Use of isopycnic-coordinate ocean models in long-term global simulations

Rainer Bleck

NASA Goddard Institute for Space Studies
New York

June 2015

Subtitle, slightly more to the point:

Relaxing the incompressibility assumption in the isopycnic-coordinate ocean model HYCOM

The issue

In HYCOM we traditionally

(1) replace in-situ density ρ by potential density ρ_{pot}

(2) treat the fluid as incompressible.

According to Spiegel and Veronis (1960), these are defensible and mutually consistent approximations.

They create problems with thermobaricity.

More importantly, globally referenced ρ_{pot} is not necessarily monotonic in *z* in the real ocean.

What Spiegel and Veronis (1960) say:

The equations governing convection in a perfect gas are formally equivalent to those for an incompressible fluid if the static temperature gradient is replaced by its excess over the adiabatic … and the following approximations are valid: (a) the vertical dimension of the fluid is much less than any scale height, and (b) the motion-induced fluctuations in density and pressure do not exceed ... the total static variations of these quantities.

The issue (cont'd)

The Spiegel-Veronis approximation, combined with the use of ρ_{pot} as vertical coordinate, allows us to reduce the 2-term pressure gradient formula

$$a\nabla_z p = a\nabla p + g\nabla z$$

to a numerically stable 1-term expression:

$$a\nabla p + g\nabla z = \nabla_a (ap + gz)$$

where α now stands for the inverse of *potential* density ρ_{pot}

The finite-volume approach

- Goal: use realistic eqn. of state to overcome limitations of the Spiegel-Veronis approach. This requires reverting to the numerically problematic 2-term pressure gradient formula.

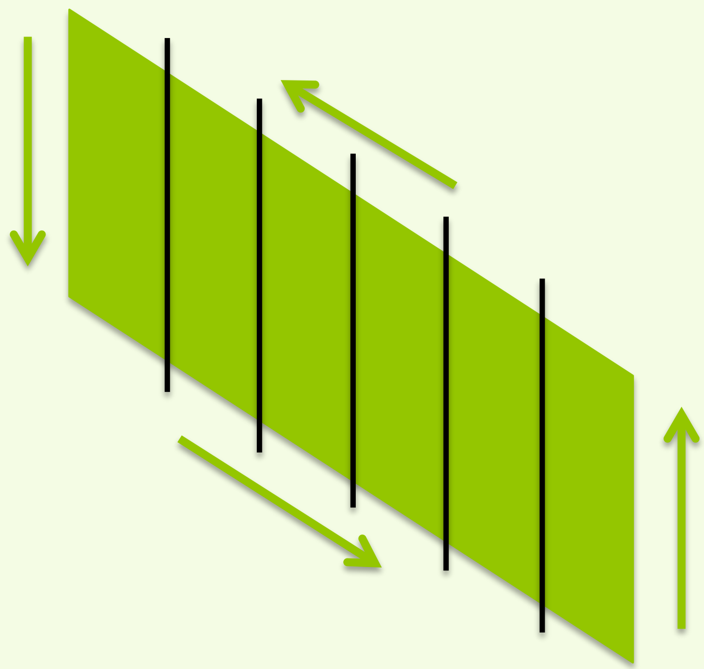
- The approach of Adcroft et al(1) is to replace the 2-term finite-difference PGF expression by a line integral of “contact pressure” along the perimeter of each grid cell in the vertical.

(1) Adcroft, A., Hallberg, R. and M. Harrison, 2008: A finite volume discretization of the pressure gradient force using analytic integration. *Ocean Modelling*. 22, (3-4), 106-113.

Green's Theorem:

$$\frac{1}{cell\,area}\iint_{area}\frac{\partial p}{\partial x}\,dx\,dz = \frac{1}{cell\,area}\oint_{perimeter} p\,\vec{k}\cdot d\vec{s}$$

"contact" pressure



Key to success:
high accuracy on
vertical segments
of line integral

Fear of coding errors….

