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The persistence of spatial patterns of beaching of current-driven pollution in a changing wind climate: a case study for the Gulf of Finland

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We analyse long-term properties of current-driven transport of various items and substances to the nearshore from the vicinity of a fairway in the Gulf of Finland under the changing wind climate. The transport is replicated using semi-Lagrangian trajectories of parcels located at the sea surface. The trajectories are reconstructed with the TRACMASS model from surface velocity fields simulated by the Rossby Centre Ocean model for 1965–2004. The proportion of hits to the southern and northern nearshore varies in single years, but their long-term chances for being hit are equal. The number of hits to single nearshore sections greatly varies along the shore and in different years. The 5-year average spatial pattern of hits is highly persistent both qualitatively and quantitatively. Although the patterns of surface currents may have reacted to changes in the wind climate, the frequency and spatial patterns of beaching of current-driven pollution have remained unchanged over almost half century.

Introduction

The relatively small and shallow Baltic Sea hosts one of the most heavily trafficked marine fairways in the World Ocean. The ships that cross this sea carry about 15% of the entire marine international cargo (HELCOM 2009). This massive flux of cargo contains numerous potentially dangerous items and substances that may threaten this area, designated as a Particularly Sensitive Sea Area by the International Maritime Organisation (IMO 2007, Kachel 2008), should an accident occur.

Even though there are many efforts towards reducing the number and severity of shipping accidents, such accidents relatively frequently occur in wintertime conditions when the presence of ice, strong winds and long hours of darkness often complicate navigation (Goerlandt *et al*. 2017) in the northern Baltic Sea. The most common accidents are groundings and collisions. They are usually reported to be caused by human error. The annual number of reported Baltic Sea accidents is 34–54 for collisions and 30–60 for groundings whereas the underreporting rate is probably as high as 40%–50% (Sormunen *et al*. 2016). A large number of ship accidents and consequences of human errors are associated with the release of harmful substances (oil or chemical pollution) into the marine environment

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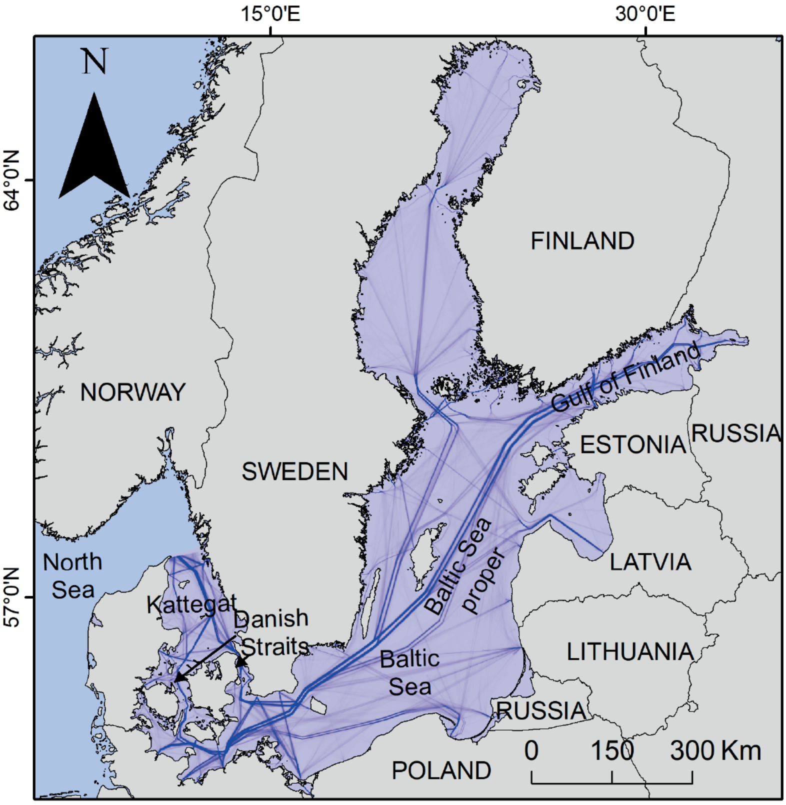

Fig. 1. The Baltic Sea with its major fairways. Image by K. Pindsoo.

(Burgherr 2007). Oil spills from maritime activities can lead to extensive damage to the marine environment in general and substantially disrupt maritime ecosystem services in the particularly vulnerable, brackish high-latitude environment of the Baltic Sea.

Despite most ships today being technically much safer than in the past, the increasing volume of transportation (Fig. 1) probably outweighs the safety gains (Hassler 2016). This conjecture is supported by recent statistics of oil spills in the Baltic Sea. While the total number of oil pollution events steadily decreased in the south-eastern Baltic Sea from 2004 to 2011, a sharp increase in oil pollution occurred in 2012, after which the oil pollution level remained at the same level until 2015 (Bulycheva *et al.* 2016). The main polluters were vessels with the oil originally released along the fairway in the open sea. However, oil spills usually cause the largest adverse effects on biodiversity in coastal areas (Helle *et al.* 2016) or in marine protected areas (MPAs). It is therefore important to include, in addition to specific factors such as accident probabilities or the trajectories of spilled oil, a broad a view of the consequences; e.g., the chances for the released oil to reach vulnerable spots such as high-value shores and MPAs (e.g., Delpeche-Ellmann and Soomere 2013). The relevant assessments have shown that the oil spills in the Baltic Sea may impact coastal areas at a distance of many tens of kilometres from the oil release site (Depellegrin and Pereira 2016).

The links between the oil release areas and potential vulnerable regions most importantly depend on the current-, wind- and wave-induced transport of oil spills. Studies of these aspects have a long history in the Baltic Sea basin. A detailed overview of the relevant work for the Gulf of Finland (Fig. 2) can be found, e.g., in (Soomere and Quak 2013). The studies of (Lagrangian) transport of oil spills extend from sophisticated reconstructions of single events (De Padova *et al.* 2017, Kordas *et al.* 2017) to the construction of statistical distributions of probabilities of drift of potentially dangerous

