Manuscript Number: **gmd-2018-112**

Article Title: **FESOM-C v.2: coastal dynamics on hybrid unstructured meshes**.

GMD

Dear Editor,

Thank you for the opportunity to answer to the issues raised by the reviewer and improve the manuscript.

In the following we will answer the comments in detail:

Referee #2: Modelling coastal dynamics on unstructured meshes poses - although a number of models and discretization already exists – still a number of challenges concerning stability, efficiency and performance compared to observations. The paper addresses these questions and describes a possible solution by using the proposed hybrid finite-volume cell vertex discretization. I appreciate the detailed level of description and recommend publishing it with some revisions. The overall presentation is well structured and clear, although some more explanations in the text would help the reader to follow the arguments and descriptions. The article tries to cover the mathematical description, testing and validation/real cases, which is a lot for just one article. Each part could easily be extended to be more valuable. Especially the conclusion that the results qualitatively and quantitatively agree with observation is not thoroughly supported by the presentation in the article (most of the German water level stations are missing like e.g. Cuxhaven).

Answer: We are very grateful to the reviewer for his efforts in reading carefully our manuscript and giving us very useful and concrete comments which hopefully will help us to improve largely the paper.

Referee: Page 2, Line 31: Describing the approximations as "traditional" is bit too vague. I recommend to make a reference or name it properly.

Answer: "Traditional" belongs to the standard text-book terminology. This model is based on the hydrostatic primitive equations in which the vertical momentum equation is reduced to a statement of hydrostatic balance and the "traditional approximation" is made in which the Coriolis force is treated approximately. The traditional approximation corresponds to taking $\Omega_y = 0$ *whereby the Coriolis force becomes* $f\boldsymbol{k}$, *with* $f = 2\Omega sin\varphi$, *with* $\boldsymbol{k}$ *the unit vertical vector. It is valid when the aspect ratio between vertical and horizontal scales is small* ($H/L \ll 1$) *(Marshall J., Hill C., Perelman L., and Adcroft A., (1997), Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling, J. of Geoph. Res., v102, C3, 5733-5752). We add this reference to the article.*

Referee: Page 4, Line 10: Is there any reference or reasoning, why choosing the boundary conditions that way?

Answer: The upper boundary conditions contained an error. The total depth does not enter the second condition. It occurs only when moving to the sigma coordinate. We fixed this error.

The choice of these boundary conditions (BC) in the model is because they are quite well known and have a simple physical meaning. For the BC on the surface, the square of turbulent energy is proportional to the square of the dynamic velocity u_*. The relation between the viscosity coefficient and the dynamic velocity is established by γ_ζ. Its value was estimated, for example, in the work of Kagan B.A et al., 1979 (Parameterization of the active layer in the model of large-scale interaction of the ocean and the atmosphere. -Meteorology and Hydrology, No. 12, pp.67-75). At the bottom, the link between the turbulent energy and the square of the velocity modulus is regulated by B_1 (see for example: Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys., 20, 851–875.)

Referee: Page 4, Line 14-15: This is quite short. To be complete I would expect a more detailed description about how to solve the kinetic energy equation in general or leave it completely for an appendix.

Answer: Some description and a reference to a detailed solution of this equation has been added to the text.

Referee: Page 6, Line 6: What is taken as tau_0 and tau_gamma in the experiments?

Answer: τ_0 and τ_Γ were 5.0 and 0.5 [day] respectively and were chosen experimentally.

Referee: Page 8, Line 7: Why division by H in definition of delta_i^k? Or what is Delta_i exactly?

Answer: Thanks, it was our typo error. Corrected to:

$\Delta_i^k = \Delta_i H^k$, Δ_i is vertical grid spacing.

Referee: Page 8, Line 16: I don't understand the sentence "It also improves … elevation gradient".

Answer: Filtered velocity allows us to estimate the elevation gradient in the middle of the baroclinic step (k+1 in our notation) with high accuracy. Estimation of the elevation gradient is necessary for us to correct the thickness of the layers in the transport equations.

Referee: Page 8, Line 19: If flux form is used in the temperature equation, it should be introduced before.

Answer: The equation 4 is corrected and has the flux form.

Referee: It is not clear to me, why in the eq. in l. 23 the Delta only has the index i and not k.

Answer: Thanks, it is our typo. Now in this equation:

$(\Delta_i \mathbf{u}_F)^{k+1} + (\Delta_i w_F)^{k+1} \ldots$

Referee: Page 9, Line27: What is meant by "full layers"? At cell surface or bottom?

Answer: At cell surface and bottom. In our notation, this is the index "i".

