NCAR UCAR

DOE BER SCIDAC # DE-SC0012605
Southern Ocean mixing

NASA PO project 80NSSC18K0769
Air-sea interaction and ocean mixing

NSF – NCAR-Wyoming
Supercomputing Center

NASA Salinity project
Mode waters and salinity trasnport

SubAntarctic Zone Mode Waters in high resolution CESM

Justin Small, NCAR
Daniel Whitt, Alice DuVivier, Matthew Long, William Large, NCAR
Ian Grooms, University of Colorado
Frank Bryan NCAR, Stu Bishop NCSU
Thanks to Ivana Cerovečki, Matt Mazloff, Scripps

SubAntarctic Mode Waters (SAMW) and Deep Mixing Band (DMB)

(a)

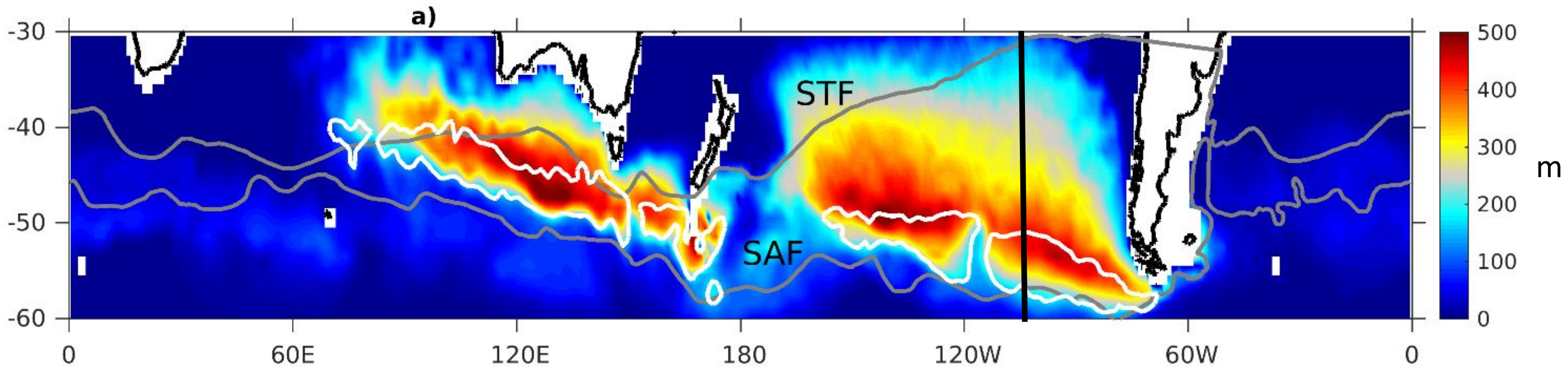


Fig. 2. a). Annual mean thickness of SAMW from ARGO (Roemmich and Gilson product), defined as a water mass with densities between 1026.6 and 1027.1kgm^{-3}, and PV less than $40*10^{-12}m^{-1}s^{-1}$. Overlaid thick white contour is 300m mixed layer depth in September in ARGO. The thick grey contours are climatological positions of the fronts given by Orsi et al. (1995): STF, and SAF as labelled.

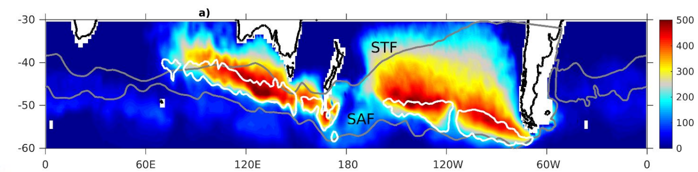
Courtesy Ivana Cerovecki, Dan Whitt

Overview of this talk

- Introduction – SAMW and bias in climate models
- 1. Sensitivity of SAMW to improvements in ocean circulation in POP and CESM1
- 2. Water mass transformation analysis for high-resolution CESM
    - Sensitivity to eddies

SubAntarctic Mode Water

- A large region of very low stratification occupying substantial fraction of upper 1000m of Southern Ocean (north of ACC)
- The mode water is subducted below the mixed layer after forming in winter mixed layer. It is consequently advected away.
- Biases in the stratification in this region could have implications for projections of heat, CO2 uptake and transport.
- McCartney (1977), McCarthy and Talley 1999, Hanawa and Talley 2001, Forget and Speer 2013, Cerovecki et al 2011, 2013, 2016 +many others.



