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Tracks of surface drifters from a major fairway to marine protected areas in the Gulf of Finland

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Abstract. Pollution caused by shipping accidents or by intentional discharge of harmful materials can be transported by currents to locations far from the source, and therefore poses a potential risk to marine protected areas (MPAs). The risk of current-driven pollution to MPAs in the Gulf of Finland is assessed by analysing the paths from 23 surface drifters crossing a major fairway in the western and central parts of the Gulf of Finland. About 2/3 of the drifters entered into one of the MPAs. The majority of drifters reached the Ekenäs Archipelago near the western coast of Finland. The travel time from the fairway to the MPAs ranged from 1.3 days to 36.1 days, suggesting that different processes may be influencing the surface circulation patterns and that the drifters can travel long distances before reaching a MPA.

Key words: Lagrangian transport, surface currents, pollution control, Gulf of Finland, marine protected areas.

1. INTRODUCTION

Pollution from shipping represents a constant threat to the marine environment especially in major industrial areas and along main navigational routes [5,15]. The core regulations aimed at preventing discharge of pollutants to the environment, such as the MARPOL Convention [9,20], place emphasisis on the design and operation of ships and handling of cargo. Despite these efforts, a large number of shipping accidents occur throughout the world.

One of the major industrial areas with navigational routes includes the Baltic Sea. The Baltic is a relatively small estuarine sea that is the host to extremely intense ship traffic: up to 15% of the world's international maritime cargo [12] passes through this sea. The associated high environmental pressure is commonly recognized and shipping accidents (Fig. 1), oil spills, pollution from shipping, and invasion of alien species are listed as potential threats to the future of the Baltic Sea [13].

As there is a limited scope for the reduction of risks through regulations aimed at individual ships [21], recent advances in technology have targeted probabilistic methods for addressing the problem [22]. A promising way is the optimization of major fairways [26]. This approach usually aims at improving the safety of navigation [4,36], in particular near harbours and congested fairways. It may also be applied to minimize the risk of pollution from ship accidents, which may be carried over long distances and may reach high-value marine areas [3,14,30], for example ports and seaside resorts with a high commercial value or marine protected areas (MPAs) with a high environmental value [7,8,27].

Recent studies of surface current conditions in the Gulf of Finland have primarily relied on analysis based on numerical ocean models [2,3]. Whilst these models can successfully predict the general circulation with reasonable accuracy, small-scale features are not so well represented (due to model resolution, forcing data used, sub-scale parameterization, etc.); hence prediction of the floating object drift [1,10] may contain significant imperfections. This shortcoming becomes even more challenging for complex estuarine environments where the surface layer is often highly turbulent. Also, to improve model predictions, it is necessary to compare model results with data obtained from field measurements.

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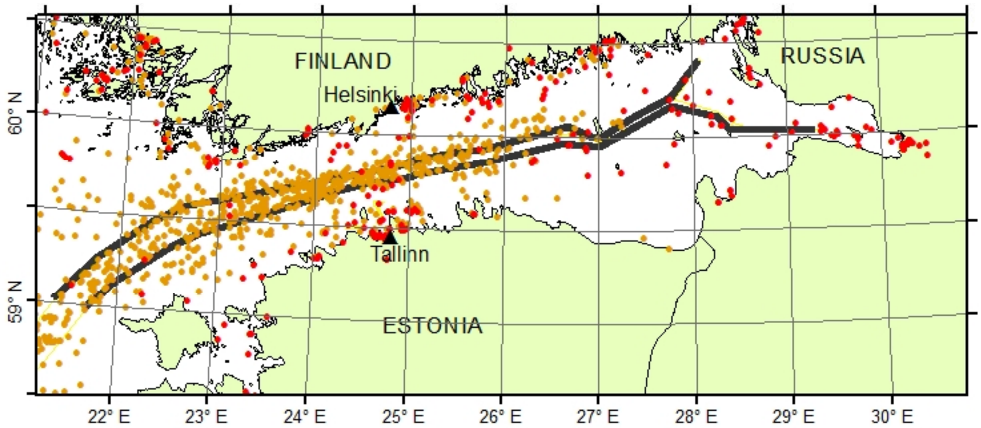

Fig. 1. The deep water navigation routes (black lines), registered shipping accidents (yellow circles), and illegal discharges of oil (red) in the Gulf of Finland. Source: HELCOM AIS.

