REQUEST FOR INFORMATION (RFI)

HYCOM

Brief overview

The HYbrid Coordinate Ocean Model (Bleck, 2002; Chassignet et al., 2003) is a global non-Boussinesq ocean circulation model that utilizes a generalized vertical coordinate to support use of isopycnal coordinate in the open, stratified ocean, with a dynamically smooth transition to pressure/level coordinates in the surface mixed layer and terrain-following coordinates in shallow coastal regions via an Arbitrary Lagrangian-Eulerian (ALE) method. HYCOM is perhaps the most widely used ocean model that is based on isopycnic coordinates and it is the backbone of the U.S. Navy and NOAA ocean prediction systems (Chassignet et al., 2009). HYCOM includes a number of parameterizations to improve representations of surface mixed layer processes as well as internal ocean mixing (e.g. Halliwell, 2004). Time integration is split between the baroclinic modes and the fast vertically uniform barotropic mode using an explicit subcycling of the barotropic mode. The model supports general orthogonal grids, currently global configurations use either the POP dipole grid or, more commonly, a Mercator grid matched to a dipole patch at 47°N, i.e. a tripole grid that creates a regular grid without a singularity over the Arctic.

Criteria #1: *A strong partnership between the developers of the model and the CESM community*

The HYCOM community has been working closely with the CESM community over the past few years – HYCOM is now in CESM (project led by Cecelia DeLuca and Mariana Vertenstein) and several HYCOM-CESM runs out 50 years with HYCOM 2.2.98 in a 1° grid configuration have been performed. A brief preliminary comparison of HYCOM-CESM and POP-CESM on the same 1° grid is included below as a separate section. We have also provided a HYCOM-CESM configuration on the 1/10° POP grid to Ben Kirtman (U. of Miami) for comparison to the POP-CESM 1/10° 100-year run (currently being tested).

Criteria #2: *A strong commitment to sustained collaboration in model development from the model's institutional home or consortium*

The HYCOM consortium has a long history of successful collaborations between universities and government agencies (NRL, NOAA). The Florida State University (FSU) HYCOM group has worked closely with NCAR to bring HYCOM in the CESM and is now in the process of comparing POP- and HYCOM-CESM simulations.

Criteria #3: *Timely and unfettered access to new developments*

The HYCOM forum and repository allows the community to provide feedback and have access to the latest developments (http://www.hycom.org).

Criteria #4: *Meet or have the potential to satisfy the technical requirements listed below*

- *Advanced dynamical core technical capabilities, including flexible vertical coordinates and resolution, advanced tracer advection schemes, natural boundary conditions on freshwater and tracers, and support for non-Boussinesq configurations;*
  HYCOM is designed to have a flexible vertical coordinate (ALE) and is non-Boussinesq. It has several tracer advection options, but the 2^{nd} order FCT is the most widely used. The current leapfrog time stepping scheme is probably the most significant limiting factor to more advanced numerics and its replacement is the most obvious large change that would greatly benefit HYCOM going forward. The standard version of HYCOM uses virtual salt flux forcing at the surface, but there are versions of HYCOM with a natural boundary condition on freshwater and tracers.
- *Model infrastructure and a development environment that provides strong support for collaborative model development with the university-based CESM community. This includes both structured programs such as Climate Process Teams and small group entrepreneurial projects;*
  The model is currently maintained by one person, Alan Wallcraft. Additional support would be needed in order to implement developments provide by CPTs and other community efforts.
- *Strong support for both regional and climate modeling applications;*
  HYCOM has been run extensively at high resolution for regional and global applications on decadal time scales. It has not been run as often for climate applications, but has participated in the CORE-forced model evaluation and presently being evaluated with the CESM framework.
- *Support for a wide range of resolutions and grids, and accompanying scale aware parameterizations;*
  Basin-scale and global configurations up to 1/50° are routinely run on various orthogonal grids – most of the existing parameterizations are for high-resolution configurations. HYCOM scales extremely well (see section below).
- *Ability to configure and run simpler idealized configurations for process modeling and educational applications;*
  HYCOM idealized configurations are routinely used for process studies and in the classroom – a two-gyre box configuration is available on the HYCOM web site.
- *Compatibility with the CESM sea-ice model;*
  HYCOM is coupled with CICE4 and we are presently testing CICE5.
- *Ability to interface with CESM coupled data assimilation system;*
  HYCOM can interface to any data assimilation (DA) scheme that uses direct or incremental insertion, and the DA scheme can be in either HYCOM layer or z-level space. We usually run MVOI or 3DVAR with the model forecast as the background and with first guess at appropriate time (FGAT) on z-levels. HYCOM is also being run with ensemble Kalman filter based DA.
- *Familiar post-processing and analysis capabilities (akin to CESM workflow tools).*
  HYCOM outputs are not presently analyzed via CESM workflow tools. Some of the tools would have to be adjusted to take into account the generalized vertical coordinate outputs.

