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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.

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 southwest, 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.

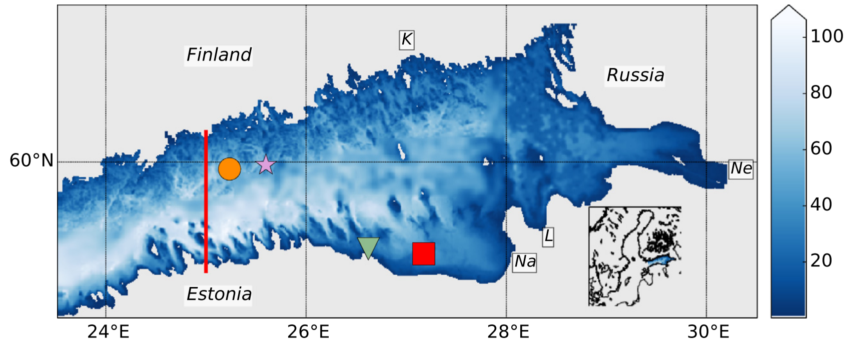

Figure 1 The model domain and bathymetry (in metres) from the fine resolution 0.25 NM NEMO setup. Stations and sites referenced in the article (from the west): H (orange circle), Kalbådagrund (magenta star), G (green triangle) and 15 (red square). The thin red line shows the location of the 25°E transect. Also indicated on the map are the approximate locations of the Neva (Ne), Narva (Na), Luga (L) and Kymi (K) river mouths. Inset is the location of the model domain on a map of the Baltic Sea. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

beginning of 2011 to the end of 2014. We considered the results from 2011 as the stabilisation of the model and chose the years 2012—2014 for closer analysis. The model saved daily mean values of temperature, salinity and current fields.

The horizontal resolution of the fine resolution setup, approximately 500 m, is well below the typical range of internal Rossby radius (2—4 km) in the GoF (Alenius et al., 2003). This configuration is based on the setup by Vankevich et al. (2016) with some modifications related to atmospheric forcing and boundary conditions. The model domain covers the GoF east from longitude 23.5°E, where an open boundary to the Baltic Proper is located (see Fig. 1). Model bathymetry is based on Andrejev et al. (2010). This setup has 94 *z*-coordinate (with partial step) vertical layers. The topmost vertical layers are 1 m thick, and the layer thickness slightly increases with depth, being about 1.08 m at the lower bound of the *z*-axis. The time step of the model was 100 s. The ice model LIM3 was included in the setup (Vancoppenolle et al., 2009). Due to the high computational requirements of the configuration, and since the focus of this study is on the ice-free period, the ice model was only run with a thermodynamical formulation. Like Vankevich et al. (2016), we used initial conditions for the beginning of 2011 from the operational version of HIROMB (High Resolution Operational Model for the Baltic). The lateral boundary condition on the open boundary was taken from the coarser setup. Flather boundary conditions were used for barotropic velocities and sea surface height; flow relaxation was used for temperature and salinity.

The coarser 2 NM NEMO setup for the Baltic Sea and the North Sea was also used for analyses. This setup was documented and validated in Westerlund and Tuomi (2016) and is based on the NEMO Nordic configuration by Hordoir et al. (2013a, 2013b, 2015). The layer thickness of this setup starts from 3 m in the surface layer, growing with depth. Unlike in Westerlund and Tuomi (2016), the boundary condition of the coarse setup was updated to use Copernicus Marine Environment Monitoring Service (CMEMS) Global Ocean Reanalysis product (Ferry et al., 2016) to improve the representation of sea levels in the model. Furthermore, the additional strong isopycnal diffusion that was previously applied in the Neva estuary, described in Hordoir et al. (2015), was turned off in order to make the description of currents in the eastern part of the GoF more realistic. The bathymetry of the setup was updated to the latest version of the NEMO Nordic bathymetry and the ice model of the coarser setup was turned off to improve run times.

2.1.2. Meteorological forcing

We used forecasts from the HIRLAM (High Resolution Limited Area Model) numerical weather prediction system (HIRLAM-B, 2015) of the Finnish Meteorological Institute (FMI) for atmospheric forcing. Its domain covers the European region with a horizontal resolution of 0.15° (V73 and earlier; before 6 March 2012) or 0.068° (V74; after 6 March 2012). Vertically the domain is divided into 60 (V73) or 65 (V74) terrain-following hybrid levels, the lowest level being about 12 m above the sea surface. The forecasts are run four times a day (00, 06, 12, and 18 UTC) using boundary conditions from the Boundary Condition Optional Project of the ECMWF (European Centre for Medium-Range Weather Forecasts). Each day of forcing was extracted from the 00 forecast cycles with the highest available temporal resolution in the model archive, varying from 1 to 6 h.

Forcing taken from HIRLAM includes the two-metre air temperature, total cloud cover, mean sea-level pressure and 10-m winds, and either the two-metre dew point temperature or relative humidity, depending on the availability in the model archive. Forcing was read into the NEMO run with CORE bulk formulae (Large and Yeager, 2004).

2.1.3. River runoff and precipitation data

River runoff forcing for the four main rivers running into the GoF was based on data obtained from two sources. For the river Kymi, we used the same climatological runoff data from Stålnacke et al. (1999) as was used in Vankevich et al. (2016). The discharges for the Neva, Narva and Luga rivers were from HydroMet, received as a part of the Gulf of Finland Year 2014 (GoF2014) project.

The sensitivity of the model configuration to changes in the river runoff forcing was evaluated by running experiments for the years 2013—2014 with modified runoffs. The first experiment had no river runoffs and the second experiment had runoff volume multiplied by two.

Precipitation fields were climatological and based on downscaling of the ERA40 reanalysis for the period 1961—2007 (cf. Hordoir et al., 2015).

2.1.4. CMEMS reanalysis product

In addition to NEMO, we used CMEMS Baltic Sea Reanalysis (Axell, 2016) to further analyse the circulation in the gulf. This product is based on the HIROMB model with the horizontal resolution of approximately 3 NM, with 51 vertical levels. The top layer in this model is 4 m thick and layer thickness increases with depth. This product implements a data assimilation algorithm for salinity, temperature, and ice concentration and thickness.

2.2. Measurements

2.2.1. CTD

Usually model development and evaluation are limited by the availability of measured datasets with sufficient temporal and spatial resolutions. We hoped to be a little bit better off with the GoF2014 dataset. The official GoF2014 data covers the whole gulf with data from 1996 to 2014 from Estonia, Finland and Russia. This dataset consists of almost 38,500 depth observations with several parameters from 53 different observation stations covering the whole gulf. The number of visits to stations varies and only some of them can be considered to be like a time series.

Additionally, the FMI did three one-week CTD surveys with over 80 stations each in the western gulf, in Finnish and Estonian waters. One of these was done in 2013 and two were done in 2014. These surveys were planned to collect data on temperature, salinity and density fields for model development. The horizontal spacing of the stations was around 4 NM across the gulf and around 9 NM along the gulf. The observation grid was a compromise between the needed resolution (the Rossby radius of deformation is of the order of 2—4 km), the available ship time and the area that we wanted to cover. CTD casts were done at every station with SeaBird SBE911 ctd.

The 2013 observations were made 3—7 June 2013, from east to west. In 2014 there were two cruises, the first 15—19 June, from west to east, and the second 8—12 September, from west to east. The duration of each cruise was five days. Thus, the whole grid may not be considered synoptic. The time of each section across the gulf was of the order of 6 h and those sections may be considered rather synoptic, though the transversal Seiche period of the gulf is of the same order. For analysis, the cruise data was then interpolated to a 3D grid using the DIVA (Data-Interpolating Variational Analysis) interpolation method (Troupin et al., 2012).

2.2.2. Weather stations

We used wind measurements from the FMI's coastal weather station Kalbådagrund (location shown in Fig. 1) in order to evaluate the accuracy of the meteorological forcing. This weather station is considered to be representative for open sea weather conditions in the Gulf of Finland and it has been used in many earlier studies (e.g. Lips et al., 2011; Tuomi et al., 2012). At Kalbådagrund, wind measurements are made at 32 m height. From this station, we have data for the main meteorological parameters at 10-min intervals.

