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Physical processes in the transition zone between North Sea and Baltic Sea. Numerical simulations and observations

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ABSTRACT

The dynamics in the transition zone between the North Sea and Baltic Sea are analyzed here using data from a 22-year-long climatic simulation with a focus on the periods 1992–1994 and 2001–2003 when two recent major inflow events occurred. Observations from gauges and in situ measurements are used to validate the model. Parameters, which cannot be easily measured, such as water and salt transports through straits, have been compared against similar previous estimates. The good performance of simulations is attributed to the finer resolution of the model compared to earlier set ups. The outflow in the Kattegat, which is an analogue of the tidal outflows, tends to propagate to the North over the shallows without showing a substantial deflection to the right due to the Earth's rotation. The inflow follows the topography. The different inflow and outflow pathways are explained as a consequence of the specific combination of bathymetry, axial and lateral processes. The circulation in Kattegat is persistently clockwise with an eastern intensification during inflow and a western one during outflow regimes. The tidal wave there propagates as Kelvin wave, keeping the coast on its right. The flows in the two main straits reveal very different responses to tides, which are also highly asymmetric during inflow and outflow conditions. The circulation has a typical two-layer structure, the correlation between salinity and velocity tends to increase the salt transport in the salinity conveyor belt. The transversal circulation in the entrance of the Sound enhances the vertical mixing of the saltier North Sea water. The long-term averaged ratio of the water transports through the Great Belt and the Sound is ~2.6-2.7 but this number changes reaching lower values during the major inflow in 1993. The transports in the straits are asymmetric. During inflow events the repartition of water penetrating the Baltic Sea is strongly in favor of the pathway through the Sound, which provides a shorter connection between the Kattegat and Baltic proper. The wider Great Belt has a relatively larger role in exporting water from the Baltic into the North Sea. A demonstration is given that the ventilation of the Baltic Sea deep water is not only governed by the dynamics in the straits and the strong westerly winds enhancing the eastward propagation of North Sea water (a case in 1993), but also by the clockwise circulation in the Kattegat acting as a preconditioning factor for the flow-partitioning.

1. Introduction

The Baltic Sea (Fig. 1a) is a semi-enclosed brackish sea. Its low salinity is due to the large runoff and limited water exchange with the North Sea, thus this basin can be considered as a big estuary of all rivers flowing into it. The surplus of fresh water in the absence of other forcing factors tends to keep the water level in the Baltic Sea higher than in the Kattegat and Skagerrak. The North Sea - Baltic Sea Transition Zone (for brevity NBTZ), which includes the Kattegat and Danish Straits, is the only connection of the Baltic Sea to the ocean. The width of the straits, the Great Belt, the Sound (known in Danish as *Øresud)* and the Little Belt, are 16–32, 4 and 1 km, respectively. The Baltic Proper and the NBTZ are separated by two sills (Fig. 1b): the Darss Sill (depth of 18 m) and Drogden Sill (depth of 8 m) where the inflowing North Sea water is subjected to substantial mixing.

Compared to other similar transition zones (e. g. Black Sea – Mediterranean and Mediterranean – Atlantic Ocean, Stanev and Lu, 2013; Sannino et al. 2009), the connection between the Baltic Sea and the ocean is more complex because of the multiple straits. Under different weather or circulation conditions their individual contribution to the exchange between basins varies, an issue which has not been enough addressed in the literature because of the lack of observations over larger areas and longer times. However this issue is central to the problem of ventilation of deep Baltic Sea by the North Sea water (Meier, 2005, 2007).

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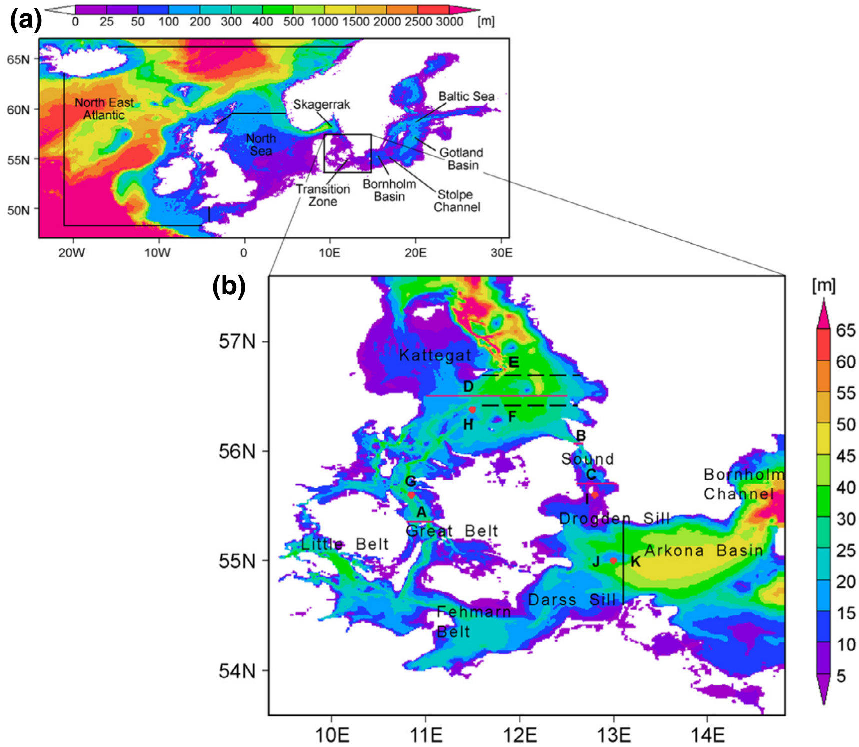

