A COMPARISON OF HYCOM AND MOM6 VERTICAL COORDINATES

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BASIC ALE APPROACH

- **For each time step:**
- **Solve the layered continuity equation**
  - ◦ **Move all the layers**
- **Apply Arbitrary Lagrangian Eulerian (ALE) method in the vertical**
  - ◦ **Regrid: select the "desired" layer structure**
    - – **Power of ALE method is in the choice of new layer locations**
    - – **Geopotential and terrain-following coordinates can easily be "emulated" by holding the interfaces fixed in time**
    - – **HYCOM HYBGEN and MOM6 HYCOM1:**
      - · **Favor isopycnals that outcrop into fixed depth layers**
  - ◦ **Remap: from the source to the regrid layers**
    - – **Interfaces can move, but the fluid does not move**
    - – **Choose interpolation that is conservative, with no new extrema**
      - · **Typically Piecewise Parabolic Method (PPM), Colella and Woodward (1984), with layer edge values from a cubic polynominal**
    - – **Nominally, this does not change the solution but it does add diffusion**

HYCOM ALE: HYBGEN (ALSO NOW AVAILABLE IN MOM6)

- Regridding uses entrainment
  - Source and target is layer average sigma2 potential density
  - Maintain isopycnal layers
    - If layer is too heavy, entrain from lighter layer above
    - If layer is too light, entrain from heavier layer below
  - If an interface needs to move both up and down, we pick one
    - Can lead to thick-thin-thick layer structure, which reduces the effective vertical resolution
- Use PCM for near-isopycnal layers (e.g. within $0.01 kg/m^3$ of target) for both regridding and remapping
  - Greatly simplifies entrainment/detrainment regridding
    - Detrainment (thinning) does not change layer density
  - PCM is 1st order accurate and very diffusive
    - Regridding does not effect most (isopycnal) layers
      - No regridding, no loss of accuracy and no diffusion
- For fixed and non-isopycnal layers, vertical remapping typically uses PPM with WENO-like cubic polynomial edge calculations
- Produces noisy interfaces, that require an interface smoother

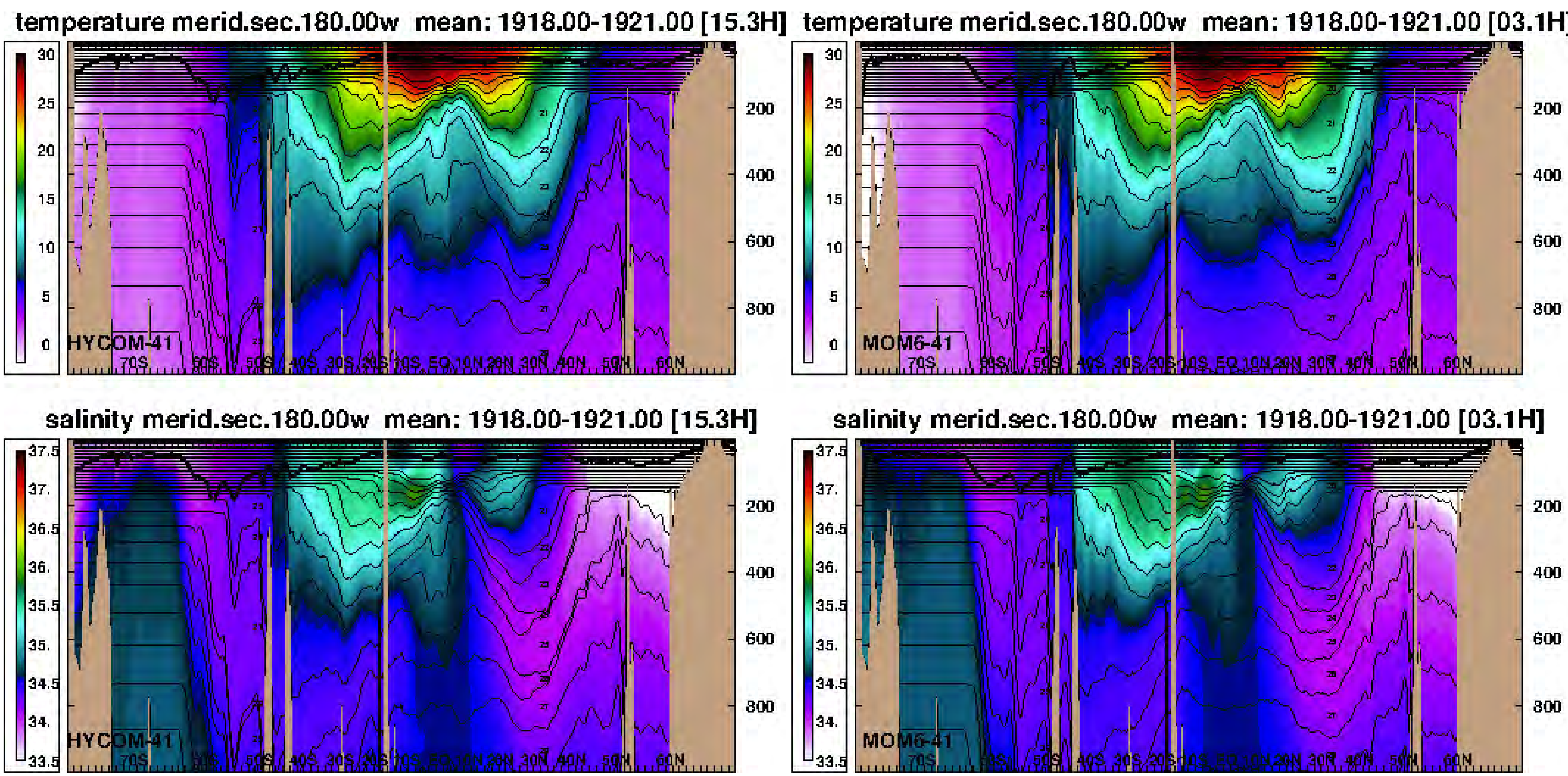
MOM6 ALE: HYCOM1

- Regridding walks a monotonic vertical profile
  - Source is layer sigma2 potential density, with 1% (say) compressibility
    - Source usually increases with depth, and is forced to be stable
      - Density(K+1) = MAX(Density(K), Density(K+1))
  - From these layer densities and the layer thicknesses, construct a vertical profile using piecewise polynomials
    - Regridding and remapping may use different profiles
      - P1M_H2, linear between H2 interfaces, was the only practical scheme
      - PPM_CW, adds a monotonic profile constraint to _H4 edges, Colella and Woodward (1984), and is now the recommended option
  - Target is interface sigma2 potential density plus compressibility factor
  - The new interface depths are at the location of targets on the profile
    - Unique mapping from a monotonic profile to the target isopycnals
- Vertical remapping typically used PPM_H4 for all layers, where H4 indicates a cubic polynomial calculation of interface (edge) values
  - PPM_CW is slightly more diffusive but can be used for regrid and remap
- Produces smooth interfaces, no need for an additional interface smoother

PACIFIC VERTICAL CROSS SECTION AT 180°E 0-1000m

- **MOM6 and HYCOM twin 41-layer simulations on 1/12° global tripole grid**
  - ○ **10 years with CFSR 2003 repeated atmospheric forcing**
- **Isopycnals “outcrop” into fixed depth layers**
- **HYCOM shows some indication of thick-thin-thick layers (3 year mean)**