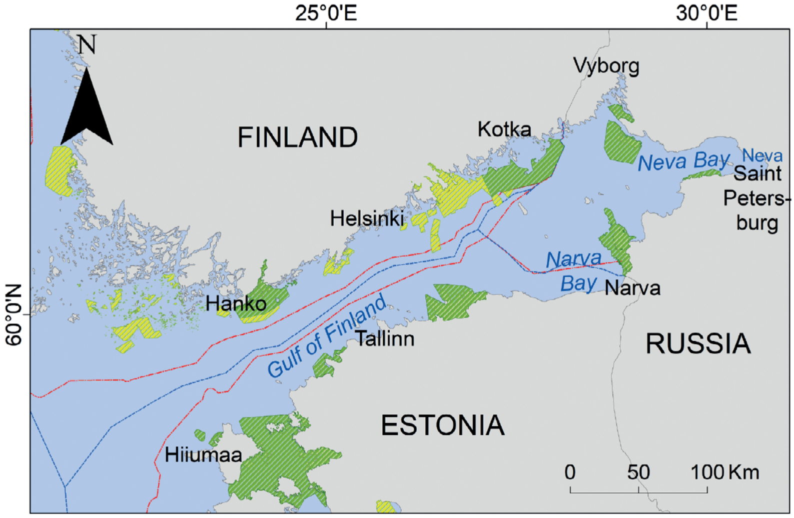

Fig. 2. The Gulf of Finland with its Marine Protected Areas highlighted (green and yellow regions). The red lines separate territorial waters and blue dashed lines depict the borders of economic zones. Image by K. Pindsoo.

items and substances to the vulnerable areas and the time it takes for such drift to occur (Andrejev *et al*. 2011, Soomere *et al*. 2011a, 2011b, Viikmäe and Soomere 2014, 2016), and the analysis of the robustness of such distributions (Viikmäe *et al*. 2013). An occurrence of the drift of a certain item to the nearshore is called nearshore hit in the text below.

The majority of studies into statistical properties of the trajectories and transport of oil spills from the vicinity of the fairway to vulnerable areas of the Baltic Sea have been performed in the context of the Gulf of Finland while a few (Höglund and Meier 2012, Lehmann *et al*. 2014) cover the entire Baltic Sea.

Most of the listed studies have focused either on the reconstruction of single events or have limited the simulations to the minimum time period after which the main statistical properties reach a saturation level or a limiting value. This time scale is about five years in the conditions of the Gulf of Finland (Andrejev *et al*. 2011). This time evidently reflects certain joint properties of the system of currents and the geometry of this water body. The shape of the gulf has been basically constant over many decades except for slow changes owing to the postglacial uplift (Leppäranta and Myrberg 2009) and local changes to sand spits and coastline location (Ryabchuk *et al*. 2012). These changes evidently do not alter the rate of nearshore hits by current-driven transport.

However, the wind system over the entire Baltic Sea has substantially changed over the last half century. In particular, the directional structure of winds has undergone large alterations. A major rotation of geostrophic air-flow over the southern part of the sea occurred in the 1980s (Soomere *et al*. 2015). A shift of the North Atlantic storm track to the north-east has led to longer persistence of weather patterns and enhanced variability of pathways of storm cyclones (Rutgersson *et al*. 2014). The changes become evident in terms of wave-driven set-up (Pindsoo and Soomere 2015) and extreme water levels (Soomere and Pindsoo 2016) in the Gulf of Finland.

It is generally understood that three factors (currents, winds and waves) basically define the drift of various objects and substances in the surface layer (Vandenbulcke *et al*. 2009). If the wind properties have undergone major alterations, it is likely that the system of currents also reacts to these changes. As the Lagrangian transport in sub-basins of the Baltic Sea does not always follow the classic counter-clockwise pattern (Soomere *et al*. 2011c, Soosaar *et al*. 2014), the reaction of the currents may largely impact the entire transport system in this water body.

The purpose of this paper is to analyse the associated changes in the statistical properties of the transport of passive substances in the surface layer over four decades. We follow the line of thinking of previous studies of surface Lagrangian transport. In particular, we focus specifically on the properties of current-driven surface transport from the fairway region to the nearshore as these properties are fairly robust with respect to various perturbations (Viikmäe *et al*. 2013).

Our study area, the Gulf of Finland (Fig. 2), is a north-eastern elongation of the Baltic Sea. It is a relatively shallow (average depth 37 m) sub-basin with a length of 400 km and width of 48–125 km. The gulf stretches from the Baltic Sea Proper to Saint Petersburg and hosts very high ship traffic. The mean circulation in the gulf is cyclonic (Leppäranta and Myrberg 2009). Although the long-term mean currents are weak, with an average speed of 5–10 cm s^{-1}, the circulation system in some areas is relatively persistent (Andrejev *et al*. 2004a, 2004b). During storms the surface currents can exceed 50 cm s^{-1}. The water masses in the gulf are strongly stratified and on many occasions the motions in the uppermost layer are only weakly connected with the motions in the lower layers. Lagrangian transport patterns are extremely complicated in the gulf due to the diversity of water masses and the abundance of mesoscale features of different size and nature (Väli *et al*. 2018).

Statistical analysis of a large number of Lagrangian trajectories of virtual parcels (that represent the potential pollution passively carried by surface currents) is an efficient method for the identification and visualisation of usually hidden properties and semi-persistent patterns of current-induced transport in this water body (Soomere *et al*. 2008, 2010). It is usually implemented for positively buoyant bodies and substances by means of locking the virtual parcels in the surface layer. Even though the impact of wind and waves may modify single trajectories (Viikmäe *et al*. 2013) and the areas from which the transport of pollution to the nearshore is most likely (Murawski and Woge Nielsen 2013), the pattern of hits to the nearshore and the time scale for such hits is almost invariant with respect to the presence of wind and waves (Viikmäe *et al*. 2013). Similarly, adding a substantial random component to the motion of passive parcels does not change the areas of cluster (Väli *et al*. 2018). For this reason it is acceptable to ignore the impact of wind and waves and to focus only on the current-driven transport.

Previous studies have addressed the time it takes for virtual parcels to reach the nearshore (particle age) and the probability of nearshore hits (Soomere *et al*. 2010, 2011) over 5-year simulation periods, and also the temporal and spatial patterns of nearshore hits over 5- or 10-year simulations (Viikmäe *et al*. 2010, 2014, 2015). Most of the studies have been performed for the years 1987–1991 while only Viikmäe and Soomere (2014) address the years 1987–1996.

An analysis of the long-term (40-year, 1965–2004) properties of the temporal scales for nearshore hits (Viikmäe *et al*. 2016) reveals considerable changes in the relative frequency of hits to the northern and southern shores of the Gulf of Finland. It is likely that this alteration stems from changes in the spatial patterns of current-driven transport and is accompanied by certain changes in the most frequently hit sections of the coasts. Such changes may greatly increase the exposedness and vulnerability of MPAs in the gulf (Delpeche-Ellmann and Soomere 2013).