Mode water bias: sections across SAMW

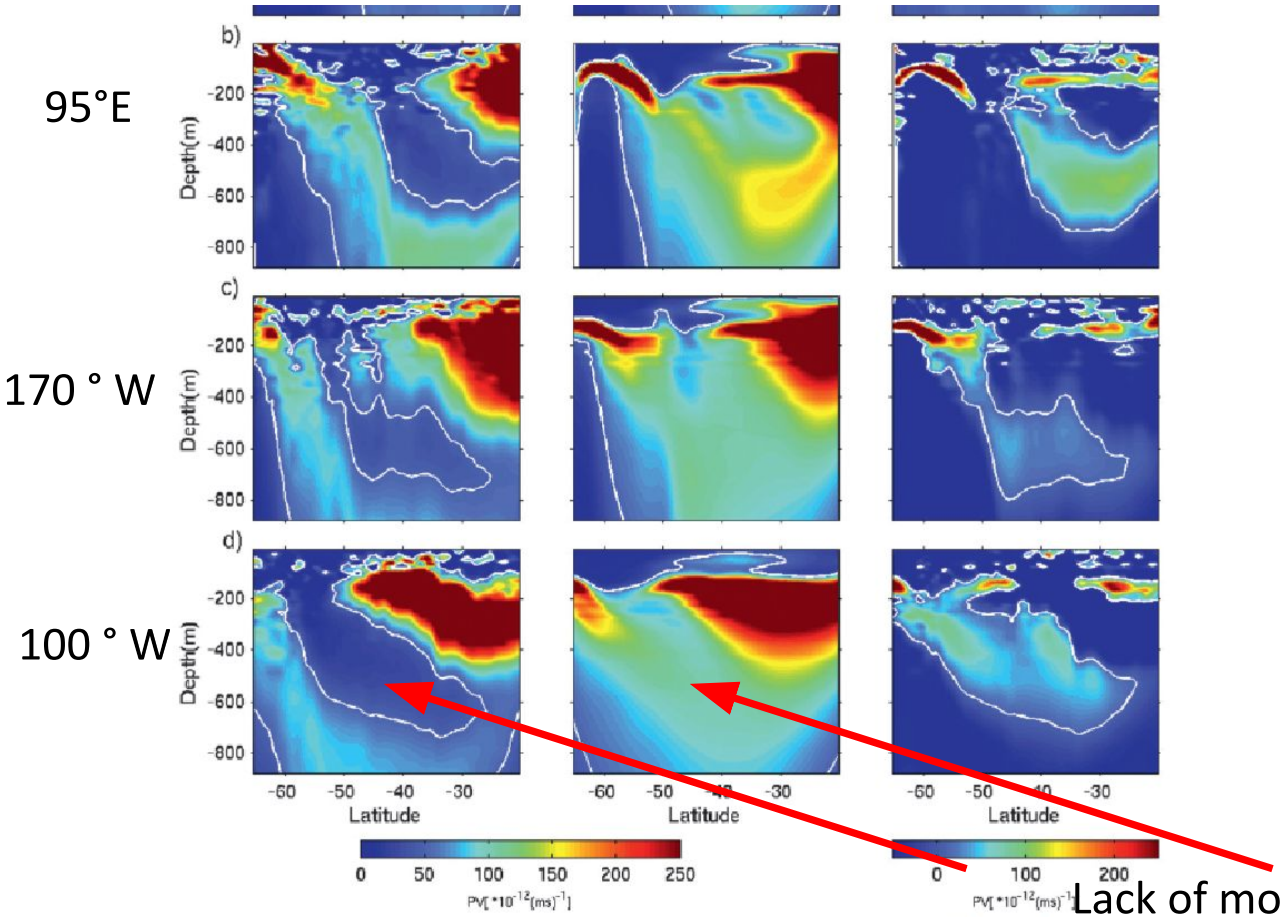


FIG. 9. Comparison of winter (August–October) potential vorticity [$\times 10^{-12}$ (m s)$^{-1}$] for (left) CARS2009, (center) CCSM4, and (right) CCSM4 minus CARS2009 for (a) the Atlantic (335°E), (b) Indian (95°E), (c) western Pacific (190°E), and (d) eastern Pacific (260°E) sectors of the Southern Ocean. The potential vorticity and potential vorticity difference 50×10^{-12} (m s)$^{-1}$ (white contour) is shown on (left) and (center), and (right), respectively. Location of each section is shown in Fig. 8.

Weak stratification water formed in deep mixed layer region, subducted and transported Equatorward.

Planetary Potential vorticity
f/rho0 ∂ρ/ ∂ z
Is weak in the mode water region
Weijer et al. 2012, Sallee et al 2013

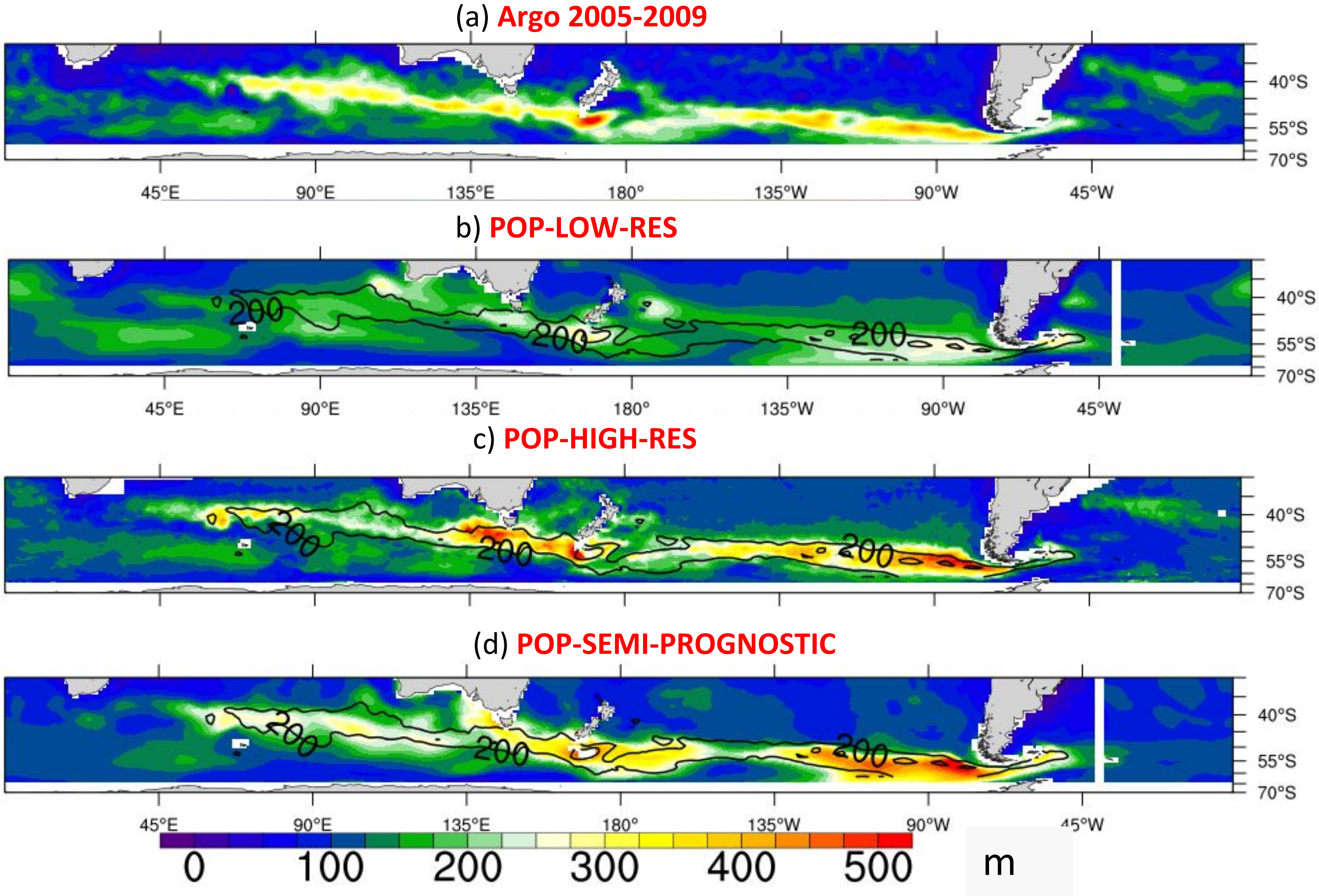
PV 5e-11 $m^{-1}s^{-1}$ =Approx density gradient of 0.05kg/m3 per 100m

