Responses to Referees

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Contents

1 Response to RC1

Main comments:

1) What are the detailed differences between your coupling module and the UWGeodynamics module? I speculate that you added the IB scheme, but the description in Section 2.2.2 is not clear about how it is implemented. Some details about this IB scheme need to be added. How exactly is the velocity evaluated on the S-surface and transferred to Badlands? What interpolation methods are used? The particle adjustment process based on surface changes (distinguishing sediment from air) requires more detail.

Response: The UWGeodynamics module integrates Badlands with Underworld using an Eulerian scheme. We've made enhancements to the velocity "base surface" to accurately trace velocity on the "free surface," improving the interaction between the geodynamic model and surface process codes in this framework. Our new coupling framework builds upon this by employing an ALE-IB scheme. We've made enhancements to the velocity "base surface" to accurately trace velocity on the "free surface," improving the interaction between the geodynamic model and surface process codes, see details in [blog](https://www.underworldcode.org/new-features-of-the-surface-coupling-framework-in-underworld-2/). We further build new coupling framework upon this by employing an ALE-IB scheme. We have submitted a paper detailing the ALE-IB scheme for free surface simulation, and in Section 2.2.2, we've expanded the description for clarity, including a link to the submitted paper (Lu et al., 2026)

Specifically, the velocity on the S-surface rectangle is evaluated from the velocity field in Underworld using the cubic spline method within the UW2 evaluation function. This approach is highly accurate due to the higher resolution of the S-surface compared to the T-surface. Velocities are then transferred to the S-surface triangle in Badlands through a bicubic interpolation method, ensuring smooth and precise data transition.

Additionally, we've elaborated on the particle adjustment process, which distinguishes between sediment and air and adjusts particle positions based on surface elevation changes. This is crucial for accurately modelling sediment deposition and erosion. Details of this algorithm have been added to the revised manuscript.

2) The benchmark results in Fig. 4 are not very clear to me (see details below). Response: See details below.

3) The sediment distribution differences between schemes (Figure 10a,b) are subtle, yet the tectonic deformation is more different at the collision front (Fig. 10c,d). Why? Response: The subtle differences between the schemes are due to variations in the accuracy of sediment transport dynamics. However, the more pronounced differences in tectonic deformation at the collision front result from differential stress propagation, influenced by varying sediment volumes.

Minor suggestions:

38, typo: FasScape to FastScape

Response: Corrected.

Eqs 4-5, the C and phi are messed up. It's better to define the starting cohesion (C_0) and friction angle (ϕ_0).

Response: Corrected, added definitions of C_0 and ϕ_0.

131, do you have a criterion for choosing the subtimesteps dt_{sp}?

Response: We typically choose dt_{tec} by considering factors such as the Courant-Friedrichs-Lewy (CFL) condition to ensure numerical stability. For dt_{sp}, we often use a value that is 0.5, 1/3, or smaller relative to dt_{tec}, depending on the specific requirements of the simulation.

138-139, Is the grid used in Badlands the triangular grid as shown in Figure 1? Although the ALE-IB scheme avoids interpolation from particles to grid nodes at the surface in Underworld 2, how is the processing carried out in the process of converting from surface rectangular grids in Underworld 2 to more refined rectangular grids and further triangular grids in Badlands? If interpolation is still used, what impact will it have on the result?

Response: In Badlands, two types of meshes are used: triangular (for main calculation) and rectangular (for maintaining tectonic input). The ALE-IB scheme reduces the need for interpolation by utilizing a particle-based approach on the surface. However, when converting from the surface rectangular grids in Underworld 2 to the refined rectangular and triangular grids in Badlands, interpolation remains necessary. Initially, we transfer velocities from the Underworld 2 mesh to the S-surface rectangle in Badlands. This step is highly accurate due to the higher resolution of the S-surface compared to the T-surface. Subsequently, velocities are transferred to the S-surface triangle using a bicubic interpolation method in Badlands, ensuring a smooth and precise data transition. While interpolation can introduce minor discrepancies, our approach is designed to minimize these effects, ensuring they do not significantly impact the overall results.

140-144, As mentioned above, a more detailed ALE-IB implementation scheme needs to be described. Response: We've expanded the description for clarity

167, the air density is set to be 0 kg/m3. Do you solve the energy equation, and does it have problems? Response: We do solve the energy equation, this simplification does not pose significant problems. In practice, the value of 0 is replaced by an extremely small value to prevent computational issues.

208, add units for Kd and Kf Response: added.

Fig. 4, SP should add the abbr. for SP-surface process in the figure caption. Response: added.

Fig. 4, why isn't the deposition/sedimentation at the trough? Did the two models use the same random noise? Does the change of random noise have a significant impact? Besides, a figure of the differences in topography and erosion/deposition between these two schemes can better show the distinctions between the two schemes. Response: Deposition and sedimentation occur near sea level (set at an elevation of 0 km). We did not introduce random noise. The differences in sediment are due to the performance of Badlands under different coupling frameworks. Figure 4(e) and (f) illustrate these differences between the two schemes. We explored displaying the erosion and deposition profiles of the ALE-IB and Eulerian models as a superimposed figure. However, given the subtlety of the differences between the two models, such an overlay does not provide meaningful visual clarity, and we therefore chose to present the results in their current form.

Fig. 5, drainage colorbar adds unit Response: The discharge shown here uses dimensionless quantities. Since the SI unit for these is simply 1, we have left it blank.

Table 2, your rheological model has no pressure dependence, activation volume is not used, but you show it here. So, do you use the activation volume in your viscosity? Response: We did use the activation volume, which was missing in Equation (7). We have added the "PV" term to the equation to correct this oversight.

