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Temporal scales for transport patterns in the Gulf of Finland

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Abstract. The basic time scales for current-induced net transport of surface water and associated time scales of reaching the nearshore in the Gulf of Finland, the Baltic Sea, are analysed based on Lagrangian trajectories of water particles reconstructed from three-dimensional velocity fields by the Rossby Centre circulation model for 1987–1991. The number of particles reaching the nearshore exhibits substantial temporal variability whereas the rate of leaving the gulf is almost steady. It is recommended to use an about 3 grid cells wide nearshore area as a substitute to the coastal zone and about 10–15 day long trajectories for calculations of the probability of reaching the nearshore. An appropriate time window for estimates of the properties of net transport patterns is 4–10 days.

Key words: hydrodynamic modelling, currents, Lagrangian transport, Gulf of Finland, Baltic Sea.

1. INTRODUCTION

International ship transport has dramatically increased in the Baltic Sea basin over the last two decades and at present accounts for up to 15% of the world's cargo transportation. The largest threat to the environment is oil transportation that has increased more than by a factor of two in 2000–2006 [1]. One of the major marine highways in the European waters enters the Baltic Sea through the Danish Straits, crosses the Baltic Proper and stretches through the Gulf of Finland (Fig. 1) to Saint Petersburg, the major population and industrial centre in this area, and to a number of new harbours in its vicinity. Sustainable management of this traffic flow is a major challenge in the Baltic Sea, which is designated as a Particularly Sensitive Sea Area by the International Maritime Organization [2,3].

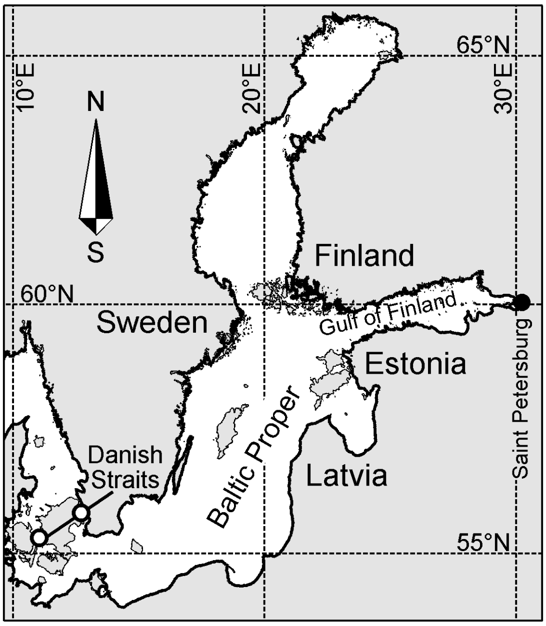

Fig. 1. Location scheme of the Baltic Sea and the Gulf of Finland.

Frequent stormy winds, short period of daylight and cold weather in autumn and winter make the shipping quite tricky in the entire Baltic Sea. The presence of heavy ice almost every winter drastically complicates the navigation in the Gulf of Finland, the easternmost prolongation of the Baltic Sea with a length of about 400 km, maximum width of 125 km and a mean depth of 37 m [4]. As the width of this gulf is at some places below 50 km and in many places water is too shallow, there are several narrow passages where the concentration of traffic is exceptionally high. In addition, the fairway from the Baltic Proper to the eastern region of the gulf crosses intense fast ferry traffic between Helsinki and Tallinn where more than 50 gulf crossings take place daily during the high season [5]. These features increase the risk of a potential release of various adverse impacts (oil or chemical pollution, lost containers or other large buoyant items, etc., and associated impacts or hazards to both the environment and to other vessels) owing either to an accident, technical problems or human mistakes or mis-behaviour.

The drift of agents of adverse impacts released into the surface layer (oil spills, lost containers, etc.) is influenced by wind stress, waves, and currents. The properties of transport by wind and waves are relatively well known [6,7]. Much less is known about the transport driven by the field of currents [8]. Currents are created under influence of several local and remote forcing factors, which makes their prediction quite challenging. It is even more complicated in strongly stratified sea areas such as the Gulf of Finland where the drift frequently is steered by multi-layered dynamics [9].

Surface currents in the Gulf of Finland are highly variable both seasonally and annually [4,10]. Recent analyses have demonstrated the existence of semi-persistent patterns of currents in this gulf and in some other parts of the Baltic Sea [11–13]. Such patterns with a lifetime of a few weeks apparently provide relatively fast current-driven transport in certain sea areas. This combination serves as a challenge for a technology that attempts to use the marine dynamics for reducing the risk of coastal pollution [14]. The goal of such technologies is to minimize the risk of pollution (and to identify areas, which are statistically safer to travel to) in terms of minimizing the probability of reaching the valuable areas. An equivalently equal gain is a systematic increase of time during which an adverse impact (for example, an oil spill) reaches a vulnerable area after an accident has happened.

