Dear Reviewer#1,

Thank you very much for your comprehensive review of our manuscript. Please find below our replies to your comments. Note that below your comments are written in blue while our replies are black.

A review of "Very high-resolution modelling of submesoscale turbulent patterns and processes in the Baltic Sea" (authors Reiner Onken, Burkard Baschek, and Ingrid M. Angel-Benavides)

Overall rating

This is an interesting study aimed to simulate submesoscale patterns in the Baltic Sea and comprehensively discuss different aspects of the phenomenon. The paper can be eventually published after moderate revision.

There are several major remarks and a handful of minor ones and typos.

Major remarks:

1 In R100 the atmospheric forcing was turned off "to analyse the kinematic and dynamical properties of STPPs without disturbing effects". However, one would expect the that the STPPs generated without and with atmospheric forcing to be substantially different,

They are indeed substantially different, see below

while the goal of the study is to model STPPs in the Baltic Sea, that is, including all "disturbing effects" existing in reality.

You are right, the goal of this study is *to understand and and interprete the observed features by means of of high-resolution modeling* (see manuscript P1 L21). However, in order to *understand* the features, all "disturbing effects" have to be ignored for the time being. This is only possible in numerical models, where – in the present case – the atmospheric forcing was turned off in R100. Of course, this is a simplification, but simplifications are the strength of any model (not just numerical models) to understand complicated processes. Moreover, the impact of atmospheric forcing on the evolution of STPPs is in the works in a follow-up study.

<u>Proposed action</u>

We will add a corresponding remark in the Introduction and at the beginning of Section 4.

In view of the above, I'm not sure that e.g. the main features of the evolution of submesocsale eddy C3 shown in Fig. 10 will be reproduced by R100 with turned on atmospheric forcing. Could the authors present analogue of Fig. 10 with turned on atmospheric forcing?

Fortunately, the results of an R100 run with full atmospheric forcing are still available. We will first demonstrate the impact of atmospheric forcing by the corresponding equivalent of Fig. 6, labelled as Fig. 6EQUIV. A comparison reveals that the atmospheric forcing has a dramatic impact on all near-surface variables. Primarily, the patterns of relative vorticity and divergence are blurred and do not allow any meaningful interpretation.

We plotted as well the equivalent of Fig. 10 with atmospheric forcing, but the result was as expected: there is no submesoscale eddy C3 at all, at least not in the corresponding location. We will save ourselves the plots.

<u>Proposed action</u>

In order to demonstrate the impact of atmospheric forcing, it is suggested to add Fig. 6EQUIV in the revised manuscript.

2 The prognostic run of R500 started from initial and boundary conditions generated by not eddy-resolving HBM on June 1, 2016, and already in 15 days, on 15 June, the R100 was initialized from R500. The 15 day period does not seem long enough to provide a well-developed (populated with eddies) STPPs from not eddy-resolving initial fields.

We do not agree. According to Fig. 3 and P7 L22–25, the spin-up time of R500_NF was estimated to 12 days. And the right column of Fig. 2 confirms that already on 10 June the domain is populated with mesoscale meanders and eddies. The mesoscale activity then increases until 20 June but it remains more or less constant thereafter. Hence, 15 June is well suited to initialize R100. Please note that R100 was initialized from R500 (not from R500_NF) which did not provide a realistic estimate for the spin-up period.

Very high-resolution modelling previously performed in the Baltic Sea (more specifically, in the Gulf of Finland) by Väli et al. (2017) showed that some cyclonic eddies that can be referred as submesoscale creatures in view of the relative vorticity well exceeding f, can live more for than a month. The only comparison of the simulated STPPs with satellite imagery for the modelled period showed that the observed cyclonic spiral, the most prominent feature of the Sentiel-3 image (Fig. 4, bottom) had rather sluggish counterpart in R500

Why do you say that the spiral is “sluggish” in R500? In Fig. 4, we compared tracer patterns at the surface which do not provide any information about the magnitude of currents.

and no counterpart in R100 (cf. Figs. 4 and 5).

Unfortunately, on 23 June in Fig. 5 are shown only salinity (left column) and temperature (middle) while velocity vectors were omitted. In Fig. 5EQUIV are plotted the same variables for a zoomed area but with vectors of the near-surface velocity superimposed. Those vectors indicate clearly the centre of the cyclone at about the same position as in Fig. 4a. Hence, there *is* a counterpart in R100.