3. Results

3.1. The mean circulation field in the Gulf of Finland in the NEMO model

In the Gulf of Finland, the persistency of the circulation field (defined as the ratio of the vector velocity to scalar speed) is known to be rather low. Alenius et al. (1998), among others, cite Palmén's estimates, which ranged from 6% to 26% for long-term persistency. This means that the current field is very variable in time (and space). Therefore it is to be expected that the residual circulation pattern is different from year to year too. We present here the mean circulation patterns from the two NEMO model setups, averaged over time and depth. Depth averaging was done from the surface to 7.5 m depth. These limits for averaging were chosen to make sure that averaging does not include the thermocline, which can at times be shallower than 10 m.

The annual mean circulation, modelled with 2 NM NEMO, was quite different for the years 2012—2014 (Fig. 2). Of these years, 2012 resembles most the traditional mean circulation patterns, while the years 2013 and 2014 showed quite different mean circulation fields. In 2012, there was a westward residual current on the northern coast (also called the Finnish Coastal Current, Stipa, 2004) with speeds of a few centimetres per second and a relatively strong jet with top speeds over 10 cm s^{-1} along the south-eastern coast, west of Narva Bay. In 2013, the residual in the northern coast is eastward and the jet on the southern coast is even stronger than in 2012. In 2014, the residual in the northern gulf is weak, only a few centimetres per second, but the jet on the southern coast exists still.

The annual mean circulation from the fine resolution 0.25 NM setup showed similar results to the 2 NM setup, as shown in Fig. 3. However, as this setup also resolves the submesoscale, the overall picture is much more detailed. While the circulation direction is similar to that in the coarser NEMO setup, the 0.25 NM NEMO setup generally simulated higher mean current speeds. Contrary to the 2 NM NEMO setup, there was no clear outflow on the northern coast in 2012, albeit the general flow direction was the same. In 2013 and 2014, the residual circulation patterns were mostly similar to those in the coarser run.

The mean circulation for the whole period 2012—2014 shows four circulation loops in the gulf (Fig. 4). The centre of the first loop is located at approximately 23.5°E (loop A, in the nomenclature of Lagemaa, 2012). As this loop is very close to our 0.25 NM setup domain boundary, we only capture it fully in the coarser model. The second loop (B) is roughly at 25°E. The third loop (C), at 27°E, includes the coastal current west of Narva Bay. The fourth loop (D), at 28.5°E, is located in the Neva estuary.

The wind measurements at the Kalbådagrund weather station were used, along with corresponding HIRLAM model data, to evaluate whether the differences in the annual mean circulation patterns could be linked to differences in the wind conditions in 2012—2014. All the years have a dominating wind component from the south-southwest (Fig. 5). There are, however some differences in the frequency and magnitude of the easterly winds between the years. In 2012, the

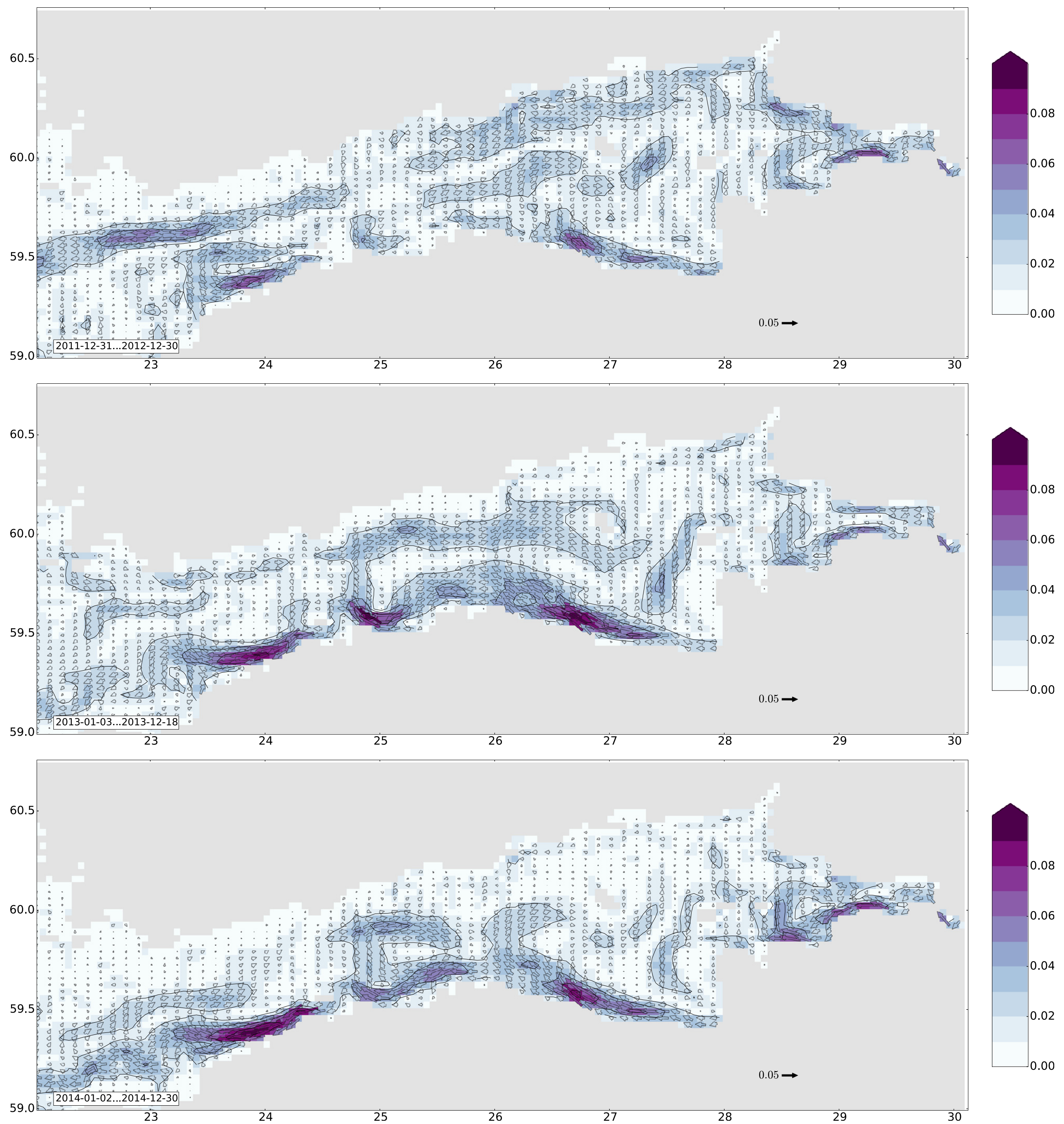

Figure 2 Annual mean circulation in the 2 NM setup averaged from 0 m to 7.5 m depth for the years 2012 (top), 2013 (middle) and 2014 (bottom). Velocities are in m s^{-1}. Vector arrows are drawn for every other grid point in the longitudinal direction and for every grid point in the latitudinal direction.

quantity of easterly winds is smallest and in 2014 it is largest. In 2013, there is also a significant component of high wind speeds from the west, contrary to the other years. We also compared the forcing wind field to the measured values at Kalbådagrund and found that HIRLAM forecast the wind speed and direction fairly well. In 2012, there were relatively few differences, although the forcing data shows weaker south-eastern winds than the measurements. In 2013, the forcing data has a stronger component of northerly winds than the measurements. In 2014, easterly winds are not as well represented in the forcing data.

