# The role of western boundary currents in the ocean uptake and storage of anthropogenic carbon: a modeling perspective

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# Motivation: Part I

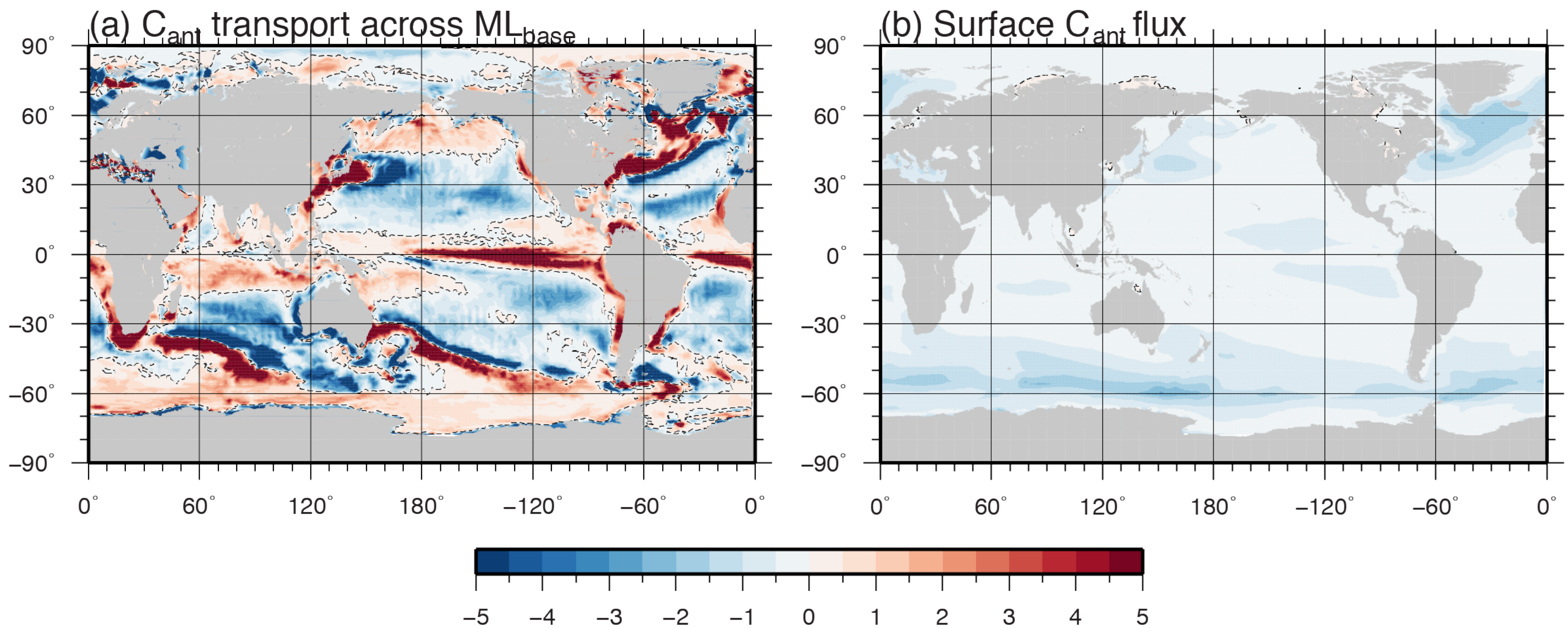
1. What is the role of western boundary currents and their extension regions in the ocean uptake of anthropogenic carbon ($C_{ant}$)?

2. Modeling inferences suggest that ~60% of $C_{ant}$ is taken up via gas exchange for densities less than the base of the thermocline ($\sigma_0$=26.6), while only 40% accumulates within the same density class

***3. Hypothesis***: Western boundary currents and their extension regions serve as conduits for the ejection of $C_{ant}$ from the thermocline and into the large subpolar reservoirs

# Re-emergence of $C_{ant}$ in 1995 (*Toyama et al.*, J.Clim., 2017)

For a widely-used global ocean biogeochemistry model (NEMO-PISCES)
Consider $C_{ant}$ fluxes averaged over 1995 across $ML_{base}$ (left) and air-sea $C_{ant}$ fluxes (right)