This paper focuses on the potential exposure of MPAs to shipping-related pollution in the Gulf of Finland via long-range current-driven transport in the surface layer. This first systematic examination of trajectories obtained from surface drifters deployed in the Gulf of Finland during the period 2010–2014 [29,32] provides a new perspective for risk assessment with respect to shipping-related pollution in the Gulf of Finland. We compare statistical properties of the drifter trajectories with the basic conclusions of earlier numerical simulations [7,8,16]. The procedure applied investigates drifter trajectories starting from the ship fairway. A more detailed comparison of the drifter data with results of recent simulations is presented in this volume [35].

2. STUDY AREA: THE BALTIC SEA, GULF OF FINLAND

The circulation patterns of the Baltic Sea are generally considered to be well understood [18]. However, for the Gulf of Finland there still remain many gaps in our understanding of the variability and structure of the mean circulation, especially in the surface layer [24]. The main driving forces of currents in the Gulf of Finland are wind stress, density variations in the water column, and sea surface slope [2]. The resulting circulation system is superimposed by the in- and outflow of water masses forced by specific atmospheric conditions. In particular, the flow at the uppermost layer of the sea is often almost detached from the general circulation [17,24]. The long-term mean circulation need not always reflect various (multi-)weekly events in the surface layer [16], but their impact on the transport in the surface layer may be essential [19].

The circulation of the uppermost layer of the Gulf of Finland is commonly thought to be mainly wind driven and only weakly coupled with the flow in deeper layers. It is generally cyclonic with an average velocity of a few centimetres per second, and especially in the eastern part of the gulf it is characterized by small-scale eddies [24]. An examination of the 5-year averages of numerically simulated currents at depths of 0–2.5 m [27] revealed some counter-intuitive features. Most strikingly, the mean circulation hosts a slow anti-cyclonic gyre in the wide eastern part of the gulf [27]. A similar structure was recently shown to exist also in the Gulf of Riga during certain seasons [31]. This gyre is occasionally superimposed by intense meridional (cross-gulf) transport. This pattern is not present during all seasons and thus does not become evident in yearly averages; however, it may substantially modify the pathways of pollution propagation and impact the probability and the time it takes pollution to reach MPAs.

The main shipping fairway in the Gulf of Finland (Fig. 1) is a rather narrow corridor along the southwest–northeast axis of the gulf, from the Baltic Proper to St. Petersburg, with branches reaching northward and southward towards major ports. Assuming the risk of a ship accident is primarily concentrated within the fairway, each fairway segment can be treated as a potential source for pollution. Based on this approach, and using information about the surface currents derived from numerical models, assessments of the risk of pollution reaching the coast have revealed a significant spatial variability in the level of exposure for different coastal sections [3,34], and highlighted sections of the fairway where the risk of pollution reaching the coast is enhanced [34]. Seasonal changes in the patterns of surface currents in the Gulf of Finland are reflected in the extensive seasonal variation of the optimum fairways [23].

3. FIELD EXPERIMENTS

A series of surface drifter experiments was performed in the Gulf of Finland in 2010–2014 [29,32] (Fig. 2a). The basis of drifters was a 2 m long semi-submersible plastic tube (Fig. 2b), containing a tracker device and a battery pack. The active device was a GPS/GPRS tracker programmed to send the real-time GPS measured geographical coordinates of the drifter at regular intervals, usually every 10 or 15 min, and with an accuracy of 3–10 m. The drifter designs before 2013 had a battery lifetime of 2–3 weeks, which was extended to 4–5 weeks in 2013. More detailed information on the drifters and experiments can be found in [29,32].

A total of 78 drifters were deployed in 2010–2014 in locations close to the southern (Estonian) coast and primarily concentrated near Tallinn (Fig. 1). All deployments were made during the relatively calm spring and summer seasons, from April to September. Usually 2–3 drifters were deployed simultaneously within a small area in order to provide information about their relative spreading [29,32]. The eight drifters deployed in 2010 only sent data when connected with the Estonian GSM network and did not record tracks in the northern part of the Gulf of Finland, hence these records were not included in the following analysis.

This study focuses on the behaviour of drifters that may reflect the drift of pollution released from the major fairway. This limits the entire pool of drifters to a total of 23 (out of 70) drifter trajectories that traversed from the Estonian coast towards the central part of the Gulf of Finland and at some time intersected the major fairway. This pool involves five drifters deployed in 2011, seven drifters in 2013, and 11 drifters in 2014. The majority of the drifters reached land after crossing the fairway, with a slightly higher number reaching the Estonian coast (8 out of 23) than the Finnish coast (6/23). The remaining drifters (9/23) were lost at sea. This result is consistent with the assumption that the fairway location is close to the equiprobability line (of the probability of current-induced drift of passive pollution parcels to the either coast of the Gulf of Finland) [27]. However, the uncertainty of the indicated proportions is fairly large due to the small sample available, and the above numbers might have been altered if a few of the drifter tracks had deviated slightly from their actual tracks, or if the lifetime of the drifter battery packs had been extended.

The emphasis, similarly to [6,7], is on the trajectories of these drifters that have reached a MPA. Their properties have been analysed with respect to (1) the time it took a drifter to arrive in a MPA (equivalent to the particle age in [3]) and (2) the location along the fairway from where the drifters exerted their journey to a MPA (the source of hits [7]).

The implementation of the Vessel Traffic Separation System in the Gulf of Finland led to the presence of two branches of the fairway from the entrance of the gulf until the Kunda–Kotka line [25], the southern branch heading to the east and the northern branch to the west. To realistically represent this situation, the northern and southern borders of the deep water navigation areas and navigation lines from the HELCOM Baltic Sea data and map service (maps.helcom.fi/website/mapservice/index.html) were used to define two possible fairways (Fig. 2). Further, we assume an equal probability of a ship accident along any section of each fairway at any time. This assumption is realistic for most of the major fairway except its junction with the Tallinn–Helsinki ship lane [21,22]. This feature is implicitly accounted for by means of having most drifters deployed in the vicinity of this junction (Fig. 3).

(a) (b)

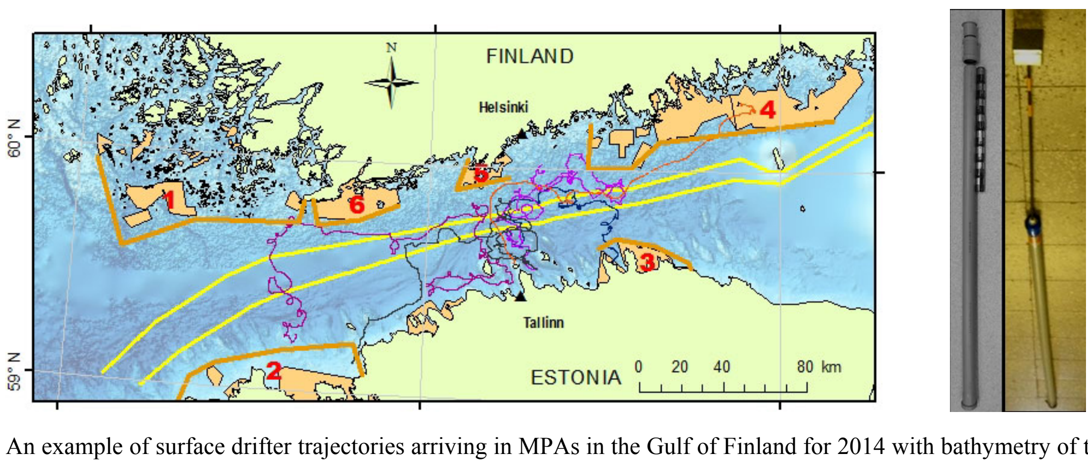

Fig. 2. (a) An example of surface drifter trajectories arriving in MPAs in the Gulf of Finland for 2014 with bathymetry of the area in the background. (b) A view of the drifter version used in 2010–2012 and a block of eight standard D-size batteries (left) and the drifter used in 2013 and onward experiments (right).

