Available online at www.sciencedirect.com
ScienceDirect
Estuarine, Coastal and Shelf Science 74 (2007) 641–654
ESTUARINE COASTAL AND SHELF SCIENCE
www.elsevier.com/locate/ecss

Elucidating the dynamics and mixing agents of a shallow fjord through age tracer modelling

Karin E. Gustafsson*, Jørgen Bendtsen

National Environmental Research Institute, University of Aarhus, Frederiksborgvej 399, P.O. Box 358, 4000 Roskilde, Denmark

Received 8 June 2006; accepted 9 May 2007
Available online 5 July 2007

Abstract

The mixing agents and their role in the dynamics of a shallow fjord are elucidated through an Eulerian implementation of artificial tracers in a three-dimensional hydrodynamic model. The time scales of vertical mixing in this shallow estuary are short, and the artificial tracers are utilized in order to reveal information not detectable in the temperature or salinity fields. The fjord's response to external forcing is investigated through a series of model experiments in which we quantify vertical mixing, transport time scales of fresh water runoff and estuarine circulation in relation to external forcing.

Using age tracers released at surface and bottom, we quantify the time scales of downward mixing of surface water and upward mixing of bottom water. Wind is shown to be the major agent for vertical mixing at nearly all depth levels in the fjord, whereas the tide or external sea level forcing is a minor agent and only occasionally more important just close to the bottom. The time scale of vertical mixing of surface water to the bottom or ventilation time scale of bottom water is estimated to be in the range 0.7 h to 9.0 days, with an average age of 2.7 days for the year 2004.

The fjord receives fresh water from two streams entering the innermost part of the fjord, and the distribution and age of this water are studied using both ageing and conservative tracers. The salinity variations outside this fjord are large, and in contrast to the salinity, the artificial tracers provide a straight forward analysis of river water content. The ageing tracer is used to estimate transport time scales of river water (i.e. the time elapsed since the water left the river mouth). In May 2004, the typical age of river water leaving the fjord mouth is 5 days. As the major vertical mixing agent is wind, it controls the estuarine circulation and export of river water. When the wind stress is set to zero, the vertical mixing is reduced and the vertical salinity stratification is increased, and the river water can be effectively exported out of the fjord.

We also analyse the river tracer fields and salinity field in relation to along estuary winds in order to detect signs of wind-induced straining of the along estuary density gradient. We find that events of down estuary winds are primarily associated with a reduced along estuary salinity gradient due to increased surface salinity in the innermost part of the fjord, and with an overall decrease in vertical stratification and river water content at the surface. Thus, our results show no apparent signs of wind-induced straining in this shallow fjord but instead they indicate increased levels of vertical mixing or upwelling during down estuary wind events.

Keywords: tracers; modelling; vertical mixing; mixing processes; boundary layers; estuarine dynamics; age tracer

1. Introduction

In shallow systems, time scales of vertical mixing are short and the turbulent surface and bottom boundary layers may overlap. Due to the intermittent absence of vertical gradients of salinity and temperature, the magnitude of vertical mixing is, however, difficult to detect via these parameters. Instead, artificial age tracers may be added to a hydrodynamic model in order to quantify the vertical mixing on short time scales ranging from hours to days (Bendtsen et al., 2006). Several studies discuss the concept of age for estimating time scales for transport and mixing of water and dissolved substances (e.g. Bolin and Rodhe, 1973; Zimmermann, 1976; Stuiver et al., 1983; Takeoka, 1984; Thiele and Sarmiento, 1990; Delhez et al.,

* Corresponding author.
E-mail address: kgu@dmu.dk (K.E. Gustafsson).

0272-7714/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ecss.2007.05.023

1999; Deleersnijder et al., 2001), and artificial age tracers have been introduced in hydrodynamic models in studies of coastal and open seas (e.g. Gustafsson, 2000; Delhez and Carabin, 2001; Delhez and Deleersnijder, 2002), fjord estuaries (e.g. Engqvist, 1996) and river estuaries (e.g. Shen and Haas, 2004; Shen and Lin, 2006).

