline variations in the Northern Baltic Proper and associated meso-and basin-scale processes. *Oceanologia* 48(S): 91–117.

Engqvist A., Döös K. & Andrejev O. 2006. Modeling water exchange and contaminant transport through a Baltic coastal region. *Ambio* 35: 435–447.

Gerdes R., Köberle C. & Willebrand J. 1991. The influence of numerical advection schemes on the results of ocean general circulation models. *Clim. Dyn*. 5: 211–226.

Gästgifvars M., Lauri H., Sarkanen A.-K., Myrberg K., Andrejev O. & Ambjörn, C. 2006. Modelling surface drifting of buoys during a rapidly-moving weather front in the Gulf of Finland, Baltic Sea. *Estuar. Coast. Shelf Sci*. 70: 567–576.

Gibbs M.T., Bowman M.J. & Dietrich D.E. 2000. Maintenance of near-surface stratification in Doubtful Sound, a New Zealand fjord. *Estuar. Coast. Shelf Sci*. 51: 683–704.

Griffa A., Piterbarg L.I. & Ozgokmen T. 2004. Predictability of Lagrangian particle trajectories: effects of smoothing of the underlying Eulerian flow. *J. Mar. Res*. 62: 1–35.

Hibler W.D. 1979. A dynamic thermodynamic sea ice model. *J. Phys. Oceanogr*. 9: 817–846.

Hunke E.C. & Dukowicz J.K. 1997. An elastic-viscous-plastic model for sea ice dynamics. *J. Phys. Oceanogr.* 27: 1849–1867.

Jönsson B., Lundberg P. & Döös K. 2004. Baltic sub-basin turnover times examined using the Rossby Centre Ocean Model. *Ambio* 23: 257–260.

Keevallik S. & Soomere T. 2010. Towards quantifying variations in wind parameters across the Gulf of Finland. *Estonian J. Earth Sci*. 59: 288–297.

Killworth P., Stainforth D., Webb D. & Paterson S. 1991. The development of a free-surface Bryan-Cox-Semtner ocean model. *J. Phys. Oceanogr*. 21: 1333–1348.

Kononen K., Kuparinen J., Mäkelä K., Laanemets J., Pavelson J. & Nõmmann S. 1996. Initiation of cyanobacterial blooms in a frontal region at the entrance to the Gulf of Finland, Baltic Sea. *Limnol. Oceanogr*. 41: 98–112.

Lehmann A., Krauss W. & Hinrichsen H.-H. 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. *Tellus* 54A: 299–316.

Meier H.E.M. 2001. On the parameterization of mixing in three-dimensional Baltic Sea models. *J. Geophys. Res*. 106(C12): 30997–31016.

Meier H.E.M. 2007. Modeling the pathways and ages of inflowing salt- and freshwater in the Baltic Sea. *Estuar. Coast. Shelf Sci*. 74: 717–734.

Meier H.E.M., Döscher R. & Faxén T. 2003. A multiprocessor coupled ice-ocean model for the Baltic Sea: application to salt inflow. *J. Geophys. Res*. 108(C8), 3273, doi:10.1029/2000JC000521.

Myrberg K. & Andrejev O. 2003. Main upwelling regions in the Baltic Sea — a statistical analysis based on three-dimensional modelling. *Boreal Env. Res*s. 8: 97–112.

Osinski R. & Piechura J. 2009. Latest findings about circulation of upper layer in the Baltic Proper. In: *BSSC 2009, August 17–21, 2009, Tallinn, Estonia, Abstract Book*, p. 103.

Räämet A. & Soomere T. 2010. The wave climate and its seasonal variability in the northeastern Baltic Sea. *Estonian J. Earth Sci*. 59: 100–113.

Samuelsson P., Jones C.G., Willén U., Ullerstig A., Gollvik S., Hansson U., Jansson C., Kjellström E., Nikulin G. & Wyser K. 2011. The Rossby Centre Regional Climate Model RCA3: Model description and performance. *Tellus* 63A: 4–23.

Savijärvi H., Niemela S. & Tisler P. 2005. Coastal winds and low-level jets: simulations for sea gulfs. *Quart. J. Roy. Meteor. Soc. B* 131: 625–637.

Soomere T. & Keevallik S. 2001. Anisotropy of moderate and strong winds in the Baltic Proper. *Proc. Estonian Acad. Sci. Eng*. 7: 35–49.

Soomere T. & Keevallik S. 2003. Directional and extreme wind properties in the Gulf of Finland. *Proc. Estonian Acad. Sci. Eng*. 9: 73–90.

Soomere T. & Quak E. 2007. On the potential of reducing coastal pollution by a proper choice of the fairway. *J. Coastal Res*. Special Issue 50: 678–682.

Soomere T., Myrberg K., Leppäranta M. & Nekrasov A. 2008. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia* 50: 287–362.

Soomere T., Viikmäe B., Delpeche N. & Myrberg K. 2010. Towards identification of areas of reduced risk in the Gulf of Finland, the Baltic Sea. *Proc. Estonian Acad. Sci*. 59: 156–165.

Stevens D.P. 1991. The open boundary condition in the United Kingdom Fine-Resolution Antarctic Model. *J. Phys. Oceanogr*. 21: 1494–1499.

Vandenbulcke L., Beckers J.-M., Lenartz F., Barth A., Poulain P.-M., Aidonidis M., Meyrat J., Ardhuin F., Tonani M., Fratianni C., Torrisi L., Pallela D., Chiggiato J., Tudor M., Book J.W., Martin P., Peggion G. & Rixen M. 2009. Super-ensemble techniques: application to surface drift prediction. *Progr. Oceanogr*. 82: 149–167.

Webb D.J., Coward A.C., de Cuevas B.A. & Gwilliam G.S. 1997. A multiprocessor ocean circulation model using message passing. *J. Atmos. Oceanic Technol*. 14: 175–183.

Paper B

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OCEANOGRAPHY

Towards identification of areas of reduced risk in the Gulf of Finland, the Baltic Sea

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Abstract. A Lagrangian trajectory model, TRACMASS with the use of velocity fields calculated by the Rossby Centre (Swedish Hydrological and Meteorological Institute) circulation model, is employed to analyse trajectories of current-driven surface transport in the Gulf of Finland, the Baltic Sea, for the period of 1987–1991. Statistical analysis of trajectories is performed to calculate a map of probabilities for adverse impacts released in different sea areas to hit the coast. There is a clearly defined curve (equiprobability line) in the western part of the gulf from which the chances of the propagation of adverse impacts to either of the coasts are equal. The current-driven propagation of tracers from a wide area (of reduced risk) to the coast in the central and eastern parts of the gulf is unlikely within about three weeks. A safe fairway in terms of coastal protection goes over the equiprobability line and the area of reduced risk.

Key words: pollution transport, risk analysis, currents, hydrodynamic modelling, Gulf of Finland, Baltic Sea.

INTRODUCTION

The existence of quasi-persistent patterns of currents in various parts of the Baltic Sea (Lehmann et al., 2002; Andrejev et al., 2004a, 2004b; Osinski and Piechura, 2009) leads to the interplay of the high variability and extreme complexity of the surface currents with the presence of rapid pathways of the current-driven transport (Soomere et al., 2010). This combination opens a principally new way towards a technology that uses the marine dynamics for the reduction of environmental risks stemming from shipping and offshore and coastal engineering activities. The key benefit is an increase in the time during which an adverse impact (for example, an oil spill) reaches a vulnerable area after an accident has happened (Soomere and Quak, 2007). The use of this technology, however, requires adequate estimates of the persistency and variability of the patterns, and of the confidence and uncertainty related to their practical use.

The drift of adverse impacts, oil spills, lost containers, ships without propulsion, etc. is jointly governed by wind stress, waves, and currents. The properties of transport by wind and waves are understood quite well (ASCE, 1996; Sobey and Barker, 1997; Reed et al., 1999; Castanedo et al., 2006). As the instantaneous field of currents is created under the joint influence of a large pool of local and remote forcing factors, the prediction of the current-induced contribution to the drift is still a challenge. Theoretically, transport of water particles and drift of tracers can be described to some extent with the use of deterministic circulation models. There is, however, not yet a model capable of sensibly forecasting the drift or a deterministic method to combine different models to reproduce the floating object drift (Vandenbulcke et al., 2009). The results are highly sensitive with respect to the particular model and small variations of the initial and forcing conditions (Griffa et al., 2004). The problem is even more complicated in strongly stratified sea areas such as the Gulf of Finland where the drift is frequently steered by multi-layered dynamics (Gästgifvars et al., 2006).

A feasible way to reduce the uncertainties of the current-induced drift patterns consists in the implicit or explicit use of statistical approaches. An attempt in this

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direction is made by means of numerical identification of patterns of net transport and the ratio of the net and bulk transport in the Gulf of Finland, the Baltic Sea (Soomere et al., 2010).

The focus of this paper is a statistical technique for the optimization of the potential risk stemming from anthropogenic activities in elongated sea areas. The classical definition of risk expresses it as the product of the probability of an accident and the cost of its consequences. The cost of the consequences of an accident in the marine environment substantially depends not only on the nature or magnitude of the adverse impact but also on the place hit. Moreover, the consequences could frequently be reduced by gaining some time to combat the adverse impact.

We aim at decreasing the risk by means of maximizing the time over which the current-driven propagation of the consequences of an accident will affect high-cost areas. As the nearshore frequently has the largest ecological value (Kokkonen et al., 2010), in this study we consider the coastal zone as a generic example of a high-cost area. The proposed approach is evidently independent of the particular definition of the coastal area and, equivalently, of the particular form of the cost function.

A direct application of the approach is a problem of the optimization of marine transport routes in order to minimize the probability of a coastal pollution and/or to maximize the time over which adverse impacts reach the coasts. For open ocean coasts this can be done by shifting the fairway offshore or by relocating it in a certain manner to minimize the adverse impacts to the environment (Stokstad, 2009).

A key question for narrow bays and elongated sea areas is how to minimize the joint probability of hitting either of the coasts. The first-order solution for narrow basins is the equiprobability line, from which the probability of propagation of pollution to either of the coasts is equal. If the transport patterns were completely isotropic and homogeneous, this line would coincide with the axis of the basin. For wider sea areas there may also appear quite a wide area of reduced risk, from which the propagation of pollution to any of the coasts is unlikely. The safest fairway would thus follow a combination of the equiprobability line and the area(s) of reduced risk.

A systematic solution to the formulated problem presumes inverse tracking of the propagation of adverse impacts. It is well known that neither a straightforward solution to this problem nor a universal solution method exists. We shall address it by means of statistical analysis of a large pool of numerically simulated trajectories of drifters in the surface layer. The key idea, therefore, is not to produce another operational model to represent the drift after an accident has actually happened but rather to identify beforehand the regions where it is statistically safer to travel.

The analysis is performed for the Gulf of Finland (Fig. 1), an elongated, stratified sub-basin of the Baltic Sea with a length of about 400 km, width between 48 and 125 km, and a mean depth of 37 m only. This region, declared a particularly sensitive sea area by the International Maritime Organisation (Soomere et al., 2008), hosts extremely heavy and rapidly increasing ship traffic.

The calculations are based on the results of long-term, high-resolution simulations of the circulation in the entire Baltic Sea. A Lagrangian trajectory model is applied to extract useful information from these simulations. The goal is to evaluate favourable features of the current-driven transport that have time scales of the order of a week and that can be extracted neither directly from the velocity data nor from the long-term average circulation patterns.

MODELLING THE ENVIRONMENT

The tool for the analysis of current-driven transport of adverse impacts is a Lagrangian trajectory model, TRACMASS (Döös, 1995; Vries and Döös, 2001). It uses pre-computed three-dimensional Eulerian current velocity fields to evaluate an approximate path of water particles (equivalently, neutral tracer of an adverse impact) based on an analytical solution of a differential equation for motion that depends on the velocities on the grid box walls. This off-line method of calculation makes it possible to reckon a large pool of trajectories for different starting instants and positions once the velocity fields are available. The method was originally developed for stationary velocity fields (Döös, 1995; Blanke and Raynaud, 1997), then expanded to time-dependent fields (Vries and Döös, 2001) by implementation of a linear interpolation of the velocity field both in time and in space, and has become a standard tool for studies of complex motions of water particles in the marine environment (Jönsson et al., 2004; Döös and Engqvist, 2007).

In this study we use the surface-layer velocity fields calculated for 1987–1991 for the entire Baltic Sea using the Rossby Centre Ocean circulation model (RCO) with a temporal resolution of 6 hours. This time period was chosen in order to make the results comparable with circulation simulations (Andrejev et al., 2004a, 2004b) and studies of average transport patterns in the same basin (Soomere et al., 2010). The RCO is a primitive equation circulation model coupled with an ice model (Meier et al., 2003). It covers the entire Baltic Sea with the horizontal resolution of 2 × 2 nautical miles and uses 41 vertical levels in *z*-coordinates. The thickness of the uppermost layer is 3 m.

The model is forced by wind data on the 10 m level, air temperature and specific humidity on the 2 m level, precipitation, cloudiness, and sea level pressure fields, and it also accounts for river inflow and water exchange through the Danish Straits. This data set is calculated from the ERA-40 re-analysis using a regional atmosphere model with a horizontal resolution of 25 km (Höglund et al., 2009). As the atmospheric model tends to underestimate extreme wind speeds, the wind is adjusted using simulated gustiness. Further details of the model set-up and validation experiments are discussed in (Meier, 2001, 2007; Meier et al., 2003).

Trajectories of water particles (equivalently, current-driven propagation of an adverse impact) are simulated for a few weeks for certain distributions of the initial positions. The resulting trajectories are saved for further analysis and the simulations for the same initial positions of particles are restarted from another time instant. The process is repeated over the chosen time period.

High risk to a nearshore section is assumed when pollution reaches a distance of less than three grid points (about 11 km) from the coast (cf. Lessin et al., 2009). As a first approximation, the percentage of tracers that approach the nearshore zone of this width within a certain time interval is used as an estimate of the risk. Alternatively, the average time it takes the tracer to reach such points is a measure of risk associated with the starting point. In this study we use a simplified approach and rely only on the fact of reaching the nearshore.

In order to avoid problems connected with potentially insufficient accuracy of the representation of vertical velocities in the RCO model, the trajectories are locked in the uppermost layer. This is done by means of switching off the three-dimensional tracing in the TRACMASS model. The resulting trajectories are, thus, not truly Lagrangian: they are not passively advected by the velocity fields and rather represent motion of tracers that are slightly lighter than the surrounding water (such as oil in otherwise calm conditions) or are confined to the upper layer by other constraints. This set-up of trajectory modelling is best suited for representing, for example, the drift patterns of lost containers.

TIME SCALES AND PATTERNS OF TRANSPORT

First a series of experiments was performed to estimate the typical time over which the particles reached the nearshore. The trajectories were started from centres of 96 cells located along the straight line in Fig. 1, roughly representing the axis of the Gulf of Finland (that is, at points remotest from the coasts). The simulations were started at midnight each calendar day in 1987 and run for 10 days. As discussed below, this is roughly the time during which the largest amount of tracers released along the axis of the Gulf of Finland reaches the nearshore.

The number of particles that entered the nearshore (called below hits of the nearshore) during these days showed very high variability (Fig. 2). The count (equivalently, the percentage of particles) varied from zero up to about 60. In general, the smallest number of hits occurred in the calm season (April–July) and the highest, not surprisingly, in the windy autumn and winter season. There was, however, also a certain time section of the calm period when the number of hits was close to 50.

On average, about 30% of the particles released along the axis of the gulf hit the nearshore of either of the coasts within 10 days. This estimate is in accordance with numerical results of Prof. S. Ovsienko (pers. comm.) and apparently reflects the lower bound of the probability for a hit of a coastal zone by an adverse impact released in a random location of the gulf. Other factors influencing the drift such as wind, waves, and spreading (of oil spills) apparently increase this probability as they generally magnify the excursions of the released substances and/or enlarge the sea area hosting the adverse impact.

The typical time for a hit in both calm and windy seasons also largely varied. For example, Fig. 3 illustrates that in May 1987 a few hits occurred already during the first day of propagation while in July the first hit took place only on the ninth day. The further behaviour of the particles was also substantially different. In May the maximum number of particles located in the nearshore was 19 and almost no hit was observed starting from day 8. The number of such particles was between 30 and 43 during almost a week (days 12–17) in July (Fig. 3). In total, no more than 19% of the particles simultaneously resided in the nearshore in May whereas this percentage reached 43 in July.

The typical time of the first hit to the coast was 3 days in 1987. A substantial number of hits, though, occurred already on the first day, which also was the median value of the number of days in question. This low number apparently is due to the smallness of the basin and the closeness of some of the release points to the coastal zone. The typical time when the largest number of particles was found in the nearshore was 11 days from the start of the simulations in 1987. This value is close to the median value (12 days).

The overall character of the current field is well known for the Gulf of Finland. The vertically averaged mean circulation of this basin is cyclonic with an average velocity of a few centimetres per second (Alenius et al., 1998; Lehmann et al., 2002). This overall scheme is superposed by numerous meso-scale baroclinic eddies and many local features (Andrejev et al., 2004a, 2004b; Soomere et al., 2008). The transport in the uppermost layer is largely governed by the Ekman drift, especially in relatively windy seasons when the dynamics of the uppermost layer is apparently to some extent decoupled from the underlying layers.

These motion configurations are, however, only valid on average. The above estimates suggest that the transport of adverse impacts to the coasts not necessarily follows the long-term average flows. Instead, it is governed by much faster processes and has the time scale of a few days up to a few weeks. One of the reasons for the extreme complexity of current patterns in this basin is that the internal Rossby-radius of deformation (which governs the size of meso-scale features) is only 2–4 km in the Gulf of Finland. This feature indicates the necessity of the use of high-resolution models (≤ 1.5 km) for this water body (Alenius et al., 2003).

A great role of local, short-term drivers is reflected in the extremely large variability of the probability of hitting the southern and northern coasts of the Gulf of Finland (Fig. 4) for different time periods. In the simulation started on 1 October 1987 almost all hits to the nearshore occurred along the northern coast whereas 59% of the particles reached the nearshore. The overwhelming majority of particles launched on 1 December, however, came to the southern coast (52% of the particles reached the nearshore in this case).

THE EQUIPROBABILITY LINE

The presented examples show that there exists no a priori safe location in the Gulf of Finland in terms of a low probability of the propagation of adverse impacts to the coastal area. A first step towards solving the problem of minimizing the probability of hitting any section of the coast is to identify a line (or area) from which the probability of the propagation to the opposite coasts is equal. In simulations below, the southern coast represents the coastline of Estonia whereas the coasts of Russia and Finland are merged to represent the northern coast.

Below we use two methods (a direct method and a smoothing one) for numerical estimation of the location of the equiprobability line and areas of reduced risk. Both are based on tracking trajectories with the use of the TRACMASS code and differ only in how the trajectories are grouped in the evaluation of the probability the particles released in a particular sea area enter a nearshore region. The difference in the positions between the two estimates of the location of the line can be interpreted as a rough measure of the uncertainty of its location. The deviation of this line from the axis of the gulf characterizes the asymmetry of the surface-layer current-driven transport in this basin.

The simulation process is depicted in Fig. 5. In order to obtain reliable statistics of the transport patterns, the simulations cover a relatively long time interval t_D, which typically involves at least one season but frequently one or more years. It is divided into time windows of equal length $t_W << t_D$. The duration t_W is chosen based on the above estimates of the typical time scales of phenomena under research and typically is from a few days up to a few weeks. The windows are separated from each other by the time lag $t_S << t_W$, the duration of which varies from 6 hours (which is the time step of available velocity fields) to 10 days.

A pool of trajectory simulations is started at a certain time instant t_0 when a cluster of particles is released into the Gulf of Finland. In the above examples one particle was released into the centre of each grid cell of a set of 96 cells along a straight line more or less coinciding with the axis of the gulf (Fig. 1). For the simulations below, one or more particles were released into each of 3131 sea points of the gulf.

The trajectories are first simulated over a time window $[t_0, t_0 + t_W]$. The results are saved for further analysis. The same cluster of tracers is then released at time instant $t_0 + t_S$. The trajectories are again calculated over a window with a duration of t_W. The process is repeated $(t_D - t_W)/t_S$ times. Finally, the outcome of simulations is averaged over all time windows. For example, for a yearly simulation with the time window of $t_W = 20$ days and with a lag $t_S = 10$ days, the averaging is performed over 35 ensembles of trajectories, the last examples of which start on 12 December and end at the midnight of 31 December.

Within each time window, the instantaneous position $[x_{ij}(t), y_{ij}(t)]$ and the distance $\Delta_{ij}(t)$ of the trajectory from the coast were calculated for the entire time window and for each of the released tracers. Here i is the grid cell number, $1 \leq i \leq N$, N is the total number of cells into which the tracer is released, j is the number of a tracer particle in the i-th cell, $1 \leq j \leq N_i$, and N_i is the total number of particles released into the i-th cell. The instantaneous location of the tracer is used to estimate whether the trajectory has entered the nearshore.

The direct method for the estimation of the location of the equiprobability line and safe areas in the Gulf of Finland is based on point-wise analysis of what happens with the trajectories for each of $N = 3131$ grid cells in the gulf with the time lag of 10 days. Four particles ($N_i = 4$, $1 \leq i \leq N$) are released in each grid cell (symmetrically with respect to the cell centre) at the beginning of each time window. A count is made if over 50% (that is three or all four) of the trajectories travelled to the same coast within the time window. If yes, the cell is assumed the value of $c = \pm 1$ depending on the count of the hits to the nearshore of the southern or the northern coast. If no more than two tracers reached a particular coast within the time window (incl. the situation when two tracers reached the southern and the other two the northern coast), the cell is assumed the value of $c = 0$. Finally, a map reflecting the probability of hitting the nearshore of either of the coasts is obtained as an average of the described distributions over all the windows of the time interval in question. From the construction of this map it follows that the range of the resulting values $\overline{c}$ for a cell is from –1 to 1 and an estimate of the probability for tracer drift to the southern or the northern nearshore can be obtained by means of cell-wise mappings $p_N = (1+\overline{c})/2$ or $p_S = (1-\overline{c})/2$, respectively.

The resulting distributions depend on a number of parameters used in the calculations. Quite substantial seasonal and less pronounced interannual variability of these maps and the resulting location of the equiprobability line are discussed below. We performed several sensitivity experiments by means of varying the length of the time window t_W and the time lag t_S between the time windows. The results were almost insensitive with respect to the variation of the time lag from one day up to ten days provided the entire time interval of interest t_D was long enough compared to this lag. This feature is not unexpected because the averaging procedure over a pool of time windows suppresses the role of each single distribution. Also, the results showed almost no dependence on the length of the time window provided it was long enough to cover about 50% of the first hits of the tracers to the nearshore. Notice that the optimum values of the listed parameters are strongly site-specific and should be re-evaluated for each sea area and problem under investigation.

The use of the discussed time window means that only hits within the first 20 days of the dynamics are accounted for in the resulting maps. Strictly speaking, the results, therefore, are based only on a fraction of all the tracers and serve as an approximation of the desired spatial probability distribution. As the majority of particles have already hit one of the coasts within this length of time window, the resulting map reflects the behaviour of this majority. Also, it is natural to assume that the further hits have the same probability distribution of hitting the different coasts and thus the corrections potentially resulting from waiting until all the tracers hit a coast would be fairly minor.

The resulting map (Fig. 6) reveals the presence of two basically different areas of the gulf. In the western part there is a narrow sea area in which the average values for the cells are close to zero. Tracers released to either side of this area have a high probability of drifting to the relevant coast. This area evidently can be interpreted as the estimate of the location of the equiprobability line. In the central and eastern parts of the gulf, however, there is a wide area in which $|\overline{c}| \leq 0.1$. Consequently, propagation of tracers from this area to either of the coasts is generally unlikely. Such areas apparently host no well-defined equiprobability line. Instead, they entirely serve as almost safe regions (areas of reduced risk) in terms of coastal pollution.

Both the locations of these areas, potentially impacting either of the coasts, and the location of the equiprobability line reveal substantial seasonal variability (which will be discussed in detail elsewhere). Consequently, a similar variability exists for both high risk and reduced risk areas in this basin. The variability is the largest for the entrance area of the Gulf of Finland, which apparently is strongly affected by the dynamics of the open Baltic Sea.

Similar maps for annual probabilities of hitting different coasts also reveal certain interannual variability (Fig. 7). There are, however, features that persist over many years and also become evident in analogous maps for different seasons. There is a persistent area of reduced risk in the central and eastern parts of the gulf approximately between the Tallinn–Helsinki line and the latitudes of Narva Bay. To the north of Narva Bay there usually is a high probability of the propagation of an adverse impact to the southern coast. The equiprobability line is usually located to the north of the axis of the gulf except for a small part of this water body. There is a characteristic area to the north of Hiiumaa stretching almost to the Finnish archipelago from where the transport of adverse impacts to the Estonian nearshore has a relatively high probability.

The described method of cell-wise analysis of the transport generally leads to a considerable level of noise that does not always result in a clear separation of sea areas with the prevailing direction of the transport to a particular coast, especially in the central and eastern parts of the gulf. A part of the noise apparently is connected with a small number of tracers (four) for each cell.

In order to suppress the noise and to estimate the uncertainty of the location of the line and areas in question, we use another method that involves an implicit local smoothing process. The sea area is divided into clusters of 3 × 3 grid cells. By tracing nine trajectories in each cluster (one from each cell) it is established whether the majority of the trajectories end up at one of the coasts or stay in the open sea area. The basic idea is the same as above, only the values of $N_i = 9$, $1 \leq i \leq N$, and the initial positions of the tracer with respect to the cluster centres are different. The equiprobability line and the low-risk areas are based on probabilities calculated for the centres of the clusters. The resulting maps of probabilities of hitting the opposite coasts (Fig. 8) are qualitatively similar to those in Fig. 6. The equiprobability line is located in almost the same position as for the above method. The locations for the line based on these two estimates practically coincide between Hiiumaa and the Finnish mainland, differ by 1–2 grid points (3–6 km) in the western and eastern parts of the Gulf of Finland, and reach 3–4 grid points (up to 14 km) in a small section between Tallinn and Helsinki.

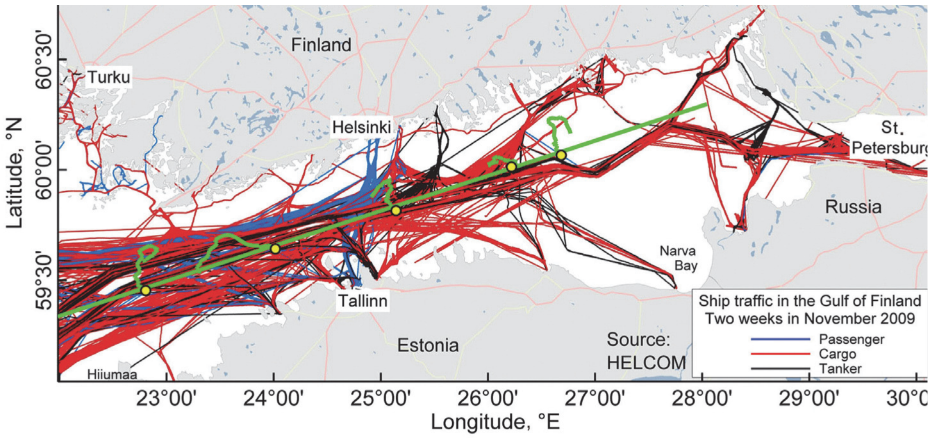

Fig. 1. Scheme of the current major fairways in the Gulf of Finland. The green straight line shows the initial location of tracers used for the construction of Figs 2–4 and the green curves show examples of trajectories, starting from points indicated by yellow circles.

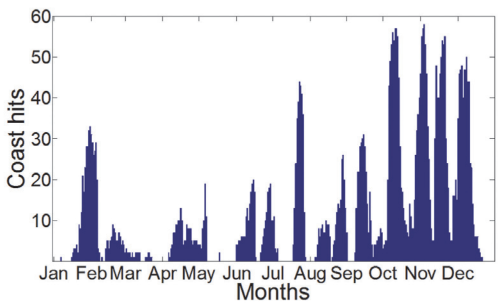

Fig. 2. Percentage of particles entering the nearshore during 10 days for the year 1987. The horizontal axis shows the starting time of calculations.

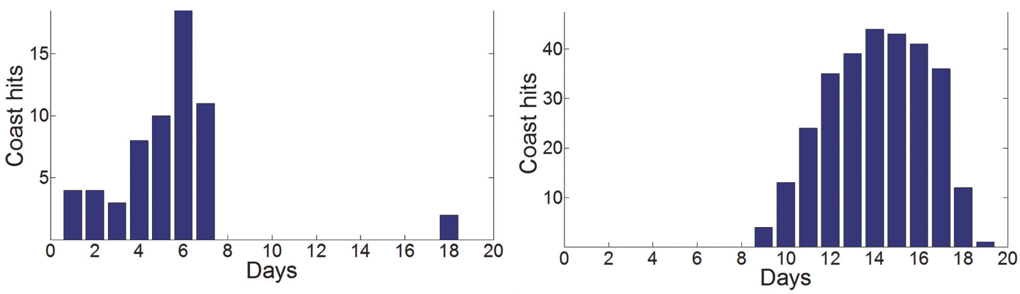

Fig. 3. Percentage of particles located in the nearshore on different days after their release on 1–20 May 1987 (left panel) and on 10–30 July 1987 (right panel). The horizontal axis shows the consecutive number of a day for the particular run.

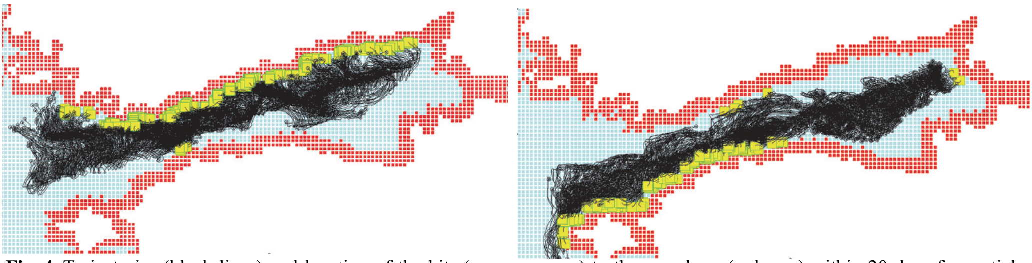

Fig. 4. Trajectories (black lines) and location of the hits (green squares) to the nearshore (red area) within 20 days for particles released on 1 October (left panel) and on 1 December 1987 (right panel).

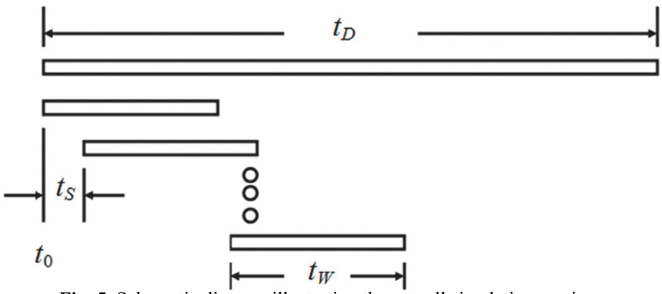

Fig. 5. Schematic diagram illustrating the overall simulation routine.

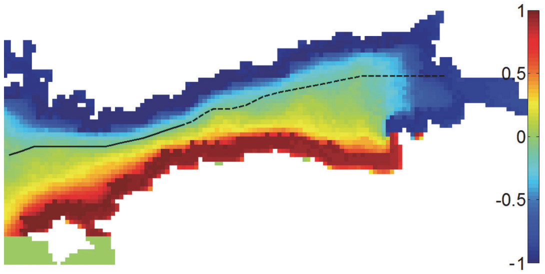

Fig. 6. Probabilities of hitting the nearshore of the northern or the southern coast for the years 1987–1991 calculated with the use of the direct method. The red colour indicates a high probability of transport to the southern (Estonian) coast and the blue colour, to the northern coast. The green colour marks the estimated location of the equiprobability line (black line) and the areas from which transport to either of the coasts is unlikely.

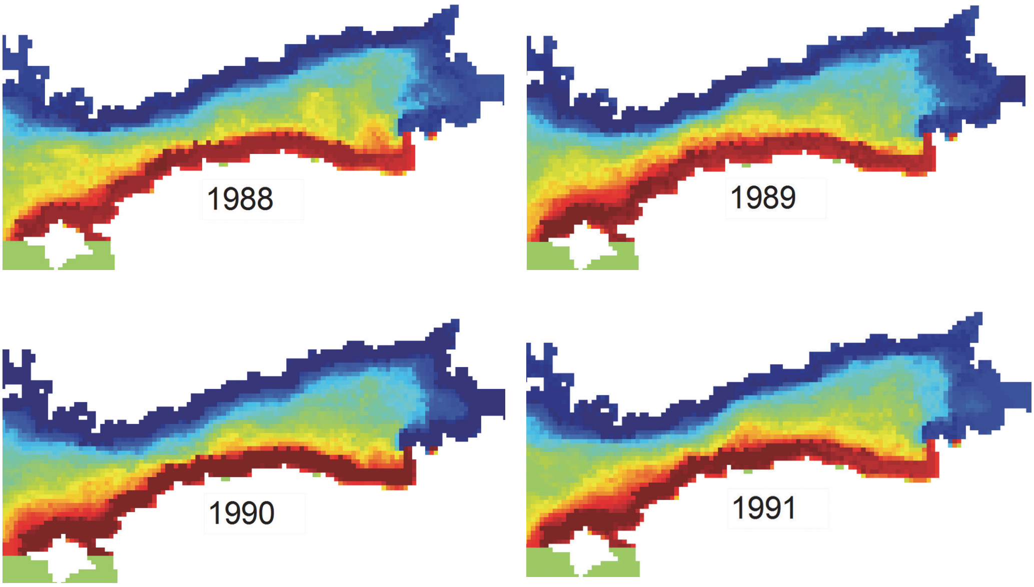

Fig. 7. Probabilities of hitting the nearshore of the northern or the southern coast for the years 1988–1991 calculated with the use of the direct method. Notations and scales are the same as for Fig. 6.