Proposed action
Horizontal velocity vectors might be superimposed to salinity and temperature on 23 June in Fig. 5, however, that might make the figure unreadable. Instead, this issue will be discussed in the text.

If the R500 started earlier, e.g. on May 1, the observed spiral would be probably reproduced more realistically/reliably. Since the submesoscale eddies can travel for a long distance (Väli et al., 2017) it seems preferable also to take the nested domain for R500 larger, e.g. including the whole Arkona and Bornholm basins.

In our opinion, the issue with the spiral is solved (see above) – isn‘t it? Please note that other observed features of Fig. 4b (C2 and the fronts in the NW corner) are reasonably well reproduced in Fig. 4a. We doubt that the suggested earlier start of R500 would lead to a significant improve of the model results.
On the other hand, a start of R500 on 1 May would mean to redo the entire manuscript, including all the graphics. Moreover, no atmospheric forcing is available for May; we would have to purchase it from DWD.

Proposed action
none

3 The authors did not seem to be able to find any convincing link between the results of the field experiment “Expedition Clockwork Ocean” and the submesoscale modelling they carried out. The related pieces of text and drawing (Fig. 16) could be dropped, which would make this long

article easier to read.

Most of the work for this article was done in 2017/2018. A that time, tangible observational results from “Expedition Clockwork Ocean“ were not yet available.

Proposed action
We will drop Fig. 16 and the related pieces of text.

4 It seems that the authors are not familiar with recent publications on STPPs modeling in the Baltic Sea (Väli et al., 2017, 2018). Meanwhile, based on a 0.125 nautical mile grid model of the Gulf of Finland, Baltic Sea, Väli et al. (2017; 2018) found submesoscale patterns of relative vorticity, absolute horizontal gradient of potential density and many other tracers similar to presented in this paper, so it would be nice to compare one with the other.
Citation:
Väli, G., V. Zhurbas, U. Lips, J. Laanemets, 2017. Submesoscale structures related to upwelling events in the Gulf of Finland, Baltic Sea (numerical experiments), J. Mar. Syst., 171(SI), 31–42.
Vali G., Zhurbas V.M., Laanemets J., Lips U., 2018. Clustering of floating particles due to submesoscale dynamics: a simulation study for the Gulf of Finland. Fundamentalnaya i prikladnaya gidrofizika, 11(2), 21-35, DOI: 10.7868/S2073667318020028 (open access at http://hydrophysics.info)

Thank you very much for your tip! We have downloaded the above articles.

Proposed action
The desired comparison will be done.

Minor remarks
P7L5 “a high-salinity eddy in the Arkona Basin, and mushroom-like patterns east and southeast of Bornholm on 1 and 10 June, respectively” There is no any high-salinity eddy in the Arkona Basin on 1 June when both HBM and R500/R500NF display the same not eddy-resolving pattern (see Fig. 2).

You are right!

Proposed action
The corresponding sentences will be rephrased.

P7L26 “An analysis of the prognostic fields of R500_NF yielded an unexpected finding: the tracer fields exhibit much more spatial variability in comparison to the corresponding fields of R500 (see the right panel in Fig. 2)” To my mind, it is a very expected finding: results of remote sensing (Kubryakov and Stanichny, 2015), modelling (Zhurbas et al., 2008; Väli et al., 2017) , and even laboratory experiments (Zatsepin et al., 2005) showed that mesoscale/submesoscale structures begin to grow rapidly when the wind subsides.

You are right!

Proposed action
The corresponding sentences will be rephrased; missing references will be included.

Citation:
Kubryakov A.A., Stanichny S.V., 2015. Seasonal and interannual variability of the Black Sea eddies and its dependence on characteristics of the large-scale circulation, Deep-Sea Research I,

97, 80–91.

No open access; ordered via library

Zatsepin AG, Denisov ES, Emelyanov SV et al., 2005. Effect of bottom slope and wind on the near-shore current in a rotating stratified fluid: laboratory modeling for the Black Sea, Oceanology 45(Suppl 1): S13–S26.

Not available online. Full text requested via Research Gate

Zhurbas, V., J. Laanemets, and E. Vahtera, 2008. Modeling of the mesoscale structure of coupled upwelling/downwelling events and the related input of nutrients to the upper mixed layer in the Gulf of Finland, Baltic Sea, J. Geophys. Res. - Oceans, 113, C05004.

P8L20. It seems worth to compare the tracer patterns of $|\nabla\rho|$ and ζ with that of Väli et al. (2018) simulated in the Gulf of Finland at 0.125 nautical mile grid.