CGD
Climate & Global Dynamics

Methods

- Previous papers point out that MLD is deepened in ocean models with high resolution (Lee et al 2011, McClean et al 2011, Li and Lee 2019)
- Other papers point out importance of continuous, downstream air-sea heat loss to mode water formation
    - downstream of regions such as Agulhas Return Current (Lee et al 2011, Wang et al 2014)
    - and in SubAntarctic Zone (Cerovecki et al 2011, 2013, 2016)
- We investigate sensitivity to ocean model resolution
    - Compare 1deg. against 0.1deg ocean, forced ocean-ice simulations
- And we investigate sensitivity to "fixing" the mean circulation via a semi-prognostic method
    - Replace model density with observed density in hydrostatic equation – Greatbatch et al 2004
    - Leads to improved mean geostrophic flow

MLD in Argo & forced ocean-ice models. Austral winter, JAS.



Contours of 200m, 400m MLD from ARGO overlaid.

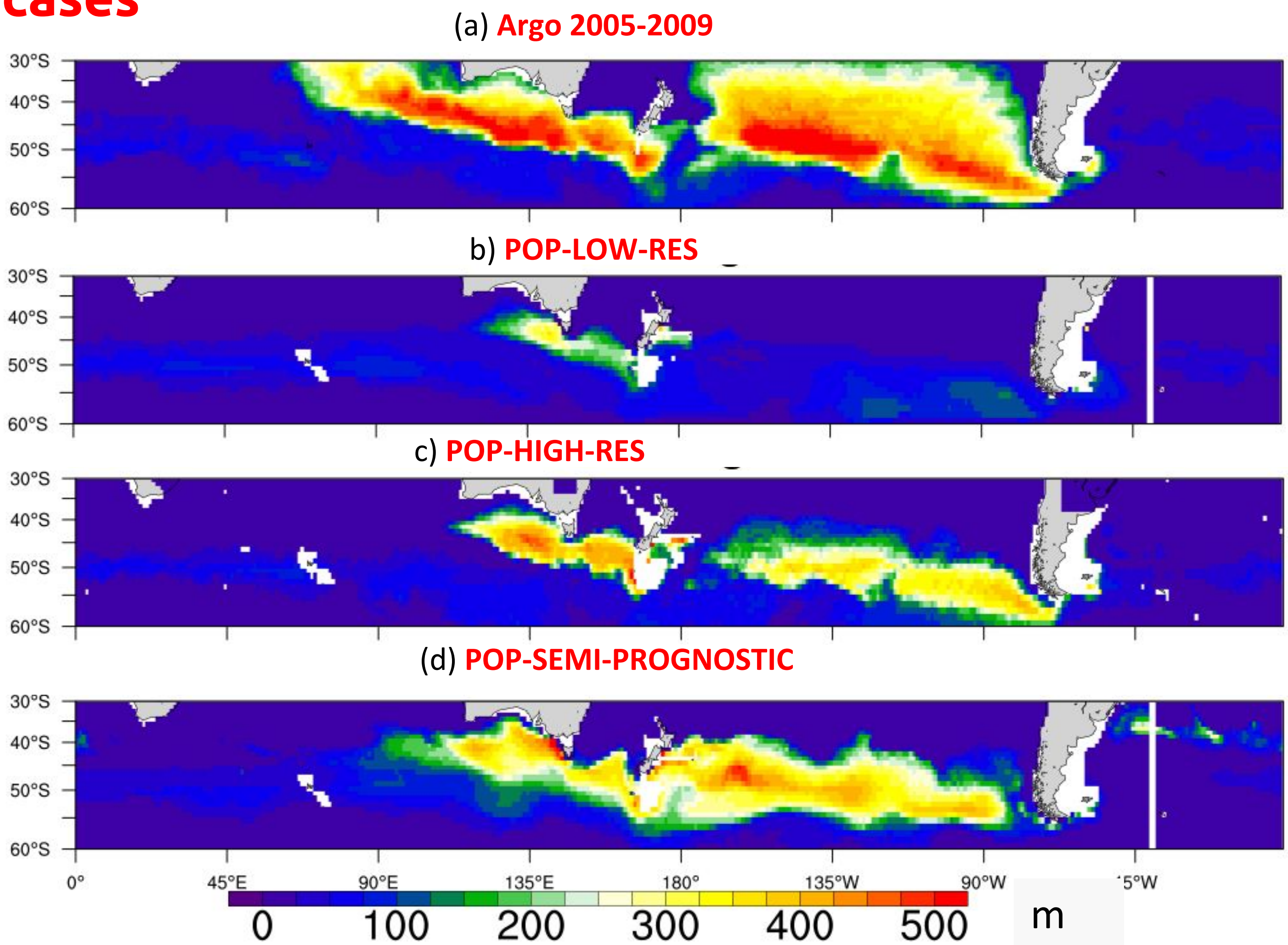
MLD defined based on density 0.03kgm^{-3} threshold.

There is sensitivity to MLD definition.