Criteria #5: *State-of-the-science parameterizations (comparable to those in the present POP) suitable for use in coarse resolution climate models*

HYCOM does not have a lot of parameterizations for use in coarse resolution climate models. It does have GM90, but it is turned off when in fixed pressure/z-coordinates. The diffusivity tensors are also not rotated when in pressure- or sigma-coordinates. This is not an issue as long as the fixed coordinates are confined within the mixed layer, but this would need to be implemented for weakly stratified regions. HYCOM also does not have subgrid scale mixed layer parametrizations

Criteria #6: *Published solutions showing a model version that is comparable to POP in the context of Coordinated Ocean-ice Reference Experiments (CORE)*

The HYCOM solutions have been published in the series of recent CORE articles (8 papers published or submitted). As Gokhan is much aware, the AMOC in our first submission collapsed, mostly because of the weak SSS (4 years) restoring. With a slightly stronger restoring around Antarctica ((6 months, 4 years everywhere eslse) as well as other modifications (Large and Yeager bulk formula, wind instead of wind-stress, improved thermobaricity), the AMOC is stable and the HYCOM solution is within the range of the CORE results. This latest configuration is discussed in the papers on the interannual to decadal variability of the AMOC (Danabasoglu et al. 2015), the southern ocean circulation (Farneti et al. 2015), the hydrography of the Arctic Ocean (Ilicak et al. 2016) and the North and equatorial Pacific Ocean circulation (Tseng et al., 2016). The AMOC strength at 26.5ºN on the lower side of CORE-II group simulations with an average of ~12 Sv for the last 20 years of simulation, but with an interannual variability well in the range of all the other submissions. In the Arctic, HYCOM showed similar biases in T and S as NCAR in the ocean interior but stronger (weaker) transports at Bering strait and Davis strait (Fram strait and the Barents Sea opening). In the Southern Ocean, HYCOM had a transport of 156 Sv at the Drake Passage, very close to the CMIP5 average of 151 Sv as well as the NCAR's average of 149 Sv. The sea-ice extent of HYCOM in the region was in the lower range in either the summer or the winter.

Danabasoglu, G., et al., 2014: North Atlantic Simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part I: Mean States, Ocean Modelling, 73, 76-107, doi: 10.1016/j.ocemod.2013.10.005.

Danabasoglu, G. et al., 2015: North Atlantic simulations in Coordinated Ocean-ice Reference Experiments phase II (CORE-II). Part II: Inter-Annual to Decadal Variability. Ocean Modelling, 97, 65-90, doi: 10.1016/j.ocemod.2015.11.007.

Downes, S. M., et al., 2015: An assessment of Southern Ocean water masses and sea ice during 1988-2007 in a suite of inter-annual CORE-II simulations, Ocean Modelling, 94, 67-94, doi:10.1016/j.ocemod.2015.07.022.

Farneti, R. et al., 2015: An assessment of Antarctic Circumpolar Current and Southern Ocean meridional overturning circulation during 1958–2007 in a suite of interannual CORE-II simulations, Ocean Modelling, 93, 84-120., doi:10.1016/j.ocemod.2015.07.009.

Wang, Q. et al., 2016: An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part I: Sea ice and solid freshwater. Ocean Modelling, 99, 110-132, doi: 10.1016/j.ocemod.2015.12.008.