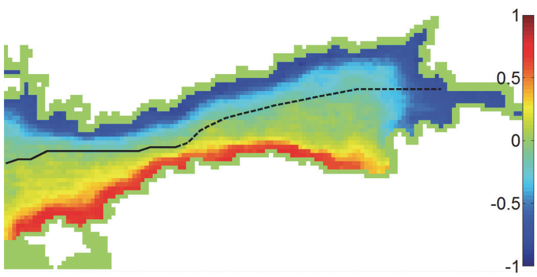

Fig. 8. Probabilities of hitting the nearshore of the northern or the southern coast for the years 1987–1991 calculated with the use of the smoothing method. Notations are the same as for Fig. 6. Notice that this method is only meaningful for the clusters whose centres are located at a distance of >11 km from the coast.

DISCUSSION AND CONCLUSIONS

The primary purpose of this research was to find a first guess to the solution to a variation of the inverse problem of the identification of the areas in which an accident would least likely affect the coasts of the Gulf of Finland. The results revealed several unexpected features of the distribution of the probabilities of the transport to the different coasts. A well-defined equiprobability line is substantially shifted northwards from the axis of the gulf in its western part. The fairly small difference (usually below 6–7 km, at a few locations around 10 km) between its locations obtained by the two methods – an estimate of the uncertainty related with this type of solution – supports the reliability of the analysis.

Therefore, the probability that adverse impacts released to the entrance area and the western part of the gulf hit the southern coast is considerably larger than that they hit the northern coast. This property apparently matches the joint effect of the prevailing direction of strong and persistent winds (they are from the southwest) and the geometry of this basin. The resulting Ekman transport is predominantly to the east but also has a considerable component to the south (Soomere et al., 2010). This conjecture is consistent with the asymmetric distribution of the frequency of upwellings in the Gulf of Finland (which mostly occur along the northern coast of this water body (Myrberg and Andrejev, 2003)) and the accompanying prevailing transport of surface waters to the south.

In conclusion, application of a trajectory model and pre-computed velocity fields combined with relevant statistical analysis serves as a feasible method to determine areas of high and low risk in terms of coastal pollution in different basins of the Baltic Sea with their specific hydrographic characteristics, like in the elongated Gulf of Finland. This technology has a clear potential to reduce the consequences of an accident (equivalently, to impact the decision-making process concerning spatial planning of dangerous activities) in the statistical sense. Straightforward extensions of the proposed approach eventually are useful for preventively placing dangerous activities in regions in which an accident would have a minimum threat to vulnerable areas.

ACKNOWLEDGEMENTS

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REFERENCES

Alenius, P., Myrberg, K., and Nekrasov, A. 1998. Physical oceanography of the Gulf of Finland: a review. *Boreal Env. Res.*, **3**, 97–125.

Alenius, P., Nekrasov, A., and Myrberg, K. 2003. The baroclinic Rossby-radius in the Gulf of Finland. *Cont. Shelf Res.*, **23**, 563–573.

Andrejev, O., Myrberg, K., Alenius, P., and Lundberg, P. A. 2004a. Mean circulation and water exchange in the Gulf of Finland – a study based on three-dimensional modelling. *Boreal Env. Res.*, **9**, 1–16.

Andrejev, O., Myrberg, K., and Lundberg, P. A. 2004b. Age and renewal time of water masses in a semi-enclosed basin – application to the Gulf of Finland. *Tellus*, **56A**, 548–558.

[ASCE] American Society of Civil Engineers. 1996. State-of-the-art review of modeling transport and fate of oil spills. ASCE Committee on Modeling Oil Spills, Water Resources Engineering Division. *J. Hydraul. Eng.*, **122**(11), 594–609.

Blanke, B. and Raynaud, S. 1997. Kinematics of the Pacific Equatorial Undercurrent: an Eulerian and Lagrangian approach from GCM results. *J. Phys. Oceanogr.*, **27**(6), 1038–1053.

Castanedo, S., Medina, R., Losada, I. J., Vidal, C., Mendez, F. J., Osorio, A., Juanes, J. A. and Puente, A. 2006. The Prestige oil spill in Cantabria (Bay of Biscay). Part I: Operational forecasting system for quick response, risk assessment, and protection of natural resources. *J. Coastal Res.*, **22**(6), 1474–1489.

Döös, K. 1995. Inter-ocean exchange of water masses. *J. Geophys. Res.*, **100**(C7), 13499–13514.

Döös, K. and Engqvist, A. 2007. Assessment of water exchange between a discharge region and the open sea – a comparison of different methodological concepts. *Estuar. Coast. Shelf Sci.*, **74**, 585–597.

Gästgifvars, M., Lauri, H., Sarkanen, A.-K., Myrberg, K., Andrejev, O., and Ambjörn, C. 2006. Modelling surface drifting of buoys during a rapidly-moving weather front in the Gulf of Finland, Baltic Sea. *Estuar. Coast. Shelf Sci.*, **70**, 567–576.

Griffa, A., Piterbarg, L. I., and Ozgokmen, T. 2004. Predictability of Lagrangian particle trajectories: effects of smoothing of the underlying Eulerian flow. *J. Mar. Res.*, **62**, 1–35.

Höglund, A., Meier, H. E. M., Broman, B., and Kriezi, E. 2009. *Validation and Correction of Regionalised ERA-40 Wind Fields over the Baltic Sea Using the Rossby Centre Atmosphere Model RCA3.0*. Rapport Oceanografi No. 97, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.

Jönsson, B., Lundberg, P., and Döös, K. 2004. Baltic sub-basin turnover times examined using the Rossby Centre Ocean Model. *Ambio*, **23**(4–5), 257–260.

Kokkonen, T., Ihaksi, T., Jolma, A., and Kuikka, S. 2010. Dynamic mapping of nature values to support prioritization of coastal oil combating. *Environ. Modell. Softw.*, **25**(2), 248–257.

Lehmann, A., Krauss, W., and Hinrichsen, H.-H. 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. *Tellus*, **54A**, 299–316.

Lessin, G., Ossipova, V., Lips, I., and Raudsepp, U. 2009. Identification of the coastal zone of the central and eastern Gulf of Finland by numerical modeling, measurements, and remote sensing of chlorophyll *a*. *Hydrobiologia*, **692**, 187–198.

Meier, H. E. M. 2001. On the parameterization of mixing in three-dimensional Baltic Sea models. *J. Geophys. Res.*, **106**, 30997–31016.

Meier, H. E. M. 2007. Modeling the pathways and ages of inflowing salt- and freshwater in the Baltic Sea. *Estuar. Coast. Shelf Sci.*, **74**, 717–734.

Meier, H. E. M., Döscher, R., and Faxén, T. 2003. A multi-processor coupled ice-ocean model for the Baltic Sea: application to salt inflow. *J. Geophys. Res.*, **108**(C8), 3273.

Myrberg, K. and Andrejev, O. 2003. Main upwelling regions in the Baltic Sea – a statistical analysis based on three-dimensional modelling. *Boreal Env. Res.*, **8**, 97–112.

Osinski, R. and Piechura, J. 2009. Latest findings about circulation of upper layer in the Baltic Proper. In *BSSC 2009 Abstract Book, August 17–21, 2009*. Tallinn, 103.

Reed, M., Johansen, O., Brandvik, P. J., Daling, P., Lewis, A., Fiocco, R., Mackay, D., and Prentki, R. 1999. Oil spill modeling towards the close of the 20th century: overview of the state of the art. *Spill Sci. Techn. Bull.*, **5**(1), 3–16.

Sobey, R. J. and Barker, C. H. 1997. Wave-driven transport of surface oil. *J. Coastal Res.*, **13**(2), 490–496.

Soomere, T. and Quak, E. 2007. On the potential of reducing coastal pollution by a proper choice of the fairway. *J. Coast. Res.*, Special Issue **50**, 678–682.

Soomere, T., Myrberg, K., Leppäranta, M., and Nekrasov, A. 2008. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia*, **50**, 287–362.

Soomere, T., Delpeche, N., Viikmäe, B., Quak, E., Meier, H. E. M., and Döös, K. 2010. Patterns of current-induced transport in the surface layer of the Gulf of Finland. *Boreal Env. Res.*, **15**, in press.

Stokstad, E. 2009. U.S. poised to adopt national ocean policy. *Science*, **326**, 1618.

Vandenbulcke, L., Beckers, J.-M., Lenartz, F., Barth, A., Poulain, P.-M., Aidonidis, M., Meyrat, J., Ardhuin, F., Tonani, M., Fratianni, C., Torrisi, L., Pallela, D., Chiggiato, J., Tudor, M., Book, J. W., Martin, P., Peggion, G., and Rixen, M. 2009. Super-ensemble techniques: application to surface drift prediction. *Progr. Oceanogr.*, **82**(3), 149–167.

Vries, P. de and Döös, K. 2001. Calculating Lagrangian trajectories using time-dependent velocity fields. *J. Atmos. Ocean. Techn.*, **18**(6), 1092–1101.

Laevaliiklusega seonduvate keskkonnariskide optimeerimise võimalustest Soome lahes

Tarmo Soomere, Bert Viikmäe, Nicole Delpeche ja Kai Myrberg

On analüüsitud hoovuste tekitatud lisandite transporti Soome lahe pinnakihis aastatel 1987–1991. Rootsi Meteoroloogia ja Hüdroloogia Instituudi arvutatud hoovuste kiiruste andmestikust on tarkvara TRACMASS abil leitud lisandite edasikandumise trajektoorid. Nende statistilise analüüsi kaudu on hinnatud erinevatele merealadele sattunud lisandite randa triivimise tõenäosust. On näidatud, et Soome lahe lääneosas eksisteerib nn võrdtõenäosusjoon, millest põhja poole sattunud lisandid triivivad suurema tõenäosusega lahe põhjaranda, ja vastupidi. Soome lahe idaosa avamerel on piirkonnad, kuhu sattunud lisandite kandumine randa on vähetõenäoline. Ohutuim laevatee kulgeb piki kirjeldatud joont ja läbi selliste piirkondade.

Paper C

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Investigating the Marine Protected Areas most at risk of current-driven pollution in the Gulf of Finland, the Baltic Sea, using a Lagrangian transport model

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ABSTRACT

The possibility of current-driven propagation of contaminants released along a major fairway polluting the Marine Protected Areas (MPAs) in the Gulf of Finland, the Baltic Sea, is examined using a 3D circulation model, a Lagrangian transport model and statistics. Not surprisingly, the number of hits to the MPA decreases almost linearly with its distance from the fairway. In addition, the potential pollution released during a ship accident with the pollutants carried by currents may affect MPAs at very large distances. Typically, a fairway section approximately 125 km long (covering about 1/3 of the approximate 400-km-long gulf) may serve as a source of pollution for each MPA. The largest MPA (in the Eastern Gulf of Finland) may receive pollution from an approximately 210-km-long section (covering about 1/2 of the entire length of the gulf). This information may be useful in assisting maritime management.

1. Introduction

The Baltic Sea, located in Northern Europe, is the Earth's largest and relatively shallow (average depth of 54 m) brackish water body (surface area of 392,978 km^2) (Leppäranta and Myrberg, 2009). It is a unique and sensitive marine environment subject to extreme anthropogenic pressure (HELCOM, 2010) and, apparently, is one of the top ten most-threatened waters in the world (Uggla, 2007). The main environmental threats affecting this sea area are oil spills, pollution from shipping and offshore industry, and eutrophication caused by external loads (Backer and Leppänen, 2008; Backer et al., 2010; HELCOM, 2010). Influenced by the ports of its many surrounding countries, the Baltic Sea is known as one of the busiest shipping domains in the world (Rytkönen et al., 2002). The high probability of this sensitive marine ecosystem suffering damage due to anthropogenic influences, especially caused by shipping activities, has been signaled by the designation of the Baltic Sea by the International Marine Organization (IMO) as a Particularly Sensitive Sea Area (PSSA). This indicates that specific measures (such as ship routing and strict vessel requirements) can be used to control the maritime activities in this area to protect coastal states, flag states and the environmental and shipping community.

Although the Baltic Sea is a shelf sea connected to the Atlantic Ocean, it has very limited water exchange with the ocean via the Danish Straits. The background for its internal dynamics is formed through the interplay between (i) inflowing saline, dense waters from the North Sea flowing into the bottom layer, (ii) less dense, fresh riverine waters flowing into the system in the upper layer and (iii) the complicated geometry and bathymetry of the basin (Leppäranta and Myrberg, 2009). This interplay leads to the formation of an almost permanent, strong density stratification and substantial spatial salinity gradients (Leppäranta and Myrberg, 2009). The sea is micro-tidal and is not host to any persistent jet currents. Pronounced salinity gradients and rich meso-scale dynamics (associated with a small internal Rossby radius that is on the order of 10 km in the open Baltic Sea and 2–4 km in its sub-basins) distinguish this basin from large lakes and create a similarity of its basic processes to those occurring in the open ocean (Feistel et al., 2008). Its circulation pattern normally consists of a number of synoptic-scale circulation cells superposed by density- and buoyancy-driven currents all of which are substantially modified by the bathymetry and geometry. In the winter season, the northern parts of the Baltic Sea are covered by ice, and during severe winters it can be completely frozen.

Due to its small size, extensive archipelago regions and shallow depths, one of the most sensitive domains of the Baltic Sea is the Gulf of Finland. Over the years, shipping activity has increased and continues to increase in the gulf due to the economic growth of the surrounding countries and increased oil export from Russia (Knudsen, 2010). The Helsinki Commission (HELCOM) has identified within the gulf (thus within the PSSA) several Marine Protected Areas (MPAs) (Fig. 1). These areas, due to their ecological, social or scientific characteristics, are either more vulnerable and/or of larger importance than other areas. Similar to many other domains of the World Ocean, most of the MPAs in the Baltic Sea are along shipping lanes or near human centers of activity, and thus, the chance of

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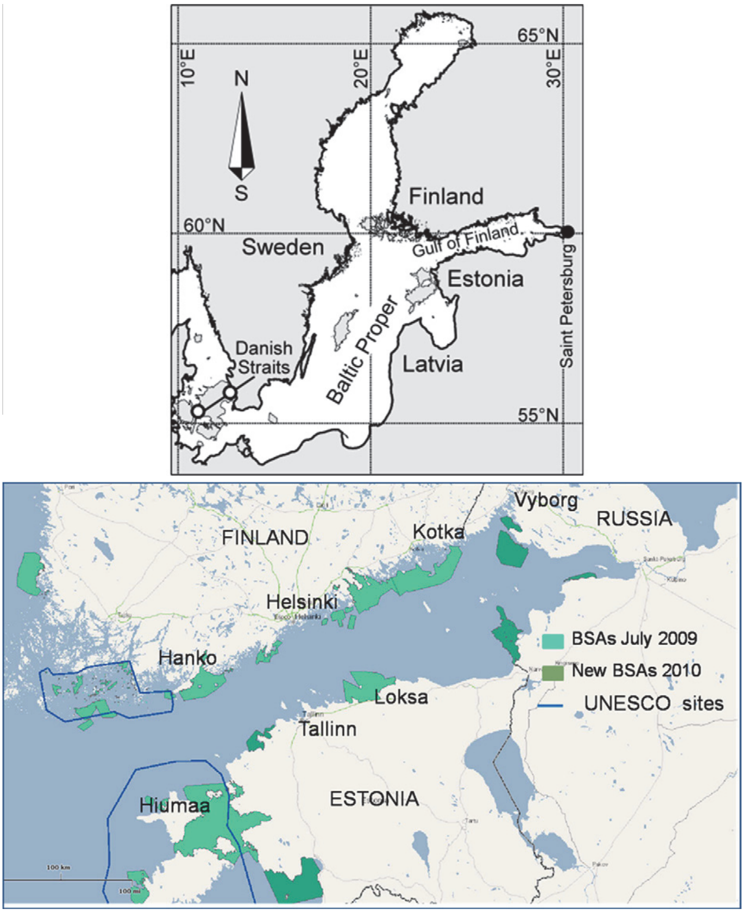

Fig. 1. Location scheme of the Baltic Sea and Gulf of Finland (above) and the Marine Protected Areas in the Gulf of Finland (UNESCO sites and Baltic Sea Protected areas (BSA)) used in this study (below). Sourced from HELCOM.

chemical and biological pollution is also high in these regions (Boersma and Parrish, 1999).

