Referee #1

The authors thank the referee for the constructive comments, which helped us to improve the manuscript.

Referee: The discussion part at the moment is too shallow for scientific publication.
Authors: The discussion was revised and extended:

"We used state-of-the-art modelling framework NEMO initially developed for the open ocean to build an eddy resolving model of the GOF. To evaluate the model skill and performance two different solutions where obtained: commonly used 2 km grid and 0.5 km eddy resolving fine grid.

With the resolution of 0.5 km the model starts to resolve sub-mesoscale eddies. In the ocean, sub-mesoscales are scales of motion equal or less than the baroclinic Rossby radius of deformation. For the GoF the baroclinic Rossby radius is varying between 2-4 km and we need at least 4 points to resolve the eddy. According to Gent and McWilliams (1990), the eddies can act to re-stratify the UML of the ocean, causing the vertical transport through the thermocline.

In this study we were not able to identify the vertical motion in the model solution associated with small scale eddies. We can explain this fact by the effect of parameterization of convective flow which we cannot avoid due to hydrostatic assumption of the model. Hydrostatic hypothesis removes convective processes from the initial Navier-Stokes equations and so convective processes must be parameterized instead. As it presented in section 3.1 we had tested an interaction of all available in NEMO parameterisations of convective processes with turbulent mixing in the frame of the hydrostatic assumption. We found that GLS or even modified TKE closure schemes can describe convective processes in UML of GOF without additional convective adjustment procedures. But in all the cases convective parameterization sets locally very high values of vertical viscosity and diffusivity coefficients wherever the vertical instability appear and, in other words, "kills" any small scale vertical motion by smoothing the velocity field.

From the other hand effect of resolved lateral sub-mesoscale processes was investigated in section 4 Results. It was shown that sub-mesoscale motion affects the plume propagation caused by salty water intrusion to the GOF from the Baltic sea. Generally speaking this process had found to be dominated in formation of shape of termocline through the summer season, while the depth of UML was formed by an intensive mixing during spring upwelling. In both cases advective processes act as the main "driving force".

Presented model demonstrates a substantial improvement in the basin stratification compared to previous numerical studies. Traditional point of view is that the small scale processes such as turbulence provide the majority of mixing in vertical direction. Most commonly 1-D approach is used to set up vertical mixing by tuning a turbulent scheme. For the GOF as an enclosed basin with complex bathymetry and strong stratification mixed layer dynamics can be strongly affected by lateral advective processes. Adequate representation of lateral processes by the model let us decrease the role of background constants in turbulent mixing scheme (we set them to minimum possible values). This simplifies the traditional trade-off between the depth and sharpness of the thermocline. Setting the background values of vertical eddy viscosity and diffusivity to 10e-5 and 10e-7 correspondently let us keep the sharp form of the thermocline and halocline while UML depth corresponds to observations.

Since the time period of the runs was rather short (less than 1 year) and the model had not been used before it is obvious that choose of some parameters might have been somewhat improper for the use in this study. Through fine tuning of the model better results could be probably obtained. However, the focus in this study was to examine the differences arising from different horizontal resolutions, the fact that model parameters were similar in each case should be considered to be far more important than the quantitative agreement between observations and model results. Actually, it was shown that the model results for both resolutions are in a reasonable agreement with available observations. In some cases 0.5 model performs better and at the same time there are areas not covered by observations where we can note more substational difference between models. It is found that simulations which resolve submesoscale are characterized by the deeper UML with more complex structure in the regions of the GOF directly affected by the upwelling/downwelling.

The GOF is a highly dynamic region with lateral currencies causing the temperature contrasts and/or rapid temporal variations on the surface. From the satellite picture we can identify whether the model reproduce properly the frontal structure at the surface. For example, the temperature drop during an upwelling event and resulting temperature contrast at the surface reach 2.5 ºC. We assume it to be a considerably more substantial signal comparing to known uncertainties of satellite SST measurements (0.5 C [ftp://podaac.jpl.nasa.gov/allData/modis/docs/modis_sst.gd.html].) The usage of results of hydrodynamic modelling together with SST information can provide an extended analysis and deeper understanding of the upwelling process. Re-stratification of the UML caused by upwelling results in changes of the SST pattern that can be observed from satellites. From the comparison of modelled and observed from satellite SST we can identify whether the model reproduce the stratification itself and as a result properly reproduce the frontal structure at the surface.

