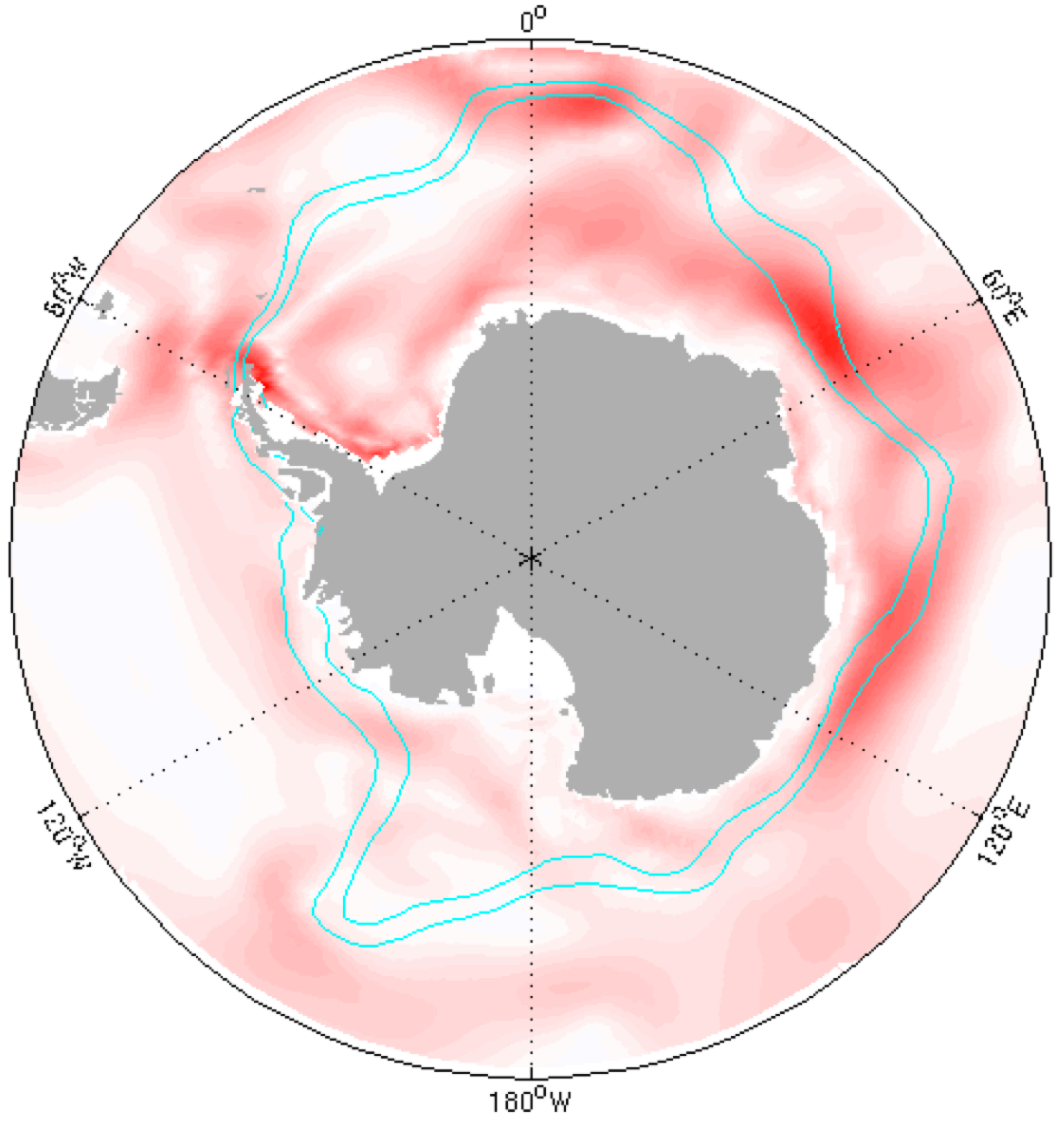
Dynamical controls on the depth of the boundary between bottom and deep waters in the Last Glacial Maximum Atlantic

Dan Amrhein
LuAnne Thompson

University of Washington
amrhein@uw.edu



Ames Research Center

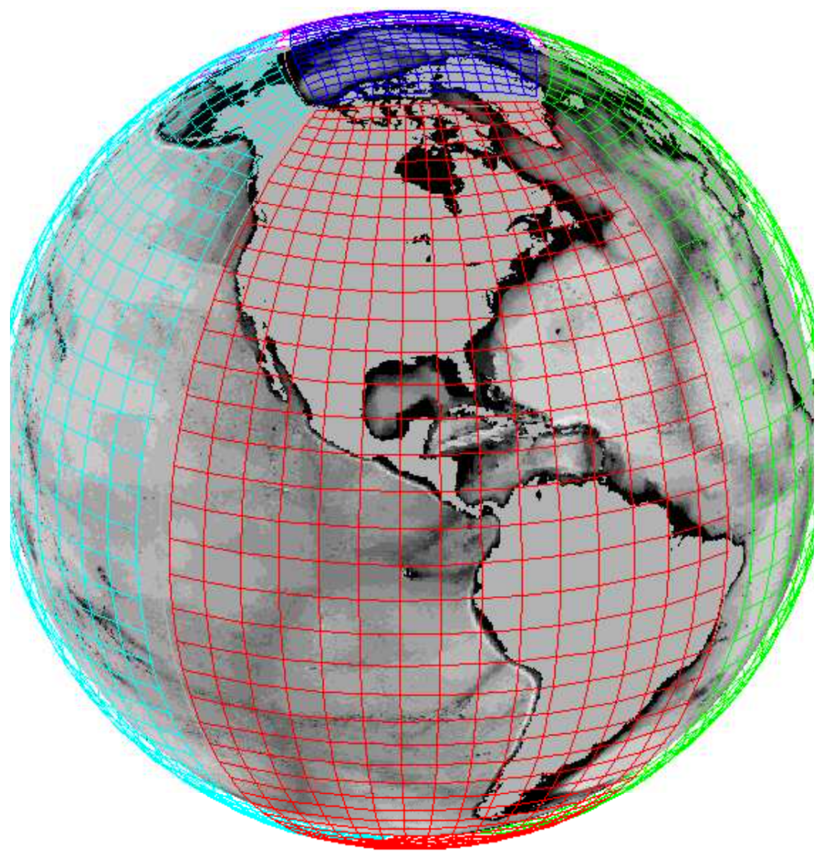
Motivation: LGM state estimation

$$\frac{D\mathbf{u}}{Dt} + \mathbf{f} \times \mathbf{u} = -\frac{1}{\rho}\nabla_z p$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\ldots$$

+



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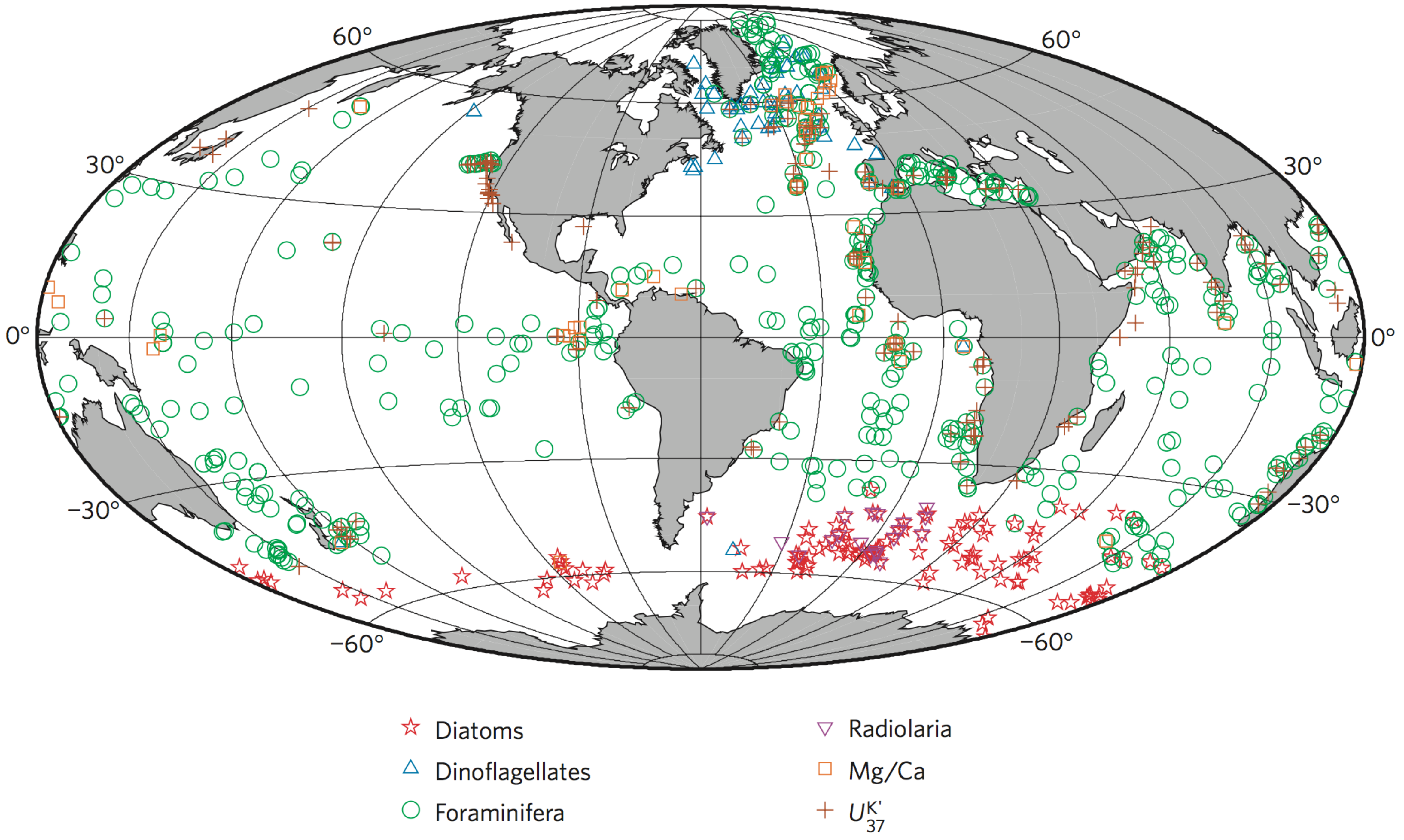

The dream: Reproduce *all available LGM observations* in an ocean model

Dail (2014)
Kurahashi-Nakamura et al. (2017)
Amrhein et al. (2018)

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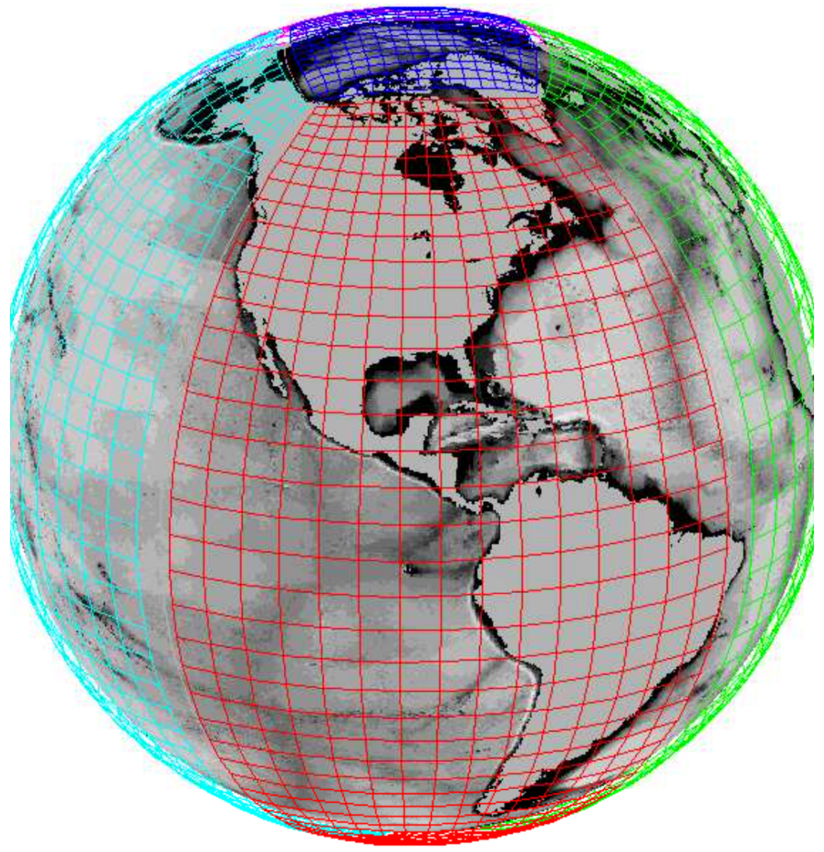