Processes leading to deeper winter MLD in POP simulations

- Improved ocean circulation leads to weaker stratification year-round
  - Consequently deeper winter MLD
- Two main processes
- More air-sea heat loss in SubAntarctic Zone
  - A consequence of warmer SST, air-sea feedback
- More transport of salinity in upper layers into SubAntarctic Zone
  - Destabilizing influence
- See Small et al. 2020 (Clim. Dyn., under repeated revision)

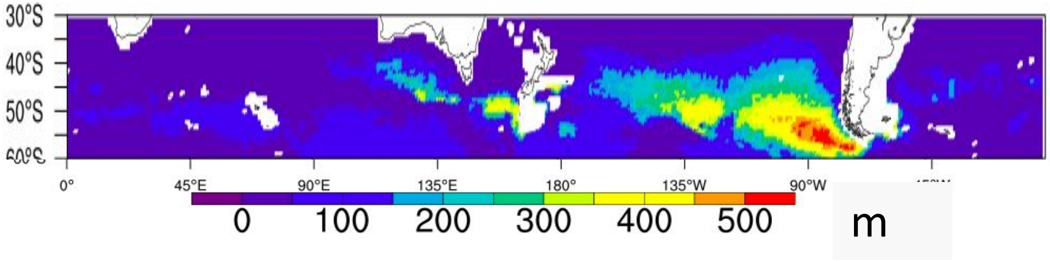
Mode water thickness. Annual mean. Argo and forced ocean-ice cases



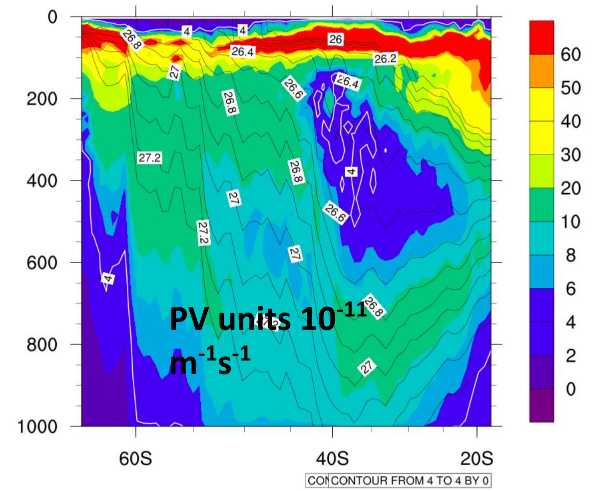
Potential densities between 1026.6 and 1027.1kgm^{-3}, and PV less than 40*10^{-12}m^{-1}s^{-1}

Mode water thickness. Annual mean. High-resolution coupled CESM and Argo

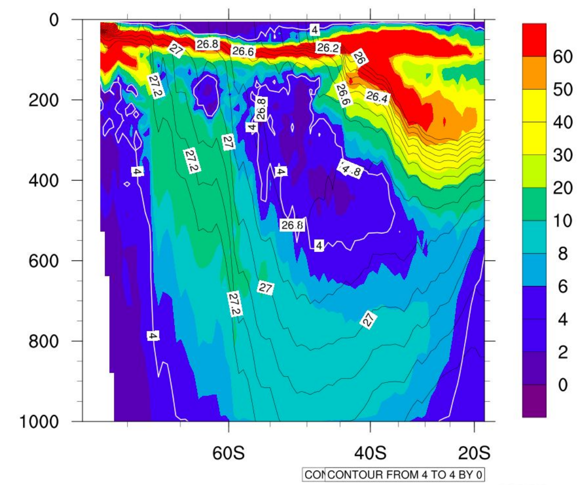
CESM-HR Strict definition: PV < 4e-11, 1026.6<PD<1027.1



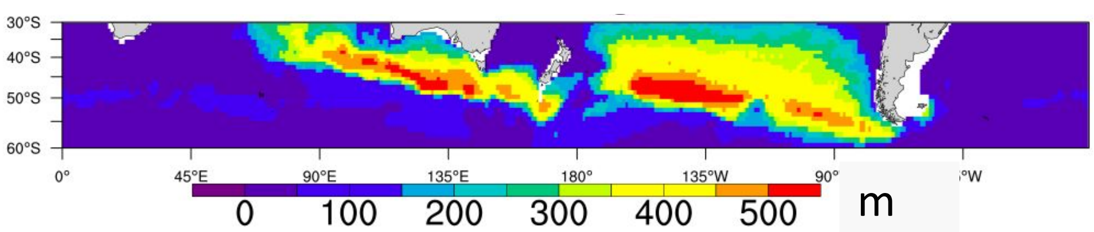
PV section at 90E, February



PV section at 105W, February



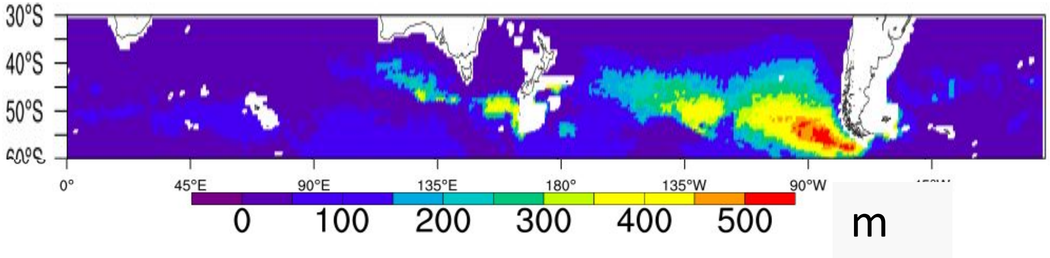
ARGO



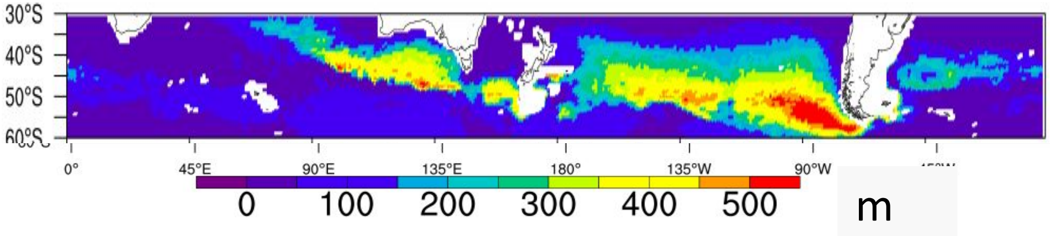
Annual mean of SAMW thickness. The strict definition (used for top panel and Argo) is PV < 4e-11, 1026.6<PD<1027.1. Right panels: cross-sections from CESM-HR.