HYCOM HYBGEN | **MOM6 HYCOM1**



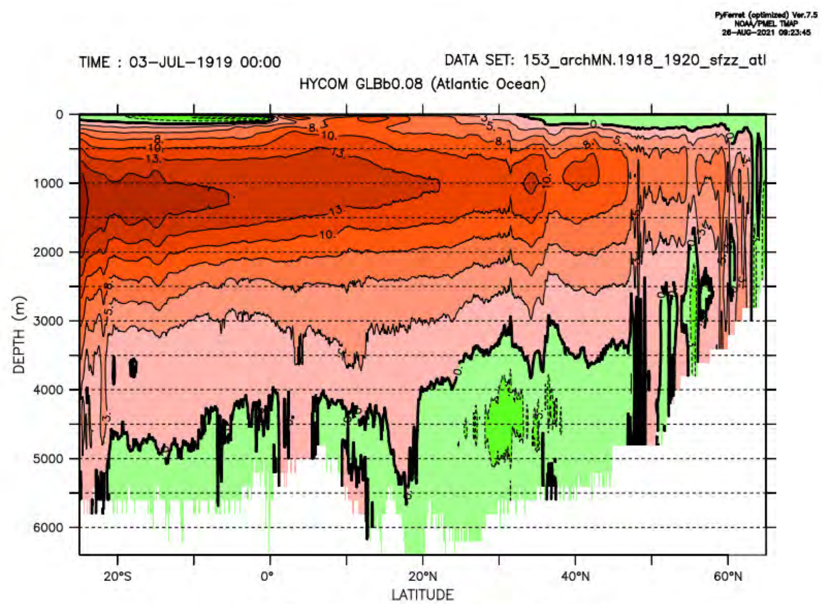
HYBGEN vs HYCOM1

- HYBGEN assumes the source layer structure is close to the desired result, HYCOM1 makes no such assumption: it is a general vertical interpolator
- MOM6 requires a vertical interpolator: HYBGEN can't fill this role
  - For initialization, INTERPOLATE_SPONGE_TIME_SPACE and ODA_INCUPD
- HYBGEN often produces a thick-thin-thick layer structure, and HYCOM1 does not
- HYBGEN maintains isopycnal layers exactly but HYCOM1 does not
  - If a layer changes thickness adiabatically:
    - Its layer average potential density (HYBGEN) is unchanged
    - Its interface potential density (HYCOM1) is not, because this depends on nearby layer thicknesses and densities and the compressibility factor (since depth has changed)
  - The associated interfaces are moved by the HYCOM1 regridder and preserved by the HYBGEN regridder
- In general, HYBGEN moves interfaces significantly less than HYCOM1, so HYBGEN causes less diapycnal diffusion than HYCOM1

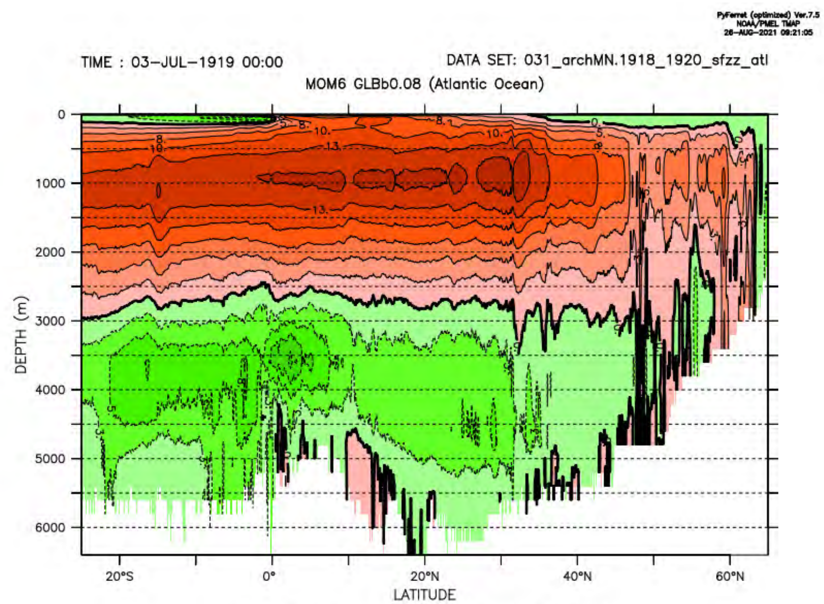
ATLANTIC OVERTURNING STREAMFUNCTION, OVER YEARS 8-10 (I)

- **0.08 degree Global with 41 layers, CFSR 2003 repeated forcing**
- **25S to 65N and 0 to 6500m depth, 2.5 Sv contour interval**

GLOBAL HYCOM (HYBGEN) **GLOBAL MOM6 (ORIGINAL HYCOM1)**



z.ov.strfn mean [15.3H] (Sv)



z.ov.strfn mean [03.1H] (Sv)

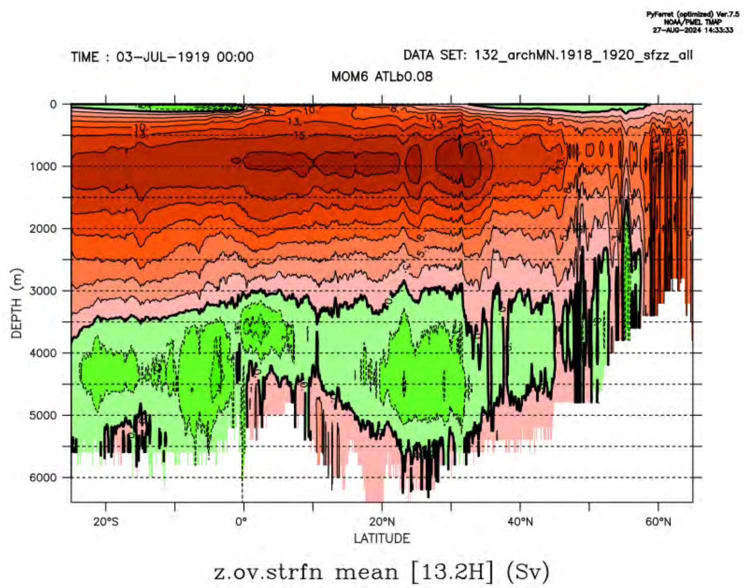
HYCOM at 26°N: max 11.6Sv at 1000m; 0Sv at 3500m
MOM6 at 26°N: max 14.0Sv at 0900m; 0Sv at 2730m
RAPID array at 26°N: max 17.0Sv at 1000m; 0Sv at 4300m

- **An isopycnal favoring model should have deeper overturning that HYCOM1**

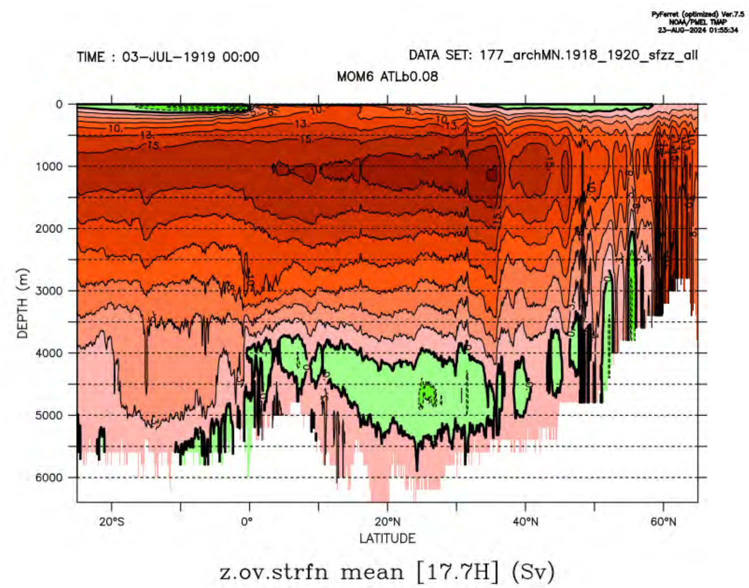
ATLANTIC OVERTURNING STREAMFUNCTION, OVER YEARS 8-10 (II)

- **MOM6 0.08 degree Atlantic-only with 41 layers, CFSR 2003 repeated forcing**
- **25S to 65N and 0 to 6500m depth, 2.5 Sv contour interval**