Wang, Q. et al., 2016: An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part II: Liquid freshwater. Ocean Modelling, 99, 86-109, doi: 0.1016/j.ocemod.2015.12.009.

Ilicak, M., et al, 2016: An assessment of the Arctic Ocean in a suite of interannual CORE-II simulations. Part III: Hydrography and fluxes. Ocean Modelling, 100, 141-161, doi: 10.1016/j.ocemod.2016.02.004.

Tseng, Y. et al, 2016: North and Equatorial Pacific Ocean circulation in the CORE-II hindcast simulations. Ocean Modelling, in review.

Criteria #7: *A realistic expectation that a configuration of the model would satisfy CESM3 science requirements in a timely manner*

I would think so, provided an investment in implementing the necessary coarse-grid parametrizations.

Criteria #8: *A modern code base that adheres to software engineering best practices with scalability and computational performance on modern architectures comparable to, or better than, POP.*

The HYCOM code base is based on MICOM and has only gradually been improved over time. Its performance is good in Mflops (see section on parallelization below), but it does require more computational resources than POP in a twin setup because of ALE. HYCOM's time step is also shorter than POP's.

Criteria #9: *A commitment to comprehensive model documentation*

The current documentation (available at www.hycom.org) is targeted at operational use of HYCOM. It is fragmented and does not cover recent changes to its capabilities.

Parallelization

The basic parallelization strategy is domain decomposition, *i.e.*, the region is divided up into smaller sub-domains, or tiles, and each processor "owns" one tile. A halo is added around each tile to allow communication operations (*e.g.*, updating the halo) to be completely separated from computational kernels. Rather than the conventional 1 or 2 element wide halo, HYCOM has a 6 element wide halo which is "consumed" over several operations to reduce halo communication overhead. For global and basin-scale applications it is important to avoid calculations over land. HYCOM fully "shrink wraps" calculations on each tile and discards tiles that are completely over land. HYCOM goes farther than most other structured grid ocean models in land avoidance by allowing more than one neighboring tile to the north and south. For example, one option for a global grid is equal sized tiles that a) allow rows to be offset from each other if this gives fewer tiles over the ocean and b) allow two tiles to be merged into one larger tile if less than 50% of their combined area is ocean. A conventional (36 by 32) 4 neighbor equal sized global tiling would use 863 MPI tasks out of 1152 original tiles, but HYCOM only needs 781 MPI tasks. More memory is required on some tiles and the communication overhead is slightly increased, but the 10% saving in MPI tasks is a significant optimization given the computer requirements of this application. HYCOM also allows parallelization via loop-level OpenMP directives and supports dual level parallelization via both domain decomposition (MPI) and OpenMP. Loop level OpenMP parallelization is typically applied to the "J" (latitude) do loop, and, to maximize the work per J loop ,the K (layer) do loop is often inside the J loop. Even so, a major subcomponent, such as the momentum equation, will typically require several J loop blocks. The mixed layer and the hybrid (ALE) grid generator act on one K-column at a time, which maximizes the opportunity for parallelization.

Alan Wallcraft (NRL-SSC) recently updated the standard 0.04 (1/25°) degree global HYCOM benchmark, used in the HPCMP "TI" benchmark suite, to HYCOM 2.2.98 which includes land masks in place of do-loop land avoidance. Results are shown in Fig. 1. Fig. 1 (left panel) reports total core hours on the y-axis, so a horizontal line would be perfect scaling. HYCOM is actually super-scalar out to 4000 cores and takes the same number of core hours on 1000 and 16000 XC40 cores. Fig. 1 (right panel) compares HYCOM 2.2.98 to the old 2.2.27 version, with static (common block) memory allocation and do-loop land avoidance. The blue curve is the same result as in the 1st figure, with 2.2.98 super-scalar from 1000 to 4000 cores. The red curve is 2.2.27 which performs about the same as 2.2.98 on 1000 cores but shows a gradual loss of scaling on more cores. The 2.2.27 result is not bad, but 2.2.98 is much better and can achieve an overall cost reduction of ~20% on larger core counts.

