Towards ALE vertical coordinates in NEMO

Notes by Alex Megann for NEMO Kernel WG meeting on 30 May 2018

Numerical mixing in ocean models

Most ocean models use constant-depth levels ("z-coordinate").

- Advective transport is along the principal coordinate axes.

Mixing schemes imply natural separation between isopycnal (along density surfaces) and diapycnal (across them) directions, but these are generally not parallel to coordinate axes.

Flow across a coordinate surface inevitably leads to diapycnal mixing.

Examples:

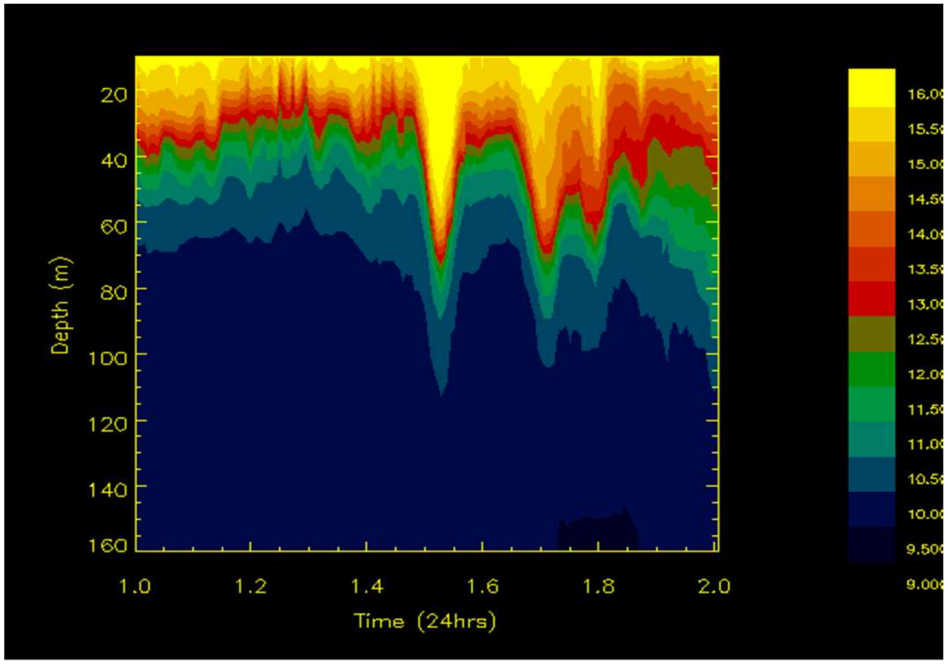
- Transient vertical displacements (heave) of density surfaces associated with eddies and waves;

- Overflows of dense water (e.g Arctic water) over sills

Isopycnal heave

During passage of non-breaking surface and internal waves, as well as tides and eddies, density surfaces rise and fall (isopycnal heave).

Normally adiabatic and does not usually lead to significant mixing (in the real world, that is!)