Mode water thickness. Annual mean. High-resolution coupled CESM and Argo

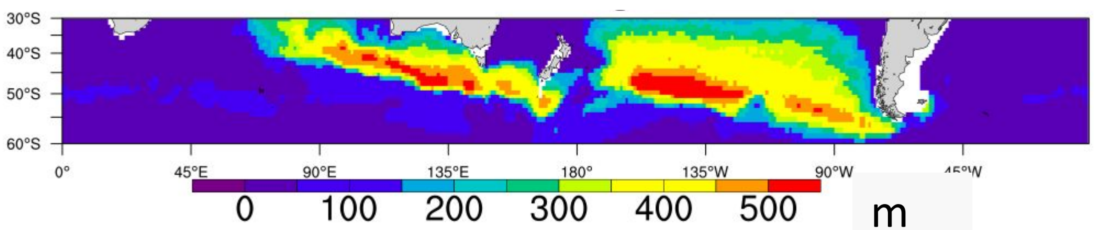
CESM-HR Strict definition: PV < 4e-11, 1026.6<PD<1027.1



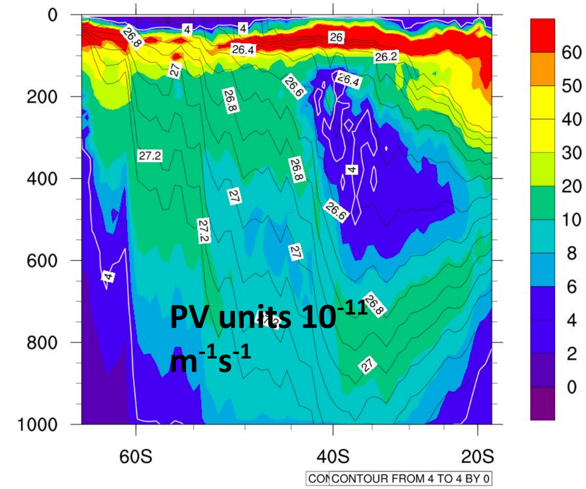
CESM-HR Alternative definition: PV < 5e-11, 1026.5<PD<1027.1



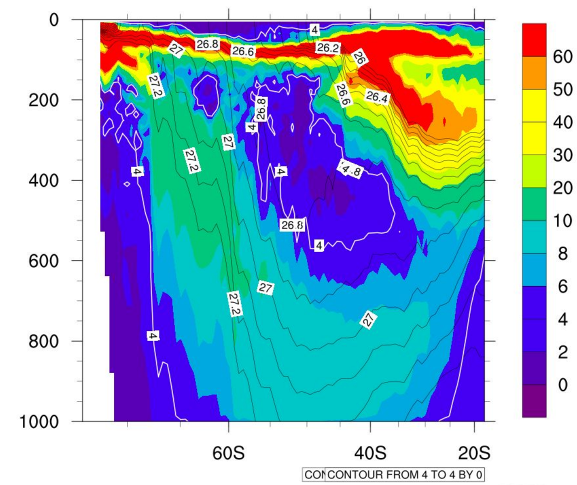
ARGO: Strict definition



CESM-HR PV section at 90E, February

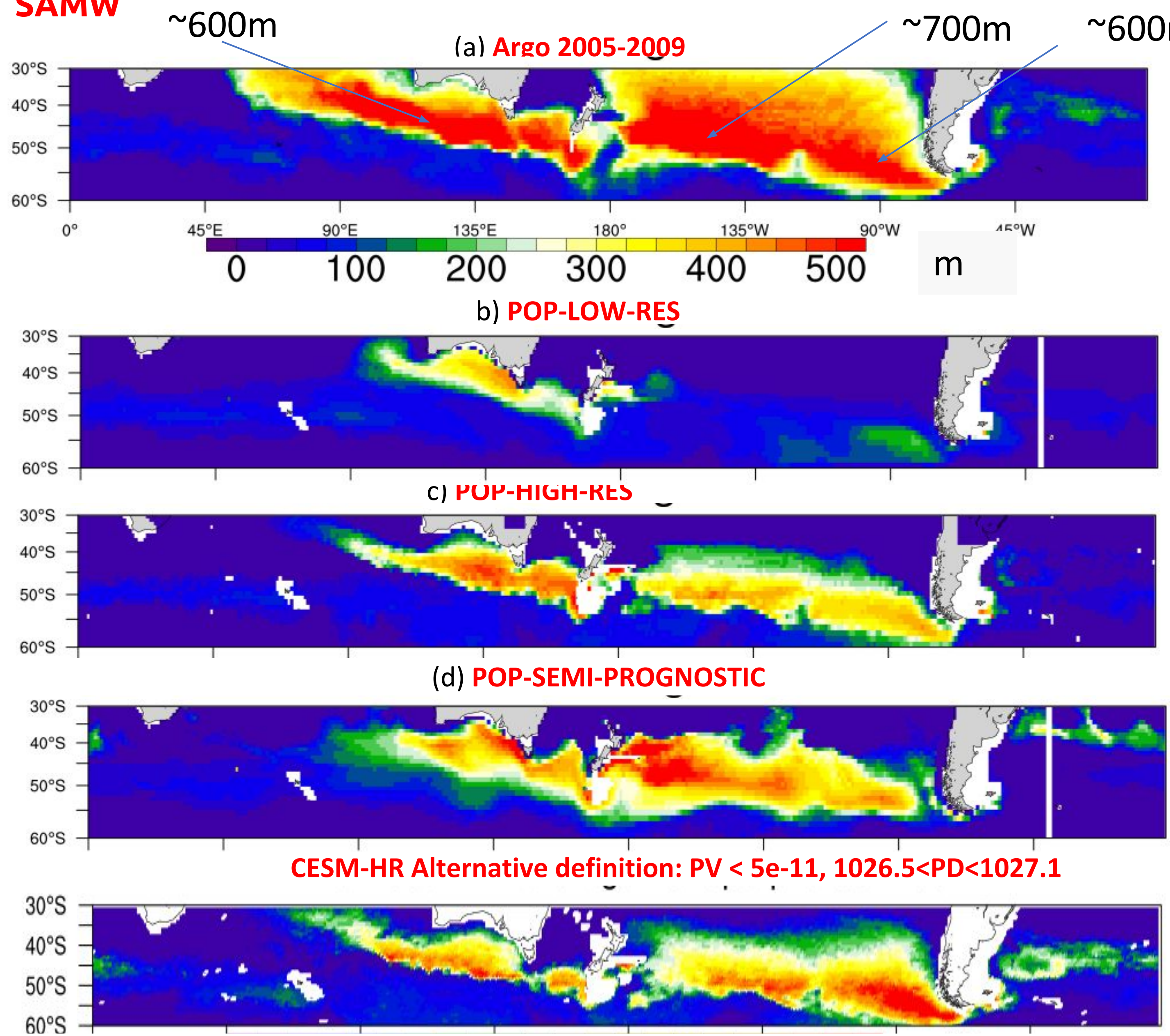


CESM-HR PV section at 105W,



Annual mean of SAMW thickness. The strict definition (used for top panel and Argo) is PV < 4e-11, 1026.6<PD<1027.1. Middle panel is an alternative definition more suitable for model distribution of densities: see other variants on next slide. Right panels: cross-sections from CESM-HR.