A generic example of vulnerable areas is the nearshore that usually has the largest ecological value. While the probability of coastal pollution for open ocean coasts can be reduced by shifting ship routes farther offshore, the problem for narrow bays, like the Gulf of Finland, is how to minimize the probability of hitting any of the coasts. The first order solution is the equiprobability line, the probability of propagation of pollution from which to either of the coasts is equal [13]. There may also exist areas of reduced risk, propagation of pollution from which to either of the coasts is unlikely. The safe fairway would either follow the equiprobability line or use an area of reduced risk.

The problem of identification of areas of reduced risk is addressed in [13,15] by means of statistical analysis of a large pool of Lagrangian trajectories of test particles, constructed based on the results of a 3D circulation model. Such an analysis also allows the identification and visualization of several properties of currents that cannot be extracted directly from the current fields. The results, however, depend to a certain extent on the choice of the underlying velocity fields as well as the governing parameters for the trajectory calculations such as the initial location of test particles released into the sea, the duration of single trajectory simulations, the number of trajectories involved for each calculation session, etc.

The purpose of this study is to evaluate certain spatial and temporal scales necessary to be covered in such simulations in order to reach representative results in the context of the Gulf of Finland. After a short description of the modelling environment we focus on requirements for the basic parameters of the calculations such as the width of the coastal zone and the duration of trajectory calculations. Finally, the range of time scales for which semi-persistent patterns may be important in this basin is estimated and the sensitivity of the results on the choice of the time lag between subsequent trajectory simulations is discussed.

2. MODELLING ENVIRONMENT AND METHODS

In this study, the 3D velocity fields, simulated for 1987–1991, provided by the Swedish Meteorological and Hydrological Institute, were used for calculations of trajectories of potential adverse impacts. This time period was chosen in order to make the results comparable with circulation simulations [11,16] and studies into probability distributions for coastal hits in the Gulf of Finland [13]. The velocity fields were calculated by the Rossby Centre Ocean circulation model (RCO). This is a primitive circulation model coupled with an ice model [17] that covers the entire Baltic Sea with a spatial resolution of 2×2 nautical miles (NM) and has 41 vertical layers in *z*-coordinate. We only use the horizontal velocities in the uppermost, surface-layer with a thickness of 3 m. A time step splitting scheme is used in the RCO, with 150 s for the baroclinic and 15 s for the barotropic time step in underlying runs. In order to keep the data set of currents within a reasonable limit, the model output is saved with a temporal resolution of 6 h.

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. It also accounts for river inflow and water exchange through the Danish Straits. The forcing data is calculated from the ERA-40 re-analysis using a regional atmosphere model with a horizontal resolution of 25 km and a scheme of adjusting the wind properties using simulated gustiness [18]. Details of the model set-up and validation experiments are discussed in [17,19,20]. Given the very small internal Rossby radius in the Gulf of Finland (typically 2–4 km [21]), the model apparently resolves a certain part of the meso-scale dynamics in this gulf in terms of statistics of meso-scale eddies but an exact representation of the location and properties of single eddies cannot be expected. The model also captures inertial waves in the gulf but owing to a coarse resolution of the saved output data (about half of the period of internal waves), the role of these oscillations in the drift of particles is apparently only partially accounted for.

The current-driven transport of adverse impacts is analysed with the use of a Lagrangian trajectory model, TRACMASS [22,23]. It uses pre-computed 3D Eulerian current velocity fields to evaluate an approximate path of water particles (equivalently, of an adverse impact with neutral buoyancy). The model relies on an analytical solution of a differential equation for motion that depends on the velocities on the grid box walls using linear interpolation of the velocity field both in time and in space.

As we are specifically interested in surface transport patterns, the test particles are locked in the uppermost layer as in [13,15]. The resulting trajectories are, thus, not truly Lagrangian: they are not passively advected by the velocity fields and basically represent motion of objects that are slightly lighter than the surrounding water (such as oil in otherwise calm conditions) or objects which are confined to the upper layer by other constraints (for example, lost containers).

The overall procedure is as follows [13]. First, the initial locations of a certain number of water particles (interpreted as carrying an adverse impact) are specified. The time period of interest $[t_0, t_0 + t_D]$ with duration of t_D (usually ≥ 1 year) is divided into time windows of fixed length t_W. The motion paths (trajectories) of the cluster of water particles (interpreted as current-driven propagation of the adverse impact) are first simulated over the interval $[t_0, t_0 + t_W]$. The resulting trajectories are saved for further analysis. The simulations for the same initial positions of particles are restarted at another time instant $t_0 + t_S$. The trajectories are again calculated over a time window with a duration of t_W (that usually to a large extent overlaps with the previous window). The process is repeated $(t_D - t_W)/t_S$ times (Fig. 2). 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.

It is intuitively clear that the key time scale of the described method is the length of the time window. In the context of simulation of pollution transport the basic requirement is that t_W has to be long enough to allow for a significant number of particles to reach the vulnerable area(s). The choice of the time period $[t_0, t_0 + t_D]$ may also substantially affect the results as demonstrated in [13] on the example of monthly and seasonal variations of the properties of certain sets of trajectories. The choice of the time lag and the initial locations of the particles apparently have less significant impact on the results but may still affect the reliability of the conclusions.