In this paper we analyse systematically the temporal changes in the location of the most frequently hit nearshore areas in the Gulf of Finland. To make the results comparable with earlier conclusions, we employ the same circulation and trajectory models and input data. In essence, we simulate current-induced transport of virtual passive parcels locked in the surface layer of the Gulf of Finland to the coastal regions of the gulf. As most of the oil pollution in the Baltic Sea occurs due to ship traffic, the problem is analysed using the statistics of the trajectories that start from the vicinity of the fairway. The central goal is to quantify the long-term spatial pattern of nearshore hits and to identify temporal changes in its statistical properties.

Modelling environment

In this study we use modelled 3D velocity fields for 1965–2004 from the Rossby Centre Ocean (RCO) circulation model developed and run in the Swedish Meteorological and Hydrological Institute. As this model has been extensively described and validated (Meier 2001, 2007, Meier *et al*. 2003, Höglund and Meier 2012, Meier and Höglund 2013) and its output data set has been used for many studies of Lagrangian surface transport in the Gulf of Finland (Soomere *et al*. 2010, 2011a, 2011b, 2011c, among others), we only shortly depict its main features. The model is a primitive equation circulation model that covers the entire Baltic Sea with a spatial resolution of 2 nautical miles (about 3.6 km) and has 41 vertical layers in *z*-coordinates. In this study we concentrate solely on the effects of surface currents. For this reason only the horizontal velocities from the 3 m thick uppermost (surface) layer with a temporal resolution of 6 h are used.

The model is forced by the standard atmospheric data on the 10 m level. The forcing data is calculated from the ERA-40 re-analysis using a regional atmosphere model with a horizontal resolution of 22 km (Höglund *et al*. 2009, Samuelsson *et al*. 2011). The model also accounts for the river inflow and the presence of ice. The water level at the open boundary in the northern Kattegat is specified using hourly tide gauge recordings in this area. The properties of water masses at this boundary are derived from observed climatological mean temperature and salinity profiles (Meier *et al*. 2001).

The RCO model is barely eddy-permitting in the study area because the internal Rossby radius in the Gulf of Finland usually does not exceed 2–4 km and often is even smaller (Alenius *et al*. 2003). Therefore, a higher-resolution model is desirable to resolve the major part of mesoscale features. However, long-term simulations with a much finer model would be computationally unfeasibly costly. As we are specifically interested in statistical features of current-driven transport and their possible changes over many decades, we admit as a trade-off that the model does not accurately represent all mesoscale features. An encouraging feature of such a trade-off is that many core features of current-driven transport almost do not depend on the model resolution (Andrejev *et al*. 2011). Moreover, even quite large random disturbances to modelled trajectories of simulated parcels do not alter the Lagrangian transport patterns of surface currents in the study area (Viikmäe *et al*. 2013).

The precomputed surface velocity fields from the RCO model are used as input to a Lagrangian trajectory model TRACMASS (Döös 1995, De Vries and Döös 2001) of virtual parcels. This model relies on an analytical solution of a differential equation for motion that depends on the properties of motion at the ocean model grid box walls using a linear interpolation of the fluxes (of volume or mass) both in time and in space. We employ so-called off-line mode (in which the velocity fields pre-exist) and a non-spreading version of the TRACMASS (in which it is assumed that the velocities retrieved from a circulation model fully represent the motions in the ocean). In this implementation the effects of subgrid-scale turbulence on the motion of fluid parcels are ignored (Döös *et al*. 2013, 2017). As the main features of the spatial pattern of current-driven hits are almost insensitive to subgrid-scale turbulence (Viikmäe *et al*. 2013), the use of this assumption apparently does not affect the results of our study.

Consistently with the aim to study the properties of surface transport, we use surface velocities for the evaluation of trajectories of virtual parcels. Doing so implicitly means that the selected parcels are locked in the uppermost layer as in (Soomere *et al*. 2010, Andrejev *et al*. 2010) and are only advected by horizontal velocity. The resulting trajectories of parcels thus represent purely current-driven motion of objects that are slightly lighter than the surrounding water or objects or are confined to the upper layer by other constraints.

Method

As we are interested in the patterns of transport of pollution possibly released from ship traffic or occurring during ship accidents, we focus on trajectories of parcels that start their journey in a region that roughly follows the major fairway in the Gulf of Finland from the Baltic Sea proper to Saint Petersburg (Fig. 1). In order to mimic the natural spread of ship tracks and to take into account the travel separation scheme, virtual parcels are selected in a three RCO model grid cells wide (about 11 km) strip that matches the shape of the fairway. In each simulation one parcel is selected at the centre of each of the 309 grid cells that are in this strip (Fig. 3).

The surface flow simulated by circulation models is largely alongshore in the nearshore cells. This means that virtual parcels usually do

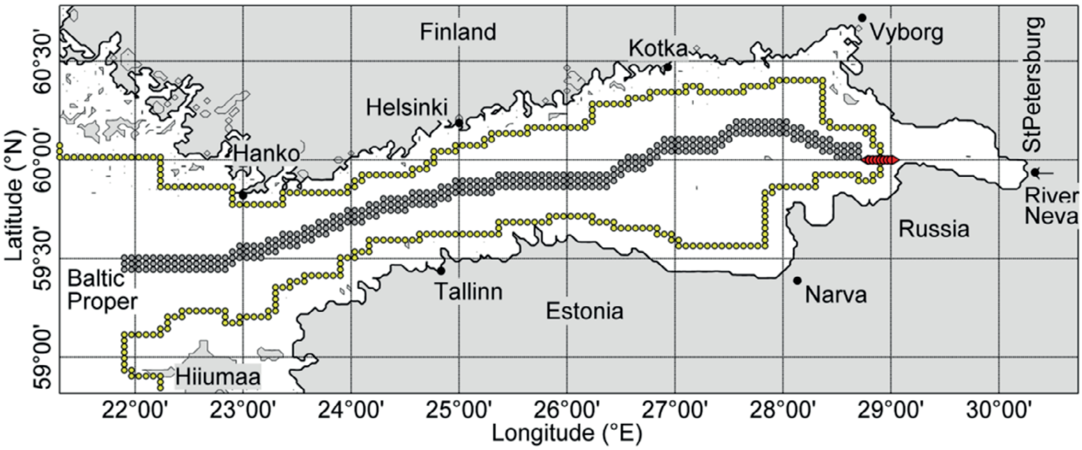

Fig. 3. The initial location of selected water parcels along the major fairway and the border of the nearshore in the Gulf of Finland. The red double arrow indicates the separation point of the 'southern' and 'northern' parts of the nearshore.

not reach the shore. For this reason we define a virtual coastal line at a certain distance from the model coast. This approach is often used in simulations of the beaching of oil (Broström *et al*. 2011). A reasonable location for such a virtual coastline (interpreted below as the seaward boundary of the model nearshore) for the trajectories in the combined RCO-TRACMASS model is at a distance of three grid cells (about 11 km) from the model land area (Viikmäe *et al*. 2010) (Fig. 3). The border of the nearshore defined in this manner is mapped with 331 grid cells.