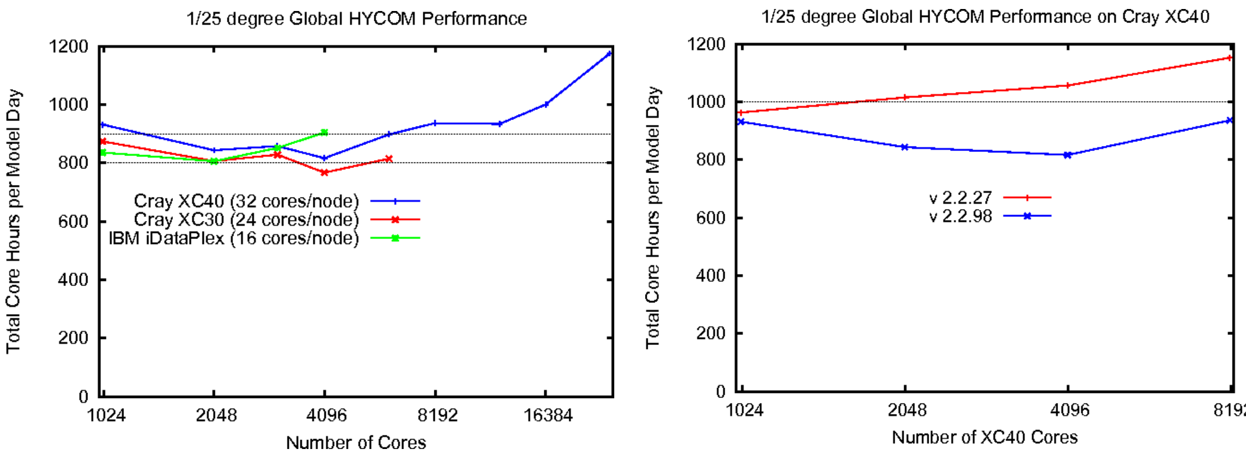

Figure 1. *Left panel*: Core-hours per simulated model day as a function of core count for HYCOM on three machines. *Right panel*: Core hours as a function of core count for two different HYCOM versions on a Cray XC40.

HYCOM-CESM and POP-CESM comparison

The ocean grid is gx1v6 and the atmospheric CAM grid is 1.9º x 2.5º. Both simulations start from rest from the PHC2.0 Levitus climatology and are performed for 45 years. No sea surface temperature or sea surface salinity restoring is applied, but a normalization of the salt flux is performed at the surface. Both simulations show similar behaviors in term of drift of SST and SSS. HYCOM-CESM has however a larger increase of the global temperature after 45 years (Fig. 2). The SST and SSS biases are, overall, of the same order of magnitude between the two simulations, except in a few regions, like the northeast Pacific ocean where a higher SST bias and a saltier surface is observed in HYCOM-CESM when compared with POP-CESM (Fig. 3). We also notice a slightly saltier ocean surface in the HYCOM-CESM Arctic. The main difference is found in the North Atlantic, in the region of the Labrador Sea where HYCOM-CESM has a fresh and cold bias whereas POP-CESM shows a warm and salt bias. This result is the direct consequence of the over-extended ice cover in the region as seen in Fig. 4. While the sea-ice extent is well within the range of the observations in most of the Arctic, the HYCOM-

CESM ice cover expands too much in the North Atlantic, especially in the Labrador Sea that is completely covered during the winter unlike POP-CESM. In the Antarctic, the POP-CESM ice cover is close to the NSICS climatology in term of extent and concentration. The HYCOM-CESM ice concentration is however weaker than POP-CESM, especially in the Weddell Sea.