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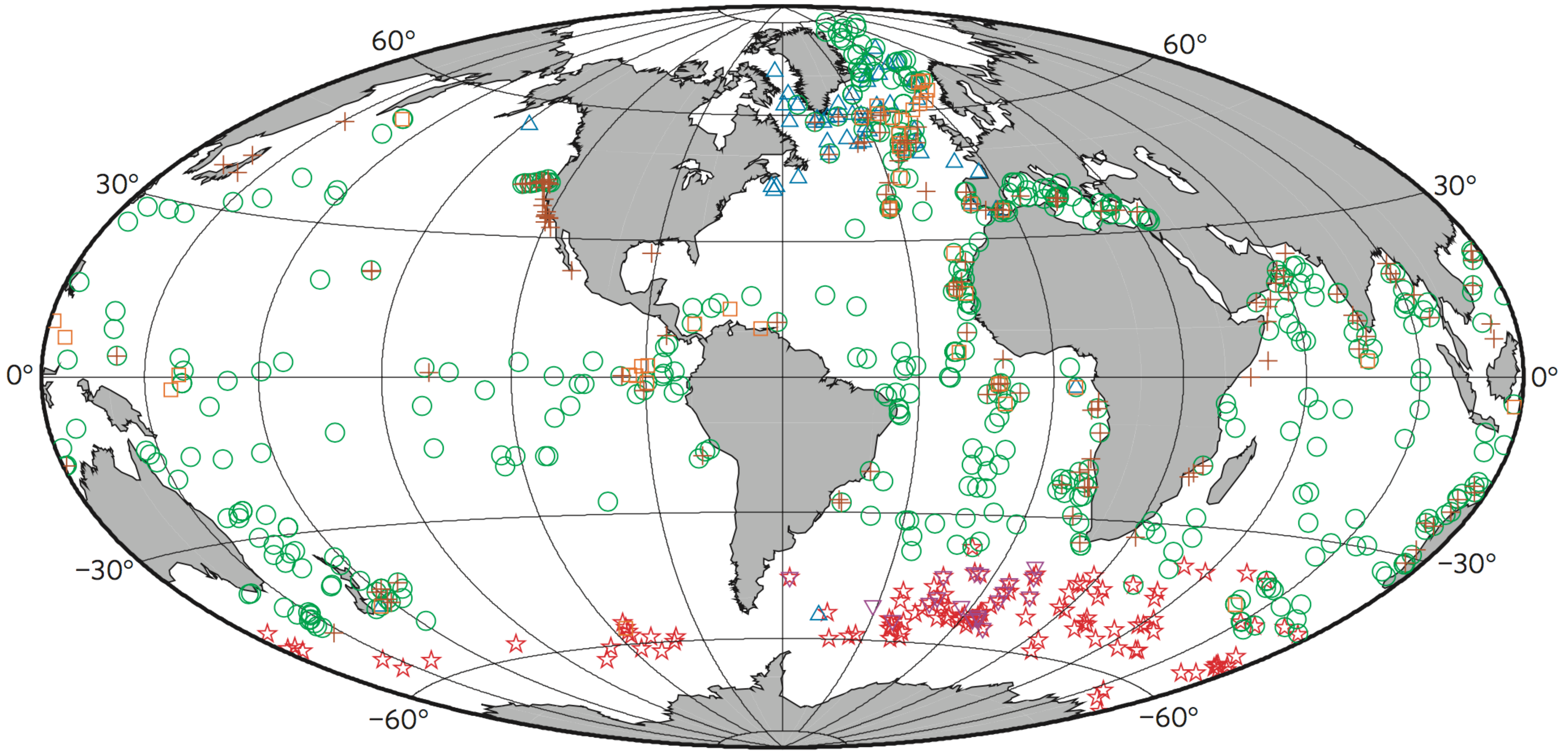
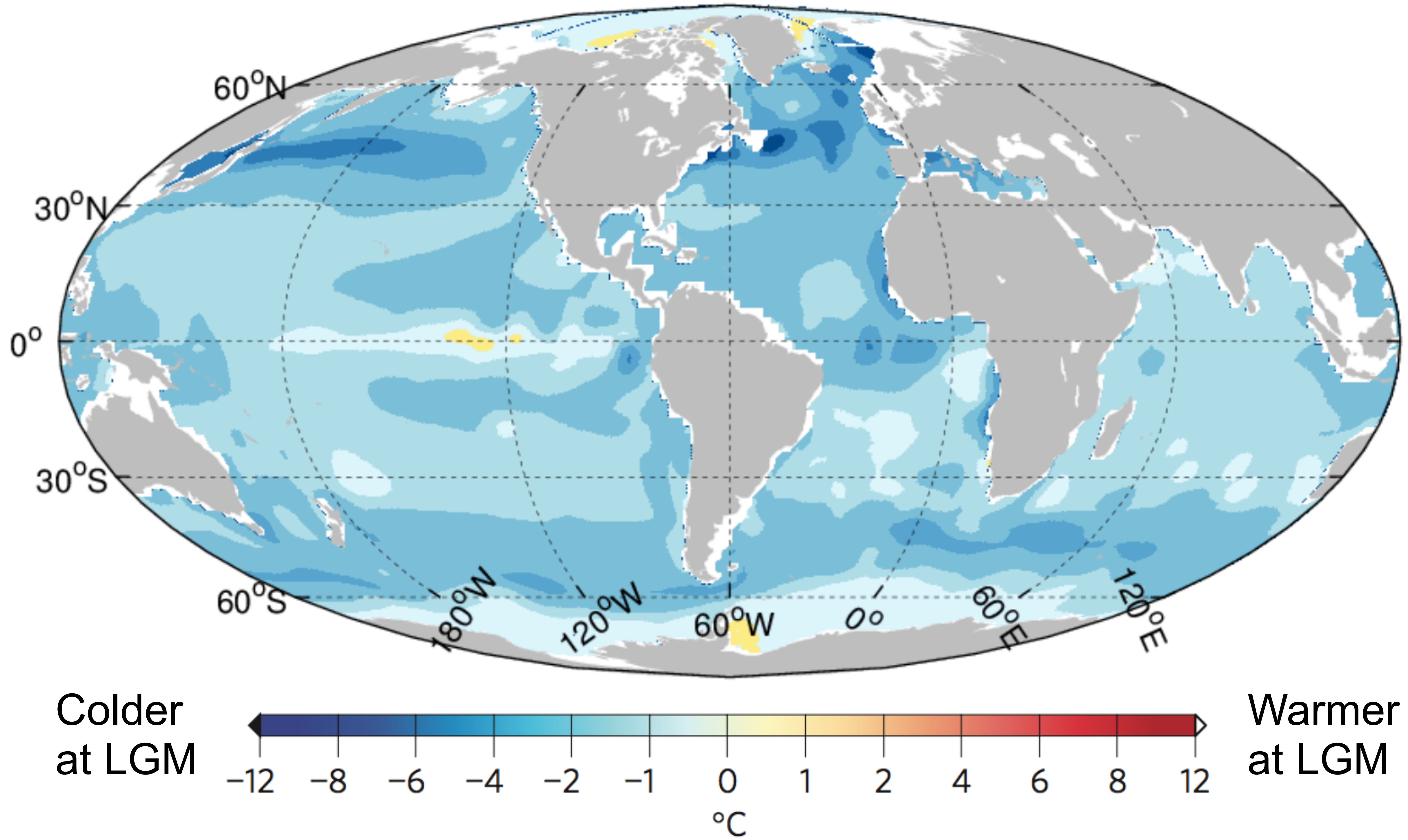


The dream: Reproduce *all available LGM observations* in an ocean model

…by using the MITgcm (primitive equation + sea ice) by adjusting atmospheric conditions using the adjoint gradient approach

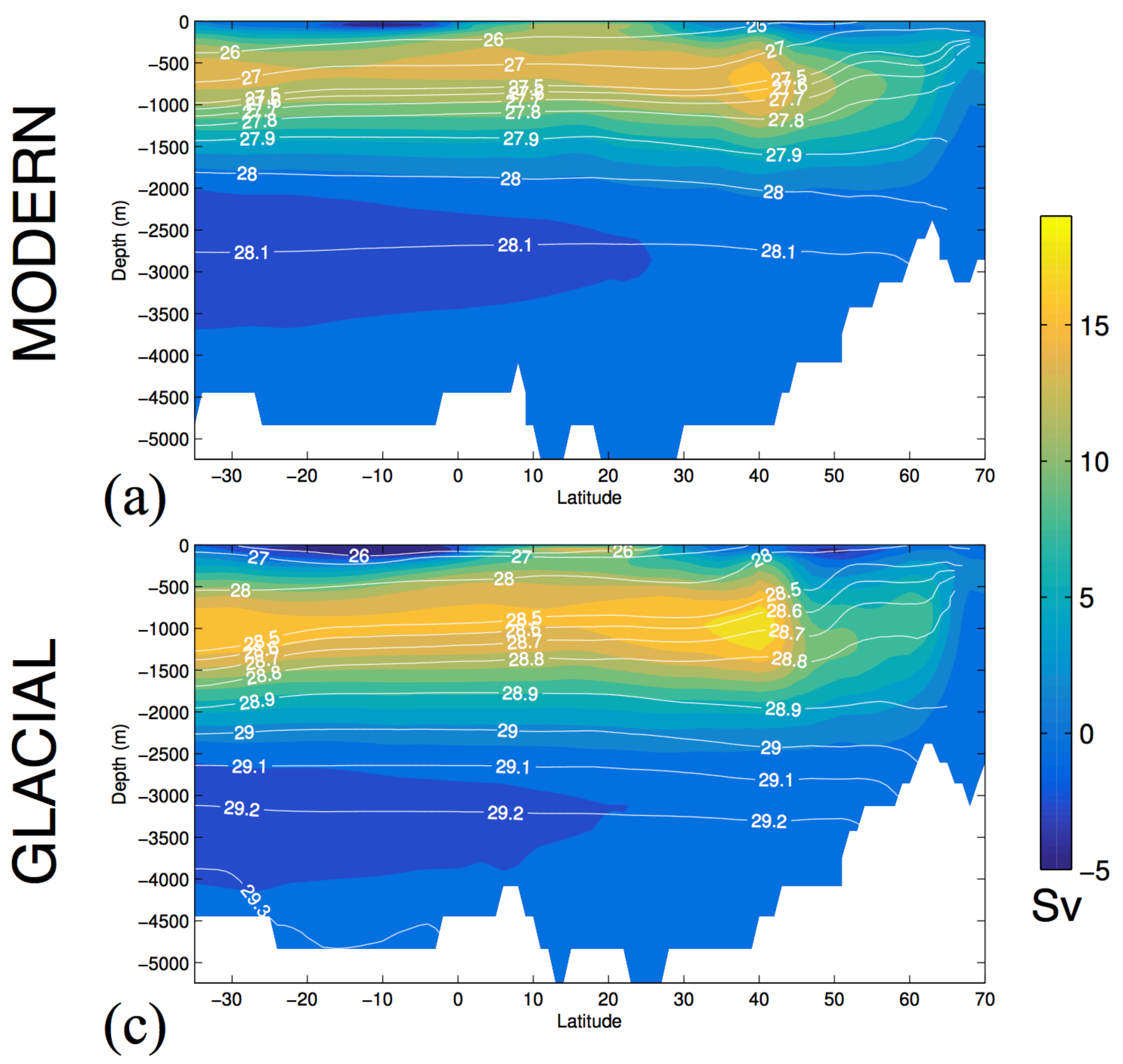
=



Waelbroeck et al. 2009

Abyssal circulation: Stronger, deeper upper AMOC cell at LGM?

LGM state estimate



Amrhein et al. (2018)

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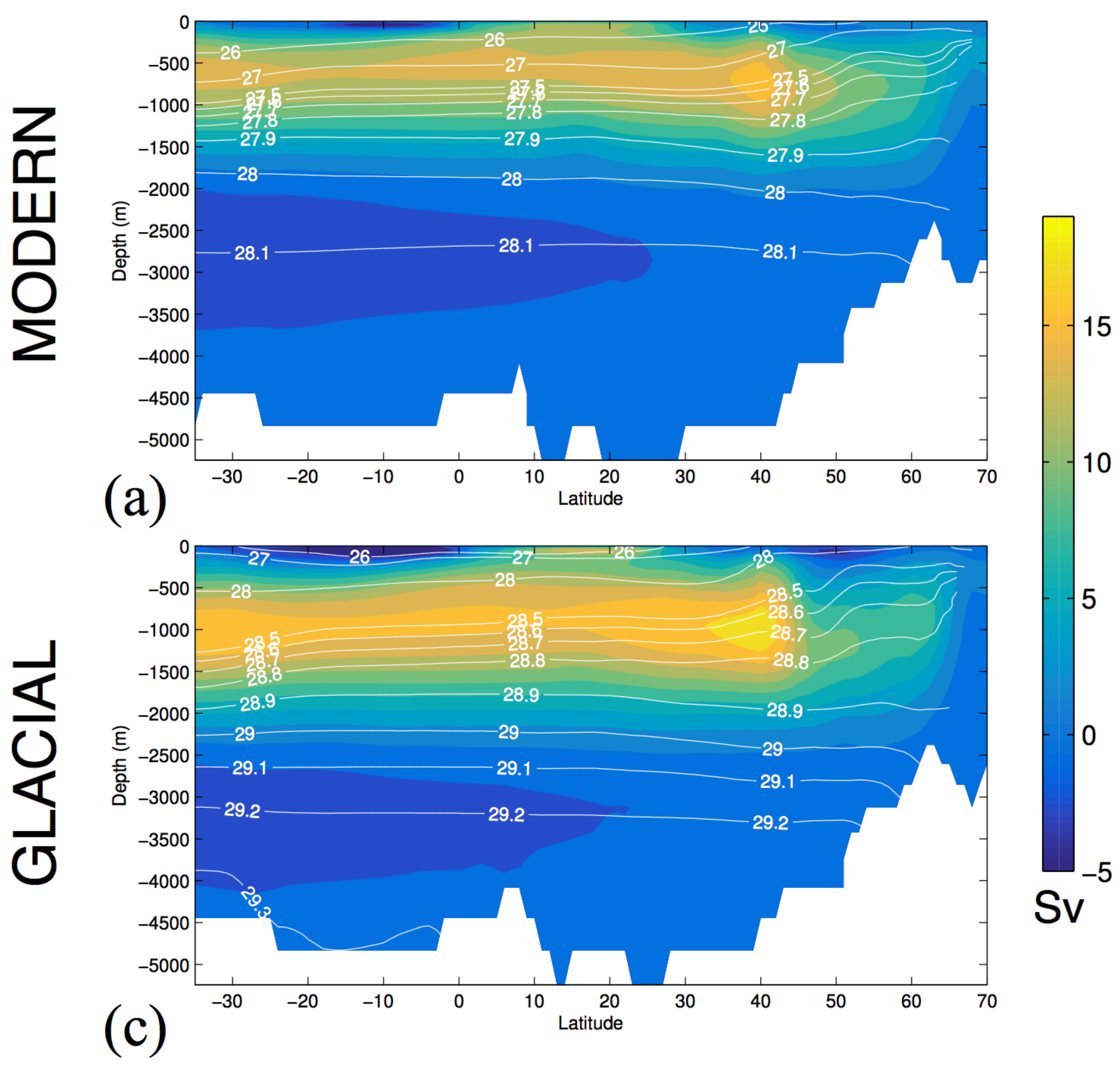
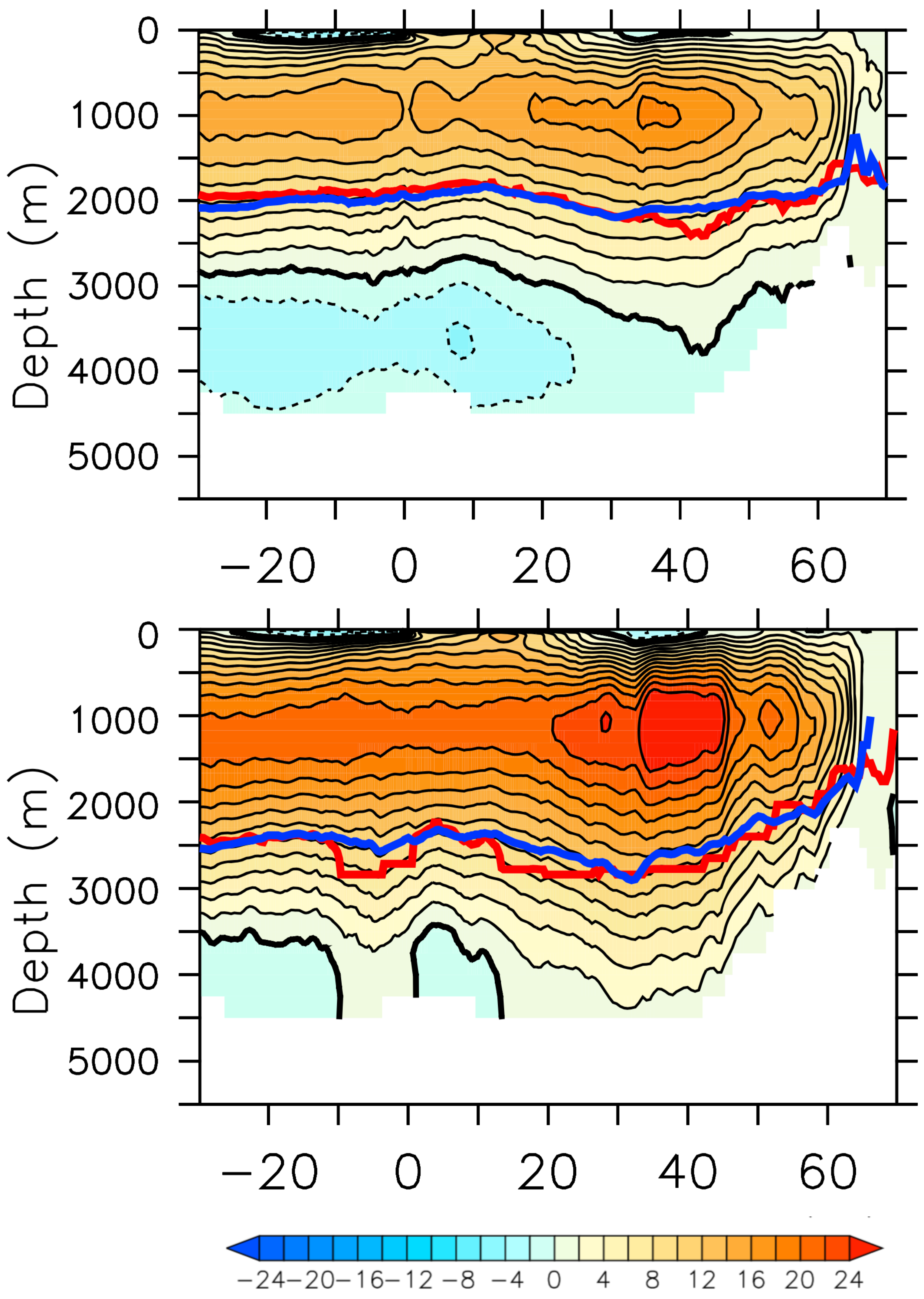


PMIP3 model mean



Muglia and Schmittner (2015)

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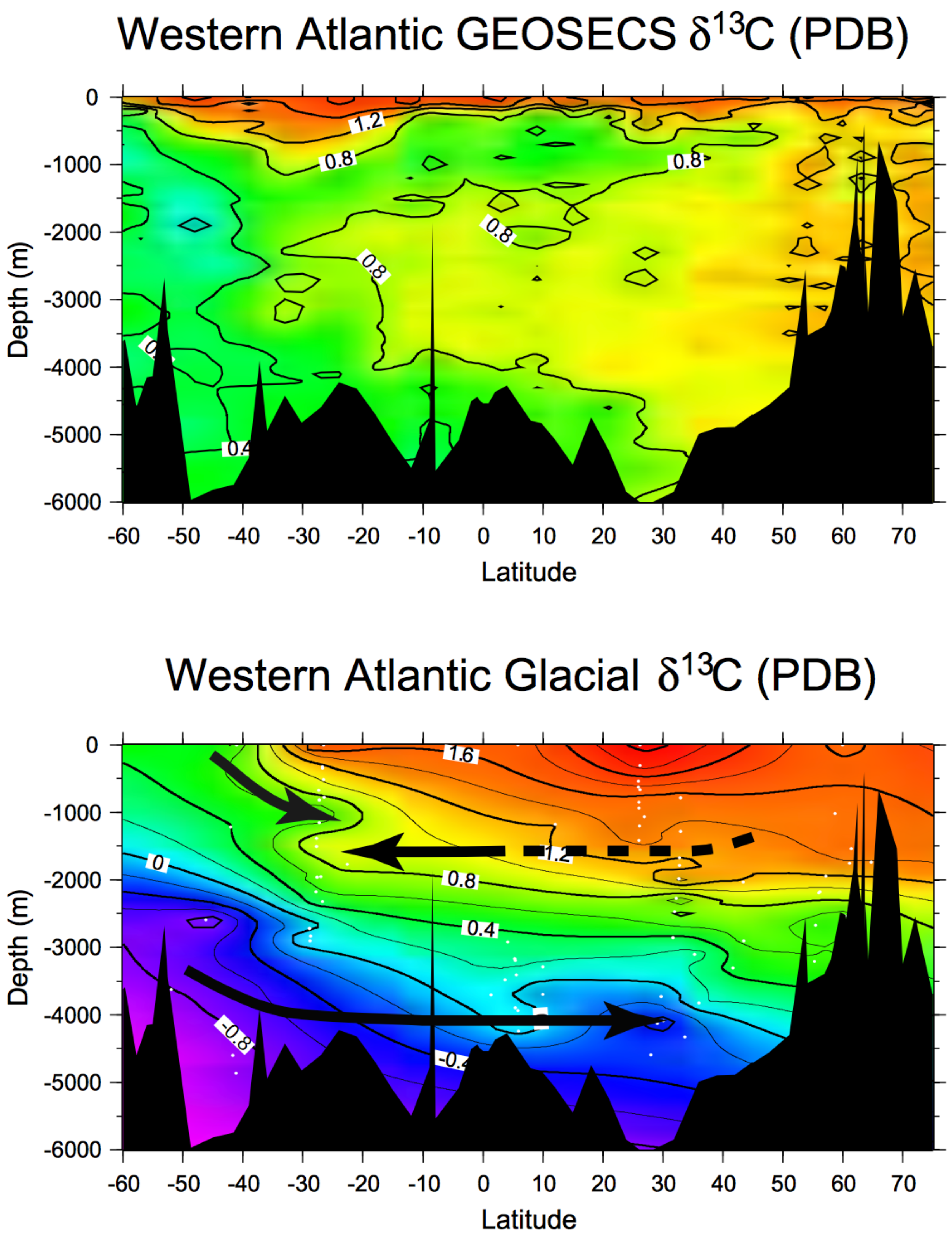

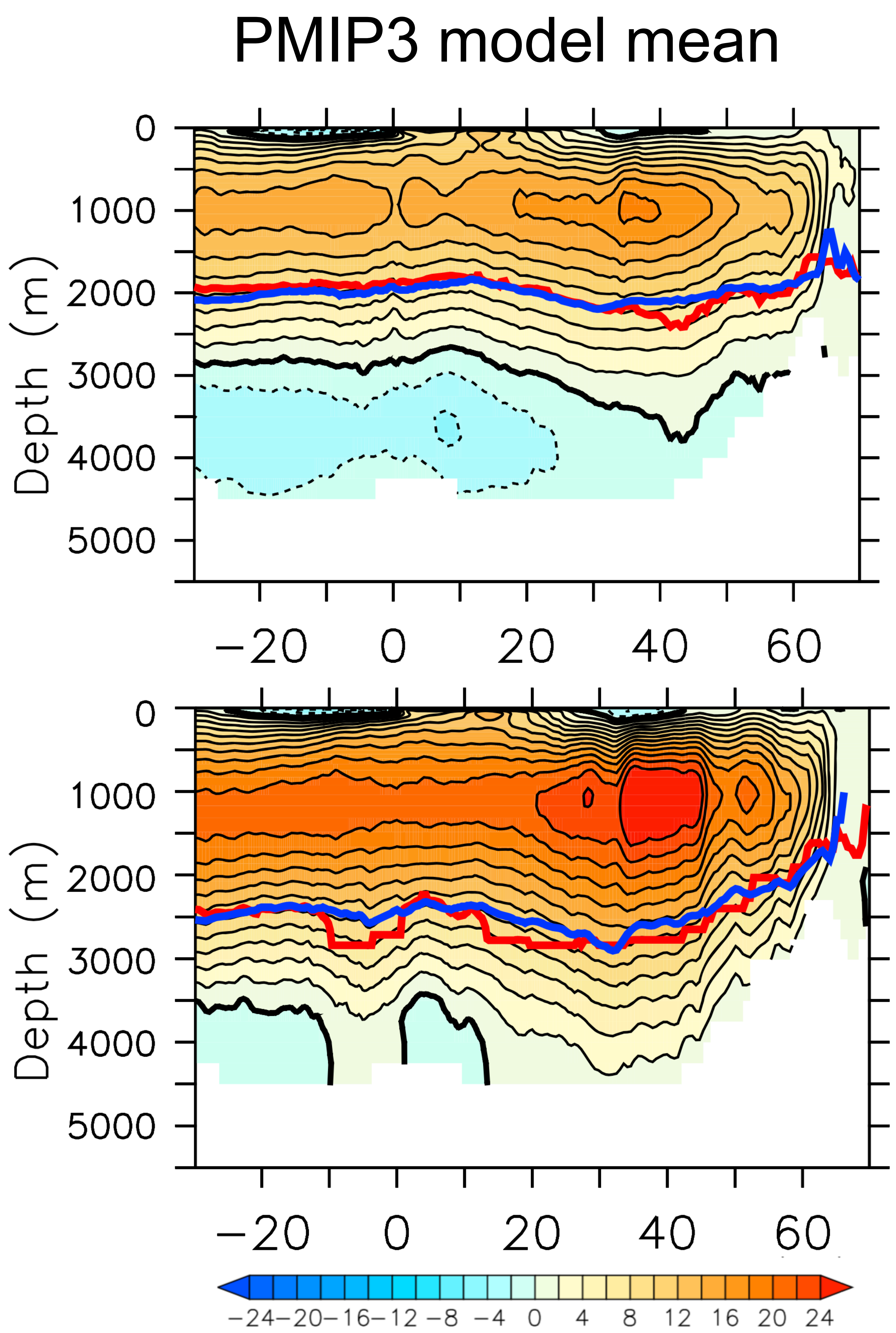

Curry and Oppo (2005); see also Boyle and Keigwin (1982), Curry and Lohmann (1982), Oppo and Lehman (1993), Lund et al. (2011)…