The Gulf of Finland, located in the northeastern extremity of the Baltic Sea, is an elongated sub-basin with a length of ~400 km, width of 48–125 km and a mean depth of 37 m. The gulf receives a large amount of freshwater due to the River Neva at its eastern end and experiences intense water exchange through an open connection with the main Baltic basin at its western entrance (Andrejev et al., 2004). This results in a large spatio-temporal variability in salinity and temperature, both in vertical and horizontal directions. Due to its combination of an extensive archipelago and shallow depths, this area probably hosts the most interesting dynamical features (meso-scale eddies, fronts, specific mixing conditions, optional ice cover and the possibility of anticyclonic gyres in the surface circulation) among the parts of the Baltic Sea (Andrejev et al., 2004; Soomere et al., 2008, 2011a). The small internal Rossby radius (typically 2–4 km) makes the gulf particularly challenging for numerical modeling studies.

Due to the strong stratification, the impact of direct atmospheric forcing on the Baltic Sea water masses is usually restricted to the upper layer, with a typical thickness of 40–80 m. This decoupling is even more substantial in summer when a well-mixed surface layer, with a typical thickness of 15–20 m (and even smaller in the Gulf of Finland where wave-induced mixing is less intense), is formed due to heating. Consequently, a large part of the energy supplied by wind to the water masses is concentrated in the currents in the uppermost layer. These currents thus play a relatively large role in the transport of pollution in the Baltic Sea in contrast with other basins with weaker stratification.

Even though there are measures in place to protect the marine environment, accidents do occur in the maritime shipping industry. The consequences frequently endanger the PSSAs and MPAs (Dalton and Jin, 2010). For example, the *Full City* vessel accident led to the release of an estimated 300 tons of oil into the Skagerrak, next to the Baltic Sea, in 2009 (Broström et al., 2011). Several dozen tons of oil were released into the Gulf of Finland in two accidents in 2006 (Soomere and Quak, 2007). In 2003, the Polish cargo ship *Gdansk* collided with the Chinese Bulk ship *Fu Shan Hai*, and extensive resources were mobilized to restrict the oil leakage (HELCOM, 2009). The most severe event was the case of the MV *Prestige*, which set sail from Saint Petersburg, Russia. On reaching Galicia, Spain, she leaked 63,000 tons of heavy fuel oil in 2002.

The commonly used approach to manage potential maritime pollution is to develop quick remedial action plans in the event of an accident (e.g. Keramitsoglou et al., 2003; Kostianoy et al., 2008, among many others). Another, rapidly developing approach is the preventive maritime planning strategy; for instance, the optimization of shipping routes (Schwehr and McGillivary, 2007) or designation of MPAs or PSSAs and their policies and regulations (Ko and Chang, 2010; Hassler, 2011; Rusli, 2012) may be employed to account for the effects of a pollution accident before it actually happens.

For both approaches, knowledge of the path of the pollutants' transport is necessary to determine where they may travel and the time pollutants may take to reach a particular area. Pollution propagation is governed by the complex interaction of currents, wind, waves, tides, density plumes, and a number of physical and chemical processes (e.g., weathering of oil pollution, dispersion of chemicals and change in the radioactivity level of nuclear waste). While several pollution models exist that consider all the necessary oceanic parameters and properties of the pollutants, in simulating the path of the pollutants they still suffer from some limitations that result in imperfect predictions (Ambjörn, 2007). The direct impact of wind and waves on the propagation of pollution and objects in the upper layer of the sea is relatively well understood (Ardhuin et al., 2009). Although there exist successful attempts to replicate the three-dimensional (3D) propagation of oil spills (Chang et al., 2011), modeling and tracking of the pathways of pollution particles and the regions of their impact is extremely complicated, even for small sea domains (Vandenbulcke et al., 2009; Fingas, 2011).

This situation calls for us to take a step back and make more efforts towards a better understanding of current-driven transport, which can be applicable to pollution propagation. A feasible way to do this is to use statistical methods for the quantification of transport properties (Abascal et al., 2010; Soomere et al., 2010). Because most of the transport occurs in a Lagrangian framework, a reasonable method is to use the paths of current-driven trajectories as single realizations of pollution pathways (Ohlmann and Mitarai, 2010; Soomere et al., 2011b; Chang et al., 2011). Approaches combining these two constituents are becoming increasingly popular in studies related to the transport of different objects and substances in the marine environment, from fish eggs and larvae to toxic algae, oil pollution and marine litter (Korotenko et al., 2004, 2010; Chrastansky and Callies, 2009; Korajkic et al., 2009; Gräwe and Wolff, 2010; Havens et al., 2010; Mariani et al., 2010; Monzon-Argullo et al., 2010; Yoon et al., 2010). The basic idea is that, through modeling the Lagrangian transport of currents, we are presumably able to simulate the statistical properties of the paths of possible pollutants.

In the Baltic Sea, several studies have been performed using different perspectives to determine how pollution may affect the environment and, specifically, the MPAs. Aps et al. (2009a) considered the MPAs at the southern coast of the Gulf of Finland using a Bayesian network and from the perspective of the species that would be most affected by pollution. In addition, a geographic information system database combined with Bayesian networks was used to select the best available oil spill response and to evaluate the overall environmental impact of a spill (Lecklin et al., 2011; Aps et al., 2009b). These studies mostly suggest remedial actions after the accidents have actually occurred.

An increasing number of studies have focused on preventive optimization of the consequences of potential accidents in terms of current-driven hits of pollution to vulnerable domains. These studies used high-resolution 3D circulation models specifically tuned to the Baltic Sea conditions, different models to simulate the path of the current-driven possible pollutants and statistical analyses. Analyses were performed for the southwestern Baltic Sea (Lu et al., 2012), the Baltic Proper (Viikmäe et al., 2011; Meier and Höglund, 2012) and the Gulf of Finland (Andrejev et al., 2011; Soomere et al., 2011b) using both Lagrangian (Soomere et al., 2011c) and Eulerian transport approaches (Meier and Höglund, 2012). The results have been combined with models for optimization of ship routes to determine the areas that are statistically safer to travel in terms of the risk of coastal pollution (Andrejev et al., 2011; Soomere et al., 2011b) and to specify the (equiprobability) line that would equally divide the costs of pollution on opposite coasts (Soomere et al., 2010, 2011c; Viikmäe et al., 2011).

However, the underlying approximations of these efforts were not particularly realistic. Most of the studies listed in the previous paragraph assumed that (i) the most vulnerable areas were nearshore and (ii) the "values" of all nearshore areas were equal. As most of the MPAs consist of specific nearshore and offshore areas (Fig. 1), the patterns of hits to the MPAs may considerably differ from patterns of hits to the entire nearshore area (cf. Viikmäe et al., 2010). In this study, we focus on scenarios of current-driven pollution transport in a more realistic environment where the "value" of different nearshore or offshore areas may be substantially different. We keep the perspective of preventive optimization of the costs before an accident actually occurs. The central goal is to establish whether any realistic ways may exist to preventively protect a set of existing or planned MPAs by means of adjusting the location of possible accidents within confined waters where a general shift of the fairway further offshore (Schwehr and McGillivary, 2007) is not possible.

The configuration of the set of existing MPAs in the Gulf of Finland in 2009–2010 (Fig. 1) is used as a test case. Following other authors (Andrejev et al., 2011; Soomere et al., 2011b), we concentrate on the properties of current-driven transport in the uppermost layer. This framework is directly applicable to persistent, neutrally buoyant 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., Periáñez, 2004). This setup is only conditionally valid for oil pollution, as it does not consider other metocean drivers, chemical processes, buoyancy effects, etc. The use of the current field to simulate the drift of oil pollution is most applicable 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) and also during the presence of ice cover (up to 6 months in some years; Sooäär and Jaagus, 2007) when the current field is almost totally disconnected from direct atmospheric influence. The setup in use is, however, of clear value to improve the practical use of the intrinsic dynamics of currents to preventively reduce the costs of accidents at sea (Soomere and Quak, 2007).

The basic difference from the above-mentioned studies is that the cost of accidents that result in pollution that would impact MPAs is assumed to be higher than the cost of similar accidents that would leave the MPAs intact. Using velocity field data, tracking of the Lagrangian motion of the current-driven particles and classical statistical methods, we investigate, for the case of a pollution accident along the fairway, which MPAs would most likely be hit by current-driven pollution and the sources along the fairway that would affect these MPAs the most. We also establish which sections of the fairway offer the most danger to the existing MPAs. This information is directly applicable to marine management when designing fairways or deciding the boundaries of MPAs or possible policies.

2. Methods

We follow the first three steps of a four-step technique (Soomere et al., 2011b) to quantify the potential of different sea areas to be affected by current-driven pollution. To correctly predict the path of pollutants, first, extensive knowledge of the velocity field of the sea area is required. Second, a Lagrangian model is applied to reconstruct the transport of water particles in the uppermost layer of the sea, which is assumed to imitate the propagation of pollution. In contrast to the efforts of other authors (Soomere et al., 2011b, 2011c; Meier and Höglund, 2012) to quantify the entire offshore area, we limit our calculations to the vicinity of the major fairway, similar to Chrastansky and coworkers (Chrastansky and Callies, 2009; Chrastansky et al., 2009). This choice is justified by the virtual impossibility of freely adjusting the location of the sailing route owing to other constraints (e.g., water depth), safety considerations (e.g., avoiding sailing exactly above the major gas pipeline) and political matters (as a large part of the Gulf of Finland belongs to territorial waters of three states). Third, a statistical analysis of the Lagrangian trajectories is performed to determine the patterns and trends of the transport. We focus on the quantification of links between the potential locations of pollution and the MPAs and leave out the fourth step of the technique – the optimization of the fairway.

In this study, we use the 3D velocity data for the Gulf of Finland calculated using the Rossby Centre Ocean (RCO) circulation model (Meier et al., 2003; Meier, 2007) and provided by the Swedish Meteorological and Hydrological Institute in the framework of the BONUS+ BalticWay cooperation. The RCO is a Bryan-Cox-Semtner primitive equation circulation model with a free surface and open boundary condition in the northern Kattegat (North Sea) that covers the entire Baltic Sea with a regular rectangular grid having a horizontal resolution of 2×2 nautical miles. It is coupled to a Hibler-type sea ice model and thus appreciably replicates the presence of ice cover, the changes in the sea-atmosphere interaction during the ice cover, and the relevant changes to the dynamics of currents in the entire water column, including the uppermost layer.

The model uses 41 layers delimited by *z*-coordinates, with thicknesses from 3 m close to the surface and increasing to 12 m at $\geqslant$250 m depth. The numerically simulated motion of the uppermost layer (depths 0–3 m) apparently mimics, to a large extent, the impact of wind (in particular, the wind-driven Ekman layer) on the substances located in this layer. As mentioned above, the direct impact of wind on objects on top of the water is intentionally ignored. The velocity dataset used in this study was for the period 1987–1991 in order to make the results comparable with those of previous studies (Soomere et al., 2011c). The particular model run was forced with numerically reproduced realistic meteorological data (wind data at the 10 m level, 2 m air temperature, 2 m specific humidity, precipitation, total cloudiness and sea level pressure fields) from a regionalization of the ERA-40 re-analysis over Europe, which used a regional atmospheric model with a horizontal resolution of 25 km during 1961–2007 (Höglund et al., 2009; Samuelsson et al., 2011). As the atmospheric model tends to underestimate wind speed extremes, the wind is adjusted using simulated gustiness to improve the wind statistics. Standard bulk formulas are used to calculate the air-sea fluxes over open water and over sea ice. For further details of the model set-up and validation, the reader is referred to Meier (2001, 2007) and Meier et al. (2003). The model apparently resolves the major part of the reaction of water masses and associated velocities to realistic atmospheric and lateral forcing over the entire five-year period in question, including periods with ice cover. However, the model does not account for the roughness of the lower surface of the ice (e.g., ridging).

The Lagrangian trajectories of selected water particles (which are assumed to represent the pathways of current-driven motion of pollution) are computed from the RCO velocity fields using the TRACMASS model (Döös, 1995; de Vries and Döös, 2001). The calculations are performed in the off-line mode (after the circulation model has been integrated and the velocity fields have been stored, once every 6 h). The velocities defined using a B-grid cell-staggering technique (at the corners of each cell) in the RCO model are recalculated for a C-grid (at the walls of each grid cell) for use in TRACMASS by simple linear interpolation. The zonal and meridional displacement of the trajectory inside each grid box and the time it takes for it to reach the wall of the neighboring cell are calculated using an analytical solution to the relevant linear ordinary differential equation. The smallest transit time in either direction indicates at which wall of the grid box the trajectory will exit (de Vries and Döös, 2001). This procedure of building a trajectory is repeated in each subsequent cell and/or time instant.

The point sources are placed along a line that roughly follows the major fairway from the Baltic Proper to Saint Petersburg. The fairway is represented as a belt with a width of three grid cells (about 16 km, that is, about 1/3 of the technically navigable area in the gulf in its narrowest section) covering the majority of possible sailing lines (Fig. 2) and consisting of 309 grid cells in the RCO model. One particle is selected at the center of each of these cells. As we focus on the role of relatively large-scale current-driven transport, we do not use any artificial means to replicate the impact of subgrid turbulence. Such means might improve the formal statistics of the spreading of initially closely located particles or tracers (see Andrejev et al., 2011 for discussion) and/or affect the rate of hitting the nearshore area (Broström et al., 2011), but they apparently do not improve the statistics of current-driven transport of pollution to offshore-located domains.

Particles that leave the Gulf of Finland through the open boundary with the northern Baltic Proper are ignored in the calculations. According to Viikmäe et al. (2010), they usually form less than 10% of the all particles released in the entire Gulf of Finland. As the velocity component normal to the rigid boundaries (bottom and coast) vanishes in the boundary cells, the trajectories calculated using the TRACMASS code never reach such a boundary. The process of beaching pollution is usually solved indirectly (for example, by including artificial spreading of the Lagrangian trajectories (Andrejev et al., 2010)) or by defining a control line for coastal hits at a certain distance from the geographical coast (Broström et al., 2011).

In order to create a sufficiently large pool of independent trajectories, the period of interest was divided into 20 day-long, partially overlapping sections (time windows). The calculations started at 00:00 on 01.01.1987 and were performed until 24:00 on model day 20.01.1987. The coordinates of the instantaneous trajectory points were saved once every 6 h. A new set of calculations started at model day 10, at 00:00 on 10.01.1987 and was again performed for 20 days. The process was repeated for the remaining years of interest and resulted in a set of 180 trajectories for each grid cell.

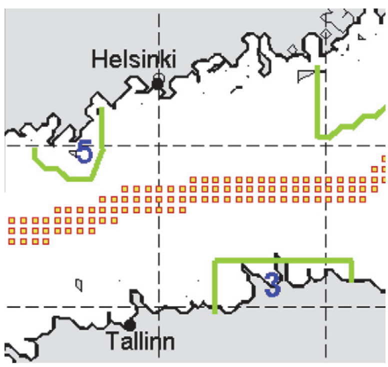

Fig. 2. A selection of the locations of the potential source points along the fairway in the sea area between Tallinn and Helsinki.

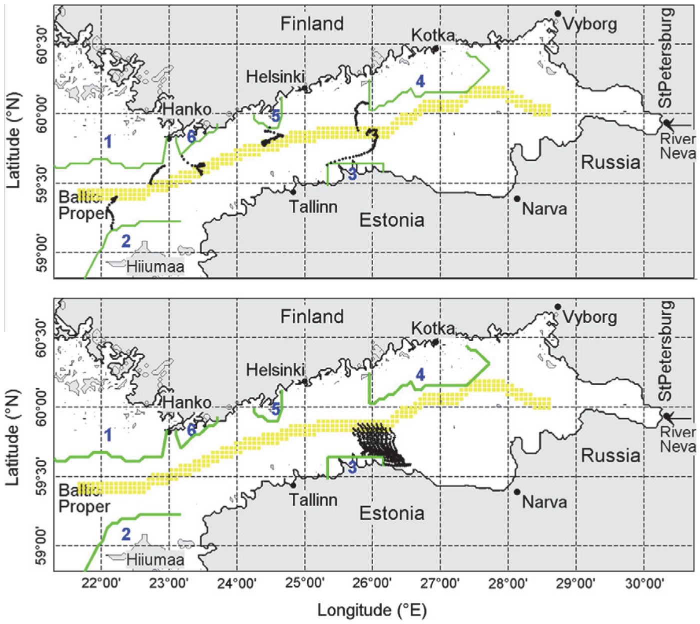

Fig. 3. Examples of the sources (cells along the yellow line) and shapes (black dotted lines) of trajectories the MPA (upper panel); the set of trajectories that hit MPA 3 during 20 days in July 1988 (lower panel). MPA 1 is the Southern Archipelago Sea, MPA 2 – the West Estonian Archipelago Biosphere Reserve, MPA 3 – Lahemaa National Park, MPA 4 – the Eastern Gulf of Finland, MPA 5 – the Kirkkonummi Archipelago, MPA 6 – the Tammisaari Archipelago.

Estimates provided in Viikmäe et al. (2010) suggest that this choice allows proper resolution of the spatial distribution of the probability of coastal hits and the time it takes for the pollution to reach the coast. As hits to the offshore MPAs are apparently much more frequent (there is no boundary effect that redirects motion, as there is near the coast), this selection is apparently suitable for our purposes.