Another central feature is how the vulnerable area is defined. This is less important when the vulnerable region extends to offshore where the presence of the coast does not directly modify the flow. It becomes, however, decisive when the vulnerable area is the coast itself. The circulation models usually assume that the velocity component normal to the sea bottom vanishes. For shallow-water coastal areas this often means that the simulated flow is largely longshore. Consequently, the propagation of the particles' trajectories simulated by TRACMASS (which does not account for any sub-grid scale effects and fully follows the precomputed velocity fields) close to the coast is very unlikely and the probability of hitting a nearshore area may be underestimated. In this case it might be necessary to associate the vulnerable areas with grid cells located at a larger distance from the coastline.

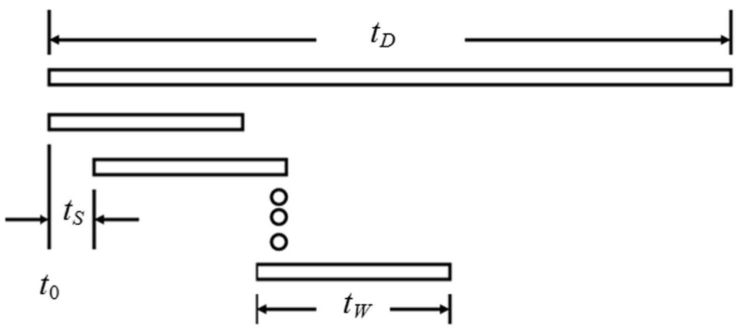

Fig. 2. Definition sketch of splitting the simulation period into time windows.

3. DEFINITION OF THE NEARSHORE

The procedure of the definition of the coastal zone is tightly related to the problem of the adequate choice of t_W. As the potential side effects, connected with boundary effects in the nearshore, apparently are most pronounced for the particles released relatively far offshore, the relevant simulations are performed for particles initially placed in the middle of the Gulf of Finland. The trajectories were started from centres of 93 cells along a straight line roughly representing the axis of the gulf (that is, at points remotest from the coasts, Fig. 3). The simulations were started at midnight each calendar day in 1987. This year as well as the 5-year period 1987–1991 were quite typical in terms of wave intensity [24,25] and thus also in terms of energy supply to water masses. There were no exceptional storms in this year and the annual mean wind speed at the Island of Utö [24] and at Kalbådagrund were just a few percent lower than the 5-year average for 1987–1991.

Numerical experiments with the use of $t_W = 20$ days [13] suggest that in many cases the trajectories first enter the nearshore area after about 10 days of propagation. Such events are below called hits to the nearshore or coastal hits. The time window used for calculations of statistics of coastal hits should account for such situations. On the other hand, t_W should not be much longer than the typical time during which the largest number of hits occurs. Also, the typical spreading of initially closely located particles over the time window should remain well below the width of the narrowest part of the gulf. If the latter condition is violated, the uncertainty in the positioning of the particle caused by sub-grid-scale turbulence would be about the same size as the extension of the open sea area and the related statistics of coastal hits would be meaningless.

Recent numerical simulations [15] and ongoing drifter experiments (K. Döös, pers. comm., 2010) suggest that the typical spreading rate is about 2 mm/s (and apparently somewhat larger in strong wind conditions) both in the Gulf of Finland and in the Baltic Proper. Therefore, within about three weeks of windy

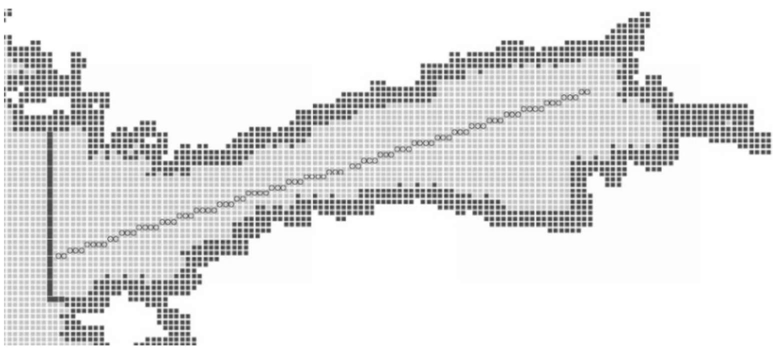

Fig. 3. Starting points of trajectories (grey circles located approximately along the axis of the Gulf of Finland) in simulations of coastal hits. Dark grid points indicate the nearshore area of alert zone 3. The entrance line to the gulf (bold line) is set along 59°N and 21°48′E.

months the sub-grid turbulence may separate the particles, in average, by 15 km. This suggests that for time windows longer than about 20 days the final position of the particle would be basically random. Based on these arguments, t_W was set to 15 days in simulations described in this section.

