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Interactive comment on "An axisymmetric non-hydrostatic model for double-diffusive water systems" *by* Koen Hilgersom et al.

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First of all, we would like to thank Referee #1 for reading the manuscript carefully and expressing his/her thoughts on where the manuscript should be improved. We hope that our answers and improved submission take away most of the referee's major concerns. In the following, we answer the comments point by point (Section 1) and provide an overview of the changes made to the manuscript based on these comments (Section 2).

1 Comments and answers

1. It is not clear what the main objectives are in the paper. The test cases are 2DV. Why do you have to solve the equations in cylindrical coordinates? The reason for developing a non-hydrostatic model in cylindrical coordinates should be clearly stated.

This article explores the density-driven flow in radial direction around a central seepage source. In two of the test cases (Case 1 and 2), this inflow is absent. However, these test cases also serve to test the functioning of the axisymmetric model set-up.

The introduction of the article already explained why an hydrodynamic model in cylindrical coordinates can be preferential in some specific cases (lines 50-53). We found reason to develop a non-hydrostatic model in cylindrical coordinates, because these axisymmetric cases exist, for example in river deltas with saline seepage. The presented model set-up allows to correctly represent the volumetric (in)flow in the model. In the updated version of our article, we therefore extended the paragraph (lines 50-53) to clearly state the existence of axisymmetric cases. The following text will replace the last sentence of this paragraph: "Examples of such cases are close-to-circular water bodies with uniform boundaries, and the flow around a central point (e.g., a local inflow from a pipe or groundwater seepage). The occurrence of local saline seepage inflows into shallow water bodies of contrasting temperatures has been described by De Louw et al. (2013). Hilgersom et al. (2016) have shown how these local inflows can induce thermohaline stratification in the shallow surface water bodies above these inflows." The requirement to correctly represent the volumetric flow in the modelling approach will now be better stated in lines 63-64, where we explain why we develop an axisymmetric variation of SWASH (see our answer to Referee #2).

2. To my knowledge, double diffusion is sensitive to turbulence models. Usually largeeddy simulations are conducted to capture the instability. However, no turbulence model is presented in the paper.

We agree that the inclusion of turbulence is important when modelling double diffusion, and therefore our simulations did employ a turbulence model. In the manuscript, the inclusion of the standard k-ε turbulence model was briefly mentioned in lines 88-90. As it is definitely relevant to stress the importance of turbulence modelling, we will expand more on the inclusion of the turbulence model in a new version of the manuscript. The following new paragraph will replace the sentences about the horizontal and vertical viscosity: “In this RANS model, turbulence is modelled with the standard k-ϵ model (Launder and Spalding, 1974). The modelled eddy viscosity is added to the molecular viscosity, yielding a non-uniform vertical viscosity ν_v. For the calculations in this article, the horizontal kinematic viscosity ν_h is set uniform to its molecular value ($\sim 10^{-6} m^2 s^{-1}$). "

3. The sensitivity of the numerical results on grid should also be discussed. Since the numerical diffusion would contaminate the physics.

The referee raises an important issue here, although grid sensitivity is usually more an issue in DNS models. A sensitivity analysis is therefore beyond the scope of this paper. We refer to our answer to Referee #3 for a discussion based on some results for grid sensitivity tests. In the paper, we would like to stick to the presentation of the method and show several test cases to verify and validate the model. We recommend a more thorough sensitivity analysis in a future study, as knowledge of the grid sensitivity of the model results is essential for future applications.

In our manuscript, we already focussed on the importance of the model grid selection when discussing the major disadvantage of 3-D models: they are highly computational expensive for the fine meshes required to correctly approach the salt and heat transport. We agree that the modelled physics can be highly influenced by the model grid and that we can better highlight the issue of grid sensitivity in this paper. We therefore decided to add a sentence to the Conclusions that pays attention to the fact that numerical results, and especially those for double-diffusive systems, can be sensitive to

the selection of the model grid. This sentence will be included in a new final paragraph of the Conclusions that sets out the applicability of the model and future recommendations: “Although the model is already able to show expected behaviour in the double-diffusive regime, we recommend a further exploration of its limitations and possibilities. For example, a grid convergence study should indicate whether the selected mesh size yields a convergence of results for all diffusion and advection dominated cases. Further, a comparison with DNS model results would support the validation of the model. In future applications, we stress that this model approach should be employed as a RANS model that simulates thermohaline stratification processes on a larger scale. As such, the model can be favourable in applications that allow an axisymmetric approach."

4. eq. (12): in 2DV and 3D models, bottom friction is usually accounted for through a bottom roughness. Chezy coefficient is often used in 2DH models. Why do you choose Chezy coefficient instead of bottom roughness? How does this coefficient affect your results?

We completely agree that the inclusion of a Chézy bottom friction is an unusual approach for a multilayer model. In fact, the presented model code provides the option to calculate with a logarithmic wall approach including the Nikuradse roughness height to determine the bottom friction, which is a far more common practice. The bottom friction is incorporated in the presented cases to slightly impede the high flow velocities that can locally occur, and not to approach a specified level of bottom roughness. Due to familiarity and simplicity, the authors had therefore selected a Chézy coefficient. Instead of what was presented in Eq. 12, the Chézy bottom friction was already scaled to the flow profile in the bottom layer and should have actually been presented as follows:

$$\nu_v \frac{\partial u}{\partial z}\bigg|_{z=-d} = \frac{g}{C^2} \cdot U^2 \cdot \frac{u_{k=1}}{|u_{k=1}|} \tag{1}$$

To assess the effect of the Chézy bottom friction compared to the law of the wall, we repeated Case 3 for both bottom friction boundary conditions (Figure 1). For these calculations, we applied a horizontal mesh size of 5 mm and an inflow velocity of 1 mm s^{-1})[1]. The results show how much the Chézy boundary description affects the flow patterns in the model, especially near the grid centre. The improper flow description near the bottom boundary yields an improper friction of the local friction and in the end yields a far more turbulent flow. Figure 1 shows that the Chézy friction causes a lot more turbulent mixing of heat compared to the logarithmic wall description with a Nikuradse roughness height of 0.1 mm. Also for a roughness height of 10 mm (not shown here), the logarithmic wall law yields a steady growth of the bottom layer without a lot of turbulent mixing.

To conclude, we would also like to stress that the application of the law of the wall is the most common practice for multilayer flow modelling. For this reason, and because of the results that we have shown, we recommend that the users of the model follow this approach instead of using the Chézy bottom friction. In a new upload of our dataset, we will disallow the use of other friction coefficients which are intended for depth-averaged calculations for the axisymmetric case in the model code. In the article, we will not mention the possibility to use a Chézy coefficient anymore, and we will formulate the bottom boundary condition for u-momentum for our simulations with the logarithmic wall law. We thank the referee for pointing this out.

5. theta is used for the tangential direction in section 2.1. However, this becomes alpha in section 2.3. Please make it consistent throughout the paper.

We thank the referee for making us aware of the inconsistent use of theta. We replaced theta in Section 2.1 by alpha, when introducing the cylindrical coordinates. In the

[1]It should be mentioned here that the result plotted in Figure 8 of the manuscript was actually calculated for an inflow of $2 \cdot 10^{-4}$ m s^{-1}, and not $1 \cdot 10^{-3}$ m s^{-1} as was indicated in Table 1 (we will repeat all simulations with a different bottom friction, so this will be corrected in a new manuscript).

updated version of our article, theta is only employed as an implicitness factor in the theta scheme.

2 Changes to the manuscript

Based on the comments of the referee, we will apply several changes to the manuscript:

- We will better define the purpose of the model and the article, by modifying and extending:
  - lines 50-53, better explaining that situations of seepage inflows in shallow waters, causing thermohaline stratification, actually exist;
  - lines 63-64, better explaining why we choose for an axisymmetric approach over an 2-DV approach (to better simulate the volumetric inflow of the central seepage source).
- We made clearer that this RANS model does employ a turbulence model (the standard k-ϵ model), by modifying and extending lines 87-90.
- We have tested for numerical grid convergence and we will add a sentence to the conclusions to focus on the issue of grid sensitivity of the model.
- The simulations will be performed again and uploaded as a new dataset, where:
  - the simulations will now be done with a logarithmic wall approach where bottom friction is determined by a Nikuradse roughness height instead of a Chézy coefficient;
  - the published code will not allow the option anymore to incorporate Chézy, Manning or any other coefficient that applies for depth-averaged calculations, as soon as the axisymmetric option is selected;
  - the results for Case 3 (double-diffusive convection) will now be presented for an

inflow velocity of 0.001 m s^{-1} (in the previous manuscript, we accidentally added the results for a simulation with an inflow velocity 0.0002 m s^{-1}, which was not in accordance with Table 1 and made the results less comparable to Case 4).

- The tangential direction of the axes in cylindrical coordinates is now defined as alpha throughout the article.

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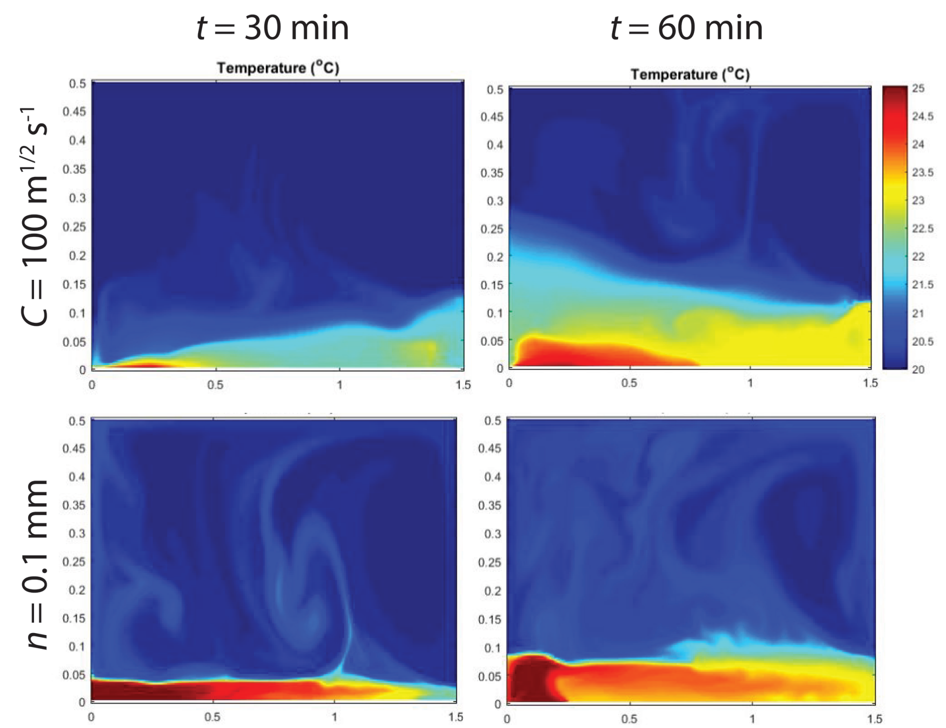

Fig. 1. Comparison between bottom friction boundary conditions described by a Chézy coefficient C and the logarithmic wall with a Nikuradse roughness height n at 30 min. and 60 min. after the start of the run