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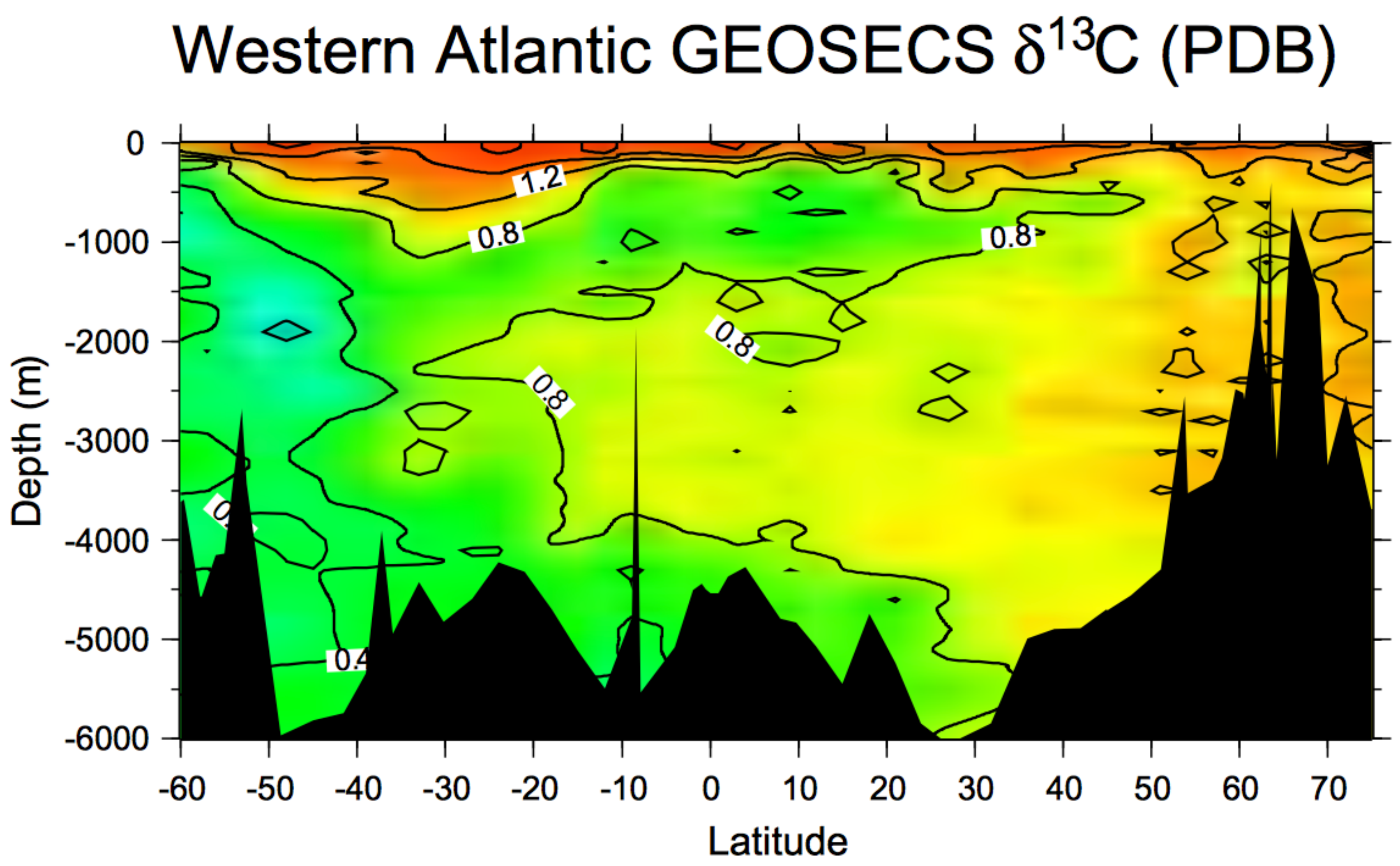
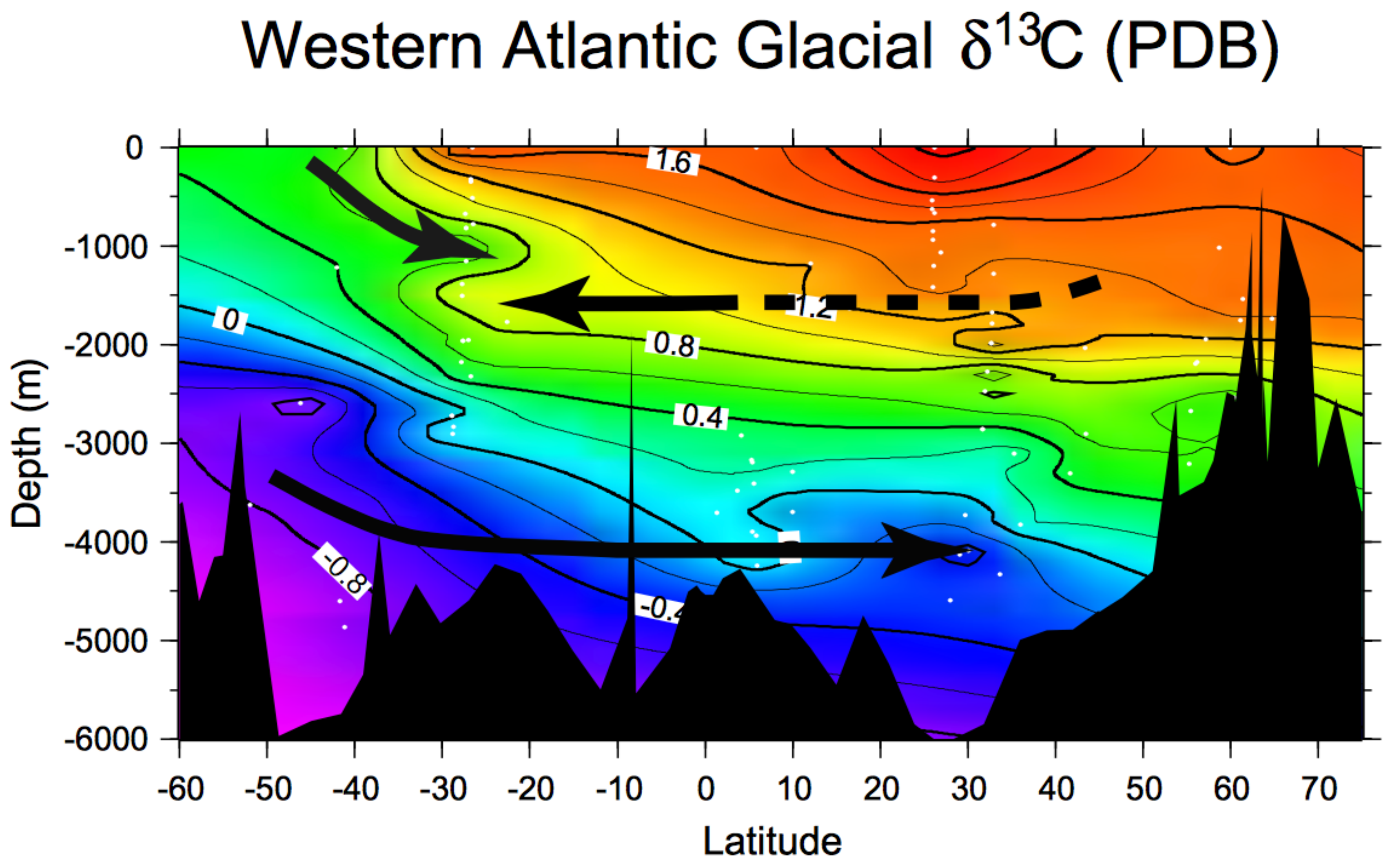




How does assimilating tracer observations change the behavior of a primitive-equation model?

What are physical mechanisms for increasing the presence of southern-source waters in the Atlantic?

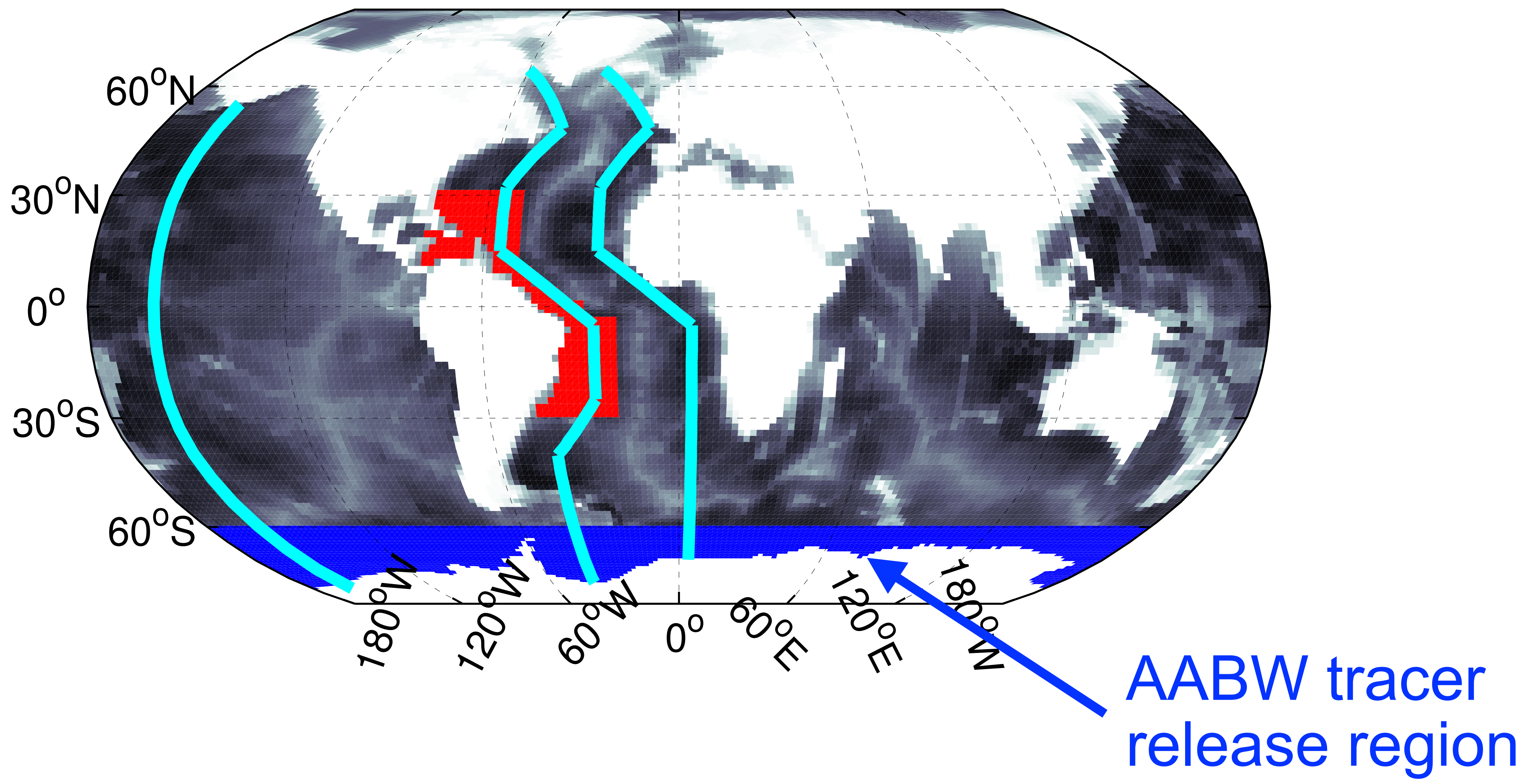
Curry and Oppo (2005); see also Boyle and Keigwin (1982), Curry and Lohmann (1982), Oppo and Lehman (1993), Lund et al. (2011)…

An ideal perturbation approach to inferring ocean dynamics from deep ocean tracers

Hypothesis
We can use the MITgcm adjoint to diagnose "recipes" for increasing AABW in the Atlantic

Amrhein et al. in prep.

An ideal perturbation approach to inferring ocean dynamics from deep ocean tracers



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1. 2x2 degree MITgcm run for 5000 years under modern conditions.