The nearshore area was simulated by means of three zones with a typical width of 1, 2 and 3 grid cells from the coast, called alert zone 1–3 below. The width of each zone was kept both in the direction of the coordinate axes as well as in the NW–SE and NE–SW direction. Simultaneously with tracking the transport of particles to the nearshore we also checked whether the particles were carried out of the Gulf of Finland. The border between the gulf and the Baltic Proper was set slightly to the west of Hiiumaa (Fig. 3). A hit to each of the three alert zones occurs when a particle first time enters the relevant zone. The presence of each particle in an alert zone (or its drift out of the gulf) is accounted for only once and its subsequent presence or re-entering the alert zone (or the gulf) is ignored. This method of counting implicitly means that particles that have drifted out of the gulf have never entered any of the alert zones.

The monthly average number of hits of particles to the alert zones and the share of particles leaving the gulf considerably vary for different seasons (Fig. 4). The average probability of entering alert zones 1 and 2 during spring and summer months is very low, about 2% and 4%, respectively, while during windy months it grows up to 20% and 30%, respectively. The annual average probability of entering these zones is about 5% and 11%, respectively. The small probabilities of entering zones 1 and 2 suggest that the statistics of hits to the nearshore, based on trajectories reaching these zones, may have quite large uncertainty, especially during spring.

A similar seasonal variability becomes evident for the alert zone 3. The annual probability of entering this zone is 18% whereas during the windy months almost a half of the released particles entered this zone. The annual average of the joint probability for a particle to either enter alert zone 3 or to leave the gulf is about 30%. This probability exhibits extensive short-term variability (Fig. 5).

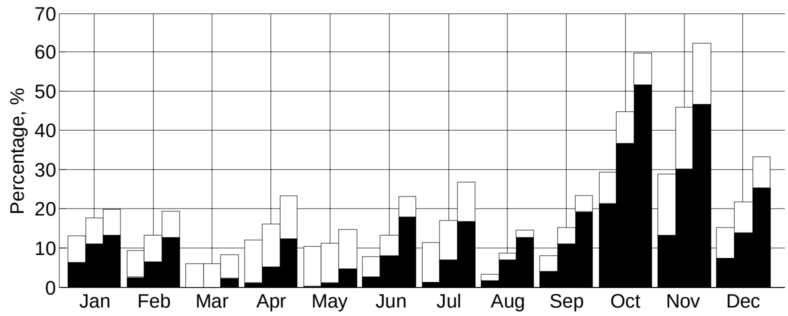

Fig. 4. Monthly mean percentage for coastal hits (filled parts of bars) and the particles leaving the gulf (white parts of bars) in 1987 for t_w = 15 days. The left, middle and right bars show the results for alert zones 1, 2 and 3, respectively.

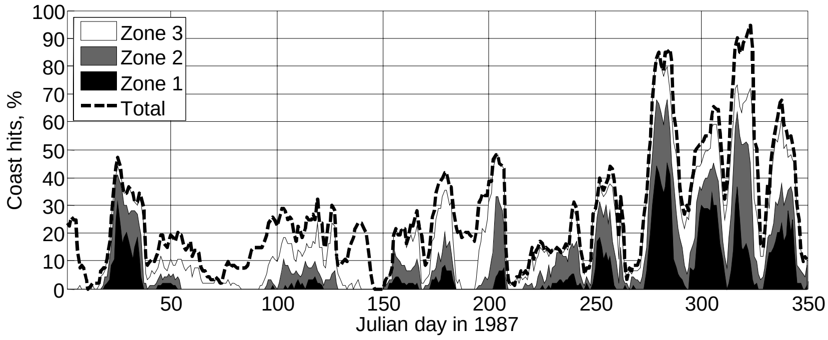

Fig. 5. Percentage of hits to the nearshore for t_w = 15 days for different starting instants of trajectory calculations in 1987. The uppermost dashed line shows the total percentage of particles that have either hit the coast or drifted out of the gulf.

Its values are quite close to 100% during the windiest periods. This considerable amount of hits suggests that statistics, calculated with the use of alert zone 3 as a model, nearshore is representative for the velocity data in use. Notice that the particles in this experiment are released at a maximally large distance from the coasts. For randomly distributed particles the relevant probabilities obviously will be much higher.

4. TIME SCALES OF HITTING THE COAST AND LEAVING THE GULF

A series of experiments was performed to estimate the typical time over which the particles reached the nearshore. Test particles were released at the largest possible distance from the coast for a given longitude and alert zone 3 was chosen to represent the nearshore. Doing so apparently results in an estimate for the upper bound of the relevant time scale. The simulations were started, as in the previous sections, at midnight each calendar day in 1987 but run for 3–13 days. Figure 6 first indicates that the probability of coastal hits has a substantial seasonal variability for all choices of t_W. Interestingly, this probability may be quite large for some relatively calm months.

Given the relatively large initial distance between particles and the coast, it is not unexpected that the chances for a particle to hit the coast increase rapidly when t_W increases from 3 to 10 days. The rate of increase is evidently essentially non-linear and considerably decreases when the time window is lengthened from 10 to 13 days. An exception is the flow in January and July when the frequency of coastal hits for other time window lengths is small. As discussed above, for the windiest months about a half of particles either hit the coast or leave the gulf by the 15th day (Fig. 4).

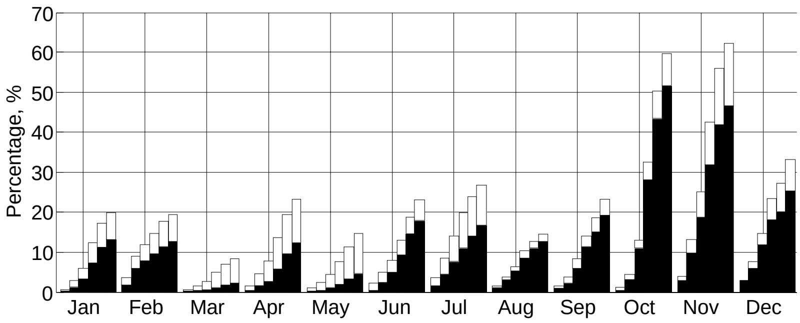

Fig. 6. Monthly mean percentage of coastal hits (black) and leaving the gulf (white) for different lengths of the time window for alert zone 3 in 1987. For each month, columns from left to right show the percentage for t_W = 3, 5, 7, 10, 13 and 15 days.

Therefore, we can conclude that the total number of coastal hits grows rapidly within the first 10 days after a release of the potential adverse impact. The increase rate considerably decreases after that but does not stabilize within even two weeks. This feature is not unexpected and basically reflects the complexity of the dynamics of the Gulf of Finland.

The results obtained with the use of alert zones 1 and 2 (equivalently, with different widths of the coastal zone) are qualitatively similar to the presented ones. They are, however, not directly comparable and building a quantitative measure for their comparison is meaningless as these situations reflect completely different problem setups.

The number of particles, drifting out of the gulf, increases more or less linearly. Comparison of Figs. 5 and 7 demonstrates that there is no evident correlation between the probabilities for nearshore hits and for leaving the gulf. Interestingly, the number of particles that have drifted out of the gulf insignificantly depends on the particular choice of the alert zone and exhibits much smaller seasonal variability.

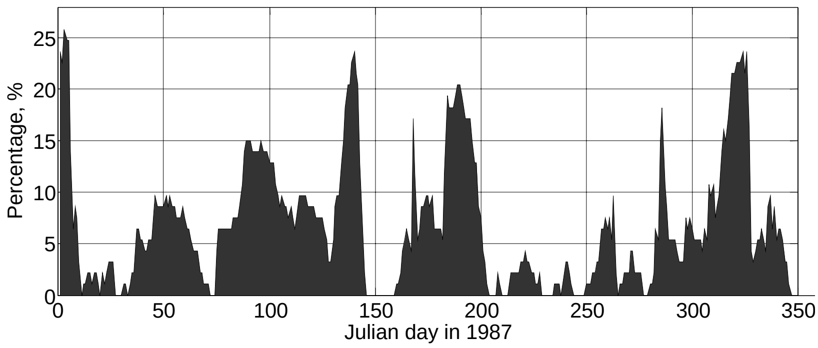

Fig. 7. The percentage of particles that have left the gulf within 15 days for alert zone 3 and different starting instants of trajectory calculations in 1987.

For the calmest months, there are always more particles leaving the gulf than hitting the coast whereas during the windiest months particles tend to hit the coast rather than leave the gulf (Fig. 6). This feature suggests that the ‘open sea’ and ‘nearshore’ dynamics in the Gulf of Finland are relatively well separated even when the nearshore is defined as an 11 km wide area and covers over 40% of the width of the gulf in its narrowest part. The particles tend to more frequently leave the gulf during spring and summer and less frequently during the windy months. This is somewhat counter-intuitive because surface currents should be more intense during windy months.

The mismatch between the rates of hitting the coast and leaving the coast may stem from the different balance between the impact of the Ekman drift and the mean circulation and internal meso-scale dynamics on the surface drift in different seasons. According to the traditional idealized view, the mean circulation of the Gulf of Finland (that is large enough to experience the effects of the Earth’s rotation) is cyclonic and intrinsically baroclinic (due to the pronounced horizontal buoyancy gradients) with an average velocity of a few cm/s [4,10]. Both the mean and instantaneous circulation patterns contain numerous meso-scale eddies (analogues to oceanic synoptic rings) with a typical size clearly exceeding the internal Rossby radius [16]. The RCO model, although it is probably not able to reproduce details of meso-scale dynamics, is still apparently capable to mirror the basic features of the meso-scale eddies. Owing to the small internal Rossby radius (2–4 km [21]), the presence of a number of meso-scale eddies with typical diameters in the order of 10–20 km is expected in the Gulf of Finland. Simulations in [11,16] suggest that also long-living meso-scale eddies apparently gradually drift to the west and in this way contribute to the motion of entrained surface particles towards the Baltic Proper.

The surface dynamics is largely determined by the Ekman drift and relatively weakly correlated with the dynamics of underlying water masses during windy months. In calm seasons and under ice cover, however, the underlying dynamics evidently will play a much larger role in the surface dynamics. Such a situation has been described in [9] for decreasing wind conditions when the surface drift apparently was strongly affected by subsurface dynamics.