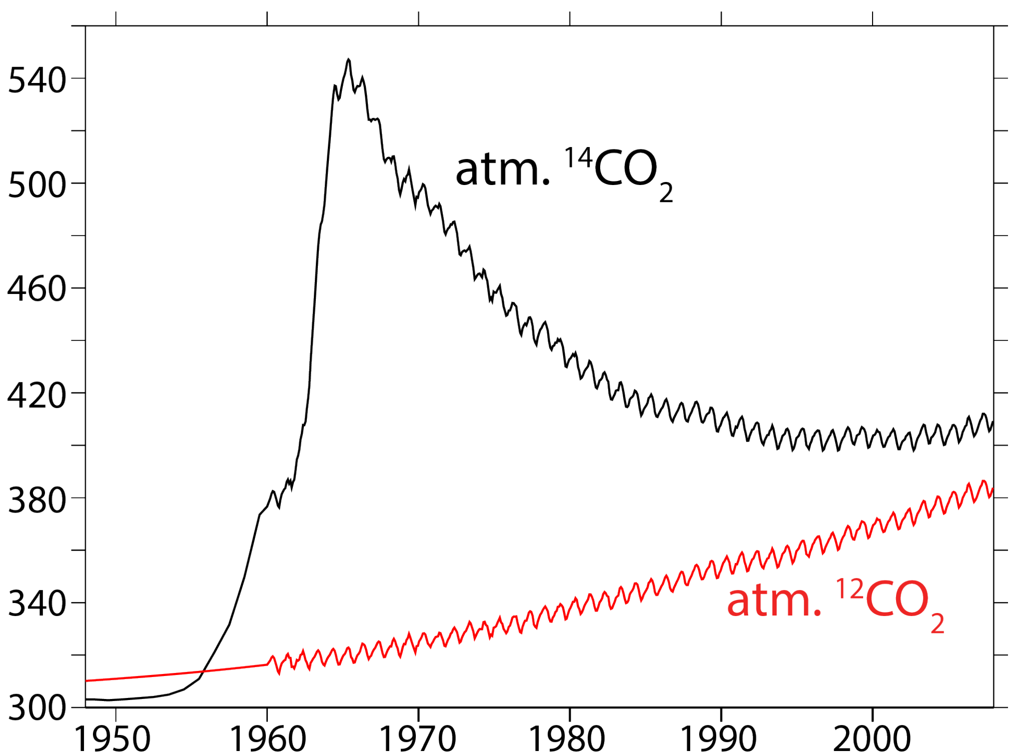

Modeling results from NEMO-PISCES (ORCA2 2° configuration) for anthropogenic carbon ($C_{ant}$);
(a) Annual mean obduction (postive) and subduction (negative) rates for $C_{ant}$ in 1995, and
(b) annual mean gas exchange rate of $C_{ant}$ in 1995 (molC/$m^2$/yr) [Toyama et al., 2017]

Western boundary currents and extension regions as "hot spots" for re-emergence of $C_{ant}$ for non-eddying model , consistent with *Qiu and Huang* (1995) dynamical study

But what happens to $C_{ant}$ subsequent to re-emergence in WBC & extension regions?

# Motivation : Part II

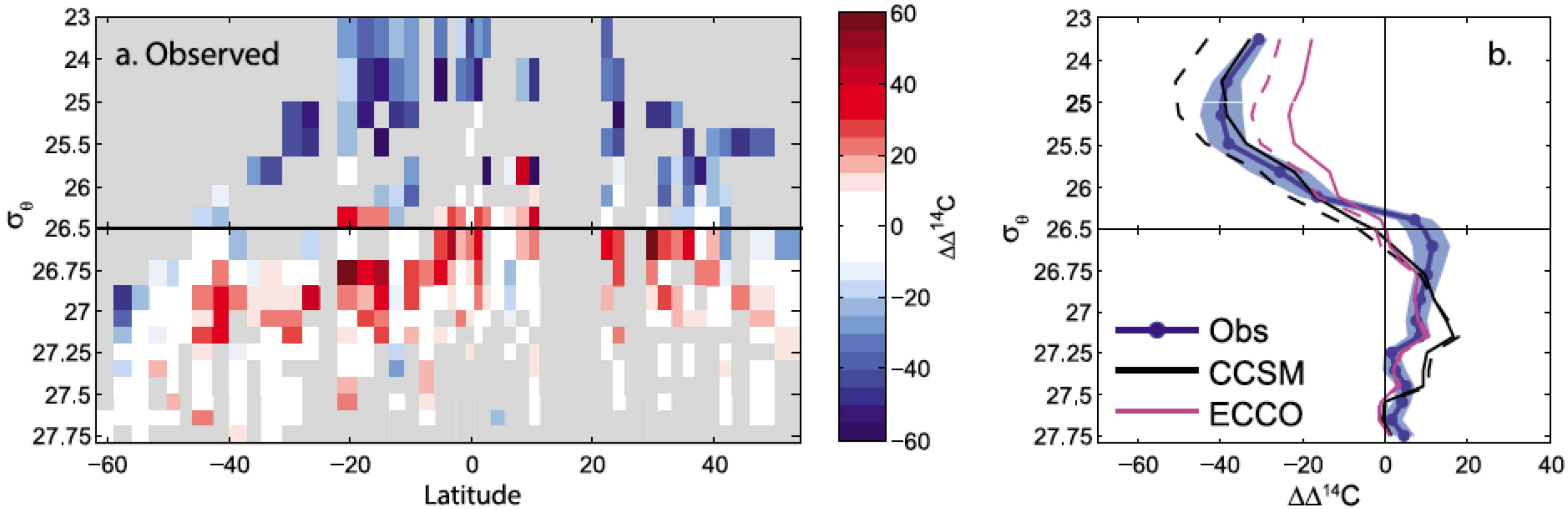
Bomb-radiocarbon (bomb-$^{14}CO_2$) had a relatively "pulsed" atmospheric time history (over 1955-1963) than anthropogenic carbon emissions