3.2. Benchmarking the circulation field

As validation of the whole circulation field is difficult and spatial coverage of measurements is sparse, we instead

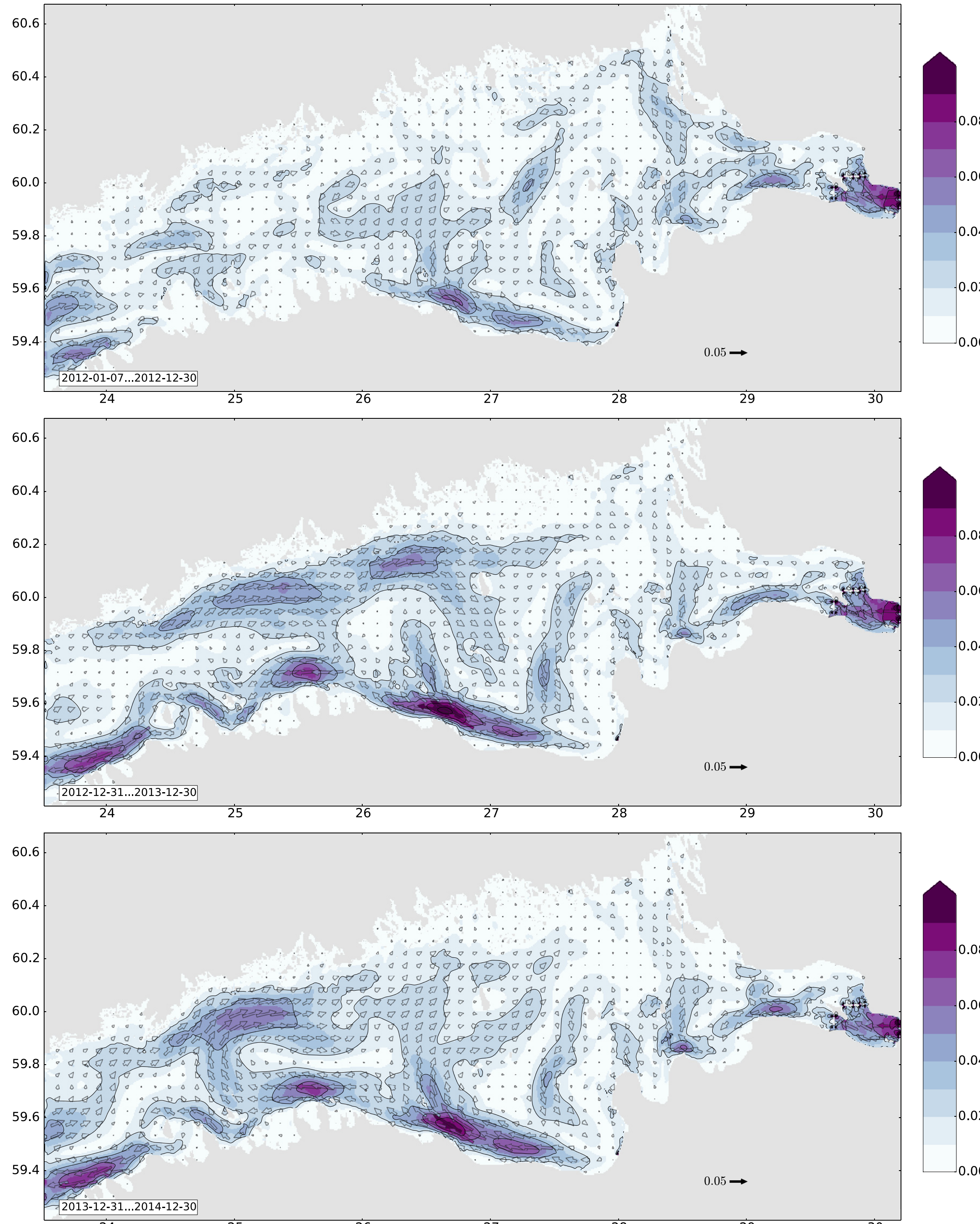

Figure 3 Annual mean circulation in the 0.25 NM setup averaged from 0 m to 7.5 m depth for the years 2012 (top), 2013 (middle) and 2014 (bottom). Velocities are in m s^{-1}. Vector arrows are drawn for every 13th grid point in the longitudinal direction and in every 11th grid point in the latitudinal direction.

benchmark the two NEMO setups against the HIROMB-based CMEMS product. We consider this model indicative of the general performance of hydrodynamic models in the area (cf. Myrberg et al., 2010). In the HIROMB results, the outflow in the northern gulf is clearly visible in 2012, almost non-existent in 2013 and reversed in 2014 (Fig. 6). The direction of flow is more uniform and the field is smoother than in NEMO. Furthermore, HIROMB does not show a clear coastal current on the southern coast in 2012. The years before 2012 had a similar mean circulation pattern as the

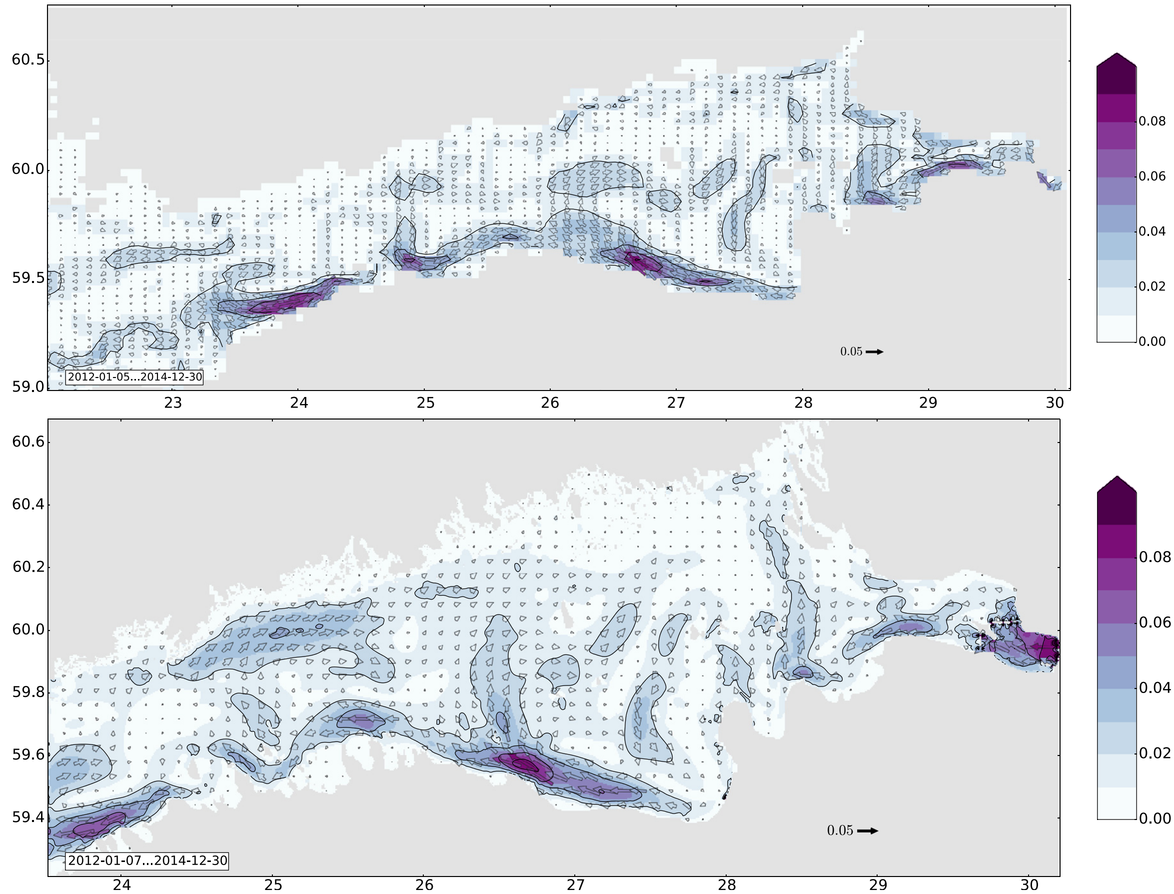

Figure 4 Mean circulation for 2012—2014 averaged from 0 m to 7.5 m depth in the 2 NM (top) and the 0.25 NM (bottom) setup. Velocities are in m s^{-1}. For the upper figure, vector arrows are drawn for every other grid point in the longitudinal direction and for every grid point in the latitudinal direction. For the lower figure, vector arrows are drawn for every 13th grid point in the longitudinal direction and in every 11th grid point in the latitudinal direction.

year 2012 (not shown here). In the 2013 results there is a marked difference: in NEMO the residual current in the Finnish coast is mainly to the east, while in HIROMB it is to the west. In other areas the speeds in NEMO are stronger but the directions are similar to those of HIROMB. The reversal of the outflow in 2014 from that of 2012 is more or less similar in the coarser NEMO model and in HIROMB. All the models show a clear alongshore current on the southern coast in 2014 too.