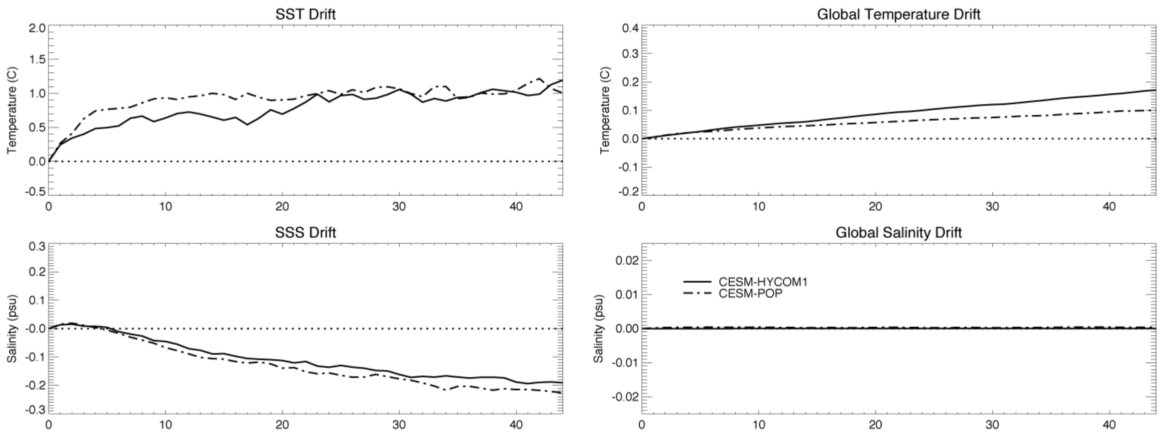

Figure 2. Evolution of the SST drift (top left), SSS drift (bottom left), global temperature drift (top right) and global salinity drift (bottom right) for HYCOM-CESM (black) and POP-CESM (dash-black).

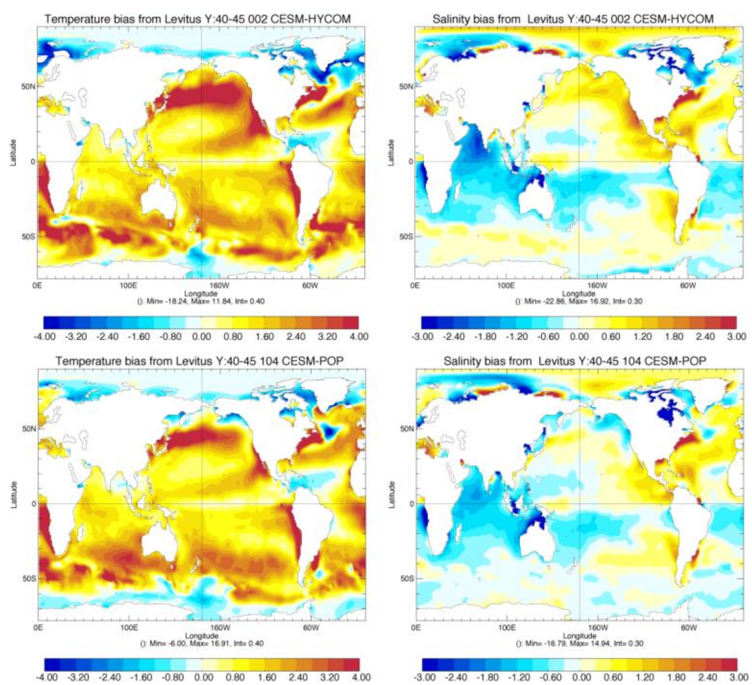

Figure 3. SST (left) and SSS (right) bias from the PHC2 Levitus climatology for HYCOM-CESM (top) and POP-CESM (bottom) averaged over the last 5 years of simulation.

