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ORIGINAL RESEARCH ARTICLE

Attributing mean circulation patterns to physical phenomena in the Gulf of Finland

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Summary We studied circulation patterns in the Gulf of Finland, an estuary-like sub-basin of the Baltic Sea. According to previous observations and model results, the long-term mean circulation in the gulf is cyclonic and mainly density driven, whereas short-term circulation patterns are wind driven. We used the high-resolution 3D hydrodynamic model NEMO to simulate the years 2012—2014. Our aim was to investigate the role of some key features, like river runoff and occasional events, in the formation of the circulation patterns. Our results show that many of the differences visible in the annual mean circulation patterns from one year to another are caused by a relatively small number of high current speed events. These events seem to be upwelling-related coastal jets. Although the Gulf of Finland receives large amounts of fresh water in river runoffs, the inter-annual variations in runoff did not explain the variations in the mean circulation patterns.

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1. Introduction

The Gulf of Finland (GoF) in the Baltic Sea is a long, estuary-like sea area that is a direct continuation of the Baltic Proper. Short-term surface circulation in the gulf is mainly wind driven. The stability of currents varies from season to season. The relatively large freshwater input from the eastern end and the more saline deep water flow from the main basin at the western end maintain horizontal density gradients. The

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dominating south-westerly winds, freshwater input locations and the rotation of the Earth lead one to expect that the long-term mean circulation pattern would be cyclonic. Such residual circulation in the gulf was already described by Witting (1912) and later by Palmén (1930) in his classical study of circulation in the sea areas around Finland. For in-depth descriptions of the gulf, see e.g. Alenius et al. (1998), Soomere et al. (2008, 2009), Leppäranta and Myrberg (2009), and Myrberg and Soomere (2013).

In recent years, the circulation patterns in the gulf have been studied in many numerical model studies. While the model results have generally agreed with the features described by Witting, the results of the model studies vary somewhat from each other. For example, Maljutenko et al. (2010), Elken et al. (2011), Soomere et al. (2011) and Lagemaa (2012) show stronger mean currents west of Narva Bay on the southern coast than what was reported earlier by Andrejev et al. (2004). Also, the intensity of the outflow from the gulf seems to differ from one study to another and from one year to another. Where Andrejev et al. (2004) and Elken et al. (2011) observed a clear outflow in the subsurface layer, Maljutenko et al. (2010) did not. Lagemaa (2012) found the outflow to differ significantly from one year to another.

There are some obvious reasons for the differences between model results. Different studies have simulated different years, and model setups have been different. Also, there is significant inter-annual variability in the mean circulation. But these differences in results may also indicate that the reasons why such a statistical mean circulation pattern emerges are still not fully understood. By studying the physical mechanisms underlying the mean circulation pattern, we can also better understand the relative strengths and weaknesses of different hydrodynamic models and model configurations. For example, if we find that models overestimate or underestimate the effect of certain forcing inputs to the mean circulation, we know those processes need further attention in the model.

Suhhova et al. (2015) speculated that the role of upwelling-related coastal jets may be significant for the mean circulation in the gulf. Coastal upwelling is prevalent in the Gulf of Finland (Lehmann and Myrberg, 2008). Because the dominating wind direction in the GoF is from the south-west, upwelling events are expected to be more common in the northern (Finnish) side of the gulf than in the southern (Estonian) side. A coastal jet is developed simultaneously with the upwelling event. In the GoF, these jets have been both directly observed (e.g. Suursaar and Aps, 2007) and modelled (Zhurbas et al., 2008).

The effects of the residual circulation pattern can be indirectly seen, for example, in the intensity and whereabouts of the salinity gradients across the gulf. The salinity field in the gulf varies significantly both in space and in time. The four largest rivers in the area flow to the eastern gulf. The GoF receives the largest single freshwater input of the whole Baltic Sea from the river Neva at its eastern end. One way to view the gulf is to think of it as a transition zone between the fresh waters of the Neva and the brackish waters of the Baltic Proper (Myrberg and Soomere, 2013). The surface salinity decreases from 5 to 6.5 in the western part of the GoF to about 0 to 3 in the easternmost part of the gulf (Alenius et al., 1998).[1] In the western part of the GoF, a quasi-permanent halocline is located at the depth of 60—80 m and the bottom salinity can reach values up to 8—10 when more saline water masses advect from the Baltic Proper. In the eastern part of the GoF, there is no permanent halocline and the salinity typically increases linearly with depth. Changes in circulation patterns are relatively quickly reflected in the mean salinities, especially in the volatile upper layers. This means that it is possible to indirectly validate the mean circulation field of the gulf by investigating the patterns of salinity in the gulf. This method has been previously employed by e.g. Myrberg et al. (2010) and Leppäranta and Myrberg (2009).

The residual mean circulation must be distinguished from the instantaneous or short-term circulation patterns. It lies more behind the scenes but is nevertheless important for many applications, such as estimating the transport, distribution and residence times of substances discharged to the sea. These substances can be, for instance, nutrients from the land or oil and chemicals from accident sites. Improving substance transport estimates is a high priority task in the area as the coastline is densely populated and ship fairways are highly trafficked. When high-resolution numerical models are used in these tasks, they must be able to faithfully reproduce the mean circulation patterns. Correctly working numerical models can bring significant added value to decision support systems that are built to evaluate the effects of environmental protection measures on marine systems. Unfortunately, evaluating model performance is not straightforward. Where current measurements exist, they lack coverage, both spatial and temporal. Thus, questions remain about the accuracy of modelled circulation patterns.

Our objective is to study how physical processes are attributed to features that are observed in mean circulation patterns. We use the numerical 3D model NEMO (Madec and the NEMO team, 2008), an increasingly popular model in the investigations of the Baltic Sea, to calculate the mean circulation pattern in the Gulf of Finland for the years 2012—2014. We use two setups of the model, one fine resolution and one of coarser resolution, which are validated against observations and benchmarked against other model data. We analyse some of the key circulation features and especially the contribution that high current speed events make to the longer term averages. Finally, we investigate how these details relate to specific phenomena such as upwelling.

2. Material and methods

2.1. Modelling

2.1.1. NEMO

We used two setups of the NEMO 3D ocean model (V3.6), a coarse resolution setup with a two nautical mile (NM) horizontal resolution covering the Baltic Sea and the North Sea area, and a fine resolution setup for the Gulf of Finland with 0.25 NM horizontal resolution. We ran the model from the

[1] All salinities in this paper are on the practical salinity scale.