Proposed action
To be done

P9L23 It seems worth to compare the relative vorticity statistics with that of Väli et al. (2017).

Proposed action
To be done

P10L28. "The topography of potential density surfaces in the anticyclone shows that the patches are accompanied by large excursions of isopycnals, indicating intense internal wave activity." ROMS is a hydrostatic model which does not describe internal waves except for near-inertial waves that propagate almost vertically and therefore are hardly able to produce large vertical excursions of isopycnals at short horizontal scales of O(1km). Please comment the issue.

It is known to the authors that internal waves are insuffienctly reproduced in hydrostatic models. Therefore, we just started to investigate this issue in greater detail in our group with CROCO, a non-hydrostatic version of ROMS_AGRIF.

Proposed action
The corresponding passages in the manuscript will be rephrased.

P17L19-22. Ro~O(1) and Ri~O(1) are mentioned as the criteria of submesoscale fronts, but in Fig. 14 the plot of Ri is missing (in contrast to the Ro plot).

You are right!

Proposed action
We will add a plot of the Richardson number.

P17L31. Fig. 15 is really a spectacular satellite image of a phytoplankton bloom but in the context of this article, it seems far-fetched because it was received at another time, in another place with other bottom topography, shoreline, stratification, currents, atmospheric forcing... The fact that the Rossby radius in this place is of the same order than that of the Bornholm and Arkona basins does not seem to be a serious legitimation. The authors did not model circulation off the Estonian coast and therefore have no information on whether Ro is large enough to attribute the spirals in Fig. 15 to submesoscale structures. I would suggest to drop Fig. 15 and the related piece of text.

Proposed action
Fig. 15 will be dropped

P18L30. “Moreover, salinity was chosen for comparison because it is the primary component controlling the stratification in the Baltic Sea.” There is some confusion here... That is true that in the whole the Baltic Sea stratification is controlled by salinity due to the presence of a lower layer filled with high salinity water of the North Sea origin. But in the upper layer of 60-m depth (i.e. above the permanent halocline), density stratification is primarily controlled by temperature, especially in Summer when the seasonal thermocline is developed. The 15-m depth salinity in Fig. 17 (right) displays ~0.1 psu excess in the C3 centre which contributes to density stratification as much as the temperature deficit of ~0.3°C, but one would expect that the actual temperature deficit is much larger, e.g. >1°C, and therefore the salinity is a secondary component controlling the stratification in C3 (i.e. the salinity in C3 behaves like a passive tracer). To clarify the issue, please add the 15-m depth temperature to Fig. 17.

Proposed action
The 15-m temperature was added (see Fig. 17EQUIV). The figure caption and the corresponding text passages will be modified accordingly.

Table 2. Were A^T_H , A^M_H [m^4s^{-1}], and A^M_H [m^2s^{-1}] really taken constants? Why the Smagorinsky parameterization was not applied?

We do not really understand your question. A^T_H , A^M_H, and A^M_H are the *coefficients* of the bi-harmonic and mono-harmonic formulation for horizontal diffusion and horizontal eddy viscosity, where the bi-harmonic formulation is – to our knowledge – the so-called Smagorinsky parameterization.
Both formulations were tested with various coefficients, and those listed in Table 2 were considered to be the best job in the sense “minimum diffusion but maximum damping of numerical (2-deltax) noise“.
Are we wrong?

Technical corrections/typos

P6L4. cyle→cycle OK
P11L3. Class number is missing. OK
P12L10. Two “are” in a row OK
P13L21. Two “is” in a row OK
P18L23. “spiraliform” . Google Translator doesn’t know such a word.
But dict.leo.org (German ← → Englisch) does!
Table 1. The number of vertical layers is 10. This is a typo, isn't it?
No – there are K=10 layers; what seems to be the trouble?
Figs. 9, 10, 11, and 13. Scale for velocity vectors is missing.
The plots were done with the MATLAB function *m_quiver.m*
We will try to add a scale.

We hope that our proposed actions satisfy your criticism!