The shallow Danish estuary "Horsens Fjord" has a mean depth of only 2.9 m. The vertical stratification in the fjord is primarily associated with large variations in salinity outside the fjord in addition to buoyancy input to the fjord in the form of river discharge. Due to the shallowness of this fjord, the vertical mixing is related to the turbulent boundary layer dynamics on short time scales. The vertical mixing in the surface boundary layer is associated with surface forcing due to wind, and intermittent wind bursts may ventilate the water column down to a few meters depth (e.g. Bendtsen et al., 2006). The bottom boundary layer dynamics is related to bottom friction and vertical shear caused by barotropic flow components. These are normally associated with tides, but can also be due to wind surge effects. The dynamics and estuarine exchange flow are regulated by the vertical mixing. In order to analyse the general dynamics of the fjord in relation to the major mixing agents, we introduce various types of artificial tracers in a three-dimensional hydrodynamic model of the fjord and study the fjord's response to external forcing (e.g. tides and winds) through a sensitivity study. By analysing the vertical distribution of age tracers released at bottom or surface, we quantify the vertical mixing in the fjord in relation to external forcing.

The vertical mixing and horizontal transport of river water containing dissolved substances and nutrients have implications on the water quality parameters and the biogeochemical cycling and retention of nutrients discharged to the fjord (e.g. Stedmon et al., 2006). The export of river water and estuarine exchange may be controlled by several factors. Winds and tides provide energy for vertical mixing, but may also contribute to increased stratification due to straining of along estuary gradients (Simpson et al., 1990; Scully et al., 2005). The amount of fresh water discharge also plays a role in regulating the wind and tidally induced mixing and estuarine exchange flow through its effect on vertical stratification (e.g. Shen and Lin, 2006; Bendtsen et al., 2007).

Due to the variable conditions outside Horsens Fjord, estimates of river water content in the fjord via salinity are, however, dependent on a correct account for the inflows of water of much varying salinity. By releasing artificial river tracers in a hydrodynamic model of the fjord, we may detect and quantify the distribution and transport time scales of river water in the fjord. The river water content is analysed by marking the river runoff with a conservative (i.e. not ageing) reference tracer where the resulting tracer field is directly proportional to the distribution of river water in the fjord, in similar to what could be told from the salinity field if salinity was to be constant at the open boundary. In addition, an age tracer is added to the river water in order to analyse the transport time scales and estuarine circulation in relation to external forcing.

In Section 2.1, we introduce the reader to Horsens Fjord. This is followed by a presentation of the hydrodynamic model of the fjord (Section 2.2), and the implementation of artificial age tracers (Section 2.3). The sensitivity study is outlined in Section 2.4. Results are presented and discussed in Section 3, and the paper is concluded by a short summary (Section 4).

2. Model simulations

2.1. Horsens Fjord

Horsens Fjord is located on the east coast of Jutland, Denmark (Fig. 1). It is about 10 km long and 5 km wide and has a volume of 0.132 km^3. The mean depth of the fjord is 2.9 m, and the deepest part of the fjord is a narrow ship route channel of 6 m depth which goes from the entrance area of the fjord to Horsens Harbour in the western innermost part of the fjord. The major fresh water sources are the two streams, Hansted Å and Bygholm Å, both located in the innermost western part of the fjord. The drainage areas for these two streams constitute 290 km^2 or 70% of the total drainage area for Horsens Fjord. The average discharge during 2004 is 2.1 m^3/s for Bygholm Å and 1.9 m^3/s for Hansted Å. The fjord has been monitored as a part of the Danish National Monitoring Programme during the last decade where two stations inside the fjord and one station outside the fjord have been visited about once a week. The measurements of salinity at these stations in 2004 are shown in Fig. 2. Station 5790 is 4 m deep and is situated in the inner western part of the fjord on the flank of the 6 m deep ship route channel, and the 17 m deep station 6489 is located in the entrance area of the fjord. Station 6883 is located about 10 km outside the fjord. The fjord enters Kattegat Sea, which consists of the transition zone between the Baltic Sea and North Sea. The advection of water masses from the Baltic Sea estuary is regulated by the large-scale atmospheric conditions and water level in the Baltic Sea–North Sea system and is associated with large differences in salinity in the Kattegat Sea (Fig. 2c). This may lead to inflows to Horsens Fjord of much varying salinity. In addition, the deepest waters of the fjord are well ventilated (Fig. 2b) as the fjord does not have a sill in the entrance area. Instead, there is a deep passage in the form of a narrow and long submarine channel which stretches from the fjord mouth towards the open sea, through the otherwise rather shallow coastal area outside the fjord. The deep passage has a maximum depth of 22 m.

2.2. The hydrodynamic model

A three-dimensional primitive equation model based on the COHERENS model (Luyten et al., 1999) is used for hydrodynamic simulations of the fjord system during the year 2004. The model solves the hydrodynamic equations on a Cartesian C-grid and a vertical sigma coordinate system. This implies a fixed number of vertical grid levels over the whole model domain, and we use 15 layers with an equidistant spacing of the layers in the vertical. The horizontal grid is equidistant with