Statistical properties of the current-induced transport from the fairway to the nearshore are calculated based on the analysis of trajectories of virtual parcels selected in the fairway region and passively carried by surface currents during a certain time interval (called a time window). As this approach and its limitations are presented in detail in (Soomere and Quak 2013), we discuss here only the core features relevant to the particular problem.

The average time it takes for a parcel selected or released in the Gulf of Finland to drift to the nearshore (called particle age in Andrejev *et al.* 2011) is about 5 days. This time is somewhat longer (6–9 days) for parcels released in the central part of the gulf. To reliably represent the hits to the nearshore by pollution released in the vicinity of the fairway, the duration of trajectories should be at least twice as long as this time. The use of much longer trajectories is unreasonable because the probability of nearshore hits rapidly decreases after reaching a maximum value (Viikmäe *et al*. 2010). Moreover, exceedingly long trajectories may approach close to each other at certain time instants, after which they would be correlated.

An adequate representation of statistical features of transport requires the use of a sufficient number of uncorrelated trajectories. The number of simultaneously calculated independent trajectories is implicitly limited by the number of grid cells used for seeding the parcels. It is possible to formally increase the number of trajectories by mimicking the contribution of subgrid-scale motions towards spreading trajectories in the real ocean, e.g., by inserting random disturbances to the trajectories (e.g., Kjellsson *et al*. 2013, Väli *et al*. 2018). Doing so may improve, e.g., the match of transport speed and dispersion with their actual values but this is counterbalanced by a loss of transport direction and possibly other properties (Kjellsson *et al*. 2013).

Following Soomere and Quak (2013), we repeat the calculations with a certain time lag in order to produce a sufficient number of uncorrelated trajectories. As the surface drift speed in the Gulf of Finland is typically 0.1–0.2 m s^{-1} (Kõuts *et al*. 2010) and the current patterns are normally strongly circularly polarised (Lilover and Stips 2011), a parcel is only relocated a few kilometres a day. Therefore, only the trajectories that lag at least a couple of days behind the previous one can be treated as independent in our modelling environment.

Based on these arguments, we use in this study 20 day trajectories and each new set of trajectories starts with a time lag of 5 days. The calculations are organised following the procedure presented in (Soomere *et al*. 2010, Viikmäe *et al*. 2010). One parcel is selected at the centre of each ocean model grid cell near the fairway at 00:00 on 1 January each year. The trajectories of all 309 parcels are calculated until 00:00 on 20 January. A new set of 309 parcels is released in the same locations at 00:00 on 6 January and their trajectories are again evaluated over 20 days. The process is repeated until the end of the year. An equal number of sets of 309 × 6 = 1854 trajectories are used in each month, starting on days 1, 6, 11, 16, 21 and 26, with the total number of 72 sets (22 248 trajectories) per year.

Similarly to previous studies (Soomere *et al*. 2010, 2011, Viikmäe *et al*. 2010, 2014), we only consider the trajectories that enter the nearshore at least once. For each such trajectory, the initial location of the parcel, the point at which the trajectory reaches the nearshore (executes a nearshore hit) for the first time and the time elapsed from the release of the parcel (particle age) (Andrejev *et al*. 2011) are saved. Further behaviour of the trajectory is ignored. The total number of 20 day long time windows during the 40-year interval is 2880 and the simulations result in 889 920 single trajectories, out of which 479 477 or 53.9% reached the nearshore. Even though this rate varies to some extent for different years, each year is characterised by > 10 000 such trajectories out of total 22 248 trajectories evaluated for each year.

Results

Statistical parameters of hits to the nearshore

The average number of hits to single nearshore grid cells per annum is about 35. The maximum counts of hits are by an order of magnitude larger (Table 1). The northern nearshore received the highest number of hits (270–350 per year in the most frequently hit locations) between 23°30´E to 25°30´E and between 28°30´E and 29°00´E. Hits to the southern nearshore are more equally distributed. The largest number of nearshore hits (200–300 hits per year) occurred between 23°30´E and 24°30´E, near 25°30´E and close to 28°00´E (Fig. 4).

Although the number of hits to the opposite coasts varied annually by about ±10%, hits to the northern coast slightly (by around 1%, 247 541 *versus* 231 936) dominated over hits to the southern coast over the 40 years. Therefore, the hypothesis that the Estonian coastline is more exposed to current-driven pollution (Soomere and Quak 2007) is not supported by our calculations. The proportion of the hits to different coasts varies much more over these years (Viikmäe *et al*. 2014).

To systematically estimate the differences in the spatial distributions of nearshore hits in different decades, we divide the simulation time interval into eight 5-year periods from 1965 till 2004 and calculate correlations between the dif-

Table 1. Basic properties of the 5-year average number of nearshore hits per single coastal segment over different time intervals.

	1965–1969	1970–1974	1975–1979	1980–1984	1985–1989	1990–1994	1995–1999	2000–2004	1965–2004
Mean	173.2	180.4	184.4	172.6	169.1	199.9	195.6	173.5	181.1
Std. dev.	10.8	10.9	11.3	10.1	10.1	11.1	11.5	10.3	10.8
Median	107.0	118.0	113.0	122.0	116.0	146.0	130.0	113.0	120.6
Mode	48.0	36.0	14.0	16.0	10.0	23.0	10.0	29.0	23.2
Kurtosis	9.8	9.6	9.6	9.2	9.8	7.3	8.7	7.9	9.0
Skewness	2.4	2.3	2.3	2.2	2.3	1.9	2.2	2.0	2.2
Maximum	1162	1189	1280	1131	1254	1137	1178	1122	1280
Sum	57318	59704	61044	57120	55961	66165	64747	57418	479477