Refinement of the model resolution below the level of 0.5 km would be of limited benefit in a hydrostatic model. For the purpose of deep investigation of submesoscale processes in GOF such as transport across the UML and on/offshore the nonhydrostatic formulation is needed. It lets us avoid “artificial smoothing” of the velocity field. Other possible improvements of the model performance, which we are planning for the next steps, will include sensitivity tests for the different boundary conditions with higher spatial resolution at the open boundary and surface and utilisation of rrecently available data with high spatial coverage from the expeditions during the Gulf of Finland Year 2014.”

Referee: According to the authors, the data coverage was not enough to outline the differences in behavior of the model results. Why not use longer simulations?

Authors: We need special data which have extensive coverage and high resolution in space and time, otherwise such simulations will be not very informative because we will not be able compare these results with observations. Only recently some relevant data has become available from expeditions during the Gulf of Finland Year 2014. We plan to use them in further studies.

Referee: In addition, one of the stated objectives of this paper was to give insight into the sub-mesoscale and basin-scale processes in the GoF. Although the upwelling is presented, there is not much about the sub-mesoscale processes. I would not consider parameterization of convective flows as sub-mesoscale processes, but instead some small-scale eddies and spots with large vorticity. The role of that kind of features to the vertical transport through the thermocline has not been discussed at all in this paper.
Authors: In the ocean, sub-mesoscales are scales of motion equal or less than the baroclinic Rossby radius of deformation. The horizontal resolution of the model equal to 0.5 km (for the GoF the baroclinic Rossby radius is approx. 2-4 km) enables models to resolve sub-mesoscale eddies. As well as satellite picture, a complex spatial pattern of fronts characterized by filaments can be noted from the model solution.

According to Gent and McWilliams (1990) eddies can act to re-stratify the UML ocean. The referee is absolutely right that generally small-scale eddies as a major result of the eddy-resolving model simulations can cause the vertical transport through the thermocline. At the same time we were not able to identify the vertical motion in the model solution associated with small scale eddies. We can explain this fact by the effect of parameterization of convective flow which we cannot avoid due to hydrostatic assumption of the model. Parameterization of convective flow sets locally definite values of vertical viscosity and diffusivity coefficients in UML and, in other words, “kills” any small scale motion by smoothing the velocity field. We had tested all the available schemes for convective processes parameterization (convective adjustments and advanced turbulent closure schemes) and shown that all of them act in the same way – cause UML deepening which was different for 2 km and 0.5 km solutions.

At the same time the indirect effect of resolved sub-mesoscale processes investigated in section 4 Results. It was shown that sub-mesoscale motion affects the plume propagation.

Direct study of UML re-stratification caused by sub-mesoscale eddies could be done in future by implementing of the non-hydrostatic model which let us to remove artificial diffusion from the model solution.

We agree with the referee that the objective “to provide an insight into the submesoscale and basin-scale processes in the GOF” may sound too ambitious and we will replace it by “to provide an insight into the lateral advection processes in GOF.” (P2399 L1).

Referee: 1. Please include a separate figure with model domain shown in respect to the overall Baltic Sea and transect at 25.5E. The location of the boundary 23E could also be shown on that figure.
Authors: Model domain shown in respect to the overall Baltic Sea has been included to the paper as Fig. 1.