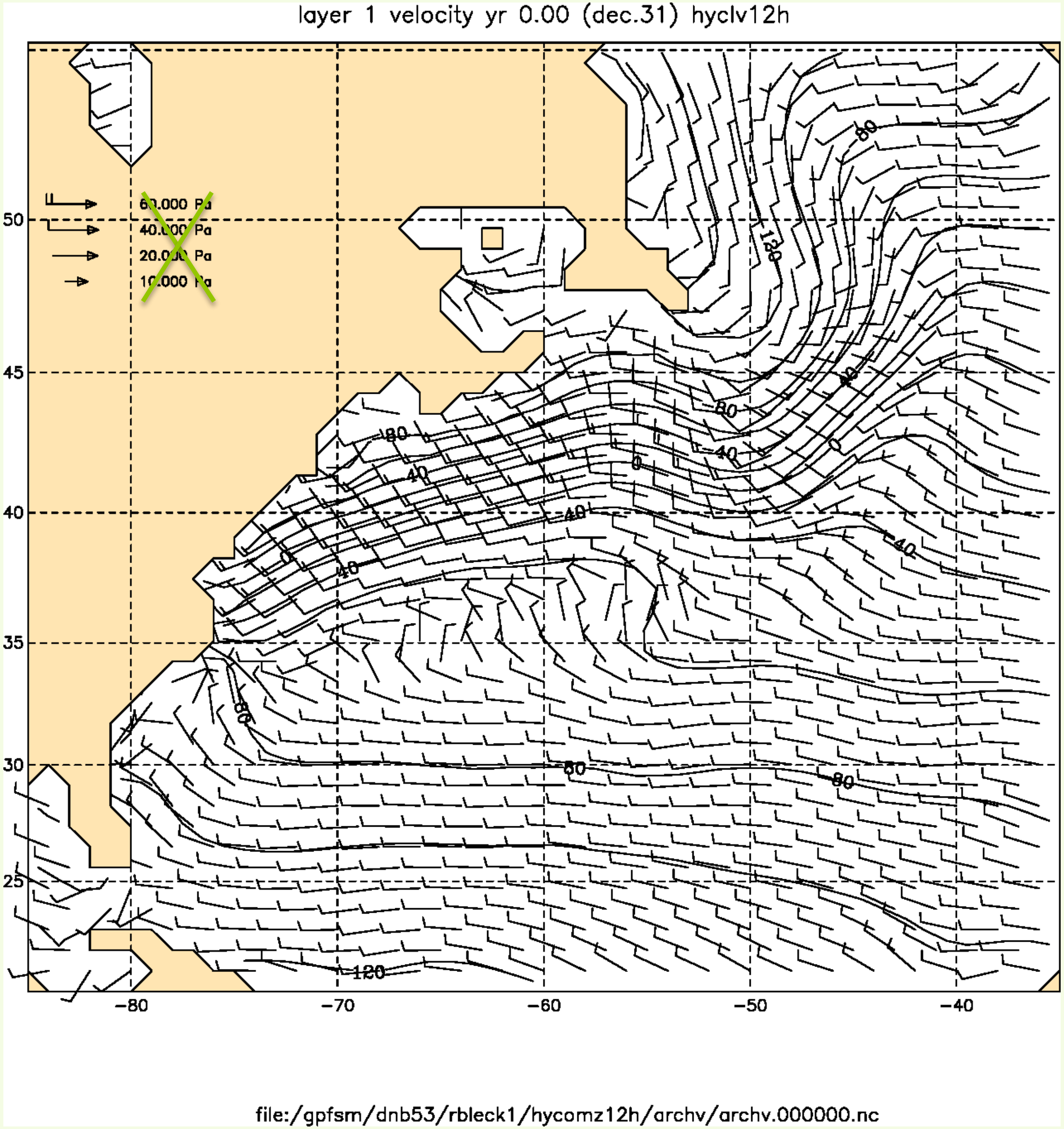
Validating PGF code: test 1

- Define spatially varying, strongly sloping layer interfaces and rugged bottom topography.
- Make *T,S* globally constant.
- Set sea surface height = 0.
- Get consistent bottom values of p and z via downward integration of hydrostatic eq^n.
- Integrate upward to find gz where needed.
- Compute *PGF* at all grid points.
- Correct answer to look for: *PGF = 0* everywhere.

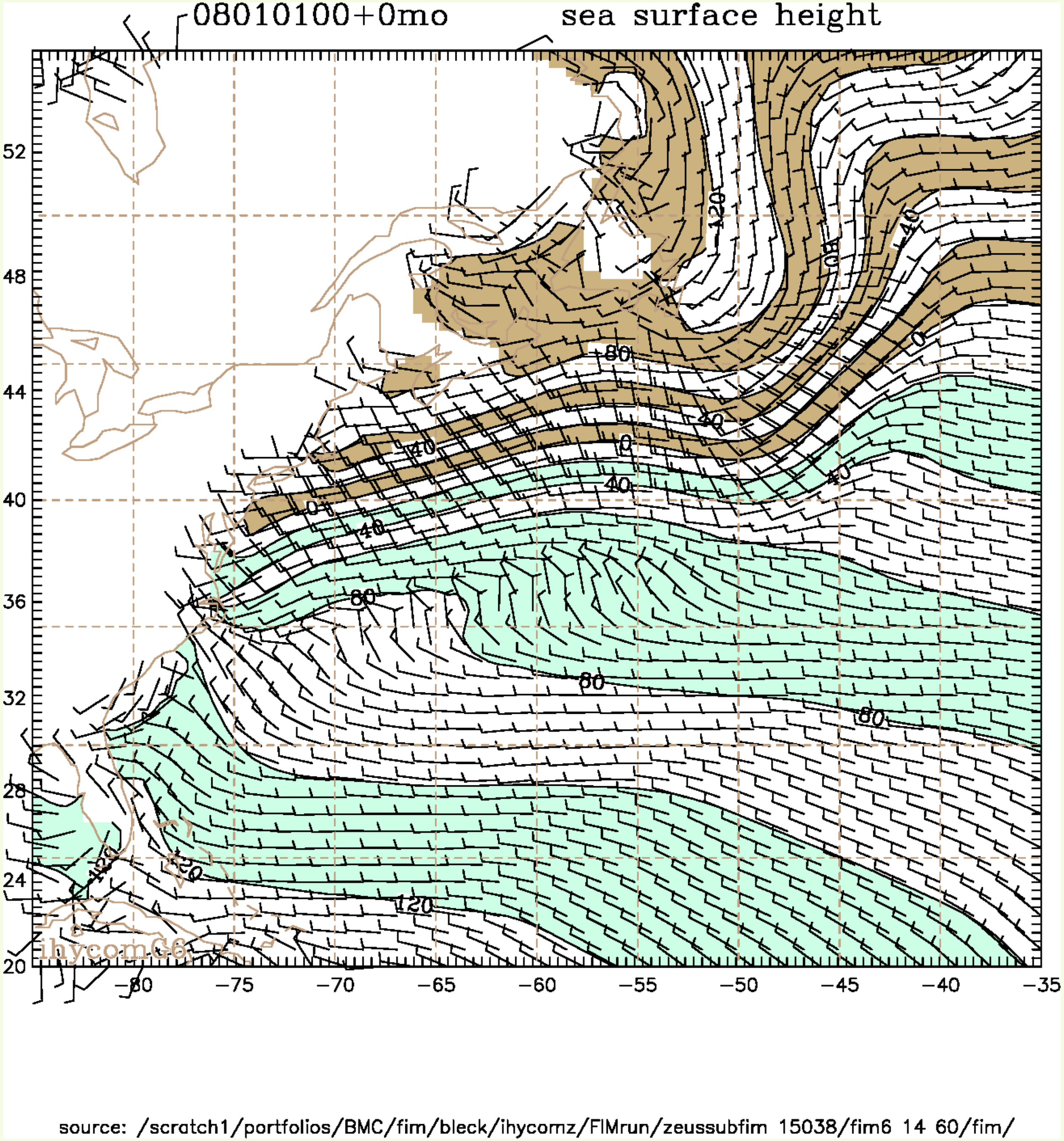
Validating PGF code: test 2

- Use realistic model state, including spatially varying layer interfaces and bottom topography.
- Cook up variable *SSH* (for example, let *SSH* ~ *SST*).
- Set *T,S =const* in **uppermost** model layer.
- Get consistent bottom values of p and z via downward integration of hydrostatic eq^n.
- Integrate upward to find gz where needed.
- Overlay top-layer geostrophic velocity vectors on *SSH* map.
- Check whether velocity vectors exactly follow *SSH* contours.

Testing the PGF code in Hycom: surface geostrophic flow superimposed on sea surface height



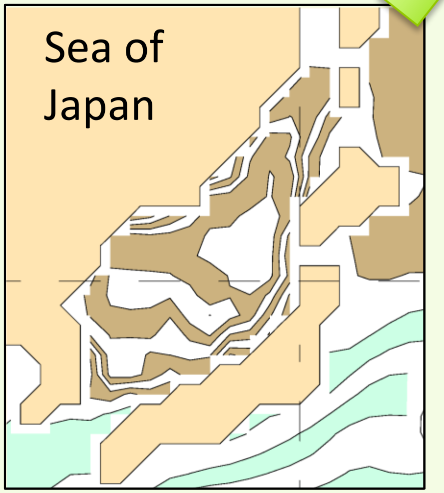
Same test, but in icosahedral version of Hycom: surface geostrophic flow superimposed on sea surface height