3.3. Salinity validation

We compared the model salinity with observations, as the mean salinity field can be used as a proxy for the mean circulation field. In these comparisons we used the CTD survey data from 2013 to 2014. Model data has been averaged over the span of the cruises (cf. Section 2.2.1). North—south salinity cross-sections show that the 0.25 NM NEMO model is able to describe the vertical structure of the water column rather well (Fig. 7). In the near-surface layers, however, the freshest water is somewhat incorrectly placed in each case in both NEMO and HIROMB. In 2013, the surface layer in NEMO was less saline than in the observations. In 2014, the observations show less saline water on the northern coast. The model shows the opposite.

3.4. Attributing the features of the mean circulation field with physical phenomena

3.4.1. River runoff

As the Gulf of Finland is in many ways like a large estuary, the density gradients are significant for the mean currents in the gulf. Therefore, correctly prescribing river runoff forcing is even more important than in the other sub-basins of the Baltic Sea. Runoff data with high enough temporal resolution is still inaccessible or sometimes non-existent for many rivers. Therefore it is common to use data from hydrological models, such as E-HYPE (Donnelly et al., 2016) or climatological runoff data (e.g. Bergström and Carlsson, 1994).

The datasets gathered during the GoF2014 include monthly mean runoffs from the Neva, Narva and Luga rivers from recent years. This allowed us to compare them to respective values from E-HYPE. The comparison showed that the modelled runoffs often differ significantly from the observed ones. For example, for the GoF2014 study period

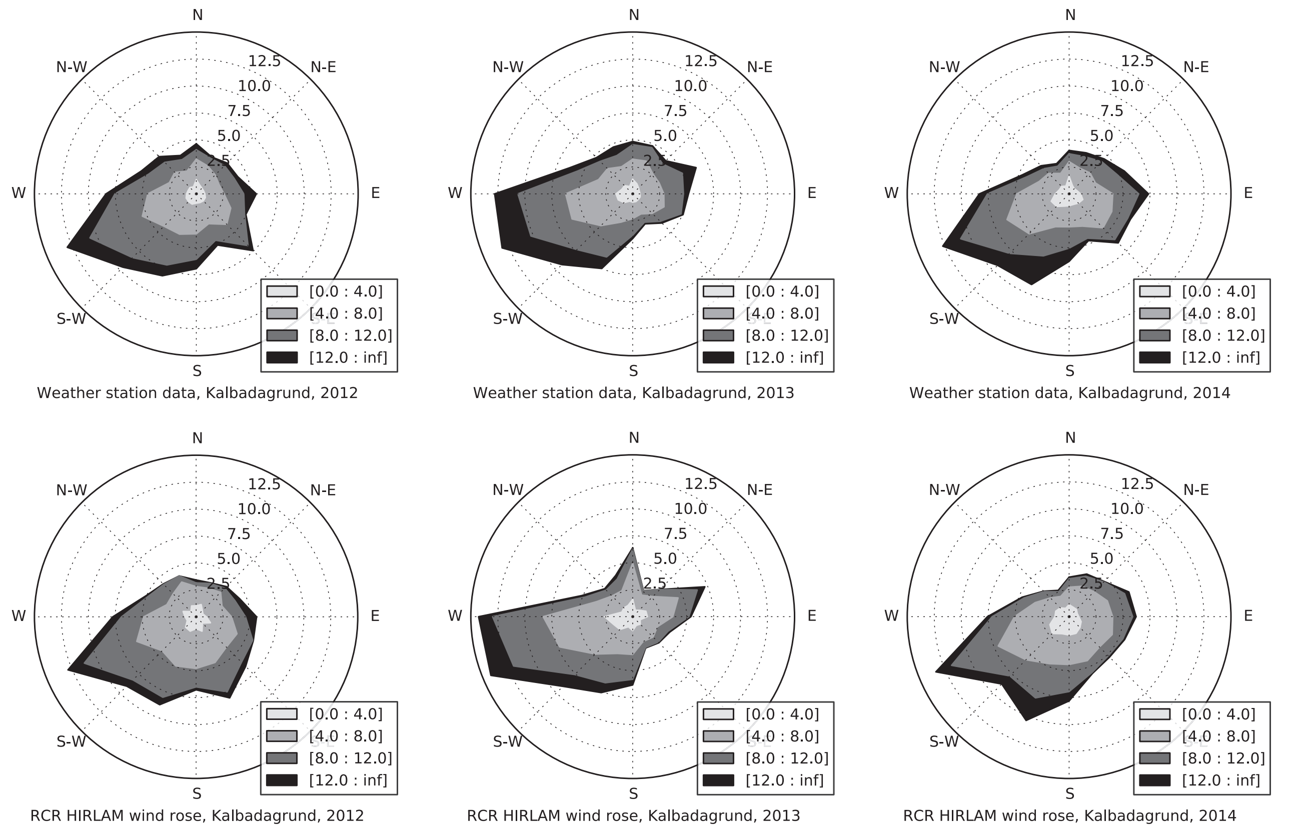

Figure 5 Annual wind roses at Kalbådagrund meteorological station in 2012, 2013 and 2014. Top: observation; bottom: HIRLAM model 10 m winds. Wind speeds are in m s^{-1}, frequencies are in percent.

1996—2014, the mean observed runoff from the Neva was 2345 $m^3 s^{-1}$ (about 73 $km^3 a^{-1}$, which is in one year almost 7% of the volume of GoF: 1090 km^3). The mean runoff from E-HYPE was 1881 $m^3 s^{-1}$, which means almost a 28% difference from the observed value. More detailed information about GoF2014 and the dataset can be found in Raateoja and Setälä (2016).

To investigate how incorrectly estimated river runoffs could affect the modelled circulation patterns, we performed two simulations with the 0.25 NM NEMO setup using modified runoff forcing, namely (1) no runoff from the four major rivers into the gulf and (2) doubled runoff from the four major rivers into the gulf. Although, this approach is somewhat artificial, it shows how sensitive the modelled near-surface current fields are to river runoff forcing. The changes in the river runoff mainly affected the magnitude of the near-surface currents, as shown in Fig. 8. There were hardly any changes in the direction of the mean currents. When the runoffs are doubled, the Neva river plume became very easily identifiable. Compared to the reference run (Fig. 4), the highest mean current speeds increased by roughly half.

3.4.2. High flow speed events

The averaging of variable currents over time periods of years can hide different kinds of physical situations. Rare high energy events can show up and even dominate averages in certain areas. A relatively small number of days with high current speeds can contribute to the mean circulation field in a significant way. We demonstrate this using the coastal flow near the northern coast of the gulf as an example.

To quantify the contribution of days with high current speeds, we divided the model dataset into two parts based on the modelled current speed at a point near the Finnish coast. This point is indicated in Fig. 1 as site H. It was chosen because it is in an area where strong coastal currents were seen in the NEMO results (Fig. 4).

We found that strong current episodes contributed significantly to the formation of the jet in the residual pattern of currents on the Finnish coast (Fig. 9). Even though days with high current speeds are only 18% of all days in 2012—2014 (when the criterion for high current speed is 10 cm s^{-1} daily mean speed), they still are a major contribution to the overall mean circulation field. If we removed the days with strong currents from the analysis, the magnitude of the eastward current in the Finnish coast was smaller, but the direction was still towards the east. For example, mean current speed was approximately 3.3 cm s^{-1} at site H in 2012—2014. If we include only days with strong currents in the calculation, the magnitude of the current was 1.3 cm s^{-1}, which is around 41% of the total. The direction of the current in both cases was nearly the same. On the southern coast, a similar analysis revealed the same, with high current speed days contributing significantly to the coastal current visible in the annual mean circulation field (not shown).