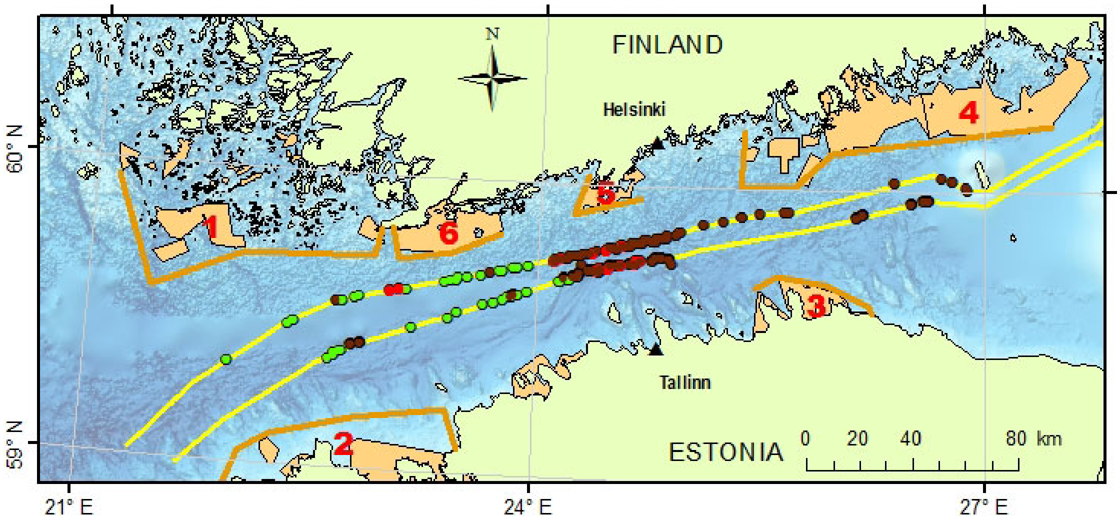

Fig. 3. The location of start positions of sub-tracks of drifters in the Gulf of Finland along the main fairway for 2011 (red), 2013 (green), and 2014 (brown). The MPAs are defined and numbered as in [7]. MPA 1: Southern Archipelago Sea; MPA 2: West Estonian Archipelago Biosphere Reserve; MPA 3: Lahemaa National Park; MPA 4: Eastern Gulf of Finland; MPA 5: Kirkkonummi Archipelago; MPA 6: Ekenäs Archipelago.

The locations of the six MPAs used in this study (designated HELCOM MPAs [7]) were obtained from the above HELCOM service. There have been minor changes in size and shape of the MPAs over the years, thus the configuration used in this study reflects an approximation of the present MPAs with somewhat smoothed borders (Fig. 3).

In principle, any instance when a drifter crossed the major fairway as defined above could potentially represent a separate accident or any other release of oil. Following this logic, the original drifter tracks were split into several sub-tracks. Each sub-track was represented with a start position and time counter defined by the original surface drifter crossing either the northern or southern branch of the fairway and extending to the end of the drifter lifetime (Fig. 3). Once a drifter arrived in a MPA its further path was ignored similarly to the analysis in [27,33]. Since the MPAs extend some distance offshore, drifters that were designated as 'lost at sea' could still contribute to the number of drifters that would reach a particular MPA over longer travel times.

4. RESULTS

4.1. Temporal scale of a drift from the fairway to a MPA

From the 23 surface drifters that crossed one or both of the fairways, 15 (about 65%) passed through or ended their drift within one of the six MPAs (Fig. 4). Thus, four or five drifters each year reached a MPA (100% of drifters in 2011, 71% in 2013, and 45% in 2014). In 2011, all five drifters from this pool (three released in June and two in August) ended up in MPA 6. The end points were more diverse in other years: two drifters released in May 2013 came to MPA 2, three devices deployed in September 2013 to MPA 6, one drifter from those deployed in April 2014 hit MPA 3 and another MPA 4. One drifter released in May 2014 reached MPA 6 and another MPA 2, and one drifter that started its journey in August 2014 hit MPA 4.

To analyse the drift time from the fairway to a MPA, a drifter's tracks are calculated from the time the drifter crossed a fairway branch. Most drifters crossed the fairway multiple times, resulting in a sequence of sub-tracks with different start positions and start times for each drifter. In all cases except one (drifter No. 3, 2013; below denoted as #2013-3) the drifter crossed both branches. The number of crossings occasionally differs between the southern and northern branches; in some cases radically (8/0 times, respectively, for one drifter in May 2013; 1/9 times for a drifter in April 2014), which indicates that the drifter had been meandering close to the fairway.