Referee: Page 10, Line 14-17: Maybe the reformulation and the matrices could be given in more details in an appendix?

Answer: In our opinion, a more detailed description of the least squares method is not required. This method is well known and quite widely used.

Referee: Page 10, Line 20: Define scalar control volumes.

Answer: The definition is present in Fig. 1. A link to this figure has been added to the text.

Referee: Page 11: As there are several possibilities: How do you compute layer thickness for the tracer advection?

Answer: The vertical grid spacing is recalculated on each baroclinic time step for the vertices, where ζ is defined. It is interpolated from vertices to cells and to edges with the weight function w_{cv}.

Referee: Page 12, Line 4: What is meant by "symmetrized following the standard practice" exactly? Give at least a reference.

Answer: "Symmetrized" means that the estimate on edge "e" is mean of horizontal velocity gradients computed on elements "c" and "n" (notation from article) with the common edge "e": $(\nabla u)_e = ((\nabla u)_c + (\nabla u)_c)/2$. We added this to text. (Symmetrization is needed to get non-positive kinetic energy dissipation on discrete level.)

Referee: Page 12, Line 10: This is a trivial equation. Maybe there is something missing?

Answer: The equation is indeed trivial, but not the consequences. If viscous stresses are computed using symmetric velocity gradients on edge e (see the answer above), information from the nearest neighbors will be lost in the stress divergence. Any irregularity in velocity on the nearest cells will not be penalized. The velocity gradient in the direction $\mathbf{r}$ *is the difference of velocities across the edge e divided by* $|\mathbf{r}|$. *Combining the estimate in direction* $\mathbf{r}$ *with the symmetric estimate in the direction* $\mathbf{n}$-$\mathbf{r}$ *one re-introduces coupling between the nearest velocities. This fact is well known in finite-volume literature.*

Referee: Page 12, Line 14: Do you call it the "harmonic discretization" or is there any reference to former work, where it is properly defined or derived?

Answer: Harmonic (also can be called Laplacian) viscosity discretization is the common name.

Referee: Page 12, Line 18-20: The equivalence and the trivial adjustments are not obvious for me. Could you explain a bit more.

Answer:

$$F_c = -\left(\frac{1}{\tau_f}\right)\sum_{n(c)}(\mathbf{u}_{\boldsymbol{n}} - \mathbf{u}_c)$$

On ideal (rectangles or equilateral triangles) meshes the expression above provides the discretization of the Laplacian operator. Indeed, by doing the Taylor series expansion around the center of c it is easy to see that $F_c \approx \left({a^2}/{4}\right)(\partial_{xx} + \partial_{yy})$ *on triangles and 4 times that on quads, so that* τ_f *of about 1 day corresponds to viscosity of about* $10^3\ {m^2}/{s}$ *on a mesh with a side a = 10 km.*

A reference to a more detailed description of this procedure is given.

Referee: Page 13, Line 8-10: It is a pity that these simpler experiments and especially the learned lessons are not published. It would advance the understanding of the problematic issues other developers may also be struggling with.

Answer: You are absolutely right, many test experiments could be useful in many ways. Some of the interesting test experiments have been published previously (Danilov and Androsov, 2015). Many experiments were included in our reports and presentations. In this manuscript we present one of the important experiments related to the open boundary problem.

Referee: Page 13ff: What values for tau_2d and tau_3d are used in the experiments (for real cases and the numerical performance test)?

Answer: In the Sylt-Rømø experiment we used the baroclinic (internal) time step of 7 s (τ_{3D})*, the barotropic* (τ_{2D}) *one was 10 times smaller. For the South East North Sea experiment we took* $\tau_{3D} = 70$ *s and* $\tau_{2D} = 7$ *s.*

Referee: Page 13ff: As several discretization schemes are presented in Section 2, 3 and 4, which ones are actually used in the experiments? Otherwise present only the ones used.

*Answer: In this version of the FESOM-C model we used only one **time discretization** scheme – splitting on barotropic and baroclinic mode. For **spatial discretization** we used finite-volume method. In the model code we have different implementations for momentum advection and tracer equations. In the momentum advection we used the second order upwind scheme. For tracer equation in the South East North Sea experiment we used the Miura advection scheme. For numerical stability in both experiments we used filtering procedure.*

Referee: Page 13: What open boundary forcing is used in the Sylt-Romo experiment?

Answer: The text on page 13 (Lines 28-29) describes the boundary conditions used in the model. We added the link to the source of this data:

The experiment is forced by prescribing elevation due to M_2 *tidal wave at the open boundary (western and northern boundaries of the domain) provided by H. Burchard.*

Referee: Page 14: What time scale tau_f is used in the experiments? How much additional dissipation is added in comparison to other terms in momentum equations?

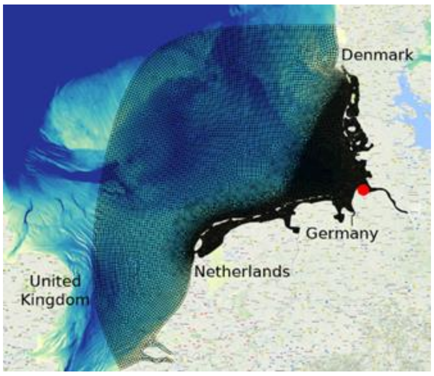
Answer: In the both experiments we used filtering with time scale parameter equal 1 day. The contribution of this term for the quad meshes is really insignificant. On the triangular meshes, its contribution is somewhat higher (as shown by the Sylt-Rømø experiment). A more detailed answer to this question can be found in the article Danilov and Androsov, 2015.

Referee: Page 14, Line 19: Fig 5 and Fig 6: A plot of the observations at low wind conditions and of the model results would help to see the "correspondence with observation".

Answer: At this stage, the experiment for Sylt-Römö was performed without taking into account atmospheric forcing. The results shown in Fig. 6 are observation. The idea was to compare the frequency spectrum in the model simulation and observations for a period without the influence atmospheric forcing (we choose a period from observation when the sea surface height average for one tidal period was very close to zero).

Referee: Page 15: A figure of the South-East North Sea grid would be nice.

Answer: We added a new figure showing the mesh.



Referee: Why only 5 sigma layers are used compared to 21 in the other experiment?

Answer: We used 21 layers for baroclinic simulation and 5 layers for barotropic.

Referee: Page 15: What simulation period is taken for the South-East North Sea experiment? Which T&S forcing has been taken at the river Elbe input?

Answer: The spin-up period was one year. Final simulation was one year long too. First month of simulation was used to adjust initial conditions. Salinity in all rivers was set to 2 [psu]. The daily temperature was taken from same source as runoff. (Radach and Pätsch , 2007 ; Pätsch and Lenhart, 2011). We added to the manuscript:

The results of these runs were used as initial conditions for 10 months final simulation.

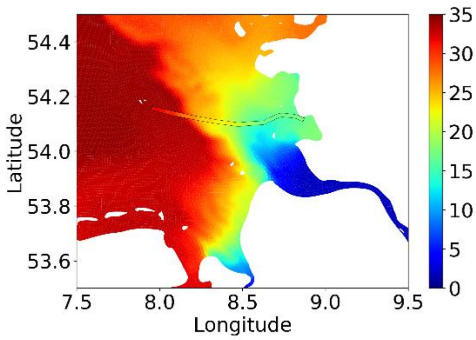
Referee: Page 16, Line 1: What is "reasonably well"? Give statistical numbers or compare to other model results.

Answer: Statistics of comparison to observations were added to the text:

To validate the simulated temperature and salinity we used data from the COSYNA data base (Baschek et al., 2016) and ICES data base (www.ices.dk). Comparison of modeled surface temperature and salinity show good Pearson correlation coefficient 0.98 and 0.9 with RMSD 1.24 and 0.98 respectively.

Referee: Page 16, Line 7-9: To my opinion the Elbe fresh water plume is further north than in the observation.

Answer: The ferry needs approximately 2 hours to go from the land to Helgoland Island. Tidal currents in this area could reach 1 m/s. During one ferry cruise the front of fresh water plume can displace by 7 km. We used snapshots to map model salinity. For technical reasons, the 3D snapshots were output approximately every 2 hours. This introduces additional technical errors in comparison. In addition to technical issues, uncertainties in runoff and T/S parameters in rivers parametrization and coarse atmospheric forcing resolution (6h in time and 200 km in space) reduce the accuracy of simulation presented in the manuscript. We work on the next manuscript with more detailed validation of similar experiment and reduced uncertainty in current simulations. Nevertheless, the simulation presented in the manuscript shows a sharp gradient of salinity 35 – 20 [psu] in the western part of the ferry track. The model show smaller salinity values in the eastern part of the track compared to the ferry data.
We redo figure in such a way that all cells of the model could be seen to answer technical question 23. We used different snapshot from the model.



Referee: Page 16, Line 23: Is the viscosity smaller because less filtering has been applied on the quadrilateral mesh? Or were other parameters also changed? A table with the used parameters for each mesh and experiment would be nice.

Answer: For all meshes we used the same filter factor. The effectiveness of the filtering procedure on triangular grids was lower. This effect is examined in more detail in the paper Danilov and Androsov, 2015.

Referee: Page 17, Line 4: What is antiphase?

Answer: "antiphase" - two opposite open boundaries have a 180° phase shift (a shift of half period) each other.

Referee: Page 18: The code is not available for non-dkrz users (FAIR principles).

*Answer: We have put the code described in the manuscript to the permanent data archive Zenodo with an open access, the doi is **https://doi.org/10.5281/zenodo.2085177**. The full model name and version number were added to the caption of the manuscript and to the code description at the Zenodo portal.*

Technical corrections:

1) When writing equations please use one line for one equation, not several equations in one line (e.g. p. 4 l. 10 or p.5 l. 25). → *Done.*

2) p. 5 l. 11: formultion -> formulation → *Thanks.*

3) p.7 l. 19: I don't' see tau_s and tau_b in the equations → *Thanks, it was our typo, changed to τ_ζ and τ_h for surface (wind) and bottom stress respectively.*

4) p.8 l. 22: termal -> thermal → *Thanks.*

5) p.10, l. 1: Here a reference to Fig. 1 would be nice → *Done.*

6) p.10, l. 3: elements = cell centers? → *Thanks, corrected.*

7) p.10, l. 30: The information that the cell thickness is estimated at cell centers should be given before the two equations of the momentum advection → *This definition has already been given in the "Spatial discretization" section (p.9 L.25-26 old version).*

8) p.11, l. 4: Put Miura, 2007 in brackets → *Done.*

9) p.11, l. 12: With left and right segments is meant s_l and s_r? Better write it and refer to Fig.1. → *The spatial structure of the grid is given above in the spatial discretization section. The link to Figure 1 is there: "The basic structure to describe the mesh is the array of edges given by their vertices v_1 and v_2, and the array of two pointers c_1 and c_2 to the cells on the left and on the right of the edge…."*

10) p.11, l. 20: Make reference to Fig.1 for definition of ny_1 → *Done.*

11) p.11, l. 25: zero flux at the bottom is Eq.8? Maybe refer to it as well? → *This condition assumes that the temperature and salinity profile is not affected by heat flux from the bottom (the bottom is isolated). In our opinion, no additional reference is required.*

12) P.12, l. 13: points are collinear, vectors are parallel. → *Now:* $\mathbf{n}$ *and* $\mathbf{r}_{cn}$ *are collinear.*

13) p.14, l. 8: For "differences in the elevation" give reference to Fig.8. → *Done.*

14) p.14, l. 16: Figure 6 -> Fig.6 → *We have left the full word (Figure) only if the sentence begins with it. The rest was replaced by Fig.*

15) p.15, l. 10: write out sigma, not greek letter → *Done.*

16) p.16, l. 4: Give reference for the 0.35 PSU/km. → *Done:*

(www.portal-tideelbe.de and J. Kappenberg, M. Berendt, N. Ohle, R. Riethmuller, D. Schuster and T. Strotmann. Variation of Hydrodynamics and Water Constituents in the Mouth of the Elbe Estuary, Germany. Civil Eng Res J. 2018; 4(4): 555643.)

17) Fig. 2.: Check caption: no comparison with GETM was carried out, no points P1 and P2 are mentioned in the text. → *Thanks, corrected.*

18) Fig. 4: The pictures should be bigger. It is not possible to see the current arrows and the legend. Depth is shown with respect to what? NN? Check caption: Is "full ebb" the time of maximum ebb speed? Maybe better give time after high water or low water. → *The size of the Fig.4 is increased. The reference to bathymetry has already been indicated in the text. We also added it to Fig. 2. We saved the term "full ebb" as before (same terminology is given in the article Purkiani et al.(2014), which we used for comparison our model simulation).*

19) Fig. 6: For the middle and the bottom panel add the displayed day in the caption. → *Done.*

20) Fig. 8: Check caption: "Spatial difference of the elevation" =? Spatial distribution of the elevation differences? → *Thanks, corrected.*

21) Fig. 10: The numbers of the stations are hardly visible. Increasing the size of the pictures could help. → *We redraw figures. We also add station Cuxhaven into analyses and figure (St. 9).*

22) Fig. 11: The caption needs to be rewritten because seemingly the lower panel does not show the running mean. The stations position could be shown in Fig 10. → *We modified the caption.*

23) Fig. 12: Why are the dry falling areas masked out in Fig. 12? It would be nice to add a coastline in Fig. 12. → *We redid the figure in such a way that all cells of the model could be seen.*

24) Fig. 13: Add in the caption to which mesh the red and black line refer to. → *Thank, done.*

We hope our answers are satisfactory and the corrected manuscript is now adequate for publication.

With our best regards,

The authors