CASL in Devito: high-fidelity geophysical fluid simulation with contour methods

Supervisor: Dr Rhodri Nelson, Department of Earth Science and Engineering, Imperial College London
Co-supervisors: Prof Gerard Gorman, Department of Earth Science and Engineering, Imperial College London

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Background

Many problems in atmosphere–ocean science involve sharp fronts, filaments and vortices that span a wide range of spatial and temporal scales. Capturing these features accurately is crucial for understanding transport of heat, tracers and momentum, but it is numerically challenging: standard grid-based schemes often smear out steep potential vorticity (PV) gradients and small-scale structures through numerical diffusion.

Contour-advective semi-Lagrangian (CASL) algorithms address this by representing PV as a set of materially conserved contours, which are advected in a fully Lagrangian way, while smoother fields (e.g. layer depth, divergence) are evolved on a grid (Dritschel *et. al,* 1999). This hybrid Lagrangian–Eulerian approach can resolve features far below the grid scale, while greatly reducing artificial diffusion compared to traditional semi-Lagrangian or pseudospectral schemes.

CASL has been successfully applied to shallow-water dynamics and extended to quasi-geostrophic and fully 3-D Boussinesq flows to study, for example, baroclinic vortex pairs at finite Froude and Rossby number, where ageostrophic effects and inertia–gravity waves play an important role (Reinaud *et. al,* 2025).

These studies demonstrate that contour methods can reveal subtle dynamical asymmetries (e.g. between cyclones and anticyclones) that may be difficult to capture with more diffusive schemes.

At the same time, domain-specific languages (DSLs) such as Devito provide a modern route to high-performance finite-difference solvers: users specify PDEs symbolically in Python, and the DSL generates optimised, architecture-specific C/CPU/GPU code with advanced loop transformations, vectorisation and MPI parallelism (Louboutin *et. al.*, 2019). Devito is already widely used for large-scale wave propagation in seismology and related fields.

However, CASL implementations are currently specialised research codes, not integrated into general-purpose DSL frameworks. This limits their accessibility, maintainability and performance portability.

Project overview

This project will integrate contour-advective semi-Lagrangian (CASL) algorithms into the Devito domain-specific language for PDEs. CASL represents sharp potential-vorticity fronts and filaments as moving contours, coupled to grid-based fields for velocity and pressure, allowing much finer effective resolution than standard schemes. You will take existing CASL codes for shallow-water and quasi-geostrophic/Boussinesq flows, extract the key algorithmic components, and redesign them so they can be expressed cleanly inside Devito. On top of this, you will build and run benchmark test cases, such as unstable jets and interacting vortices, to compare Devito–CASL against conventional finite-difference solvers in terms of accuracy, numerical diffusion and computational cost on modern CPU and GPU hardware.

Impact

The project will deliver a modern, open-source implementation of CASL within an established scientific computing framework, making advanced contour methods accessible to a much wider community than bespoke research codes. More broadly, it will show how DSLs can support unconventional hybrid Lagrangian–Eulerian algorithms, informing the design of future tools for geophysical and climate modelling where preserving sharp structures and multiscale dynamics is essential.

References

Dritschel, D.G., Polvani, L.M. and Mohebalhojeh, A.R. (1999) The Contour-Advective Semi-Lagrangian Algorithm for the Shallow Water Equations. *Monthly Weather Review*, 127, 1551–1565. https://doi.org/10.1175/1520-0493(1999)127

Reinaud, J.N., McKiver, W.J. and Dritschel, D.G. (2025) Finite Froude and Rossby number baroclinic vortex pairs. *Geophysical & Astrophysical Fluid Dynamics*, 119(2), 179–201. https://doi.org/10.1080/03091929.2025.2532978

Louboutin, M., Lange, M., Luporini, F., Kukreja, N., Witte, P.A., Herrmann, F.J., Velesko, P. and Gorman, G.J. (2019) Devito (v3.1.0): an embedded domain-specific language for finite differences and geophysical exploration. *Geoscientific Model Development*, 12, 1165–1187. https://doi.org/10.5194/gmd-12-1165-2019