The locations of the six MPAs used in this study (designated Baltic Sea protected areas and UNESCO sites; Fig. 3, Table 1) were obtained from the HELCOM Map and Data service provided on the web (maps.helcom.fi/website/mapservice/index.html). As there have been minor changes in the size and shape of the MPAs over the years (HELCOM, 2010), the configuration used in this study reflects an approximation to the present MPAs with somewhat smoothed borders. Using the above-described pool of trajectories, we identified how many particles from which fairway points travelled to each of the MPAs. A hit was counted when a trajectory entered a MPA for the first time (Fig. 3). The further behavior of this trajectory was ignored.

Table 1
The average number of hits in 1987–1991 for each of the MPA, the standard deviation (std) of this number for single years, the extension of the MPA in the east–west direction, the distance from the fairway, the average percentage of the hits among the entire pool of trajectories for the period 1987–1991, the average length of the fairway section from where the hitting trajectories started, and the std of the relevant values for single years.

MPA	Average # of hits	STD	Length of MPA (km)	Distance from fairway (km)	(%)	Length (km)	STD
1	17	1.98	89	15	39	147	26.9
2	17	3.01	85	17	31	116	11.3
3	5	2.55	44	22	34	128	34.5
4	36	5.08	96	0	56	211	24.5
5	14	3.37	22	11	39	147	18.7
6	10	3.36	33	15	33	124	31.4

3. Results

The model fairway is located almost at the centerline of the gulf. In the central part of the gulf it deviates a little bit to the south, while in the widest part of the gulf it deviates to the north due to the presence of islands. The MPA most remote from the fairway is MPA 3 (Lahemaa), whereas the fairway practically touches the southeastern border of MPA 4 (Eastern Gulf of Finland). The MPAs at the entrance to the gulf (1 and 2) are located more-or-less symmetrically with respect to the model fairway, whereas the four MPAs in the gulf interior are shifted with respect to each other in the east–west direction. This configuration is basically favorable for locally relocating the sections of the fairway that provide the highest danger to the MPAs.

MPA 4 (situated in the northeastern section of the gulf within the vicinity of Kotka) was the most frequently affected by pollution (Fig. 4). This result was not unexpected because the MPA is located in close proximity to the fairway. Another reason for frequent hits to this MPA may be the slow anticyclonic gyre (visible in a 5-year average of surface currents in this domain (Soomere et al., 2011a)) that causes (statistically) frequent displacement of current-driven transport from the fairway to the north, with subsequent hits to this MPA. MPAs 1 and 2, located in the western section of the gulf, had the second highest rate of hits. This feature may stem from a strong outflow adjacent to the Finnish coast (Andrejev et al., 2004) that tends to bring particles that deviate to the north of the fairway to MPA 1. MPA 2 is possibly impacted by a combination of strong mesoscale activity in the entrance area of the Gulf of Finland (Andrejev et al., 2004) and intense net transport along the southern coast of this area (Soomere et al., 2011a). The western side of MPA 2 also tended to be a high risk area (Soomere et al., 2010).

Somewhat surprisingly, the smallest MPA, number 5, located between Helsinki and Hanko, had a relatively high number of hits

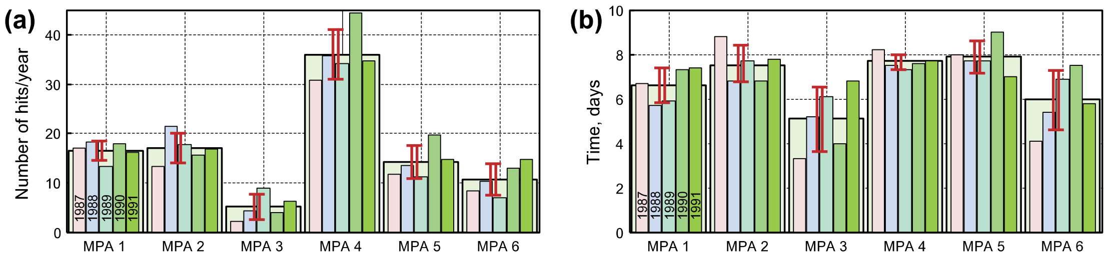

Fig. 4. The average number of hits (left panel) and the average time (days, right panel) it took to reach the MPA in 1987–1991 (wide background bar) and for single years (narrow bars) and the relevant standard deviation for each of the MPAs.

even though it lies at some distance from the fairway (Table 1). A probable reason for such frequent hits might be a cyclonic gyre that at times becomes evident in the surface layer of the western part of the gulf. Viikmäe et al. (2012) reported possible strong strain in this region associated with meridional currents that at times extended from coast to coast. This feature was speculated to reflect the existence of a semi-persistent front between water masses with different properties (Viikmäe et al., 2012). On average, particles hitting this MPA have already spent substantial time in the offshore region, from 6 to 8 days for most of the trajectories that hit the MPA (Fig. 4). During this time, a large part of pollution could be lost to weathering.

Another small MPA, number 6, had the second-lowest frequency of hits. The typical time for the hits to occur was, on average, 6 days, as for MPA 1. An interesting pattern of hits was detected for MPA 3. It had the lowest frequency of hits, however when a hit occurred it took, on average, only 5 days to reach the MPA. This property suggests that semi-persistent currents that carry surface water masses almost across the entire gulf during certain seasons (Soomere et al., 2010) may substantially affect this MPA. Also the sources of hits encompassed a wide portion of the fairway. Therefore, it could be speculated that the majority of hits to MPA 3 occurs during certain specific surface flow regimes. Analysis of the wind data for that period did not show a strong relationship between the hits and properties of the wind. Thus, it is possible that particular events (e.g., upwelling or downwelling) may influence the current-driven transport to MPA 3.

The relatively small standard deviation of the number of hits over the entire pool of trajectories suggests that the estimate for the number (or frequency) of the hits for all the MPAs by pollution stemming from the fairway is reliable. A relatively large interannual variation is seen for MPA 4. The count is almost the same for MPAs 2, 5, and 6, located in the northern gulf. The standard deviation was relatively low for MPAs 1 and 3, located in the southern gulf.

Table 1 shows the relationship between the distance and the average number of hits for the study period. Although the model is relatively crude (there were a couple of outliers for MPA 5 and 6) and the number of hits forms only a small fraction of the entire pool of released trajectories, still, an approximately linear relationship $N(x) \approx -1.3x + 36.7$ exists between the number of hits N and the distance x (km) from the fairway with a correlation coefficient

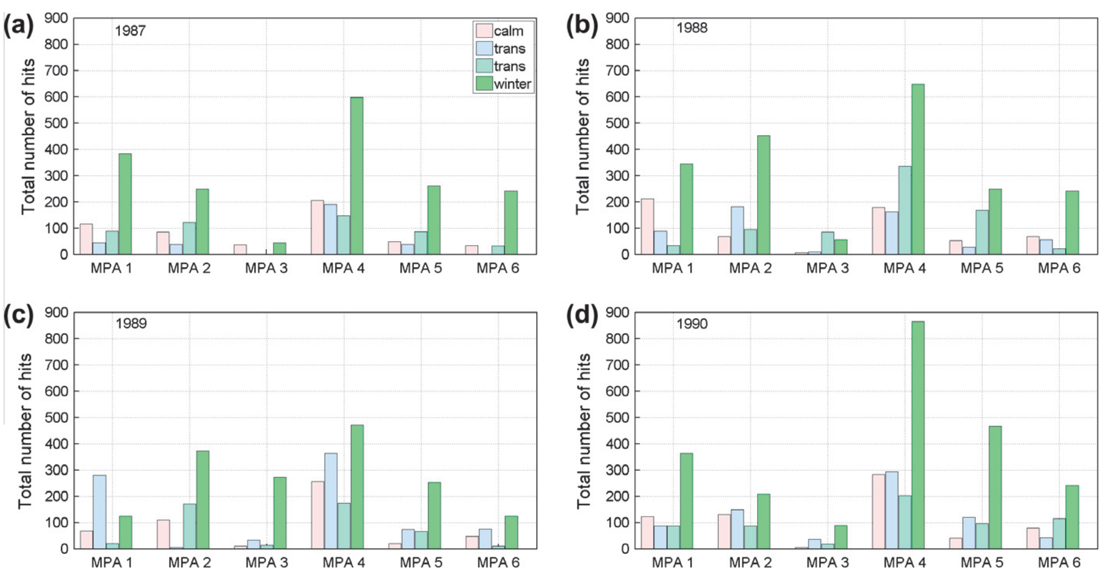

Fig. 5. Seasonal distribution of total number of hits for the windy season, transitional period from windy to calm (March–April), summer calm season and the transitional period from calm to windy (August–September) for 1987–1990.

of −0.985, which indicates that a strong relationship exists. This relationship may allow one to predict a reasonable distance for the location of the fairway in order to reduce the probability that an MPA will be polluted and thus reduce the aggregated environmental risks for this MPA.

Given the substantial seasonal variation in wind speed and current patterns in the study area (Andrejev et al., 2011), it is natural to expect that both the probability of hits and the time they take may also vary over different seasons. Following an analysis of net surface transport (Soomere et al., 2011a), the windy (winter) season was associated with October–February, and the calm season with May–July. The windy (winter) months normally provided the largest number of hits (Fig. 5). The only exceptions are for MPA 3 (situated in the southern gulf close to the town of Loksa) in 1988 and for MPA 1 (situated at the northern entrance of the gulf) in 1989 where the largest counts of hits occurred during transitional months. In the calm season, the lowest number of hits occurred in most of the MPAs.

3.1. Sources of hits from the fairway

Fig. 3 suggests that each MPA might be associated with a specific section of the fairway from which the majority of its hits stem. The hits, however, arrived to all MPAs from quite long sections of the model fairway. Although MPA 4 was only a little bit longer than MPA 1 or 2, it received, on annual average, hits from points that filled 56% (>211 km) of the fairway length. The source points were mainly from the middle to the eastern section of the fairway (Fig. 6). This is not completely unexpected, because this MPA is located at a very small distance from the fairway. It was also not unexpected that MPA 4 had the most hits occurring in the 5-year period. Unexpectedly, many hits to this MPA stemmed from sections of the fairway located far to the west of this area. The relevant trajectories entered MPA 4 through its eastern border (Fig. 3). This feature shows that the overall cyclonic circulation pattern of water masses in the Gulf of Finland (Leppäranta and Myrberg, 2009) is not necessarily valid for the surface currents. It also vividly demonstrates how complicated the current-driven patterns of pollution propagation in this water body can be, and also is consistent with the occasional occurrence of the anticyclonic gyre (Soomere et al., 2011a) in the middle region of the gulf.

Although MPA 1 and MPA 5 have largely different sizes and locations, their sources of pollution covered about 39% (about 147 km) of the fairway length from its western to middle parts. MPAs 2, 3 and 6 (located at the largest distance from the model fairway) had quite different lengths (Table 1) but still almost equal lengths (on average about 34%) of the fairway sections that often served as sources of their pollution.

There exist strong variations in the potential of different points of the described sections of the fairway to be a source of pollution for particular MPAs. The experiments performed did not reveal any clear pattern of links between particular fairway points and single

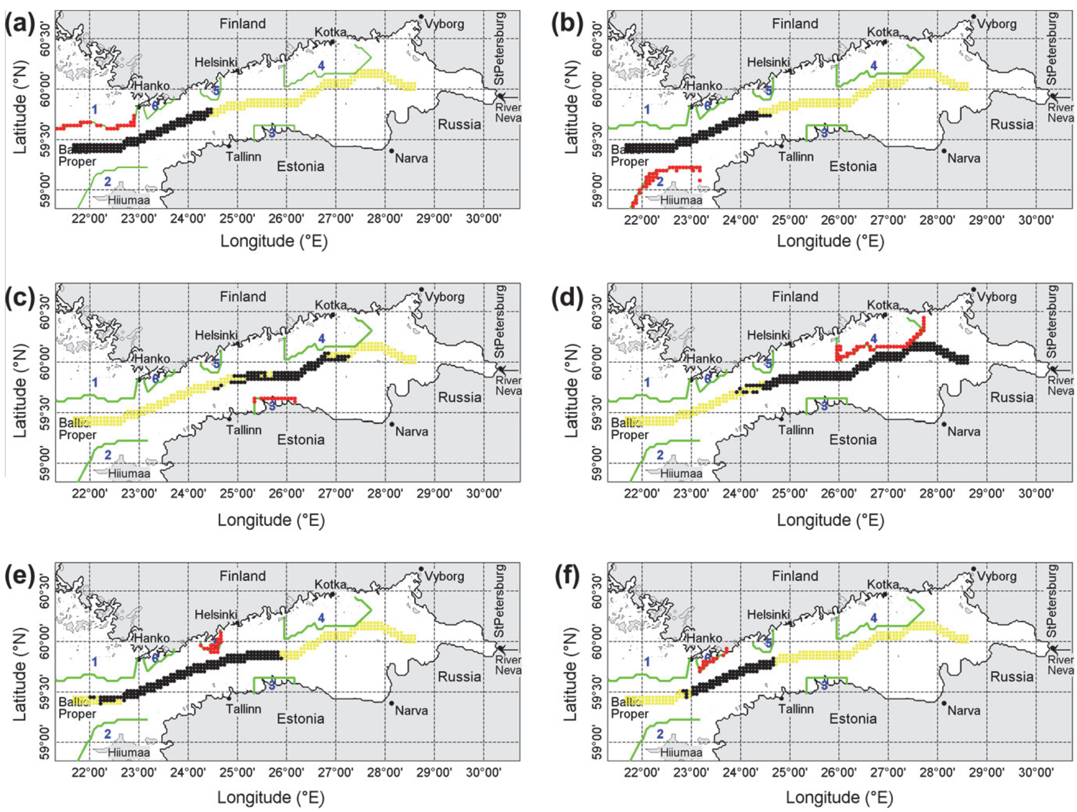

Fig. 6. The starting (black) and destination (red) points of the trajectories for single MPAs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

MPAs. Such links, however, may exist for single seasons, but much more massive calculations are evidently necessary to highlight them.

4. Discussion

The results presented characterize the role of surface currents in the transport of contaminants located in the uppermost layer in the Gulf of Finland on a time scale of the first weeks, and in this way, contribute to our understanding of the potential use of the dynamics of currents for environmental management of offshore activities. Although several underlying assumptions are not perfect, the model apparently represents the propagation of several types of pollution, especially in nearly calm conditions and under ice cover. Both of these conditions occur in the study area during several months of the year. A major approximation is that we did not use any means to replicate the impact of subgrid turbulence on the trajectories. A parameterization of subgrid effects may improve the statistics of the spreading of closely located particles (see Andrejev et al., 2011 for discussion) and/or affect the hits to the nearshore sites (Broström et al., 2011). However, it is unlikely that it would substantially improve the statistics of the current-driven transport of pollution to offshore-located domains.

The results first indicate that the patterns of Lagrangian transport may be even more complicated than expected from the classical picture of the dynamics of surface currents (Andrejev et al., 2004; Leppäranta and Myrberg, 2009). In particular, the remote impact of potential accidents via the current-driven transport extends not only over the entire North–South cross-section of the gulf but also over almost 60% of the length of the gulf. As the instantaneous current velocities are weakly correlated with the local wind properties in this water body (because of the importance of meso-scale effects in the dynamics (Leppäranta and Myrberg, 2009)), the actual variability of pollution transport under the impact of wind and waves is apparently even larger.

The key result is that the MPAs located at the entrance to the gulf and in its easternmost section are the most at risk of being polluted. There exists an almost linear relationship between the distance from the fairway and the number of hits. This outcome not only fits well with some of the previous studies but also shows the importance of the underlying oceanographic processes influencing the transport pattern and thus possible pollutants.

MPA 4 (Eastern Gulf of Finland) received the most hits, evidently due to its size and proximity to the fairway. In previous studies, this area was considered the most suitable for fairways in terms of overall probability of current-driven coastal pollution (Andrejev et al., 2011). This disagreement vividly shows how important is the proper choice of the cost function for such estimates. A relatively large number of hits to MPA 1 (Southern Archipelago Area) and MPA 2 (West Estonian Archipelago Biosphere Reserve) may be partially related with their substantial extensions into the offshore region. Note, however, that the relevant nearshore domains also had high rates of being hit (Viikmäe et al., 2011). Moreover, Aps et al. (2009a) found that the western part of the southern nearshore region of the gulf is the most vulnerable in terms of species that would most likely be affected by an oil spill.

Surprisingly, MPA 4 seems to be possibly impacted even by accidents occurring far to the west of this MPA, including areas from which pollution is usually expected to drift out of the gulf owing to the persistent flow patterns (Andrejev et al., 2004). This result indicates that there might not be a simple way to reduce the probability of pollution for all of the MPAs by shifting the fairway. The established patterns of potential sources and pollution propagation destinations show that such solutions might still be possible for single MPAs such as MPA 6 (Tammisaari Archipelago).