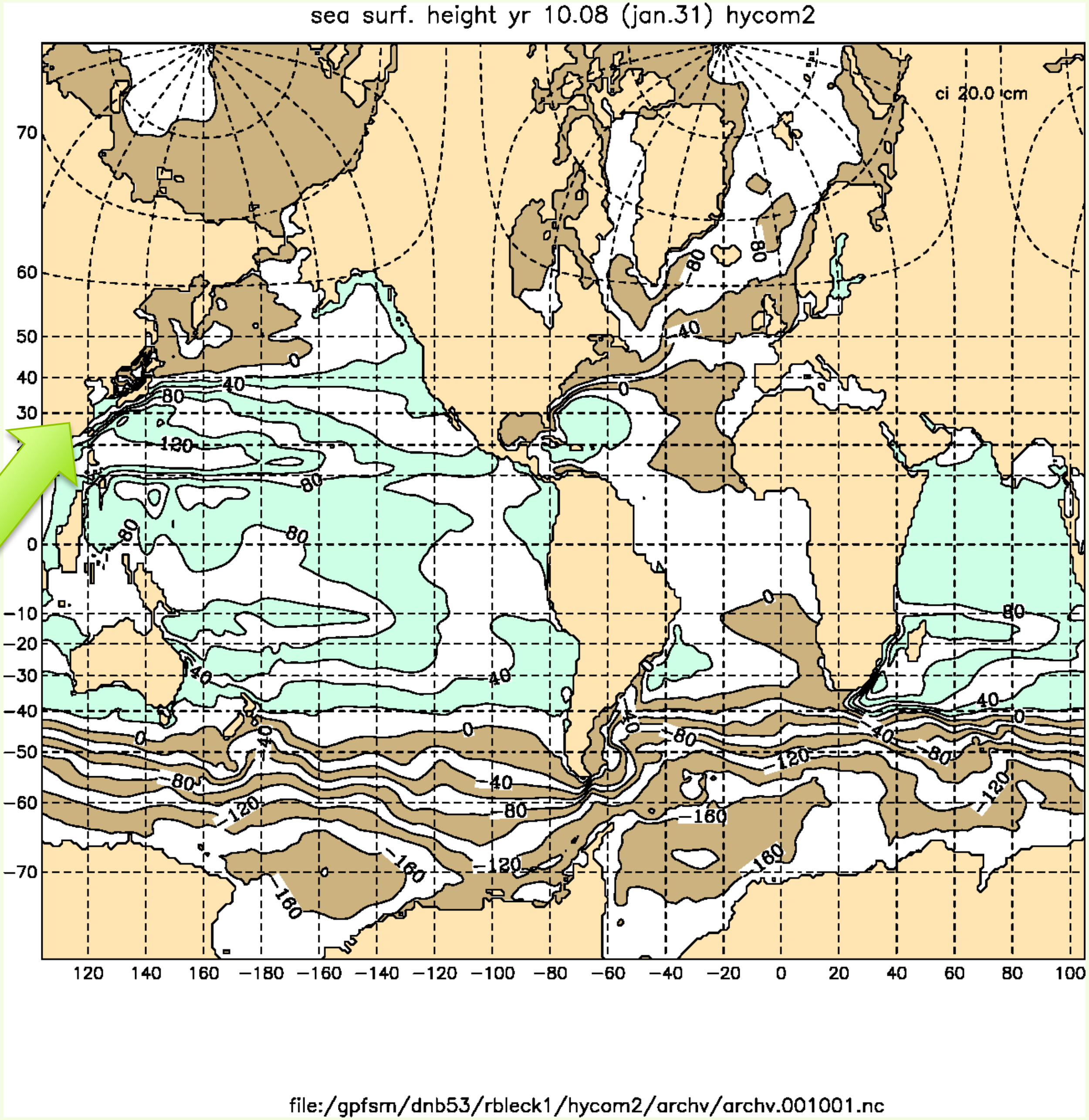


HycomC

(=hycom using compressible eqn. of state)

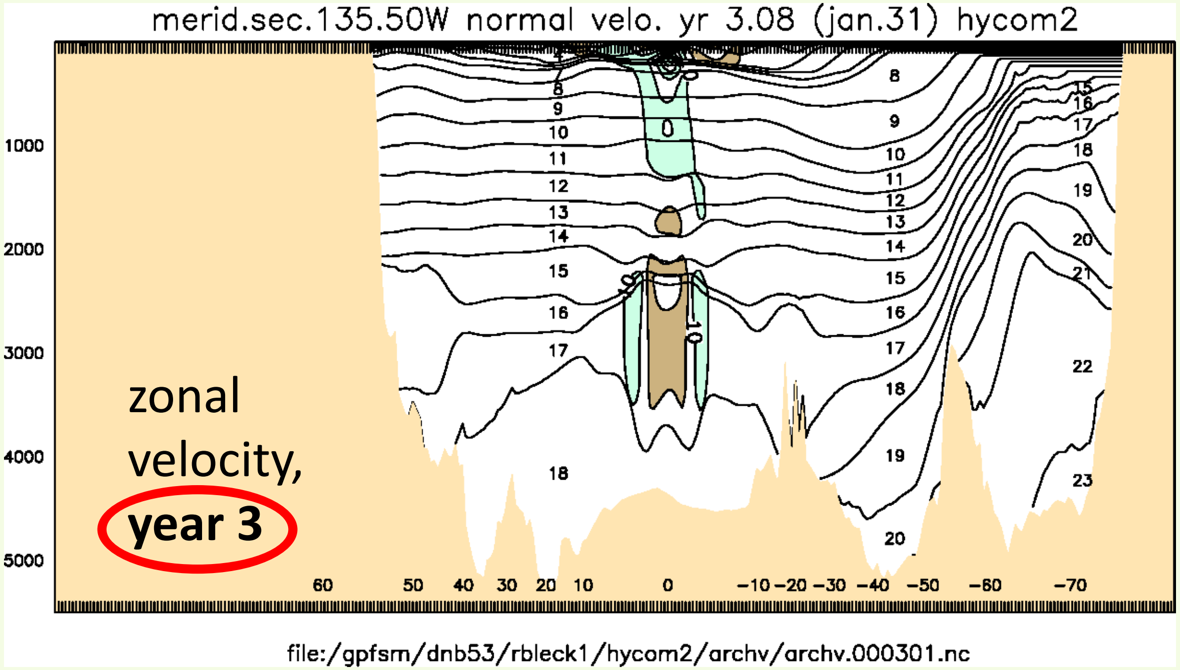
Monthly-averaged sea surface height, January **year 10**