All drifters deployed in 2011 arrived in MPA 6 within 1 to 9 days (Figs 4 and 5). Drifters deployed in August (drifters #2011-4, #2011-5) arrived quicker than those deployed in June. For that year the typical time it took a drifter to reach a MPA corresponded well with previous results, indicating a likely drift time of 5–8 days [7,33,34]. However, for the other years the typical drift time was much longer. In 2013 the drifters that reached the MPAs crossed the fairway in May (drifters

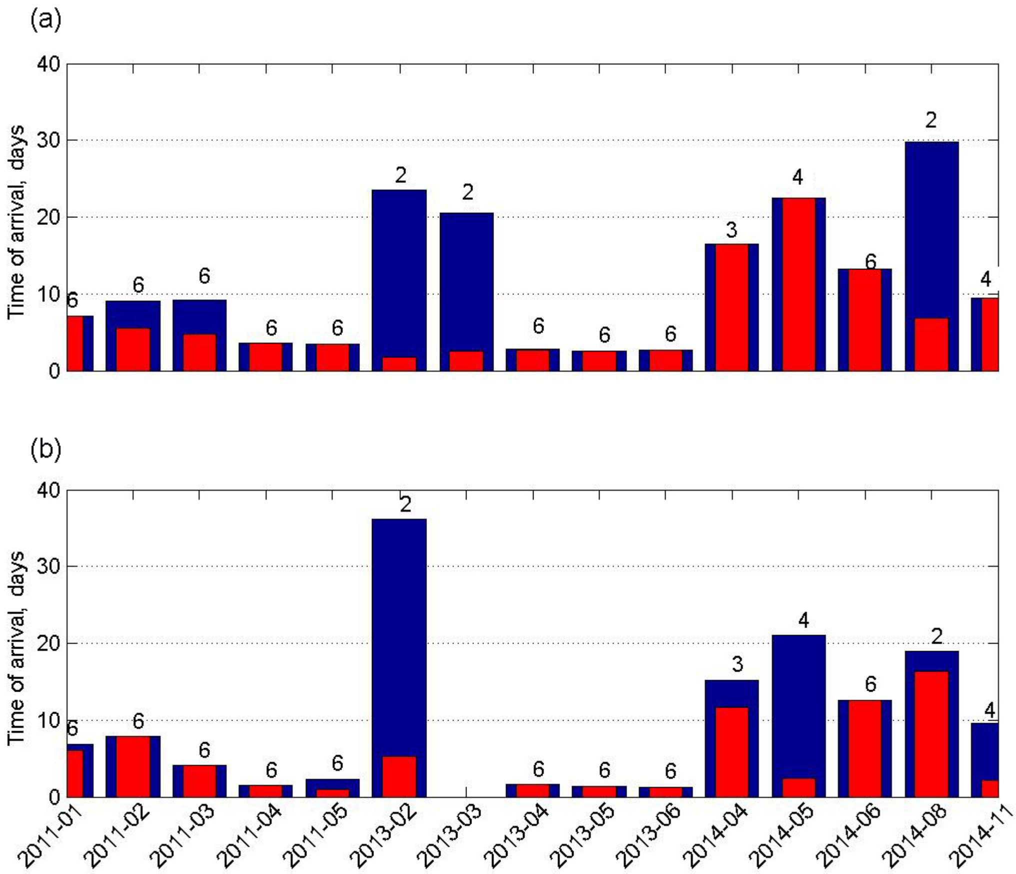

Fig. 4. The drifters (the number of drifters on the horizontal axis) deployed and the time for arrival in days in a MPA (the number of the MPA arrived at is displayed on top of the bar for each drifter). (a) Drifters originating in the southern branch of the fairway; (b) drifters originating in the northern branch of the fairway. The longest and shortest sub-tracks connecting the fairway with a MPA, associated with the drifter crossing a fairway branch, are represented by blue and red bars, respectively.