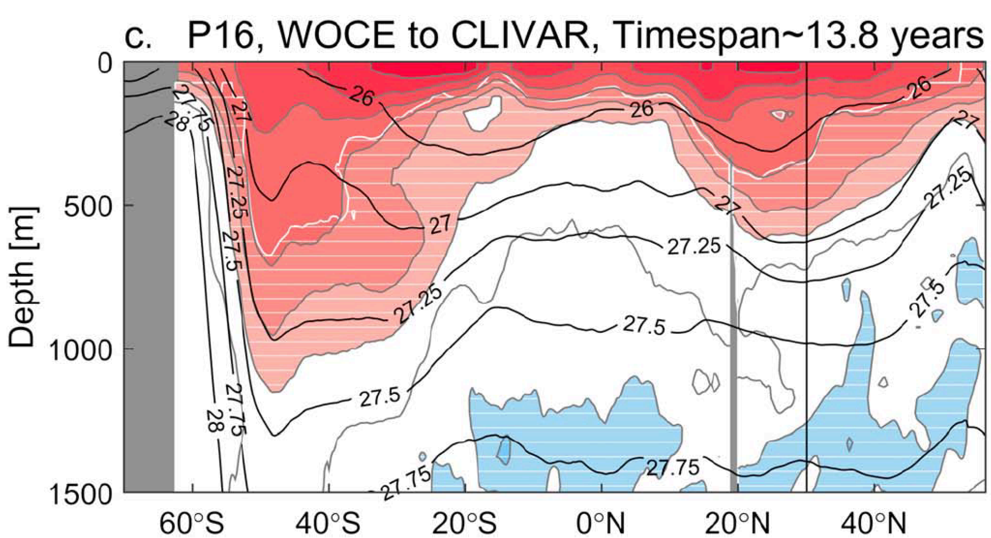

Atmospheric $^{14}CO_2$ has here been normalized by the 1890 ratio of $CO_2/^{14}CO_2$ to facilitate comparison

# $\Delta^{14}C$ and $C_{ant}$ changes along P16 (152W) between 1992 and 2006

## Observed $\Delta^{14}C$ changes along P16 (*Graven et al.*, 2012)




## Inferred $C_{ant}$ changes using eMLR along P16 (*Carter et al.*, 2017)



# Model Configuration & Analysis Framework

Here we consider a global non-eddying 1-degree configuration of MOM5-BLING (*Griffies*, 2012; *Galbraith et al.*, 2012) for modeling of **two transient tracers**

- **bomb-$^{14}$DIC**
- **Anthropogenic carbon ($C_{ant}$)**

under **CORE-II normal year forcing (NYF)** (repeating seasonal cycle) for simulations over the years **1860-2007**.