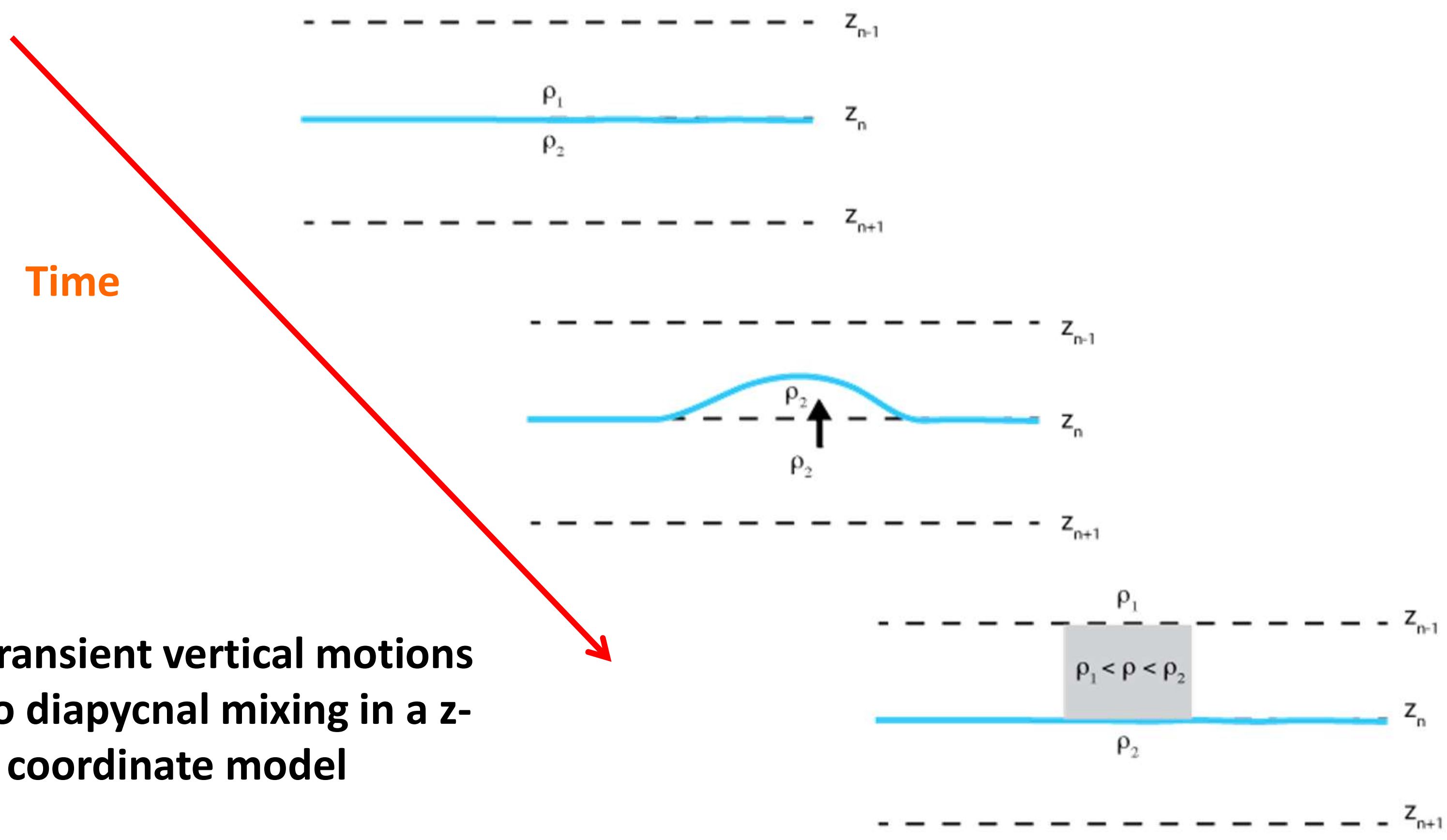


Internal waves observed in thermistor chain time series on northwest UK shelf margin

from the Shelf Edge Study Acoustic Measurement experiment (SESAME)

Numerical mixing and waves

Vertical displacements of isopycnals (heave) due to waves and eddies
--> cross-coordinate motion, naturally causing mixing.