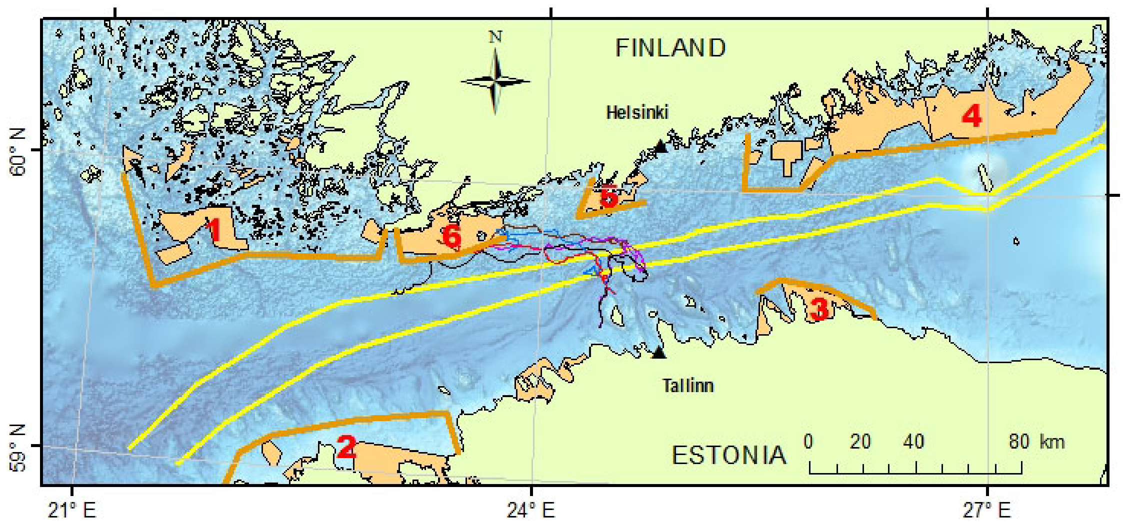

Fig. 5. Trajectories of surface drifters for 2011.

#2013-2, #2013-3) and September (drifters #2013-4, #2013-5, #2013-6). Sub-tracks that started in May arrived in MPA 2; in that case the drift time range varied from 2.5 to 36.1 days. The drift duration in September was from 1.3 to 2.7 days. The arrival time of the drifters deployed in April (drifters #2014-4, #2014-5), May (#2014-6, #2014-8), and August 2014 (#2014-11) in different MPAs varied considerably and ranged from 2.1 to 29.8 days. Thus, in general, most of the drifters arrived in MPA 2 and MPA 6, which were in the close vicinity of the sources. It was only in 2014 that drifters reached other MPAs.

The presented results first of all demonstrate substantial variation in the temporal scale that it takes passively carried items to drift from the fairway region to a MPA. This variation is consistent with the common properties of surface currents in the Gulf of Finland such as a relatively modest speed and low directional persistence [2]. It also signals that correlation times of flow fields are relatively short and therefore the ideal Kraichnan flow model is appropriate for the analysis of drift patterns of items and substances locked in the uppermost layer of the sea [11]. Although the number of drifters is not large enough to establish properties of variations in the time scale of a drift from the fairway to a MPA, the presented material evidently hints to the presence of a clear seasonal pattern. The drifters appear to be much quicker in August and September than in April or June. Part of this difference reflects seasonal variations in the current speed but the reported magnitude of variations suggests that different seasons or wind conditions may have substantially different circulation patterns [28].

In most cases the difference in time between the northern and southern branches of the fairway for a hit to MPA was about 2 days. However, in some cases the drift durations differed considerably (e.g., drifters #2013-2 and #2013-3 or drifter #2014-8). A likely reason behind this variability is that the surface circulation may be influenced by radically different forces (e.g. atmospheric conditions and the underlying circulation pattern), the balance of which may largely vary depending on the particular meteorological situation.

4.2. Sources of hits from the fairway to MPAs

It is natural to interpret the start positions of sub-tracks as the possible sources of hits of pollution that is carried by surface currents from the fairway to MPAs [7]. These locations also show extensive variability. For some years the sources were near the MPA affected. For example, in 2013 the sources were close to MPA 2 and MPA 6 and these MPAs were also the most affected ones. The situation was different in other years. For instance, in 2014 the sources of hits to the affected MPAs came from long and even remote sections of the fairway (Fig. 2).

These results support one of the major conjectures made in [7] based on the numerical simulation of Lagrangian trajectories of selected water (or pollution) parcels that were passively carried by currents in the uppermost water layer. Namely, the dynamics of surface currents in the Gulf of Finland often supports transport of pollution over long distances so that sources of pollution may not affect only the nearby MPAs. Instead, pollution to a particular MPA may come from long lengths of the fairway. This feature is exemplified in Fig. 4: in 2011 the starting points of sub-tracks were quite close to MPA 5, yet most of the drifters travelled to MPA 6.

5. DISCUSSION AND CONCLUDING REMARKS

Field experiments with surface drifters deployed in the Gulf of Finland show that 65% of the drifters that crossed the fairway reached a MPA. This indicates that the MPAs are at high risk of pollution stemming from the fairway. The majority of the drifters reached MPA 6, which suggests that this area is most at risk. This outcome is in contrast with results from model simulations performed in [7]: there it was found that MPAs in the extreme eastern (MPA 4) and western end of the Gulf of Finland (MPA 1 and MPA 2) were most at risk [7]. However, the numerical simulations were carried out with a large number of simulated trajectories distributed evenly along the entire length of the fairway (180 trajectories per year from each grid cell along the fairway [7,8]), whereas the surface drifters constituted a relatively small number of drift realizations concentrated in the area north of Tallinn. Therefore the results obtained from drifter trajectories do not disprove the earlier findings obtained by numerical simulations. In fact, the area along the fairway most frequently crossed by drifters corresponds reasonably well with the area predicted to have a high probability of reaching MPA 6 (fig. 6f in [7]).