Best regards,
Reiner Onken and co-authors

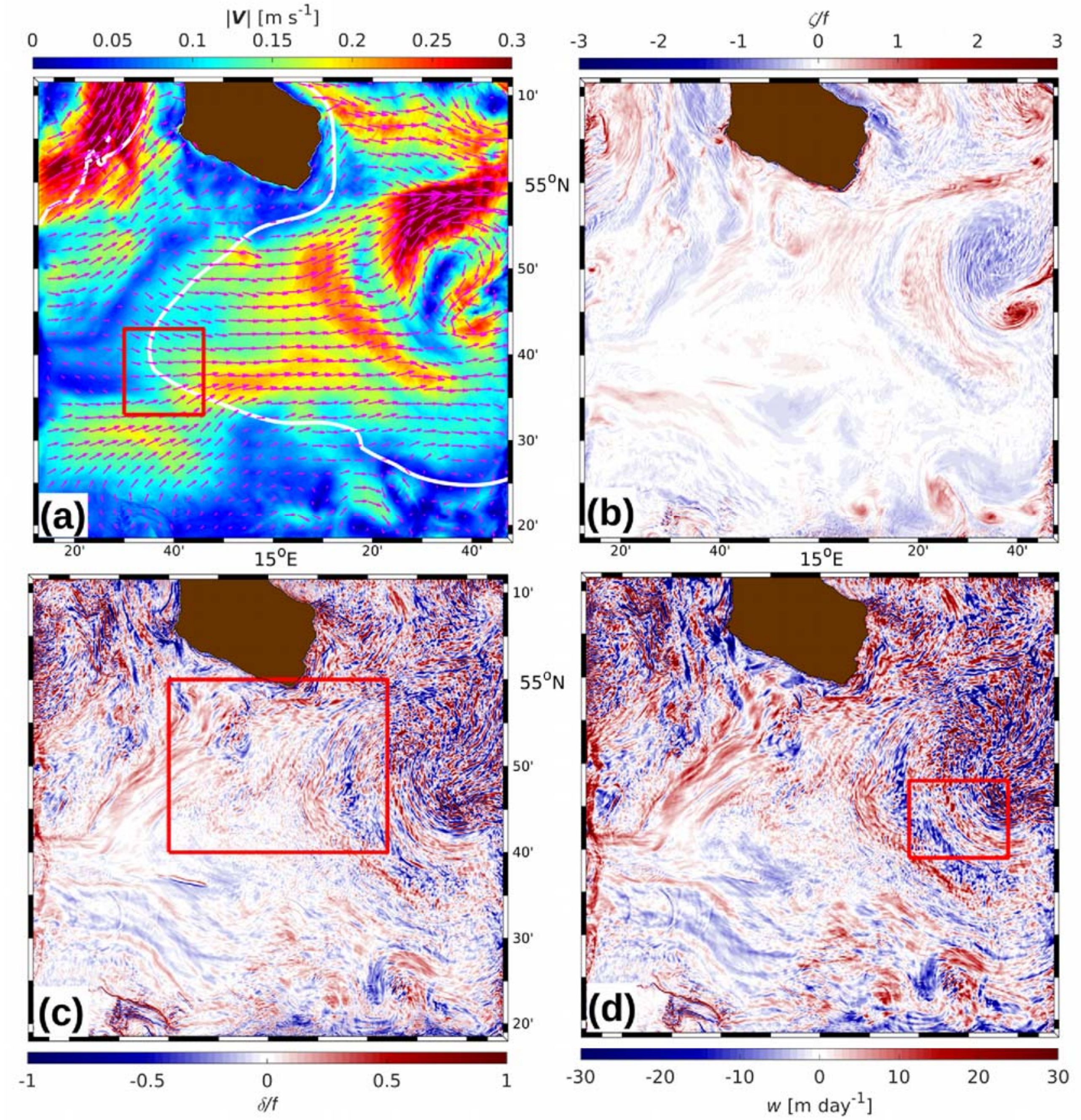

Figure 6EQUIV: Equivalent of Fig. 6 but with full atmospheric forcing.