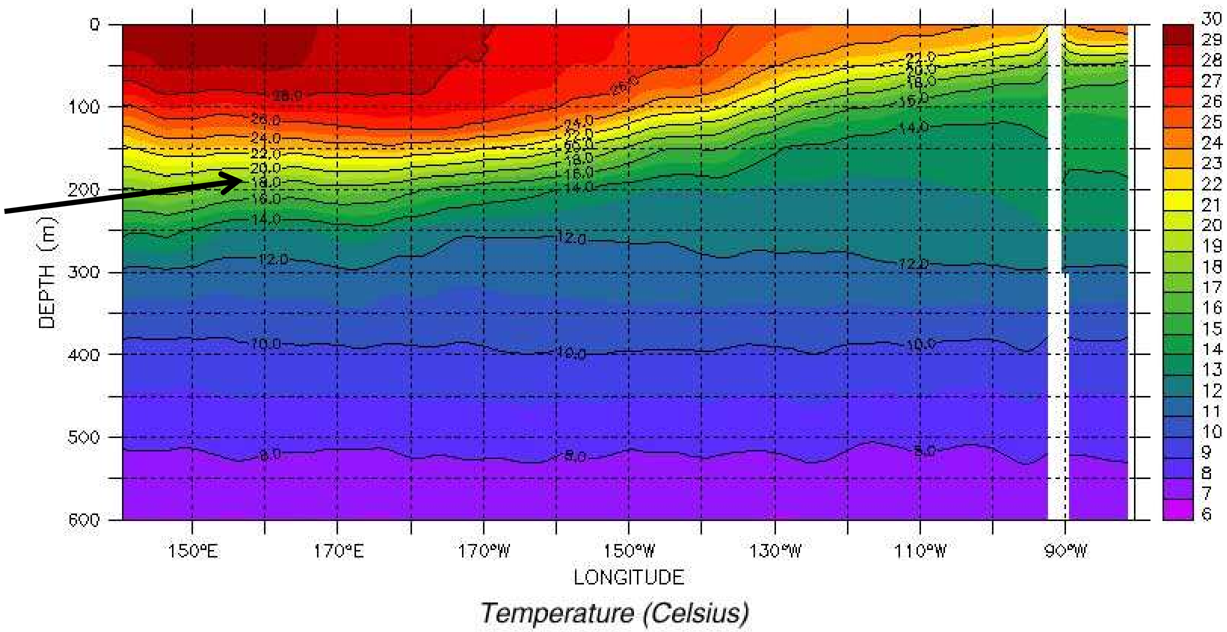
How transient vertical motions lead to diapycnal mixing in a z-coordinate model

Numerical mixing in sloping flows

In a sloping current (e.g. the Equatorial Undercurrent (EUC), but also oceanic gyres) between one coordinate level and another, numerical mixing occurs in a similar way.

Core of EUC follows approximately 18°C contour.

It rises by 150m from 150°E to 90°W: in NEMO ORCA025 grid it crosses about 15 vertical levels

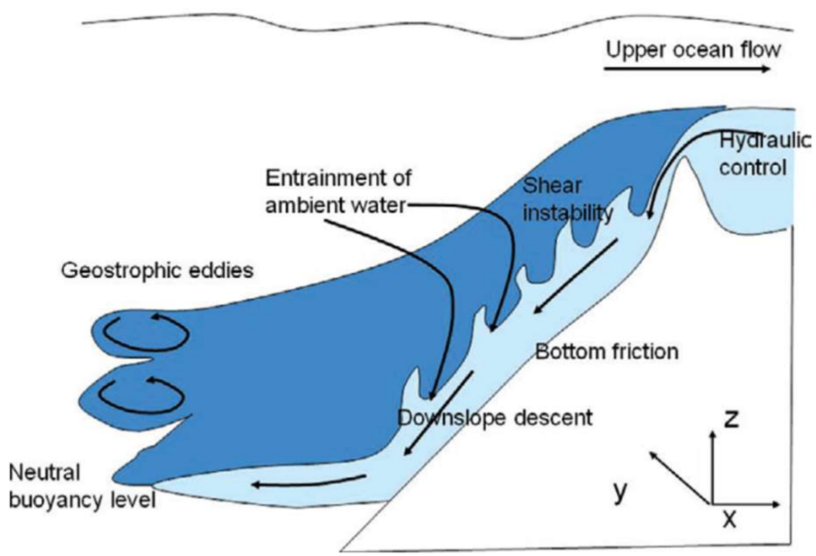


Temperature section in the Equatorial Pacific

(Figure: Texas A&M Uni)