Mode water thickness. Annual mean. Comparison of all cases with alternative definition for SAMW



Branched off cycle 5 of CORE-forced (after year 293)

About 30 years of interannual following 15 years of CORE NY initialized from obs

30 years after branched off cycle 5 of CORE-forced (after year 293)

70-80 years after initialization from obs

Potential densities between *1026.5* and 1027.1kgm^{-3}, and PV less than *5010^{-12}m^{-1}s^{-1}**

Water Mass Transformation

- Transformation of sea water from one density class to another
  - Due to the action of air-sea buoyancy fluxes and interior diabatic processes (mixing)
- Walin 1982, Tziperman 1986, Large and Nurser 2001 , Cerovecki et al. 2011, 2013, 2016, many others
- Surface effect: integrate air-sea buoyancy flux between isopycnals (i.e. density classes)

Water Mass Transformation

1. Potential density is computed from daily SST, SSS in double precision.
2. Air-sea buoyancy flux, follows Cerovecki et al 2011

$$B = B_{\mathrm{HF}} + B_{\mathrm{FW}} = (g/\rho_0)[(\alpha Q_{\mathrm{HF}})/c_p - \rho_0 \beta S(E - P)],$$

3. Water mass transformation follows Cerovecki et al 2013:

transformation rate $F(\sigma, t)$ is the air–sea buoyancy flux integrated over the outcrop window bounded by isopycnal surfaces $\sigma \pm \Delta\sigma/2$, given by

$$F(\sigma,t) = \frac{\rho_0}{g\Delta\sigma} \iint_{\mathcal{A}_S(\sigma,t)} B\delta_T(\sigma', \Delta\sigma)\, d\mathcal{A}', \qquad (4)$$

in which $\mathcal{A}'(\sigma, t)$ is the instantaneous surface bounding the volume within which the density is $\sigma \pm \Delta\sigma/2$, ρ_0 is the reference surface density, g is gravitational acceleration, and $\delta_T(\sigma', \Delta\sigma)$ is a top-hat function of σ' which is zero except in the interval $\sigma \pm \Delta\sigma/2$, where it has unit value (see, e.g., Speer and Tziperman 1992; Marshall

4. Water mass formation is the convergence of transformation, follows Cerovecki et al 2016

$\delta\sigma$ so that σ_1 need never be specified explicitly. The diapycnal water mass formation $M(\sigma, t)$ is obtained as the finite difference of water mass diapycnal transformation A with respect to density:

$$M(\sigma,t) = [A(\sigma - \delta\sigma, t) - A(\sigma + \delta\sigma, t)]/\delta\sigma. \qquad (6)$$

We follow convention and multiply M in Eq. (6) by $\delta\sigma$ so as to have a quantity with the same units as transformation rate A.

Review: Cerovecki and Marshall 2008

Cerovecki and Marshall identify two roles of eddies

i) By altering the air-sea buoyancy flux and isopycnal area
ii) By interior eddy buoyancy fluxes altering the interior diabatic flux
iii) They found these effects partially cancel
iv) We'll start by looking at effect i)

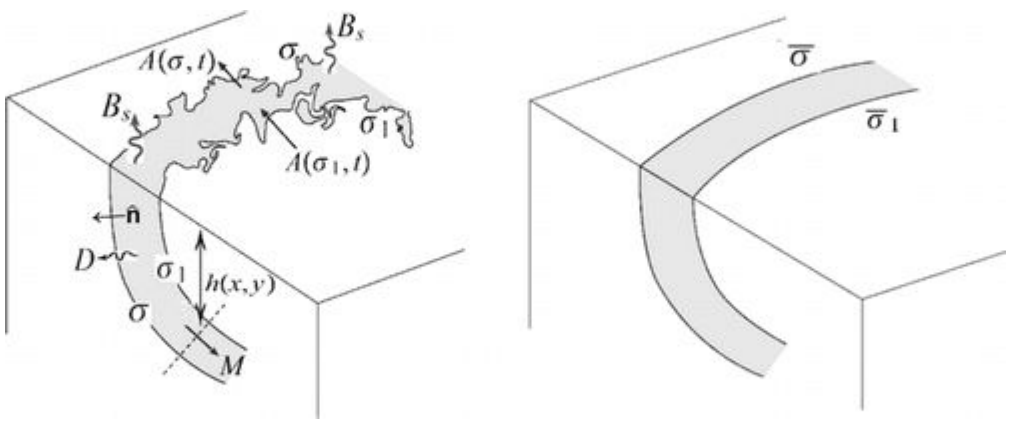
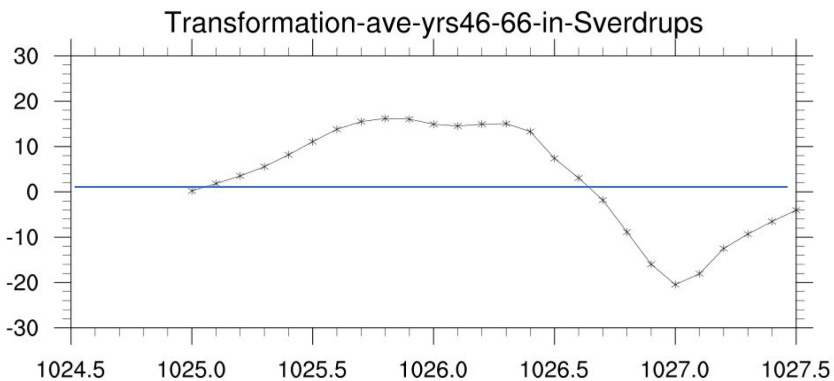