The largest MPAs, located in the eastern part of the gulf (Eastern Gulf of Finland MPA 4) and at the entrance to this water body (MPAs 1 and 2), are the most likely to be affected in the event of a ship accident. The largest number of hits tended to take place in the windy season. Consequently, the number of hits and the extension of the potential sources of pollution along the model fairway may be to some extent underestimated.

The potential sources of hits for all of the three largest MPAs encompass 31–39% (MPAs 1 and 2) or even 56% (MPA 4) of the length of the fairway. This feature makes questionable the possibility of preventive relocating of accidents. More importantly, it raises the question of the sensibility of designating current or new MPAs or possibly producing new protected habitat areas for sensitive species in domains that have too high a chance to be impacted. As it would be impossible to substantially reduce the offshore activities in the Gulf of Finland, the results vividly demonstrate the importance of having strict policies and regulations for offshore activities to protect the environment in the western and easternmost sections of the gulf from pollution. The largest chances for reducing the probability of certain MPAs to be polluted seem to exist during certain seasons in the middle sections of the gulf.

The problem of determining the MPAs most at risk of maritime pollution and suggestions for the environmental management of the nearby human activities have been discussed from many perspectives. A general feature of these debates is the extremely large variation in the predicted outcome depending on the particular viewpoint of the analysis (Lidskog and Elander, 2012). We hope that the presented material will pave the way towards a less qualitative decision-making process and will assist marine management by providing a first clue to a quantitative assessment of remote impacts to vulnerable domains via a normally concealed mechanism. Even if the method and results presented are not detailed enough to exactly characterize the risks for particular MPAs of different shapes, sizes or distances from the fairway, they still highlight a different perspective on the MPAs most at risk and the extent of the geographical location of sources of risks for these areas. A wide use of such estimates is definitely valuable for making decisions about fairway design in the vicinity of vulnerable or valuable sea areas, delimiting MPAs, or developing policies and shipping precautions in these areas.

Acknowledgements

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References

Abascal, A.J., Castanedo, S., Medina, R., Liste, M., 2010. Analysis of the reliability of a statistical oil spill response model. Mar. Pollut. Bull. 60, 2099–2110.

Ambjörn, C., 2007. Seatrack Web, forecasts of oil spills, a new version. Environ. Res. Eng. Manage. (Aplinkos tyrimai, inžinerija ir vadyba) 3 (41), 60–66.

Andrejev, O., Myrberg, K., Alenius, P., Lundberg, P.A., 2004. Mean circulation and water exchange in the Gulf of Finland – a study on three-dimensional modeling. Boreal Environ. Res. 9, 1–16.

Andrejev, O., Sokolov, A., Soomere, T., Värv, R., Viikmäe, B., 2010. The use of high-resolution bathymetry for circulation modeling in the Gulf of Finland. Estonian J. Eng. 16, 187–210.

Andrejev, O., Soomere, T., Sokolov, A., Myrberg, K., 2011. The role of spatial resolution of a three-dimensional hydrodynamic model for marine transport risk assessment. Oceanologia 53 (1-TI), 309–334.

Aps, R., Fetissov, M., Herkül, K., Kotta, J., Leiger, R., Mander, U., Suursaar, Ü., 2009a. Bayesian inference for predicting potential oil spill related ecological risk. In: Guarascio, M., Brebbia, C.A., Garzia, F. (Eds.), Safety and Security Engineering III. WIT Transactions on the Built Environment 108, pp. 149–159.

Aps, R., Herkül, K., Kotta, J., Kotta, I., Kopti, R., Leiger, R., Mander, U., Suursaar, Ü., 2009b. Bayesian inference for oil spill related Net Environmental Benefit Analysis. In: Brebbia, C.A., Benassai, B., Rodriguez, G.R. (Eds.), Coastal Processes. WIT Transactions on Ecology and Environment 126, pp. 235–246.

Ardhuin, F., Mariė, L., Rascale, N., Forget, P., 2009. Observation and estimation of Lagrangian, Stokes and Eulerian currents induced by wind and waves at the sea surface. J. Phys. Oceanogr. 39, (2820–2838).

Backer, H., Leppänen, M., 2008. The HELCOM system of a vision, strategic goals and ecological objectives: implementing an ecosystem approach to the management of human activities in the Baltic Sea. Aquat. Conserv. 18, 321–334.

Backer, H., Leppänen, J.-M., Brusendorff, A.C., Forsius, K., Stankiewicz, M., Mehtonen, J., Pyhala, M., Laamanen, M., Paulomaki, H., Vlasov, N., Haaranen, T., 2010. HELCOM Baltic Sea Action Plan – a regional programme of measures for the marine environment based on the ecosystem approach. Mar. Pollut. Bull. 60, 642–649.

Boersma, P.D., Parrish, J.K., 1999. Limiting abuse: marine protected areas, a limited solution. Ecol. Econ. 31, 287–304.

Broström, G., Carrasco, A., Hole, R.L., Dick, S., Janssen, F., Mattson, J., Berger, S., 2011. Usefulness of high resolution coastal models for operational oil spill forecast: the "Full City" accident. Ocean Sci. 7, 805–820.

Chang, Y.L., Oey, L., Xu, F.H., Lu, H.F., Fujisaki, A., 2011. 2010 Oil spill: trajectory projections based on ensemble drifter analyses. Ocean Dyn. 61, 829–839.

Chrastansky, A., Callies, U., 2009. Model-based long-term reconstruction of weather-driven variations in chronic oil pollution along the German North Sea coast. Mar. Pollut. Bull. 58, 967–975.

Chrastansky, A., Callies, U., Fleet, D.M., 2009. Estimation of the impact of prevailing weather conditions on the occurrence of oil-contaminated dead birds on the German North Sea coast. Environ. Pollut. 157, 194–198.

Dalton, T., Jin, D., 2010. Extent and frequency of vessel oil spills in US marine protected areas. Mar. Pollut. Bull. 60, 1939–1945.

de Vries, P., Döös, K., 2001. Calculating Lagrangian trajectories using time-dependent velocity fields. J. Atmos. Oceanic Technol. 18, 1092–1101.

Döös, K., 1995. Inter-ocean exchange of water masses. J. Geophys. Res. 100, C13499–C13514.

Feistel, R., Nausch, G., Wasmund, N. (Eds.), 2008. State and Evolution of the Baltic Sea, 1952–2005. Wiley, Hoboken, NJ, 703 pp.

Fingas, M.F., 2011. Buoys and devices for oil spill tracking, In: Proceedings of the 34th AMOP Technical Seminar on Environmental Contamination and Response, Environment Canada, Ottawa, ON, pp. 213–228.

Gräwe, U., Wolff, J.-O., 2010. Suspended particulate matter dynamics in a particle framework. Environ. Fluid Mech. 10, 21–39.

Hassler, B., 2011. Accidental versus operational oil spills from shipping in the Baltic Sea: risk governance and management strategies. Ambio 40, 170–178.

Havens, H., Luther, M.E., Meyers, S.D., Heil, C.A., 2010. Lagrangian particle tracking of a toxic dinoflagellate bloom within the Tampa Bay estuary. Mar. Pollut. Bull. 60, 2233–2241.

HELCOM, 2009. Reinforcing oil spill response capacity in the Baltic. Baltic Marine Environment Protection Commission. 15 pp.

HELCOM, 2010. Towards an ecologically coherent network of well-managed Marine Protected Areas – implementation report on the status and ecological coherence of the HELCOM BSPA network. Baltic Sea Environ. Proc. No. 124B, 143 pp.

Höglund, A., Meier, H.E.M., Broman, B., Kriezi, E., 2009. Validation and correction of regionalised ERA-40 wind fields over the Baltic Sea using the Rossby Centre Atmosphere Model RCA3.0. Rapport Oceanografi No. 97, SMHI, Norrköping, Sweden.

Keramitsoglou, I., Cartalis, C., Kassomenos, P., 2003. Decision support system for managing oil spill events. Environ. Manage. 32, 290–298.

Knudsen, O.F., 2010. Transport interests and environmental regimes: the Baltic Sea transit of Russian oil exports. Energy Policy 38, 151–160.

Ko, T.T., Chang, Y.-C., 2010. Integrated marine pollution management: a new model of marine pollution prevention and control in Kaohsiung, Taiwan. Ocean Coastal Manage. 53, 624–635.

Korajkic, A., Badgley, B.D., Brownell, M.J., Harwood, V.J., 2009. Application of microbial source tracking methods in a Gulf of Mexico field setting. J. Appl. Microbiol. 107, 1518–1527.

Korotenko, K.A., Mamedov, R.M., Kontar, A.E., Korotenko, L.A., 2004. Particle tracking method in the approach for prediction of oil slick transport in the sea: modeling oil pollution resulting from river input. J. Marine Syst. 48, 159–170.

Korotenko, K.A., Bowman, M.J., Dietrich, D.E., 2010. High-resolution numerical model for predicting the transport and dispersal of oil spilled in the Black Sea. Terr. Atmos. Ocean Sci. 21, 123–136.

Kostianoy, A.G., Ambjörn, C., Soloviev, D.M., 2008. Seatrack Web: a numerical tool to protect the Baltic Sea Marine Protected Areas. In: IEEE/OES US/EU-Baltic International Symposium, Tallinn, Estonia, May 27–29, 2008, IEEE, pp. 7–12.

Lecklin, T., Ryömä, R., Kuikka, S., 2011. A Bayesian network for analyzing biological acute and long-term impacts of an oil spill in the Gulf of Finland. Mar. Pollut. Bull. 62, 2822–2835.

Leppäranta, M., Myrberg, K., 2009. Physical Oceanography of the Baltic Sea. Springer, UK, 378 pp.

Lidskog, R., Elander, I., 2012. Sweden and the Baltic Sea pipeline: between ecology and economy. Marine Policy 36, 333–338.

Lu, X., Soomere, T., Stanev, E., Murawski, J., 2012. Identification of the environmentally safe fairway in the south-western Baltic Sea and Kattegat. Ocean Dyn. 62, 815–829.

Mariani, P., MacKenzie, B.R., Iudicone, D., Bozec, A., 2010. Modelling retention and dispersion mechanisms of bluefin tuna eggs and larvae in the northwest Mediterranean Sea. Progr. Oceanogr. 86, 45–58.

Meier, H.E.M., 2001. On the parameterization of mixing in three-dimensional Baltic Sea models. J. Geophys. Res. 106, C30997–C31016.

Meier, H.E.M., 2007. Modeling the pathways and ages of inflowing salt- and freshwater in the Baltic Sea. Estuar. Coast. Shelf Sci. 74, 610–627.

Meier, H.E.M., Höglund, A., 2012. Environmentally safe areas and routes in the Baltic Proper using Eulerian tracers. Mar. Pollut. Bull. 64, 1375–1385.

Meier, H.E.M., Döscher, R., Faxen, T., 2003. A multiprocessor coupled ice-ocean model for the Baltic Sea: application to salt inflow. J. Geophys. Res. 108, C3273.

Mietus M. (co-ordinator), 1998. The climate of the Baltic Sea basin, marine meteorology and related oceanographic activities, Report No. 41, World Meteorological Organisation, Geneva, 64 pp.

Monzon-Argullo, C., Lopez-Jurado, L.F., Rico, C., Marco, A., Lopez, P., Hays, G.C., Lee, P.L.M., 2010. Evidence from genetic and Lagrangian drifter data for transatlantic transport of small juvenile green turtles. J. Biogeogr. 37, 1752–1766.

Ohlmann, J.C., Mitarai, S., 2010. Lagrangian assessment of simulated surface current dispersion in the coastal ocean. Geophys. Res. Lett. 37, L17602.

Periáñez, R., 2004. A particle-tracking model for simulating pollutant dispersion in the Strait of Gibraltar. Mar. Pollut. Bull. 49, 613–623.

Rusli, M.H.B., 2012. Protecting vital sea lines of communication: a study of the proposed designation of the Straits of Malacca and Singapore as a particularly sensitive sea area. Ocean Coastal Manage. 57, 79–94.

Rytkönen, J., Siitonen, L., Riippi, T., Sassi, J., Sukselainen, J., 2002. Statistical analysis of the Baltic maritime traffic. VTT Research Report VAL34-012344, 108 pp., <www.helcom.fi/stc/files/shipping/VTTreport.pdf>.

Samuelsson, P., Jones, C.G., Willén, U., Ullerstig, A., Gollvik, S., Hansson, U., Jansson, C., Kjellström, E., Nikulin, G., Wyser, K., 2011. The Rossby Centre Regional Climate Model RCA3: model description and performance. Tellus A 63, 4–23.

Schwehr, K.D., McGillivary, P.A., 2007. Marine ship Automatic Identification System (AIS) for enhanced coastal security capabilities: an oil spill tracking application. In: Proceedings of the 2007 OCEANS Conference, Vancouver, Canada, September 29–October 04, 2007. IEEE, pp. 1131–1139.

Sooäär, J., Jaagus, J., 2007. Long-term variability and changes in the sea ice regime in the Baltic Sea near the Estonian coast. Proc. Estonian Acad. Sci. Eng. 13, 189–200.

Soomere, T., Quak, E., 2007. On the potential of reducing coastal pollution by a proper choice of a fairway. J. Coast. Res. 50, 678–682 (special issue).

Soomere, T., Myrberg, K., Leppäranta, M., Nekrasov, A., 2008. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. Oceanologia 50, 287–362.

Soomere, T., Viikmäe, B., Delpeche, N., Myrberg, K., 2010. Towards identification of areas of reduced risk in the Gulf of Finland, the Baltic Sea. Proc. Estonian Acad. Sci. 59, 156–165.

Soomere, T., Delpeche, N., Viikmäe, B., Quak, E., Meier, H.E.M., Döös, K., 2011a. Patterns of current-induced transport in the surface layer of the Gulf of Finland. Boreal Environ. Res. 16 (Suppl. A), 49–63.

Soomere, T., Andrejev, O., Myrberg, K., Sokolov, A., 2011b. The use of Lagrangian trajectories for the identification of the environmentally safe fairways. Mar. Pollut. Bull. 62, 1410–1420.

Soomere, T., Berezovski, M., Quak, E., Viikmäe, B., 2011c. Modelling environmentally friendly fairways using Lagrangian trajectories: a case study for the Gulf of Finland, the Baltic Sea. Ocean Dyn. 61, 1669–1680.

Uggla, Y., 2007. Environmental protection and the freedom of the high seas: the Baltic Sea as a PSSA from a Swedish perspective. Marine Policy 31, 251–257.

Vandenbulcke, L., Beckers, J.-M., Lenartz, F., Barth, A., Poulain, P.-M., Aidonidis, M., Meyrat, J., Ardhuin, F., Tonani, M., Fratianni, C., Torrisi, L., Pallela, D., Chiggiato, J., Tudor, M., Book, J.W., Martin, P., Peggion, G., Rixen, M., 2009. Super-ensemble techniques: application to surface drift prediction. Progr. Oceanogr. 82, 149–167.

Viikmäe, B., Soomere, T., Viidebaum, M., Berezovski, A., 2010. Temporal scales for transport patterns in the Gulf of Finland. Estonian J. Eng. 16, 211–227.

Viikmäe, B., Soomere, T., Parnell, K.E., Delpeche, N., 2011. Spatial planning of shipping and offshore activities in the Baltic Sea using Lagrangian trajectories. J. Coast. Res. 64, 956–960 (special issue).

Viikmäe, B., Torsvik, T., Soomere, T., 2012. Analysis of the structure of currents in the Gulf of Finland using the Okubo–Weiss parameter. In: Proc. IEEE/OES Baltic 2012 International Symposium "Ocean: Past, Present and Future. Climate Change Research, Ocean Observation & Advanced Technologies for Regional Sustainability", May 8–11, 2012, Klaipėda, Lithuania, IEEE, 7 pp. doi 10.1109/BALTIC.2012.6249184.

Yoon, J.-H., Kawano, S., Igawa, S., 2010. Modeling of marine litter drift and beaching in the Japan Sea. Mar. Pollut. Bull. 60, 448–463.

Paper D

Delpeche-Ellmann N., Soomere T. 2013. Using Lagrangian models to assist in maritime management of Coastal and Marine Protected Areas. *Journal of Coastal Research*, Special Issue 65, 36–41.

Using Lagrangian models to assist in maritime management of Coastal and Marine Protected Areas

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ABSTRACT

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Several previous attempts to mitigate current-driven environmental risks to the nearshore via a concealed structure of surface Lagrangian transport have assumed a constant value to the entire nearshore. We extend these attempts towards more realistic accounting for the Coastal and Marine Protected Areas (MPA). We investigate the effects shifting the present fairway would have on the amount of current-driven pollutants the MPA may receive. The Rossby Centre Ocean circulation model, the TRACMASS Lagrangian trajectory model and statistical methods were employed to identify patterns of current-driven transport in the Gulf of Finland, the Baltic Sea, for the period 1987–1991. Pollution point sources were assumed to occur along the fairway. An analysis was made on how much of the pollution travelled to each of the MPA and the time frame involved. The existing fairway passes extremely close to one of the MPA. Shifting the fairway by a small distance to the south leads to a huge decrease in the amount of pollution. However deciding to shift a fairway requires several other factors to be considered, for this may also increase the risk of pollution for other MPAs or be incompatible with the national legislation.