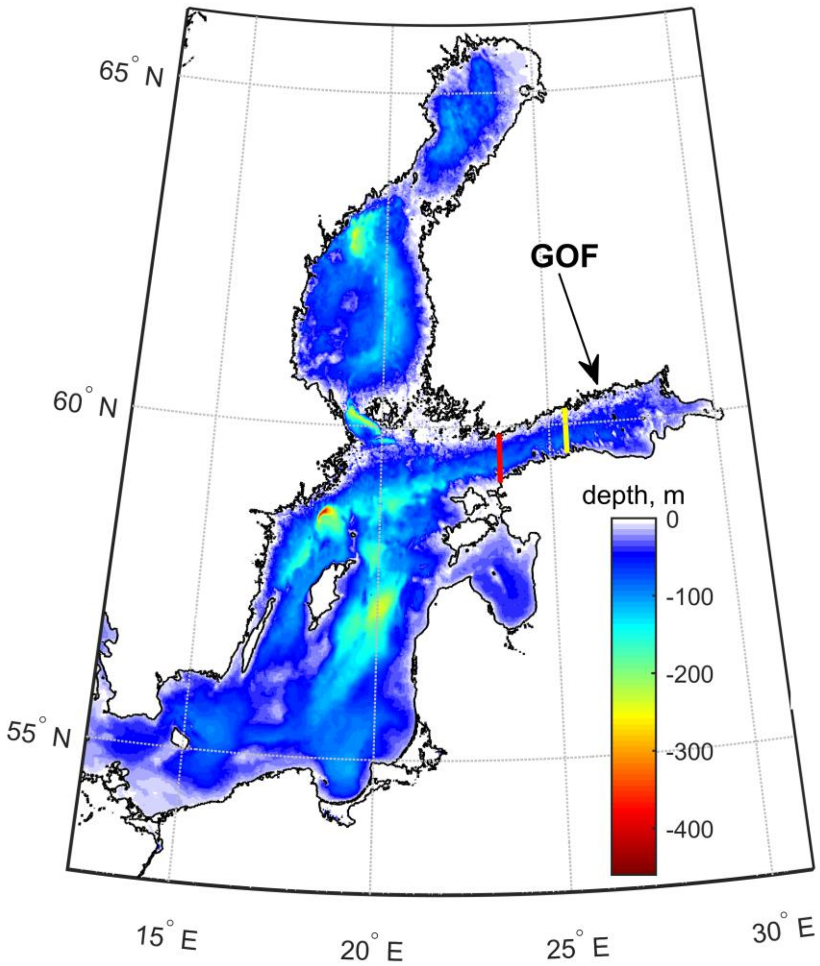


Figure 1. The bathymetry of the Baltic Sea.
Red line – open boundary of the model domain, yellow line – location of the meridional cross section for Fig. 2 (it is Fig. 1 in original version of the manuscript).

Referee: 2. Several NEMO setups are being developed around the Baltic Sea whereas some of them have already being published. What might be the main differences between these two setups (2 km and 0.5 km) and other published setups? For instance Hordoir et al 2013 and 2015.

Authors: There are NEMO setups for Baltic Sea recently published by Hordoir et al (2013; 2015). The GoF setup was developed in parallel to the Baltic Sea model development and aimed to introduce resolution able to resolve the sub-mesoscale processes in horizontal direction and insure accurate representation of the vertical structure by increasing the vertical resolution to 1 m. As it described in section 2.1, general model setup for the GoF shares most of the parameterization and schemes with Baltic Sea model excepting the turbulent closure scheme which is tuned to reproduce the GoF stratification as it described in section 3.1 “Sensitivity to vertical mixing parameterizations”.

The correspondent reference to the Baltic Sea NEMO setup will be added to section 2.1 “General model set-up” (P2400 L11).

Referee: 3. According to Section 2.1, the model setups are using boundary conditions from

HIROMB model at 23E. How reliable is the HIROMB model data at boundary?
Authors: According to the inter-comparison of several models for GoF (Myrberg et al., 2010), HIROMB was rated as the best model for the western part of the GoF. The operational status of the model gave us additional benefit.

We will insert the corresponding text in the paper (P2400 L24).

Referee: 4. Which versions of HIRLAM and HIROMB models (FMI or SMHI or . . .?) are being used and what is the temporal resolution of the atmospheric forcing and boundary conditions?
Authors: We used SMHI version of HIROMB with HIRLAM atmospheric fields included in output files as a part of a standard operational product of SMHI. Temporal resolution for the atmospheric forcing and boundary conditions is 1 hour.

We will add these remarks (P2400 L26).

Referee: 5. The authors show the impact of horizontal mixing schemes to the temperature. What is the impact of lateral parameterizations to the surface salinity and overall density gradient?
Authors: We did not explore the sensitivity of model solutions to the parameterization of the horizontal mixing. We just took horizontal mixing schemes available in NEMO and used them without tuning, so we cannot estimate their impact to the surface salinity and overall density gradient.

Referee: 6. In Section 3.1, the authors speculate on validating stratification through comparison of simulated SST with the measurements from satellite. I do not agree. Satellite measured temperature describe only the thin layer of the surface water (measured by centi- or millimeters) and can easily produce overestimated values compared to the in-situ observations, when there has been no wind and constant heating from Sun.
Authors: We would try to defend our point of view here. The GoF is a highly dynamic region with current velocities causing the temperature contrasts and/or rapid temporal variations on the surface. For example, the temperature drop during the upwelling event at the surface can reach 2.5 ºC. We assume it to be a considerably more substantial signal comparing to known uncertainties of satellite SST measurements (about 0.4 °C).

