HyPOP: Momentum and Tracers on Separate Vertical ALE Grids

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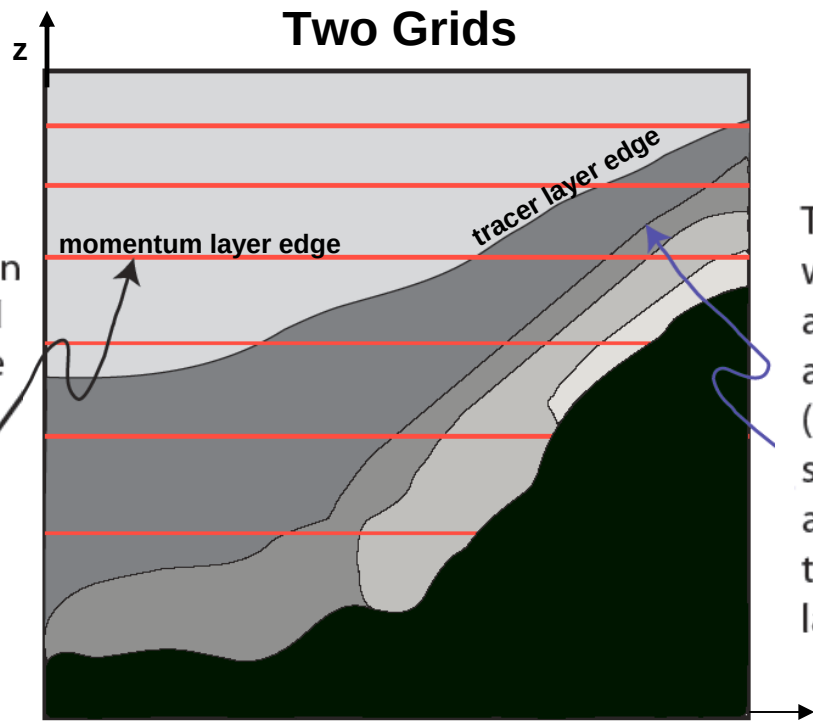
HyPOP: Motivation

- **Isopycnal grids have advantages for tracer transport:**
  - Transport and mixing in the deep ocean follows isopycnal surfaces, so isopycnal-based grids have less diapycnal mixing at depth.
  - Overflow regions better represented in isopycnal grids.
  - Z-grid models, like POP, require corrections to better represent this isopycnal flow and mixing.
- **Ice shelf/ocean interaction better modeled with layer grids**
- **We want to retain the well-tested, z-level POP formulation for the momentum equation.**
- **HyPOP solves momentum equation and tracer equations on different grids, allowing great versatility.**