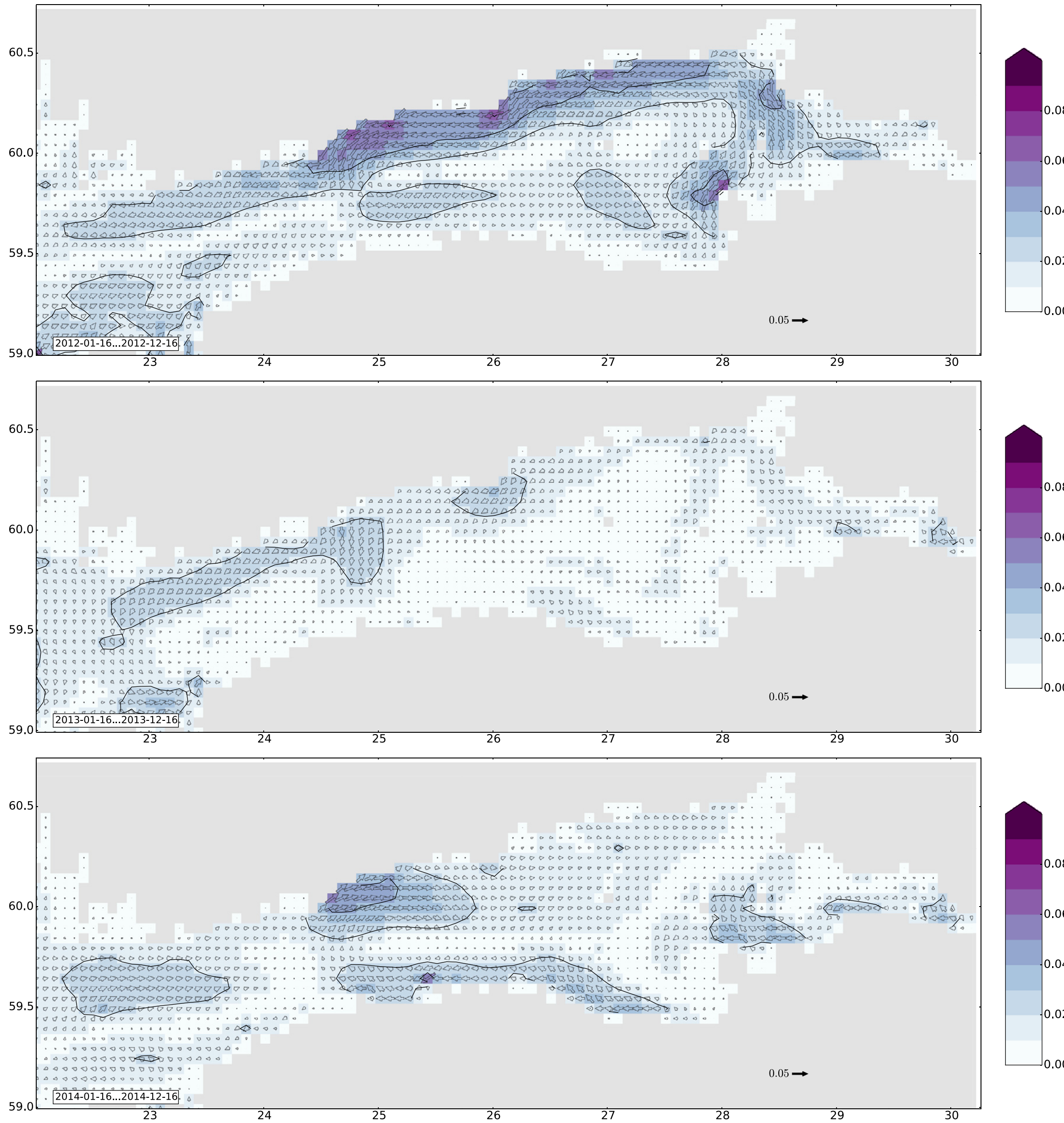

Figure 6 Annual mean circulation in the CMEMS product averaged from 0 m to 7.5 m depth for the years 2012 (top), 2013 (middle) and 2014 (bottom). Velocities are in m s^{-1}. Vector arrows are drawn for every grid point.

3.4.3. Upwelling-related jets

To further understand what sort of events contribute to the strong coastal currents in the annual mean current fields in different years, we investigated how these high-speed events relate to coastal upwelling. We selected an area in the south-eastern GoF, west of Narva Bay, for closer inspection. In this area the annual mean current fields of the 0.25 NM NEMO run showed high-speed westward currents, especially in the years 2013 and 2014 (Fig. 3). We chose the nearshore station 15 (location shown in Fig. 1) from which there were several temperature measurements available during 2012—2014. On a number of occasions, the modelled temperature decreased rapidly within a short time period during the summer stratified season, indicating a possible upwelling event (Fig. 10, upper panel). Many of the temperature drops, including the two events with the highest current speed at this station, can be associated with high-speed alongshore currents, visible in the modelled current speeds at the nearby station 15 (Fig. 10, lower panel). Similar analysis for two stations near the northern coast gave concurring results (not shown).

The model reproduced the seasonal temperature cycle in the surface layer fairly well (Fig. 10). During two of the possible upwelling events, the measured temperature also shows lower values. However, the temporal resolution of the measurements is not sufficient enough to differentiate between upwelling and cooling of surface water due to other processes.

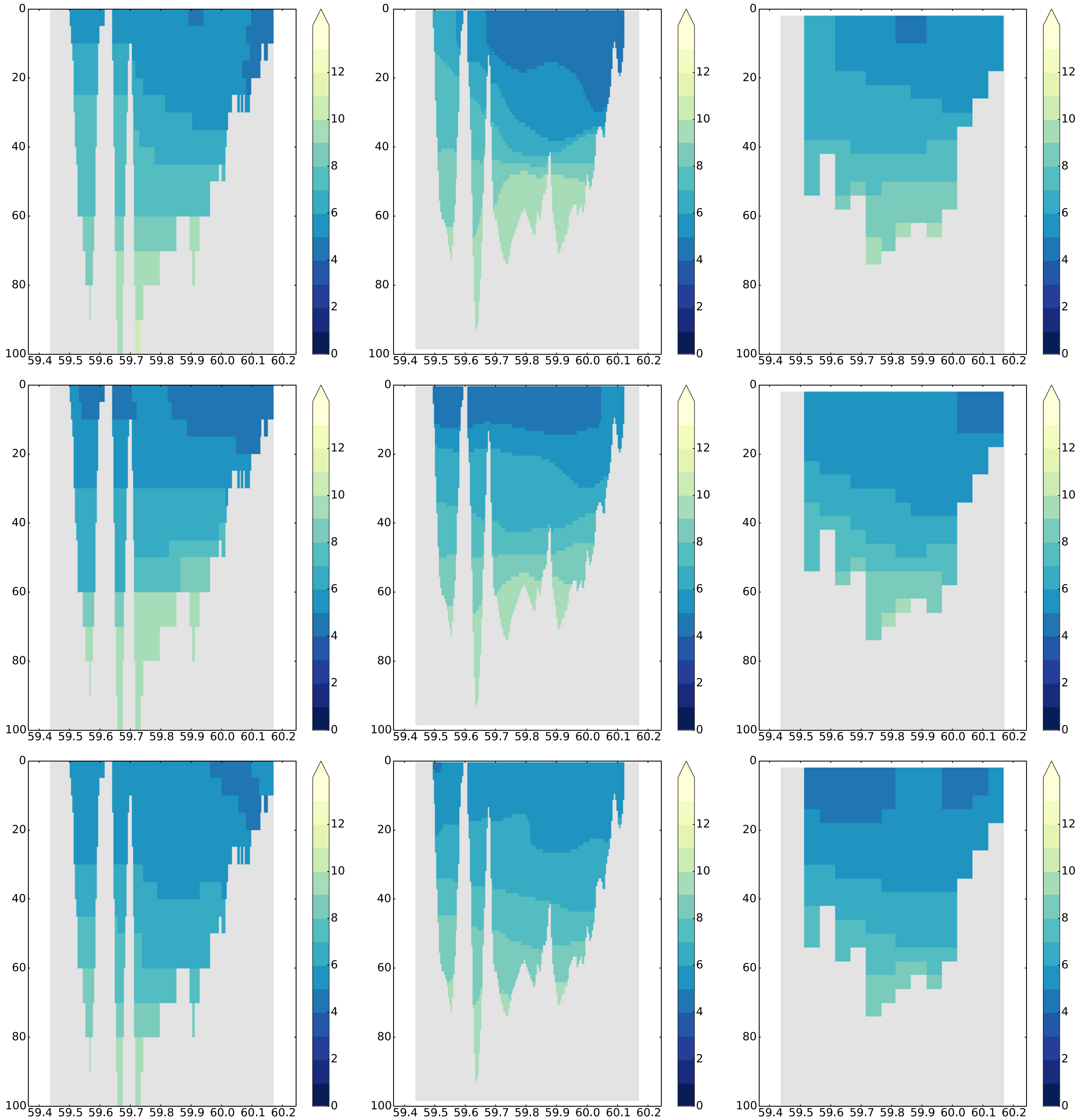

Figure 7 A south—north salinity cross-section at 25°E from gridded observations (left) and the 0.25 NM NEMO model averaged over the time span of the cruise (middle). For reference, the monthly mean from the 3 NM HIROMB-based CMEMS product is also provided (right). The June 2013 cruise (top), the June 2014 cruise (middle) and the September 2014 cruise (bottom) are shown. The south coast is on the left-hand side.

