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A Lagrangian-trajectory study of a gradually mixed estuary

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ABSTRACT

When modelling is used for investigating estuarine systems, a choice generally has to be made between applying simple mass-balance considerations or using a process-resolving three-dimensional (3-D) numerical circulation model. In the present investigation of the Gulf of Finland, a gradually mixed estuary in the Baltic Sea, it is demonstrated how Lagrangian-trajectory analysis applied to the output from a 3-D model minimizes the disadvantages associated with both of the modelling techniques referred to above. This formalism made it possible to demonstrate that the main part of the Gulf is dominated by water originating from the Baltic proper, and that the most pronounced mixing with fresh water from the river Neva takes place over a limited zone in the inner part of the Gulf. Dynamical insights were furthermore obtained by using the Lagrangian formalism to construct overturning stream-functions for the two source waters.

1. Introduction

When undertaking oceanographic analyses, one is frequently interested in following the paths of distinct water types taking part in the circulation. In the context of numerical modeling, trajectory analysis has proved to be a valuable tool for determining the origin as well as the fate of specific water masses, see, e.g. Jönsson et al. (2004). This holds true when examining processes ranging from those taking place over global scales (e.g. the thermohaline circulation) down to such local phenomena as the dispersion of pollutants from a point source. The present study will focus on intermediate-scale processes, exemplified by those in the north-eastern part of the Baltic (an area subject to considerable ecological threats due to its proximity to large cities and their associated wastewater disposal). The largest single freshwater inflow to the Baltic Sea, viz. the river Neva, is furthermore found here.

The present study is thus focused on the Gulf of Finland, cf. Fig. 1, which is an elongated estuary (with a mean depth of only 37 m) where physical processes ranging from small-scale vortices to the large-scale cyclonic circulation take place (Palmén, 1930; Andrejev et al., 2004a). The mean circulation pattern is one of an inflow to the Gulf taking place in a deep layer along the Estonian coast whereas the outflow, primarily in the form of fresher surface water, takes place slightly north of the longitudinal axis of the Gulf.

The western end of the Gulf is a direct and gradual continuation of the Baltic Proper without any morphological constraints. The eastern end of the Gulf receives the discharge from river Neva, which with a mean runoff of $2700\,m^3\,s^{-1}$ constitutes 15–20% of the total Baltic freshwater inflow. This leads not only to a salinity stratification in the vertical but also to pronounced east–west salinity gradients in which the cyclonic mean horizontal circulation pattern is reflected (cf. Figs. 1 and 2). The stratification is furthermore variable in both space and time, where the large seasonal variability of the incoming solar radiation plays a considerable role (Alenius et al., 1998). This state of affairs has, as will be seen, significant dynamic consequences. The water-masses originating from the two source regions also have markedly different characteristics, not only as regards the salinity but also the degree of anthropogenic contamination, why their ultimate fate in the Gulf is of considerable practical environmental interest. This general question has been dealt with in a number of investigations, most recently in one due to Andrejev et al. (2004b) where it was shown that the renewal time of the water masses of the entire Gulf is around 1–2 years and that the water-age distribution in the Gulf is spatially non-homogenous with the highest ages ($\sim$2 years) found in the southeastern part of the Gulf. The scope of this study, however, had the consequence that the ultimate fate of the Baltic and Neva source waters was not fully ascertained by Andrejev and co-workers.

The classical technique to resolve this question is based on an investigation of the tracer equation within the circulation-model framework. This Eulerian formalism, however, has the drawback of overestimating diffusive effects, and furthermore many circulation