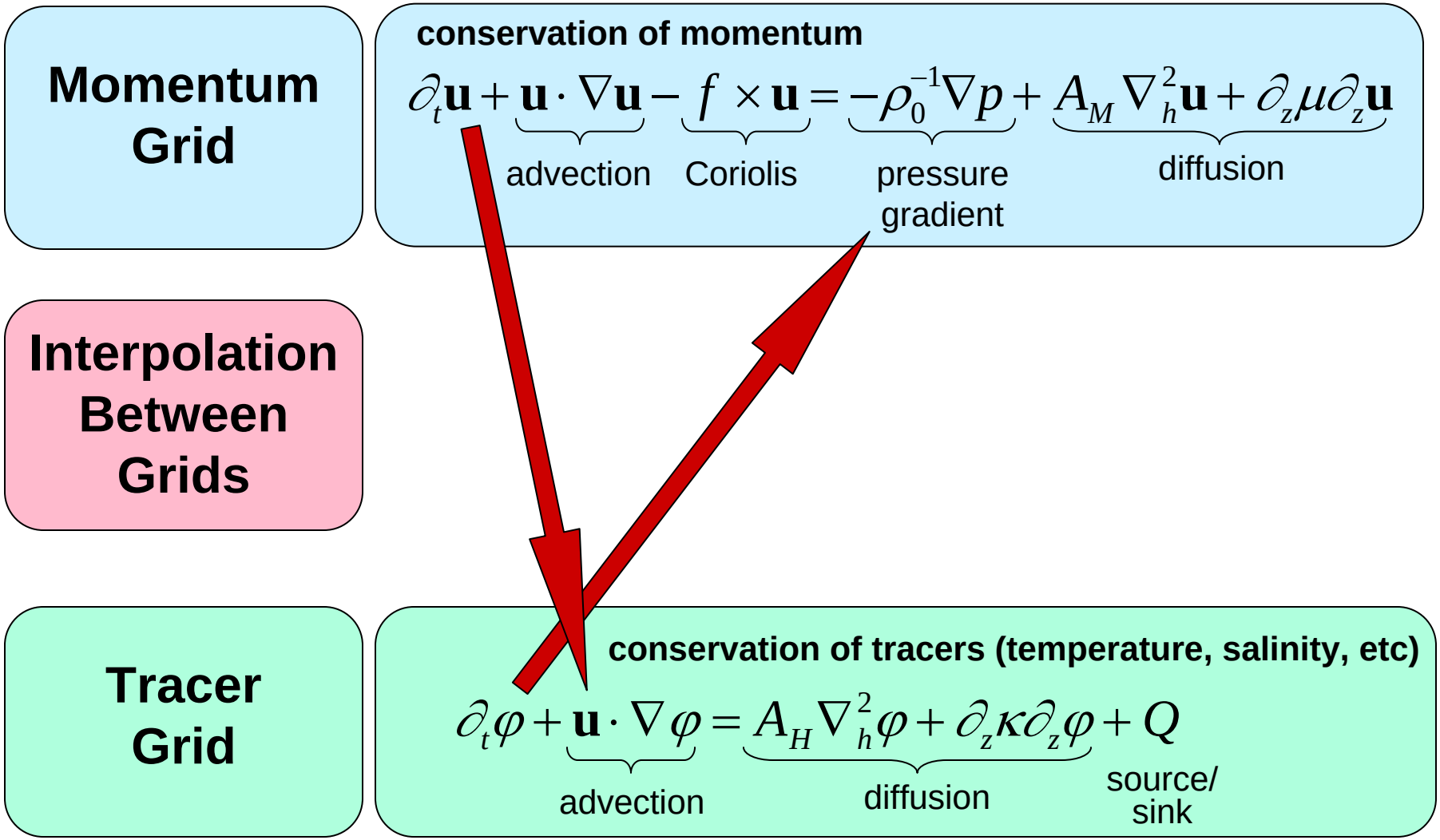
HyPOP: Momentum Grid and Tracer Grid

The momentum equation is discretized on a z-level grid in order to minimize truncation errors and reduce spurious motion near boundaries.



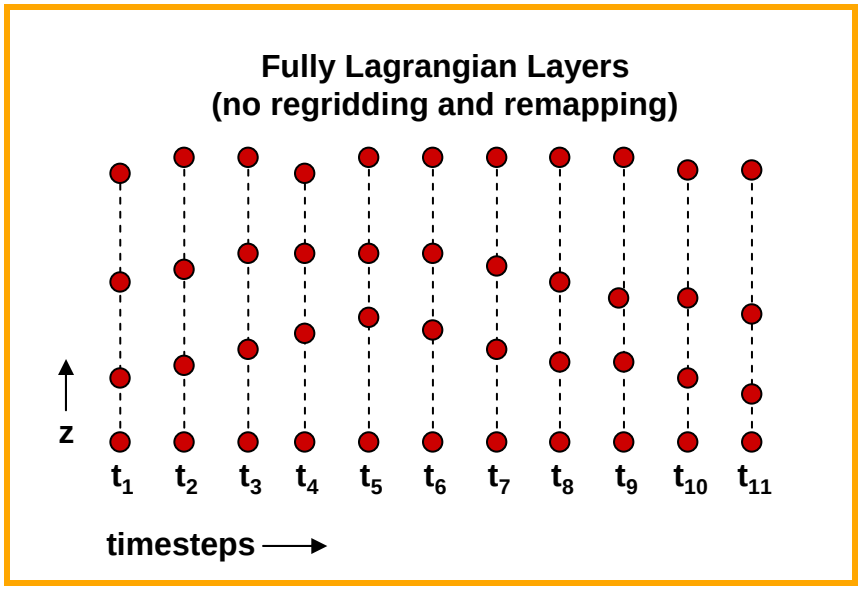
The mass equation, along with tracer equations such as temperature and salinity, are defined in isopycnal (Lagrangian) layers. Near the surface where diabatic effects are strong, the layers will transition to Eulerian, z-level layers.