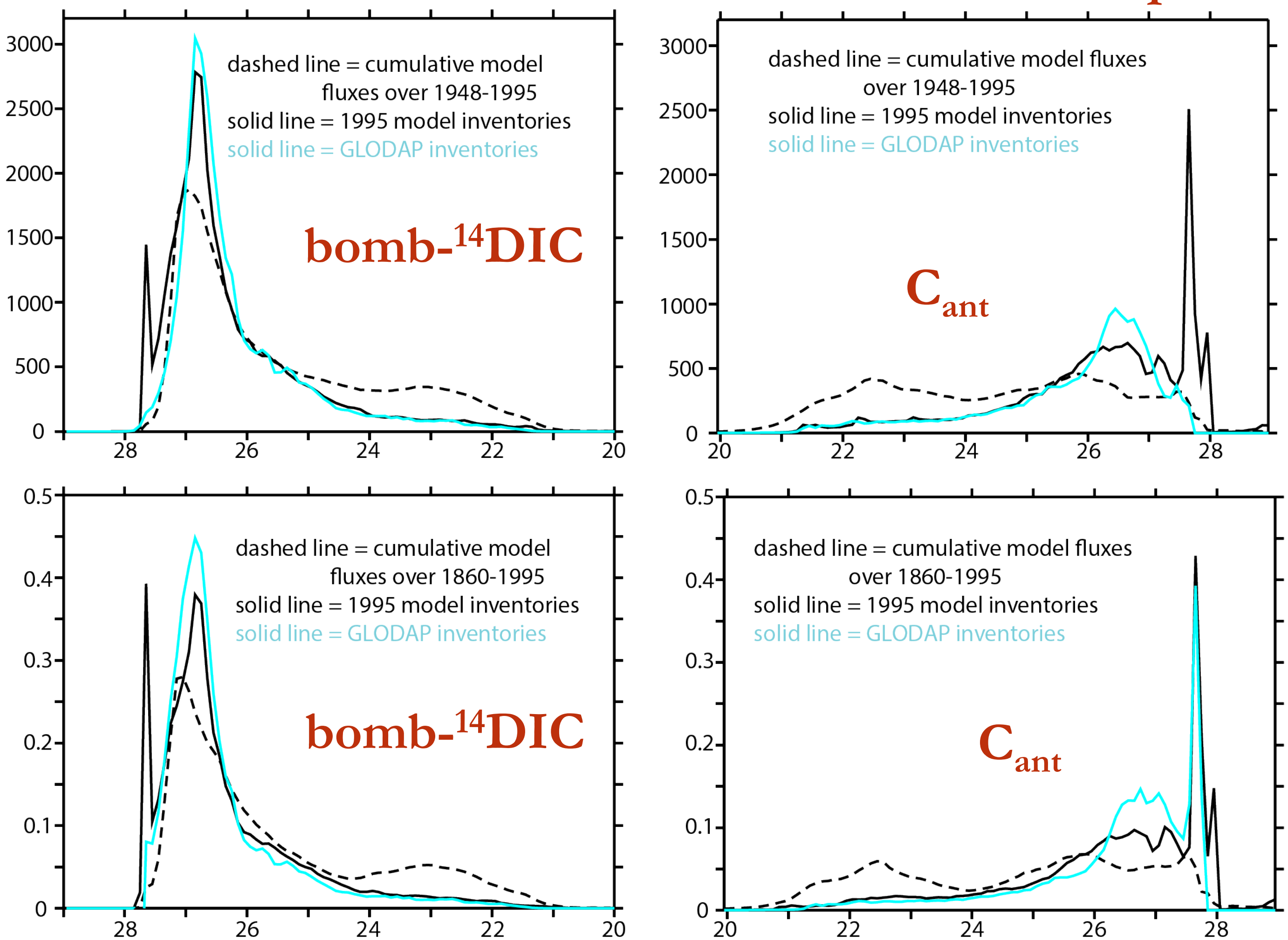
Water mass transformation diagnostics are applied for both bomb-$^{14}$DIC and $C_{ant}$ following the method described by *Iudicone et al.* (2011); *Iudicone et al.* (2016); and *Zhai et al.* (2017; GRL in press).

[transformation diagnostics & tendencies in MOM5 have been applied in the dynamical studies of *Palter et al.* (2014) and *Griffies et al.* (2015]

# Modeled transient tracers in density framework for WOCE-era (1995)

## Southern Hemisphere

## Northern Hemisphere




**Cumulative fluxes larger than inventories over waters lighter than western subtropical/subpolar boundaries**

**Inventories larger than cumulative fluxes for waters denser than subtropical/subpolar boundaries**

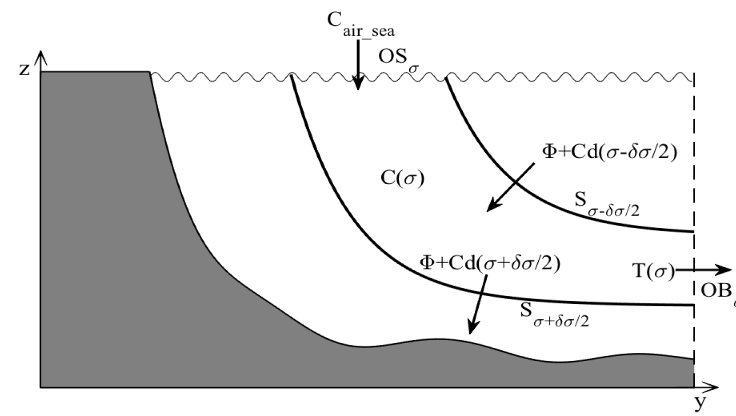
**Consistent with view of *Iudicone et al.* (2016) that $C_{ant}$ is absorbed via gas exchange over broad expanses of the Subtropical Cells**

