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The use of Lagrangian trajectories for the identification of the environmentally safe fairways

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ABSTRACT

We propose and test a method for the optimisation of marine fairways to minimise the risk to high-value areas, based on statistical analysis of Lagrangian trajectories of current-driven pollution transport. The offshore areas are quantified according to the probability of pollution released in these areas to reach vulnerable regions. The method contains an eddy-resolving circulation model, a scheme for tracking of Lagrangian trajectories, a technique for the calculation of quantities characterising the potential of different sea areas to supply adverse impacts, and routines to construct the optimum fairway. The gain is expressed in terms of the probability of pollution transport to the nearshore and the associated time (particle age). The use of the optimum fairway would decrease the probability of coastal pollution by 40% or increase the average time of reaching the pollution to the coast from 5.3 to about 9 days in the Gulf of Finland, the Baltic Sea.

1. Introduction

There are an increasing number of studies into Lagrangian propagation and trajectories of various substances in marine environment, both natural constituents such as suspended matter (Graewe and Wolff, 2010), fish eggs and larvae (Mariani et al., 2010) or turtle hatchlings (Monzon-Argullo et al., 2010) or different adverse impacts such as oil (Korotenko et al., 2004), microorganisms (Korajkic et al., 2009) or marine litter (Yoon et al., 2010). The majority of the relevant research addresses the direct problem of current-induced propagation of passive tracers (e.g. Korotenko et al., 2010). The studies cover a wide range of applications, from a verification of the classical circulation models beyond that offered in a Eulerian assessment (Ohlmann and Mitarai, 2010) up to intricate statistical models of oil spill propagation based on a large number of propagation scenarios (Abascal et al., 2010) and coastal risk evaluation systems based on simulating the transport of underlying contaminant or toxic algae (Chrastansky and Callies, 2009; Havens et al., 2010). Following the widely used approach in atmospheric sciences (e.g. Lin et al., 2004; Witham and Manning, 2007), the analysis of Lagrangian trajectories is now commonly used for the restoration of the link between the source and impact areas of pollution in marine environment (Chrastansky et al., 2009, among others). The fundamental aim of studies into Lagrangian transport usually is the determination of which vulnerable environments would be most seriously damaged so that they may receive priority protection (see Abascal et al., 2010 and references therein).

Our aim, however, is to go one step further: to systematically characterise the damaging potential of the offshore areas of possible release of adverse impacts in terms of their transport to vulnerable regions. This is a variation of the general problem of spatial quantification of current-induced Lagrangian transport. Its central goal is to identify the areas, propagation of adverse impacts from which to high-value areas is most unlikely. A prerequisite for the feasibility for this approach is the presence of nontrivial, anisotropic internal dynamics of surface currents, smart use of which may open a qualitatively new way of protecting vulnerable (e.g. coastal) areas (Soomere and Quak, 2007; Soomere et al., 2010).

In general, one has to solve an inverse problem of pollution propagation in order to gather progress in this direction. Although many trajectory-tracking models are formally invertible, such problems are frequently mathematically ill-posed and no universal method exists for their solving. The relevant methods and technologies are, however, of great practical importance for particularly vulnerable seas or coastal regions of relatively small size (such as the North Sea or Baltic Sea and especially the narrow and shallow Gulf of Finland) that host extremely heavy ship traffic in the immediate neighbourhood of valuable resources. In a certain way, this

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approach is a generalisation of the work (Abascal et al., 2010) towards the systematic estimation of the probability of a region to be polluted by an oil spill, the time taken for the oil to reach a specific site, and the areas that could be a threat for a given shoreline based on a large set of Lagrangian trajectories of oil propagation.

An approximate solution to the problem of quantification of the level of danger posed by different sea areas to vulnerable regions can be obtained by means of statistical analysis of a large number of solutions of the associated direct problem of propagation of water particles in three-dimensional environment (Abascal et al., 2010; Soomere et al., 2010). This approach, based on a pool of relatively short (about 10 days) Lagrangian trajectories has highlighted the presence of very rich, usually concealed internal structure of semi-persistent transport patterns in certain sea areas (Soomere et al., 2011). Such transport may be at times largely directed across relatively narrow regions and/or may lead to unexpectedly high probability of transport of adverse impacts between certain regions (Lekien et al., 2003). A number of questions related to the optimum choice of the parameters of the relevant numerical method and the time scales and persistency of such patterns have been addressed in (Viikmäe et al., 2010).

The obvious practical outcome of studies of this kind is the possibility to redirect potentially dangerous activities into specific sea areas (called areas of reduced risk), current-induced transport of potential adverse impacts from which to vulnerable regions is either unlikely or takes a long time.