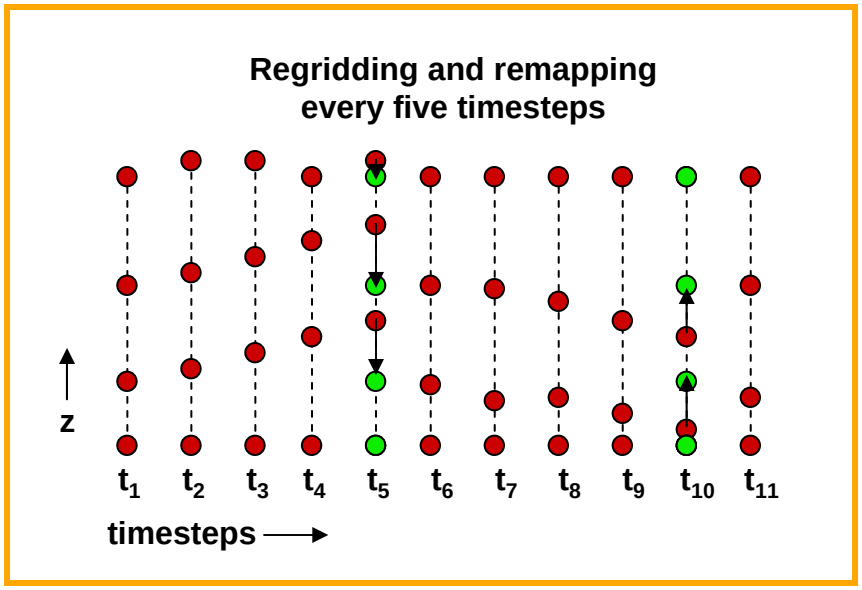
HyPOP: Momentum Grid and Tracer Grid



ALE: Arbitrary Lagrangian-Eulerian Coordinates

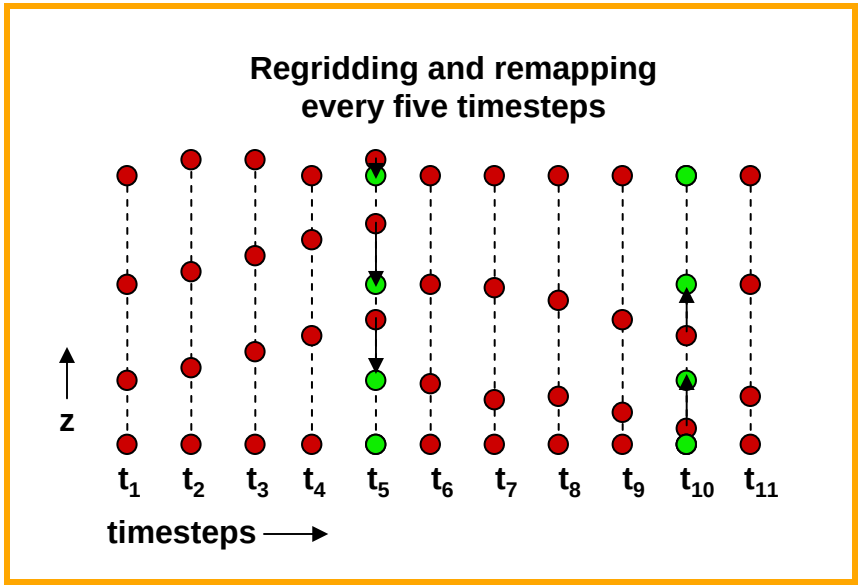
- **Isopycnal coordinates are naturally Lagrangian; isopycnal surfaces move with the fluid.**
- **ALE algorithm consists of three parts:**
  1. Lagrangian steps, where vertical grid moves with the fluid.
  2. Regridding step, where grid is modified to ensure it is smooth and well-spaced.
  3. Remapping step, where variables are conservatively transformed from the old grid to the new.





ALE: Targets for Regridding

- **Regridding and remapping may be done:**
  - after every step
  - after every n steps, or
  - based on grid criteria
- **Grid criteria that initiate regridding and remapping would include:**
  - Layers that deviate too far from the target grid
  - Layers that are too thin or too thick
  - Layer interfaces that are not smooth



HyPOP: Versatility in both Tracer and Momentum Grids

- **HyPOP's software infrastructure allows great flexibility in vertical grids.**
- **The tracer and momentum grids may each be Z-level or ALE.**
- **Possible configurations include:**

Tracer grid: / Momentum grid:	Z-level	ALE (isopycnal, Z on top)
Z-level	POP mode	'Standard' HyPOP mode
ALE (isopycnal, Z on top)	NA	hybrid layered model
ALE (Z near topography)	NA	mixed ALE mode

- **This framework allows us to make quantitative comparisons to test:**
  - Improvements in tracer advection and diffusion on a Z versus isopycnal grid.
  - Additional computation required for interpolation when two grids are used.