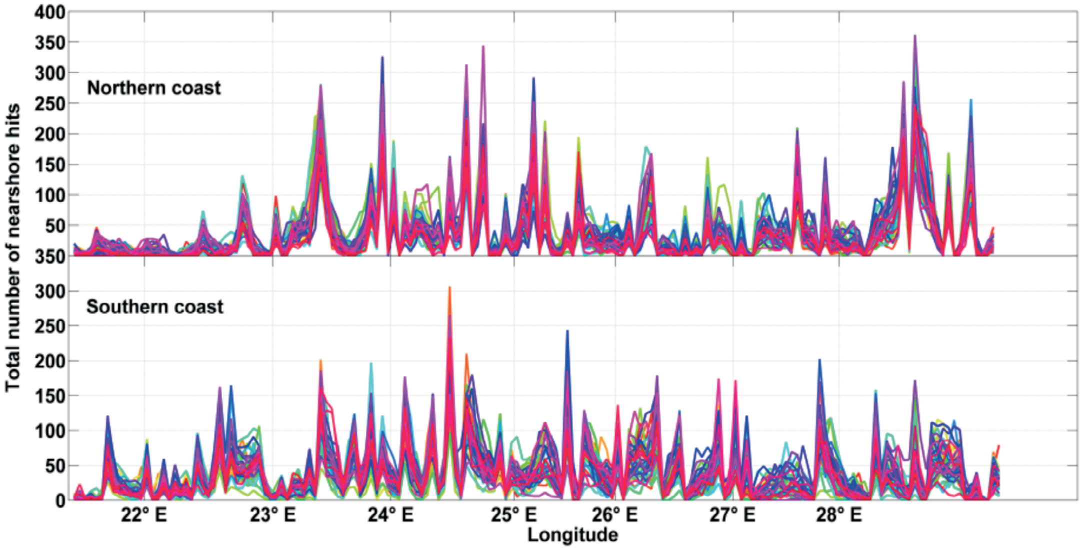

Fig. 4. The total number of nearshore hits from different fairway points in the Gulf of Finland for 1965–2004. Each line (40 in total) indicates the annual number of nearshore hits. The upper panel shows the nearshore hits to the Finnish coast and the lower panel to the Estonian coast.

ferent data sets. The main statistical properties of the number of coastal hits in single segments vary insignificantly between the 5-year intervals and over the entire simulation interval 1965–2004.

The total number of nearshore hits for single 5-year periods varies from 55 961 to 66 165. The average number of coastal hits per segment varies about ±10% (from 169.1 to 199.9 in 5 years or from 34 to 40 per annum) from the long-term mean (Table 1). The maximum number of coastal hits in 5 years in a single segment has even smaller variation (from 1131 to 1280 or less than ±7%). The standard deviation varies from 10.1 to 11.5 (±14% from its average value) and the median from 107 to 146 (±20%). The mode of this data set exhibits very large variations, from 10 to 48 in different 5-year intervals. This variation has no clear trend and thus basically reflects the sensitivity of this quantity with respect to relatively small changes in the forcing.

The skewness (a measure of asymmetry of probability distributions) for the distributions of nearshore hits for these periods varies from 1.9 to 2.4, but is mostly 2.2–2.3. The limited variation in the skewness indicates that all distributions have a similar level of asymmetry. The positive values of skewness signal that the "tail" of the distribution is located to the right of the most frequent values. The kurtosis is much greater than 3 for all distributions in question. This feature indicates that the distributions are strongly leptokurtic: the bulk of the data appears in a narrow range and forms a clear and tall maximum of the probability density whereas the "tail" of the distribution approaches zero more slowly than a Gaussian distribution. Such processes tend to have more positive outliers than the normal distribution. Therefore, usually the number of hits is close to the long-term mean. However, it may be much larger in single years but normally not significantly below the long-term average. Importantly, both the kurtosis and skewness of the set of hits to single segments are stable over the entire set of simulations (Table 1). The mode has largest variations among the classic parameters of pointwise numbers of nearshore hits. It varies from 10 to 48. This variation indicates that in some years almost all hits are concentrated in a small number of nearshore segments while in some other years the hits may be distributed much more evenly.

Spatial distribution of hits to the nearshore

The number of nearshore hits to some of the segments that have an average or smaller number

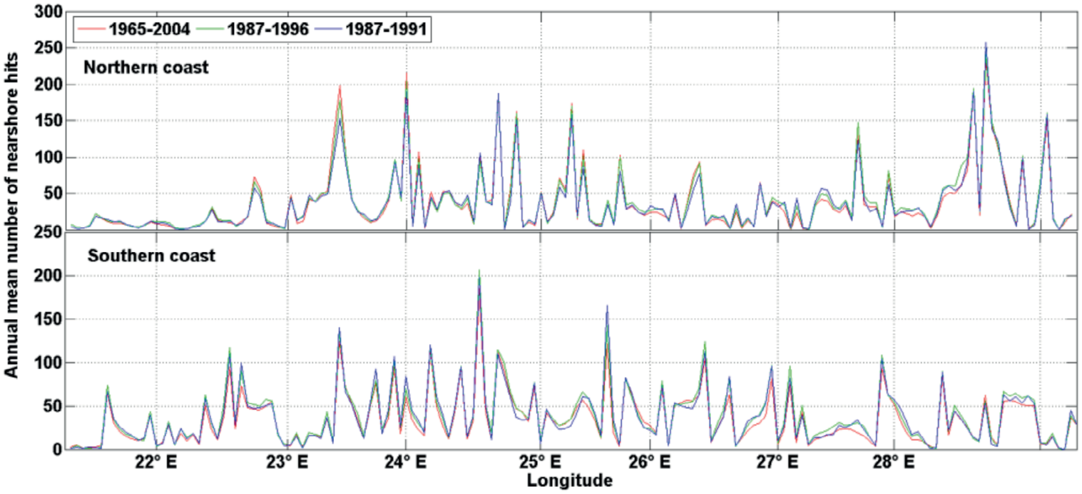

Fig. 5. A comparison of the annual average spatial pattern of nearshore hits for 1987–1991, 1987–1996 and 1965–2004.

of hits varies substantially (by up to an order of magnitude) between different years (Fig. 4). The spatial pattern of hits and especially the position of relatively frequently hit nearshore locations have the same qualitative shape in all years. This shape persisted even in the years such as 1984 when the wind directions and properties of wave-driven sediment transport in the coastal zone were unusual in most of the Baltic Sea region (Soomere and Viška 2014).

The variations in the spatial pattern of hits to the nearshore are much smaller for single 5-year simulations. The resulting pattern is very stable over many decades (Fig. 5) in terms of both relatively frequently hit and sheltered coastal segments. The relative number of hits in different nearshore locations averaged over 5 years still varies by up to ±20% in single segments but the qualitative pattern of hits remains exactly the same. The rate of hits evaluated for different time intervals shows some minor differences in coastal sections in the vicinity of Tallinn and in Narva Bay. The annual average number of nearshore hits for the longest simulation period is slightly lower in some locations than for shorter ones. This is an expected feature due to the longer averaging of results.