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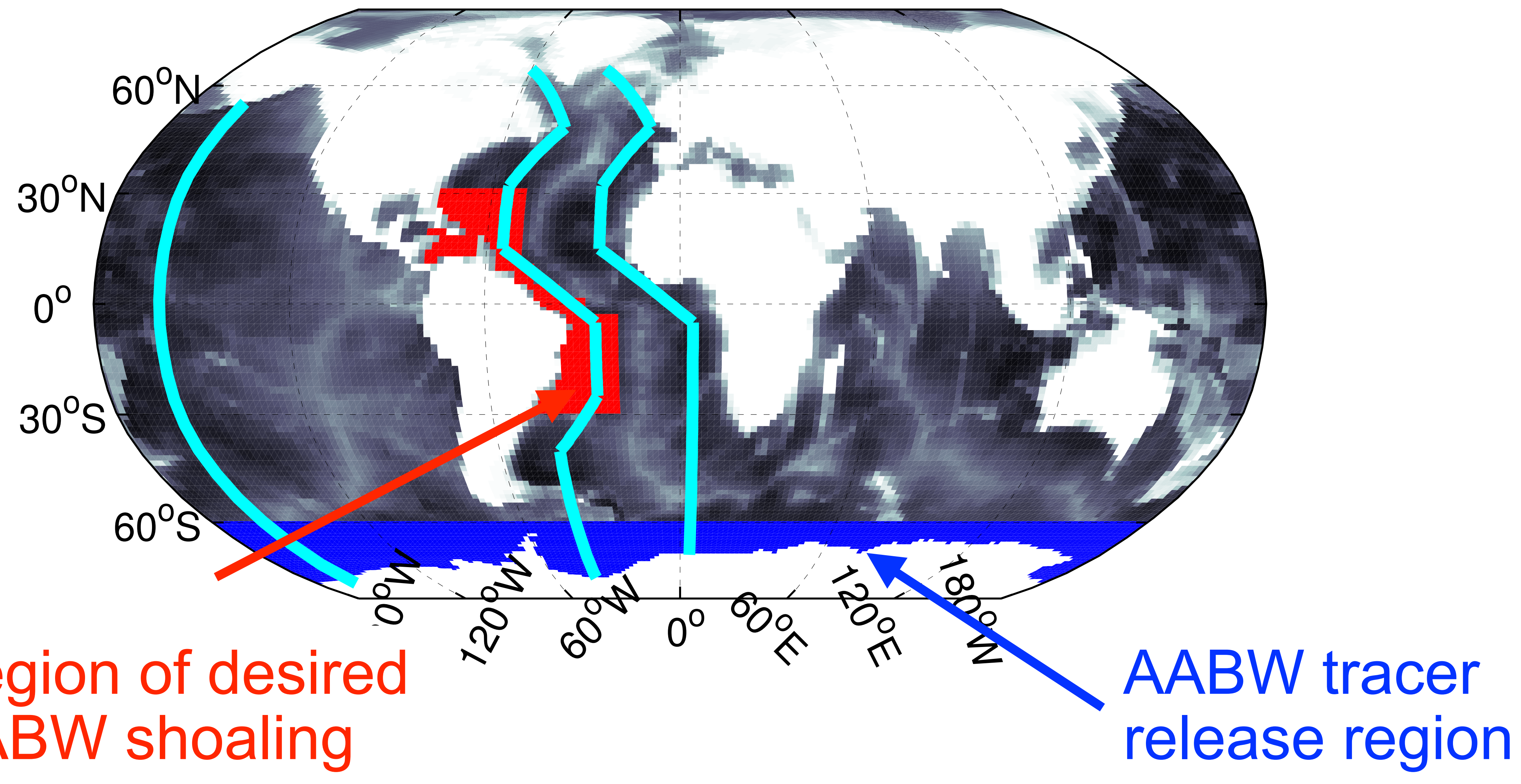

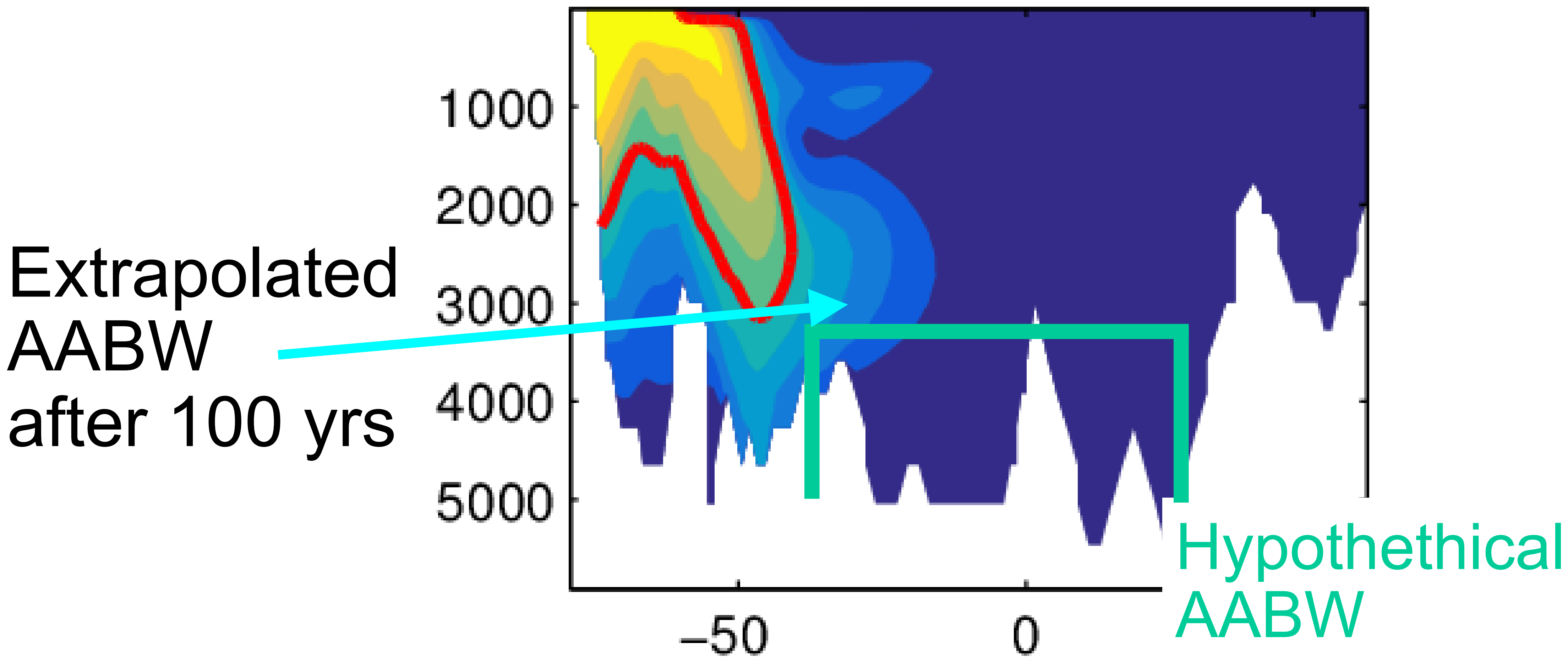

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1. 2x2 degree MITgcm run for 5000 years under modern conditions.

2. Use the adjoint to derive perturbations to **wind stress, air temperature, and precipitation** that increase the amount of (extrapolated) AABW

$$J = \text{(Extrapolated AABW - hypothethical AABW)}^2$$

$$\text{Ideal perturbation} = \frac{\partial J}{\partial u}\Delta_u$$

Amrhein et al. in prep.

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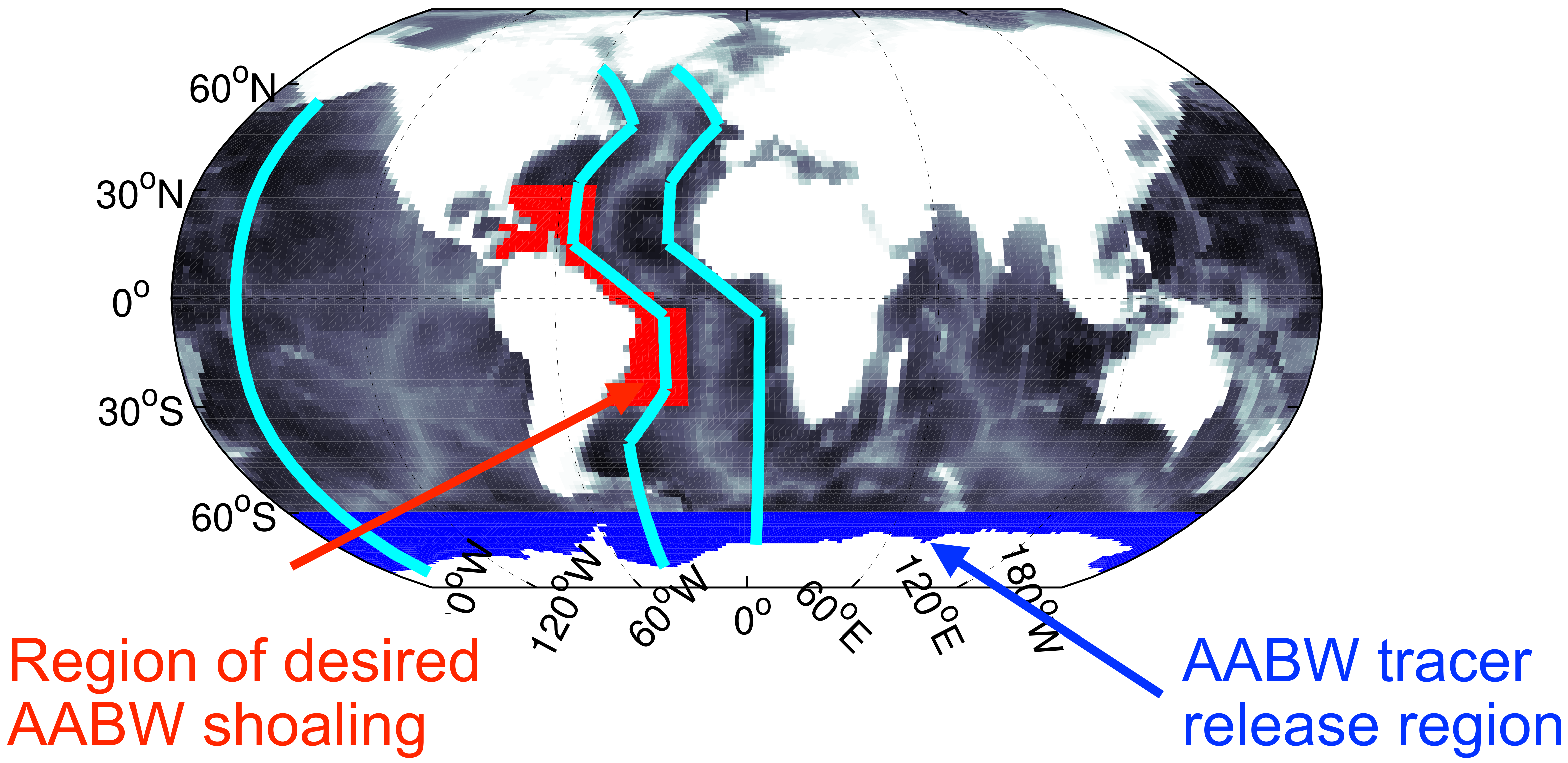