# Water mass transformation diagnostics: underlying equations

Following the method of *Iudicone et al.* (2011; 2016), water mass transformation diagnostics have been applied to output from GFDL's MOM5-BLING model (*Griffies*, 2012; *Galbraith et al.*, 2012), as presented in the study of *Zhai et al.* (2017; in press, GRL)

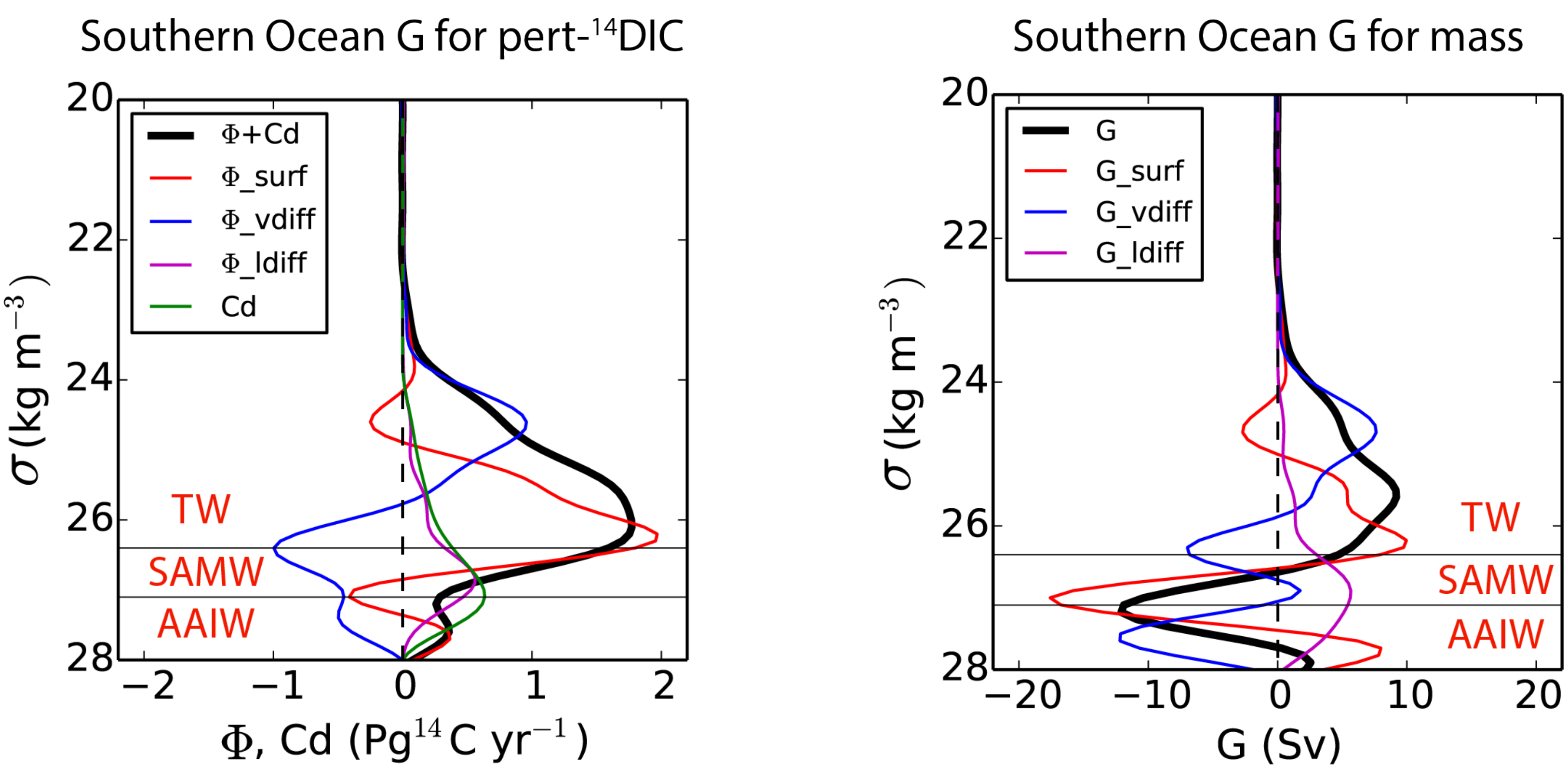
Diapycnal transports of $C_{ant}$ ($T(\sigma)$) are decomposed into diapycnal diffusive fluxes (Cd) and diapycnal transports associated with water mass transformations ($\Phi$):

$$\mathrm{T}(\sigma) = \mathrm{Cd}(\sigma) + \Phi(\sigma)$$
$$\mathrm{Cd}(\sigma) = \int_{S_\sigma} \mathbf{J}^{\mathrm{C_{ant}}} \cdot d\boldsymbol{S} \qquad (1)$$
$$\Phi(\sigma) = \frac{\partial}{\partial\sigma}\int_{V(\sigma_0,\sigma)} c\,\frac{d\sigma}{dt}\,dV$$




$$\Phi(\sigma) = \frac{\partial}{\partial\sigma}\int_{V(\sigma_0,\sigma)} c\,\frac{d\sigma}{dt}\,dV \approx \frac{1}{\delta\sigma}\int dx\,dy \int_{z(\sigma-\delta\sigma/2)}^{z(\sigma+\delta\sigma/2)} c\,\frac{d\sigma}{dt}\,dz \qquad (2)$$

