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Fast and accurate modeling of advection in geophysical flows with dynamic implicit surfaces

Henri Samuel[1], Martha Evonuk[2]

[1] *Bayerisches Geoinstitut, Universitaet Bayreuth, Bayreuth, Germany*
[2] *Department of Theoretical Physics I, Universitaet Bayreuth, Bayreuth, Germany*

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Advection is one of the major processes that commonly acts on various scales in nature (core formation, mantle convective stirring, multi-phase flows in magma chambers, subduction dynamics, salt diapirism ...). While this process can be modeled numerically by solving conservation equations, various geodynamic scenarios involve advection of quantities with sharp discontinuities. Unfortunately, in these cases modeling numerically pure advection becomes very challenging, in particular because sharp discontinuities lead to numerical instabilities, which prevent the local use of high order numerical schemes.

Several approaches have been used in computational geodynamics in order to overcome this difficulty, with variable amounts of success. Despite the use of correcting filters or non-oscillatory, shock-preserving schemes, Eulerian (fixed grid) techniques generally suffer from artificial numerical diffusion. Lagrangian approaches (dynamic grids or particles) tend to be more popular in computational geodynamics because they are not prone to excessive numerical diffusion. However, these approaches are generally computationally expensive, especially in 3D, and can suffer from spurious statistical noise.

As an alternative to these aforementioned approaches, we have tested the Level Set and Particle Level set methods against the robust and popular tracer-in-cell method on well-known 2D thermochemical benchmarks and typical 3D convective flows. Although the Level Set method has some advantages over the tracer-in-cell method it generally fails to resolve fine (sub-grid) scale features and requires high resolution in order to conserve mass accurately.

However, the use of Lagrangian tracers in the particle level set method yields much more accurate solutions of purely advective transport. In every case we ran we found that the Particle Level Set method accuracy equals or is better than other Eulerian and Lagrangian methods, and leads to significantly smaller computational cost, in particular in three-dimensional flows, where the reduction of computational time for modeling advection processes is most needed.