Mixing at sill overflows in the real ocean

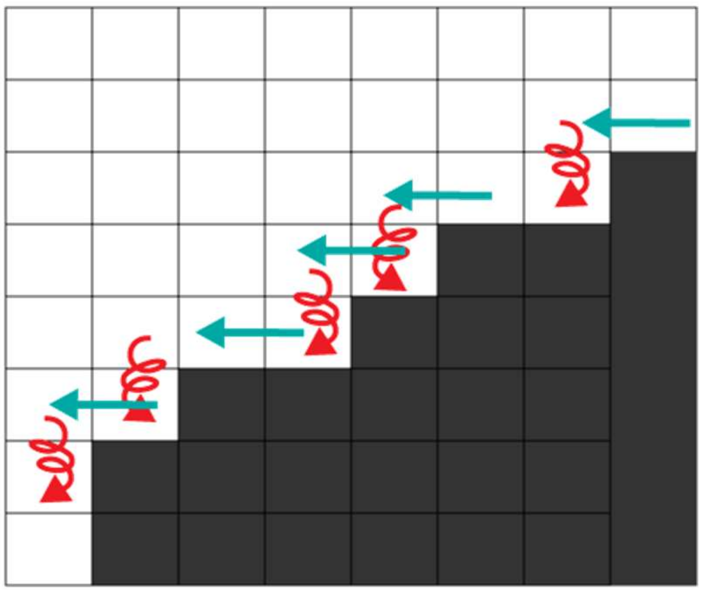
- Arctic water crosses into North Atlantic at key sills (around 600-1,000 metres depth), then flows down to the abyss or to depth of neutral buoyancy.
- Antarctic Bottom Water is formed on Antarctic shelf and then cascades off shelf edge into deep ocean.
- Entrainment processes cause mixing with surrounding water and an increase of volume transport. Should be able to parameterise these.



Processes at sill overflows
(Picture: Sonya Legg)

Mixing at sill overflows in models

Unfortunately in a z-coordinate model dense water mixes convectively with underlying water as it flows out over the sill.