Fig. 8. Schematic showing application of the formalism due to Walin (1982): (left) Sketch of the outcrop in the presence of the eddies. The shaded region $R(\sigma, t)$ is bounded laterally by two outcropping isopycnals with density σ and reference density σ_1 (less than σ), and vertically by the sea surface and a control surface $z = -h(x, y)$. Lateral volume flow $A(\sigma, t)$ across the isopycnals, whose convergence drives net subduction M across the control surface $h(x, y)$ in the ocean interior, is induced by air–sea density flux B_S acting across the sea surface and the interior density flux D acting across the lateral isotherms: $\mathbf{n}_\sigma$ is the unit vector perpendicular to the isopycnals. (right) The corresponding picture after coarse graining, which spatially smooths isopycnals and the outcropping window bounded by σ and σ_1.

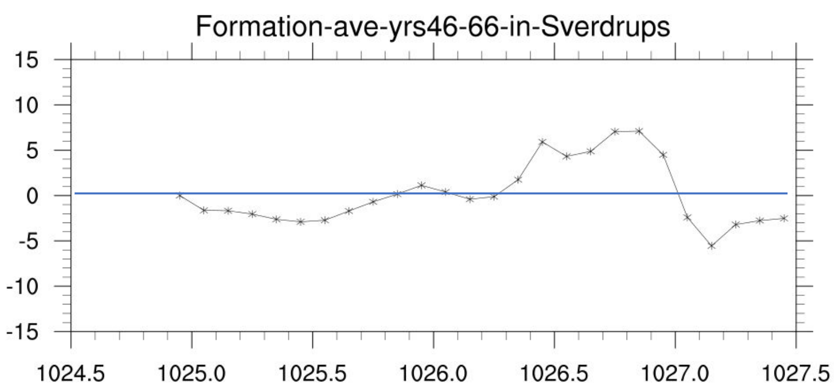
Water-mass transformation in high-res CESM

- CESM-HR (Small et al 2014)
- Start with daily data of SST, SSS, surface heat flux, surface freshwater flux
- Compute potential density using POP EOS
- Compute air-sea buoyancy flux from heat+freshwater flux (e.g. Cerovecki et al 2011)
- Compute water-mass transformation in predefined density bins of 0.1kgm-3 from 1025 to 1028 (e.g. Cerovecki et al 2013, 2016)
- Time-average over a number of years
- Sensitivity to spatial scale: repeat above but spatially smooth daily density and buoyancy flux to remove eddies

Transformation & Formation in CESM-HR



Formation-ave-yrs46-66-in-Sverdrups



20 year average in domain shown below: does not include Antarctic margin

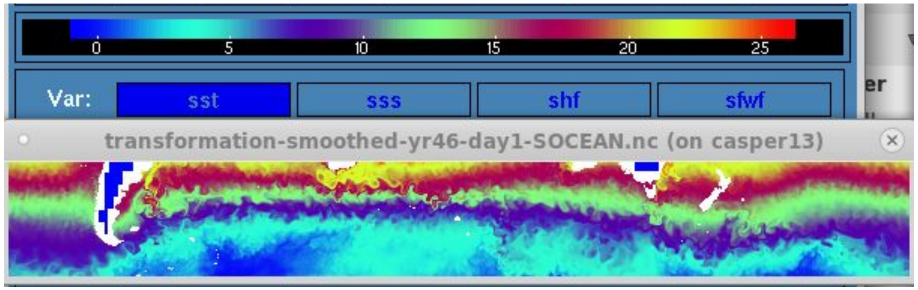


Fig. shows a daily average SST

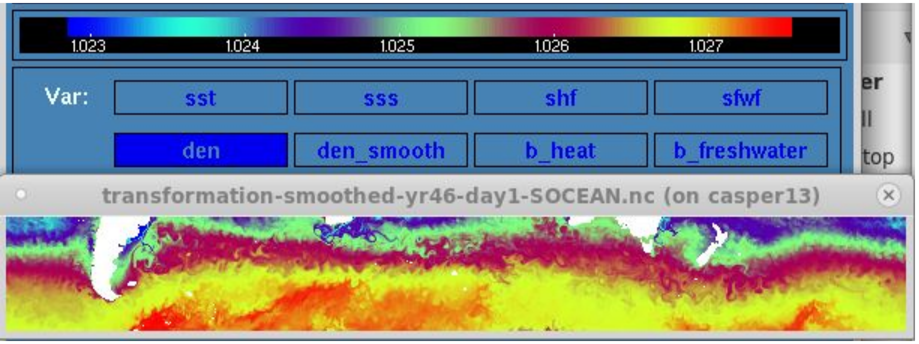
Note strong formation in 1026.45 to 1026.95 range of pden, the SAMW range in model

Investigate role of eddies, small scales

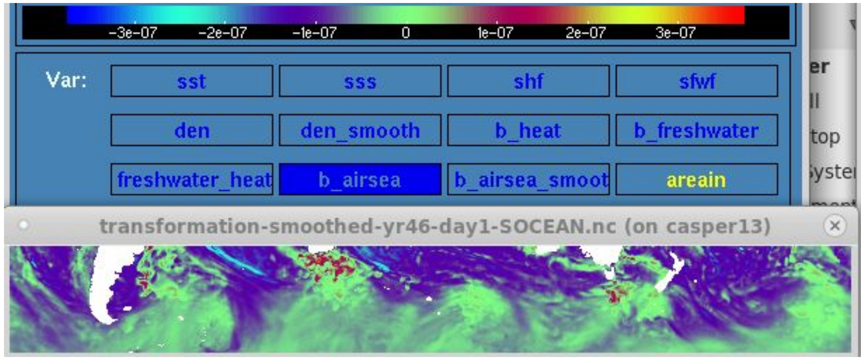
- Apply same analysis but the daily potential density and air-sea buoyancy flux are spatially smoothed to remove eddies