We tested the match of the spatial distributions of the number of hits to the different nearshore segments using the classic Kruskal-Wallis H test (Kruskal and Wallis 1952). This is a non-parametric method for testing whether different datasets (that need not follow a Gaussian distribution) originate from the same distribution. As expected, based on the visual appearance of these data sets (Fig. 5), the test confirms that the percentage of nearshore hits (from the maximum number of hits) for 1987–1991, 1987–1996 and 1965–2004 are identically distributed. The resulting p value for the null hypothesis is 0.9237. The two sample Student's t-test (Gosset 1908) led to the same result at the default 5% significance level. The correlation coefficients between the hits to single nearshore locations in the ten data sets in question varied between 0.94 and 0.99. The smallest correlation coefficients (0.94) were for the subsequent five-year intervals 1980–1984 and 1985–1989. Also, the correlation coefficients between each 5-year simulation with the long-term simulation are between 0.97 and 0.99 whereas the smallest correlation coefficient (0.97) was again for the years 1985–1989. Such a high correlation indicates that the variability between different datasets is insignificant.

Therefore, annual and inter-annual variability of the nearshore hits (Fig. 4) is significant, as can be expected. However, the qualitative shape of the relevant spatial pattern is extremely persistent even in years with very odd wind properties. Averaging over five subsequent years smoothes out most of the variability but keeps the spatial pattern of nearshore hits. The statistical prop-

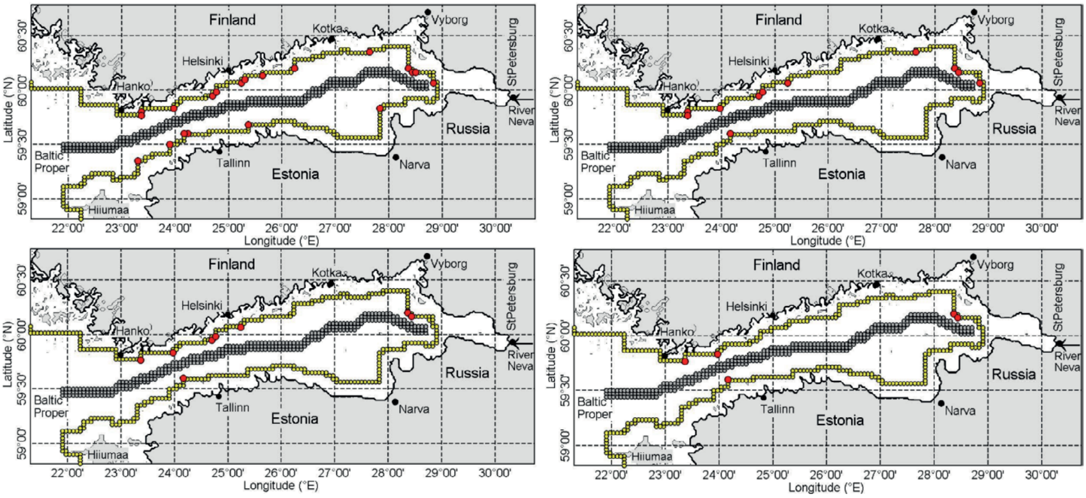

Fig. 6. Most frequently hit nearshore areas (red circles) in the Gulf of Finland. The top left panel shows the nearshore areas receiving frequent hits in at least one year from the 40-year simulation period, the top right in at least 10 years, the bottom left in at least 20 years (half the time) and the bottom right in at least 30 years.

erties of the 5-year average number of hits to different coastal sections as well as the spatial patterns of such hits are practically constant over the entire 40-year simulation time interval.

Location of vulnerable nearshore segments

The description of nearshore locations that have the highest number of hits in single years is developed using the metrics proposed in (Viikmäe *et al*. 2016). We single out the sections of the nearshore that receive the number of hits that is ≥ 60% of the annual maximum number of hits in any nearshore section. This distinguishing is made on an annual basis and such sections (grid cells) are called frequently hit locations. As the number of hits in different sections varies greatly along the shoreline (cf. Viikmäe *et al*. 2014 and below), the number of such points is usually less than 10 each year.

The nearshore hits are systematically very frequent (occurring in 30 years out of the total 40 simulation years) between Hanko and Helsinki (between 23°20′and 24°00′E) and in a short section to the south of Vyborg. The most affected section of the southern nearshore is in the vicinity of Tallinn. In total, 20 nearshore sections receive frequent hits in at least one year from a 40 year simulation period, 11 sections in at least 10 years, 8 during at least half the time (20 years), and 5 sections during 75% of the simulations (or 30 years) (Fig. 6).

The picture is asymmetric, especially in the eastern part of the gulf where the southern nearshore is hit relatively infrequently. The only area near the southern coast that often receives a high number of hits is to the west of Tallinn, around 24°00′E. This asymmetry may reflect the overall cyclonic pattern of motions in the Gulf of Finland that may become evident in the long-term average. Another possible reason for the low exposedness of the shore of eastern Estonia to current-driven pollution is a powerful and persistent flow driven by the discharge from the Neva River (cf. Andrejev *et al*. 2004a). It may redirect the surface-current-induced transport to the north-west and in this way implicitly protect the southern coast.

Somewhat less frequently affected are two nearshore areas in the vicinity of Helsinki that have the largest share of hits in 20 years out of 40 (Fig. 6). The maximum number of hits in 10 years out of 40 occurs also near Neva Bay and between Kotka and Vyborg. Finally, two more locations on the northern coast (one at the northern reach of Narva Bay, another to the east of Tallinn) and two at selected points near the northernmost tip of Estonia are the most frequently hit sections in

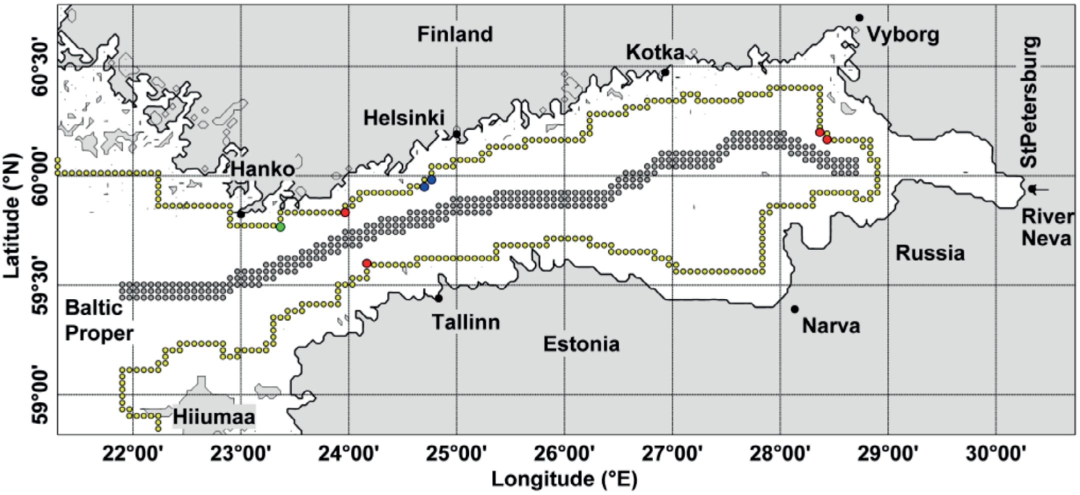

Fig. 7. A comparison of the most frequently hit nearshore areas for 1987–1991, 1987–1996 and 1965–2004. The red circles indicate areas present during all the periods, the green circle indicates area present only during 1987–1996 and 1965–2004, and the blue circles indicate areas present only during 1987–1991 and 1987–1996.