For a rough quantitative estimate of the effect that these possible upwelling events have on the annual mean current speed in this area, we focused on one specific event at station 15 in September 2013. Like in the previous section, we take the average speed of 10 cm s^{-1} as the lower limit of a high current speed day, since during these possible upwelling events the current speed peaks are clearly higher than 10 cm s^{-1} and in most of the other higher current speed events the peaks are around or smaller than 10 cm s^{-1}. This event had 15 high-speed days (from 11 to 25 Sep 2013) with a mean velocity of 18 cm s^{-1}. Averaged over the year, if we assume that the flow direction stays the same during this event, this single event contributes approximately 0.7 cm s^{-1} to the yearly mean. As the yearly mean velocity for this station was 6 cm s^{-1} in 2013, it means that this single event contributed over 10% of that figure. As there were five events in

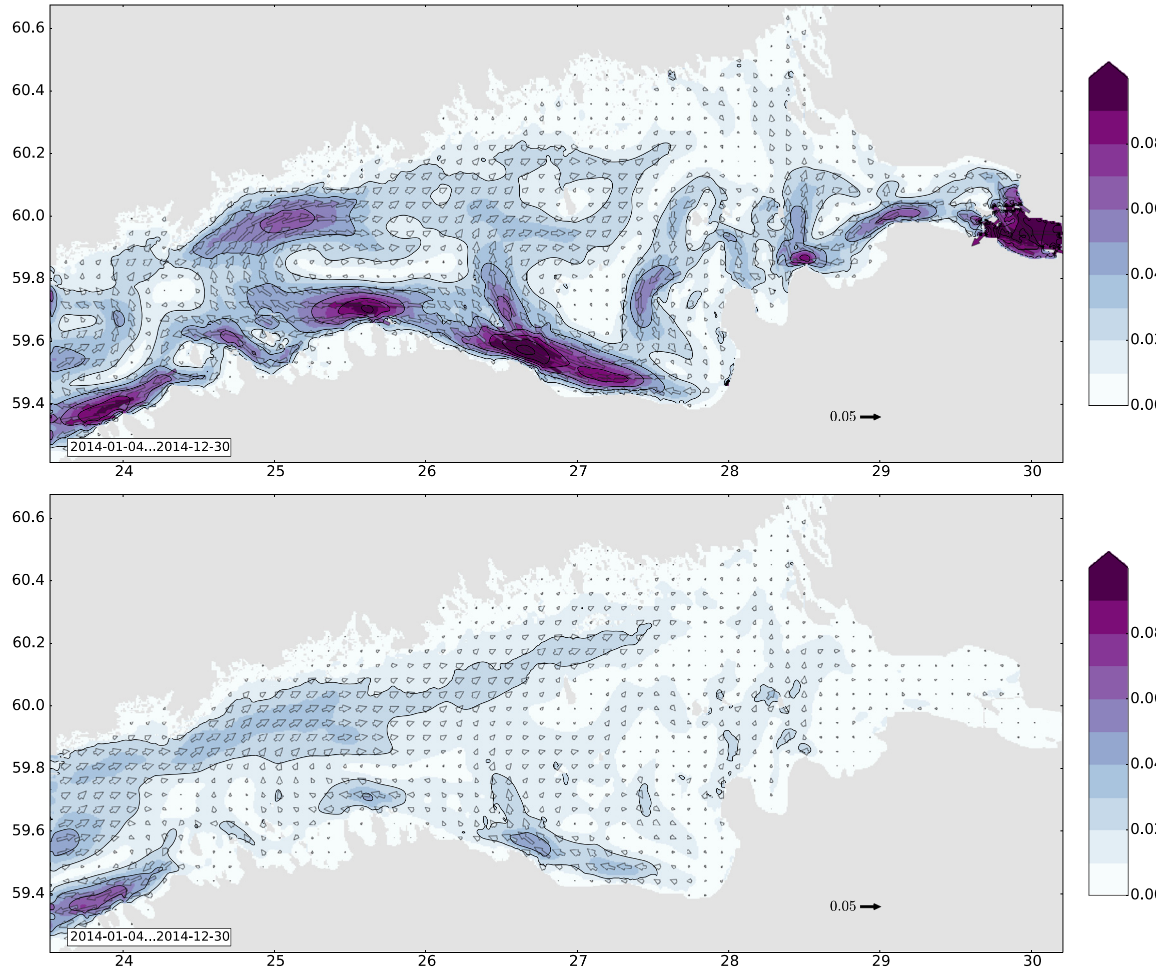

Figure 8 Mean circulation in 2014 averaged from 0 m to 7.5 m depth in two runs of the NEMO 0.25 NM setup. The top figure shows the run with double volume runoffs, the bottom run is the one without river runoff. Velocities are in m s^{-1}. Vector arrows are drawn for every 13th grid point in the longitudinal direction and in every 11th grid point in the latitudinal direction.

2013 where the current speed exceeded this threshold of 10 cm s^{-1}, these high-speed events were reflected in a significant way in the annual mean current field at this point.

The modelled surface temperature field shows that this event displays the characteristics of an upwelling event along the southern coast of the Gulf of Finland (Fig. 11). The modelled mean surface salinity field from the same day confirmed that this cooler water originated from deeper layers with more saline water. The salinity field also shows how the freshwater plume from the Neva estuary is directed towards the south-west, towards the southern coast. The extent of this event in September 2013 suggests that coastal jets might emerge further west on the southern coast, thus contributing highly to the annual mean values, as in the case of station 15.

4. Discussion

The horizontal resolution of the 3D hydrodynamic model, as well as that of the meteorological forcing, have a large effect on the modelled surface and near-surface current fields. Andrejev et al. (2010) have shown that the trajectories of Lagrangian tracers in the Gulf of Finland are much affected by the horizontal resolution of the circulation model. Of the two NEMO setups we used, the fine resolution setup (0.25 NM) has sufficient scale to solve the Rossby radius of deformation in the gulf. Compared to the 2 NM NEMO setup or the HIROMB model, the 0.25 NM setup gave more detailed mean circulation fields, as expected, but also produced somewhat different circulation in the middle part of the GoF than the coarse resolution setups. Unfortunately, the good quality datasets that are presently available are not sufficient to validate the accuracy of the simulated circulation patterns in detail.

Meteorological forcing is one of the key factors in the ability of a 3D hydrodynamic model to simulate the surface and near-surface current fields. In relatively small basins these currents are mainly driven by wind stress. In the GoF, long-term runs tend to produce a cyclonic mean surface circulation pattern as a result of the prevailing south-westerly winds, density-driven circulation, Coriolis force and topographic steering. But, the variable wind conditions have a large effect on the annual circulation patterns, as can be seen from the previous studies of Andrejev et al. (2004), Maljutenko et al. (2010), Elken et al. (2011), Soomere et al. (2011), and Lagemaa (2012).