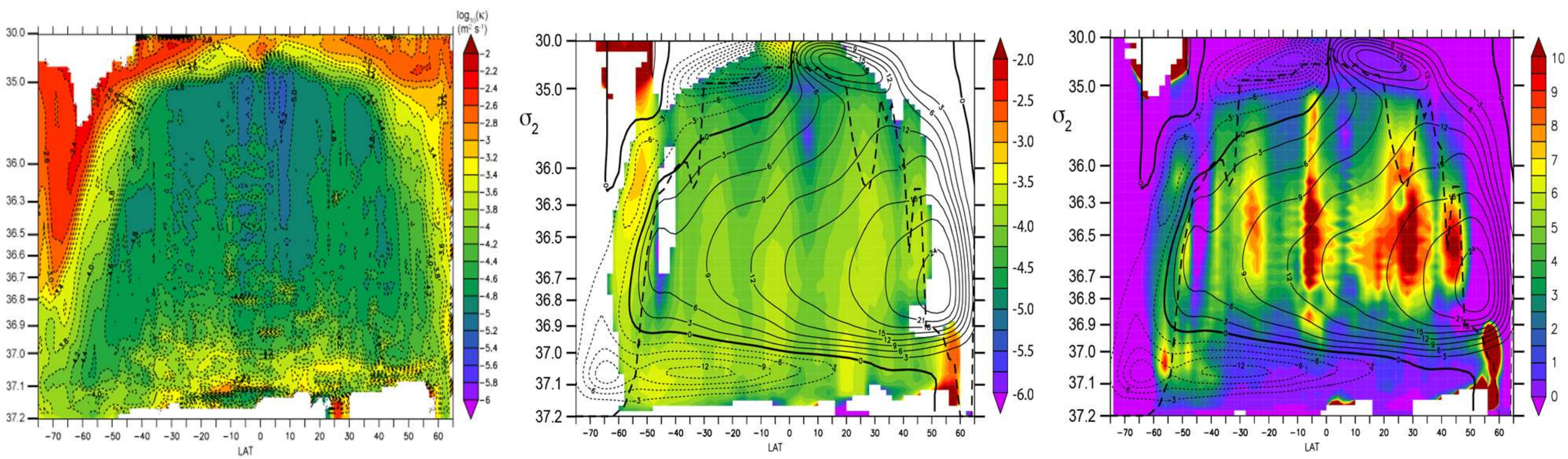


Numerical entrainment of dense overflows

In these models mixing and consequent entrainment rate are substantially larger than those observed in the real world.

How significant is numerical mixing in NEMO?

Megann (2018) showed that, in the GO5.0 NEMOv3.4 ORCA025 configuration, the diagnosed diapycnal diffusivity was 5-10 times the explicit diffusivity over much of the intermediate and deep waters of the ocean.