ORIGINAL HYCOM1



LATEST HYCOM1



ORIGINAL HYCOM1 at 26°N: max 16.5Sv at 0900m; 0Sv at 2950m
LATEST HYCOM1 at 26°N: max 18.0Sv at 1100m; 0Sv at 4000m
RAPID array at 26°N: max 17.0Sv at 1000m; 0Sv at 4300m

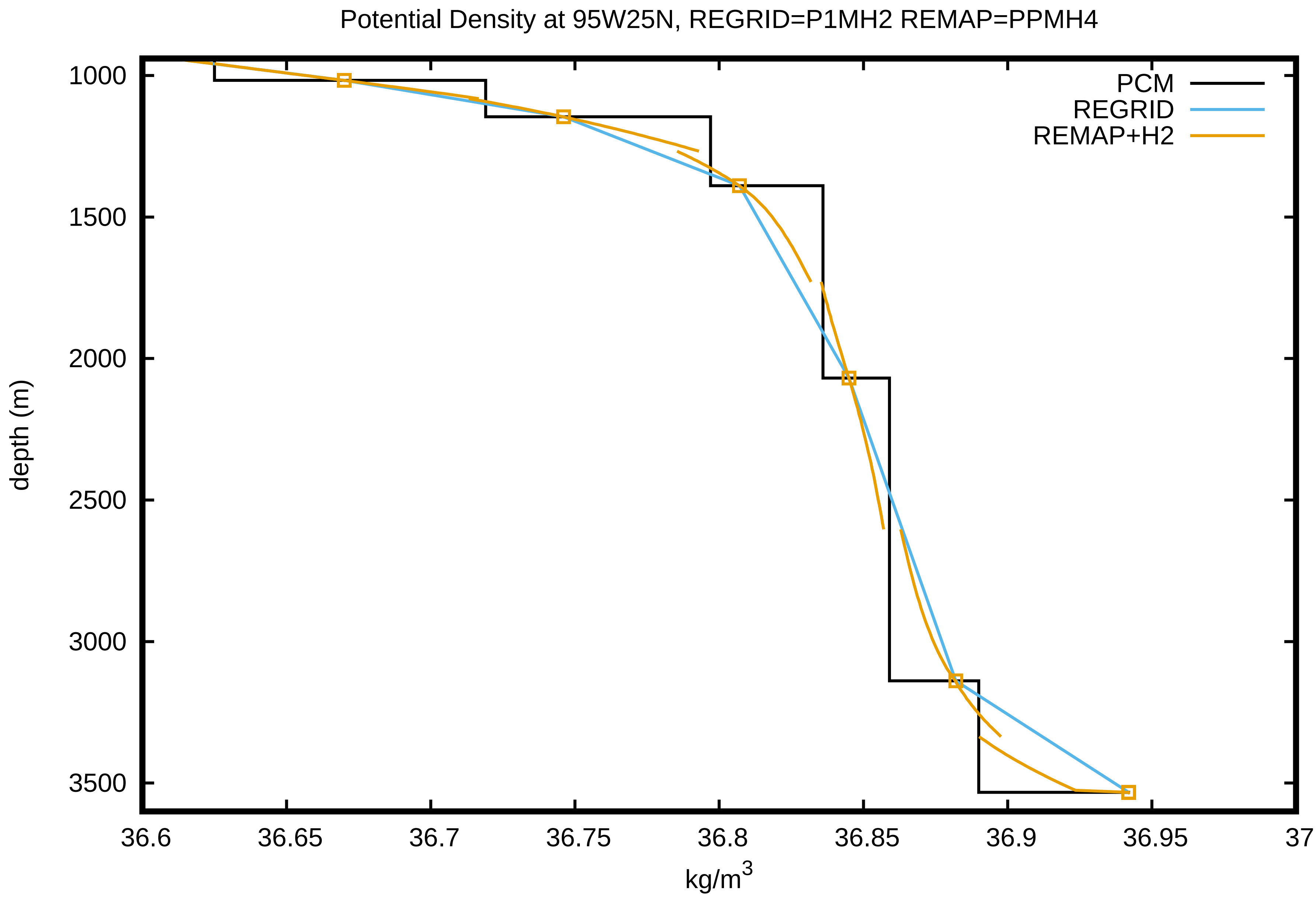
- **GLOBAL cases do not show as large an improvement**

LATEST 0.08 ATLANTIC 75-LAYER MOM6 SETUP

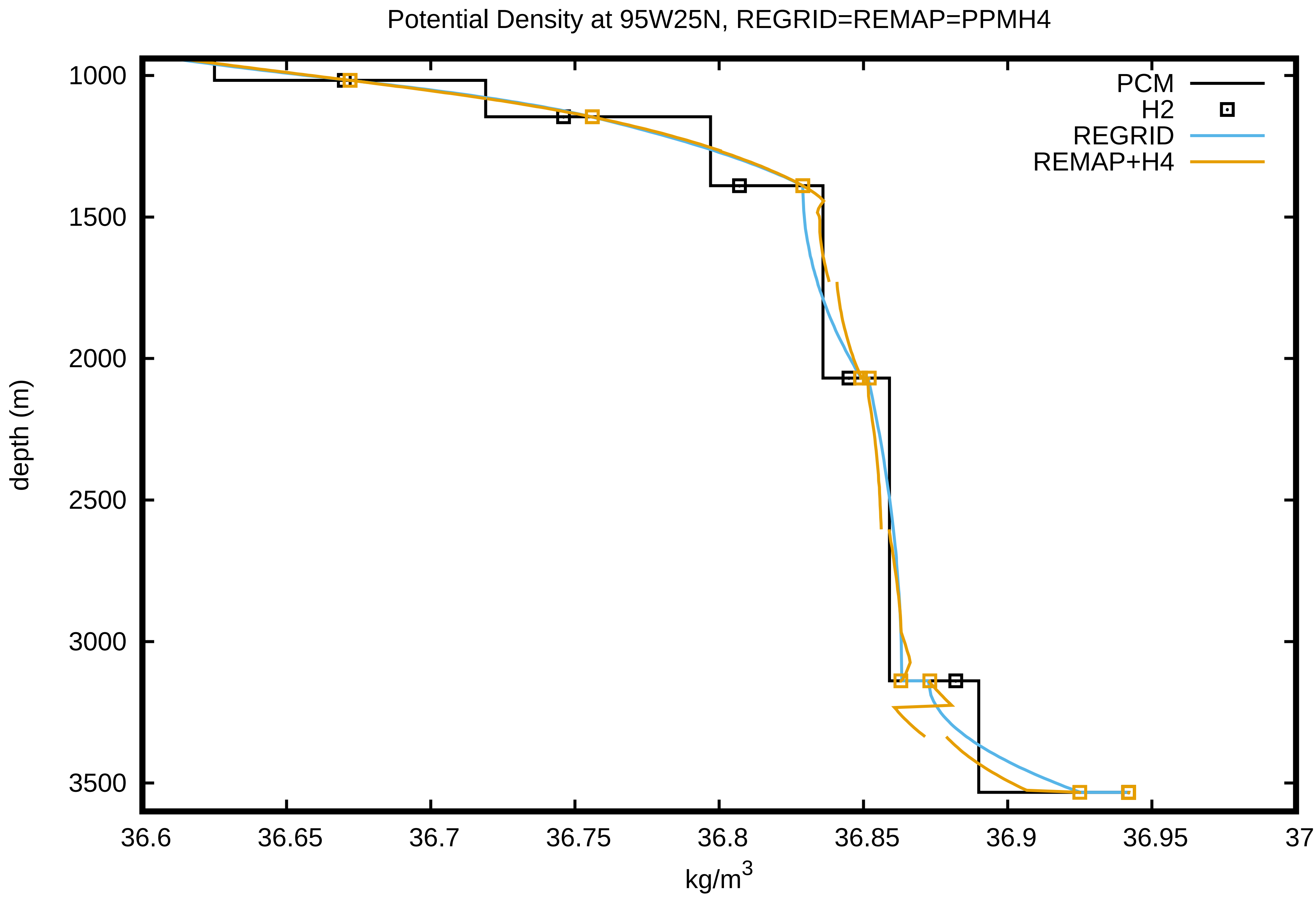
- 19.2: Same 75-layer vertical grid as OM4_25,
  EQN_OF_STATE= WRIGHT_REDUCED,
  BOUSSINESQ=False, SEMI_BOUSSINESQ=False,
  MASS_WEIGHT_IN_PGF_NONBOUS_BUG=False,
  USE_CONT_THICKNESS=True,
  REGRID/REMAP=PPM_CW, HYCOM1_ONLY_IMPROVES=True,
  REGRID_FILTER_SHALLOW_DEPTH=100,
  REGRID_FILTER_DEEP_DEPTH=125, REGRID_TIME_SCALE=6hrs,
  INTERFACE_FILTER_ORDER=4, INTERFACE_FILTER_TIME=3hrs,
  CORRECT_BBL_BOUNDS=True, BBL_EFFIC=.01, (use 0.0 for Global cases)
  SIMPLE_TKE_TO_KD=False, USE_MEKE=False,
  CORIOLIS_SCHEME="SADOURNY75_ENERGY",
  KD=.1E-4, KV=.3E-4, HENYEY_IGW_BACKGROUND=False,
  KH_VEL_SCALE=.00286, AH_VEL_SCALE=.02, no SMAGORINSKY,
  BACKSCATTER_UNDERBOUND=False,
  LOTW_BBL_ANSWER_DATE=20240731,
  DEFAULT_ANSWER_DATE=20240731,
  FRICTWORK_BUG=False, VISC_REM_BUG=False,
  USE_HUYNH_STENCIL_BUG=False
- BOUSSINESQ=True gives similar results

MOM6 ALE: HYCOM1 REGRIDDING

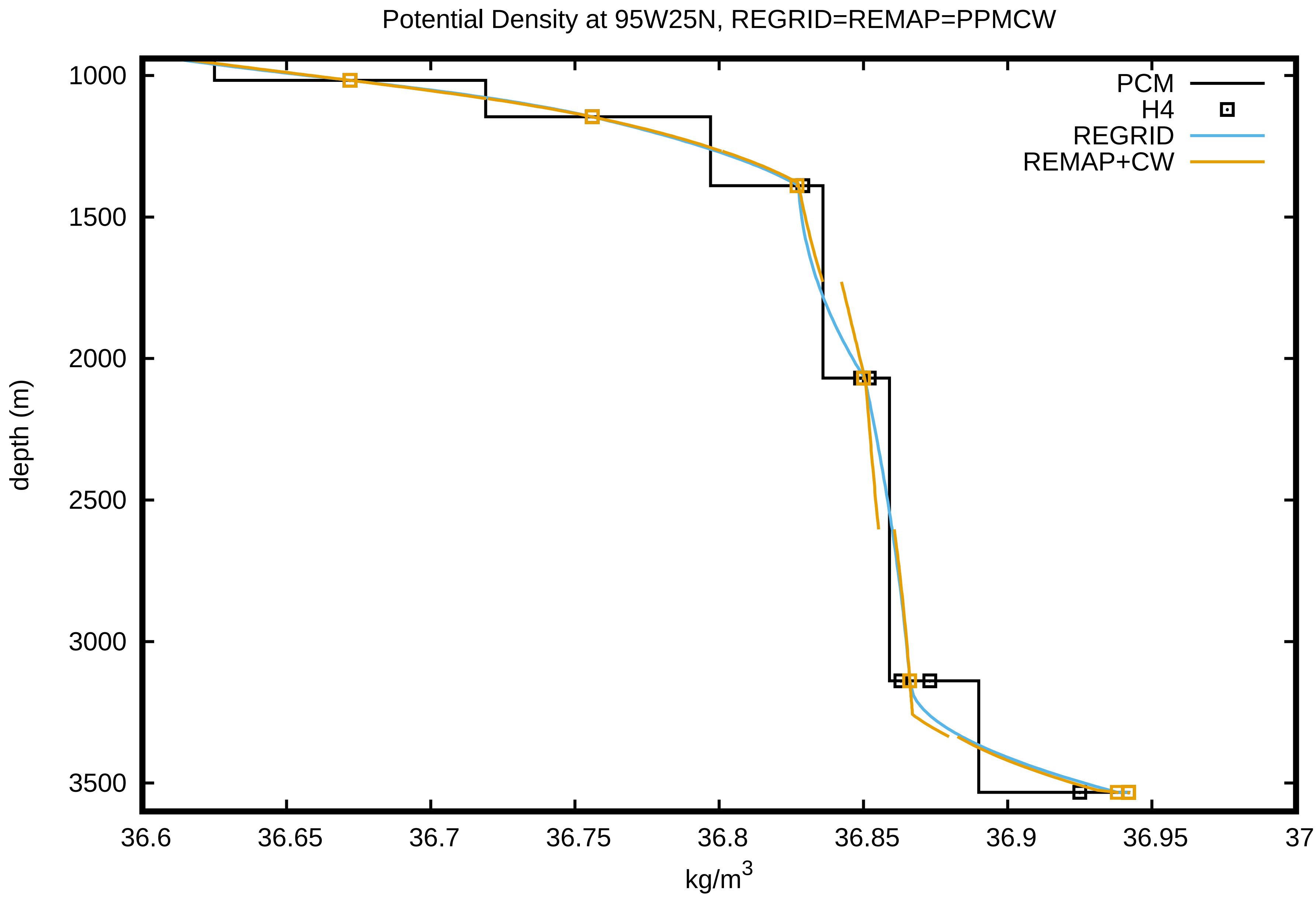
- Original approach: P1M_H2 for regrid and PPM_H4 for remap
- Why not use the remap piecewise polynomial for regrid?
  - PPM_H4 eventually produces unstable layers
- The new interface depths are at the location of targets on the profile
  - Cyan curves on upcoming plots
- However, the actual new interface densities are:
  - Remap (e.g. PPM_H4) T & S to new layers, and then reapply _H2 (linear) or _H4 (cubic) to the new layer densities and thicknesses
    - The latter step is not performed in the running model
- The new interface densities can be approximated by holding the density profile fixed except for a single interface and applying the remapping and edge recalculation steps to get the new density at that interface
  - Allows us to visualize the effect of moving the interfaces
    - Orange curves on upcoming plots
    - The actual inferface densities may be different because more than one interface could move and T & S are remapped



Potential Density at 95W25N, REGRID=P1MH2 REMAP=PPMH4
PCM
REGRID
REMAP+H2
1000
1500
2000
2500
3000
3500
depth (m)
36.6
36.65
36.7
36.75
36.8
36.85
36.9
36.95
37
kg/m3