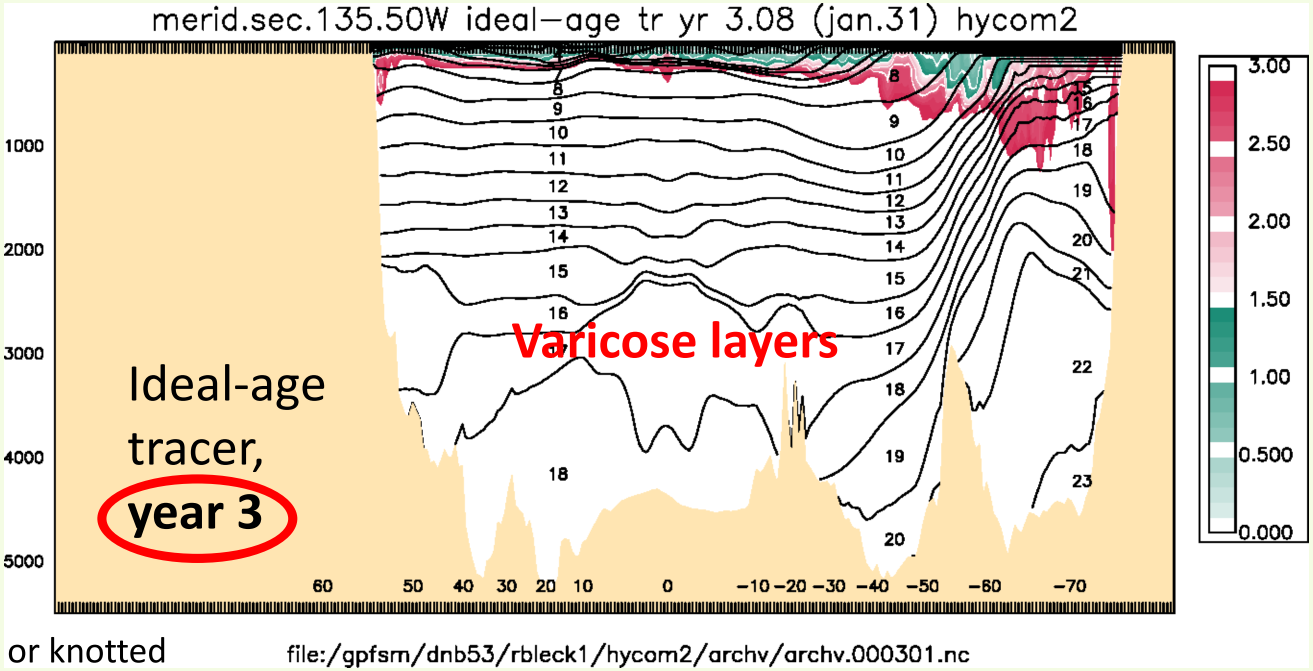
HycomC

(=hycom using compressible eqn. of state)



zonal velocity, **year 3**

Cross sections show additional problems … mid-depth varicose[1] layers

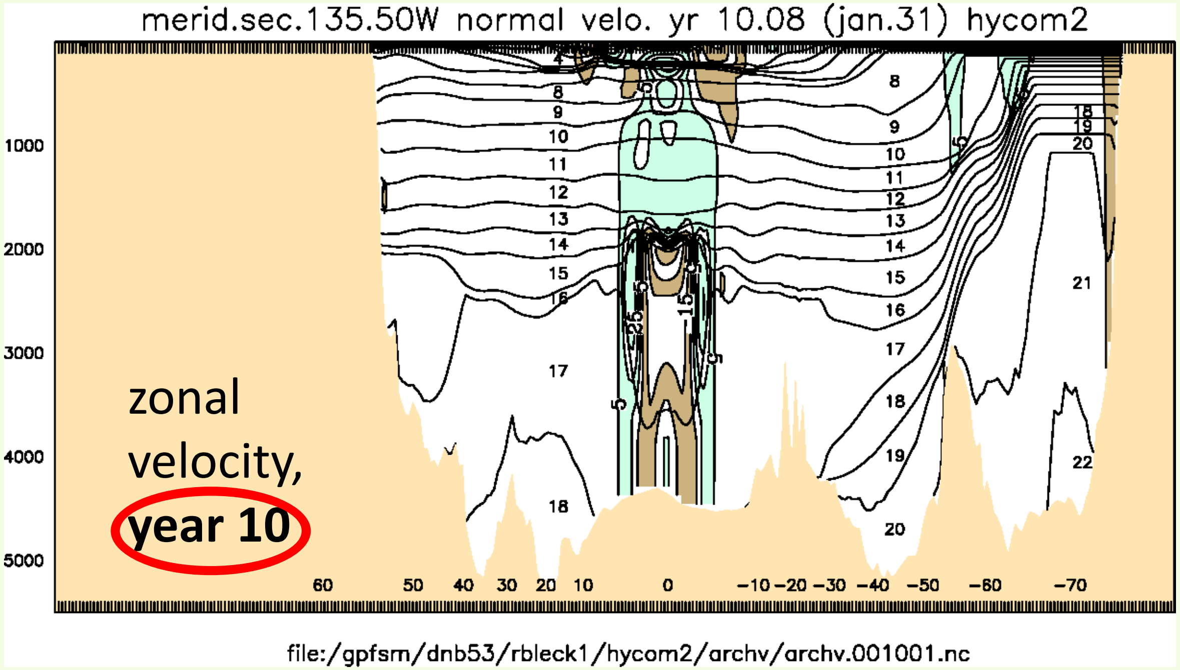


Ideal-age tracer, **year 3**

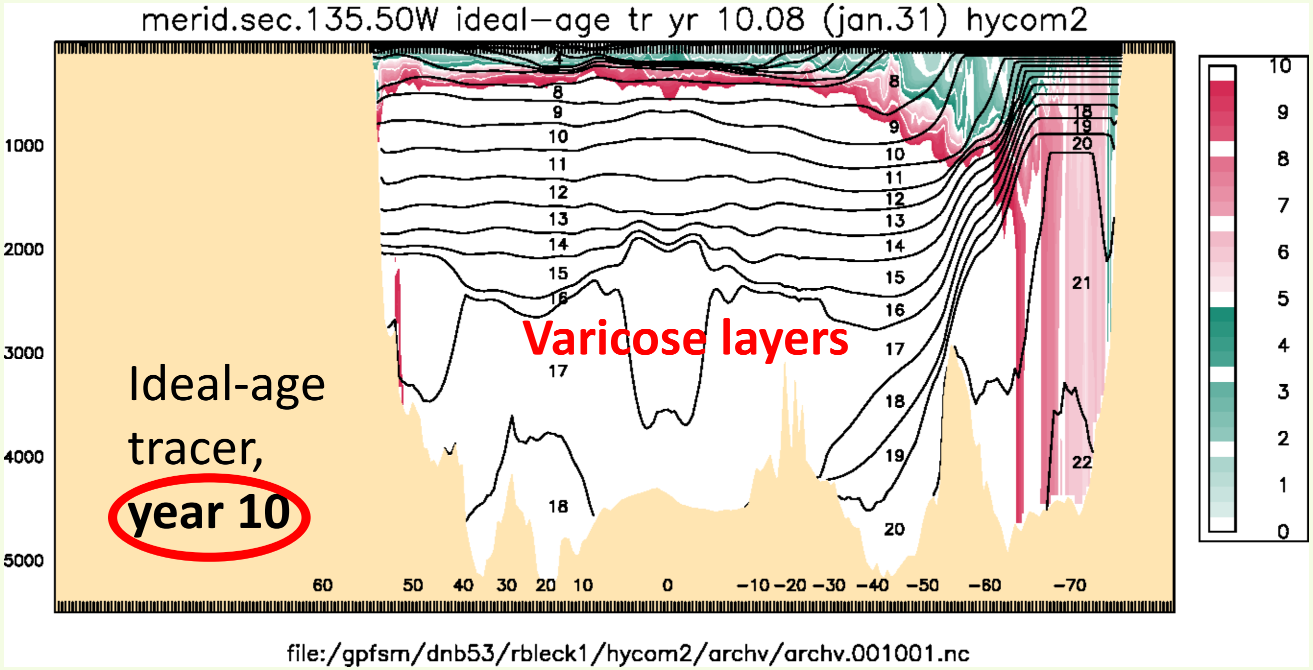
[1]varicose = abnormally swollen or knotted

HycomC

(=hycom using compressible eqn. of state)



What might create the varicose layers .... the grid generator?