# Water mass transformation diagnostics: Southern Ocean (Y<30S)




*Sign convention*: Positive values indicate a net flux from TW to SAMW

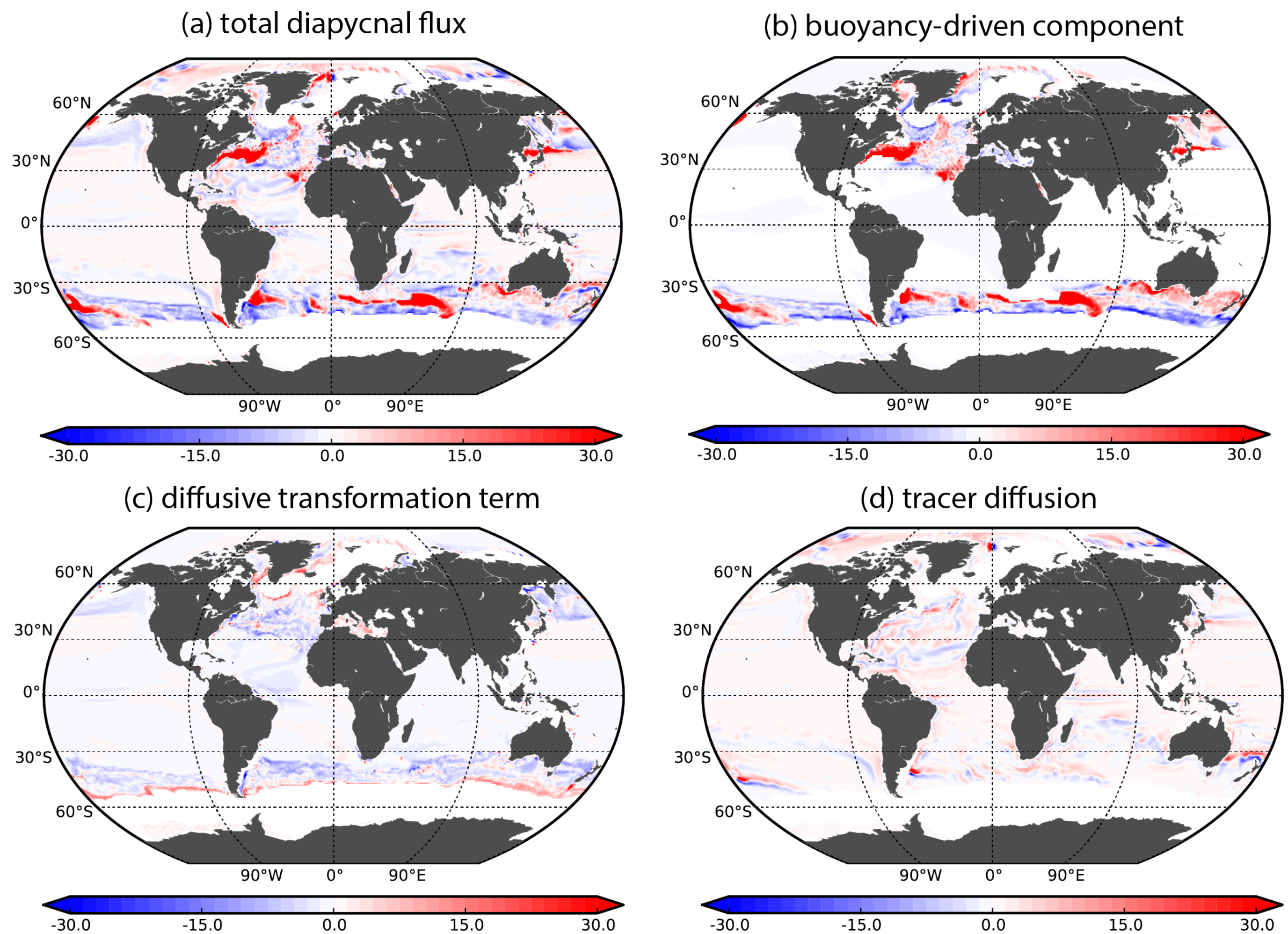
Coarse-grained layering at 30°S (Following *Sallée et al*, 2013)