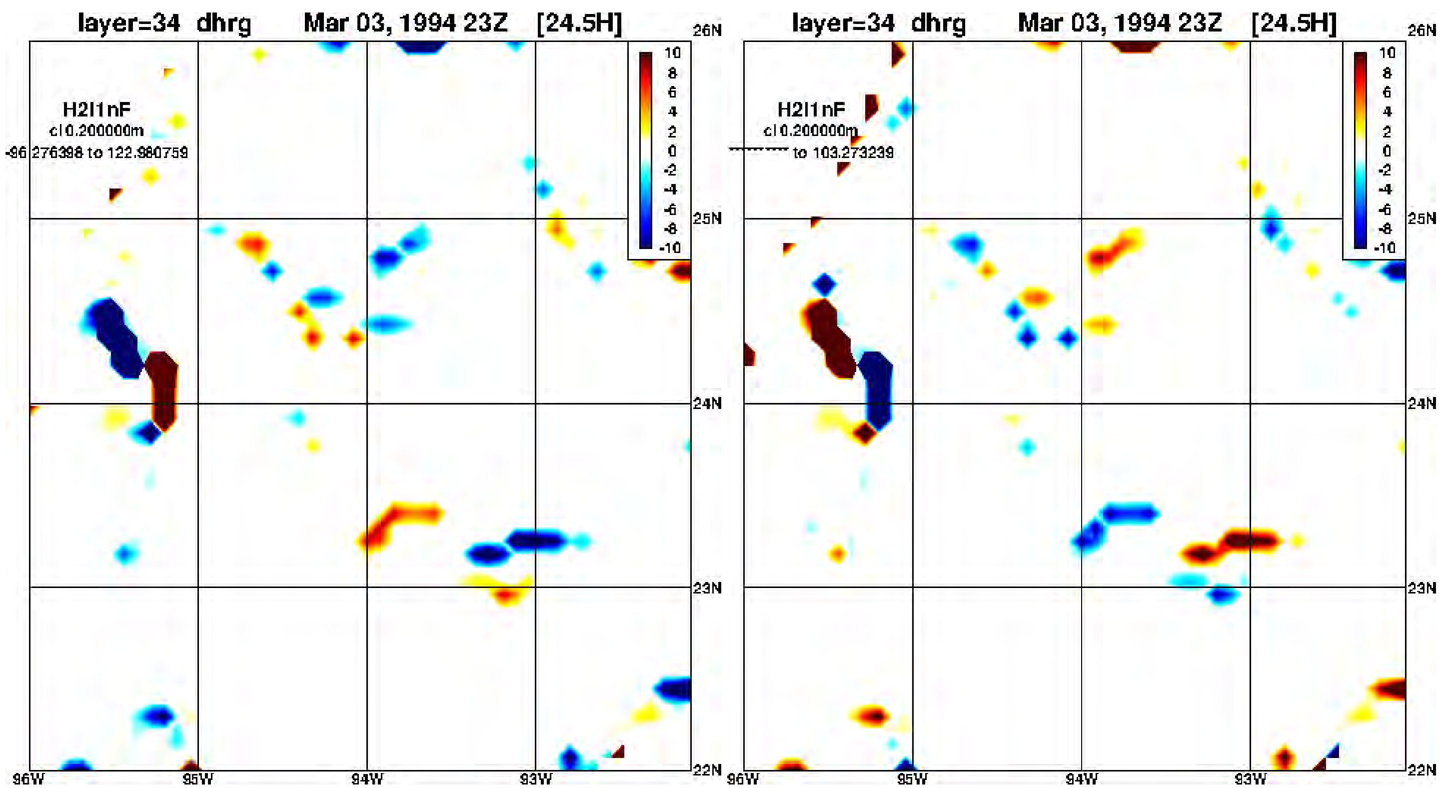
Potential Density at 95W25N, REGRID=REMAP=PPMH4
PCM
H2
REGRID
REMAP+H4
1000
1500
2000
2500
3000
3500
depth (m)
36.6
36.65
36.7
36.75
36.8
36.85
36.9
36.95
37
kg/m3


Potential Density at 95W25N, REGRID=REMAP=PPMCW
PCM
H4
REGRID
REMAP+CW
depth (m)
1000
1500
2000
2500
3000
3500
36.6
36.65
36.7
36.75
36.8
36.85
36.9
36.95
37
kg/m3

SINGLE TIMESTEP CHANGE IN LAYER 34 THICKNESS FROM REGRID

- 0.08 degree 41-layer GoM, started from GOFS 3.1 Jan 1st 1994
- Run for two months and then extend for 3 days sampling every time step
- MOM6 HYCOM1 INTERPOLATION=P1M_H2, REMAPPING=PPM_H4

1994_03_23: 20 min　　　　1994_03_23: 40 min

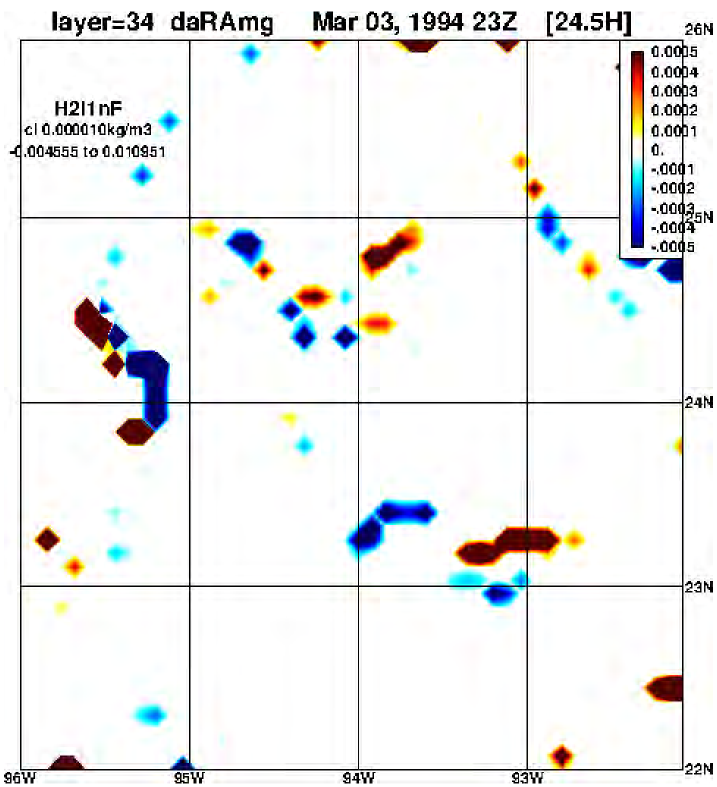


- Regrid jitter leads to excessive diapycnal diffusion

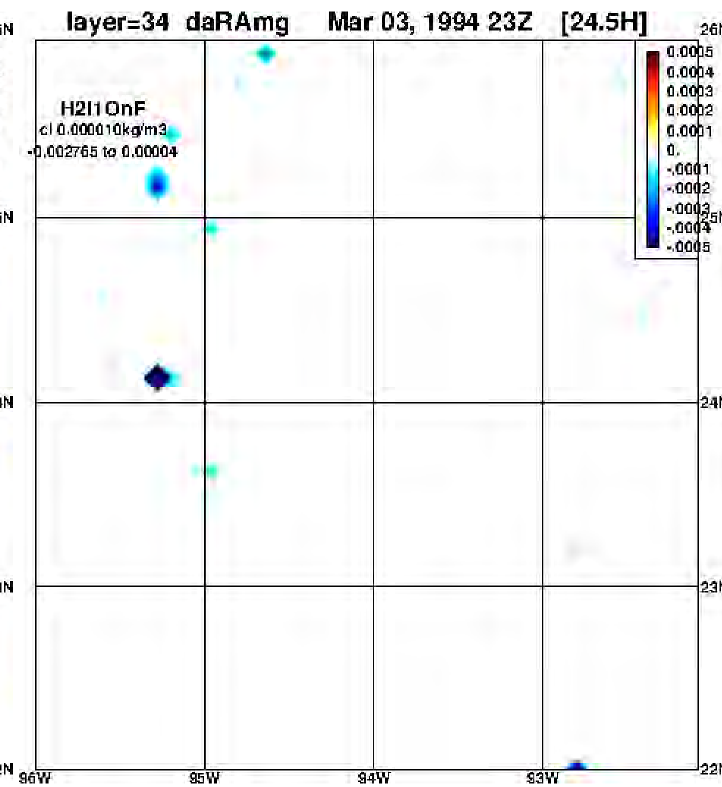
SINGLE TIMESTEP CHANGE IN INTERFACE 34 DENSITY FIT FROM REGRID

- **Actual interface density after HYCOM1 can be different from target, add HYCOM1_ONLY_IMPROVES to skip moves that cause a worse fit**
- **P1M_H2 + PPM_H4. Positive (red) values for worse fit. At 23:20.**