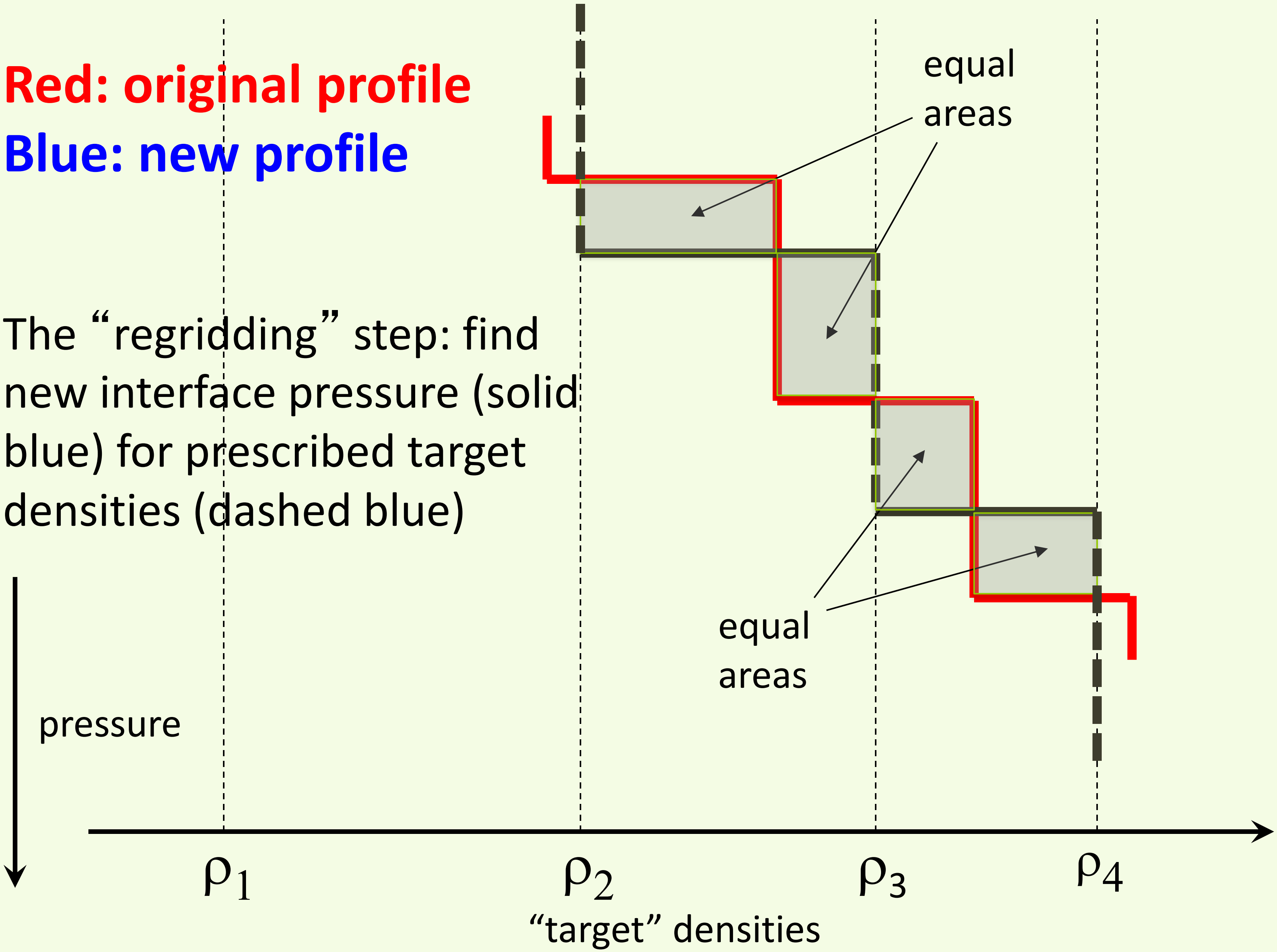


How the vertical grid generator works

- Step 1: transform input stairstep density profile to isopycnic coordinates (i.e. **regrid** vertical profile so as to restore layer densities to target).
- Step 2: Inflate massless layers created in step 1, starting at the top and stopping at the first layer not requiring inflation.
- Step 3 (common to all grid generators): **remap** vertical T/S profiles.

Red: original profile
Blue: new profile

The "regridding" step: find new interface pressure (solid blue) for prescribed target densities (dashed blue)



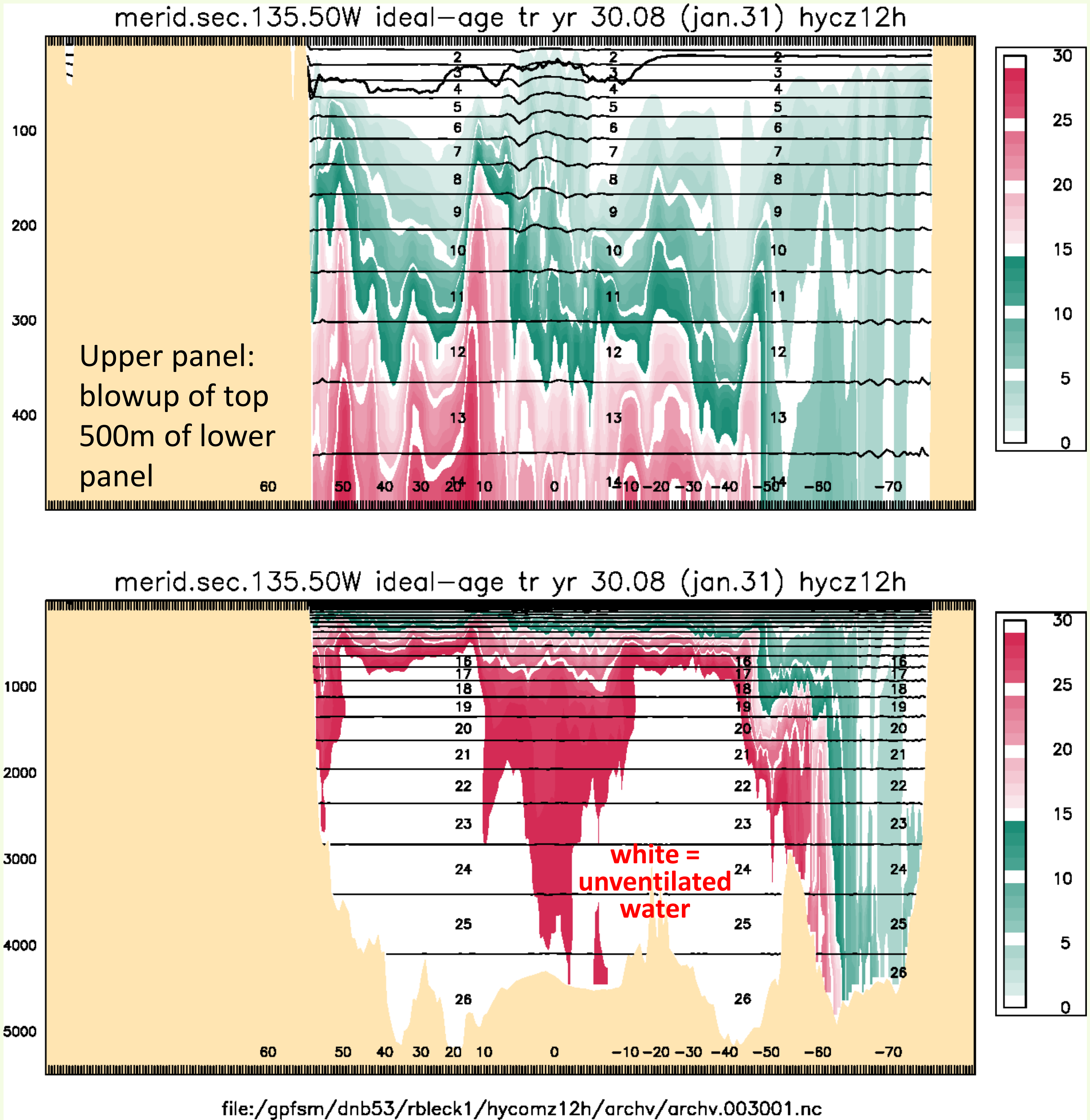
Are grid generator problems surmountable?