one single year. Therefore, in this metrics (that only takes into account the location of the sectors that have the maximum number of hits in single years) the domain to the east of Helsinki, to about 28°30´E, and an extensive nearshore area between Tallinn and Narva are relatively safe with respect to pollution originating from the model fairway. These areas receive a relatively low number of nearshore hits in all years.

Most of the northern nearshore of the gulf has a somewhat lower probability of hits than the southern shore except for short sections between Helsinki and Hanko. A large number of hits to these two sections lead to the slight predomination of the northern shore in terms of the total number of hits. The extensive variability in the spatial pattern of frequently hit nearshore domains and in the number of hits on monthly and seasonal level is natural because of high variability in the patterns of currents of the Gulf of Finland (Alenius *et al.* 1998, Leppäranta and Myrberg 2009, Myrberg *et al.* 2010). Still, it raises the question about uncertainties of the resulting estimates, especially in the spatial distribution of the most frequently hit areas. A partial answer is given in (Viikmäe *et al.* 2013) based on the analysis of this variability over longer time intervals.

The presented patterns almost exactly match the similar patterns for 5-year pointwise annual average values of nearshore hits (Viikmäe *et al.* 2014). Both reveal a medium frequency of hits in the area between Hanko and Helsinki and also in the area to the west of Tallinn, near the southern coast of the gulf, extending to Hiiumaa. The hits are most frequent in the north-western part of Estonia near 24°00´E and in the easternmost part of the gulf, to the south of Vyborg. The northern coast from Helsinki to 28°30´E and the southern coast, between Tallinn and Narva, are relatively safe (Viikmäe *et al.* 2014).

A map of the most frequently hit nearshore areas for three different periods, 1987–1991 (5-year simulation), 1987–1996 (10-year simulation) and 1965–2004 (40-year simulation) signals that the overall spatial pattern of frequently hit coastal segments is largely stable over many decades (Fig. 7). The most frequently hit nearshore points (one between Hanko and Helsinki near 24°00´E, two to the south from Vyborg near 28°30´E, and one to the west of Tallinn, also near 24°00´E on the southern coast) are present during all the simulations.

The nearshore point to the east of Hanko (close to 23°30´E) is most frequently hit only during the 10-year and 40-year simulations. Two nearshore areas, located to the west from Helsinki, close to 25°00´E, are most frequently hit during the 5- and 10-year simulation periods, but do not show this property during the long-term simulation.

Therefore, even though the number of hits has extensive temporal (monthly and seasonal) and spatial variability, the most frequently hit nearshore areas are consistently the same over the last 40 years. As the proportion of hits to the southern and northern nearshore has considerably changed (Viikmäe *et al*. 2016), it is thus likely that these areas are geometrically defined rather than resulting from a statistically stationary pattern of currents.

Links between sources and impact locations of pollution

The probability of reaching the nearshore and the time it takes vary greatly for parcels released in different sections of the fairway in the Gulf of Finland (Viikmäe *et al*. 2014). In other words, certain single locations of the existing fairway may be the predominant starting points of coastal pollution or adverse impacts that hit the nearshore or some MPAs (Delpeche-Ellmann and Soomere 2013). These locations substantially vary over different months, seasons and years but are persistent over time intervals of several years (Viikmäe *et al*. 2014).

The relatively dangerous sections are located near the bayhead of the Gulf of Finland and to the south of Vyborg. Therefore, any contaminant in the uppermost layer of the sea as well as oil spill released in these sections of the fairway has a high chance of rapidly drifting to the nearshore. This threat is enhanced by the predominance of south-western winds in this area that tend to drive the pollution towards the northern coast of the gulf. The section of the fairway between longitudes 25°E and 27°30´E provides the least danger. Generally, sections of the fairway that are the most remote from the coast provide a low level of danger of coastal pollution also in terms of particle age (Viikmäe *et al*. 2014).

An intriguing question is whether certain nearshore areas are systematically hit by adverse impacts released in specific parts of the fairway. Similarly to Viikmäe *et al* (2014), we only consider the sections of the nearshore for which the annual count of hits exceeds 60% of the maximum count for at least ten of the 40 years of 1965–2004. The total number of these sections is 37 (that is, about 11% of the grid points at the border of the nearshore). The number of hits to each such section largely varies in different years whereas these hits usually stem from quite different fairway points. Therefore, the simulations do not reveal any systematic interconnections between potential sources of pollution and places where the pollution reaches the nearshore also in the long-term run. This result, however, does not exclude the appearance of such patterns in single seasons or under specific weather conditions as suggested by the existence of rapid pathways of Lagrangian transport in some segments of the gulf (Soomere *et al*. 2011c).

The absence of a clear pattern of interconnections has important implications for pollution control measures as well as for search and rescue purposes. In particular, this feature suggests that it is generally not possible to establish, at least using the model at our disposal, from where single objects originate. The existing connections between the source and target areas have predominantly a sort of ‘many-to-one’ nature. Therefore, statistical simulations such as those that we have performed show many locations where the object is unlikely to come from. This may allow the exclusion of several potential sources of pollution (ships). Also, accurate information about the beaching time could be used for distinguishing the source and location of pollution.

The pattern of interconnections between the sources and sinks (Fig. 8) is generally analogous to the pattern established in (Viikmäe *et al*. 2014) for a 10-year simulation in 1987–1996. The interconnections of specific sections of the fairway with domains that receive frequent hits in at least 30 years out of the total 40-year simulation period, estimated based on the number of frequently hit coastal segments, are somewhat weaker than in 1987–1996. This result signals that such interconnections, generally, are not long-living, as the longer simulations seem to smooth out the resulting patterns. Still, most (albeit weak) interconnections remain the same: five nearshore points have such a link in 1965–2004 compared to seven in the 1987–1996 simulation.