IMPROVES=False



IMPROVES=True

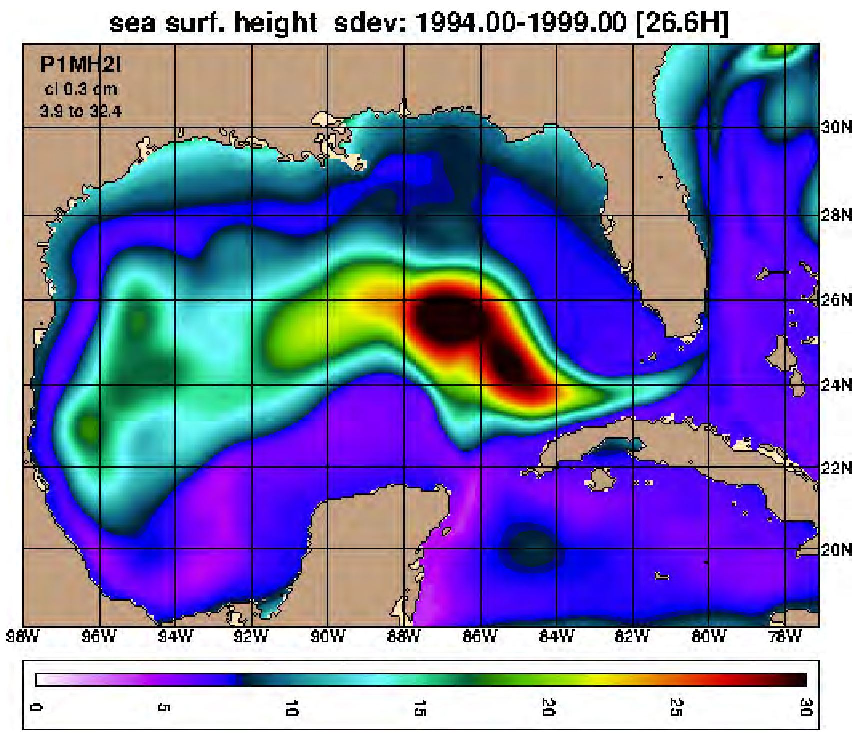


- **Significantly reduces jitter and diapycnal diffusion**

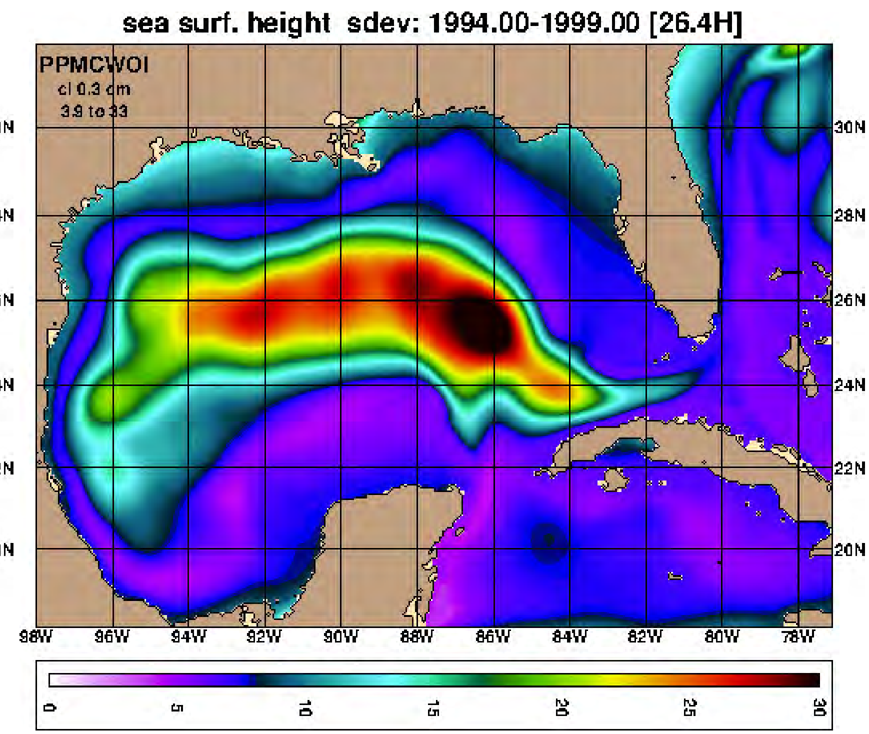
MOM6 GULF OF MEXICO SSH VARIABILITY (CM), OVER YEARS 1994-1998

- **0.08 degree 41-layer GoM, started from GOFS 3.1 Jan 1st 1994**
- **Absolute winds; no HYCOM1 compressibility factor**
- **Run for four years with HYCOM1_ONLY_IMPROVES=True**

P1M_H2



PPM_CW

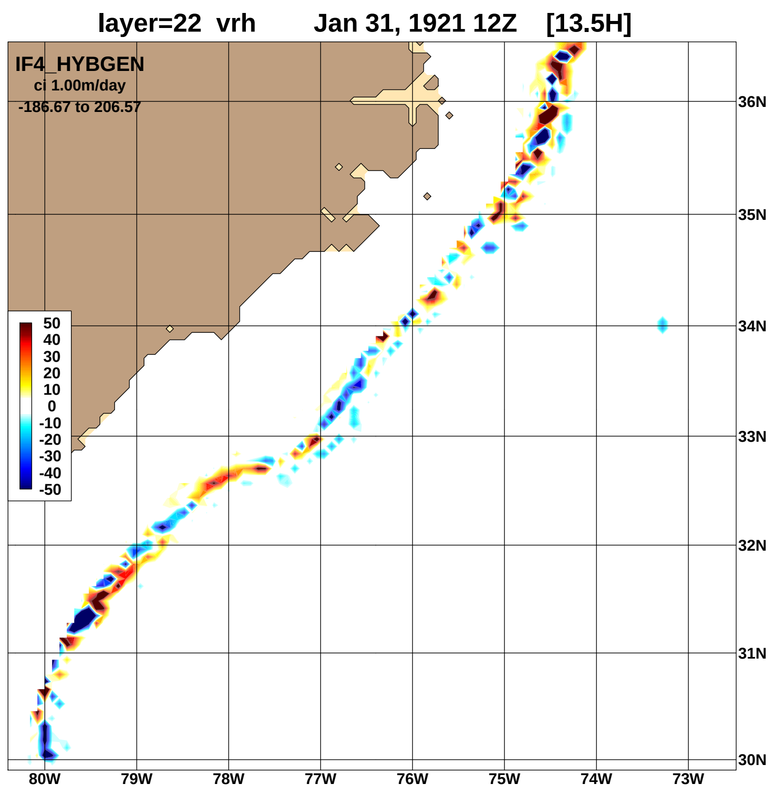


- **Eddies still shut down in Atlantic and Global cases with absolute winds**
- **Loop current eddies are small and quickly dissipate with relative winds**