TW = Thermocline Water ($\sigma_0$<26.4)

SAMW = Subantarctic Mode Water (26.4<$\sigma_0$<27.1)

AAIW = Antarctic Intermediate Water (27.1<$\sigma_0$)

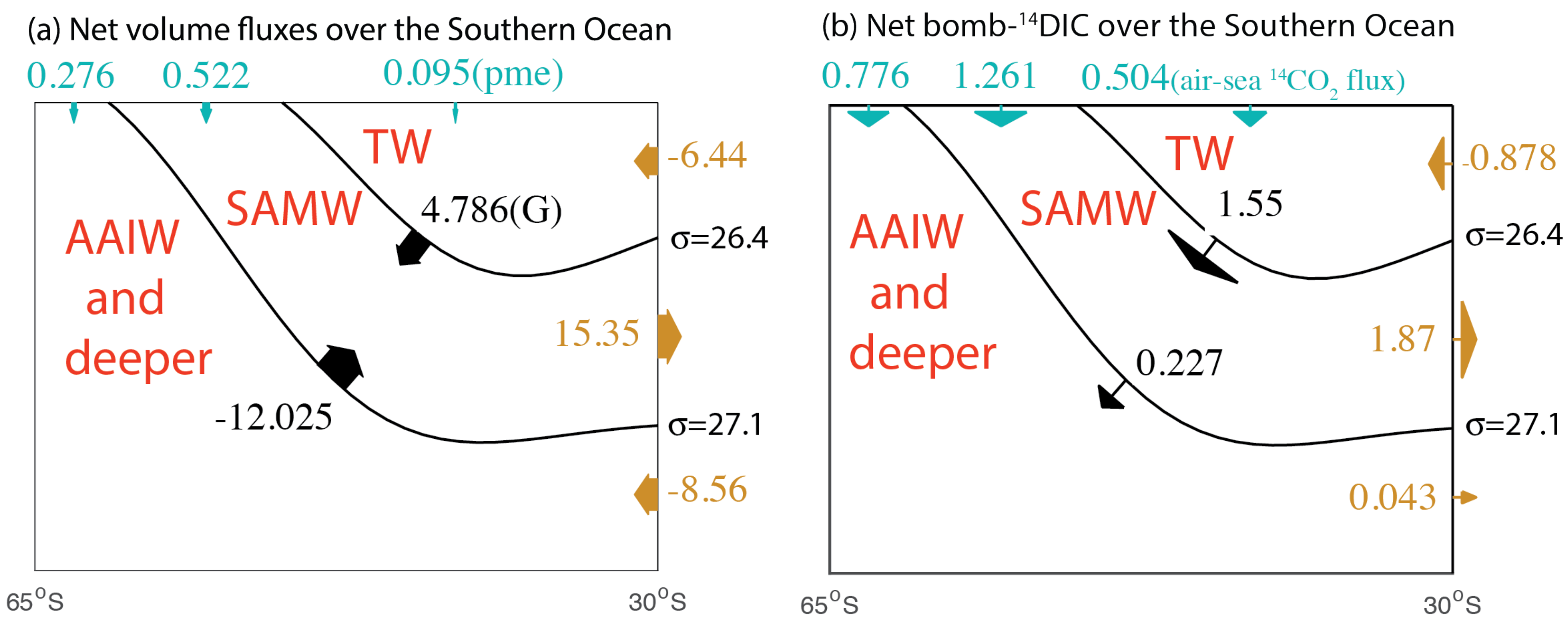
# Bomb-$^{14}$DIC fluxes across $\sigma_0$=26.4 in MOM5 averaged over 1995




*Sign convention*: Positive values indicate a flux from TW to SAMW

Fluxes of bomb-$^{14}$DIC (moles* $^{14}$DIC/m$^2$/yr) across $\sigma_0$=26.4 (TW/SAMW boundary at 30°S) dominated by buoyancy-driven component and diffusive transformation term with western boundary current regions