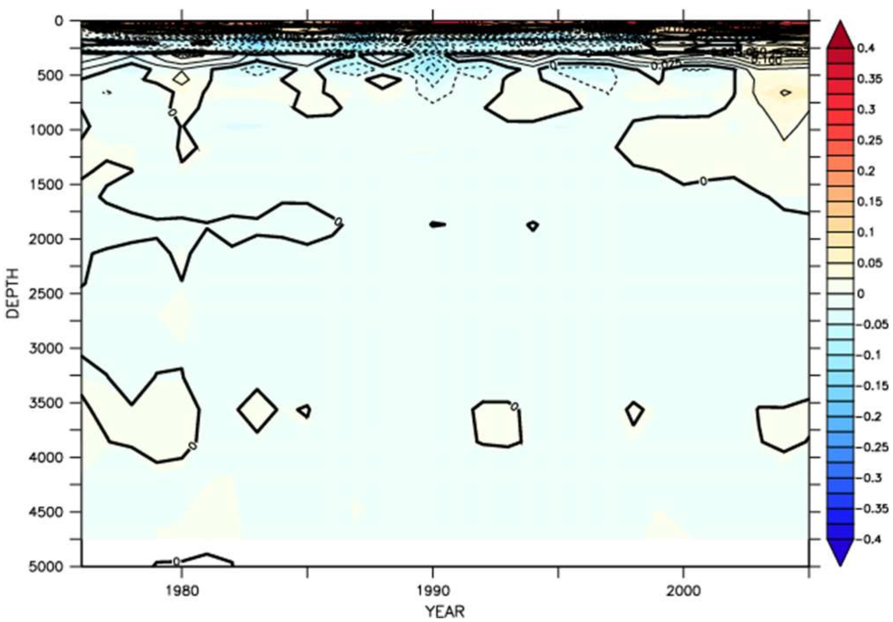


Explicit κ **Diagnosed effective κ** **Ratio of diagnosed to explicit κ**

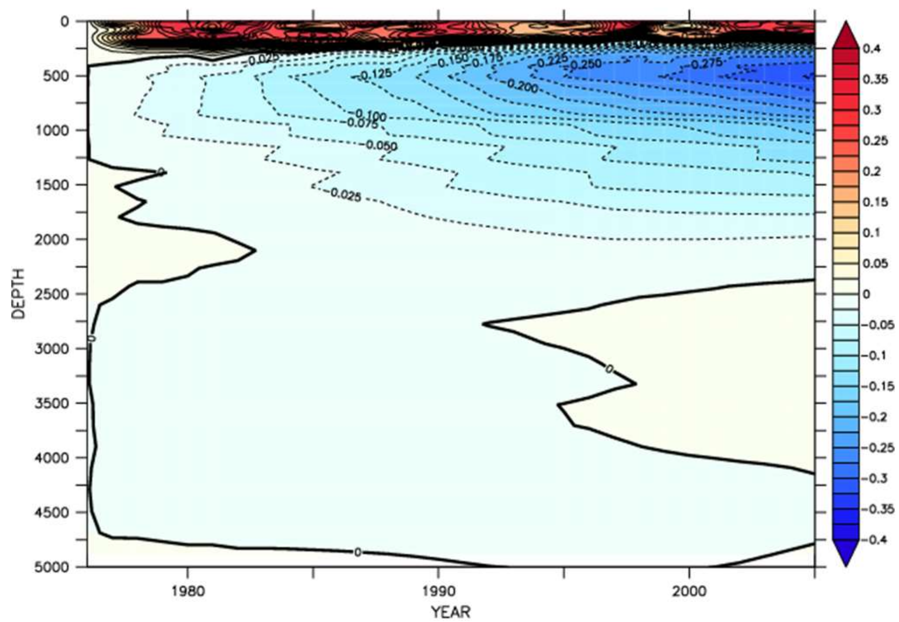
Diapycnal diffusivity κ in the global domain in GO5.0.

Consequences of numerical mixing

The GO5.0 ocean shows large-scale drifts in temperature, not totally inconsistent with excessive downward mixing of heat



Global temperature drift in EN4 climatology



Global temperature drift in GO5.0

Tackling numerical mixing

The numerical mixing in z-coordinate models arises from the combination of two causes:

- The coordinate surfaces do not correspond to any natural direction of flow, or align with isolines of any conserved field. As a result, there is a substantial amount of advection across coordinate surfaces.

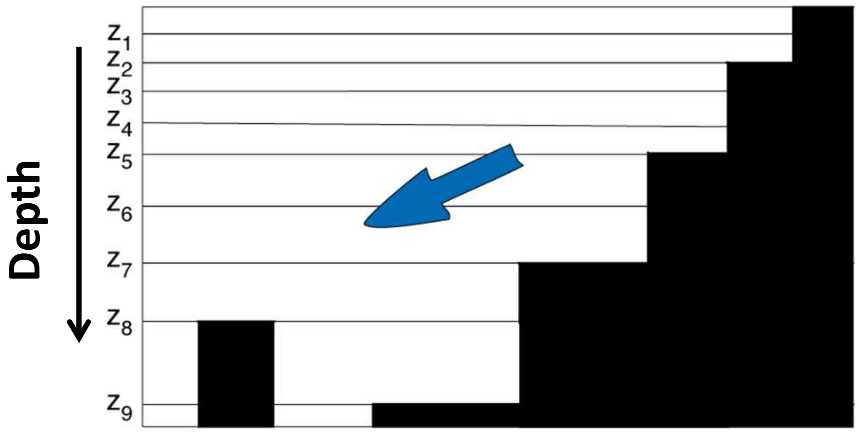
- The advection schemes have truncation errors which cause unphysical diffusive mixing.

So to address numerical mixing we need to put effort into ameliorating either or both of the above.

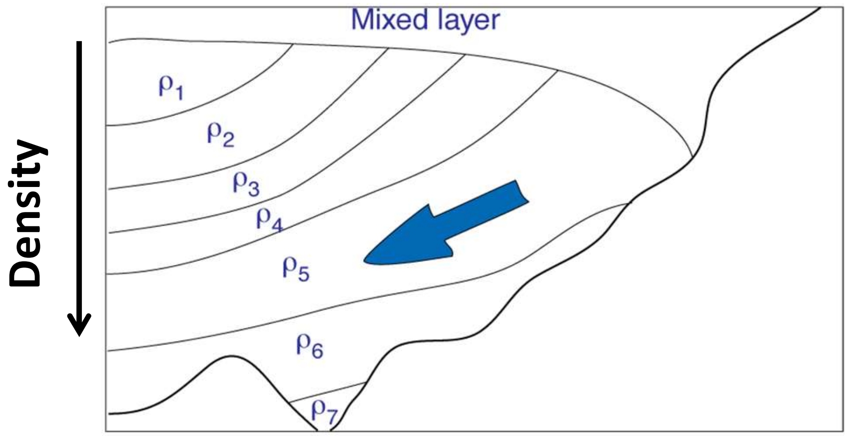
One approach is to modify the vertical coordinate so it can more naturally follow adiabatic surfaces in the model.