HyPOP: Versatility in both Tracer and Momentum Grids

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Z-level	POP mode	'Standard' HyPOP mode
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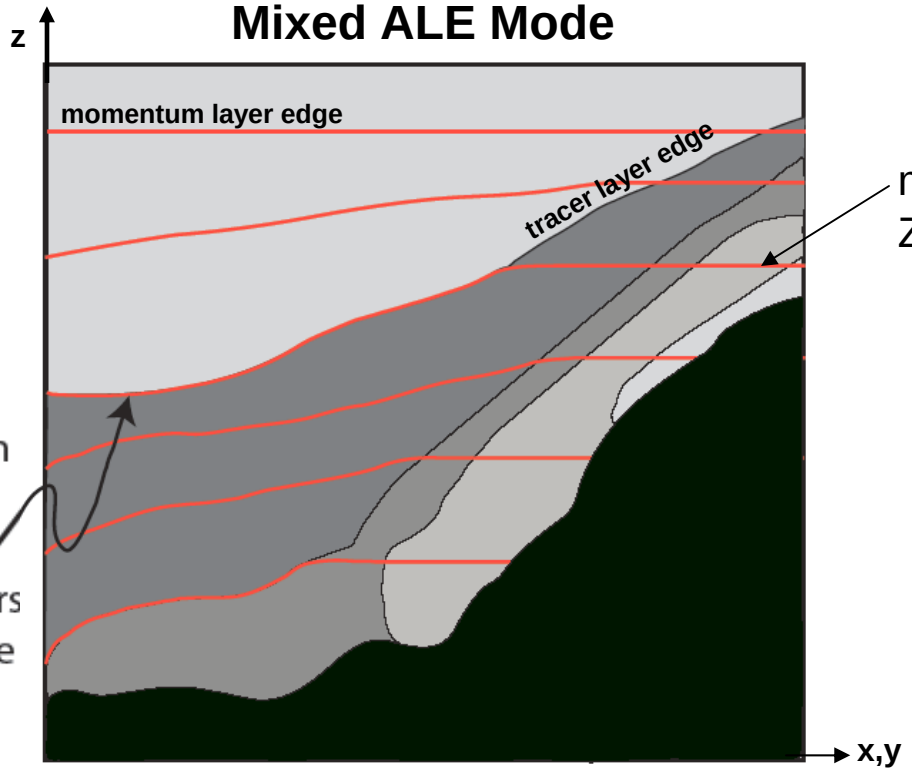
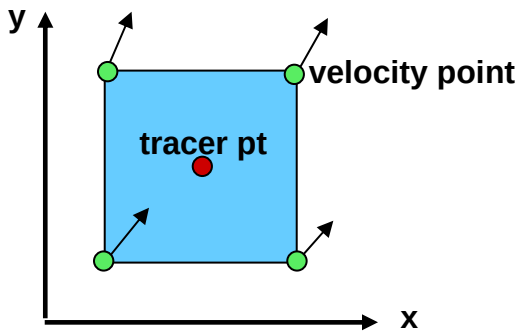


The momentum equation is discretized on a hybrid Lagrangian/z-level grid in order to minimize errors due to interpolation while also reducing spurious motion near boundaries.

Other Details

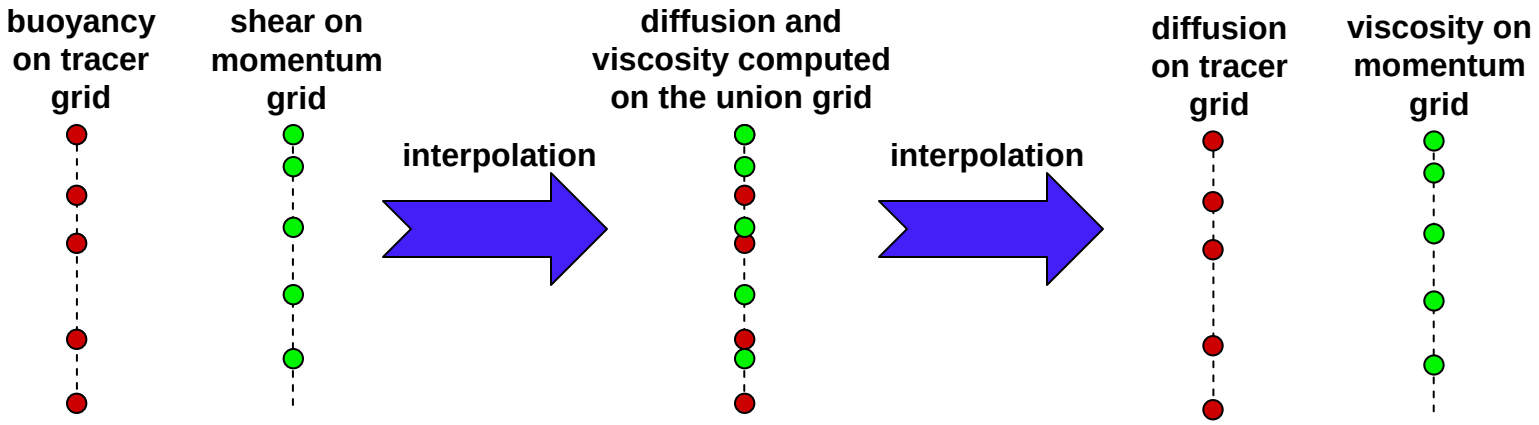
	POP	HyPOP
Horizontal Grid	B-grid	B-grid
Horizontal Advection	centered diff.	incremental remapping centered diff. still an option
Timestepping	leapfrog	leapfrog Two-level schemes to be implemented later.
Barotropic/baroclinic splitting	Split implicit/explicit	Split implicit/explicit