- Fallback option: give up on restoring toward isopycnic layer structure.
- Instead, restore toward level surfaces. Heresy
- Make restoration slow enough to render layers quasi-material during passage of gravity waves.
- Retain HYCOM's adaptive-coordinate features
  - continue to allow massless layers on sea floor (e.g. "shrink wrap" seamounts, etc);
  - unrestricted choice of bottom depth levels unrelated to interface depths.

HycomZ

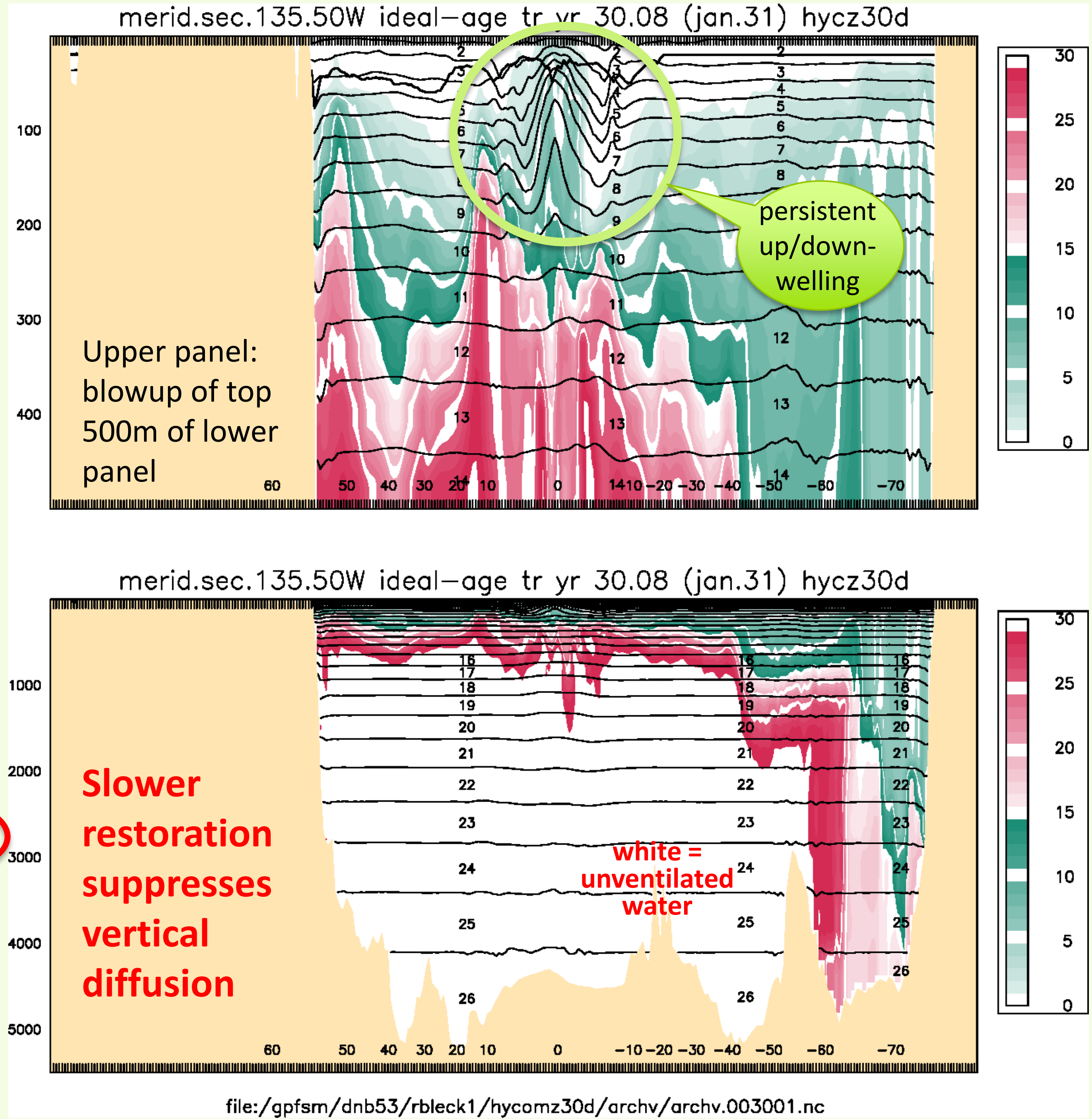
(=hycom with compressible eqn. of state and restoration toward **level** surfaces)

Ideal-age tracer at yr 30, **12-hr** coordinate restoring time



HycomZ

(=hycom with compressible eqn. of state and restoration toward **level** surfaces)