Isopycnal coordinates

Isopycnic models (e.g. MICOM, GOLD) have potential density as their vertical coordinate, instead of depth. Flow is naturally along coordinate surfaces: vertical advection is absent by construction.



Level or "z-coordinate" model



Isopycnic-coordinate model

Practical disadvantages include:

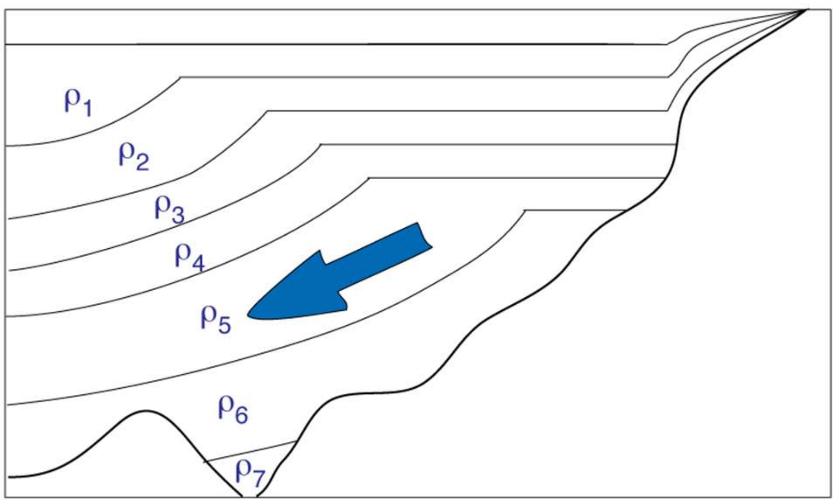
- Loss of vertical resolution in unstratified regions and within mixed layer;
- Unphysical detrainment at mixed layer base

Hybrid coordinates

Hybrid-coordinate models (e.g. HYCOM, *Bleck 2002*) combine some advantages of both depth-coordinate models and isopycnic models.

- Density levels which would otherwise outcrop into mixed layer are replaced with levels with some minimum thickness. This partially overcomes limitations of HYCOM in weakly stratified regions.

- Terrain-following coordinates can be used on the shelves to better resolve overflows.



Schematic of HYCOM hybrid-coordinate model

Arbitrary Lagrangian-Eulerian (ALE) coordinates

- In an ALE system, the coordinate interfaces evolve in time as a result of convergent/divergent volume or mass fluxes. At each time step the interface depths are updated ("regridding") and the fields within each layer are remapped onto the new vertical grid:

$$\frac{\partial \Delta z_k}{\partial t} = \nabla . (\boldsymbol{v} \Delta z_k) + (\dot{s}\, \frac{\partial z}{\partial s}_{\mathrm{bot}}) \text{ - } (\dot{s}\, \frac{\partial z}{\partial s})_{\mathrm{bot}}$$

where s is the (unspecified) vertical coordinate, Δz_k is the thickness of layer k, and ***v*** the horizontal velocity field.

How does HYCOM work?