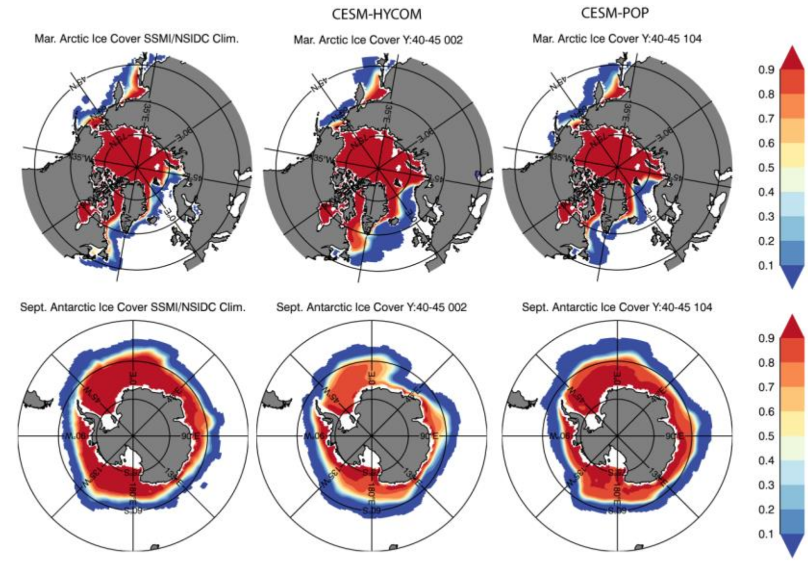

Figure 4. Sea ice concentration from NSIDC/SSMI climatology (left) in the Arctic in March (top) and in the Antarctic in September (bottom). HYCOM-CESM (middle) and POP-CESM (right) results are averaged over the last 5 years of simulation.

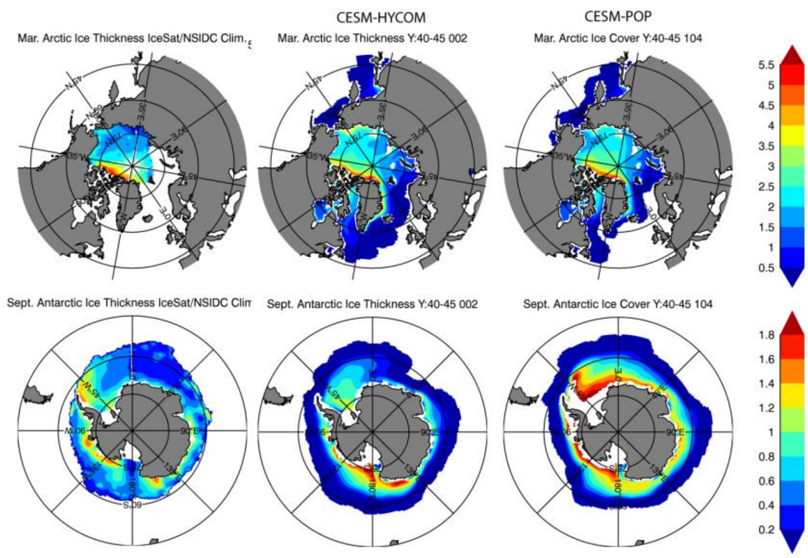

Figure 5. As Figure 4, but for ice thickness.

Despite the over-extension of the ice cover, the ice thickness in HYCOM-CESM in the Artic basin is similar to the one in POP-CESM (Fig. 5). In the Antarctic, the HYCOM-CESM presents a thinner ice cover than POP-CESM as expected from the weaker ice concentration over the region.

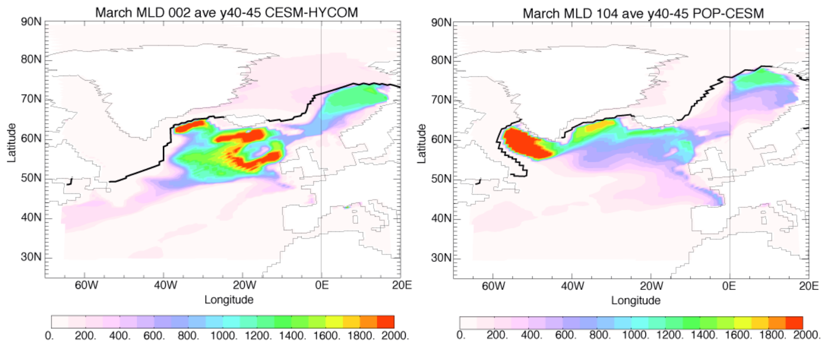

Figure 6. March mixed-layer depth (color) and ice extent (black line) averaged between year 40 and 45. A difference of density of 0.03 kg/m^3 from the surface is used to calculate the mixed layer depth.

With ice completely covering the Labrador Sea during the winter, the region of maximum mixed layer depth is shifted to the North Atlantic subpolar gyre in HYCOM-CESM, while it is located in the Labrador Sea in POP-CESM (Fig. 6). The results of a sensitivity experiment using twice the viscosity used in HYCOM-CESM (closer to that of POP-CESM) show an improvement in the extent of the ice cover over the Labrador Sea, but not enough to shift back the region of maximum mixed-layer depth from the subpolar gyre to the Labrador Sea (not shown).