Ideal-age tracer at yr 30, **30-day** coordinate restoring time

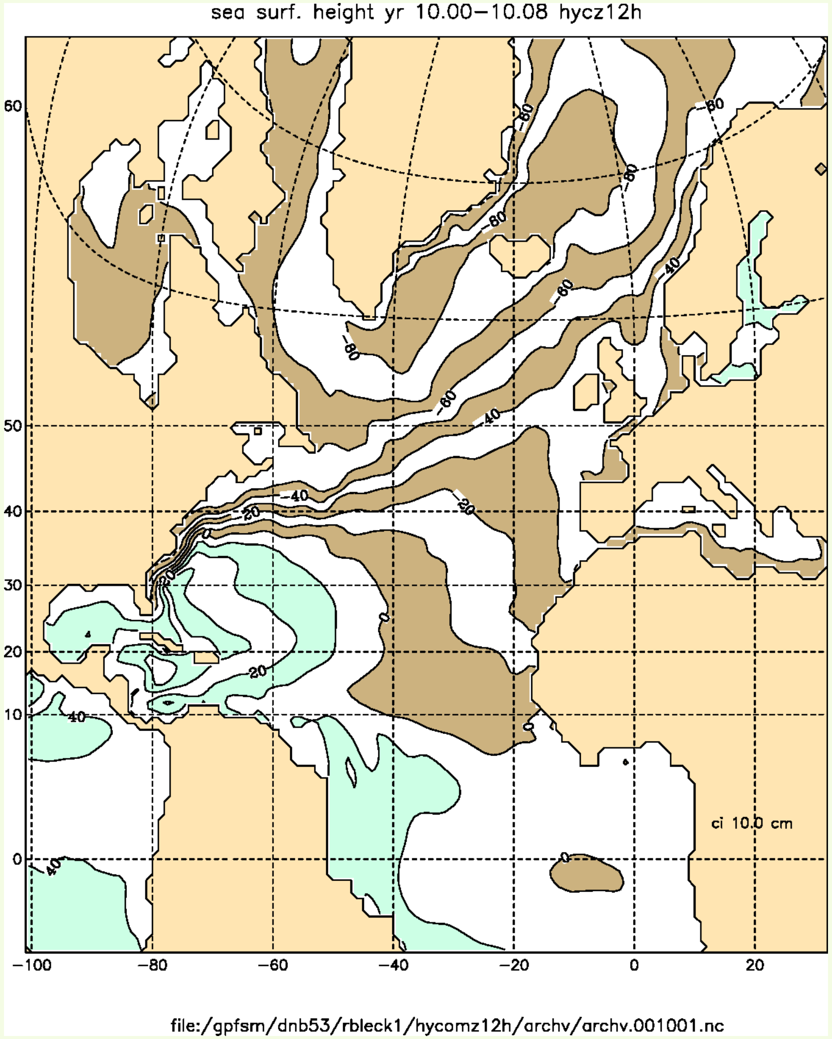
Preliminary Findings (as of April 2015)

- The finite-volume PGF approach seems workable in HYCOM, paving the way for eventual removal of the traditional Boussinesq-related dual approximation of (1) treating ocean water as incompressible and (2) using potential density as buoyancy-controlling variable *(Spiegel and Veronis, 1960)*.
- Long-term degeneracies in the isopycnic layer field presumably are caused by deficiencies in the present vertical grid generator.
- Simulations based on initialization with (and relaxation toward) level coordinate surfaces are successful.
- With sufficiently long relaxation times, HycomZ (the new compressible isobaric-layer version of HYCOM) retains its material-coordinate character with respect to passing gravity waves.

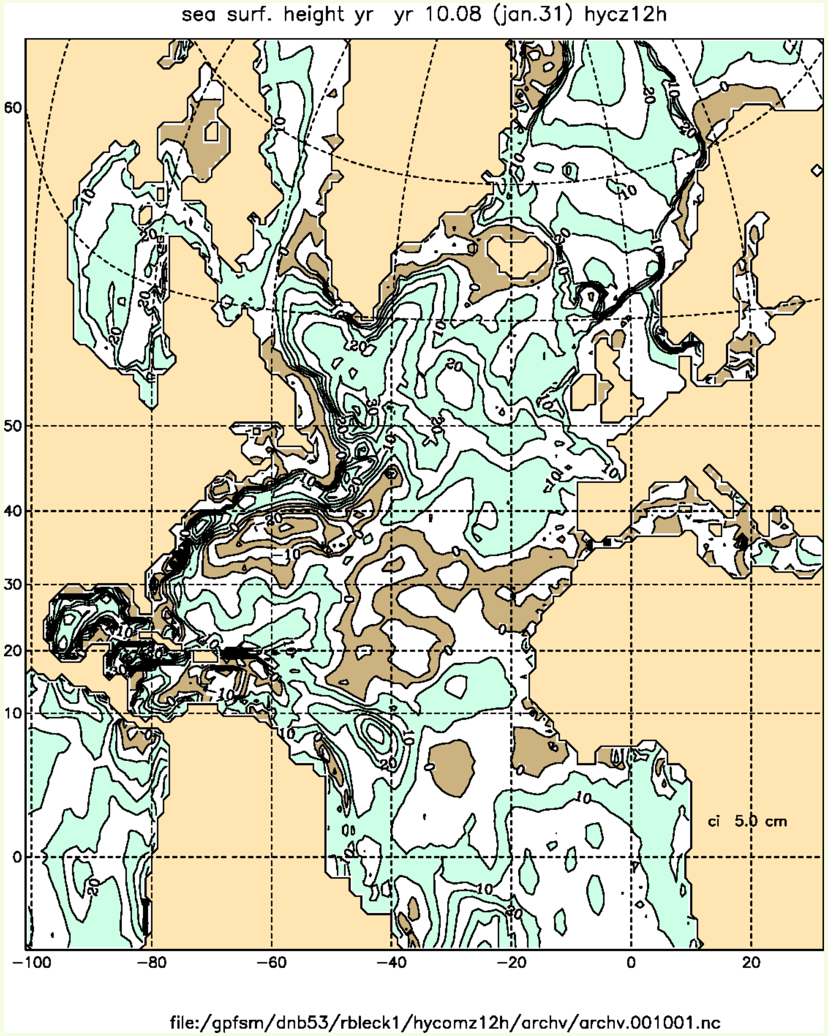
This is work in progress.