Another key component of the dynamics here is the sea-surface slope that results from the voluminous fresh water supply to the eastern part of the gulf and that enhances the outflow of water to the Baltic Proper. The more or less steady rate of particles leaving the gulf suggests that the outflow is generally regular. It only diminishes for short time intervals during windy months when wind-stress and resulting Ekman drift apparently dominate at the sea-surface, override the anisotropic transport to the west and cause relatively large excursions of the surface particles in all directions, optionally until the nearshore.

The number of particles that leave the Gulf of Finland within 15 days is typically 8–10 (about 10% of the released ones, Fig. 7) and thus their behaviour only insignificantly affects the results depicted in Fig. 6. This number, however, suggests that the surface water exchange between the Baltic Proper and the Gulf of Finland may be much more intense than the overall water exchange in the entire water column [16]. If about 10% of surface water leaves the gulf within two weeks, it might take only about half a year for the total removal of the surface water from the gulf. In reality, however, much of the water is apparently transported back and forth at the entrance to the gulf [16] and the net exchange forms a relatively small fraction from the total exchange.

5. TIME SCALES OF NET TRANSPORT PATTERNS

The persistence of currents in the uppermost layer of the Gulf of Finland, defined in terms of the conservation of the flow direction over five years [11,16] was found to be very small. This result does not contradict with the existence of semi-persistent transport pathways in which, for example, the flow direction varies over a certain shorter time scale as it is customary for coastal currents of an alternating direction. Such patterns, with a typical lifetime from the first weeks up to a few months have been recently identified for different areas of the Baltic Sea [12,16,20,26]. Their existence has a high potential for the rapid and systematic transport of different neutrally buoyant adverse impacts such as nutrients, toxic substances, or oil pollution between specific sea areas in the form of relatively stable jet-like flows over a few days.

The location and magnitude of such patterns of transport can be, to a first approximation, identified by means of numerical simulation of the net transport of water masses over relatively short time intervals. The net transport is defined here as the distance between the start and end positions of a trajectory. The resulting areas of high net transport for a single time window largely coincide with areas of large instantaneous current speeds. Such areas will generally be different for different time windows as the local jets and meso-scale eddies emerge, relocate and decay over time. An average over a large number of (optionally partially overlapping) time windows (Fig. 2) may highlight regions where water transport is systematically more intense than the average, for example, areas where jets alter their direction over time scales that are considerably longer than the time windows used for their highlighting. The properties of the resulting patterns for the Gulf of Finland will be described elsewhere [27] and here we only address their potential temporal scales and the parameters of the method for their identification.

A particular choice of the length of the time window is decisive not only for the representativeness and reliability of the statistics in the above calculations of coastal hits but also for the identification of pathways of rapid transport of water masses. A too short time window will simply lead to a somewhat smoothed pattern of the instantaneous current field while the use of a too long window would result in a variation of the mean circulation pattern.

The above material suggests that in calm conditions and under ice cover the surface transport is strongly affected by the underlying mean circulation and meso-scale dynamics. In order to properly account for the potential impact of meso-scale eddies, the relevant time window should be about the typical eddy turnover time or longer. Although the values for the internal Rossby radii are relatively well known [21], there exist very few data about the properties of single meso-scale eddies in the Gulf of Finland Numerical Simulations and a few available observations [4] suggest that the typical diameter of their cores is 10–20 km and the maximum current speed may reach values up to 35 cm/s but should normally remain between 10–20 cm/s. The typical turnover time is thus about 4–5 days. Therefore, if one aims at averaging out their impact, the relevant time window should cover several turns of typical eddies, that is, be at least 15–20 days.

A convenient quantity allowing to roughly estimate the overall ability of the calculations of the net transport to highlight rapid pathways is the difference in the speed of average net transport from the long-term average current speed for a particular t_W. This difference apparently is the largest for short time windows when the net transport speed is close to the instantaneous current speed. A sensible upper limit for t_W is such that the net transport speed becomes close to the long-term average current speed. For even longer time windows the semi-persistent flow patterns probably will be averaged out of the spatial distributions of the net transport speed.

The difference in question is estimated with the use of a sequence of simulations of trajectories for 1987–1991 with the use of variable t_W and a constant time lag of $t_S = 1$ day between the windows. One particle was released into each of 3131 grid cells in the Gulf of Finland. Figure 8 presents the average values over all five years and approximately 1900 time windows. The average speed of net transport is, as expected, the largest for relatively short time windows. It decreases rapidly, from about 4.4 cm/s to 3.4 cm/s when t_W increases from 4 to 10 days. For even longer time windows the decrease is less steep. The speed in question decreases below 3 cm/s for $t_W \geq 15$ days and is close to the long-term average speed in this basin (about 2.5 cm/s). Therefore, the range of time