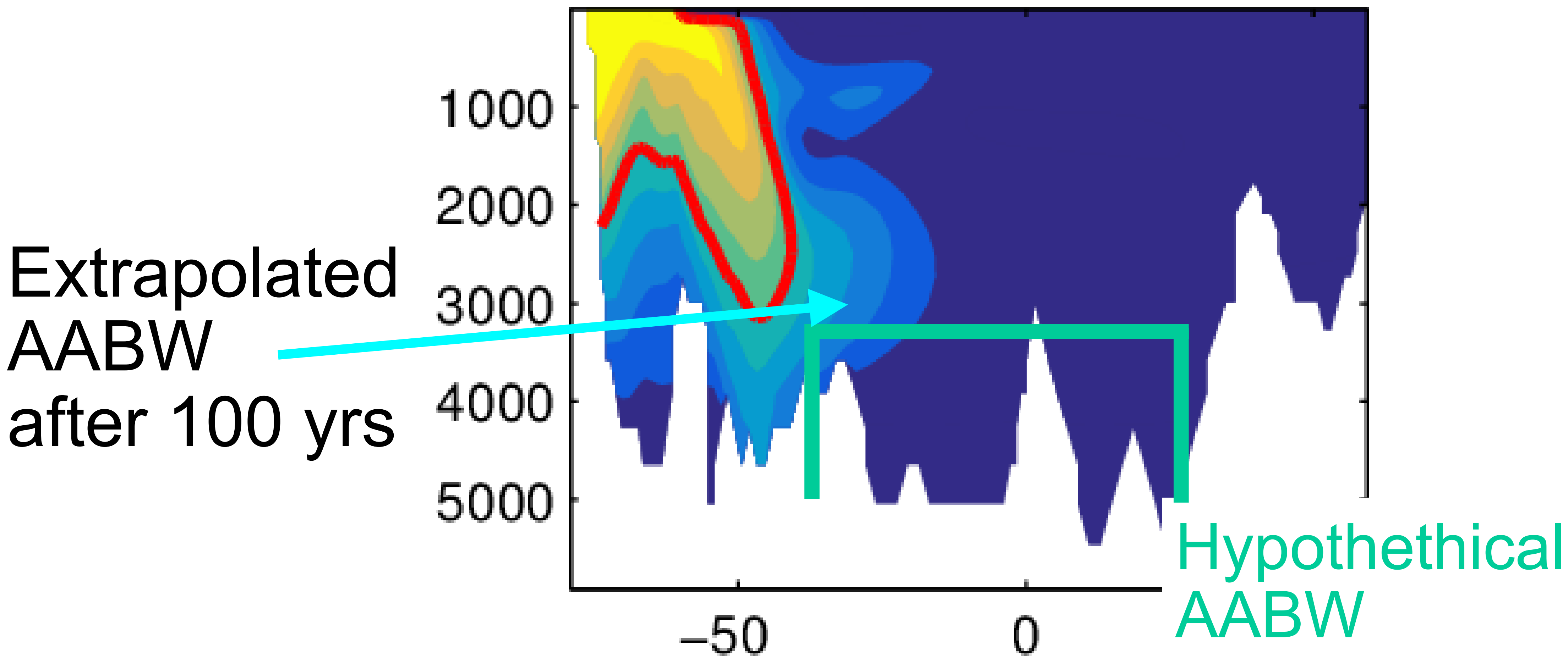

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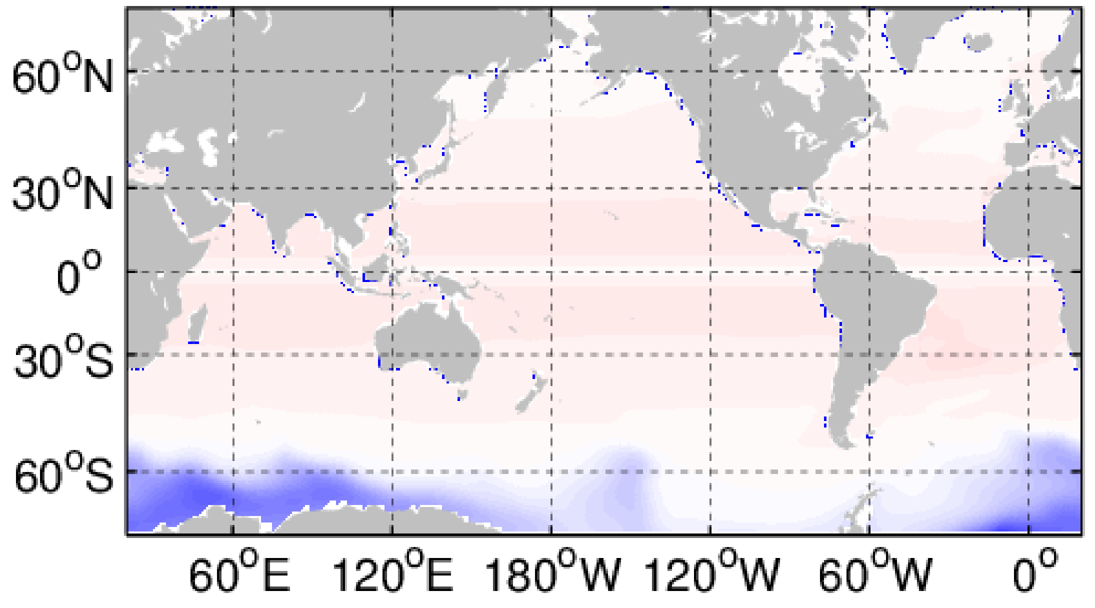
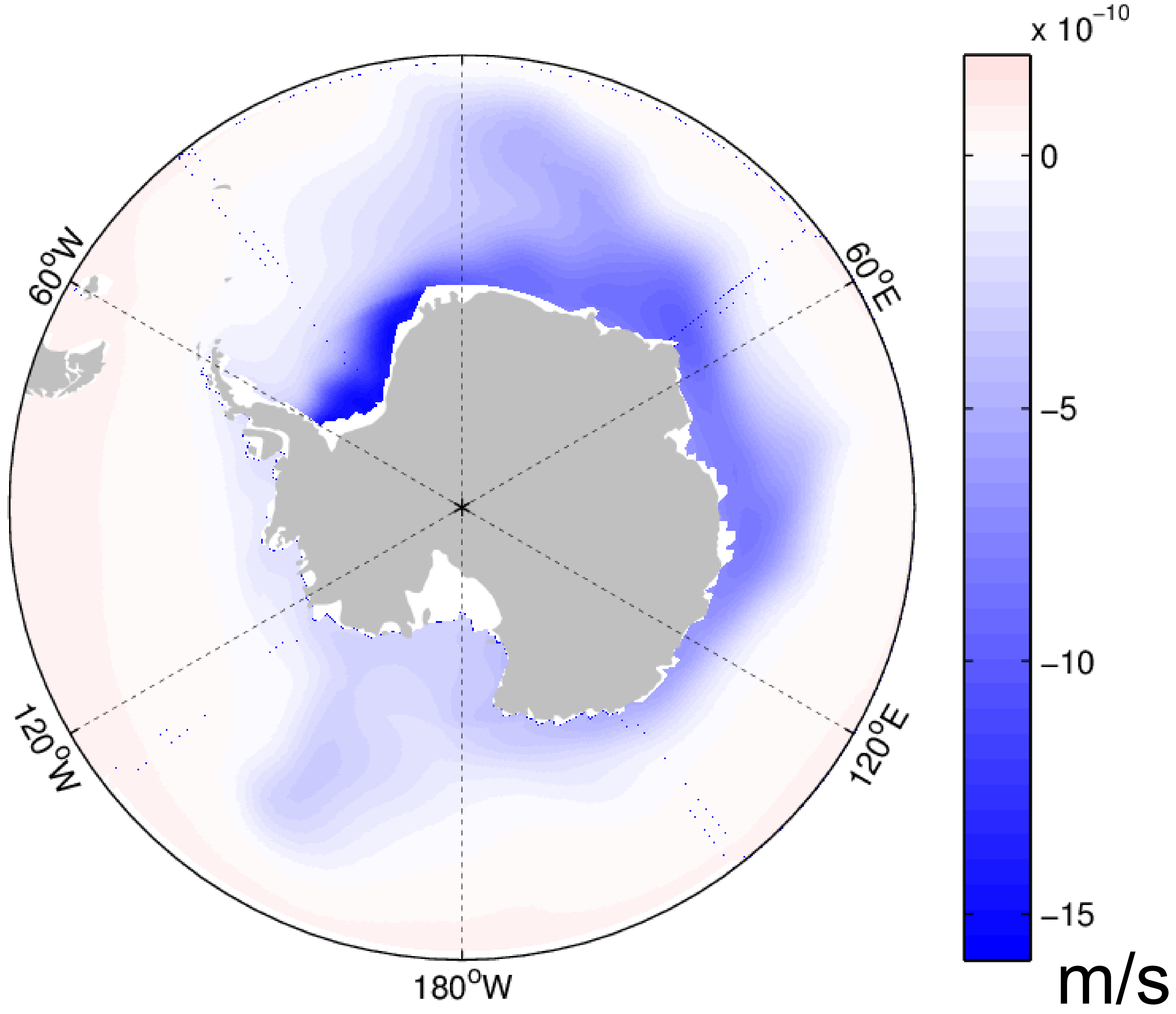
Ideal perturbation = $\dfrac{\partial J}{\partial u}\Delta_u$

3. Integrate for 1500 years under perturbations

Ideal perturbations are strongest over the Southern Ocean

Precipitation





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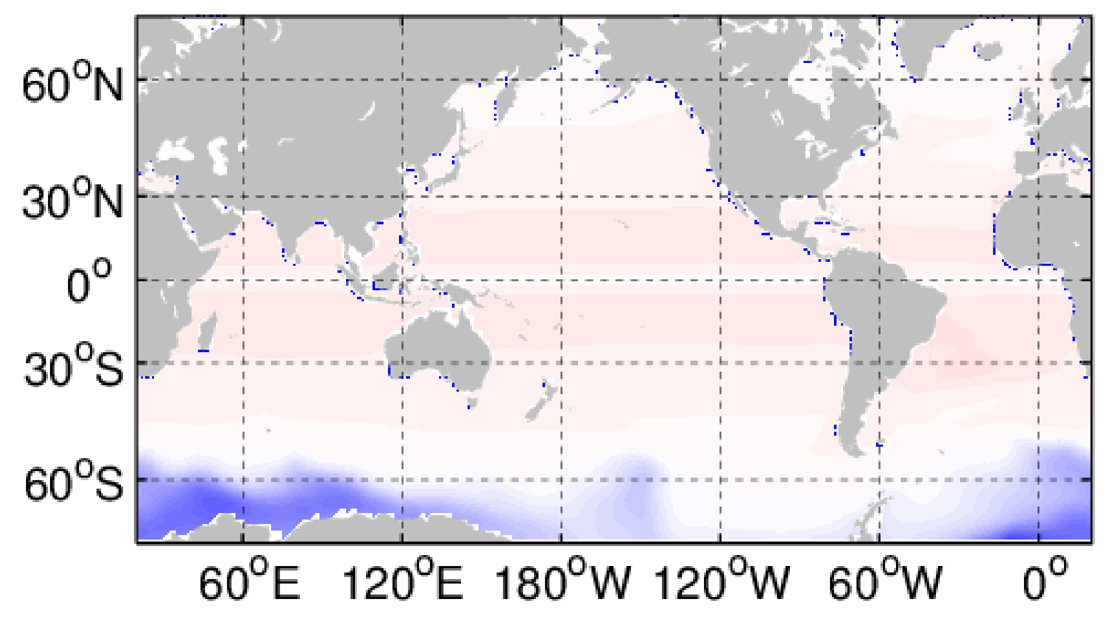
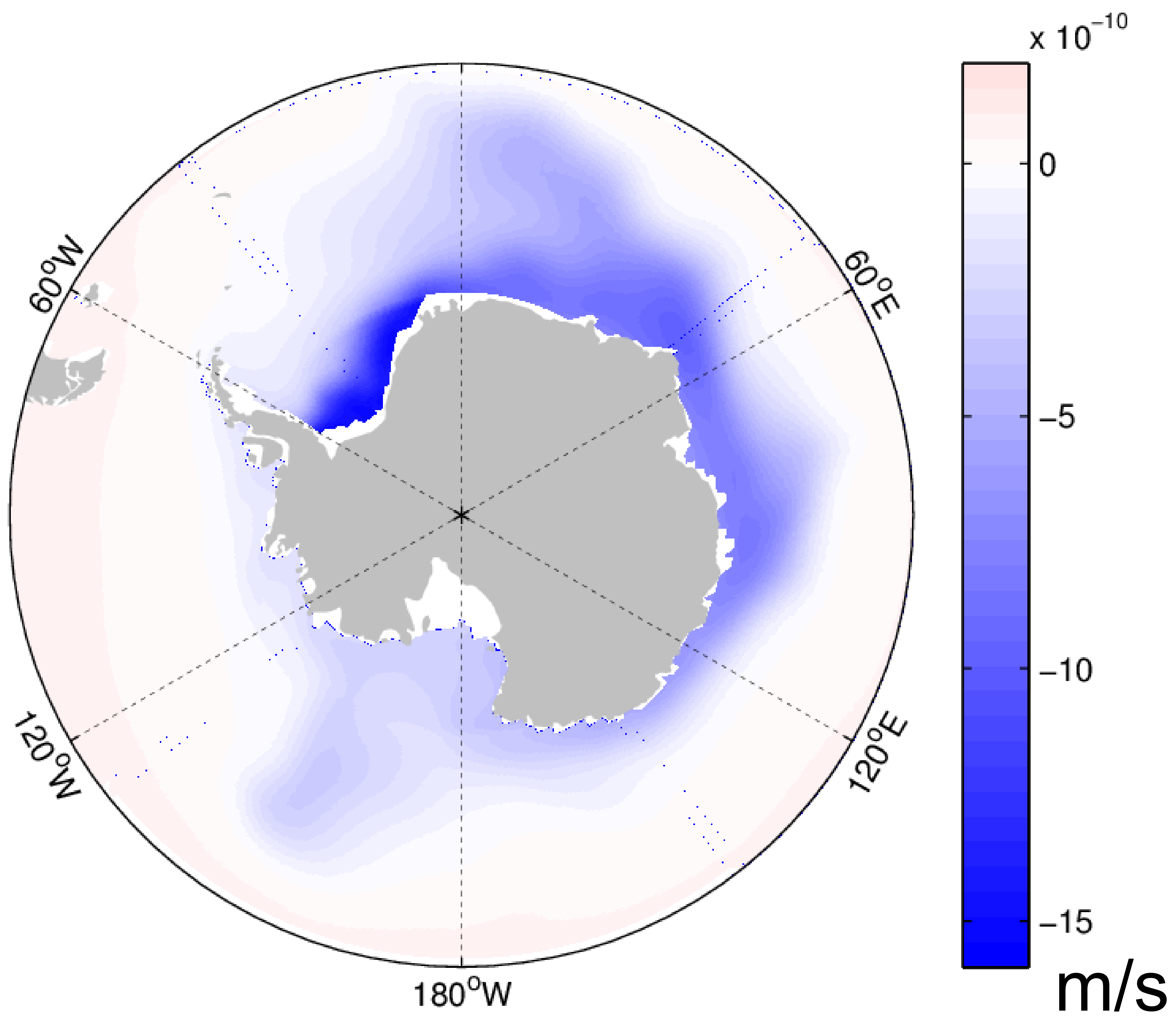
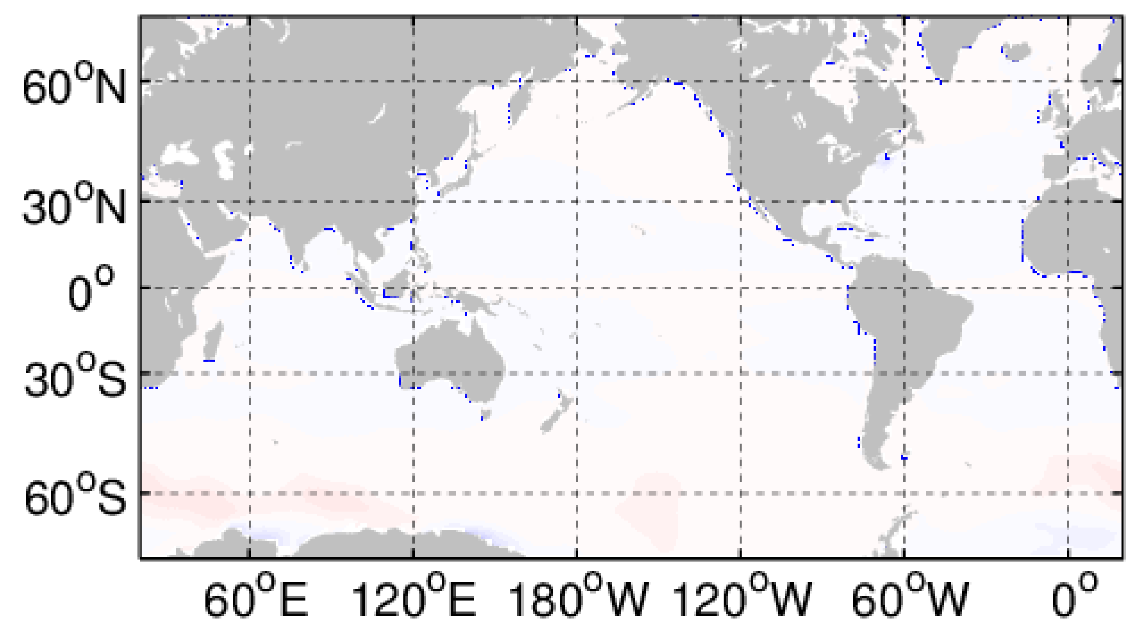
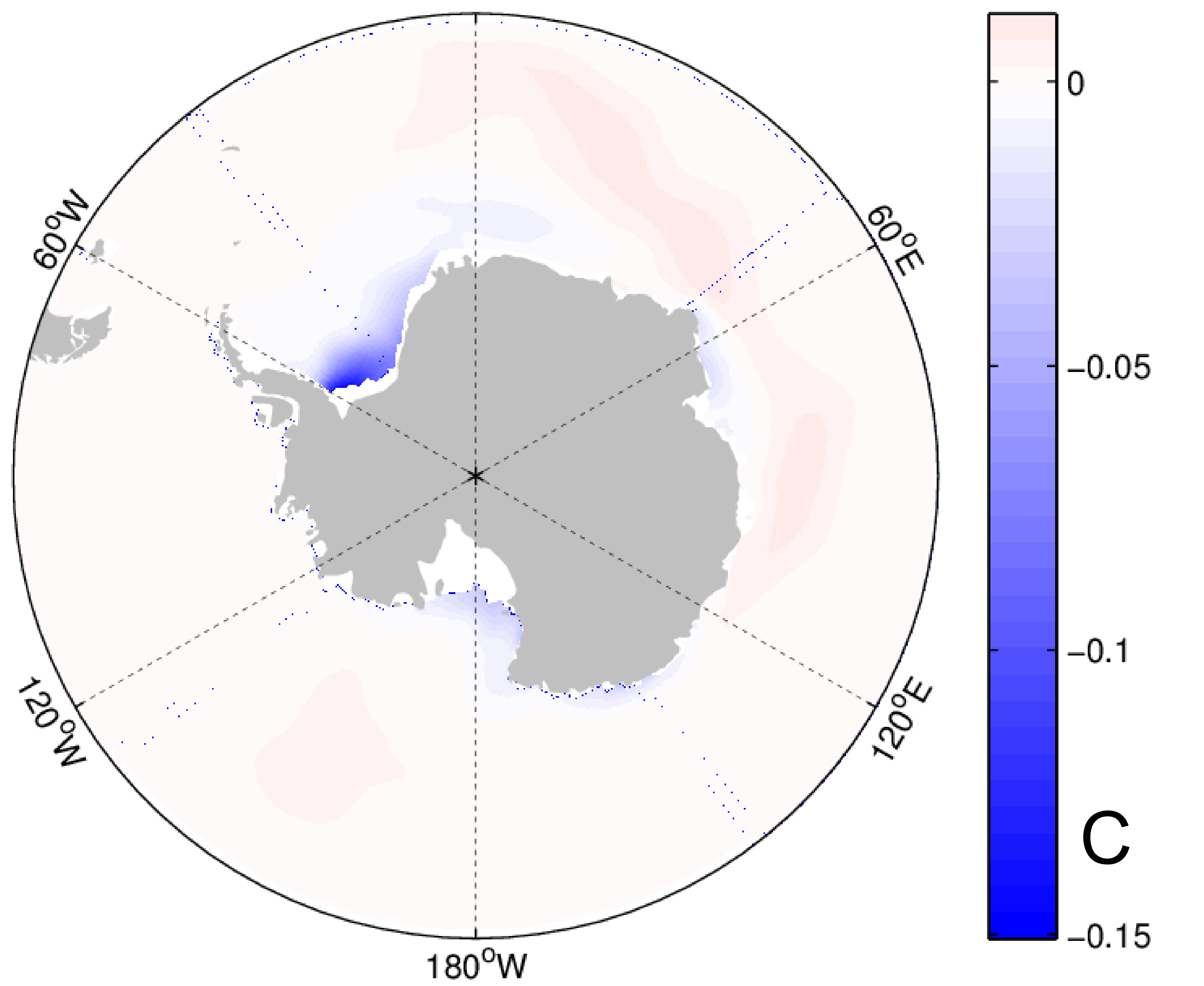