Fig. 1. (a) The three model domains (see text) and the large-scale topography (in m). (b) The bathymetry (in m) in the NBTZ as resolved by the fine resolution model (see more details further in the text). Red dots and section lines identify positions of analyses given in the text. Sections A–C are chosen for calculation of the water transport. Sections E and F are used in the analysis of vertical circulation. Section D is where particles are released in Lagrangean experiments. Section K is used to control the number of particles entering Arkona Basin. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Analyzing results of numerical simulations with the aim of understanding the dynamics of the NBTZ is the general motivation for the present research, which could contribute to quantifying the temporal and spatial variability of the inter-basin exchange. The main strategy here is to describe the specific estuarine circulation as simulated by the model focusing on those features which are not easily observed or described using the existing at present observations. The validation of the numerical model used here has been widely described by Buch and She (2005), She et al. (2007), Fu (2013) therefore this issue will focus here only on the specific model performance associated with using finer resolution, for instance.

The analysis presented in this study includes extreme and calm atmospheric conditions. The extreme ones are exemplified by the Major Baltic Inflows (MBIs), which are sporadic, and mostly barotropically driven events. Two such events, the ones in 1993 (Matthäus and Lass, 1995; Jakobsen, 1995; Lehmann 1995; Liljebladh and Stigebrandt, 1996) and in 2003 (Feistel et al., 2003a, 2004, 2006; Lehmann et al. 2004; Piechura and Beszczyńska 2004; Meier et al. 2004) are analyzed here (very recently an evidence appeared that after twelve years of stagnation a new MBI occurred at the end of 2014, Mohrholz et al. 2015). According to Jakobsen (1995), during the 1993 MBI event the volume of high salinity water (>17) transported through the Great Belt and Sound were in a ratio of 7:6, which was much bigger from the known ratio in the case of small and medium size events. Studies based on the observations (Jacobsen 1980; Fischer and Matthäus, 1996; Jakobsen and Trébuchet, 2000) and numerical modeling (Meier 1996) demonstrated that the ratio of transports through the Great Belt and Sound was ~8:3, or even 8:2 (Mattsson, 1996). A recent reanalysis was provided by Fu (2013) who used the same model as the one used here and data assimilation to estimate the transports. *One specific motivation for this paper is to analyze the partitioning of the flows between the two straits and identify the relevant physical processes behind this partitioning* (see also Seifert and Fennel, 1994; Fu, 2013).

The role of the circulation in Kattegat as a factor enhancing and controlling the transports through the straits is not very clear, neither its spatial and temporal variability. Therefore *the types of circulation in the Kattegat and its impact on the inflow-outflow dynamics (including the MBI events) are revealed in this paper.* We will demonstrate that not only during outflows, but also in the case of inflow regimes the circulation in the Kattegat is anticyclonic. Specific attention will also be given to the asymmetries in the outflow-inflow exchange, transversal circulation and the role of tides.

Recently, Burchard et al. (2005, 2009) used a horizontal resolution as high as the one used in the present paper (0.5 nm) to study the dominating dynamics in the Western Baltic Sea and validate the model performance with a focus on the mixing in the areas of Drogden Sill, Darss Sill and the Bornholm Channel. Their simulations allowed us to determine the pathways of the salt transport during medium-intensity inflow events (see also Meier, 2007), demonstrating a reasonable consistence with the observations. Although in these publications, as well as in the one of Hofmeister et al. (2011) further progress has been developed in the field of physical understanding and numerics, the authors admitted some problems with the open boundary conditions placed in the Kattegat, forcing with climatological data and initialization problems, which are not fully recovered by an annual simulation (Meier, 2007). These problems are avoided in the present study mostly because we couple the North Sea and Baltic Sea using a high-resolution two-way nested modelling system.

In Section 2 we describe the model used; followed by the analysis of physical process of the estuarine circulation, water and salt transport in Section 3; analysis of the circulation and mixing in Section 4; the propagation of water mass in Section 5. Short conclusions are formulated at the end.