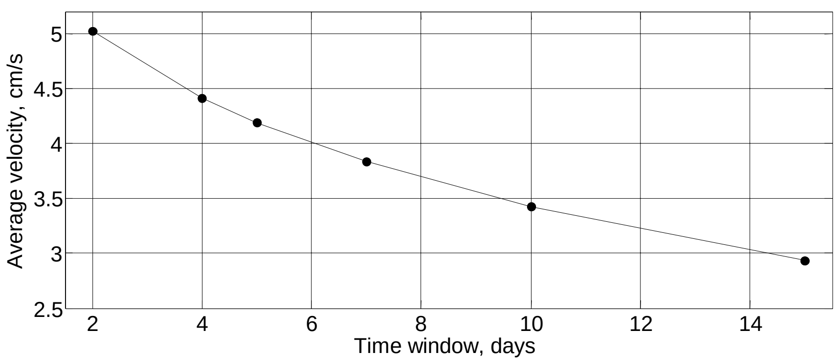

Fig. 8. Dependence of the average speed of net transport on the length of time window for 1987–1991.

windows suitable for identification of semi-persistent current patterns and in the same time capable of averaging out the potential impact of single meso-scale eddies to such patterns is between 5 and 15 days in the Gulf of Finland. Note that this estimate does not guarantee the existence of any particular patterns and only indicates the suitable range for t_W.

A complementary view to the described estimate can be obtained by means of an analysis of the relative changes in the average net transport speed when the length of the time window is increased. This is illustrated on the example of a pointwise comparison of net transport speeds against a reference set consisting of the values of net transport speed at all 3131 sea grid points averaged over all calculations of single trajectories from each point with $t_W = 2$ days and a time lag of 1 day for the years 1987–1991. Figure 9 depicts the average root-mean-square difference (RMSD) between the reference set and a similar set of speeds calculated with longer time windows. The average RMSD between the results, calculated with $t_W = 2$ and $t_W = 4$ days, is about 15% (the percentage calculated is based on the average speed of the reference set with $t_W = 2$) and increases to about 60% for $t_W \geq 20$ days. This result once more indicates that a suitable length for time windows for searching potential semi-persistent flow patterns in the Gulf of Finland should not exceed 2–3 weeks.

Finally, we shortly consider the potential sensitivity of the results of the analysis of pools of trajectories with respect to variations in the time lag t_S between the start instants of subsequent runs. Its choice essentially affects the amount of calculations. As an indicator, we compared pointwise the averaged net transport speeds, calculated for single years between 1987–1991 with the use of time lags of 1, 5 and 10 days. The impact of the particular time lag on the results is generally small even when quite large values of the lag are used (Fig. 10).

The annual RMSD of the values of the net transport speed is below 2% when the time lag is increased from 1 day to 5 days. This value increases to 2.7%–3.8% when the time lag is 10 days. The relevant absolute values of the RMSD in speed are 0.09–0.12 cm/s. These estimates suggest that for calculations of trajectories and reduced risk areas it is acceptable to use relatively large values of the

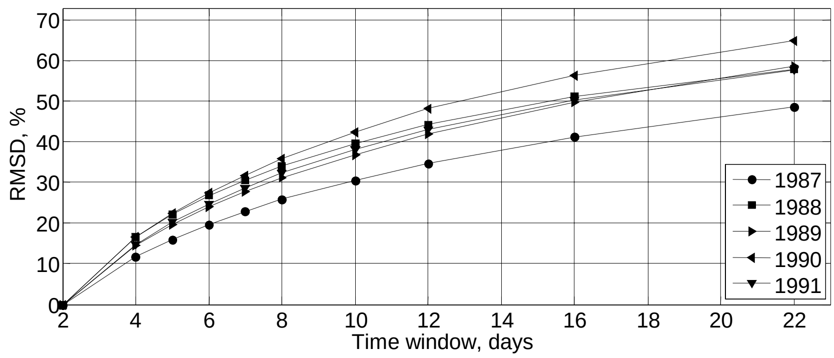

Fig. 9. Dependence of RMSD on the duration of time window for different years.

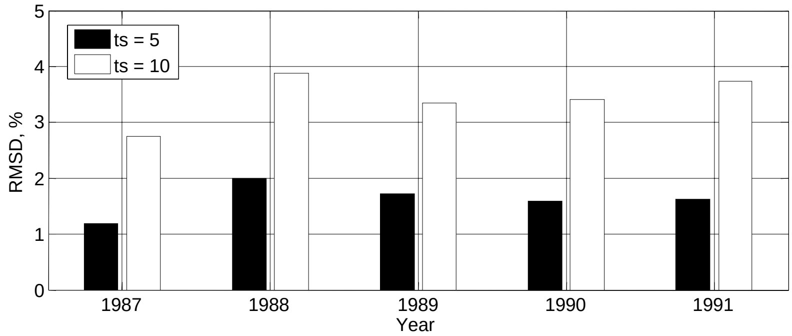

Fig. 10. RMSD of the net transport speed for t_S equal to 5 and 10 days from the speed for $t_S = 1$ day.

time lag without losing reliability of the results. This conjecture comes into importance in optimization of long-term calculations based on high-resolution simulations [15].

