GPU-accelerated large eddy simulations for process oriented climate studies

The advent of Graphic Processing Units (GPUs) has opened an enormous window of opportunity for computational fluid dynamics (Roccon et al., 2026). Direct numerical simulations (DNS) of supersonic flows around rockets, for example, that resolve down to the Kolmogorov scale of molecular diffusion have now become attainable. The adoption of GPUs in General Circulation Models (GCMs) used to simulate the oceans and atmosphere has generally lagged behind. This is partly due to: i) the stricter requirement by GCMs to accurately represent diverse phenomena across a broad range in space-time—from a few meters to thousands of kilometers and seconds to centuries—and ii) dependency on multiple modules representing different physical and chemical phenomena, which take the form of legacy codes written in Fortran. Although there are ongoing efforts to port Fortran-based dynamical cores to GPUs, the translation of legacy code purposed for Central Processing Units (CPUs) and optimization of their performance have proven to be a non-trivial task. They tend to yield a meager quadrupling in terms of energy efficiency (Lapillonne et al., 2026; Wei et al., 2023).

In this regard, the Oceananigans GCM offers a unique advantage. Written from scratch in Julia, a GPU native language, it is able to fully capitalize on the GPU architecture and provides a significant speed up and energy efficiency compared to Fortran-based state-of-the-art GCMs (Silvestri et al., 2023). For example, a MITgm run of the global ocean at $1/48°$ resolution required 70,000 CPU cores to achieve 0.05 simulated years per wall-clock-day (SYPD). Oceananigans achieved the same time-to-solution on the same problem size on only 32 GPUs, consuming roughly a factor of 40 times less energy in comparison. Another strength of Oceananigans is in its flexibility to configure realistic global simulations down to idealized large eddy simulations (LES), a feature that made MITgcm, the predecessor of Oceananigans, a popular tool for process-oriented studies of the ocean and climate.

Given the aforementioned flexibility, we propose to develop a sweep of LES to improve our understanding on the energetics of the upper ocean and inform the parametrizations of mesoscale eddies. Namely, this proposal will cover:

1. A re-examination of the connection between quasi geostrophy and primitive equations;
2. Investigation into the relation between the thermodynamic spice variable and budget of eddy kinetic energy (EKE).

Although quasi-geostrophic (QG) theory has been instrumental in elucidating the mechanism of geostrophic turbulence and developing eddy parametrizations, it remains elusive, to what extent, QG predictions are applicable to describing mesoscale turbulence in the real ocean. Namely, an undeniable discrepancy lies in the fact that velocity in primitive equations is three dimensional (3D) while it is quasi-two dimensional (2D) under quasi geostrophy. Thickness-weighted averaging the primitive equations reduces the 3D advection of mean velocity to 2D under adiabatic conditions (Uchida et al., 2023). This raises the hypothesis that it may be the residual-mean velocity (rather than the 3D Eulerian mean velocity) that should correspond to QG predictions. We shall investigate this via methods of wavenumber spectra of EKE and enstrophy where the mean flow is defined as the residual mean and eddies as the fluctuations about it. Our results will inform whether future developments of eddy parametrizations employed in climate simulations should be based on Eulerian means or residual means.

Uchida et al., (2025) recently discovered that the eddy advection of temperature and salinity tended to cancel each other out in energizing EKE. It is known that a similar partial cancellation between contributions from temperature and salinity also takes place for spice. Establishing a connection between spice and EKE budget will provide a new avenue to constrain the isopycnic eddy diffusivity widely employed to parametrize the transport of tracers such as temperature and salinity. We will examine whether spice can be a proxy for where thermodynamics contribute to the upper ocean EKE budget and its relation to eddy diffusivity using outputs from our LES.

The proposed simulations with Oceananigans will be a sweep of hydrostatic doubly-periodic flat-bottom LES with varying complexity in their boundary conditions. Our approach is kept deliberately simple in order to target the processes responsible for eddy variability and transport. A plethora of studies has demonstrated the significance of accurately representing oceanic mesoscale eddies in climate simulations (e.g., Griffies et al., 2025); our proposal will improve our understanding on mesoscale dynamics by bridging the gap between theory and application. The domain size will be $L = 200$ km in the horizontal and $H = 2000$ m in the vertical. The number of grid points in the horizontal will be 512×512, which makes our LES submesoscale rich at the resolution of ~ 390.6 m. In the vertical, we shall employ a stretched coordinate discretized over 64 layers where the grid spacing monotonically increases from 10.5 m at the surface to 122.8 m towards the bottom. Based on preliminary findings, we are able to produce 60 days of model output per wall-clock-day on a single second-tier GPU. We would like to request a wall time of 100,000 hours on a single NVIDIA A100-SXM4 GPU on the Levante supercomputer. A by-product of our proposed work is an accumulation of communal expertise in running climate-relevant GCMs on GPUs.

References

Griffies, S., et al. (2025). The GFDL‑CM4X Climate Model Hierarchy, Part I: Model Description and Thermal Properties. *Journal of Advances in Modeling Earth Systems*, https://doi.org/10.1029/2024MS004861.

Lapillonne, X., et al. (2026). Operational numerical weather prediction with ICON on GPUs (version 2024.10). *Geoscientific Model Development*, https://doi.org/10.5194/gmd-19-755-2026.

Roccon, A., et al. (2026). GPU-accelerated simulations of turbulence: Review of current applications and future perspectives. *Physical Review Fluids*, https://doi.org/10.1103/vz9c-bbzm.

Uchida, T., et al. (2023). Cautionary tales from the mesoscale eddy transport tensor. *Ocean Modelling*, https://doi.org/10.1016/j.ocemod.2023.102172.

Uchida, T., et al. (2025). Dynamics and thermodynamics of the Boussinesq North Atlantic eddy kinetic energy spectral budget. *Journal of Advances in Modeling Earth Systems*, https://doi.org/10.1029/2024MS004781.

Wei, J., et al. (2023). LICOM3-CUDA: a GPU version of LASG/IAP climate system ocean model version 3 based on CUDA. *The Journal of Supercomputing*, https://doi.org/10.1007/s11227-022-05020-2.