The question of the optimisation of the location of fairways (more generally, the location of any potentially dangerous activities in marine environment) has been addressed in numerous studies from the economical and safety viewpoints (Calvert et al., 1991; McCord et al., 1999; Iakovou et al., 1999, among others). Much less attention has been paid to the similar question of fairway choice based on environmental arguments or to the identification of the potential influence of existing fairways in terms of environmental criteria (Eide et al., 2007). An early attempt to address this problem in terms of the Environmental Impact Assessments was made in the mid-1990s (Smith, 1995). Among other parameters also "systematic consideration of the geography of shipping routes, ship types and cargoes, and environments" was suggested as a major component of the environmental management of shipping impact, in particular concerning risk and environmental impact. For the example study area of this paper (the Gulf of Finland) the relevant research is being done by the Helsinki Commission (HELCOM, 2009; Soomere et al., 2010).

In this light, the issue of direct impact of ships on whales has been considered in greatest depth (Ward-Geiger et al., 2005; Panigada et al., 2006). To reduce the threat to the whales, the Mandatory Ship Reporting System was established in July 1999 in waters off the north-eastern and the south-eastern United States. One of the results of the system was the identification of the most frequently used ship tracks. Such a "portrait" of ship traffic and fairways was suggested to be used to develop measures to reduce the threat of ship strikes. An even more serious situation concerning fin whales was reported in the Mediterranean (Panigada et al., 2006) where an urgent need was recognised "for a comprehensive, basin-wide conservation strategy ... to re-locate ferry routes to areas of lower cetacean density". A breakthrough in this direction was the decision to relocate the fairway entering the Boston harbour (Stokstad, 2009).

We focus on the complementary problem of remote impact of ship traffic on the environment that becomes evident through propagation of various adverse substances (oil pollution, chemical substances, etc.) released from ships, either occasionally or as a consequence of an accident. The aim is to decrease the impact of these substances (transported by sea currents) upon high-cost areas by means of an optimum choice of the fairway. As shallow-water areas frequently have the largest ecological and environmental value (Kokkonen et al., 2010), we consider the coastal zone as a generic example of a high-cost area. The entire approach is obviously independent of the particular definition of the high-coast areas and accounting for their internal structure is straightforward. As we are specifically interested in the contribution of surface currents to the propagation of adverse substances, the impact of wind- and wave-induced drift is ignored.

A particular solution for the problem of the specification of an optimum fairway along an elongated sea area based on the analysis of large sets of Lagrangian trajectories of potential pollution has been analysed in (Soomere et al., 2010). Their idea is to place the fairway along so-called equiprobability line so that the overall probability of the propagation of adverse impacts to the opposite coasts during a certain time interval is equal. The deviation of such a line from the centreline of the sea area characterises to some extent the asymmetry of the current patterns in the particular basin. A major shortage of this method is that it is only suitable for elongated basins and does not account for the presence of islands. Moreover, there is strong evidence that such a solution is not optimal in terms of the protection of the entire nearshore (Andrejev et al., 2011).

In this study, we generalise the method for the identification of the optimum fairway in terms of minimising the risk to the coasts to basins of arbitrary shape. We remove the division of the coasts into opposite sections and consider the entire coastline (and optionally the coasts of islands) as an equally vulnerable area. The optimisation problem is solved using two-dimensional spatial distributions of the probability of hitting any section of the coast by adverse impacts released into the sea. These distributions are calculated for a five-year test period of May 1987–December 1991. This time interval has chosen in order to make the results comparable with a number of earlier studies into the dynamics of the Gulf of Finland performed for this period (Andrejev et al., 2004a,b, 2010; Soomere et al., 2010). A complementary quantity, that equally well characterises the low or high potential of pollution released into a particular sea point to provide danger to the coasts, is the average time it takes for the pollution to reach the coast. Finally, we propose a simple algorithm for finding the optimum fairway in the context of the relevant maps for the Gulf of Finland and demonstrate that the gain from the use of such a technique could be substantial. As the entire method contains a number of technically complicated steps, most of which have been extensively discussed and verified in international literature, we intentionally concentrate on the presentation of the key aspects of the technique and omit details as much as possible.

2. Components of the method

The method for the identification of the optimum fairway, based on statistical analysis of large pools of Lagrangian trajectories of tracers proposed in (Soomere et al., 2010), basically consists of four steps. The starting point form the numerically simulated velocity fields in the sea area in question over a long time interval. The velocity data are used for the calculation of Lagrangian trajectories of selected water particles that are interpreted as passive traces or potentially adverse substances of neutral buoyancy. The trajectories are used for the construction of quantities that characterise the distribution of the level of environmental risk associated with different sea points. Differently from various direct methods of estimates of environmental risks, these quantities are associated with the points of release of adverse impacts rather than with the vulnerable areas. Finally, the spatial distributions of these quantities (optionally together with additional constraints such as the location of the harbours) are used for the identification of the opti-