6. DISCUSSION AND CONCLUSIONS

In general, it is not unexpected that the number of particles, hitting the coast and/or leaving the Gulf of Finland, exhibits substantial temporal variability and high sensitivity with respect to several parameters used in the calculation and analysis of Lagrangian trajectories of water (or pollution) particles. The major lesson is that the applications of this method for the identification of (pollution) transport patterns and areas of reduced risks, based on the analysis of large pools of trajectories of particles, need a careful choice of the governing parameters for each particular sea area and circulation model in use.

First of all, a reliable statistics of coastal hits can only be constructed when a sensible amount of particles (carrying the adverse impact) reaches the properly defined nearshore within a reasonable time. For the particular circulation model in question (Rossby Centre Ocean Model with a spatial resolution of 2 NM in the entire Baltic Sea) it is appropriate to use an about 3 grid cells (6 NM, about 11 km, called alert zone 3 above and in [13]) wide nearshore area as the proper representation of the coastal zone. A sensible length of time windows in calculations of coastal hits is, at least, 10–15 days. In average, at least one third of particles released in the gulf enter this zone within approximately two weeks. The proportion of particles drifting out of the gulf is much smaller, about 10%, more or less uniformly round the year. This rate is quite large in the context of water exchange with the Baltic Proper and suggests that the exchange of surface water might be much more intense than that of deeper water.

The character of variations in the statistics of coastal hits suggests, not unexpectedly, that the key parameter in the above estimates is the horizontal resolution of the circulation model. The minimum width for a proper representation of the nearshore in this context is about three grid cells. For the Gulf of Finland conditions the 2 NM resolution is quite coarse and does not reproduce many local bathymetric features. The basic parameters of the mean and meso-scale circulation (such as typical flow speeds and the energy balance between mean flow and synoptic eddies), however, apparently are adequately reproduced and can be used for estimates of the net transport. The temporal resolution of saved velocity data (6 h) evidently distorts to some extent the impact of inertial oscillations, but apparently is fair enough to properly account for single eddies. An increase in the temporal resolution to 3 h in the Baltic Proper and in the horizontal resolution to about 1 km in the Gulf of Finland is desirable in future experiments.

The necessary length of trajectory calculations is to a large extent governed by the width of the sea area in question or, equivalently, by the distance from the release of an adverse impact to the vulnerable area. The potential spreading of initially closely located water particles owing to sub-grid turbulence is not accounted for here. Its impact apparently is small in terms of statistics of isotropic flow patterns but may considerably affect the probability of coastal hits in elongated basins such as the Gulf of Finland.

The appropriate time windows for adequate estimates of semi-persistent transport patterns evidently should be somewhat shorter, about 4–10 days. The smallest reasonable values match the typical turnover time of meso-scale eddies in the gulf. The use of time windows longer than about two weeks apparently will smooth out such patterns because the average speed of net transport, calculated for the larger values, is close to the overall average velocity in the gulf. The dependence of the results on the time lag between the windows, estimated in terms of the RMSD of pointwise averaged net transport speed for the entire gulf, is fairly small up to time lag of 10 days.

The strong seasonality in hitting rates to the coast suggests that several properties of the transport may have time scales on the order of a few weeks. This time scale considerably exceeds the so-called synoptic time scale (the typical turnover time of the meso-scale eddies, about a week in the gulf) but is substantially shorter than the length of typical seasonal variations (2–4 months). Such a separation of the synoptic and seasonal time scales encourages the search for phenomena that persist over an intermediate time scale between the synoptic and seasonal time scales in the Gulf of Finland. This is hardly possible in the open ocean where the synoptic time scale is about 1 month and the lifetime of a large part of meso-scale features overlaps with the seasonal variations. This range is therefore the most promising for detection of yet unknown features (such as semi-persistent patterns with a lifetime about 0.5–1 month) in the dynamics of the Gulf of Finland.

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Soome lahe pinnakihi hoovustranspordi ajamastaapidest

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On analüüsitud ajamastaape, mis iseloomustavad veemasside kandumist ranna lähistele ja vee netotranspordi omadusi Soome lahe pinnakihis. Rossby Centre (Rootsi Meteoroloogia ja Hüdroloogia Instituut) tsirkulatsioonimudeli abil aastate 1987–1991 jaoks arvutatud hoovuste kiiruste andmestiku alusel rekonstrueeritud veeosakeste trajektooride analüüsi kaudu on näidatud, et tõenäosus vee kandumiseks lahe keskelt ranna lähistele varieerub oluliselt aasta lõikes, kuid pinnakihi vee triiv lahest välja on suhteliselt ühtlane. On näidatud, et sobivaks rannapiirkonna mudeliks on tsirkulatsioonimudeli kolme horisontaalsammu laiune vöönd. Usaldatava statistika leidmiseks on tarvis kasutada vähemalt 10–15 päeva pikkusi trajektooride rekonstruktsioone. Seevastu hoovuste netotranspordi omaduste leidmiseks on soovitatav kasutada 4–10 päeva pikkusi rekonstruktsioone.