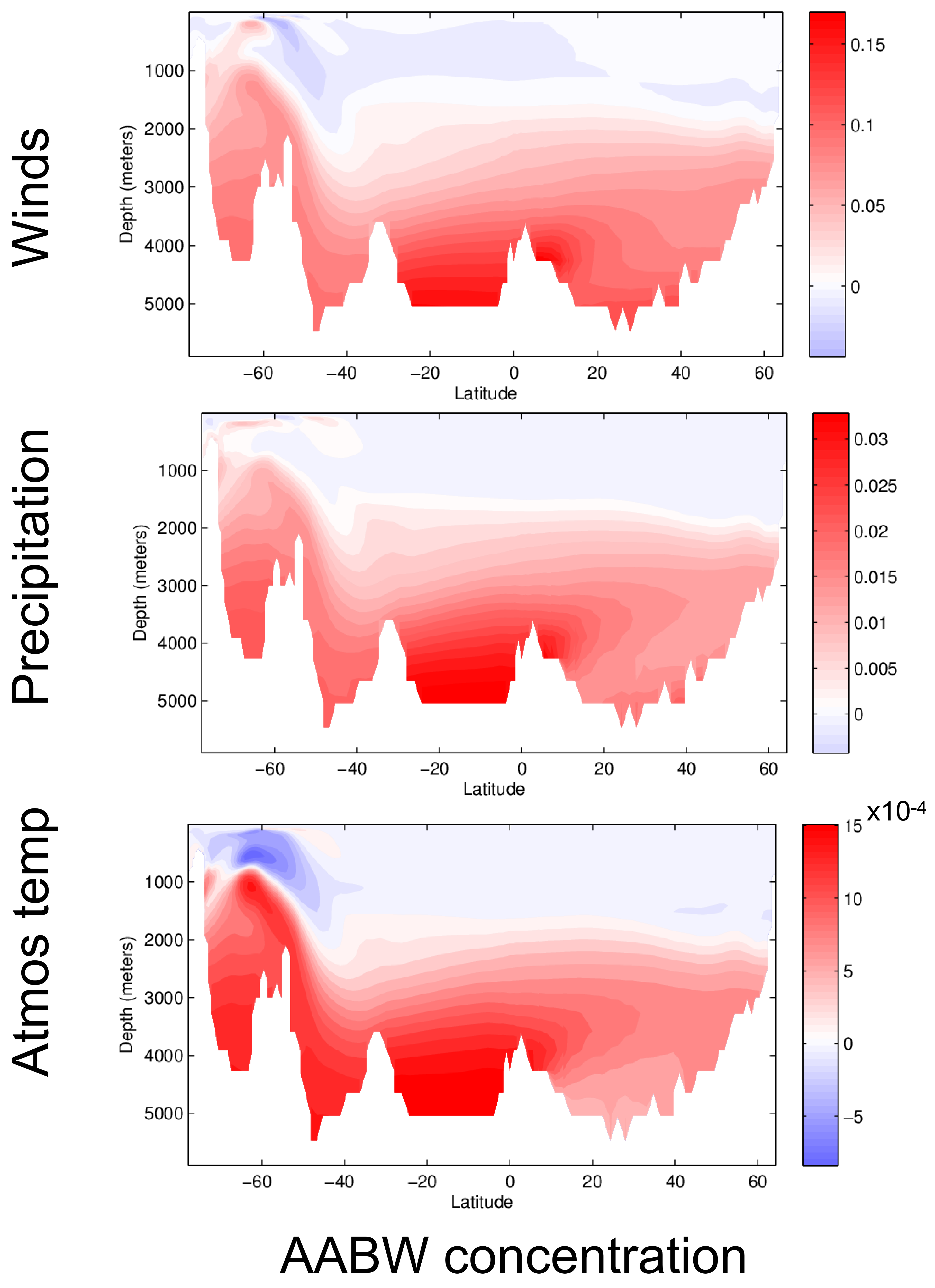
Atmos. temp





Ideal perturbations are strongest over the Southern Ocean

Perturbations to SAT, precip, and wind stress increase AABW after 1500 years



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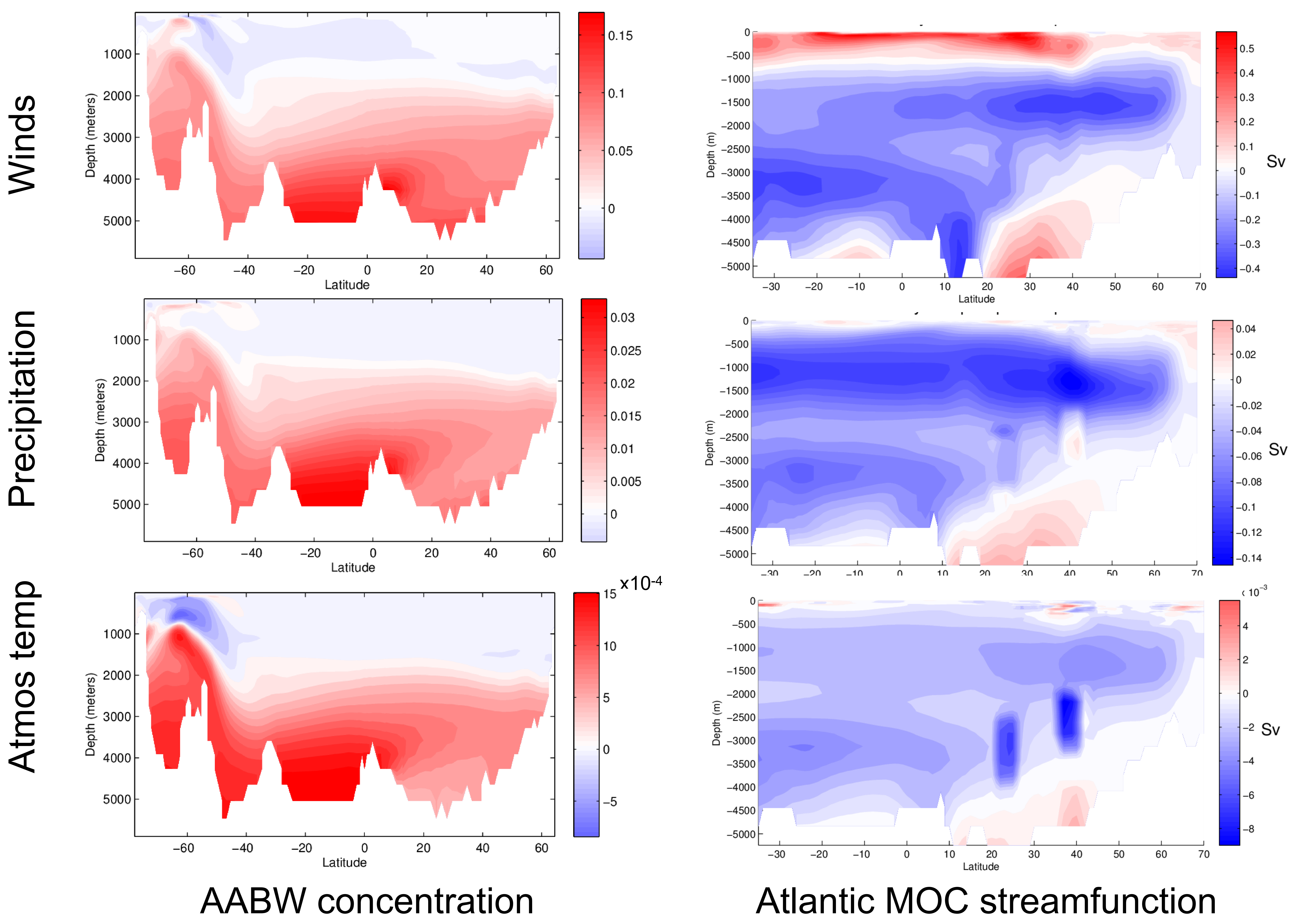
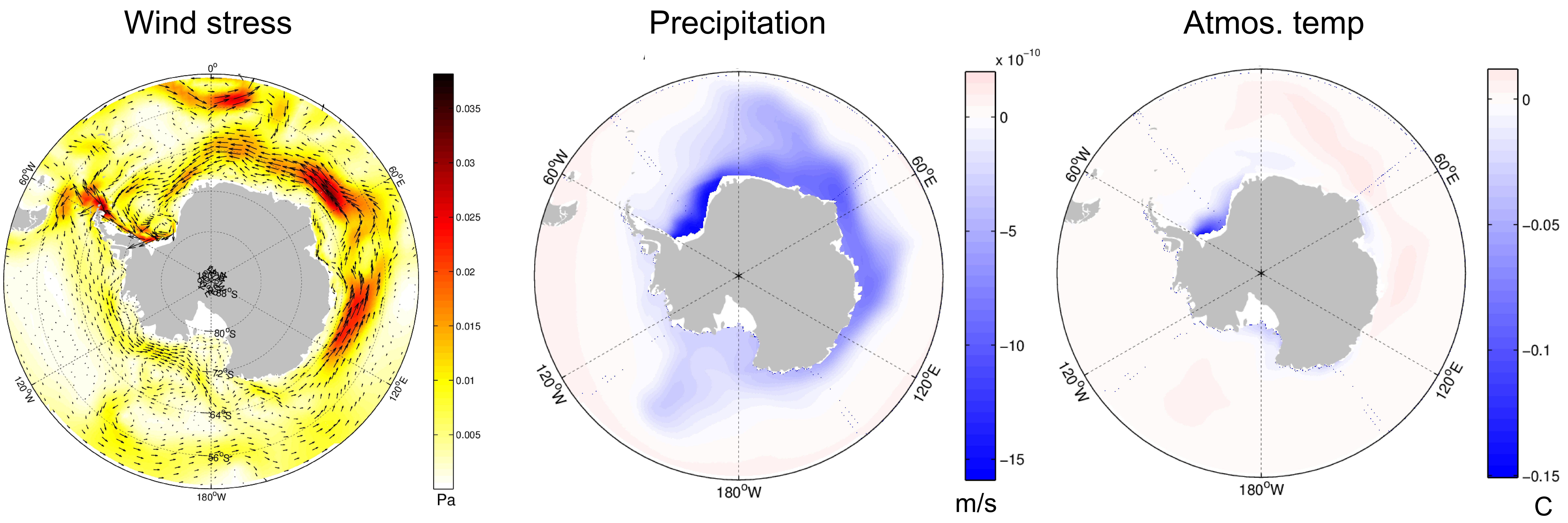