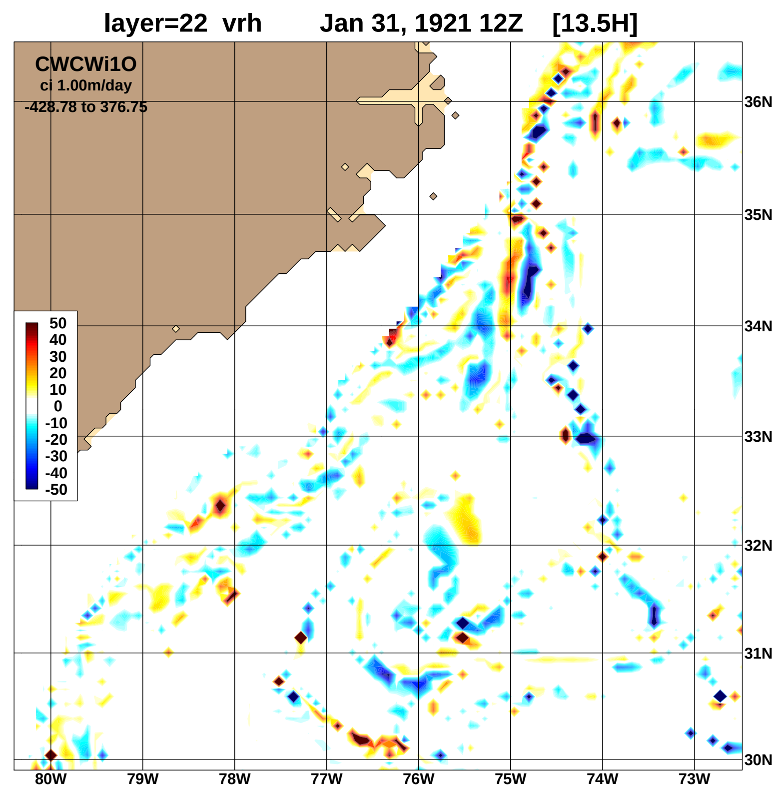
GULF STREAM LAYER 22 REGRID THICKNESS CHANGE (M/DAY) SNAPSHOT

- **0.08 degree Atlantic MOM6 with 41 layers, CFSR 2003 repeated forcing**
- **After 10 years of HYCOM1 P1M_H2: run for 31 days with new ALE options**
- **Change from REGRID only, 50 m/day is 17 cm/timestep**

MOM6 HYBGEN



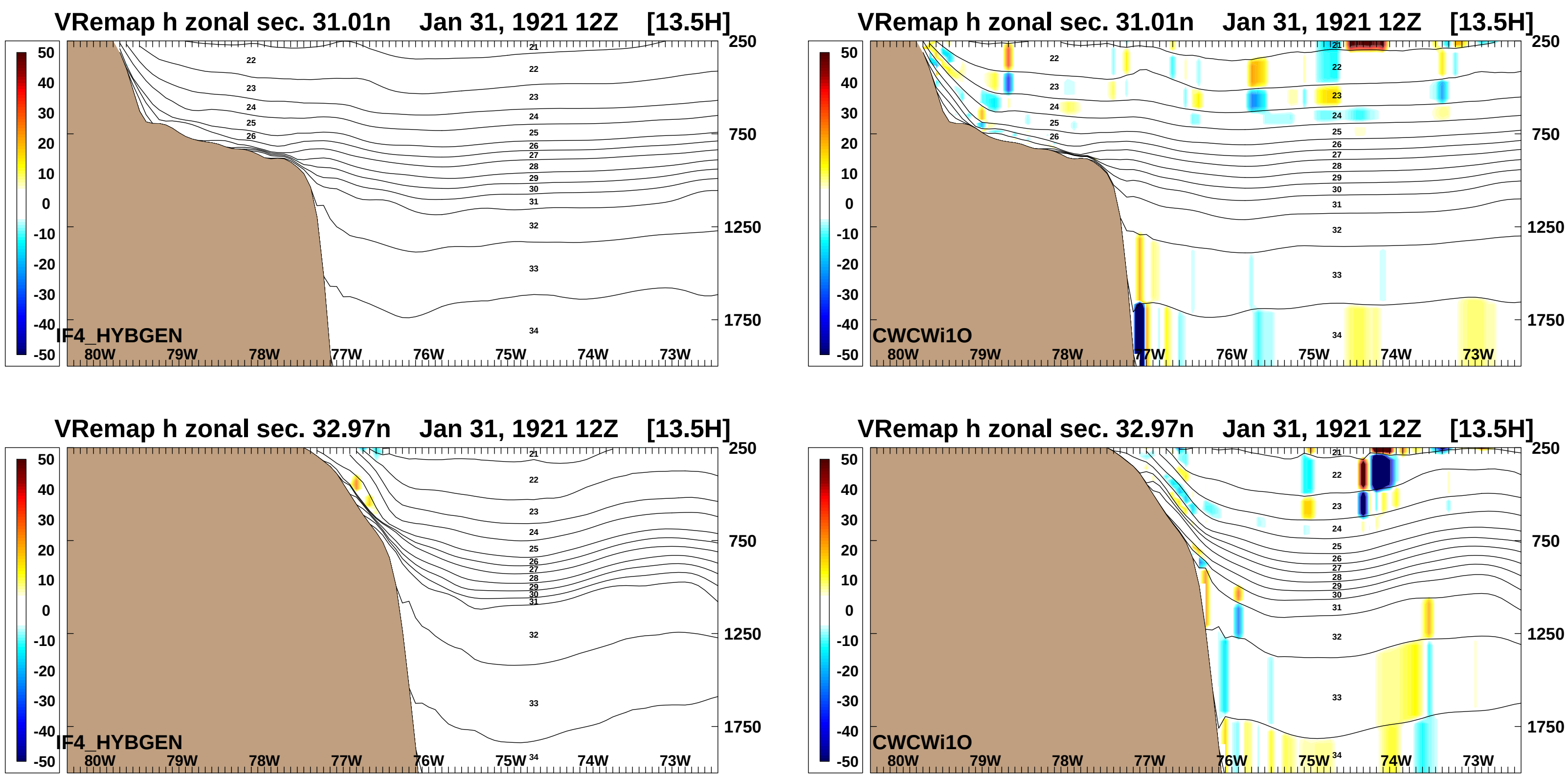
PPM_CW, ONLY_IMPROVES



GULF STREAM 31N & 33N REGRID THICKNESS CHANGE (M/DAY) SNAPSHOT

- 0.08 degree Atlantic MOM6 with 41 layers, CFSR 2003 repeated forcing
- After 10 years of HYCOM1 P1M_H2: run for 31 days with new ALE options

31N & 33N MOM6 HYBGEN | PPM_CW, ONLY_IMPROVES



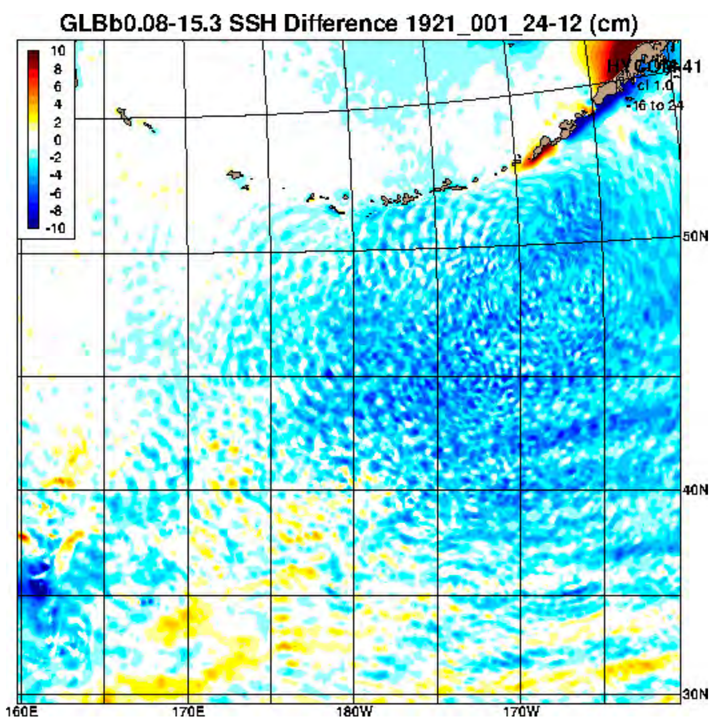
MAX_LAYER_THICKNESS (DX0K)