Model simulations in [7] also showed that, on average, pollution propagating from the major fairway of the Gulf of Finland reached MPAs in 5–8 days. This study supports this time scale but also shows that two temporal scales may exist for a drift from the fairway to a MPA. A shorter scale of 1 to 9 days matches the outcome of numerical simulations. Another, longer time scale, corresponds to drifting times of ~20 days. This observation indicates that different processes may govern circulation patterns at these scales. Motions with the shorter scale may be influenced by the atmospheric conditions or possibly by the cross-gulf transport [28]. It is likely that the longer time scale mirrors either the underlying circulation pattern of the entire Gulf of Finland or the anti-cyclonic gyre described in [28]. Long drifting time in some seasons (e.g. in May 2013 or April 2014) may simply reflect fairly calm conditions during spring. The high proportion of relatively short drift times suggests that there is often very limited time to contain pollution from reaching a MPA. Therefore, environment management plans for MPAs and pollution control should be given high priority as outlined in [7,8].

Another interesting observation is that the sources of drifters (crossing points of the fairway) do not always have a close proximity to the MPAs but at times originate in distant stretches of the fairway. Such results were also obtained in [7], where it was suggested that each MPA could be associated with a particular section of the fairway from which there is an increased probability of pollution reaching the MPA. These results are sensitive to the detailed motions of the drifters as well as the specific border assigned to the MPA. In this respect there is a subtle difference between our analysis and analysing the risk of pollution reaching any section of the opposite coasts of the Gulf of Finland [27]. The drifters crossing the fairway had almost an equal probability of reaching either of the coasts, suggesting that the fairway was located close to the equiprobability line for the Gulf of Finland in terms of pollution propagation to its northern and southern coasts [27]. The particular drifter trajectories are sensitive to small-scale deviations [32], but the equiprobability line reflects features of a large pool of real or virtual drifters and thus is not sensitive to small deviations in the drifter grounding location. In other words, the results of the analysis of drifters reaching a specific MPA are sensitive not only to the final location of the drifter, but also to the detailed drifter trajectory.

In general the presented results compare reasonably well with the outcome of simulations, with some differences that are possibly due to the limitations of the field experiments. However, the results of both the simulations and the field experiment suggest that MPAs in the Gulf of Finland are at high risk of pollution from the fairway, with the source of pollution originating far away from the MPAs in some cases. This conjecture illustrates the challenge of adequately managing the risk of pollution caused by shipping in the Gulf of Finland, as the risk management should not be solely confined to localized MPA regions, but should also take into account the risk associated with remote pollution sources.

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Triivpoide kandumine Soome lahe laevateelt merekaitsealadele

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Merre sattunud reostus ja mitmesugused potentsiaalselt ohtlikud ained ning esemed võivad pinnahoovustega väga kaugele kanduda ja ohustada ka ranniku lähistel paiknevaid merekaitsealasid. Hoovuste poolt edasi kantava reostusega seonduvaid riske Soome lahes on esmakordselt süstemaatiliselt analüüsitud mere pinnakihi liikumist järgivate triivpoide trajektooride alusel. On vaadeldud 23 poi teekonda Soome lahe lääne- ja keskosas paiknevatelt laevatee lõikudelt. Ligikaudu 2/3 neist poidest kandus merekaitsealadele, peamiselt Ekenäsi (Tammisaari) arhipelaagi lahe lääneosas Soome edelarannikul. Mõned poid triivisid ka kaugemal paiknevatele aladele. Kaitsealadele triivimise aeg varieerus 1,3 päevast 36,1 päevani. Sellist varieeruvust on interpreteeritud tõendina selle kohta, et Soome lahe pinnahoovuste süsteemis ja reostuse edasikandes domineerivad eri aegadel erineva mastaabiga protsessid ning et tuleb arvestada reostuse kandumise võimalusega reostusallikast väga kaugel paiknevatele merekaitsealadele.