Fig. 12 is not used in the main text; you may want to refer to it at line 248 (Fig. 12e, not 11e?) Response: Yes, corrected.

Table 2 defines the model names for two groups of experiments: Ex.1 vs. Ex. 2. It's very confusing when referring to e.g., CM1 from Ex.1 or Ex.2. Please use a better approach for clarity. Response: Enhance model clarity by prefixing names with 'TR-' for topography relaxation (Experiment 1) and 'CC-' for continental collision (Experiment 2).

2 Response to RC2

Main comments:

(1) The authors should expand section 2.2 to give a more in-depth description of the two implementations, as well as how they differ. In both descriptions, it sounds like the velocity is interpolated from the tectonic model to the surface processes model, and then badlands does the advection and SP routines. Is the difference only in how the interpolation is done or is there some other major difference between the two? I think updating figure 2 to show a flow chart of the Eulerian scheme next to the ALE-IB may help to understand the differences.

Response: We've clarified the description and included a flowchart for the Eulerian scheme. The key difference is that in the Eulerian approach, coupling occurs on a fixed mesh, interpolating mesh velocity from nodes to particles that form the initial 'S-surface' (before surface process advection). In contrast, with ALE-IB, the 'S-surface' aligns with the 'T-surface', providing more accurate velocity.

(2) It would be helpful to give some discrete numbers on how much the two methods differ from each other, and in the topography relaxation model, from the analytical solution. For example, in figure 4ab when examining closely the ALE-IB does seem more accurate than the Eulerian scheme, but the Eulerian scheme already seems quite accurate. How much accuracy is gained? A similar quantitative comparison would strengthen the discussion of Figures 4e–f and Figure 10. The visual differences appear minor in some cases; quantifying them would clarify whether they are negligible or meaningful for certain applications.

Response: We have calculated the L2-norm error between the schemes and analytical solution in the models without surface processes, and the relative differences in the average depth of erosion and deposition between the two schemes.

(3) It would be very helpful to include one case with a high kf value using the Eulerian scheme. Sections 3.1.2 and 3.2.2 briefly discuss increasing kf, but only for the ALE-IB implementation. Does the advantage of ALE-IB increase as erosion and deposition intensify, or do both schemes perform similarly under these conditions? Addressing this would clarify when the ALE-IB approach is necessary.

Response: We included a case with a high kf value using the Eulerian scheme in Experiment 1 for clearer comparison in Appendix. While the test results suggest that the benefits of ALE-IB do not scale with increased levels of erosion and deposition.

Minor suggestions:

Line 141 – Should this be the that velocity is evaluated on the T-surface and then transferred to Badlands? Response: The velocity on the S-surface is interpolated based on the velocity from the T-surface, where it is defined on the tectonic mesh nodes in UW2.

Line 210 – Could the authors put numbers on how close the Eulerian and ALE-IB agree with the analytical solution? Response: We added the L2 norm difference compared to the analytical solution.

Line 212 and 244 - An arrow on figure 4 and 11 to indicate what the authors mean would be helpful. Response: We added an arrow to indicate that the Eulerian scheme exhibits fluctuations.

Does the accuracy between the two schemes change depending on the number of particles per cell or model resolution? Response: The accuracy of the two schemes varies with model resolution. At extremely high resolution, both schemes exhibit similar accuracy. However, with more particles per cell, the Eulerian scheme still shows inaccuracy when mesh resolution is low.

Is there a difference in model runtime when switching to ALE-IB, or is it getting more accurate results with no significant change in computation cost? Response: There is no significant difference in model runtimes between the two schemes, though the ALE-IB scheme takes slightly longer due to the additional remeshing calculations.

From these results it appears while having surface processes affects tectonics, changing between the two schemes does not have a large change. However, because of the change in deposition, especially in the continental collision model, the ALE-IB accuracy may be particularly important when comparing modelled basins with natural observations. In the authors opinion, when is it necessary to use ALE-IB over a Eulerian scheme? Response: In general, with relatively high erosion rates and high-relief topography, where the model generates more sediments, it's better to use ALE-IB. For very large model sizes with relatively low resolution, ALE-IB is also preferable, as it can accurately trace the surface even at lower resolutions.

Figure 2: Could the authors add a flowchart of the Eulerian scheme to highlight the difference? Response: Added.

Figure 4: the SP acronym should be defined within the figure. Sealevel should be indicated on a/b to make it clear. subplots e and f need more description, what does the black line and gray area explicitly show? I think this should be made clear for all the figures that plot this. Response: The black line indicates the average value. We have also

included a description, the sea level, and defined the acronym "SP".

Figure 10: I notice in the viscosity plots that the ALE-IB has a smooth changes in slope at the surface (10c) compared to the more cell-defined one seen in 10d. Is this one of the changes from the new scheme? Response: Yes, because the viscosity field is defined on a deformed mesh. The viscosity interface is more clearly visible in the ALE-IB scheme, which also helps improve the solver's accuracy.

Table 1: Are Ex. 1 and Ex. 2 supposed to refer to whether it is the time relaxation or continental collision models? I think the authors should describe this in the caption, and add something to the model name to distinguish between which set of models they belong to. Response: Add descriptions in the caption. Enhance model clarity by prefixing names with 'TR-' for topography relaxation (Experiment 1) and 'CC-' for continental collision (Experiment 2).

References

Lu, N., Moresi, L., and Giordani, J. (2026). A novel ale scheme with the internal boundary for true free surface simulation in geodynamic models. *EGUsphere*, 2026:1–26.