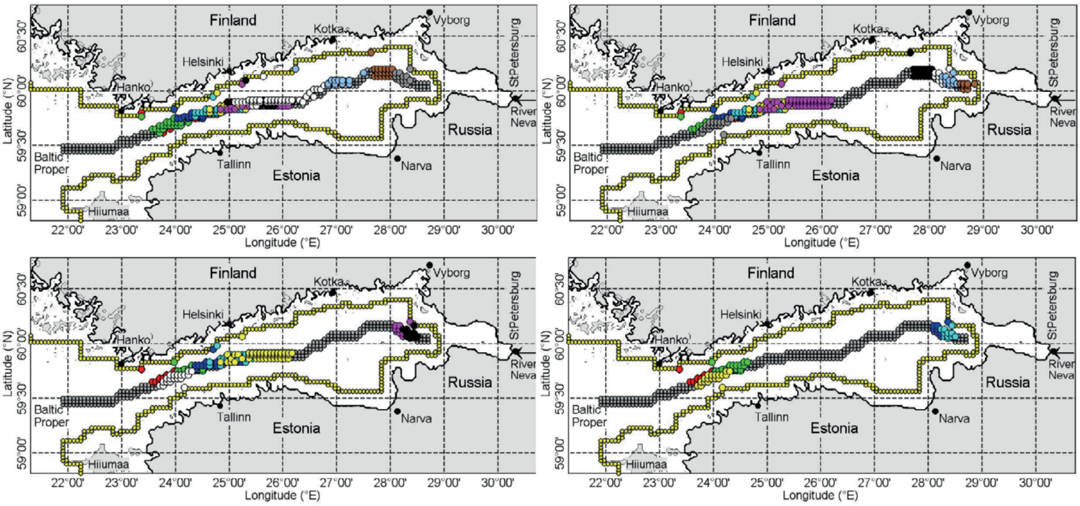

Fig. 8. Interconnection between the release locations of passively drifting parcels and sections of the nearshore where they are carried (equivalently, possible sources and sinks of pollution). The top left panel shows the nearshore areas receiving frequent hits in at least one year from 40-year simulation period, the top right in at least 10 years, the bottom left in at least 20 years (half the time) and the bottom right in at least 30 years. The colours of frequently hit coastal segments match the colour of the release locations of the parcels.

Discussion and conclusions

The core target of this paper is to corroborate whether and how much the observed changes in the wind patterns over the Baltic Sea have affected the qualitative and quantitative features of solely current-driven transport of pollution in the Gulf of Finland. The changes in wind properties involve a substantial rotation in both geostrophic (Soomere *et al*. 2015) and surface-level (Keevallik and Soomere 2014) air flow in the entire region. It is natural to expect that such changes in the wind climate are somehow reflected in the system of currents, e.g., via changes in the spatial distribution of upwellings and downwellings (Myrberg and Andrejev 2003).

To make the results comparable with earlier results, we simulated passive parcels located in the surface layer of the Gulf of Finland moving to the coastal regions of the gulf using the same circulation and Lagrangian transport models that were employed in previous studies and generously provided by the Swedish Meteorological and Hydrological Institute and Stockholm University. Similarly, we focus on trajectories of parcels selected on a line that roughly follows the major fairway in the Gulf of Finland from the Baltic Sea proper to Saint Petersburg. To understand the impact of climate changes, we cover a 40-year simulation period from 1965–2004. The results are interpreted in terms of current-driven drift of passive parcels to the nearshore of the study area. Such occasions are termed as hits to the nearshore.

As expected, the system contains a relatively large level of interannual variability in terms of hits to single nearshore locations. This variability is comparatively large in locations that have less than an average number of hits but much smaller in relatively frequently hit locations. The spatial pattern of such hits and its main statistical properties are qualitatively the same in all years. Importantly, this pattern, averaged over 5-year simulation intervals, is almost constant during the four decades of simulations also quantitatively. The classic Kruskal-Wallis H test and two-sample Student's t-test verify that the relevant distributions match each other. The correlation coefficients between 5-year averages of spatial patterns of nearshore hits vary between 0.94 and 0.99, clearly indicating that the variability between different datasets is insignificant.

In the light of this conclusion, it is not unexpected that the most frequently hit nearshore domains to the west of Tallinn on the southern coast, and between Hanko and Helsinki and a short section to the south of Vyborg are the same as identified in previous studies of current-driven transport in 1987–1991. This persistence suggests that at least part of the revealed structure reflects the geometry of the gulf rather than the gulf-specific pattern of currents.

Interestingly, this persistence does not lead to more definite interconnections between specific parts of the fairway and single (the most exposed) nearshore segments. A total of 37 frequently hit nearshore sections have a highly varying number of hits in different years. The parcels that reach these sections originate from different fairway points. Only 11 sections of the coastline out of 331 frequently receive a massive number of hits by parcels selected in relatively small parts of the fairway. The longer simulations even seem to weaken the links between the sources and places of hits of pollution even though some of the interconnections seem to be persistent. Another interesting feature is that although hits to any of the opposite coasts varied annually, the 40-year average results indicate that hits to the northern coast dominate over hits to the southern coast by around 1%.

The main message of our study is twofold. Firstly, we have, in essence, more thoroughly substantiated a conjecture made by Andrejev *et al*. (2011). Namely, in order to produce an adequate estimate of statistical parameters of current-induced drift in the Gulf of Finland, it is necessary to average over a much longer interval than one year. A five-year interval is evidently long enough. This interval is much longer than the time of spin-up of circulation models and also clearly longer than the typical residence time of water in this basin (Andrejev *et al*. 2004b).

Secondly, and more importantly, even though the patterns of surface currents may have reacted to changes in the wind climate, the patterns of frequency of beaching of current-driven pollution from the vicinity of the major fairway in the Gulf of Finland have remained unchanged over almost half century. In particular, the nearshore segments that are particularly exposed to this sort of pollution (in terms of massive coastal hits as evaluated in this paper) are the same in the changing climate. This feature carries also a partially good message: the knowledge of the location of most probable beaching segments will be of great help in planning the location of oil pollution combatting forces.

Our simulations only conditionally represent reality. For example, (oil) pollution is almost never passively carried solely by surface currents; instead, it is affected also by wind and waves. The pollution parcels are not necessarily stable and may behave differently in the coastal zone where local transport by steep and partially breaking waves (and associated strong local Stokes' drift) may substantially affect their motion. Moreover, the particular geometric shape of the study area may implicitly govern the persistence of the beaching locations. However, first results of studies into the impact of wind on the motion of sticky particles on sea surface (Giudici *et al*. 2018) indicate that several statistical properties of the system of parcels drifting on the surface of the Gulf of Finland are fairly robust.

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