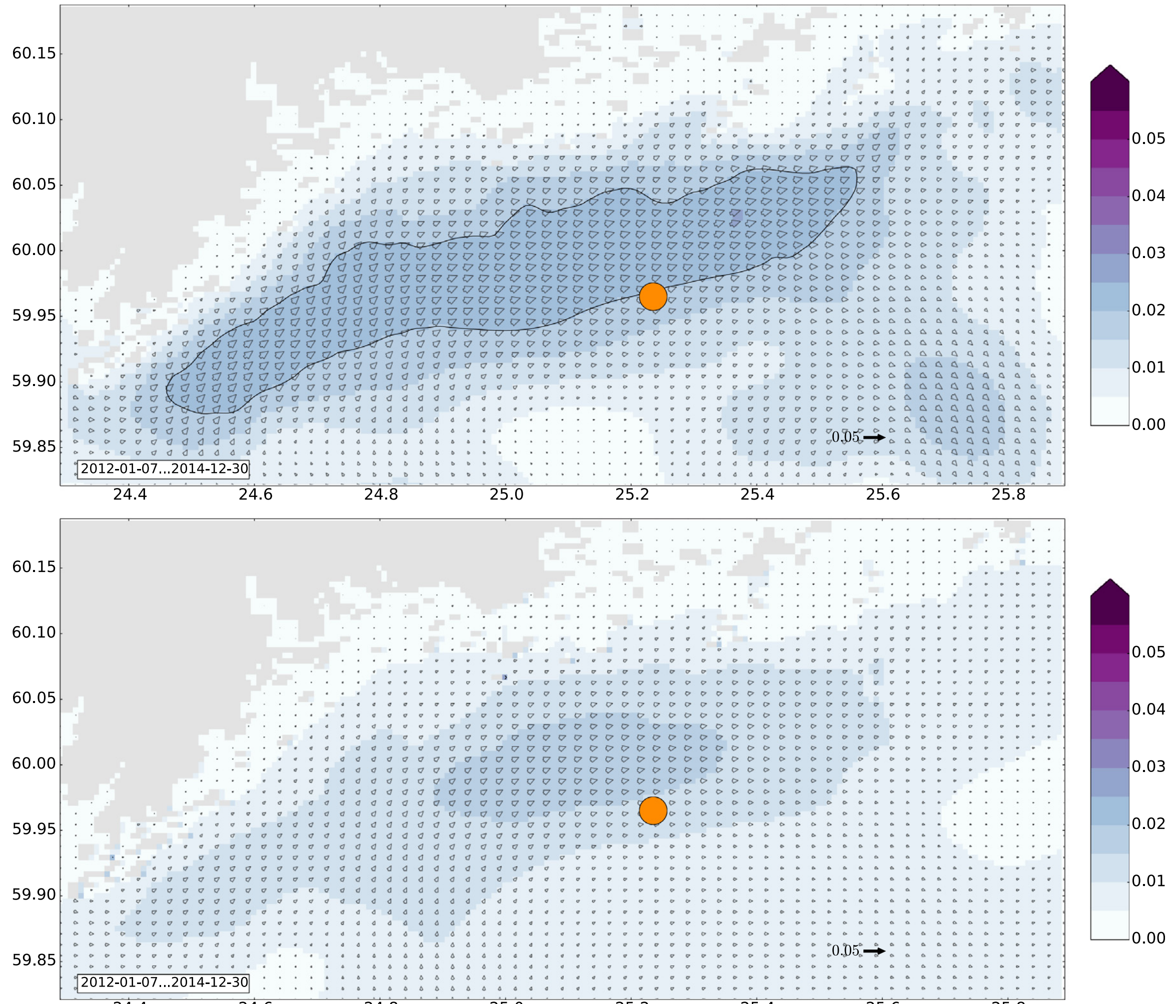

Figure 9 Mean circulation 2012—2014 off Helsinki, split into the contribution of low and high current speed days. The modelled circulation field from the 0.25 NM NEMO setup has been averaged from 0 m to 7.5 m depth. The upper panel shows the contribution of days with low modelled current speed at a chosen location (site H, indicated with an orange circle, cf. Fig. 1). The lower panel shows the contribution of days with the high current speed at the same site. The mean circulation field is the vector sum of the two figures. The limit for high-speed days was 0.1 m s^{-1}, which means that the upper figure has approximately 82% of days and the lower figure 18%. Velocities are in m s^{-1}. Vector arrows are drawn for every third grid point in the longitudinal direction and in every second grid point in the latitudinal direction. Note the colour scale, which is different from the other figures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

The wind roses from Kalbådagrund station show some variability in the directionality of the wind field over the years. Especially the proportion and magnitude of easterly winds varied. This could have a large effect on the frequency and location of the upwelling events in the gulf and influence the annual mean surface and near-surface current fields significantly. For instance, in 2013 and 2014, when the easterly winds were stronger compared to those of 2012, there were much higher current speeds on the southern coast of the GoF which we associated with coastal currents.

The meteorological forcing used in this study had a resolution of c. 7.5 km, except for the two first months of 2012 when it was coarser. This resolution is high enough to produce a wind field and other meteorological parameters in the GoF with sufficient accuracy for marine modelling. The peak of the high-wind situations is predicted more accurately than in some of the earlier modelling studies that have utilised the SMHI (Swedish Meteorological and Hydrological Institute) gridded meteorological dataset with one-degree resolution (Andrejev et al., 2004; Tuomi et al., 2012). However, a comparison of the wind roses at Kalbådagrund showed that HIRLAM was not able to describe the directional properties of the wind field in full detail. Furthermore, HIRLAM slightly underestimates higher wind speeds (of over 12 m s^{-1}). This affects the ability of NEMO to simulate the intensity of the upwelling events and the resulting coastal jets.

The upwelling-related alongshore coastal jets west of Narva Bay have been earlier presented by Suursaar and Aps (2007), who analysed RDCP (Recording Doppler Current Profiler) measurements from summer 2006 west of Narva Bay during an upwelling event. Also, Suhhova et al. (2015) have

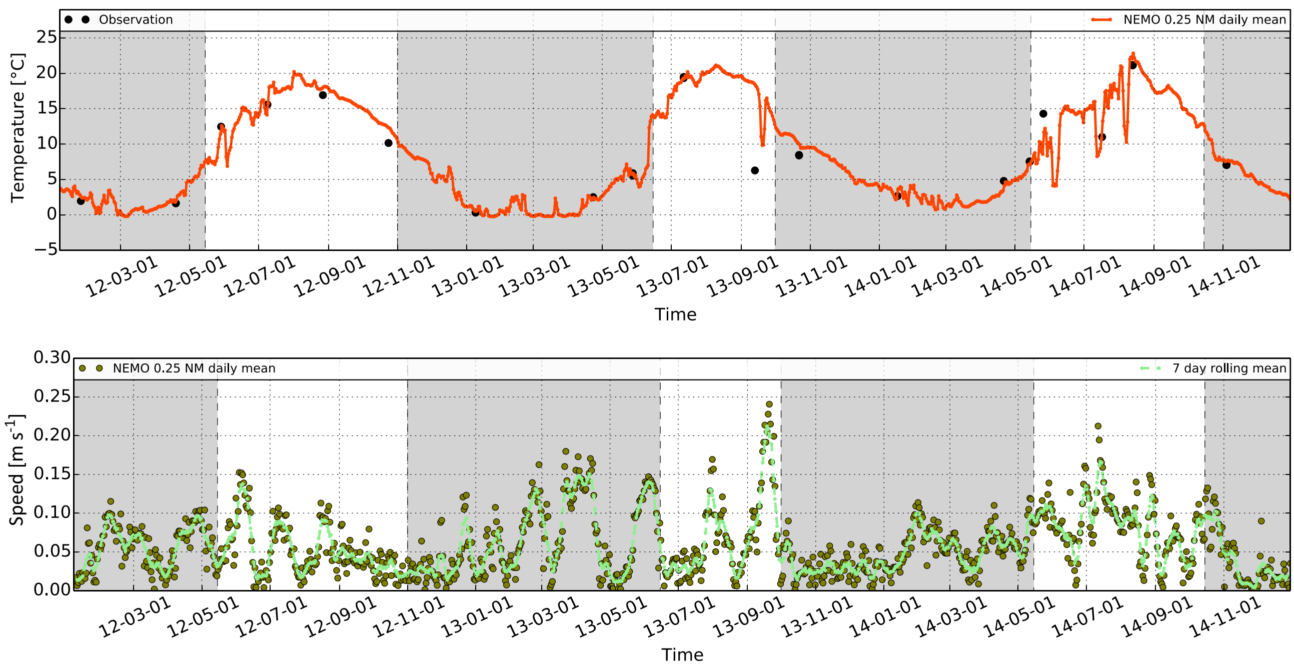

Figure 10 Top: a time series of water temperature at 5 m depth (station G). The red line is from the 0.25 NM NEMO setup and black dots are observations. Bottom: a time series of horizontal current speed at 10 m depth (station 15). Dark green dots are from the 0.25 NM setup and light green dashed line is the seven-day moving average. A shaded background indicates the approximate time intervals when there was no seasonal thermocline in the water column. The results cover 2012—2014, the date is given in the YY-MM-DD format. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

investigated the westward surface currents off the Estonian coast near the Pakri Peninsula, based on approximately four months of ADCP (Acoustic Doppler Current Profiler) measurements made in 2009 and HIROMB simulations. They found that upwelling-related jets were mainly responsible for the westward current in this area.