A recent letdown (as of June 2015)…

Sea-surface height, monthly average



Sea-surface height, snapshot



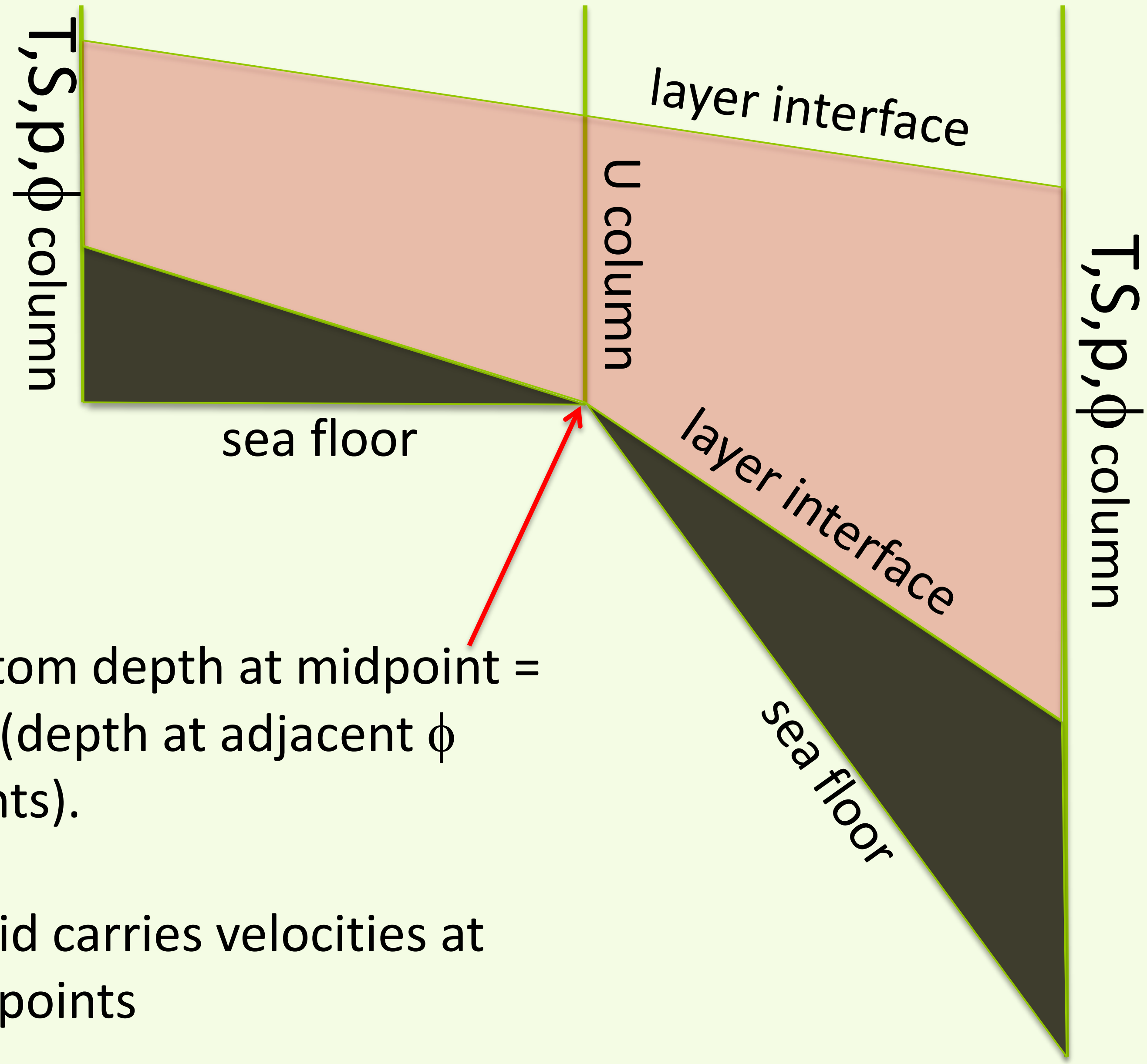
HycomZ simulation, 12-hr interface restoring time

On this somewhat pessimistic note …

Thank you

Unused slides follow

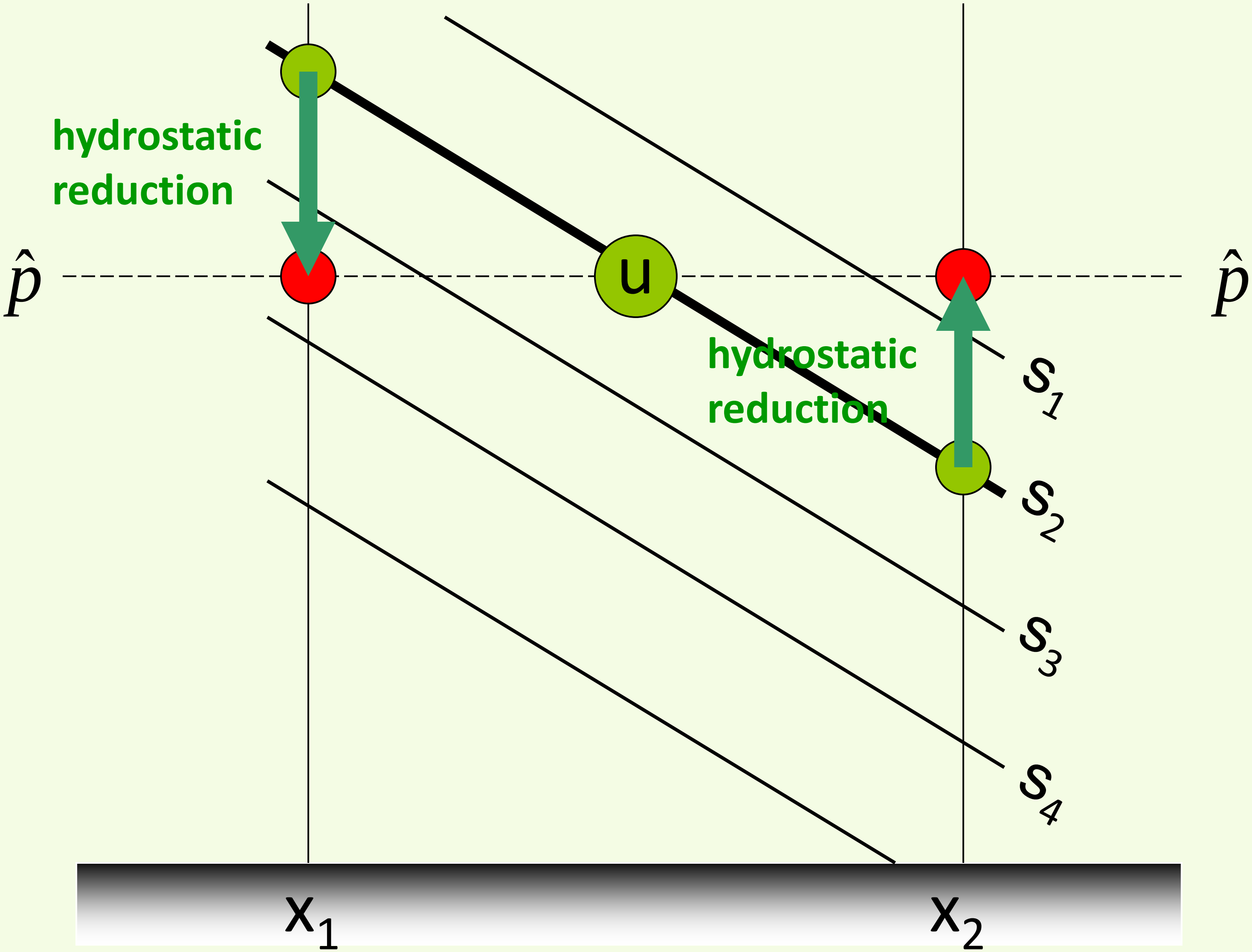
Finite-volume approach: treatment of bottom cells



Bottom depth at midpoint = **min**(depth at adjacent ϕ points).

C grid carries velocities at midpoints

How generalized-vertical coordinate models typically compute horizontal pressure gradients:



How **Janjic** proposes to compute horizontal pressure gradients: