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Geoscientific Model Development Discussions
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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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We would like to thank Referee #3 for reading our manuscript and expressing his/her thoughts. We thank the referee for the compliments for the paper structure and the model development. The major concern seems to be that the robustness of the model is insufficiently proven and that a comparison with real world data would support the presented framework. In the following, we answer the general comments point by point (Section 1), list our reactions to the detailed and technical comments (Sections 2 and 3), and provide an overview of the changes made to the manuscript based on the comments (Section 4).

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1 General comments and answers

1) It would be good to elaborate on use of SWASH vs a completely new model. Was the primary reason to take advantage of computational infrastructure? It seems like this may have been more work than starting fresh and it would be nice to include further details for this design choice.

We thank the referee for highlighting this point. In our eyes, the extension of SWASH is advantageous for multiple reasons, which we already described in the article. In our approach, we want to show how a normal 2-DV model can be easily extended to an axisymmetric model by adding few terms. Moreover, SWASH has several features that were required for our intended model application (i.e., a local groundwater inflow into a shallow water body, where the groundwater has a different salinity and temperature). These features were: calculation of the free surface, the non-hydrostatic component, the staggered grid (mass and momentum conservation), and easy extendability of the freely available code.

2) Please justify this choice of method as opposed to alternative methods, e.g., advanced mesh refinement.

Our study focuses on the development of a framework for an axisymmetric modelling approach for free-surface models. The methods that the referee refers to are advanced techniques that allow models to quicker find an accurate solution. These are very interesting techniques, but the objective of the current article is to present the derived framework.

3) Please provide additional discussion of applications and uses for this code.

Based on comments by Referee #2, we concluded that the intended applicability has not sufficiently been explained. We will therefore extend the paragraphs in the Introduction (lines 50–53 and 63–64) that introduced the applications for which we developed this modelling framework.

2 Answers to specific comments

- l. 146: Based on a comment by Referee #2, we will better formulate this in the Introduction, where we list the advantages of SWASH (lines 56–59). Instead of just mentioning that SWASH has a momentum and mass conservative grid setup, we will now write: “the staggered grid allows a momentum and mass conservative solution of the governing equations, which is required for accurate salt and heat transport modelling".
- l. 150–175: In our opinion, the presentation of the derived numerical framework is one of the major objectives of the article. Therefore, we will keep this part of the manuscript in the main text. Furthermore, it is not uncommon in papers in the field of fluid mechanics to present the numerical framework in the text.
- l. 181: The sentence was not correctly formulated: only the horizontal time integration of the transport equations is explicit. This is not expected to cause problems in the solution of the transport equations given the small time steps employed. The horizontal momentum terms are solved with MacCormack's 2^{nd} order predictor-corrector scheme.
- l. 198: We have increased the white space between the dots and the variables in the equation to increase the readability.
- Fig. 4: Although we do not see directly which lines should get a different width to make the figure clearer, we increased the width of the diffusive flux arrows to distinguish them from the water fluxes at the inflow and outflow. We hope that this will meet the expectation of the reviewer.

  The color maps of all color plots will be changed to viridis.

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- Model convergence: We have tested for grid sensitivity in the dynamical case of the double-diffusive convective layer that develops from the central inflow in the streambed (Case 3 in the article). Here, we focus on the sensitivity to the horizontal grid size, since this size is expected to be most influential in the axisymmetric approach. We have performed these tests for inflow velocities of $2 \cdot 10^{-4}$ m s^{-1} and $1 \cdot 10^{-3}$ m s^{-1}[1], and for horizontal mesh sizes of 2.5, 5, and 10 mm (the former for the period of 1 hour, the latter two for 2 hours).
  For the inflow of $1 \cdot 10^{-3}$ m s^{-1}, Figure 1 presents the results for temperature after 1 hour and 2 hours for the different mesh sizes (the salinity profiles show similar results). In this case where advection dominates, the flow near the seepage inflow, no real differences are seen for the different mesh sizes.
  For the inflow of $2 \cdot 10^{-4}$ m/s, something interesting happens (Figure 2). When the bottom layer is still thin, diffusion dominates this case: the larger diffusion of heat warms the boundary layer of the surface water on top of the inflowing groundwater at a larger rate than that salt is transported upwards. This makes the boundary layer locally unstable and leads to a sudden breaking of the developing bottom layer. This effect is seen for a horizontal mesh size of 2.5 mm, but not for larger mesh sizes, and displays a sensitivity to the grid for cases where the effect of diffusion is dominant for a thin layer near the central inflow. These effects are not seen once the bottom layer has grown further.
  Based on these results, we therefore recommend applying a fine mesh near the central inflow in case the model is applied for very small inflows in combination with the development of a very thin (initial) layer.

- Simplifications: This issue was also raised by Referee #2. The article does not aim to model double-diffusive features in detail (e.g., the shape of salt-fingers),

[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 (based on comments by Referee #1, we will repeat the simulations with a different bottom friction, so this will be corrected in a new manuscript).

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but rather their main effect on stratication and salt and heat transport on a larger scale. Whether the model is succesful in resembling these patterns on a larger scale is something that needs to be validated, and we agree that the validation was still lacking in the submitted article. To meet the concerns of the referees about the unclear presentation of our purpose (i.e., the larger scale), we will better stress this in the Introduction.

- Returning to the research question in conclusions: We agree that the Conclusions section does not clearly reflect the ultimate intentions of the article: the modelling of a central seepage inflow at the bottom boundary of a surface water body, where contrast in salinity and temperature can lead to the occurrence of double-diffusive phenomena. In a new submission, we will partly rewrite the last two paragraphs of the Conclusions to make the presented conclusions supportive to the ultimate goal. The paragraphs will be replaced by the following:

  "For our purpose of studying shallow water bodies, three aspects were important: 1) the inclusion of a free surface, 2) the efficient solution of a circular seepage inflow, which makes the problem three-dimensional, and 3) a proper simulation of density driven flow and double-diffusivity driven salt and heat transport. The former aspect was already fulfilled by employing the SWASH framework.

  The second aspect was solved by assuming axisymmetry for the Navier-Stokes equation in cylindrical coordinates. The derived numerical framework is presented as a Cartesian 2-DV description with few additional terms and width compensation factors. Our implementation of these terms in the non-hydrostatic SWASH model demonstrates the opportunity to easily expand a 2-DV model towards the presented quasi 3-D model.

  The third aspect was fulfilled by extending SWASH with a new density and diffusivity module. The case studies demonstrate explainable behaviour for density driven flow and double-diffusivity driven salt and heat transport. The formation of convective layers and salt-fingers are in accordance with the theory of double-diffusivity. A quantitative validation method was presented to evaluate the model's performance for a cold and saline inflow developing a dense water layer near the bottom. For laminar flow conditions, the numerical model showed a similar radial expansion of the bottom layer as expected from analytical results."

3 Answers to technical corrections

- l. 64: *axi-symmetric* is replaced by *axisymmetric*
- Eq. 6: Equation 6 is split over two lines
- l. 140: *the* is added between *in* and *tangential direction*

4 Changes to the manuscript

Based on the comments of the referee, we will apply the following 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).

Further, the changes listed in Sections 2 and 3 were applied based on the specific and technical comments.