ADDITIONAL INDEX WORDS: *Marine Protected Areas, pollution control, Baltic Sea, fairway, Lagrangian model.*

INTRODUCTION

Coastal and marine areas which habitats some of the richest but sensitive flora and fauna are usually not only highly populated but also under increasing anthropogenic pressure in all parts of the world. A major factor of this anthropogenic pressure is potential (oil) pollution (Kachel, 2008). In order to maintain the quality of the environment and ecosystem services, protection of valuable and vulnerable areas continues to be a challenge, for accidents do occur owing to various reasons. One of the methods used to protect these sensitive environments (areas that may be: under environmental stress, contains diverse ecosystems, of cultural importance or of economic value) is the delimitation of Marine Protected Areas (MPA). Whereby MPA are placed under particular restrictions in order to conserve the environment and are usually protected by local, state, territorial, or regional authorities.

A large part of accidents associated with the release of (oil) pollution tend to occur along shipping routes. The pollution is further carried by metocean drivers (wind, waves and currents) and may reach considerable distances from the accident location. The pathways of pollution transport in the marine environment are extremely complicated and the consequences of a particular accident (in terms of the probability of pollution for specific sea and coastal areas and the time it takes for the pollution to reach vulnerable domains) substantially depend on where exactly the pollution has been released (Andrejev *et al*., 2011).

This feature opens the way for an environmental management technique for certain potentially dangerous activities, that has the goal of minimizing pollution to the most vulnerable or valuable domains, by properly adjusting the location of these activities beforehand (Soomere *et al*., 2010). This technique is based on the quantification of the offshore areas in terms of their "ability" to serve as the starting points for the transport of pollution that finally hits some valuable regions. It may also be applicable in cases where a disaster is looming, for example, as an offshore refuge location for a leaking ship. There are several examples of vessels requiring places of refuge but which were not guided accordingly in time to prevent or minimize the consequences of some of the biggest environmental disasters: the MV *Prestige* in 2002, Galicia Spain, the MV *Erica* in 2000 in the Bay of Biscal, France, or a near miss by the MV *Castor* in 2002, Spain (Maddern and Knight, 2003).

The key aspect that may assist in controlling/managing the marine pollution problem is the ability to predict the path of the pollutants, which requires a good understanding of the ocean circulation. The path of pollutants is often simulated by models that consider many oceanic parameters and properties of the pollutants. However these models still suffer from some limitations that results in imperfect predictions of a particular (oil) spill. Although there exist successful attempts to replicate the three-dimensional (3D) propagation of oil spills (Chang *et al*., 2011), tracking of the pathways of pollution particles and the regions of their impact is extremely complicated even for small sea domains and essentially 2D motions in the surface layer (Vandenbulcke *et al*., 2009).

An alternate approach employs statistical methods to determine the patterns of current transport properties. This approach usually utilizes the path of current-driven Lagrangian trajectories of single

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passive particles located within a certain surface layer as realization of pollution pathways (Ohlmann and Mitarai, 2010; Soomere *et al*., 2011a). This method is most suitable in the prediction of transport of substances that float passively in the surface layer of the ocean and are less affected by the direct impact of wind and surface waves. Whilst this approach is not always directly applicable for oil pollution, it eventually gives good results in studies related to the transport of different objects and substances in the marine environment, from fish eggs and larvae,toxic algae and up to marine litter (Korotenko *et al*., 2010; Korajkic *et al*., 2009; Havens *et al*., 2010; Mariani *et al*., 2010; Yoon *et al*., 2010; Meier and Höglund, 2012).

The Baltic Sea is the Earth's largest and relatively shallow (average depth of 54 m) brackish water body (Leppäranta and Myrberg, 2009) and is also known as one of the busiest shipping domains in the world. It habitats a unique and sensitive marine environment (HELCOM, 2010) and apparently belongs to the top ten most threatened waters in the world (Uggla, 2007). The United Nations Convention on the Law of the Sea (UNCLOS), ratified by all countries surrounding the Baltic Sea, basically defines boundaries of sea zones (for example territorial waters, contiguous zone, exclusive economic zone, high seas zones) with specific rules and rights to the boundaries. Also the vulnerability of this sea with respect to shipping activities has been signalled in the designation of the Baltic Sea (except the Russian territorial waters) by the International Marine Organization (IMO) as a Particularly Sensitive Sea Area (PSSA). Even though the PSSA regulation does not provide specific protection it provides international recognition of the special significance of a sea area and informs mariners of the importance of taking extra care when navigating in that sea area (Kuronen and Tapaninen, 2009).

The Gulf of Finland located in the eastern extremity of the Baltic Sea is a narrow and elongated sea area with an average depth of 37 m. It hosts extremely intense ship traffic and also experiences very strong anthropogenic influence. The gulf is surrounded by three nations (Russia, Finland, Estonia), with the main cities located along the coastal areas. Due to economic growth of these countries and increased oil production in Russia the maritime traffic and oil transportation has increased tremendously after the turn of the millennium and this is expected to increase (together with associated risk of shipping accidents) even further for the future (Knudsen, 2010). Further on, the Helsinki Commission (HELCOM) has identified within the gulf several MPA (Fig. 1). These areas due to ecological, social or scientific characteristics are either more vulnerable and/or of larger importance than other areas, and a hit to these areas by pollution is unacceptable.

In the Baltic Sea there have been several attempts to use the concealed features of current-driven transport, to mitigate environmental risks to the nearshore by means of properly placing the potentially dangerous activities. The studies have employed high-resolution 3D circulation models, different models to simulate the path of the current-driven pollutants in the surface layer and statistical analysis for the south-western Baltic Sea (Lu *et al*., 2012), the Baltic Proper (Viikmäe *et al*., 2011, Meier and Höglund, 2012) and the Gulf of Finland (Andrejev *et al*., 2011; Soomere et al., 2011b) using both Lagrangian trajectory models (Soomere *et al*., 2011c) and Eulerian transport approach (Meier and Höglund, 2012). The results (the areas that are statistically safer to travel in terms of risk of coastal pollution) have been used for optimisation of ship routes (Andrejev *et al*., 2011; Soomere *et al*., 2011b) and to specify the (equiprobability) line that would equally divide the costs of pollution of opposite coasts (Soomere *et al*., 2010, 2011b; Viikmäe *et al*., 2011).

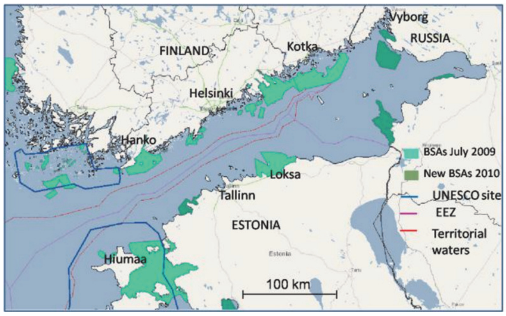

Figure 1. The Gulf of Finland and the MPAs (UNESCO sites and Baltic Sea protected areas (BSA) in July 2009) used in this study. The territorial zone (red line) and the EEZ line (magenta line) sourced from HELCOM.

All these studies assumed that (i) the most vulnerable areas were that of the nearshore and that (ii) the "value" of different nearshore areas was constant. The concept of MPAs signals that some areas are more valuable than other domains. As most of MPAs also involve certain offshore areas (Fig. 1), their vulnerability (in terms of current-driven pollution) may considerably differ from that of the nearshore.

In this study we adapt a variation of the method based on statistical analysis of a large pool of the current-induced paths of pollutants (Soomere *et al*., 2010). This method attempts to quantify the offshore in terms of the current-driven risk of pollution propagation to various valuable regions. It allows us not only to solve the areas that may be the most affected by pollution but also to identify those that are safer to travel or can be considered as potential areas for placing dangerous activities (e.g., places of refuge) (Soomere *et al*., 2011b).

Following Delpeche-Ellmann and Soomere (2012) we focus on scenarios of current-driven pollution transport in a more realistic environment in the Gulf of Finland, Baltic Sea, where the "value" of different nearshore or offshore areas may be substantially different. Using velocity field data, Lagrangian transport of the current driven particles and classical statistical methods, they quantified the chances for the MPAs to be hit if a pollution accident was to occur along the existing fairway in the Gulf of Finland, the time it would take until a hit occurs, and the locations along the fairway that affect these MPAs the most. We further investigate the points along the fairway that produced the most hits for each of the MPAs in an attempt to locate possible places of refuge for a vessel in distress and the effect shifting the fairway would have on the MPA most at risk, in order to minimize the amount of pollution. It is the intention that these results may assist in identifying potential safe areas that vessel can travel to in cases of emergencies that may limit pollution to the MPA. The political consequences of such actions are also briefly discussed.

The configuration of the existing set of MPAs in the Gulf of Finland in 2009 (Fig. 1) is used as a test case. Following (Andrejev *et al*., 2011; Soomere *et al*., 2011b) we concentrate on the properties of current-driven transport in the uppermost layer. This setup is only conditionally valid for oil pollution as it does not consider other metocean drivers (e.g., direct wind and wave impact), chemical process, buoyancy effects, etc. It is directly applicable for persistent adverse 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. Periáñez, 2004).

METHOD

We employ a method similar to that used in several earlier studies (Soomere *et al*., 2010; Andrejev *et al*., 2011, among others) that were targeted for the optimization of the fairway through the Gulf of Finland. The method consists of the following steps: (1) 3D velocity field of the sea area is obtained from a global ocean circulation model, (2) Lagrangian trajectories of selected particles in the uppermost layer of the sea, which are assumed to imitate the propagation of pollution, are constructed from this data, (3) a statistical analysis of these Lagrangian trajectories is performed to determine if any particular patterns and/or reduced risk areas exists, (4) further analysis of these results determine the best route that may limit the amount of pollution to the MPAs. Differently from previous studies we now assume that the domains of the MPAs are particularly valuable and investigate options that reduce pollution to the MPA. Instead of efforts in (Soomere *et al*., 2011b, 2011c; Meier and Höglund, 2012) to quantify the entire offshore and having in mind the practical impossibility for large shifts of the existing major fairway (Delpeche-Ellmann and Soomere, 2012), we limit our calculations to the vicinity of this fairway similarly to (Chrastansky and Callies, 2009; Chrastansky *et al.,* 2009).

The 3D velocity data of the sea surface used in this study was calculated using the Rossby Centre Ocean (RCO) circulation model (Meier *et al*., 2003; Meier 2007) for the period 1987–1991 in order to make the results comparable with those in previous studies (Soomere *et al*., 2011b). The RCO is a Bryan-Cox-Semtner primitive equation circulation model for the Baltic Sea with a free surface and open boundary conditions in the northern Kattegat (North Sea). It has a regular rectangular grid with a horizontal resolution of 2×2 nautical miles (nm) and is coupled to a Hibler-type sea ice model and thus appreciably replicates the presence and impact of ice cover to the dynamics of currents in the entire water column. The model uses 41 vertical layers with a thickness from 3 m close to the surface up to 12 m in ≥250 m depth. The particular model run was forced with meteorological data from a regionalization of the ERA-40 re-analysis over Europe using a regional atmosphere model with a horizontal resolution of 25 km during 1961–2007 (Höglund *et al*., 2009; Samuelsson *et al.,* 2011).

The Lagrangian trajectories of selected particles (that are assumed to represent the pathways of current-driven motion of pollution) are computed after the RCO model has been integrated and the velocity fields have been stored with the TRACMASS model (Döös, 1995; de Vries and Döös, 2001). The point sources (passive tracers) were placed at the centre of 309 grid cells of the RCO model located along a line that roughly follows the major fairway from the Baltic Proper to Saint Petersburg (Fig. 2). The selected cells cover a belt of a width of 3 grid cells (about 16 km, that is, about 1/3 of the technically navigable area in the gulf). As we focus on the role of relatively large-scale current driven transport, we do not use any specific means to account for subgrid turbulence.

In order to create a large enough pool of independent trajectories, the period of interest was divided into 20 day long partially overlapping sections (time windows). The calculations for the first window were performed from 00:00 on 01.01.1987 until 24:00 on 20.01.1987. The instantaneous coordinates of the trajectory points were saved once in six hours. The new set of calculations started after 10 days at 00:00 on 10.01.1987 and was

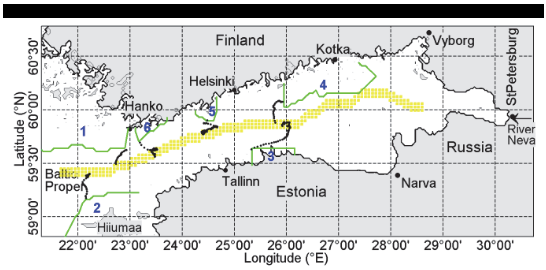

Figure 2. Examples of the trajectories sources and destinations, for when they arrived at the MPA. MPA 1 is the Southern Archipelago Sea, MPA 2 – the West Estonian Archipelago Biosphere Reserve, MPA 3 – Lahemaa National Park, MPA 4 – the Eastern Gulf of Finland, MPA 5 – the Kirkkonummi Archipelago, MPA 6 – the Tammisaari Archipelago.

again performed for 20 days. The process was repeated for the rest of the years of interest.

In this study we used the Baltic Sea protected areas and UNESCO sites designated before 2010 (Fig. 2) with somewhat smoothed borders. From the trajectory results we investigate statistically with the aid of MATLAB software the trends that may exist to identify the MPA that are most at risk by counting (i) the amount of particles that hit the MPA and (ii) from which fairway points they started and finally travelled to each of the MPA's. A hit was counted when a trajectory for the first time entered the MPA (Fig. 2). The further behaviour of this trajectory was ignored. Additionally to the analysis in (Delpeche-Ellmann and Soomere, 2012) we also now identify the effect of shifting the fairway by 1 and 3 grid cells (2 and 6 nm) to the south would have on the amount of pollution and the areas on the fairway that most of the pollution origin from and the least areas that pollution may not be sourced from.

RESULTS

The MPAs located on the eastern and western sections of the gulf were found to be the most at risk of being polluted from pollution released along the existing fairway (Delpeche-Ellmann and Soomere, 2012). The longest MPA 4 (Eastern Gulf of Finland, with extension 96 km along the model fairway) located both in Finnish and Russian waters was found to have the most hits (annual average 36, standard deviation (std) 5.1 of 11,433 released drifters). This was not surprising for the eastern section of the MPA is located in close proximity to the fairway. MPA 1 and 2 had almost equal extension (89 and 85 km, respectively) and the amount of hits (both 17, std 2.0 and 3.0, respectively). The relatively small MPA 5 (extension 22 km) had a comparable number of hits (14, std 3.4) whereas MPA 3 and 6 had, on average, below 10 hits annually.

The typical time it took for the tracers to reach a MPA varied much less. It was 7.5–8 days for MPA 2, 4 and 5, somewhat less (6–6.5 days) for MPA 1 and 6, and about 5 days for MPA 3.

Somewhat surprisingly, the sources of pollution were not confined to within the area of the MPAs but could span 100–200 km away from the MPA. Thus a general relationship between a particular MPA and sources of pollution was unlikely.

Potential Places of Refuge

In many maritime accidents a forewarning of distress is at times notified before an accident becomes serious for example in the

Prestige accident in 2002. As it is probably not easy to convince a port to host a problematic ship as occurred in the *Prestige* accident where Spanish and Portuguese authorities argued over whose responsibility it was, thus the ship was not able to make a port call or find safety in a place of refuge (Maddern and Knight, 2003). Thus it would be useful for vessels in distress to be offered in the early stages an offshore area where the consequences of an accident would be minimised to the environment. This may be very useful for the Gulf of Finland due to the narrowness of its geometry and the ecologically sensitive areas present in the marine environment.

Investigation of the sources of hits shows that they were not restricted to within the proximity of each MPA. In the contrary for each MPA the hitting trajectories had their origin from quite long sections of the fairway. The longest section of potential starting points for pollution finally reaching MPA 4 was about 210 km, that is, some 56% of the entire length of fairway in the Gulf of Finland. While it was not unexpected that MPA 4 had the most hits occurring in the 5 year period, it was unexpected that many hits to this MPA stemmed from sections of the fairway located far to the west of this area. This feature is, however, consistent with the occasional occurrence of the anticyclonic gyre (Soomere *et al.*, 2011a) in the middle region of the gulf and vividly demonstrates how complicated the current-driven patterns of pollution propagation in this water body could be.

Further examination of the interrelations between the MPAs and different sections of the fairway still highlights some useful patterns.

We now consider for each MPA the sections from where more than 70 percent of the hits originated (Fig. 3). The western section of the fairway is the most intense source of hits to the MPAs. Surprisingly, even for MPA 4 it appears that only a few points from where pollution may regularly reach this MPA were identified on the eastern section of the fairway. Moreover, these points are located essentially at the border of this MPA. This observation is consistent with earlier results (Andrejev *et al.*, 2011) where the optimum fairway was located adjacent to MPA 4.

These results also indicate that it is possible to identify for a vessel in distress and in aid of quick action a location along the fairway that minimizes the amount of pollution to a single MPA. Doing so, in general, may adversely impact other MPAs. Another projection of the possible sources presented in Fig. 4 makes it possible to identify the areas along the fairway that affect several of the MPA. So for a vessel in distress on the western section of the fairway there appears to be no reasonable location for the MPAs would all be affected by the potential pollution. However the extreme western end (that is, the open Baltic Proper) tends to

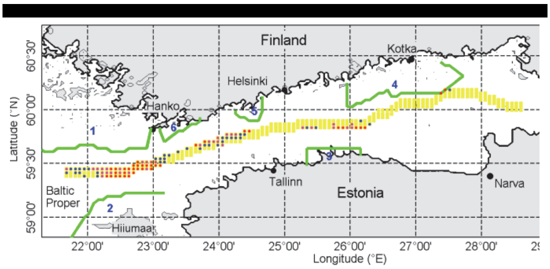

Figure 3. Locations along the fairway where >70% of the hits were sourced from for each of the MPA for the period 1987–1991. Red identifies >90%, magenta 90–80%, blue 80–70%.

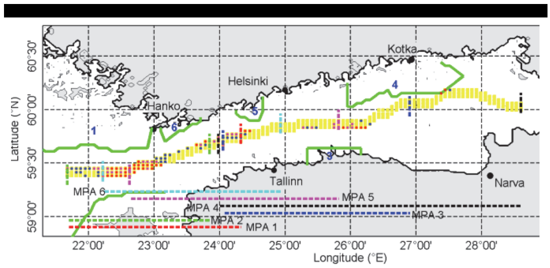

Figure 4. The distance along the fairway where the hits were sourced from for each of the MPAs. MPA 1 – red, MPA 2 – green, MPA 3 – blue, MPA 4 – black, MPA 5 – magenta, MPA 6 – cyan.

be the most reasonable location where minimum MPAs may be affected.

In the middle section the safest location would be around the Tallinn–Helsinki area. In the eastern section the safest area would tend towards the extreme eastern end. This result is counter-intuitive as according to the classical understanding of the cyclonic circulation in the Gulf of Finland pollution released in the eastern end of the gulf should drift towards MPA 4. Though these recommendations may minimize the hits to the MPA designed before 2010, the coastal areas and new MPAs (effective since 2010) may still be affected.

Shifting the fairway

The above results reveal that MPA 4 tends to be the most at risk of being polluted perhaps because of its proximity to the fairway. The results also show that it is unlikely to locate an ideal place of refuge on the western section of the fairway that would not affect any of the MPAs. It is possible technically to divert the pollution source across the gulf by diverting the accident location to the south or north of the fairway, thus we address another solution or perspective: the effect shifting the fairway laterally would have on the amount of hits to each of the MPA.

In particular, we established the impact of shifting the fairway by 2 and 6 nm (Fig. 5) on the number of hits. Shifting the fairway by 2 nm had the most impact for it decreased the number of hits by about 50% to MPA 4 (Fig. 6). Such an impact was not unexpected as the “original” fairway was located at its southern border. The other MPA’s and the origin of sources of their hits were almost not affected by this 2 nm shift.

A shift by 6 nm had the opposite effect on different MPAs. Whilst it decreased the amount of hits on the northern MPAs 1

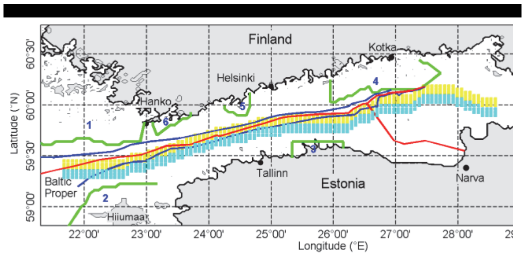

Figure 5. The different fairways used and their location with respect to the EEZ (red line) and territorial waters (blue line). Original fairway is indicated by yellow and the one shifted by 6 nm by cyan colour.

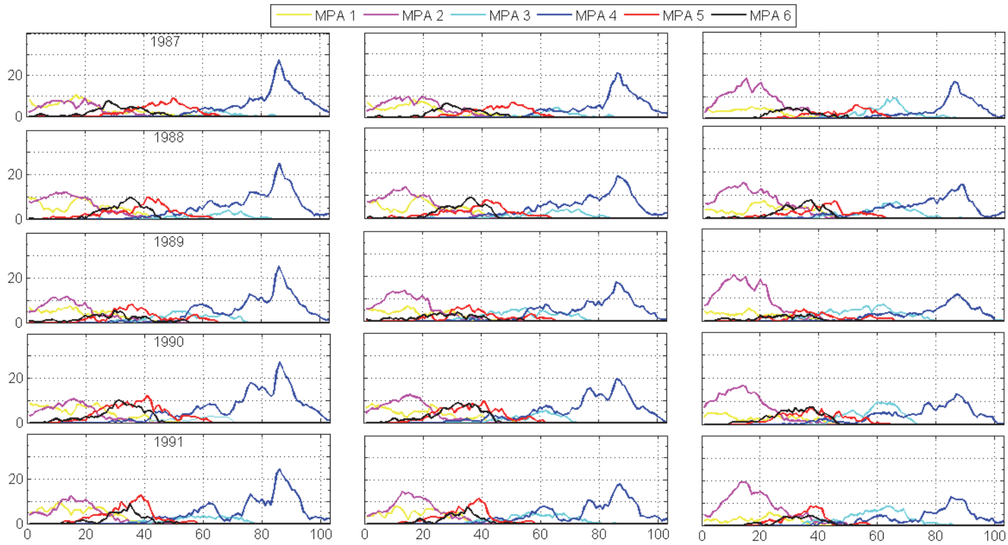

Figure 6. The number of hits averaged by similar longitude (vertical axes) in 1987–1991 for the original fairway (left column), sources shifted by 2 nm south (centre column) and by 6 nm south (right column). The horizontal axes indicate the sequential number of the RCO grid cells along the fairway from the west to the east.

and 4–6, the amount of hits on the southern MPAs 2 and 3 clearly increased. Thus a viable option would be shifting part of the fairway by 2 nm within the vicinity of MPA 4 where the most of the hits were sourced from, whilst the fairway may be shifted by 6 nm within the areas of MPA 5 and 6.

DISCUSSION

The analysis complements the results of (Delpeche-Ellmann and Soomere, 2012) that demonstrate the MPAs located in the western and eastern sections of the Gulf of Finland are the most at risk of being polluted and that it takes on average 5–8 days for the current-driven pollutants to reach the MPAs. To minimize the amount of adverse impacts that would travel to the MPAs in this manner we made an attempt to identify reasonable places of refuge along the existing fairway that minimizes the amount of pollution that would travel to the MPA (for example an areas close by that a vessel in distress can travel) and analyzed the effect shifting the fairway would have on the amount of hits. The first option basically relies on the count of where most of the hits came from on the fairway. The western section of the fairway at the entrance to the Gulf of Finland not only hosts very intense traffic but also serves as the most probable source of pollution for several MPAs. If a pollution accident was to occur there it would affect many of the MPAs in the gulf and the best scenario would be for the vessel to proceed out of the gulf. For an accident on the eastern end of the fairway mainly MPA 4 would be affected whereas, somewhat counter-intuitively the extreme east would be the best alternative. For an accident in the middle section several MPAs would be affected whereas thus there seems to exist no reasonable offshore refuge place.

Although there exists no legally binding instrument that a ship in need of assistance should follow as ships are under the jurisdiction of their flag country. At present most of the measures in place to protect the environment are not regulations but mostly guidelines that vessel and countries should follow. There is a guideline for IMO member states on how to prepare for rendering timely assistance to ships in distress. A popular method is the pre-selection of potential places of refuge (pre-selection model). These places are identified on the basis of generic assessment and when an accident occurs an event assessment is carried out for that particular place, e.g., in Spain and Denmark (Bradarić and Kostelac, 2009).

The performed analysis of the effect shifting of the fairway shows that a viable option would be to shift only certain portions of the fairway. A shift would be important for instance for MPA 4 where already a shift by 2 nm made a big difference whilst for MPA 5 and 6 a shift by at least 6 nm would make a difference.

The performed analysis also indicates that there exists no ideal solution for all parts of the gulf. For in the case of determining areas of refuge for ships in distress even though it may limit the amount of hits to the MPAs the coastal areas may still eventually be affected.

CONCLUSIONS

We believe that the presented technique and obtained information are directly applicable in marine management when designing fairways, when deciding on limits of MPA or in determining possible policies. Still, a decision for a place of refuge or to shift a fairway to reduce the amount of pollution should also consider several other factors such as depth of water, shelter from weather, good holding ground, etc. Also, possibly shifting the fairway to reduce the amount of pollution may be incompatible with the national jurisdiction rights. The present fairway passes within the EEZ of the surrounding countries. Its substantial shift would have the impact of placing the ship routes in the territorial waters. Such an action might not be possible for political reasons.

It might be, however, possible for MPA 4 which has the most hits from Russian waters and the shifted fairway would still be in the Russian waters of the Gulf of Finland.

Thus the legal rights and responsibilities of surrounding countries and the legality of some of the regulations and concepts presently being used should also be considered as important items in the decision-making process. Although we have presented a quantitative method to support maritime management decisions, qualitative solutions such as stricter policies and regulations in place for vessels that may travel within the area are still equally important.

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LITERATURE CITED

Andrejev, O., Soomere, T., Sokolov, A. and Myrberg, K., 2011. The role of spatial resolution of a three-dimensional hydrodynamic model for marine transport risk assessment. *Oceanologia*, 53 (1-TI), 309–334.

Bradarić, Z., Kostelac, M.M., 2009. Place of refuge for ships in need of assistance – methodological approach and Croatian concept. *Oceans 2009 Conference* (Bremen, Germany), Oceans – IEEE , pp 1451–1455.

Chang, Y.L., Oey, L., Xu, F.H., Lu, H.F. and Fujisaki, A., 2011. 2010 oil spill: trajectory projections based on ensemble drifter analyses. *Ocean Dynamics*, 61 (6), 829–839.

Chrastansky, A and Callies U., 2009. Model-based long-term reconstruction of weather-driven variations in chronic oil pollution along the German North Sea coast. *Marine Pollution Bulletin*, 58, 967–975.

Chrastansky, A., Callies, U. and Fleet, D.M., 2009. Estimation of the impact of prevailing weather conditions on the occurrence of oil-contaminated dead birds on the German North Sea coast. *Environmental Pollution*, 157, 194–198.

de Vries, P. and Döös, K., 2001. Calculating Lagrangian trajectories using time-dependent velocity fields. *Journal of Atmospheric and Oceanic Technology*, 18 (6), 1092–1101.

Delpeche-Ellmann, N. and Soomere, T., 2013. Investigating the Marine Protected Areas most at risk of current-driven pollution in the Gulf of Finland, the Baltic Sea, using a Lagrangian transport model. *Marine Pollution Bulletin*, 67 (1-2), 121–129.

Döös, K., 1995. Inter-ocean exchange of water masses. *Journal of Geophysical Research*, 100 (C7), 13499–13514.

Havens, H., Luther, M.E., Meyers, S.D. and Heil, C.A., 2010. Lagrangian particle tracking of a toxic dinoflagellate bloom within the Tampa Bay estuary. *Marine Pollution Bulletin*, 60, 2233–2241.

HELCOM, 2010. *Towards an ecologically coherent network of well-managed Marine Protected Areas – Implementation report on the status and ecological coherence of the HELCOM BSPA network*. Baltic Sea Environment Proceedings No. 124B, 143 pp.

Höglund, A., Meier, H.E.M., Broman, B. and Kriezi, E., 2009. *Validation and correction of regionalised ERA-40 wind fields over the Baltic Sea using the Rossby Centre Atmosphere Model RCA3.0*. Rapport Oceanografi No. 97. Norrköping, Sweden: Swedish Meteorological and Hydrological Institute.

Kachel, M.J., 2008. *Particularly Sensitive Sea Areas*. Hamburg Studies on Maritime Affairs, 13, Springer, 376 pp.

Kuronen, J. and Tapaninen, U., 2009. *Maritime Safety in the Gulf of Finland: Review on policy instruments*. Publications from the Centre for Maritime Studies University of Turku, A 49.

Korajkic, A., Badgley, B.D., Brownell, M.J. and Harwood, V.J., 2009. Application of microbial source tracking methods in a Gulf of Mexico field setting. *Journal of Applied Microbiology*, 107, 1518–1527.

Korotenko, K.A., Bowman, M.J. and Dietrich, D.E., 2010. High-resolution numerical model for predicting the transport and dispersal of oil spilled in the Black Sea. *Terrestrial, Atmospheric and Ocean Sciences*, 21, 123–136.

Knudsen, O.F., 2010. Transport interests and environmental regimes: The Baltic Sea transit of Russian oil exports. *Energy Policy*, 38, 151–160.

Leppäranta, M. and Myrberg, K., 2009. *Physical oceanography of the Baltic Sea*. Chichester, UK: Springer, 378 pp.

Lu X., Soomere T., Stanev E. and Murawski, J. 2012. Identification of the environmentally safe fairway in the South-Western Baltic Sea and Kattegat. *Ocean Dynamics*, 62 (6), 815–829.

Maddern, D. and Knight, S., 2003. Refuge for ships in distress: International developments and the Australian position. *Australian and New Zealand Maritime Law Journal*, 17, 101–118.

Mariani, P., MacKenzie, B.R., Iudicone, D. and Bozec, A., 2010. Modelling retention and dispersion mechanisms of bluefin tuna eggs and larvae in the northwest Mediterranean Sea. *Progress in Oceanography*, 86, 45–58.

Meier, H.E.M., Döscher, R. and Faxén, T., 2003. A multiprocessor coupled ice-ocean model for the Baltic Sea: Application to salt inflow. *Journal of Geophysical Research*, 108 (C8), Art. No. C3273.

Meier, H.E.M., 2007. Modeling the pathways and ages of inflowing salt- and freshwater in the Baltic Sea. *Estuarine, Coastal and Shelf Science*, 74 (4), 717–734.

Meier, H.E.M. and Höglund, A., 2012. Environmentally safe areas and routes in the Baltic proper using Eulerian tracers. *Marine Pollution Bulletin*, 64 (7), 1375–1385.

Ohlmann, J.C. and Mitarai, S., 2010. Lagrangian assessment of simulated surface current dispersion in the coastal ocean. *Geophysical Research Letters*, 37, L17602.

Periáñez, R. 2004. A particle-tracking model for simulating pollutant dispersion in the Strait of Gibraltar. *Marine Pollution Bulletin*, 49, 613–623.

Samuelsson, P., Jones, C.G., Willén, U., Ullerstig, A., Gollvik, S., Hansson, U., Jansson, C., Kjellström, E., Nikulin, G. and Wyser, K., 2011. The Rossby Centre Regional Climate Model RCA3: Model description and performance. *Tellus*, 63A (1), 4–23.

Soomere, T., Viikmäe, B., Delpeche, N. and Myrberg, K., 2010. Towards identification of areas of reduced risk in the Gulf of Finland, the Baltic Sea. *Proceedings of the Estonian Academy of Sciences*, 59 (2), 156–165.

Soomere, T., Delpeche, N., Viikmäe, B., Quak, E., Meier, H.E.M. and Döös, K., 2011a. Patterns of current-induced transport in the surface layer of the Gulf of Finland. *Boreal Environment Research*, 16 (Suppl. A), 49–63.

Soomere, T., Andrejev, O., Myrberg, K. and Sokolov, A., 2011b. The use of Lagrangian trajectories for the identification of the environmentally safe fairways. *Marine Pollution Bulletin*, 62, 1410–1420.

Soomere, T., Berezovski, M., Quak, E. and Viikmäe, B., 2011c. Modelling environmentally friendly fairways using Lagrangian trajectories: a case study for the Gulf of Finland, the Baltic Sea. *Ocean Dynamics*, 61, 1669–1680.

Uggla, Y., 2007. Environmental protection and the freedom of the high seas: The Baltic Sea as a PSSA from a Swedish perspective. *Marine Policy*, 31, 251–257

Vandenbulcke, L., Beckers, J.-M., Lenartz, F., Barth, A., Poulain, P.-M., Aidonidis, M., Meyrat, J., Ardhuin, F., Tonani, M., Fratianni, C., Torrisi, L., Pallela, D., Chiggiato, J., Tudor, M., Book, J.W., Martin, P., Peggion, G. and Rixen, M., 2009. Super-ensemble techniques: Application to surface drift prediction. *Progress in Oceanography*, 82 (3), 149–167.

Viikmäe, B., Soomere, T., Parnell, K.E. and Delpeche, N., 2011. Spatial planning of shipping and offshore activities in the Baltic Sea using Lagrangian trajectories. *Journal of Coastal Research*, Special Issue No. 64, 956–960.

Yoon, J.-H., Kawano, S. and Igawa, S., 2010. Modeling of marine litter drift and beaching in the Japan Sea. *Marine Pollution Bulletin*, 60, 448–463.

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