Illustration of smoothing: 5deg boxcar smoothing

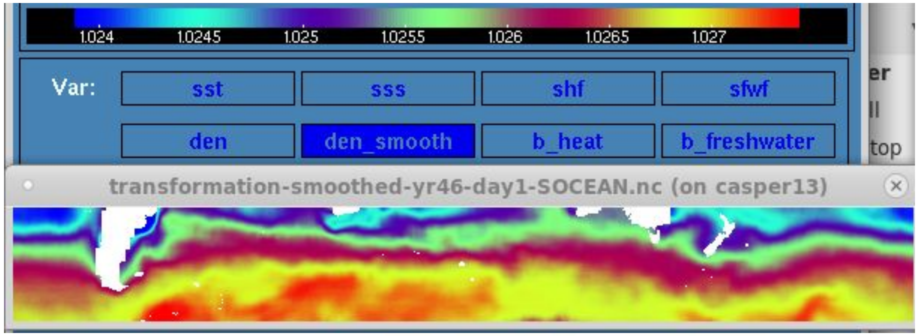
1 day potential density



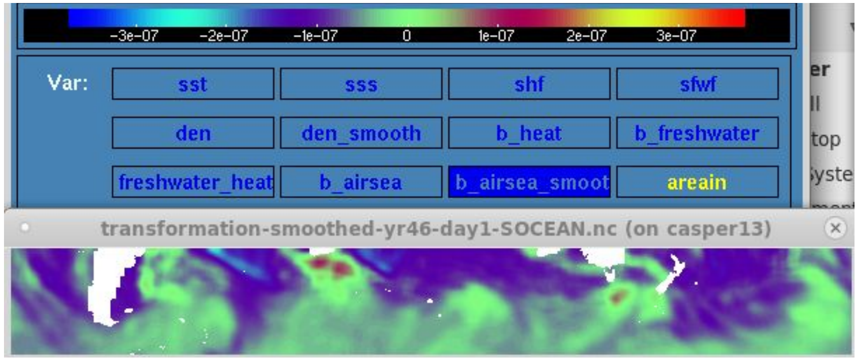
1 day air-sea buoyancy flux



1 day potential density, smoothed



1 day air-sea buoyancy flux, smoothed

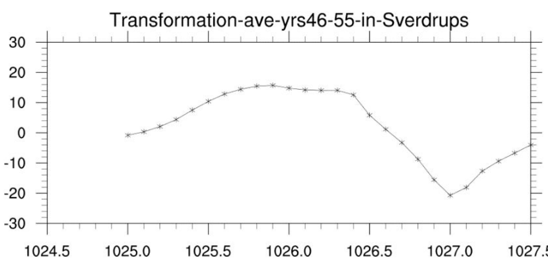


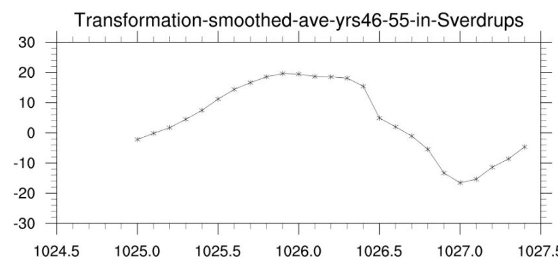
Effect of smoothing: water mass transformation/formation

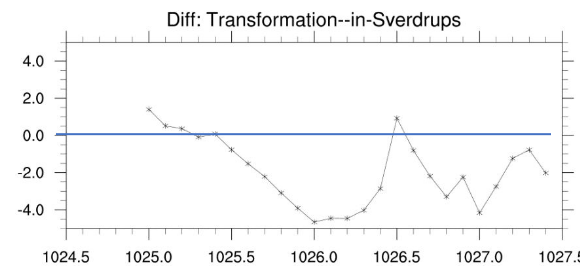
Years 46-55, original

Years 46-55, smoothed

Difference: original minus smooth



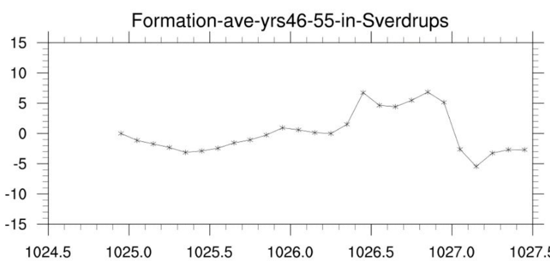


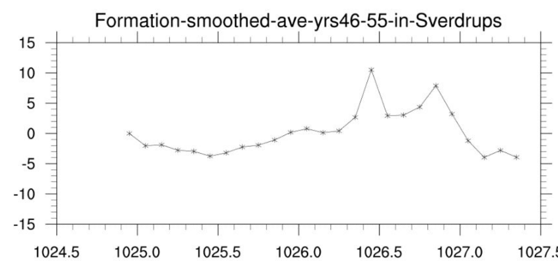


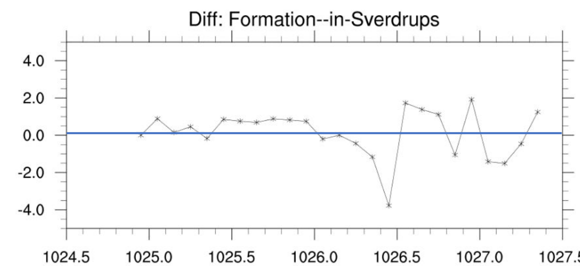
Formation-ave-yrs46-55-in-Sverdrups

Formation-smoothed-ave-yrs46-55-in-Sverdrups

Diff: Formation--in-Sverdrups







Smoothing does not make a qualitative difference. However localized differences of 2-4Sv in Transformation: original field is more negative. Formation has mixed differences, mostly +/-2Sv

Summary

- SubAntarctic Mode Water bias persists from CCSM4 to CESM1 (and most likely CESM2) for standard ocean resolution
- Higher volume SAMW found in ocean-ice experiments with improved ocean mean circulation
  - High-resolution
  - Semi-prognostic
- Coupled high resolution model has slightly lower Indian ocean SAMW densities, large volume of SAMW
- Higher volume of SAMW is consistent with deeper winter MLD, and subduction and consequent advection
- Water mass transformation framework in high-res CESM shows formation of mode waters
- Influence of eddies is small but non-negligible- removing the effect of eddies on the surface calculations leads to larger transformation