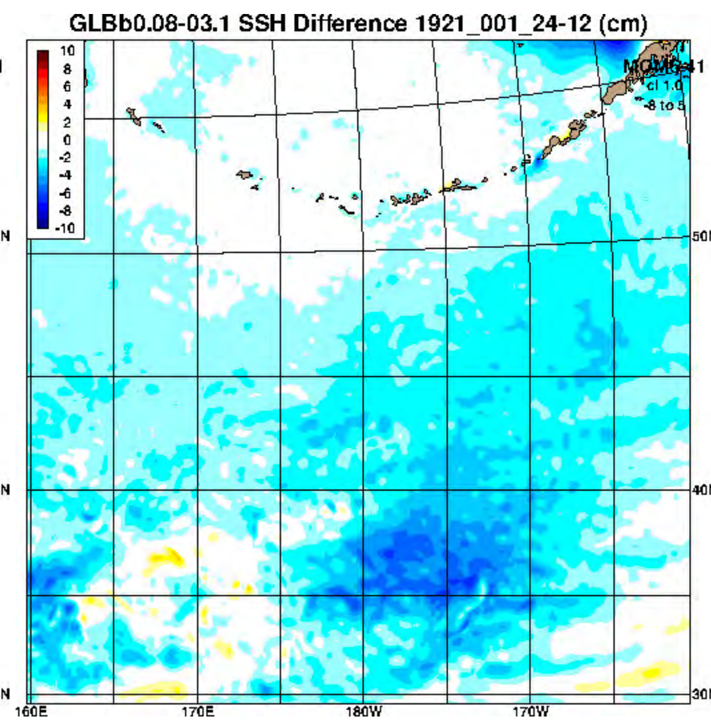
- Target density of deep layers often denser than bottom density, leading to zero thickness layers at the bottom
  - All layers are always computed, even when zero thickness
- MOM6 MAX_LAYER_THICKNESS sets a maximum thickness for each layer
  - Splits thick isopycnal layers into several layers
    - Leads to more deep inflated layers
    - Disfavors isopycnals
  - Once one layer is split, all deeper layers will be away from their target densities and so will also be split
- HYCOM (HYBGEN) has DP0K(K) as the minimum layer K thickness
  - Builds the fixed depth layers near the surface
- Added MAX_LAYER_THICKNESS to HYCOM as DX0K
- 41-layer global HYCOM setup (e.g. GOFS 3.1), has DP0K from 1 m at the surface to 600 m at depth
  - In Southern Ocean, layer 39 is the deepest inflated layer
  - With DX0K(1:41) = 750m, it is active somewhere on the globe in layers 24 to 41 and all 41 layer's inflate in the Southern Ocean

THERMOBARIC INSTABILITY IN HYCOM, NOT POSSIBLE IN MOM6

- **HYCOM uses sigma2 potential density, with a thermobaricity correction**
  - **Can be unstable (Hallberg, 2005), or cause noisy interfaces**
- **MOM6 uses in-situ density, integrating the finite volume pressure gradient force using numerical quadrature (Adcroft et al, 2008)**
- **N. Pacific: difference in SSH (cm) over 12 hours**, after 10 model years

GLBb0.08 HYCOM HYBGEN **GLBb0.08 MOM6 HYCOM1**

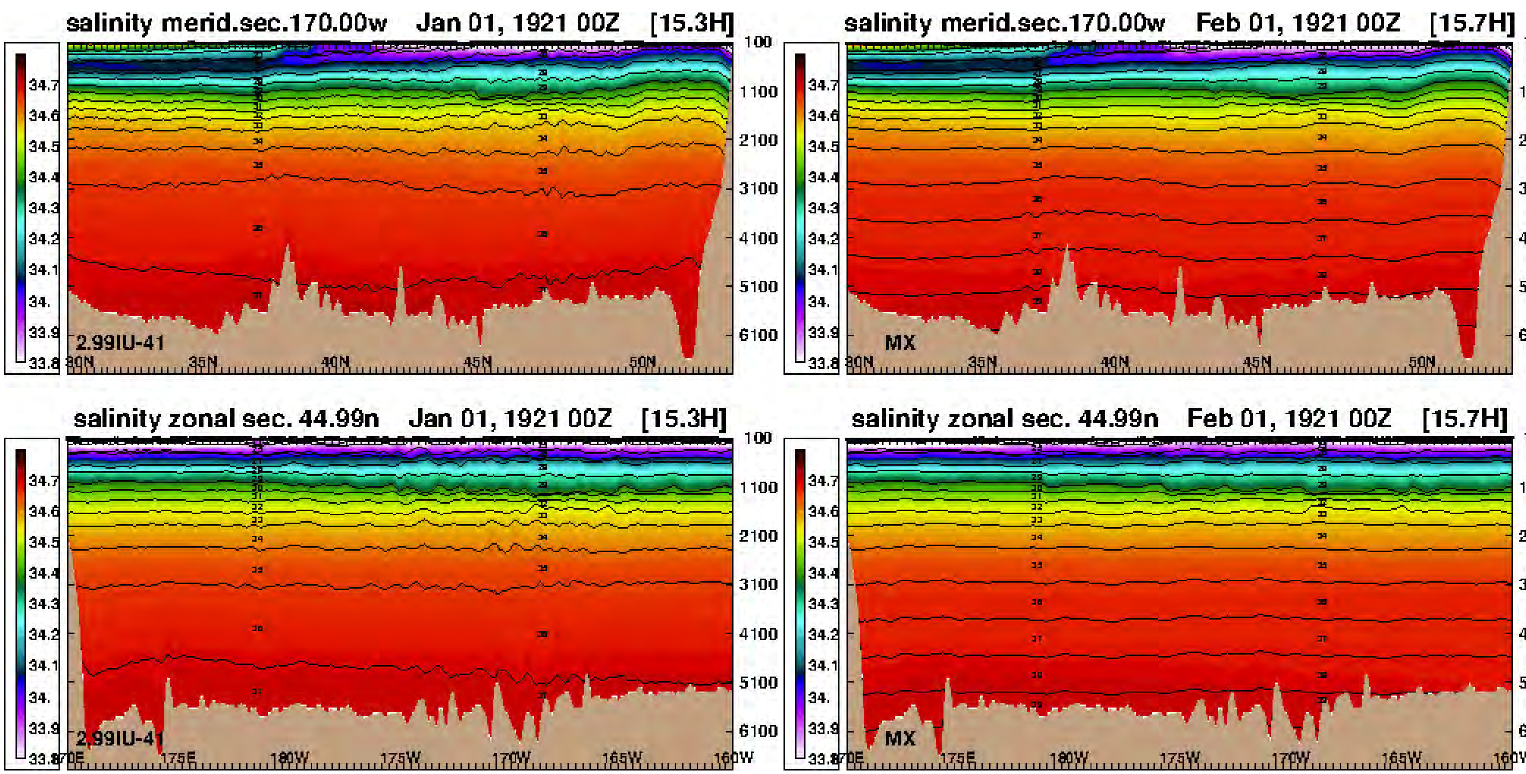




DX0K=750M WITH NO THERMOBARIC INSTABILITY - VERTICAL SECTIONS

- Start from a 41-layer no tides HYCOM GLBb0.08 case with TBI
- Extend for 1 month with DX0K=750m
- Salinity sections at 170W and 45N; layers 36:37 become 36:40
- Adding more deep isopycnal layers gives a similar improvement

Jan 1 00Z no DX0K **Feb 1 00Z DX0K=750m**



SUMMARY

- HYCOM1 with PPM_CW and HYCOM1_ONLY_IMPROVES still has more diapycnal diffusion than an isopycnal-favoring method should
  - Further improvements are possible, e.g. alternatives to the compressibility factor
- HYBGEN has minimal diapycnal diffusion, but has other issues
  - Thick-thin-thick layer structure reduces effective vertical resolution
  - Requires additional interface smoothing
- Algorithms and source code migrating between HYCOM and MOM6
  - HYBGEN is available in MOM6
    - Can't be used as the needed vertical interpolator
    - Not yet ready for production runs
    - Exposed a major bug in HYBGEN, now fixed in HYCOM
  - MAX_LAYER_THICKNESS (DX0K) has been added to HYBGEN
  - A HYCOM1-like regridder is undergoing testing for HYCOM
    - More diapycnal diffusion than HYBGEN, less than HYCOM1