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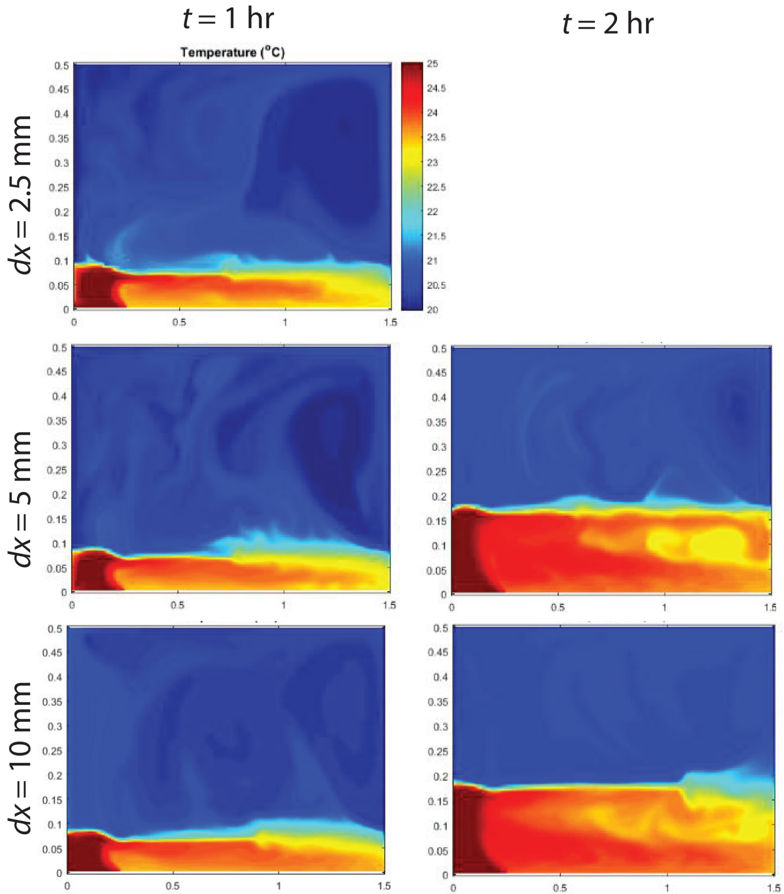

Fig. 1. Development of a double-diffusive convection layer for an inflow velocity of 1e-3 m/s.

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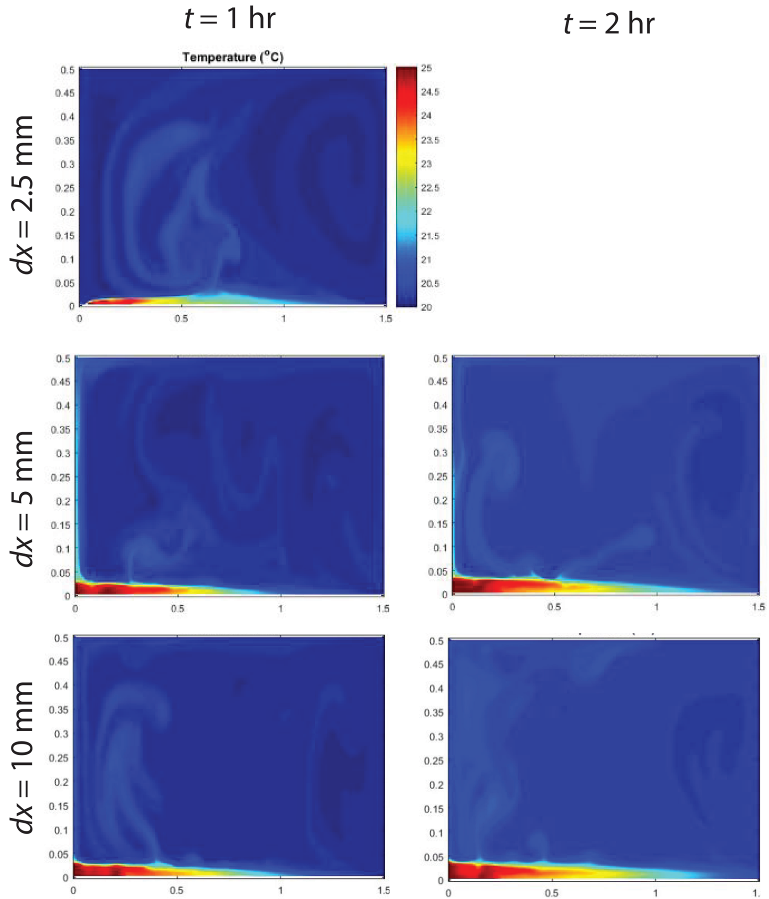

Fig. 2. Development of a double-diffusive convection layer for an inflow velocity of 2e-4 m/s.