Referee: Obviously, the simulated temperatures can be lower as they describe the uppermost 1 m layer (the vertical resolution in this study) and we should not tune model quantitatively to match the satellite observations, but instead have qualitatively the same frontal structure with the satellite observations.
Authors: Moreover, the referee tells us about the possible overestimation of satellite SST but the model results presented at figure 2 overheats the surface. We did not try to tune the model against observed temperature values. Indeed, we analyzed the frontal structure exactly in the same way as the referee suggested.

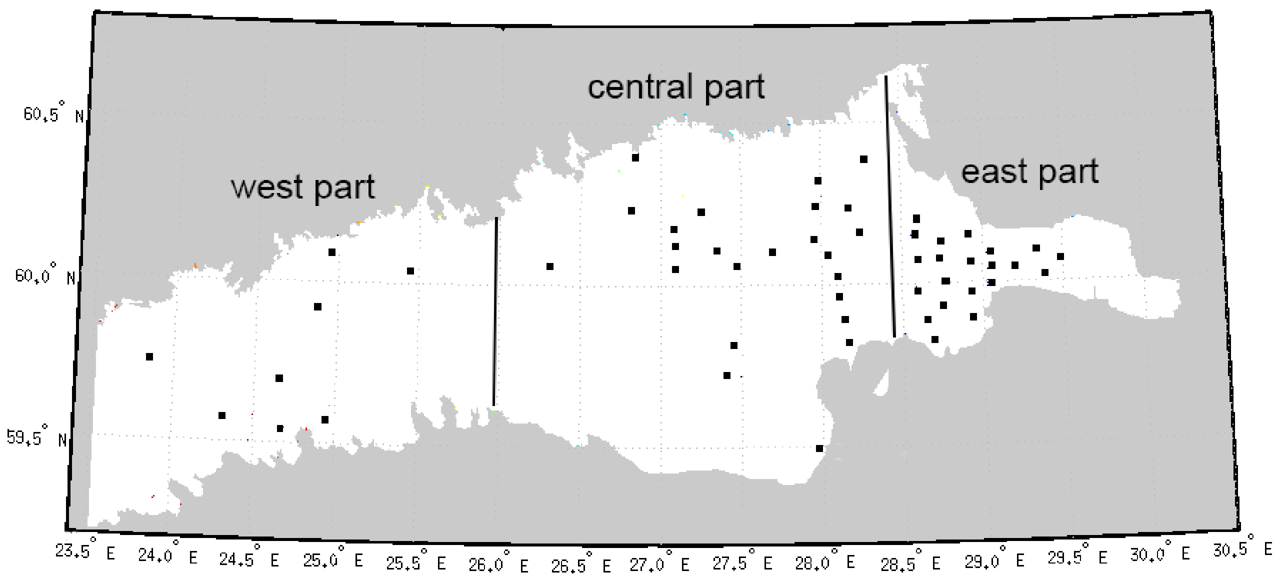
Referee: Nevertheless what is more important is that we cannot tell anything about the depth of the thermocline (stratification) based on the surface measurements and therefore

we cannot validate stratification from the surface observations.
Authors: We agree with the referee that we cannot tell anything about the depth of the thermocline (stratification) based on the surface measurements but we can identify whether the model reproduce the stratification itself and as a result properly reproduce the upwelling frontal structure at the surface.

We will insert the clarification in the paper P2406 L19 after the sentence “At the same time, the SST fields can be used as an indicator of vertical mixing processes”:

SST fields do not give direct information about stratification and a depth of a thermocline but the comparison of the model frontal structure at the sea surface and MODIS data during an upwelling event (lifting water from under the UML) could indicate how well the model reproduces stratification.

Referee: 7. Section 3.2, please show the location of east, west and central part profiles on separate figure.



Referee: Section 5: The role of sub-mesoscale flows has not been sufficiently studied. There is nothing about the eddy induced transports between the coastal and open parts of the Gulf of Finland. What is the impact of increasing resolution to the overall off-shore water exchange?
Authors: These effects have not been studied in this paper for the following reasons: 1) the measurement data, which we had at the time of our study, are mainly for the open part of the Gulf that does not allow us to do a reliable verification of the model for the coastal zone, 2) in the present study, we focused on parameterizations of vertical instead of horizontal exchange. The new dataset of the Gulf of Finland Year 2014 appeared in the end of last year will allow us to study the exchange processes between the coastal zone and the open sea, it is planned to make in the near future.