B-grid: Velocities on corners



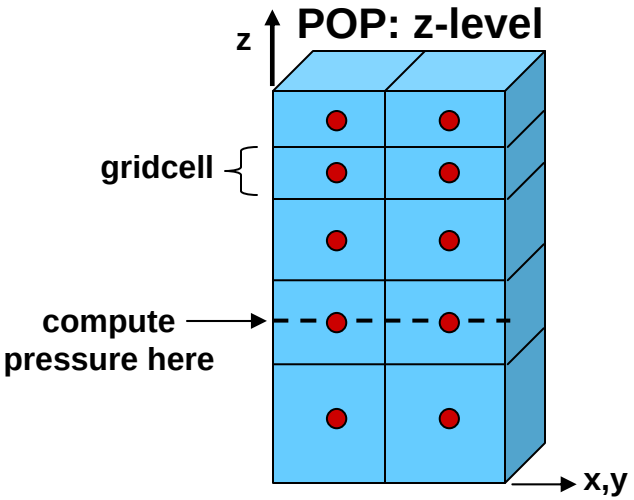
HyPOP: Vertical diffusion conducted on Union Grid

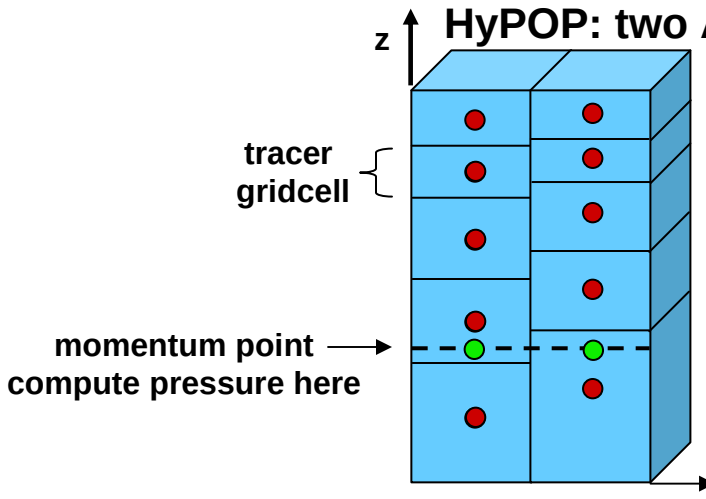
- **Vertical diffusion coefficients are needed on the tracer grid.**
- **Viscosity is needed on the momentum grid.**
- **Both are computed using parameterizations (KPP, Richardson number) that use:**
  - Shear from the momentum grid
  - Buoyancy from the tracer grid
- **Parameterizations are implemented on a Union grid.**
- **This avoids loss of accuracy due to interpolation from tracer to momentum grid, and vice versa.**



HyPOP: How do we avoid the thermobaric instability?

- The density is a function of pressure (depth) as well as T and S.
- POP: computes $p(z) = -\int_0^z \rho g dz'$ as a simple linear sum, $p_K = -g\sum_{k=1}^{K} \rho_k \Delta z_k$
- This works because neighboring columns have gridpoints at the same depth.
- HyPOP: Like HYCOM, neighboring columns have gridpoints at different depths, so computation of pressure must be more accurate. If not, spurious pressure gradients form.
- We construct a cubic spline of density in each column, and compute p at each momentum level by integration of the cubic spline.