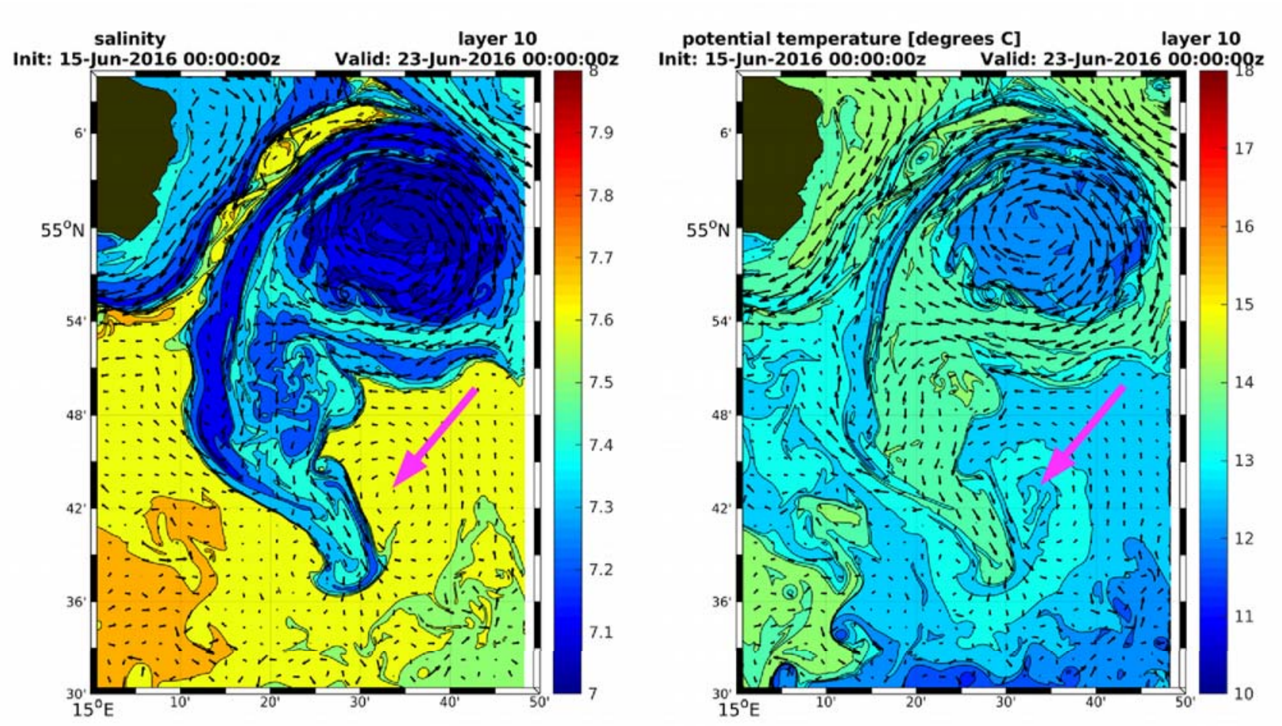

Fig. 5EQUIV: Top-layer salinity, temperature and horizontal velocity on 23 June in a subarea of R100. The magenta arrow points to the centre of the cyclonic spiral.

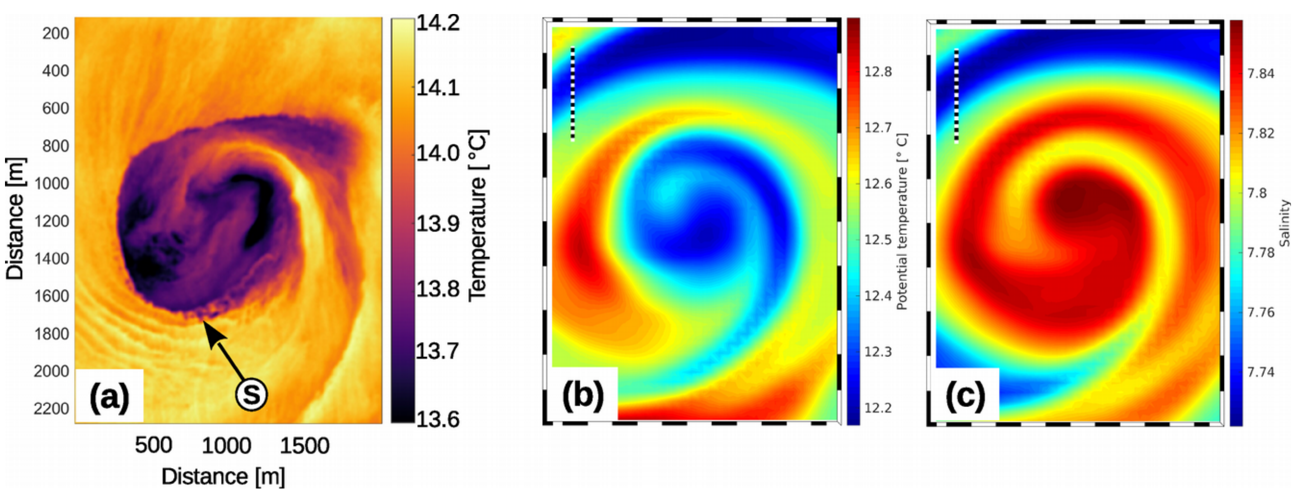

Fig. 17EQUIV: