A Diagnostic Tool for Spatiotemporal Water Mass Transformation Analysis

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Project

Metrics of Transient Ocean Tracers and Water Mass Transformations

- Gain better understanding of ocean ventilation, heat and carbon uptake
- Contribute to the assessment and development of ocean and climate models
- Reduce uncertainty in future climate projections
- In collaboration with

PCMDI

Paul Durack
Peter Glecker

NCAR

Gokhan Danabasoglu
Justin Small

U.S. DEPARTMENT OF ENERGY | Office of Science

Lawrence Livermore National Laboratory

This tool would not have been possible without…

Scripts and jupyter notebooks by Graeme MacGilchrist

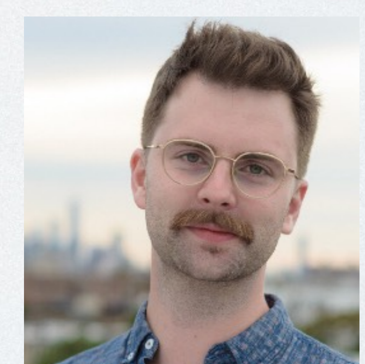
Python-based ecosystem of open-source software

SciPy jupyter INTAKE pandas xarray DASK

GCM

PANGEO

Ryan Abernathey
Julius Busecke
and others



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Outline

I. Primer on WMT (theory and underlying calculations)

II. Workflow

III. Examples
   a. Global Picture
   b. North Atlantic
   c. Southern Ocean

Primer on Water Mass Transformation

- Quantifying the rate at which water is **transformed** between water mass **classes**

- Has been applied in both observational and modelling studies over ~40 years. Recently generalized in **Groeskamp et al. (2019)**

- Classes are defined by a scalar (λ) which can represent
  - a tracer (e.g., θ, S, **carbon**)
  - or buoyancy/density (e.g., σ_0, γ_n)

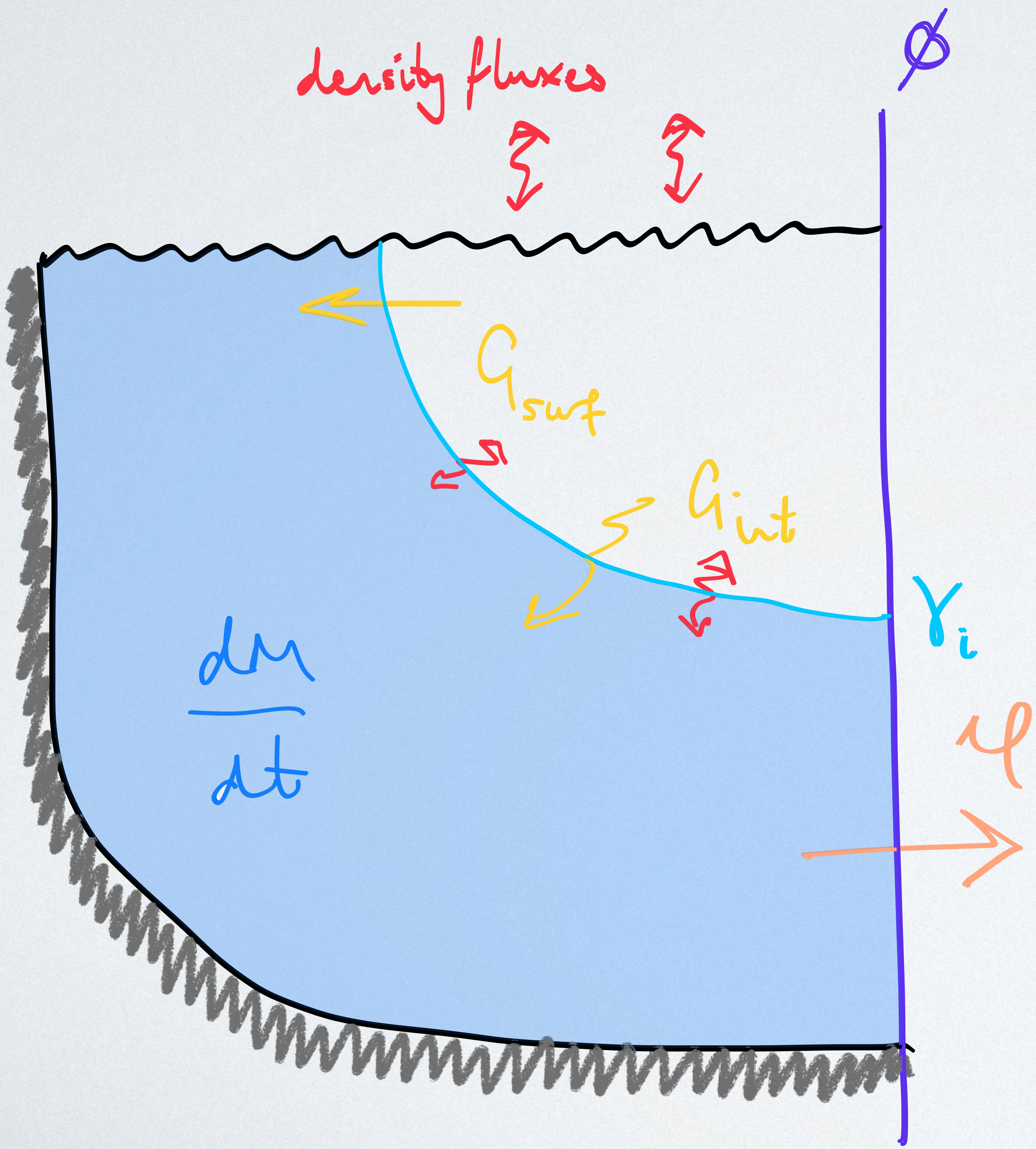
- **Transformation** (G) is the transport of water across a λ-isosurface
  ➡ Nonzero **material change** in λ:

$$\dot{\lambda} = \frac{D\lambda}{Dt} = \frac{\partial\lambda}{\partial t} + v \cdot \nabla\lambda \neq 0$$

- By convention, $G(\lambda) > 0$ means water moves to larger λ

Calculating water mass transformation $G(\lambda)$

- Traditionally, WMT in density space ($\lambda = \gamma$): Transport across neutral density surfaces



$$\frac{dM}{dt}(\gamma_i, \phi) = G_{surf}(\gamma_i, \phi) + G_{int}(\gamma_i, \phi) - \psi(\gamma_i, \phi)$$

$$G = \frac{\partial}{\partial \gamma} \iiint_{\gamma < \gamma_i} \gamma \, b \, \dot{\rho}_l \, dV$$

$\dot{\lambda}$

Courtesy of Graeme MacGilchrist

Calculating water mass transformation $G(\lambda)$

mom6-analysiscookbook.readthedocs.io/en/latest/notebooks/Watermass

MOM6-AnalysisCookbook

latest

Search docs

Read the Docs v: latest

Watermass transformation in MOM6

Contributors: Graeme MacGilchrist

Mass transport (G) across a contour of a materially-conserved tracer (λ) can be derived from the integrated diffusive tendencies of that tracer ($\dot{\lambda}$). Formally, this is written

$$G(\lambda) = \frac{\partial}{\partial \lambda} \iiint_{\lambda' \leq \lambda} \rho \dot{\lambda} dV .$$

This calculation, initially laid out by Walin (1982) and recently generalized in Groeskamp et al. (2019), is broadly known as watermass transformation and it can be used to reframe the ocean circulation in a new coordinate system.

Here, we show how to carry out this calculation in MOM6 in a variety of contexts.

Discrete formulation of watermass transformation for MOM6

For evaluation in an ocean model, we can write out a discrete version of the above equation (see Section 7.5 in Groeskamp et al., 2019):

$$G(\lambda) = \frac{1}{\Delta\lambda} \sum_n \sum_{i,j,k} \Pi(\lambda_n, \lambda, \Delta\lambda)(\rho\dot{\lambda})_{i,j,k} V_{i,j,k} ,$$

where $\Delta\lambda$ is the discrete bin width for defining λ contours, V is the grid-cell volume, and we have introduced a boxcar function to accumulate grid cells in which λ falls within the discrete bin:

$$\Pi(\lambda_n, \lambda, \Delta\lambda) = \begin{cases} 1 & \text{if } \lambda_n \in [\lambda - \Delta\lambda/2, \lambda + \Delta\lambda/2] \\ 0 & \text{otherwise} \end{cases}$$

Now, in the case of heat and salt in MOM6, it is the vertically-extensive tracer content that is conserved (see budget closure tutorial) and we can rewrite the discrete equation as:

$$G(\lambda) \approx \frac{1}{\Delta\lambda} \sum_n \sum_{i,j,k} \Pi(\lambda_n, \lambda, \Delta\lambda)(\rho\dot{\Lambda})_{i,j,k} A_{i,j} ,$$

where $\dot{\Lambda} = \int_{z_k}^{z_{k-1}} \dot{\lambda}\, dz$ is the diffusive tendency of the vertically-integrated tracer content, and A is the horizontal grid area.

Binning contributions to $\dot{\lambda}$ into λ classes

"**Watermass transformation in MOM6**" Tutorial by Graeme MacGilchrist

https://mom6-analysiscookbook.readthedocs.io

MOM6-AnalysisCookbook

Calculating λ: *Sum of tendencies / flux convergences*

- Focusing on the **process method**:

Total λ = *Interior (mixing) processes* + *Surface boundary forcing*

Material change = Sum of tendencies

Full 3D WMT

Surface WMT

- Ideally, we want both tendencies from interior and boundary
  - Requires full **3d diagnostic output**

- Practically, we can use 2d **surface fluxes** to do surface WMT
  - In the case of density, we need surface fluxes of
    - heat — `hfds`
    - freshwater — `wfo`
    - salt — `sfdsi`

CMOR

Spatial distribution of WMT

- The integrated transformation for a particular value of λ (λ_i) can be written as a surface integral:

$$G(\lambda_i, t) = \iint_{x,y} F(t, x, y)\, dA$$

- Here, F is a spatiotemporal field of transformation at the given isosurface for $\lambda = \lambda_i$

- This allows to retain spatial information of WMT, illustrating where (and when) transformation occurs in the ocean.

- A number of studies have used this method with both observation-based data and model output (e.g., Brambilla et al., 2008; Maze et al., 2009; Moorman et al., 2020)

Workflow

xarray `open_dataset / open_mfdataset / open_zarr`
om4labs `read`
intake-esm `open_esm_datastore`

→ Read

Datasets
flux/tendencies & grid info
xarray

↓

CMOR naming ⟷ Preprocessing ⟷ standard naming for coords and dims

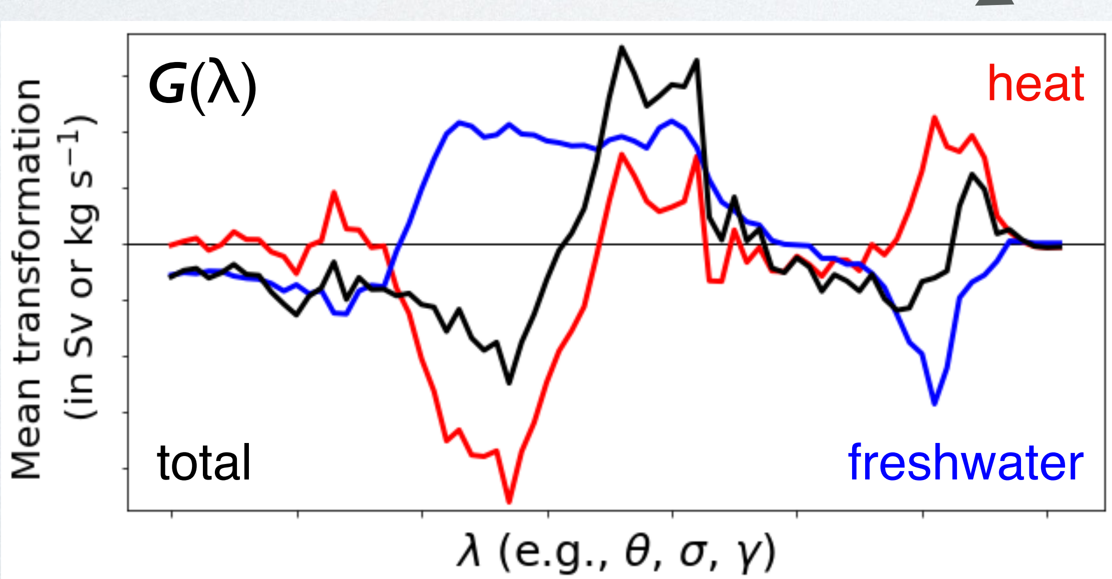
CMOR naming → surface fluxes or 3d tendencies
SWMT **3dWMT**

standard naming for coords and dims → xGCM + xhistogram

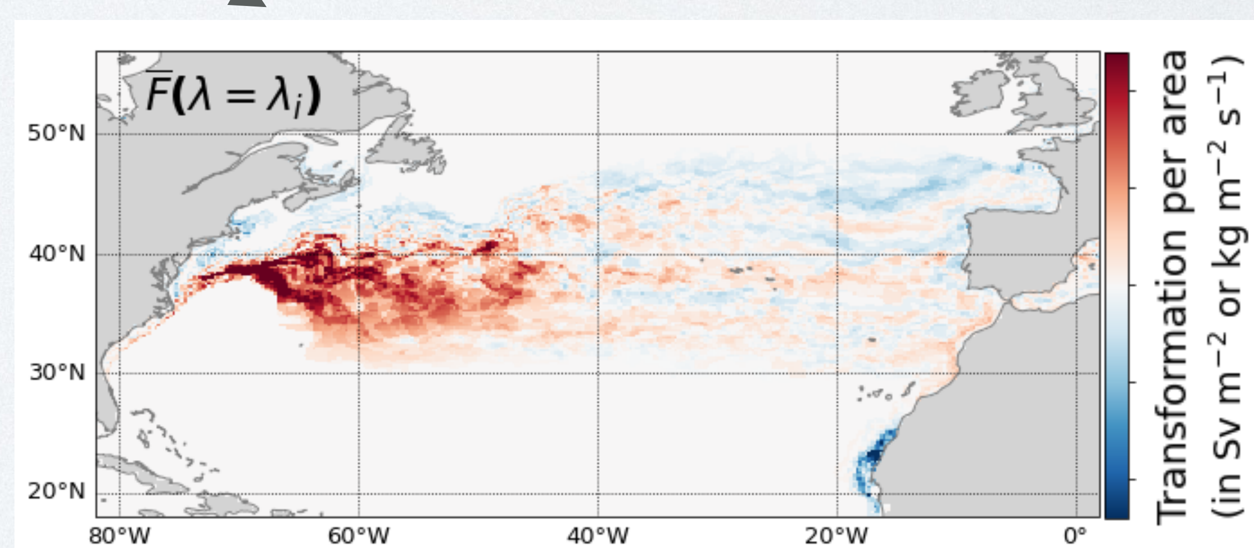
↓

WMT package **classes**

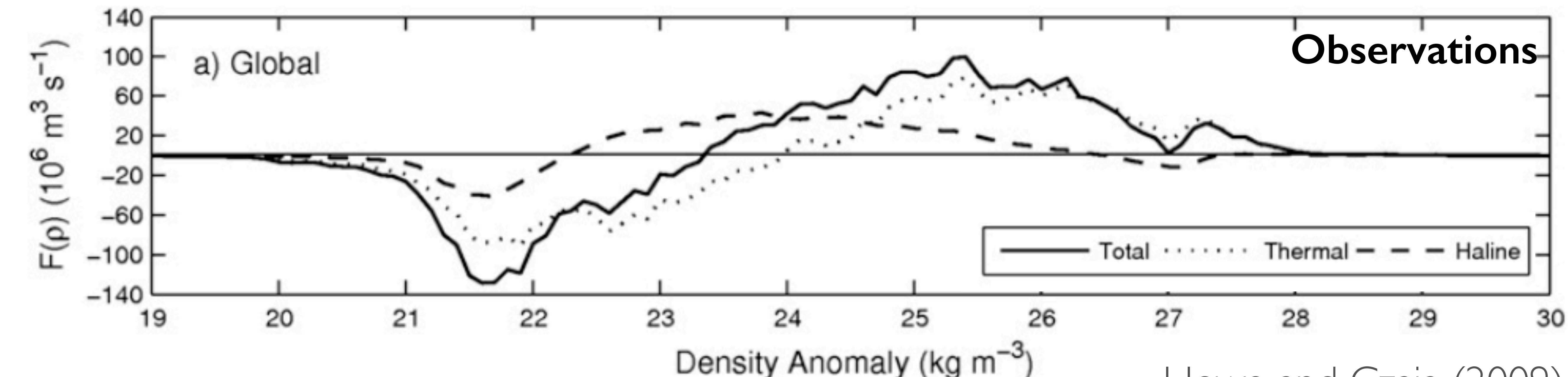
integrated form



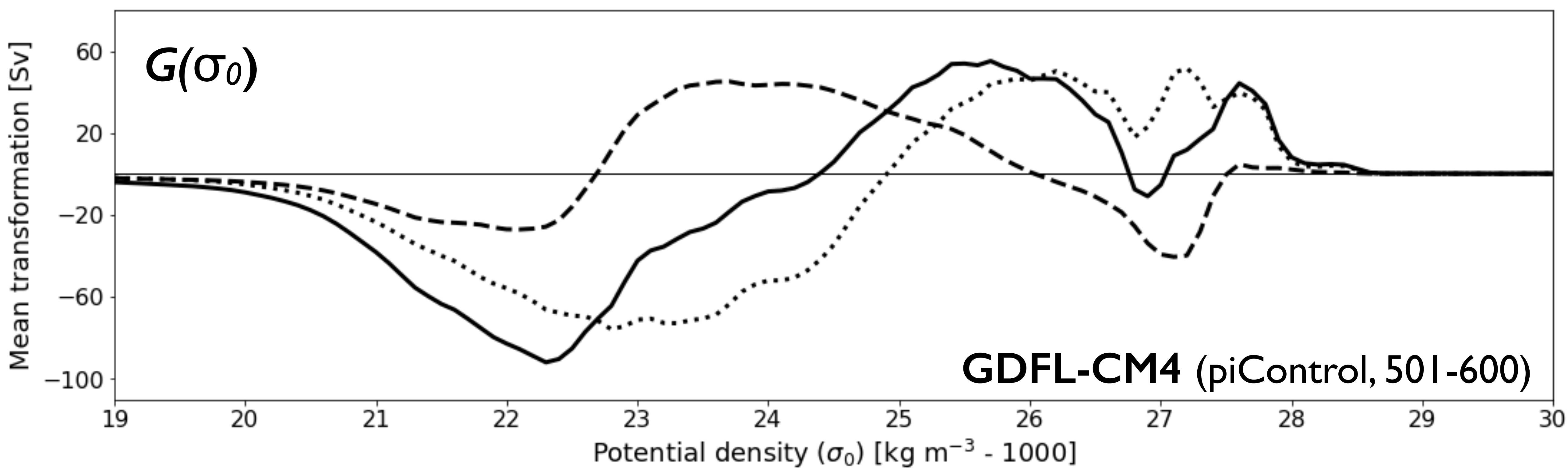
spatial map



Global Picture (Surface WMT)

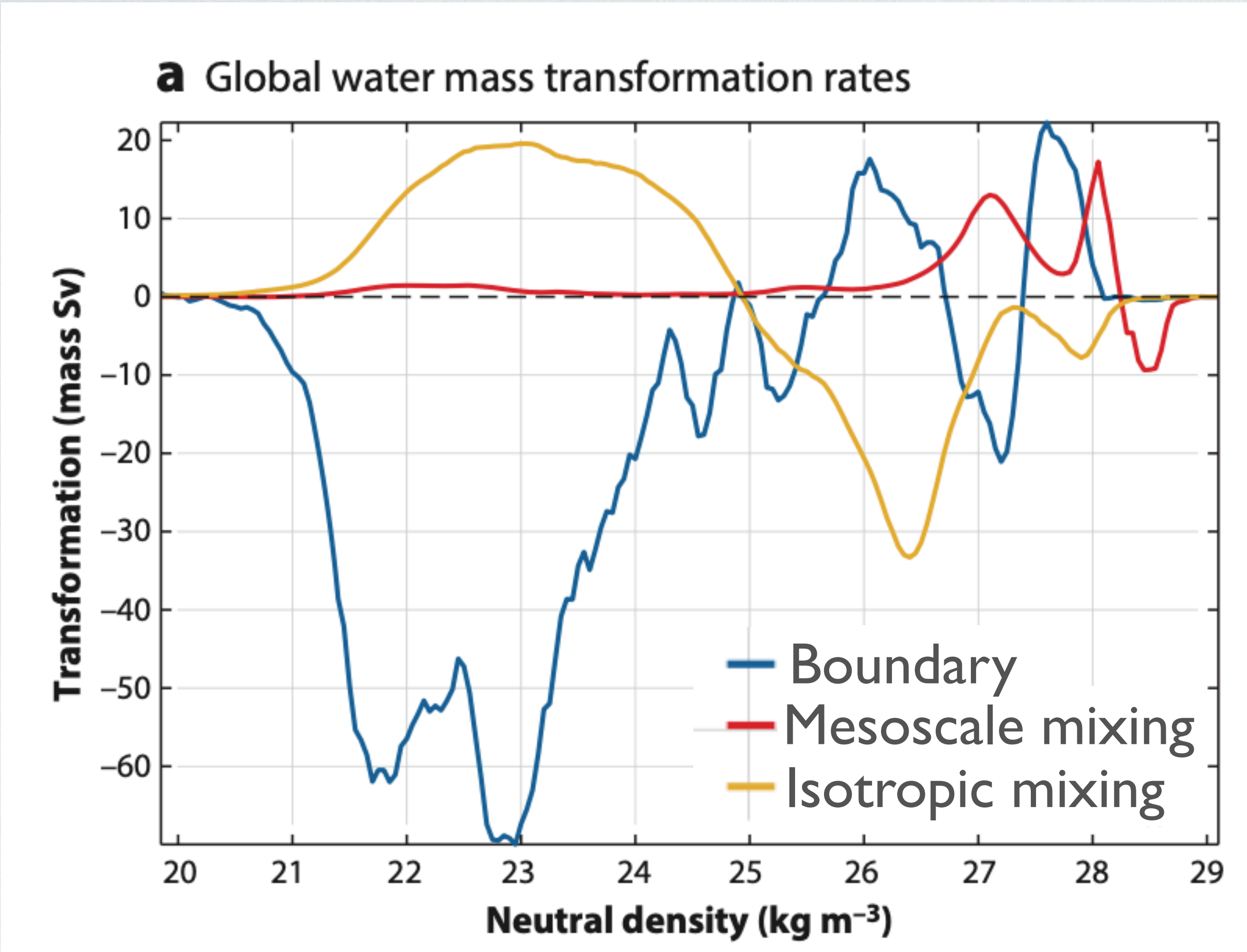


Howe and Czaja (2009)

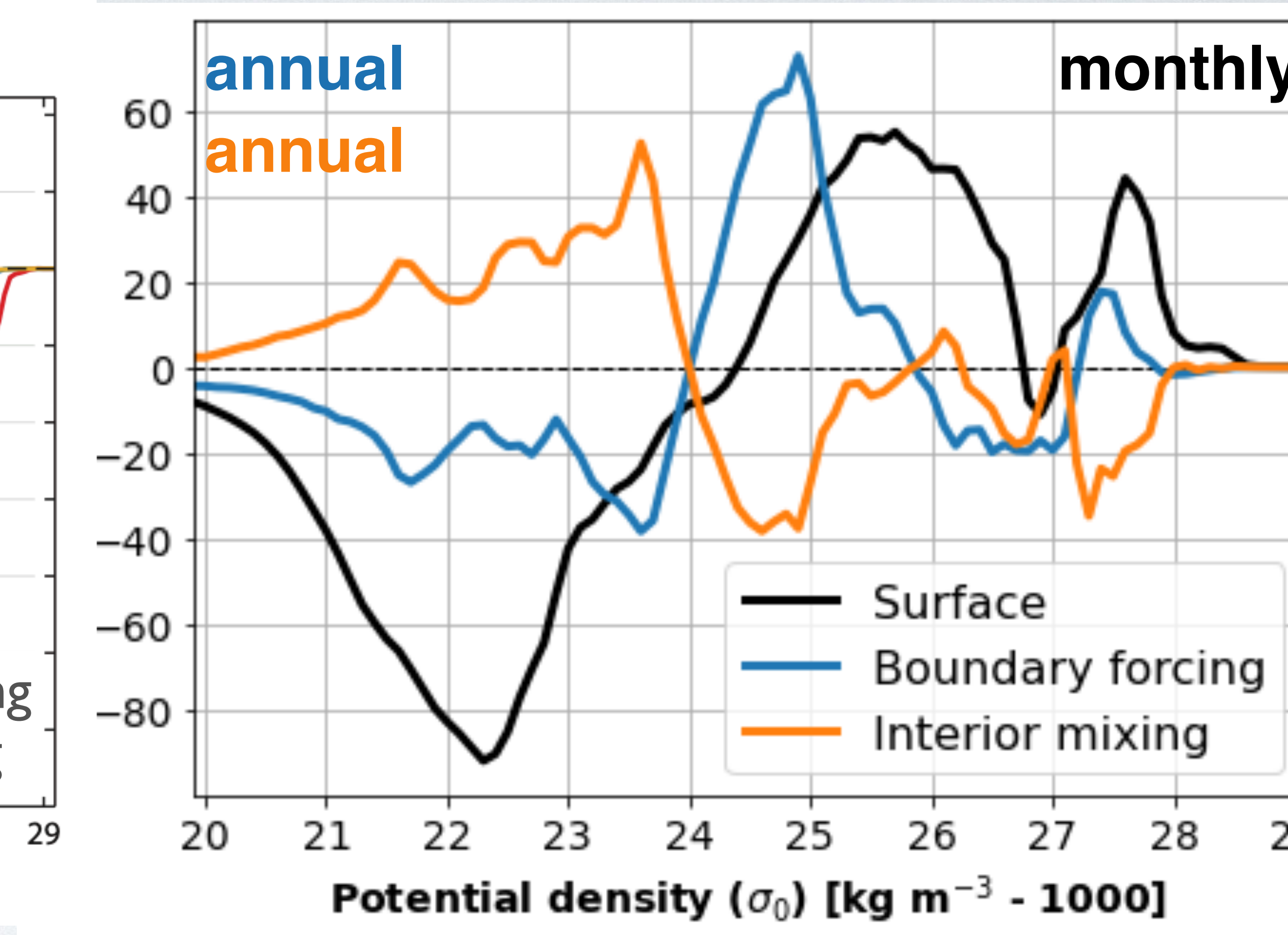


* Note the difference in vertical axes

Global Picture (Full 3d WMT)



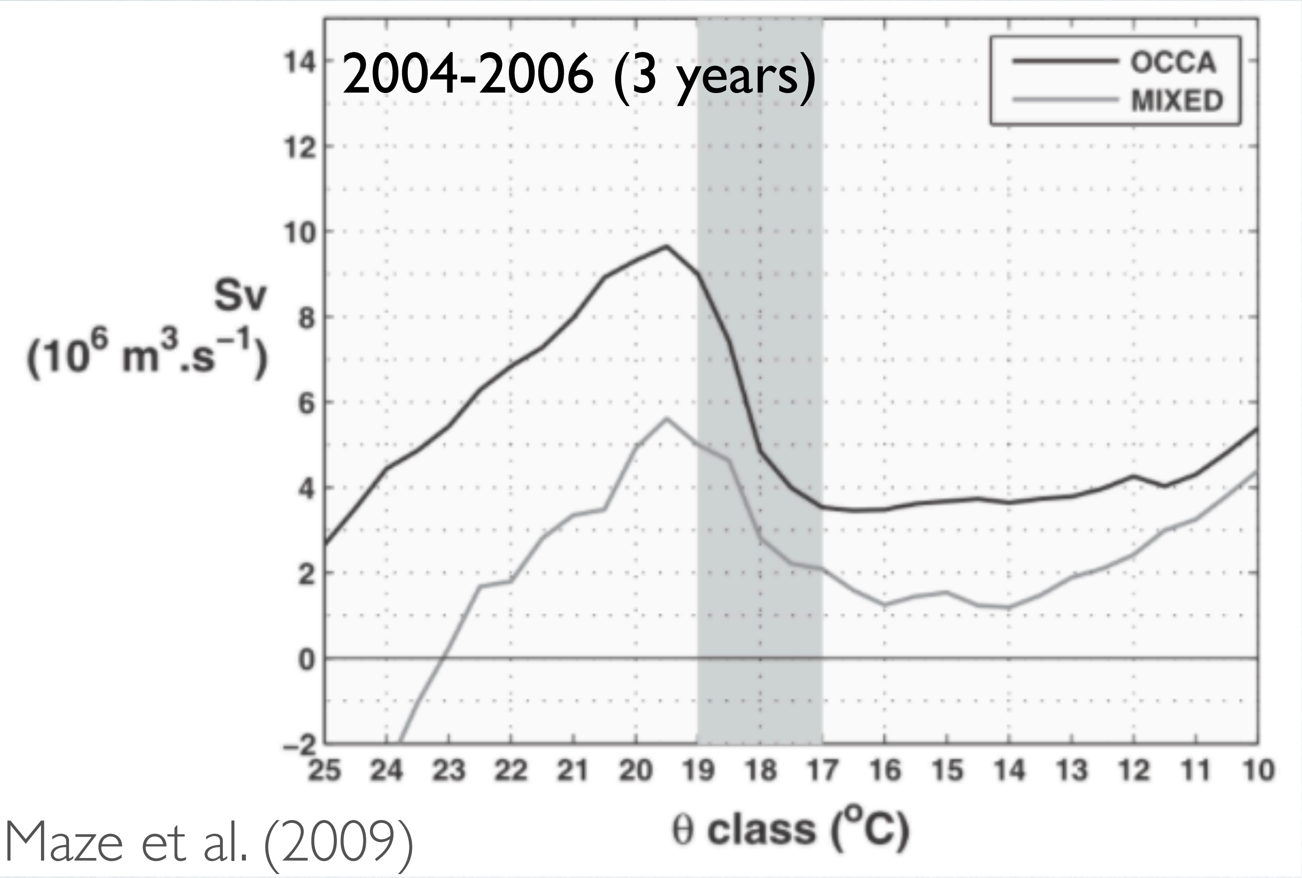
Groeskamp et al. (2019)

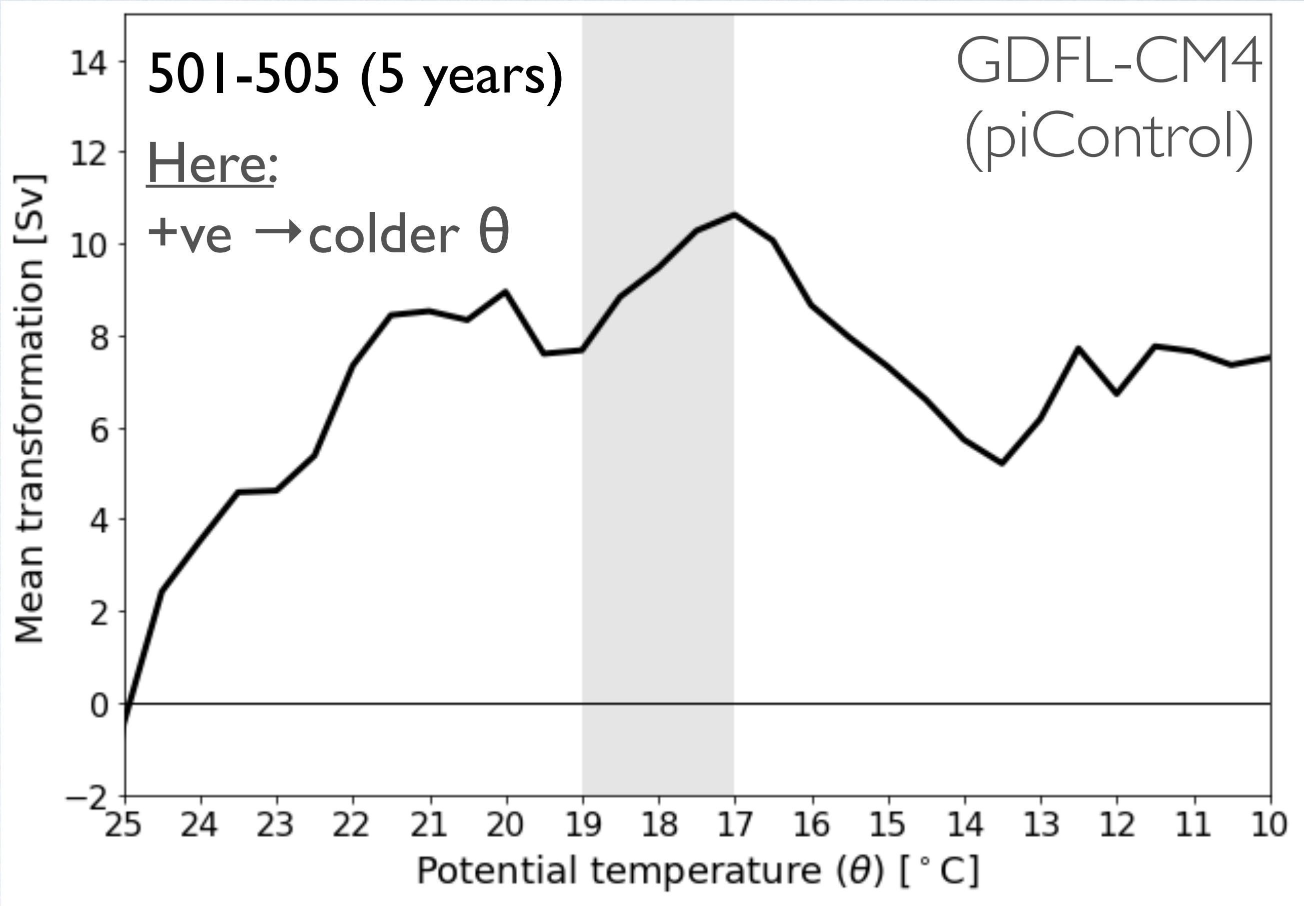


GDFL-CM4 (piControl)

- Same general distribution in density space between CM4 and observations
- However, magnitudes and relative position of the classes are different
- Currently, 3d boundary and interiors tendencies only at annual time scale
- Surface is missing SW penetration which is important (Groeskamp and Iudicone, 2018)
- 3d boundary tendency includes SW penetration

North Atlantic (WMT across θ classes)

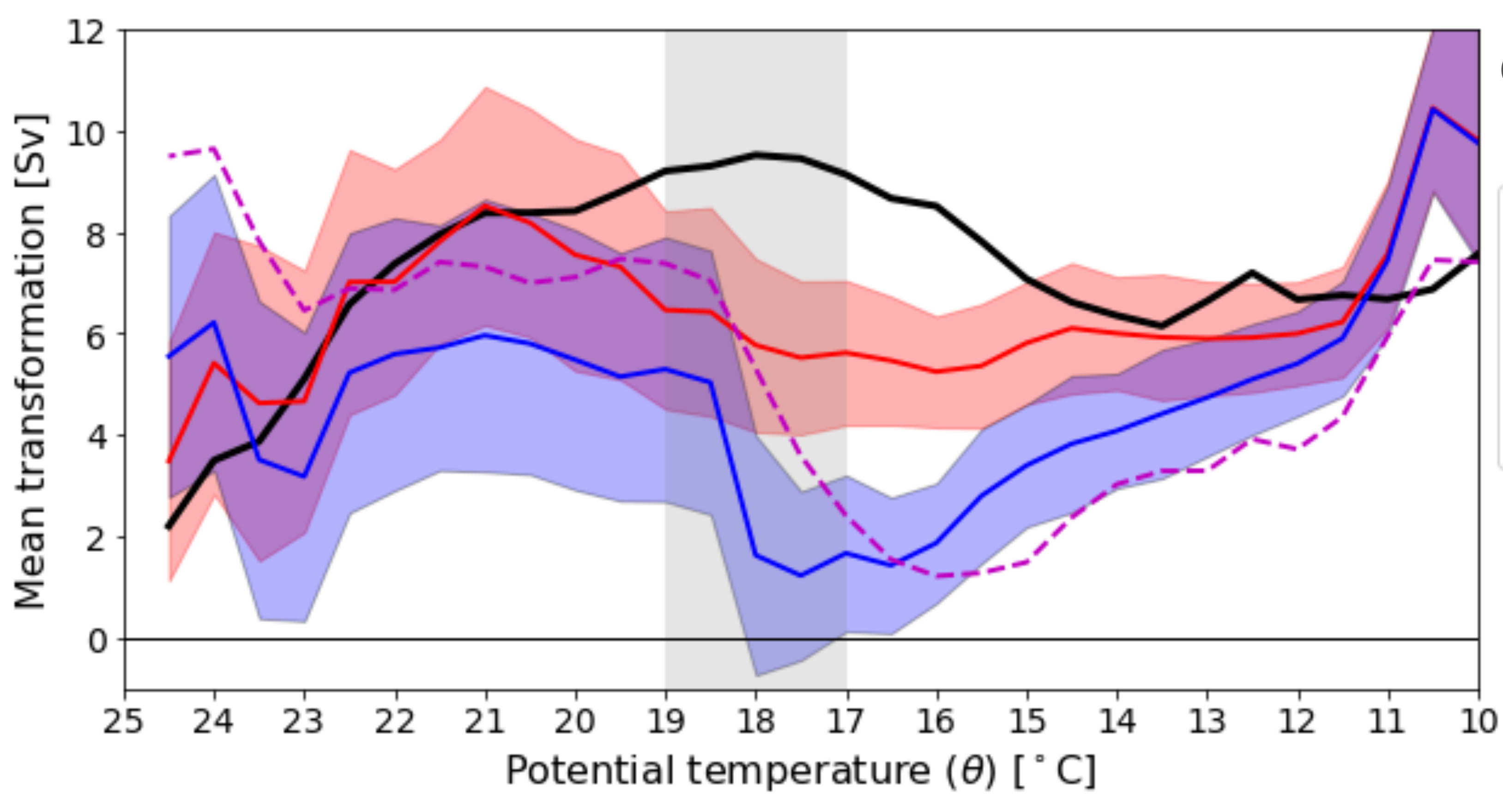




- WMT in temperature space in the North Atlantic: Consistent picture between observational-based method and model output
- CM4 pre-industrial shifted towards colder temperature relative to the observations
  - 18° water formation → 16° water formation in the pre-industrial run

North Atlantic (WMT across θ classes)

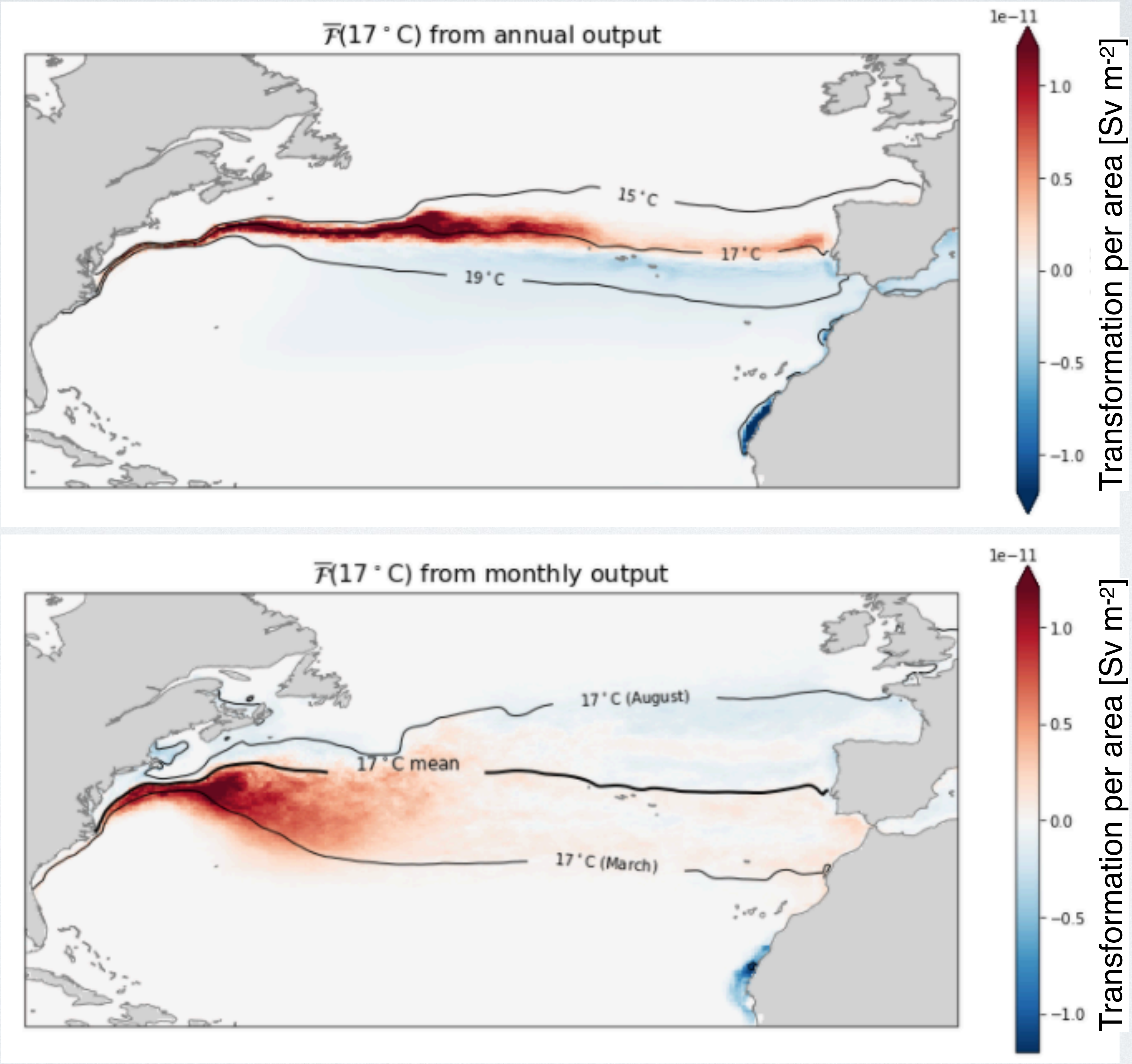
- We see large differences between the different model outputs
  - Annual vs. monthly output (surface WMT)
  - Full 3d boundary forcing versus surface
  - Compared to these differences, adding interior processes is only secondary



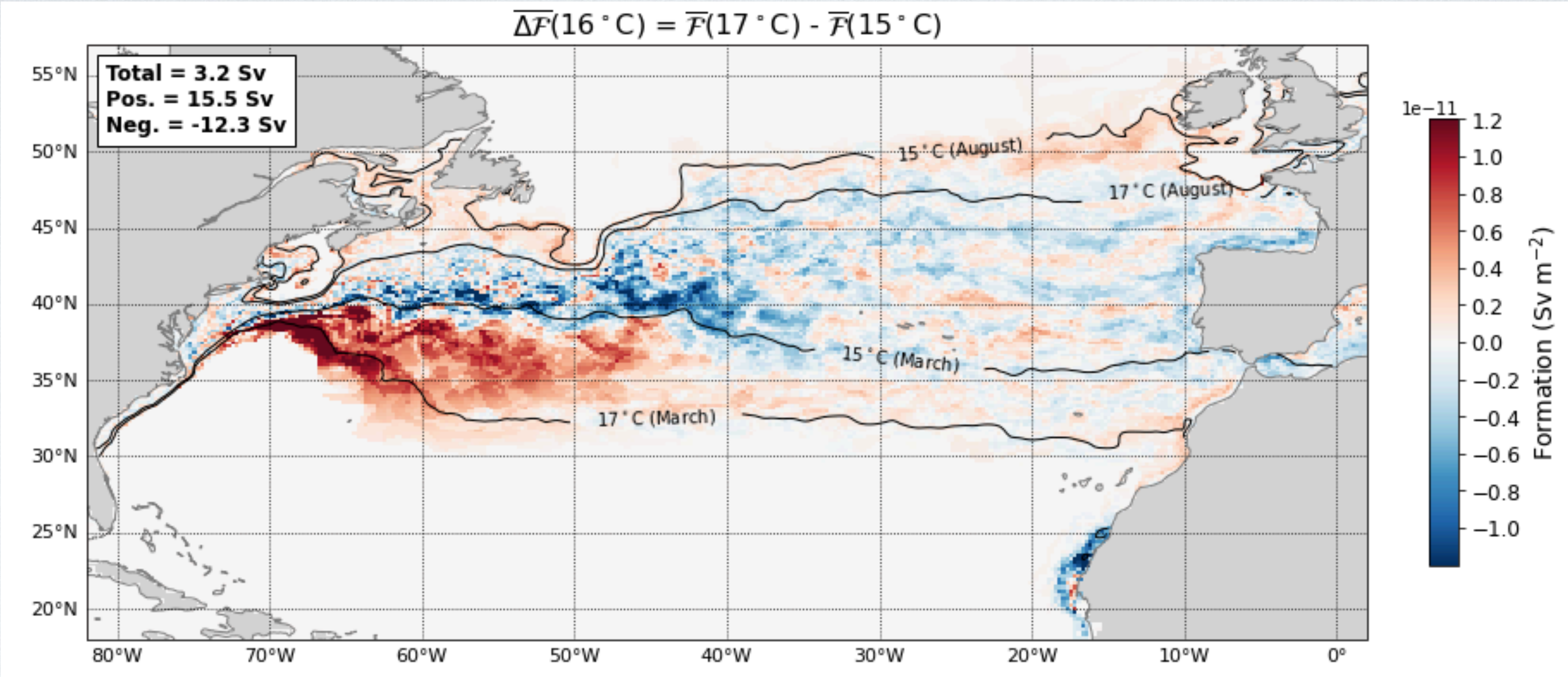
GDFL-CM4
(piControl)

501-600 (100 years)

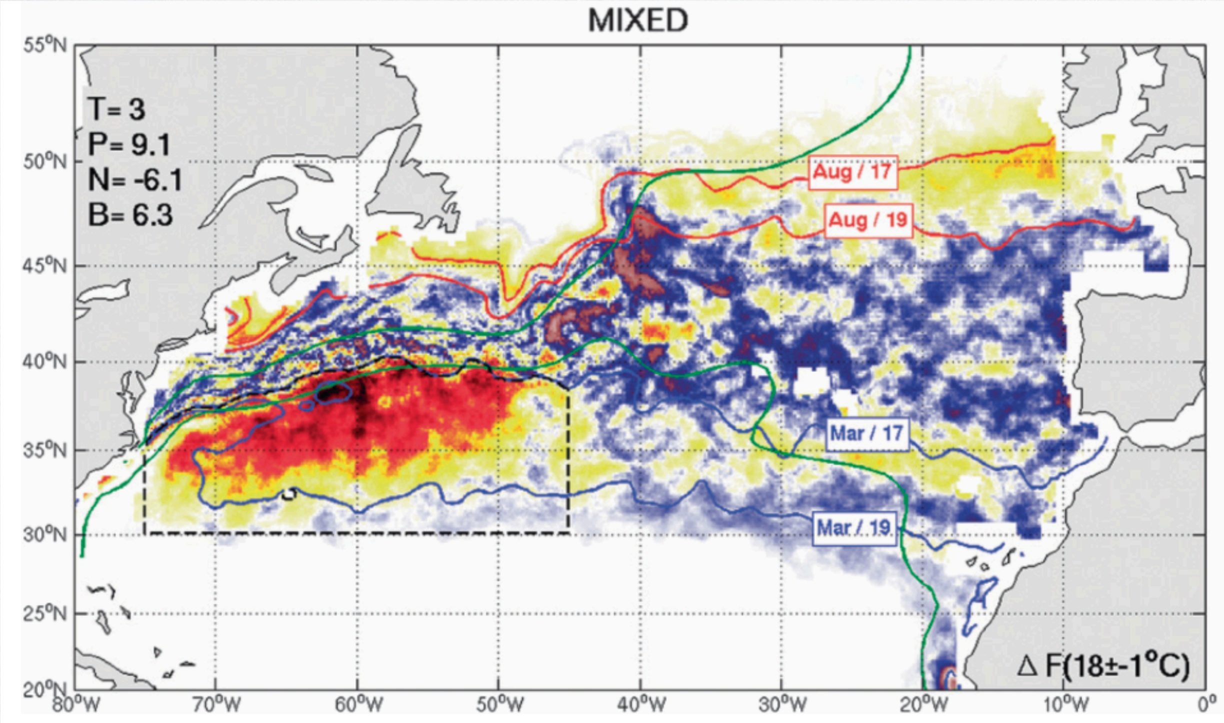
North Atlantic (WMT across θ classes)

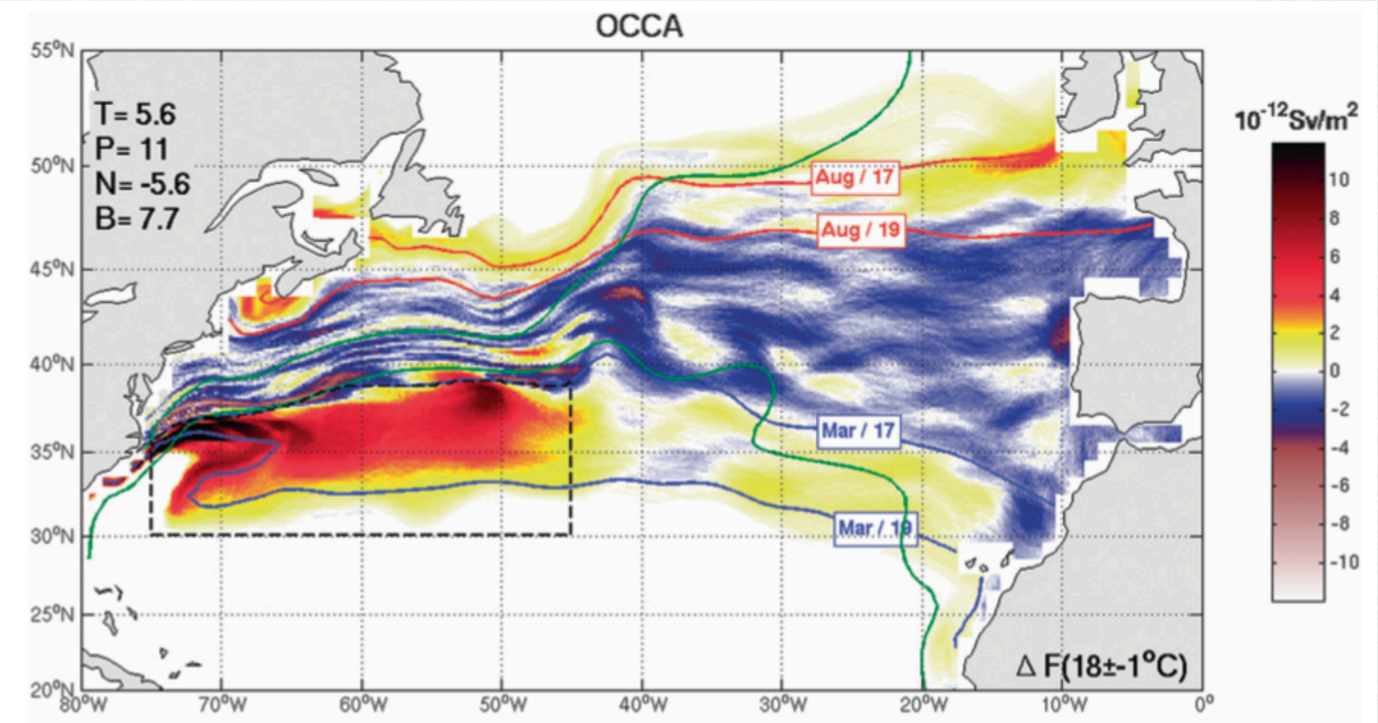


North Atlantic (Formation map)



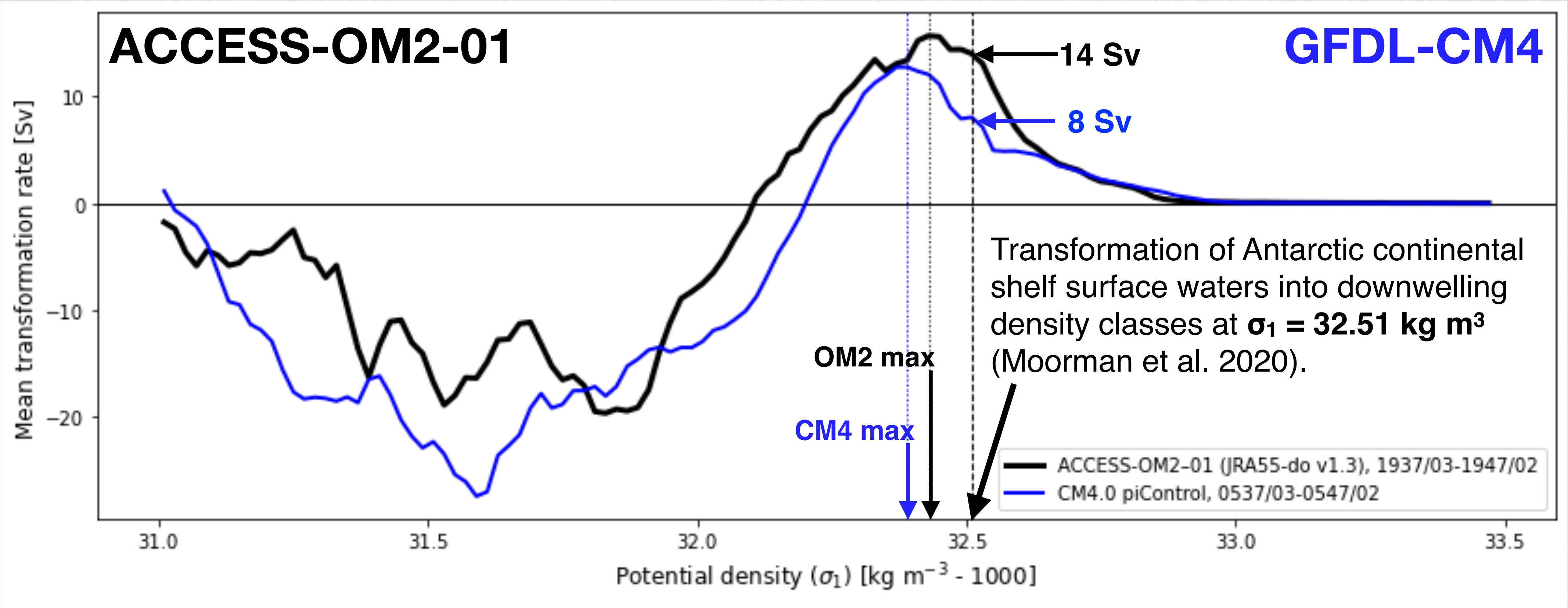
GDFL-CM4 (piControl)





Maze et al. (2009)

Southern Ocean (Surface WMT)



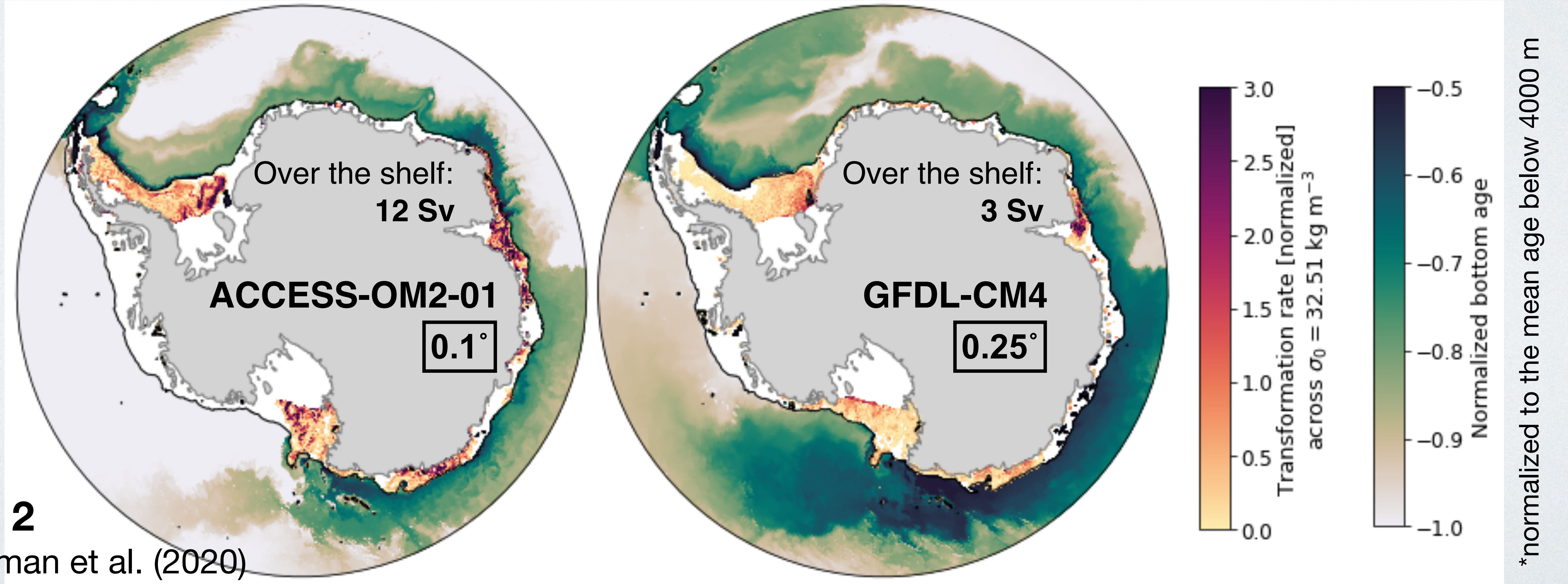
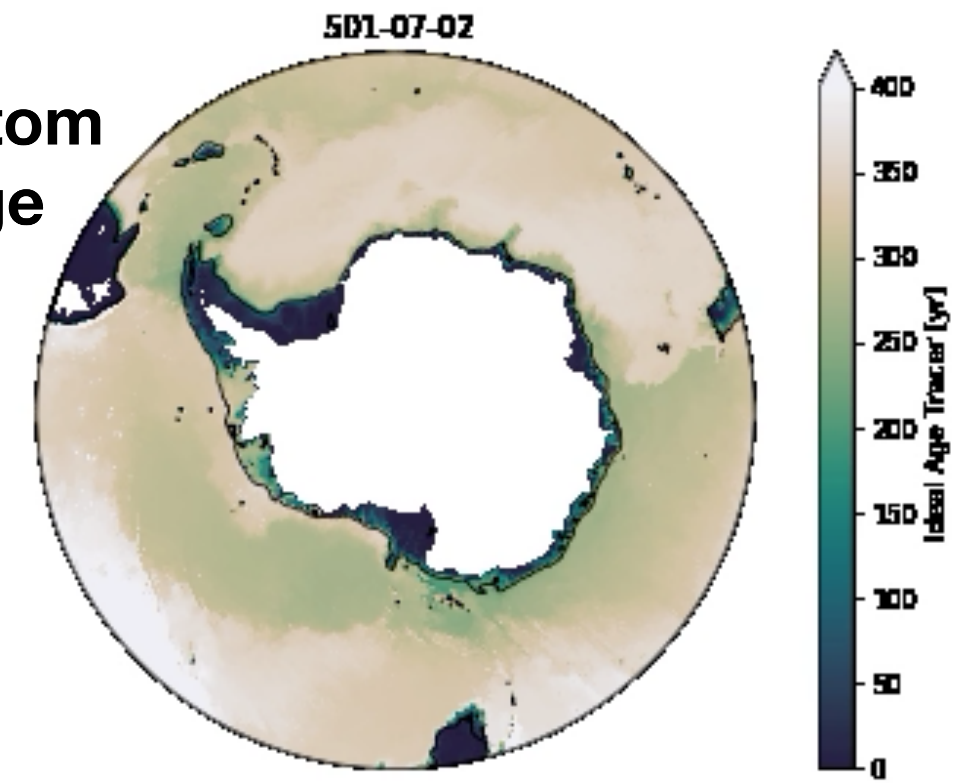


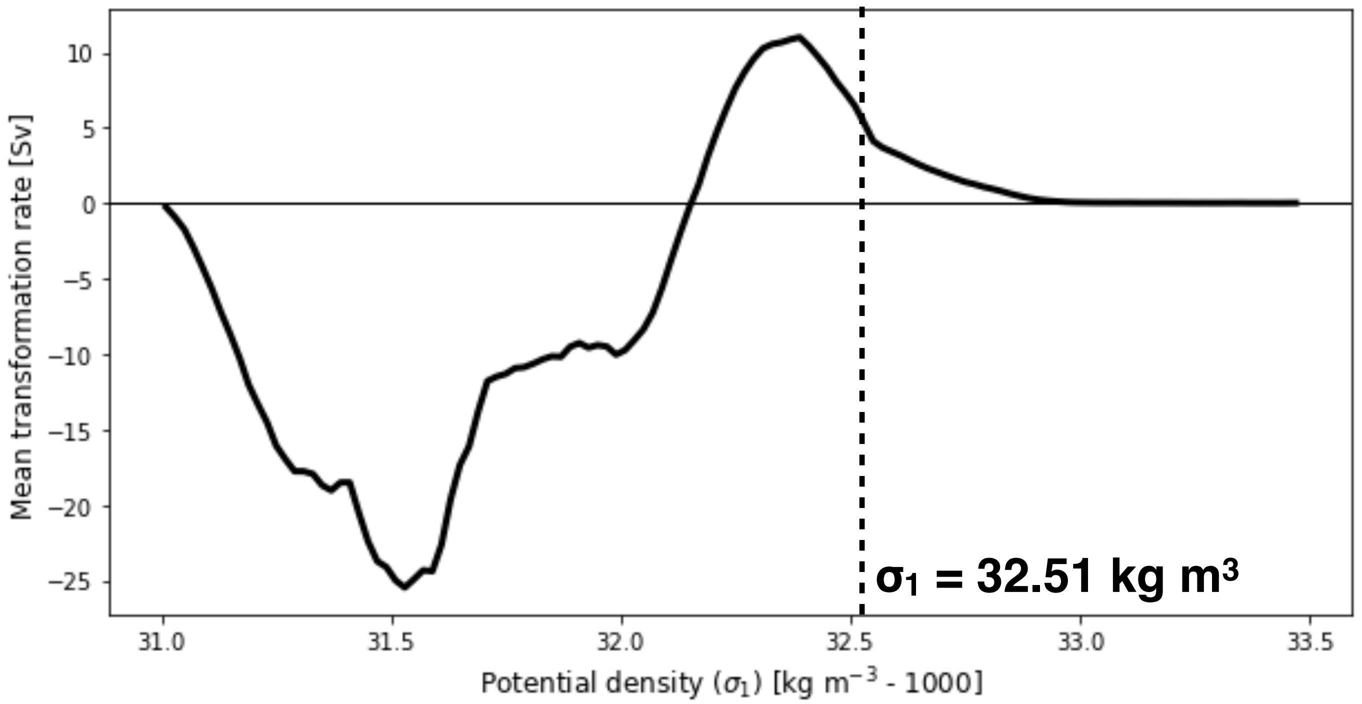
Figure 2
in Moorman et al. (2020)

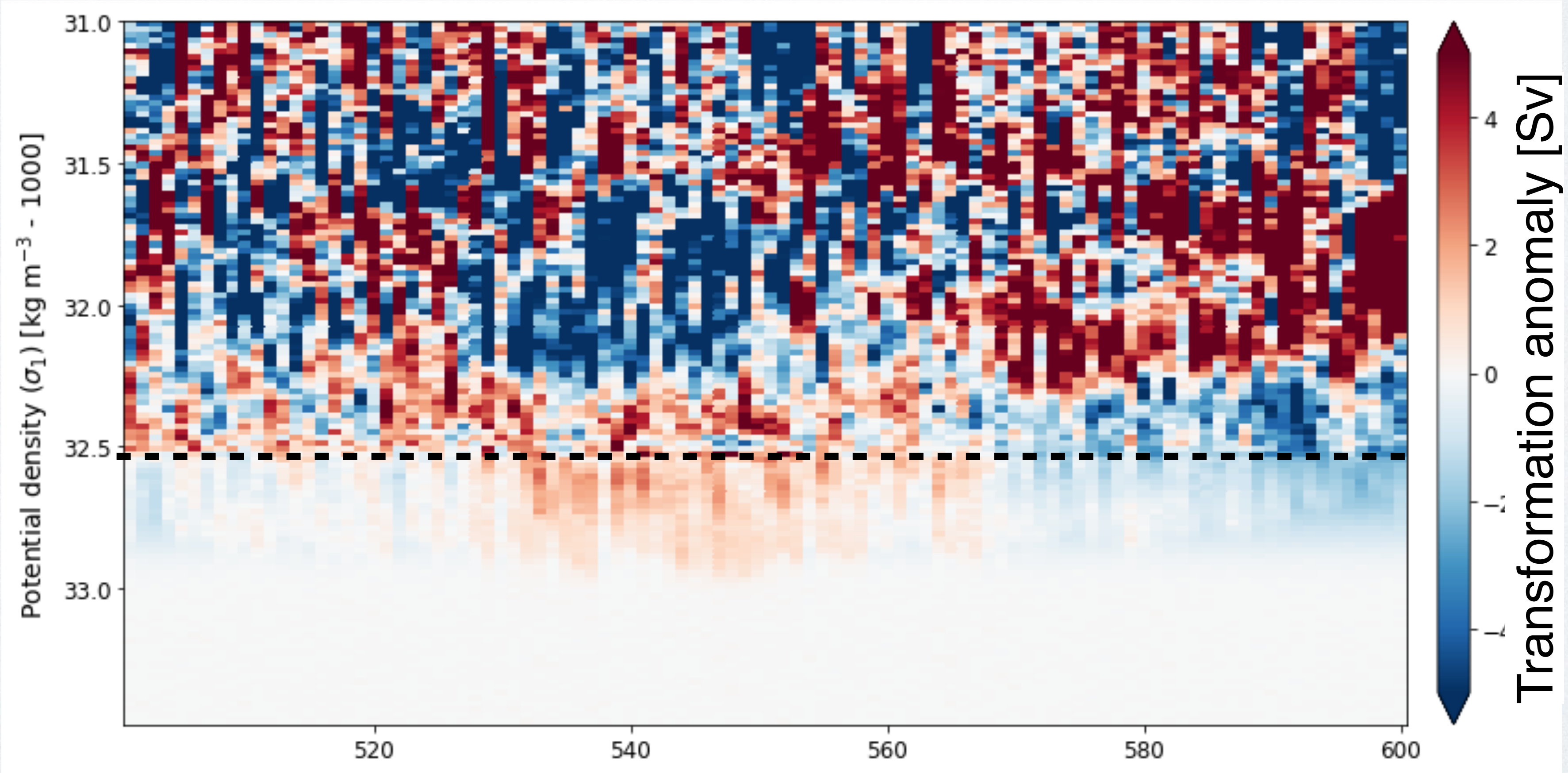
Southern Ocean (Surface WMT)

Temporal variability

Bottom age







CMIP6 surface WMT analysis

- For surface WMT we only need sea surface (2D) tracer concentration and flux fields.

- Looking at Pangeo CMIP6 archive, we have
  - Sea surface temperature (**`tos`**)
    - 51 out of 52 (historical, piControl)
  - Sea surface salinity (**`sos`**)
    - 47 out of 52 (historical) / 48 out of 52 (piControl)
  - Downward heat flux (**`hfds`**)
    - 29 out of 52 (historical) / 30 out of 52 (piControl)
  - Water flux into sea water (**`wfo`**)
    - 22 out of 52 (historical, piControl)

  ➡ **18** out of 52 with a complete set of those variables

  - Downward sea ice basal salt flux (**`sfdsi`**)
    - currently missing in all cases

PANGEO

INTAKE

+

intake-esm

+

cmip6-preprocessing

Conclusions

- Diagnostic tool that introduces the WMT framework as an additional utility to assess ocean and climate models

- Capability of assessing spatiotemporal variability in WMT

- Inter-model comparison and assessing configurations (e.g., spatial resolution, parameterizations, coupled vs. forced)

- Still "work in progress" and development ahead:
  - Decompose contributions into specific processes
  - Incorporating analysis with inert tracers (e.g., CFCs and SF6)
  - Expand the application to more models
    - Start with a selection of MOM6 simulations
    - Apply it to all CMIP models

Reference List

Brambilla, E., Talley, L. D., & Robbins, P. E. (2008). Subpolar Mode Water in the northeastern Atlantic: 2. Origin and transformation. *Journal of Geophysical Research*, 113(C4), C04025–16. http://doi.org/10.1029/2006JC004063

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