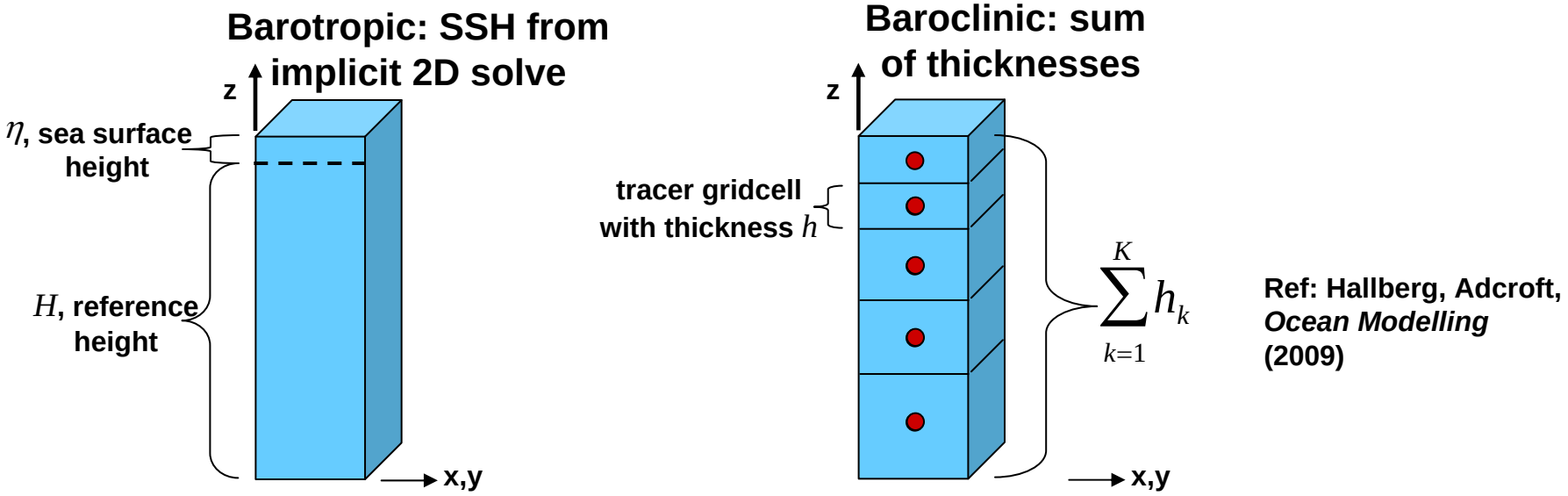




Ref: Adcroft, Hallberg, Harrison, *Ocean Modelling* (2008)

HyPOP: Reconcilining barotropic and baroclinic SSH

- **POP and HyPOP use barotropic/baroclinic splitting:**
  implicit barotropic, explicit baroclinic, with the same timestep.
- **Barotropic SSH includes surface gravity waves**
- **Layer thicknesses, which are treated as a tracer, do not include surface gravity waves.**
- **Sum of baroclinic layer thickness does not match the barotropic SSH.**
- **Correction: Could simply stretch $\sum_{k=1}^{K} h_k$ to match $H + \eta$, but this causes spurious diapycnal mass flux.**
- **We implemented a flux correction to the baroclinic layer thicknesses.**

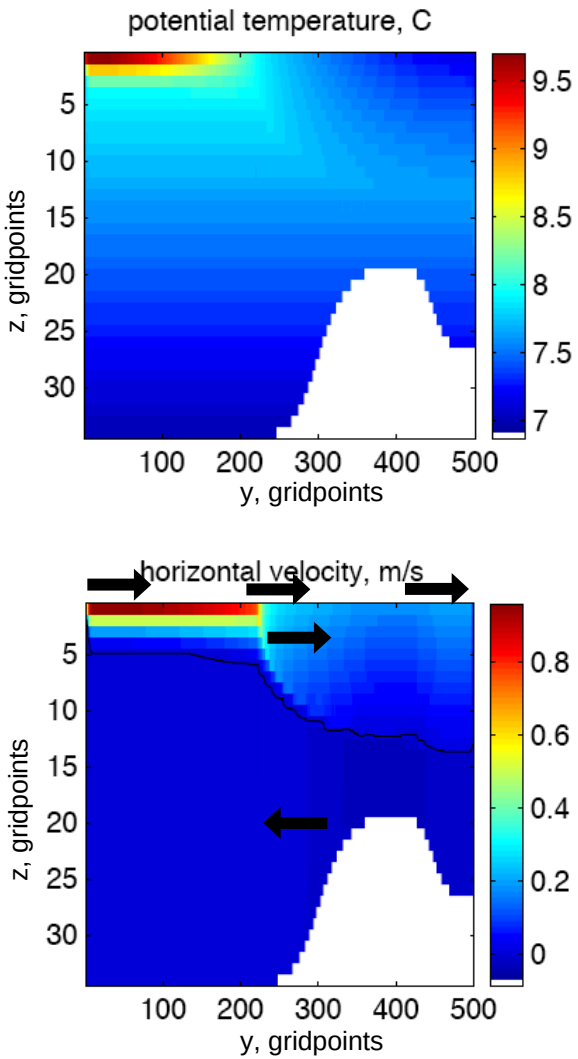


Ref: Hallberg, Adcroft, *Ocean Modelling* (2009)