- Essentially a density-coordinate model derived from MICOM: vertical coordinate in ocean interior is potential density (usually σ_2);
- Near-surface layers have minimum thickness, independent of time and x/y. Normally increases with depth, and only applies to fixed number of layers. Isopycnal layers transition to fixed layers with variable density;
- "Slack" scheme allows an elasticity of these layers on time periods shorter than 1-2 days, allowing waves to distort layer depths without incurring numerical mixing (similar to z~);
- Mixing is separated into isopycnal and diapycnal directions;
- T and S are allowed to evolve freely in each layer, so density can change. At the end of each baroclinic timestep the layer interface depth is adjusted to nudge the layer density back towards the target value using a mass-conserving advection scheme (normally PPM or higher)

Limitations of HYCOM

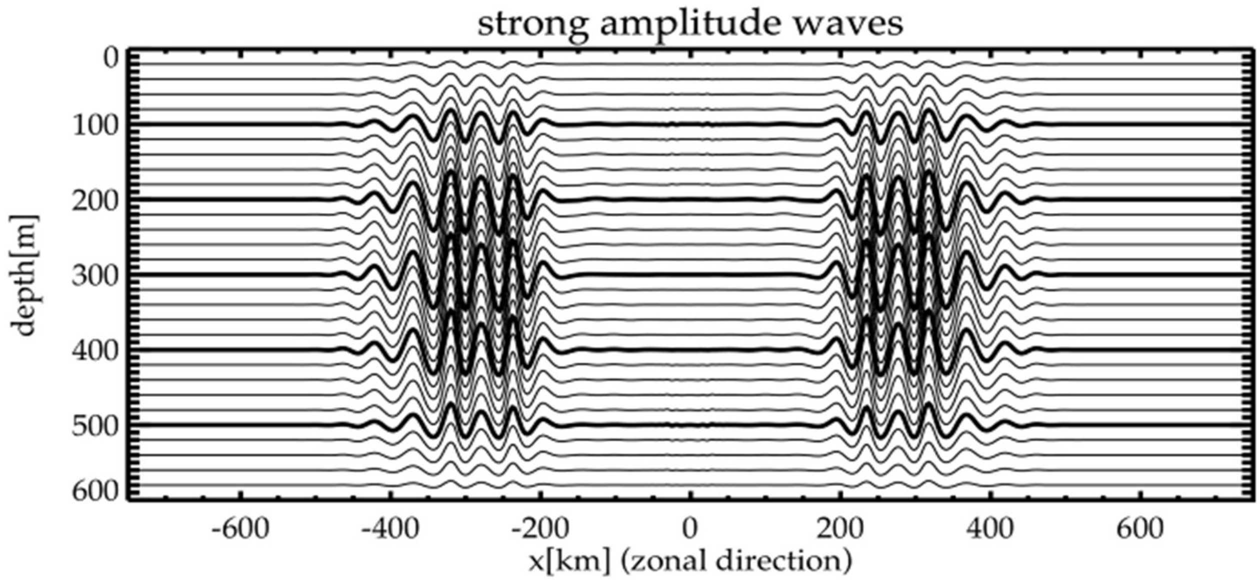
HYCOM has much reduced numerical mixing by design, but is is still not perfect.

- Vertical regridding is still necessary, because of cabbeling and thermobaricity, as well as interaction with fixed-depth near-surface layers, and numerical mixing is sensitive to advection scheme used;
- Problems with vertical resolution in unstratified regions (e.g. high latitudes) remain;
- No potential density coordinate is everywhere monotonic with depth (although sigma-2 almost so), so some water masses not representable;
- Pressure gradient errors remain, albeit at a low level: HYCOM implements a linear correction for thermobaricity based on a fixed background state;
- Transition between fixed-coordinate and isopycnic regime may be problematic (i.e. can result in excessive numerical mixing);
- Choice of minimum layer thicknesses is arbitrary.

Z~ in NEMO

- Version 3.6 and onward of NEMO have a modification **z~** to allow vertical depth coordinate to flex elastically to pass fast waves without numerical mixing (analogous to “slack” in HYCOM).

- LeClair and Madec (2011) found that **z~** reduced amount of mixing from this source by more than a factor of 5.



Vertical grid distortion associated with passage of large internal wave in NEMO channel model with z~ scheme enabled (from LeClair and Madec, 2011)