The ability of the model to simulate coastal upwelling events and their extent and magnitude greatly affects how the model simulates the alongshore coastal jets. For example, Lagemaa (2012) has shown that HIROMB model generally overestimates currents in the Estonian coast compared to ADCP measurements. He discussed that incorrectly described upwelling and downwelling jets may be one of the reasons for the overestimation. Vankevich et al. (2016) have shown that a fine resolution NEMO setup, which is similar to our setup, simulates the spatial patterns of an upwelling event well. However, further investigation of the link between the scale of the upwelling events and the magnitude of the coastal jet simulated by NEMO would be beneficial.

There are also measurements that indirectly allow us to gain some understanding about the circulation field. The profiles measured during the Gulf of Finland year 2014 gave a possibility to analyse the horizontal and vertical extent of the salinity stratification in the gulf. As our results showed, there was diversity in the ability of the models to simulate this. A situation in which less saline water is found in the southern coast of the gulf suggests that circulation has been more or less anti-cyclonic around that time. Although that situation might be rare, it has been observed several times in ferrybox measurements on the Helsinki—Tallinn route (Kikas and Lips, 2016).

Several questions remain. For example, the intensity and direction of the outflow at the northern side of the gulf differs between the models and should be investigated further. In our model runs the direction and intensity of the outflow at the Finnish coast is greatly influenced by the high current speed situations. To determine if this response is correctly estimated, the results need to be verified against current measurements. The FMI has made ADCP measurements in 2009—2014 on the Finnish coast but those datasets need further processing before they can be used for analyses. Also, more observations are needed from the Narva estuary and its vicinity. Further study is also required to quantify the impact of upwelling-related jets in the longer term. It is clear that our three-year runs do not as such represent the same thing as, say, a 30-year climatological run. If such high-resolution runs were feasible at this point in time, they would surely prove informative.

Further effort and observations are also required to understand if parameterisations in hydrodynamic models that are currently used allow the frequency and intensity of these events to be modelled correctly. For example, a more detailed investigation of the sensitivity of model results to river runoff variance might help us understand how to better capture the Neva river plume correctly after it enters the gulf. Another subject area worthy of attention is current-induced substance transport and its relation to the mean circulation field. From our results, it is clear that single high-energy events can strongly affect the mean circulation. But what this means for simulations of substances leaked into the sea is an open question still.

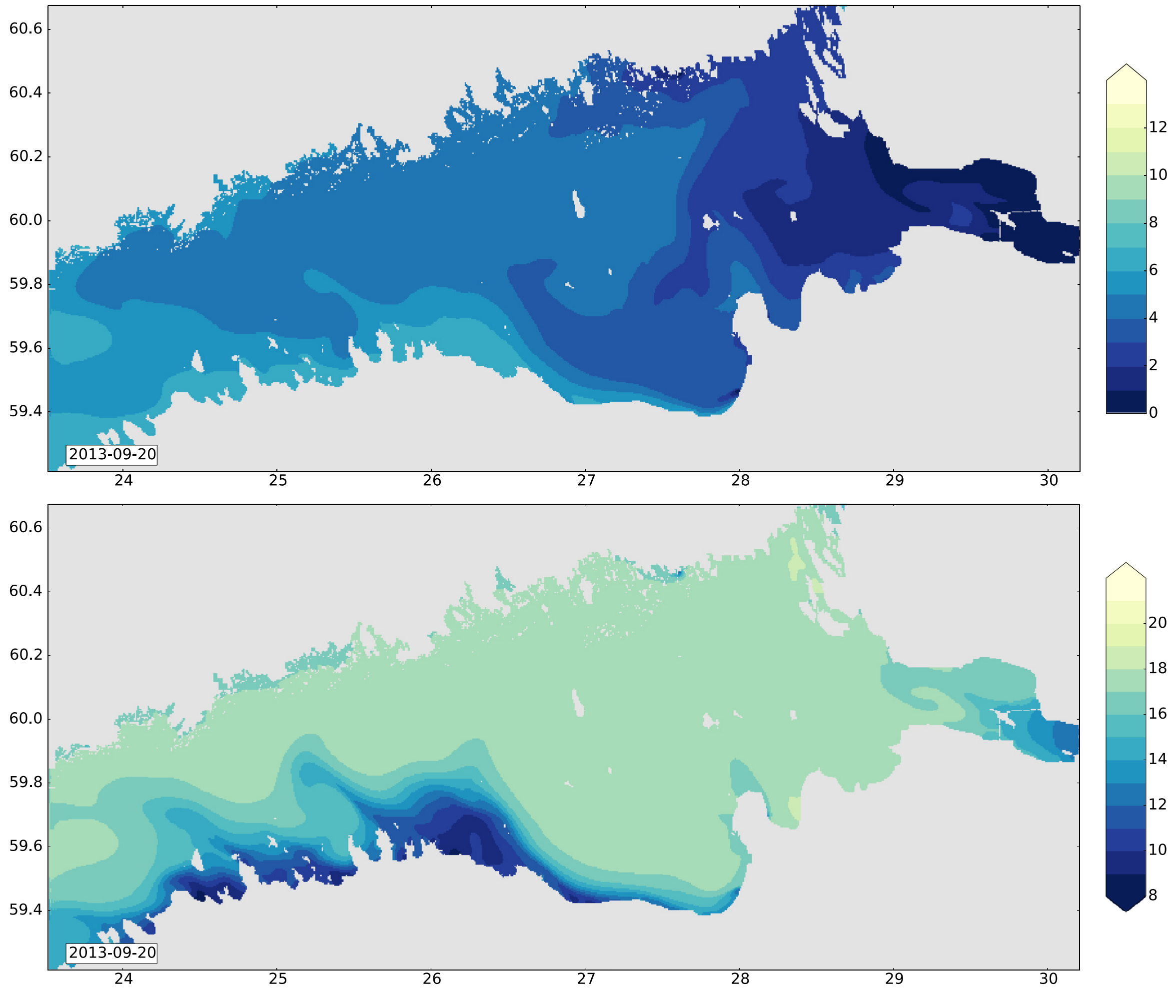

Figure 11 The surface salinity (top) and temperature (°C, bottom) fields from the 0.25 NM NEMO model run on the 20 September 2013 during an upwelling event on the southern coast of the Gulf of Finland.

5. Conclusions

In this study we analysed circulation patterns in the Gulf of Finland with two setups of the NEMO 3D hydrodynamic model.

We found that our model produces notable differences in the residual circulation patterns from year to year and from one model setup to another. Benchmarking the results to the HIROMB-based CMEMS product showed that the overall pattern was similar in both models. Comparison to salinity observations from the area revealed that vertical salinity structure was well represented. There were differences in the surface salinities, however, as is often the case for hydrodynamic models of this area. The models seem to need further development before they are able to capture the location of the surface salinity gradients in the Gulf of Finland.

We found that days with strong currents contribute significantly to the mean flow west of Narva Bay and off the Finnish coast, causing relatively strong coastal currents. We also found that most notable high-speed events were associated with upwelling.

Further, we found that the variations in runoff mainly affected the magnitude of near-surface currents. The directions of the currents seemed less sensitive to the changes. It is unlikely that runoff changes have a major effect on the year-to-year variations in the mean circulation patterns.

The experiments with the NEMO model have been beneficial to understanding the model behaviour in the area. The dynamics of the Gulf of Finland will continue to be a worthwhile topic of study as the gulf is vulnerable to accidents, and marine traffic is heavy both along and across the gulf. Also, further studies will advance the development of the high-resolution NEMO configurations for the gulf as an operational tool for everyday predictions and an aide when compiling environmental assessments of the possible changes in the gulf.

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