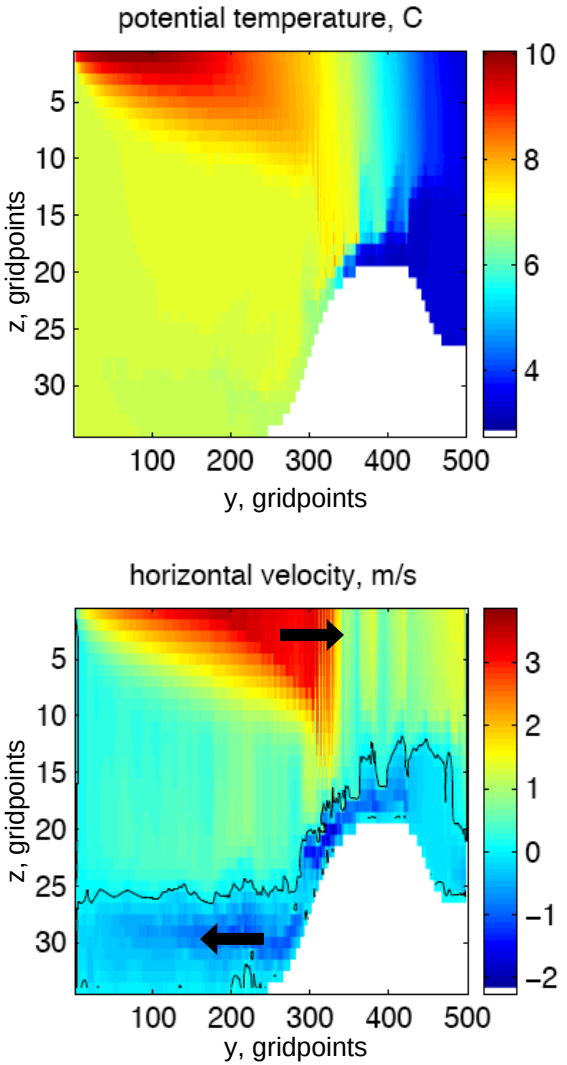
Overflow Domain and Forcing

- 2D domain, in y-z
- Coriolis force is off
- surface forcing of 12C to 2C
- surface wind stress
- vertical diffusion using kpp

POP
After one day

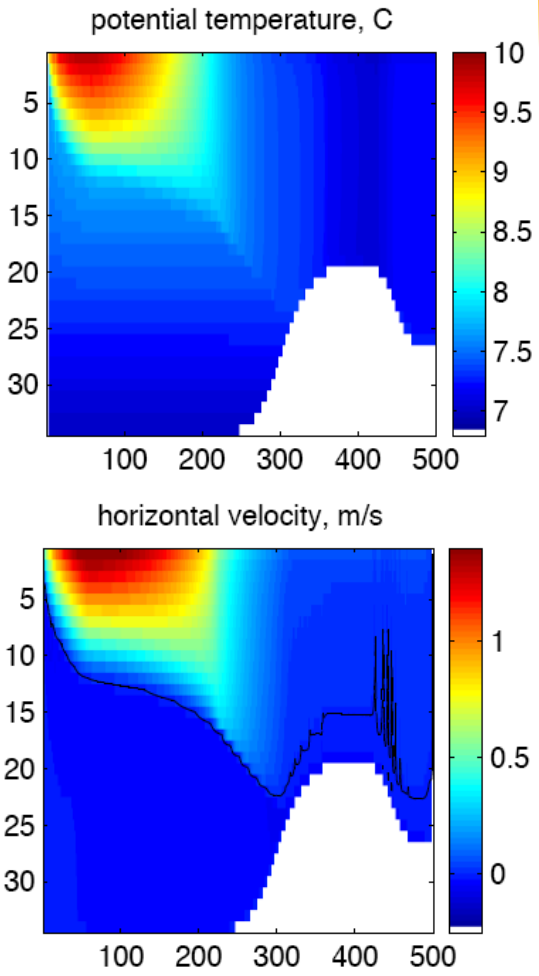


POP
After one year

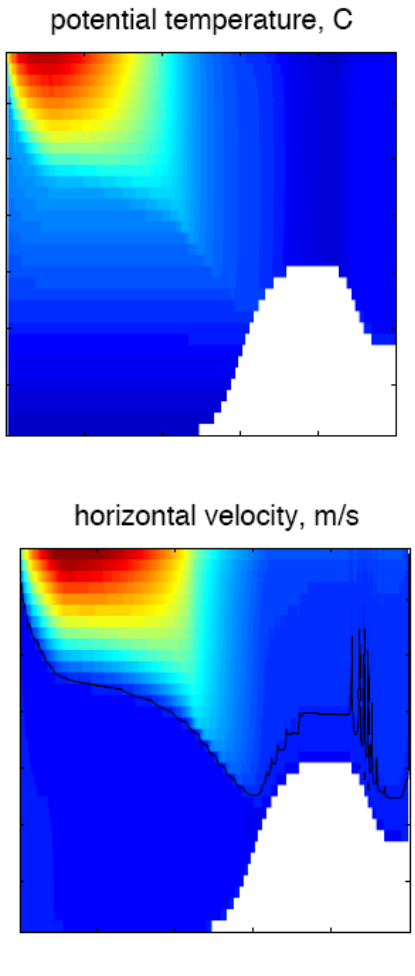


Simulation at Day 6

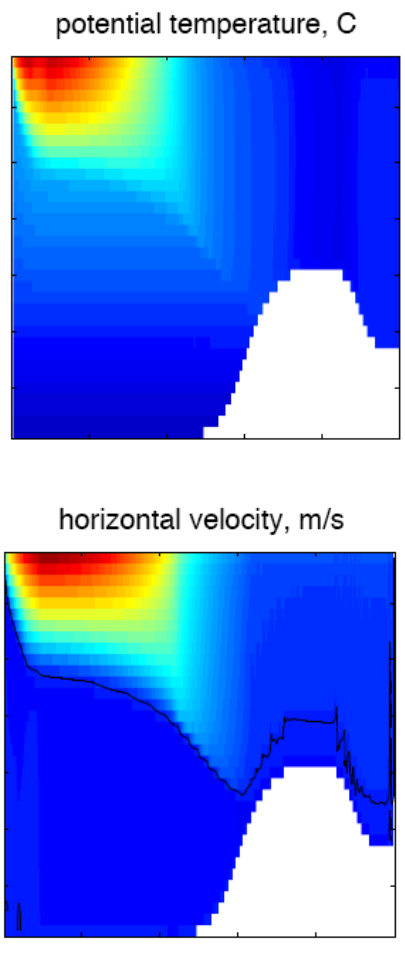
POP
One grid: Z-level
centered diff. advection



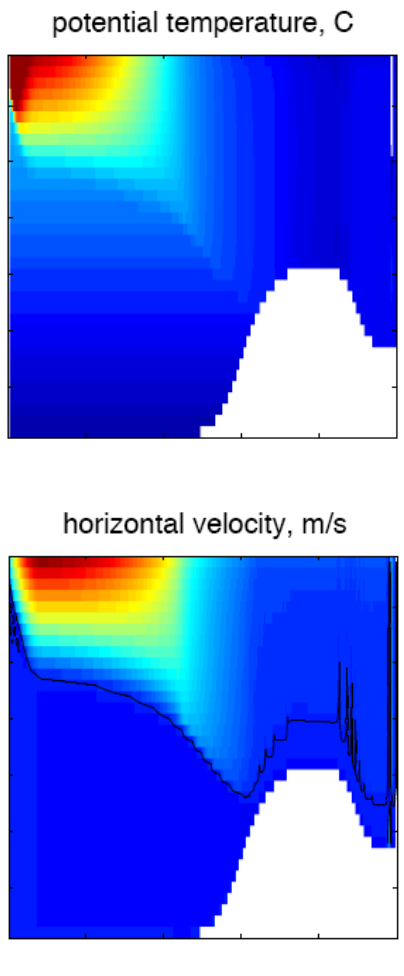
HyPOP in POP mode
momentum: Z-level
centered diff. advection
tracers: Z-level
centered diff. advection



HyPOP
momentum: Z-level
centered diff. advection
tracers: ALE, remap to Z
every 10 steps
incremental remap adv.



HyPOP
momentum: Z-level
centered diff. advection
tracers: ALE,
no remapping,
incremental remap advection



HyPOP: Conclusions

- **HyPOP infrastructure development is largely complete.**
- **Recent items:**
  - Vertical diffusion (KPP, Richardson number) conducted on union grid.
  - Cubic spline interpolation of density, integrate to compute pressure.
  - Reconciling SSH from the sum of baroclinic layer thickness with SSH from barotropic mode: use flux correction.
- **Next:**
  - Time-dependant regridding (relaxation to target grid)
  - Further testing with different vertical grids for momentum and tracers
- **Then moving into research and testing, including:**
  - Evaluate various grid combinations
  - Criteria for transition from Z-level in mixed layer to isopycnal grid at depth
  - Evaluation of HyPOP in global simulations
  - Improving efficiency of the code