Referee: The authors claim to have better results compared to previous numerical studies. Which numerical studies are being referred to? Test runs by authors or some published results by other groups? If latter, please give some references.

Authors: The references was given in introduction P2397 L23 (Myrberg et al., 2010) and P2397 L25 (Tuomi et al., 2013). We will add Hordoir et al (2013 and 2015) too.

Referee: Section 4: According to Fig. 5, the turbocline depth is clearly overestimated in the model experiments – the upper mixed layer in the observations is much shallower compared to the model experiments.
Authors: We cannot agree with the conclusion of the referee that "the turbocline depth is clearly overestimated" according to Fig. 5. Referee says that the upper mixed layer in the observations is much shallower compared to the model experiments.

Figure 5 (I, II, III) shows the vertical profiles of temperature at locations near the Finish coast. At the panel (I) UML depth for the 2 km-resolution model (dashed black line) is shallower than observed UML depth (solid black line) by 13 m. At the same time, observations and 0.5 km-resolution model (grey line) temperature are almost collocated, and UML depth reaches 40 m. At the panel (II) modeled UML depth is overestimated, but the misfit reaches 7 m for 2 km-resolution model and only 3 m – for 0.5 km-resolution model.

We cannot compare UML depth from the results presented at panel III since none of the models were able to reproduce lateral intrusions observed. The low model performance at this point can be explained by the proximity of the frontal zone between coastal and deep water masses due to the upwelling. We assume that small error in predicted location of the front can lead to serious misfits in vertical profile. Note also that the point (III) is located in a zone of rapid turbocline depth variations (see Fig. 5a and Fig. 5b). This fact confirms a complex front structure which is formed by the set of randomly spaced small-scale features. The deterministic model can only predict their appearance but not the exact location.

This clarification will be placed in the paper on P2409 L5, instead of «However, the UML depth for the 2 km model are not deep enough, barely reaching 25m depth everywhere whereas observations in western part show it values reaching a maximum of about 40m depth.»

Referee: «Is it possible that the turbocline depth is also overestimated spatially in model experiments with higher resolution?»
Authors: We cannot say anything about this assumption of the reviewer, as the available data are not enough to build a reliable picture of the changes in the turbocline depth horizontally during upwelling. We can only declare that solution on 0.5 km grid shows a deeper and more complex turbocline pattern in contrast to the solution on 2 km grid. See the paper P 2408 L25 – P2409 L4:
"It can be explained by the fact that small-scale frontal structures induced by strong horizontal gradients and captured by the fine model lead to convective instabilities (Boccaletti et al., 2007) acting to locally re-stratify UML. The model with 2 km resolution cannot resolve sub-mesoscale frontal features and high values (compared to fine resolution) of lateral diffusion coefficients act to smooth the front, in other words, decreasing potential energy of the front."

References

Boccaletti, G., Ferrari, R., and Fox-Kemper, B.: Mixed layer instabilities and restratification, J. Phys. Oceanogr., 37, 2228–2250, 2007.
Hordoir, R., Axell, L., Loptien, U., Dietze H., and Kuznetsov, I.: Influence of sea level rise on the dynamics of salt inflows in the Baltic Sea, J. Geophys. Res. Oceans, 120, 6653–6668, 2015.
Hordoir, R., Dieterich, C., Basu, C., Dietze, H. and Meier. H.E.M.: Freshwater outflow of the Baltic Sea and transport in the Norwegian current: A statistical correlation analysis based on a numerical experiment, Cont. Shelf Res., 64 ,1–9, 2013.
Myrberg, K., Ryabchenko, V., Isaev, A., Vankevich, R., Andrejev, O., Bendtsen, J., Erichsen, A., Funkquist, L., Inkala, A., Neelov, I., Rasmus, K., Medina, M. R., Raudsepp, U., Passenko, J., Soderkvist, J., Sokolov, A., Kuosa, H., Anderson, T. R., Lehmann, A., and Skogen, M. D.: Validation of three-dimensional hydrodynamic models of the Gulf of Finland, Boreal Environ. Res., 15, 453–479, 2010.