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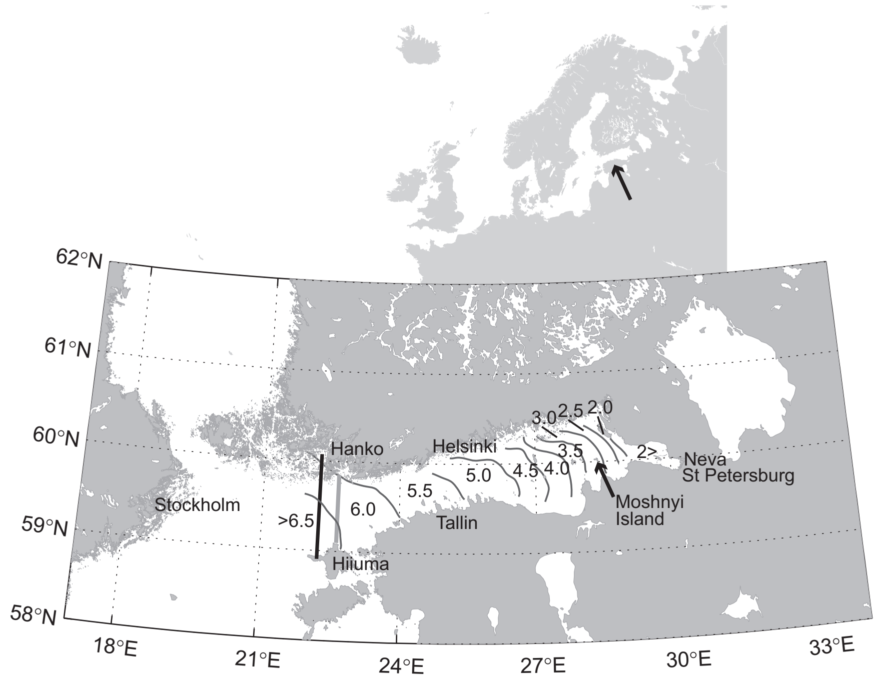

Fig. 1. Map of the Gulf of Finland where the thin black line represents the model coastline. The heavy grey line indicates where the "Baltic" trajectories are released to the Gulf and the heavy black line where all trajectories are removed. Also included are observed surface isohalines as adapted from Jurva (1951).

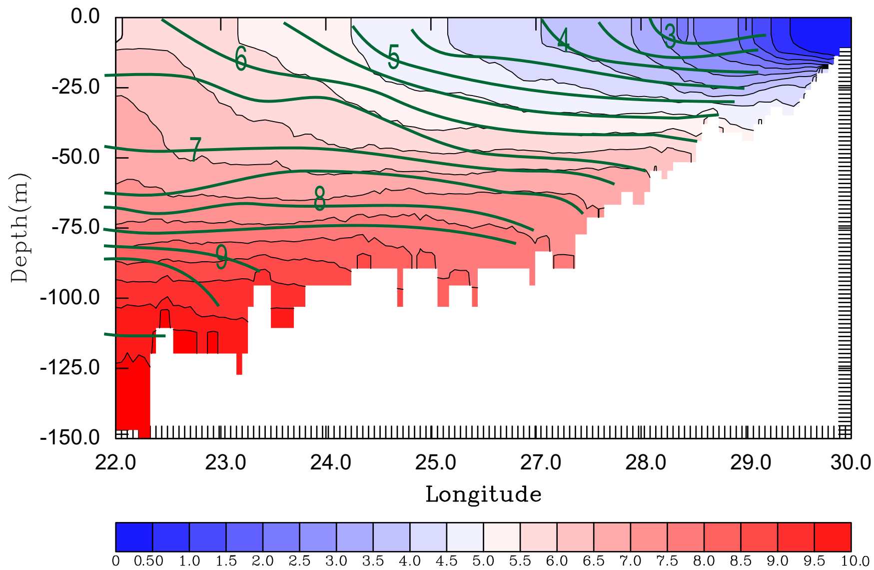

Fig. 2. Salinity sections along the central axis of the Gulf of Finland. Colour-coded contours show a long-term average of the RCO-modelled salinity field. The green lines represent observations as adapted from Jurva (1951). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

models tend to be somewhat deficient in reproducing the salt dynamics of the system under consideration.

The present investigation will instead approach the problem from a Lagrangian standpoint, i.e. using trajectory analysis. In next section the technical details of this procedure are outlined, whereafter the subsequent section deals with the results concerning mixing and water-mass composition obtained for the Gulf of Finland. Hereafter, a discussion is undertaken of the large-scale circulation in the Gulf based on a Lagrangian decomposition of the overturning stream-function, this in order to estimate the contributions of the waters originating from the river Neva and the Baltic, respectively. The study is concluded by a review of the overall outcome of the analysis.

2. Methods

Classical trajectory analysis, as primarily applied to the atmosphere, mainly relied upon graphical techniques used in conjunction with meteorological good sense and experience. Modern-day trajectory methods are, however, based on numerical circulation models. In the present study, velocity fields from the Rossby Centre Ocean (RCO) model (Meier et al., 2003) serve as the basis for the further investigations. This well-proven (Meier and Kauker, 2003) finite-difference model has 41 depth levels (at intervals ranging from 3 m in the surface region to 12 m at greater depths) and a horizontal resolution of 2 $\times$ 4 nautical miles. It is based on an Arakawa B-grid and is capable of resolving the meso-scale