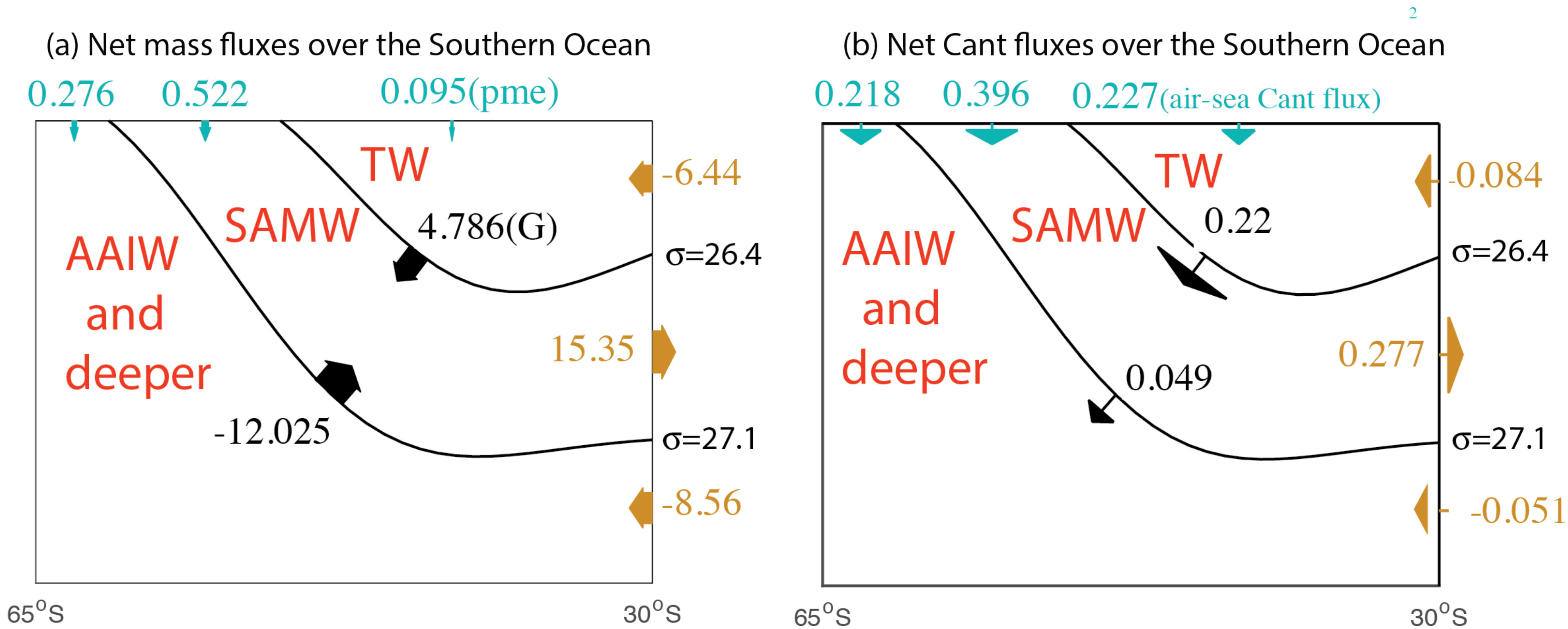
# Mass and bomb-$^{14}$DIC overturning over the Southern Ocean over 1995




~70% of formation source for SAMW reservoir for mass occurs from denser waters (12 Sv), with ~30% from above (TW)

Strong "amplification" of the TW formation source of SAMW for bomb-14DIC, at least in part reflecting meridional gradient in Revelle Factor between subtropics and circumpolar regions

# Mass and $C_{ant}$ overturning over the Southern Ocean over 1995




For $C_{ant}$ there is also a large amplification of the TW relative to the AAIW formation source for SAMW, at least in part reflecting gradients in the Revelle Factor

Contrast to bomb-$^{14}$DIC (pulsed input of $C_{ant}$) in the relative amplitudes of gas exchange uptake and TW=>SAMW transport

# Renewal timescale for thermocline

The studies of *Qiu and Huang* (1995), *Kwon and Riser* (2004), and *Suga et al.* (2008) considered **renewal timescales** for specific subtropical mode waters with **kinematic subduction diagnostics** as:

$$\tau_{renew} = (\text{Volume})/(\text{Formation\_Rate})$$

If we generalize this concept for the full thermocline volume (all waters $\sigma_0$<26.4 for our model) with net annual mean mass fluxes in each direction (~70Sv) across $\sigma_0$=26.4:

$$\tau_{renew} = 30 \text{ years for subtropical thermocline}$$

# Concluding Comments

1. Western boundary currents and their extension regions are the principal conduits for the ejection of anthropogenic carbon ($C_{ant}$) and bomb-$^{14}$DIC (a pulsed analog of $C_{ant}$) from the thermocline

2. For both $C_{ant}$ and bomb-$^{14}$DIC, the thermocline water (TW) formation source of SAMW in the Southern Ocean is amplified for the Southern Ocean (Y<30S) relative to the Antarctic Intermediate Water source, with a number of candidate contributing factors (including the meridional gradient in the Revelle factor)

3. A renewal timescale of ~30 years for the full volume of the subtropical thermocline is revealed with water mass transformation diagnostics, with western boundary currents and extension regions playing a central role in sustaining these exchanges.

# $C_{ant}$ fluxes across $\sigma_0$=26.4 in MOM5 averaged over 1995