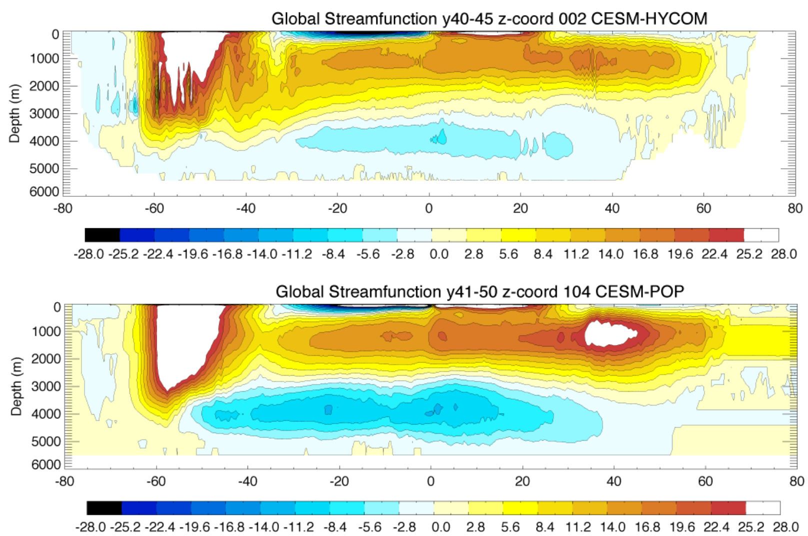

Figure 7. Global vertical streamfunction in z-coordinate averaged between 40 and 45 years for HYCOM-CESM (top) and POP-CESM (bottom).

The comparison of the global streamfunction gives us an idea of the strength of the circulation in both simulations. The HYCOM-CESM circulation is overall weaker than in POP-CESM, particularly in the lower cell, where the maximum streamfunction is close to -5 Sv while it reaches -11 Sv in POP-CESM (Fig. 10). The upper cell presents a maximum streamfunction superior to 26 Sv between 35°N and 45°N in POP-CESM while, HYCOM-CESM maximum streamfunction in the upper cell is located between 30° and 40°N with a value of 14-16 Sv. These differences in the circulation strength can also be found in the Atlantic basin. As in the global streamfunction, the maximum streamfunction at 45° and 26.5°N in the Atlantic Ocean is higher in POP-CESM than in HYCOM-CESM (Fig. 8). While the maximum streamfunction reaches 15 Sv in HYCOM-CESM at 45° and 26.5°N, POP-CESM streamfunction stabilizes around 24 Sv at 45°N and 21S v at 26.5°N after 45 years.

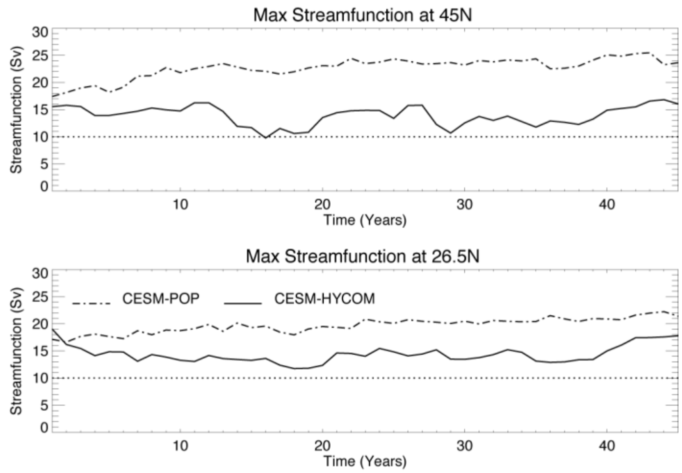

Figure 8. Evolution of the maximum streamfunction at 45ºN (top) and 26.5ºN (bottom) in the Atlantic basin for HYCOM-CESM (black line) and POP-CESM (dashed line).