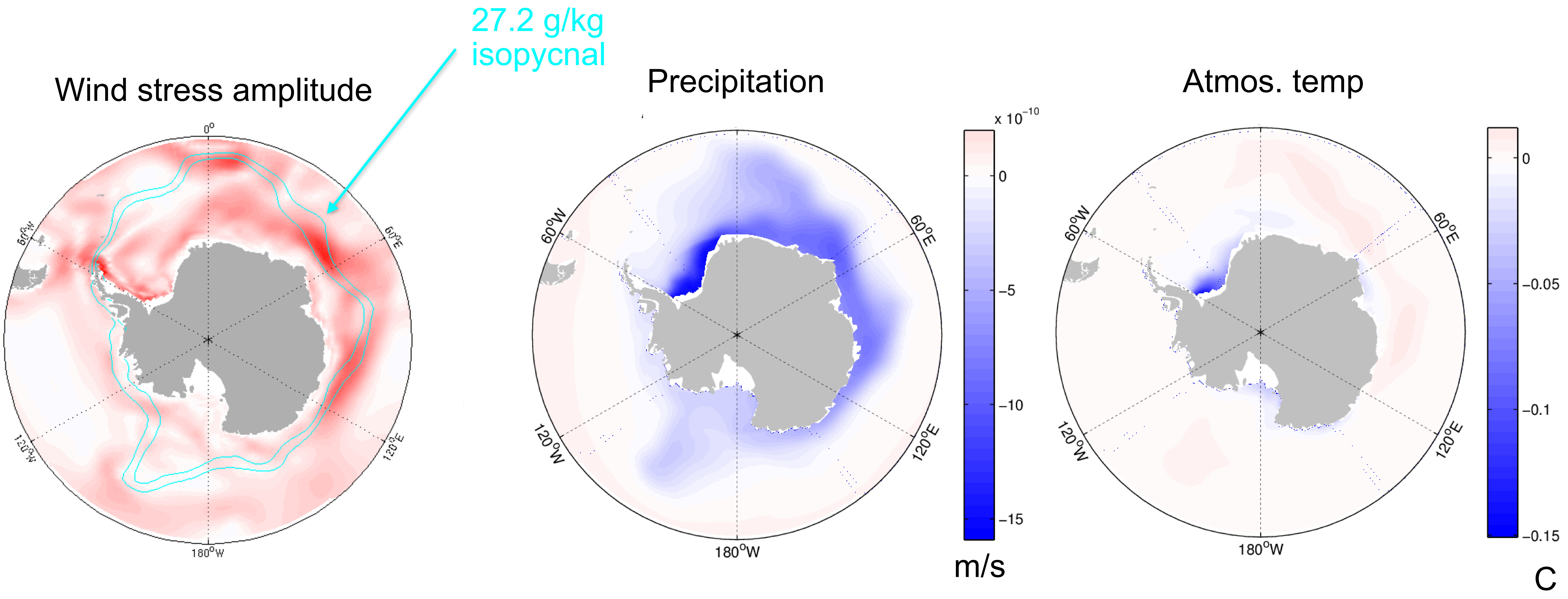
Weaker upper cell
Stronger lower cell

How do the ideal perturbations work?



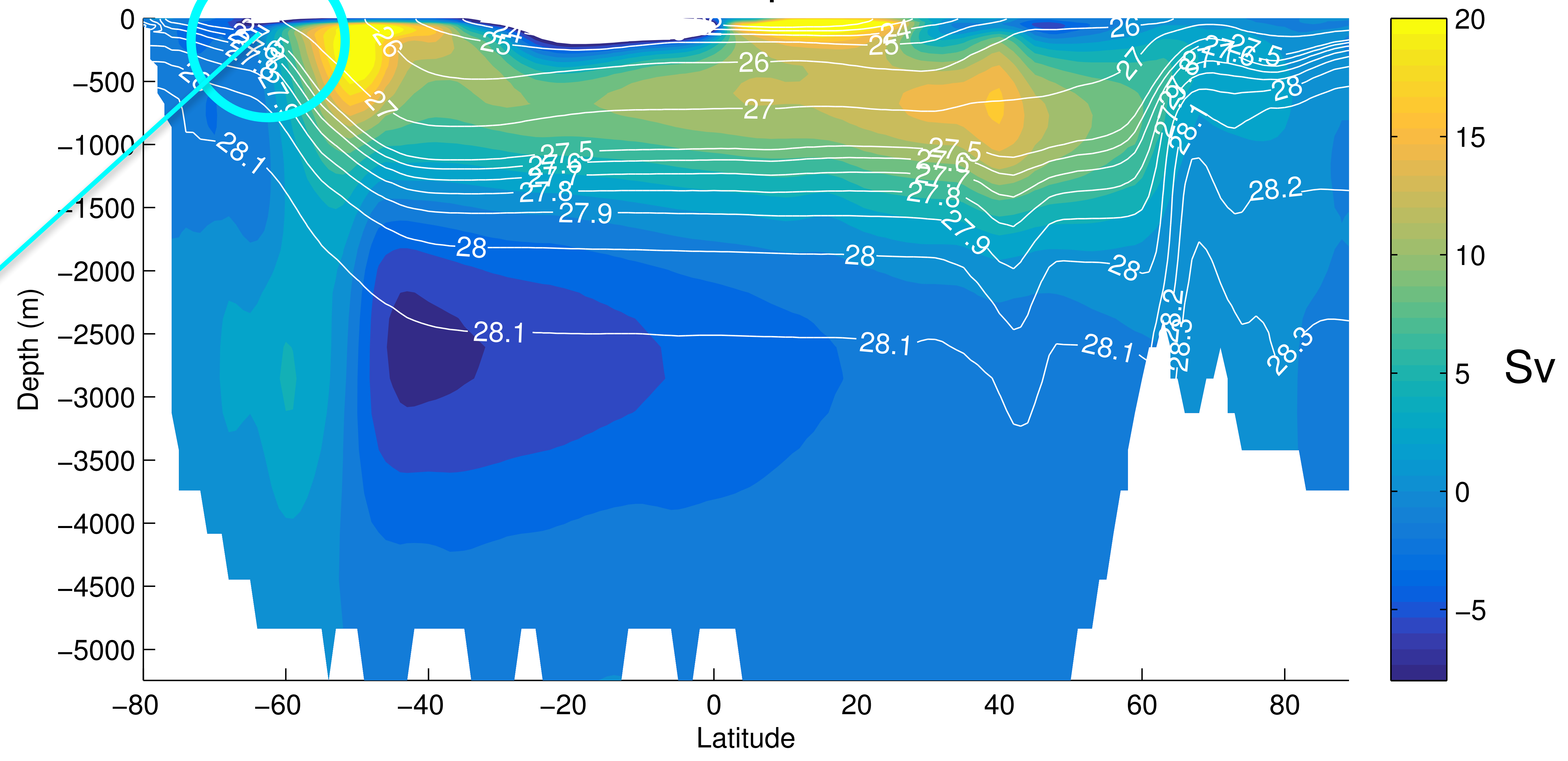
Jansen and Nadeau (2016): Buoyancy loss
around Antarctica can change abyssal watermass geometry

Ideal perturbations change the partition of surface density north and south of an outcropping isopycnal

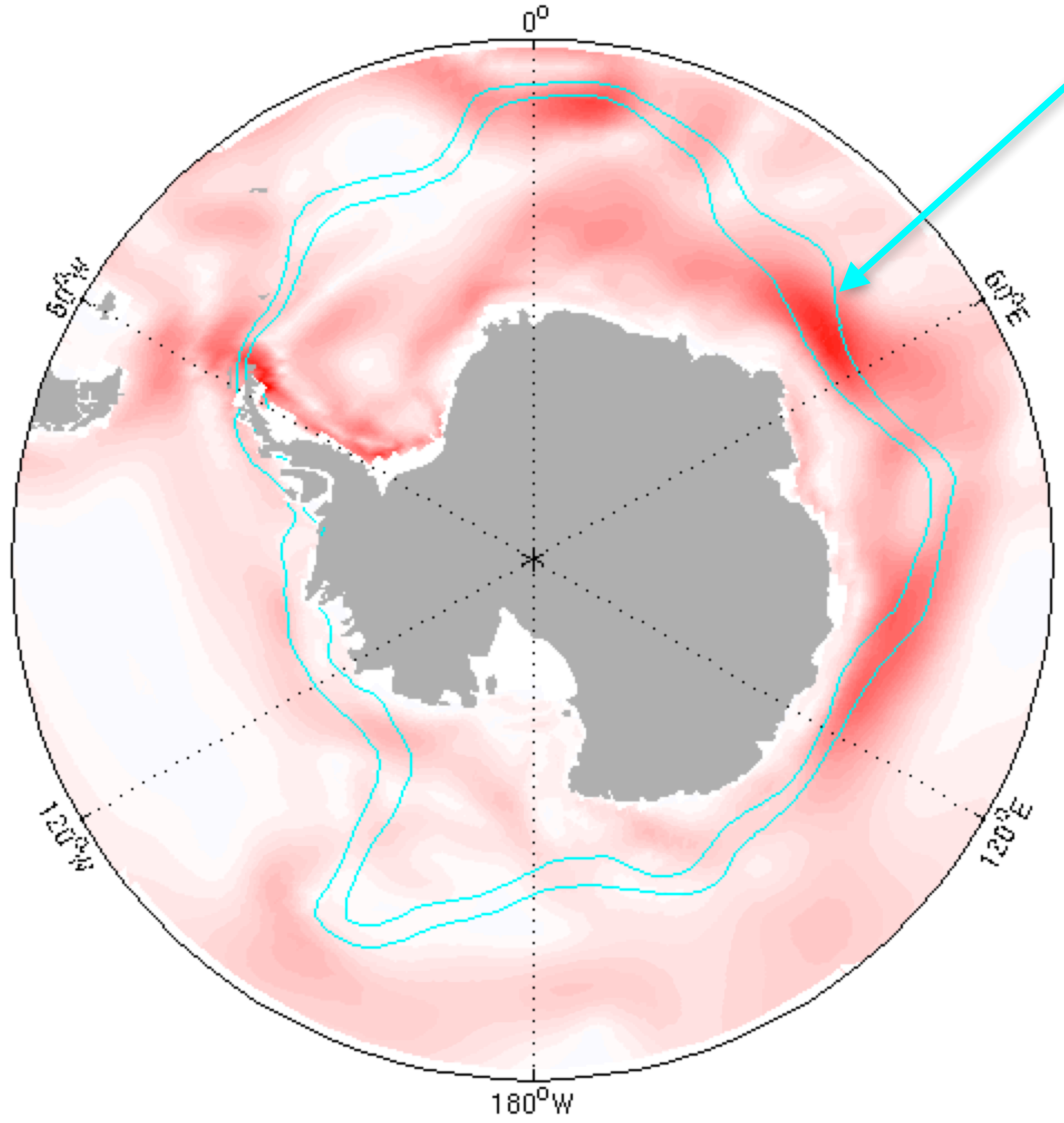


Wind stress maxima coincide with the outcropping of the isopycnal dividing upper and lower cells in the Southern Ocean

GMOC without perturbations



Wind stress amplitude



Speer (2000)

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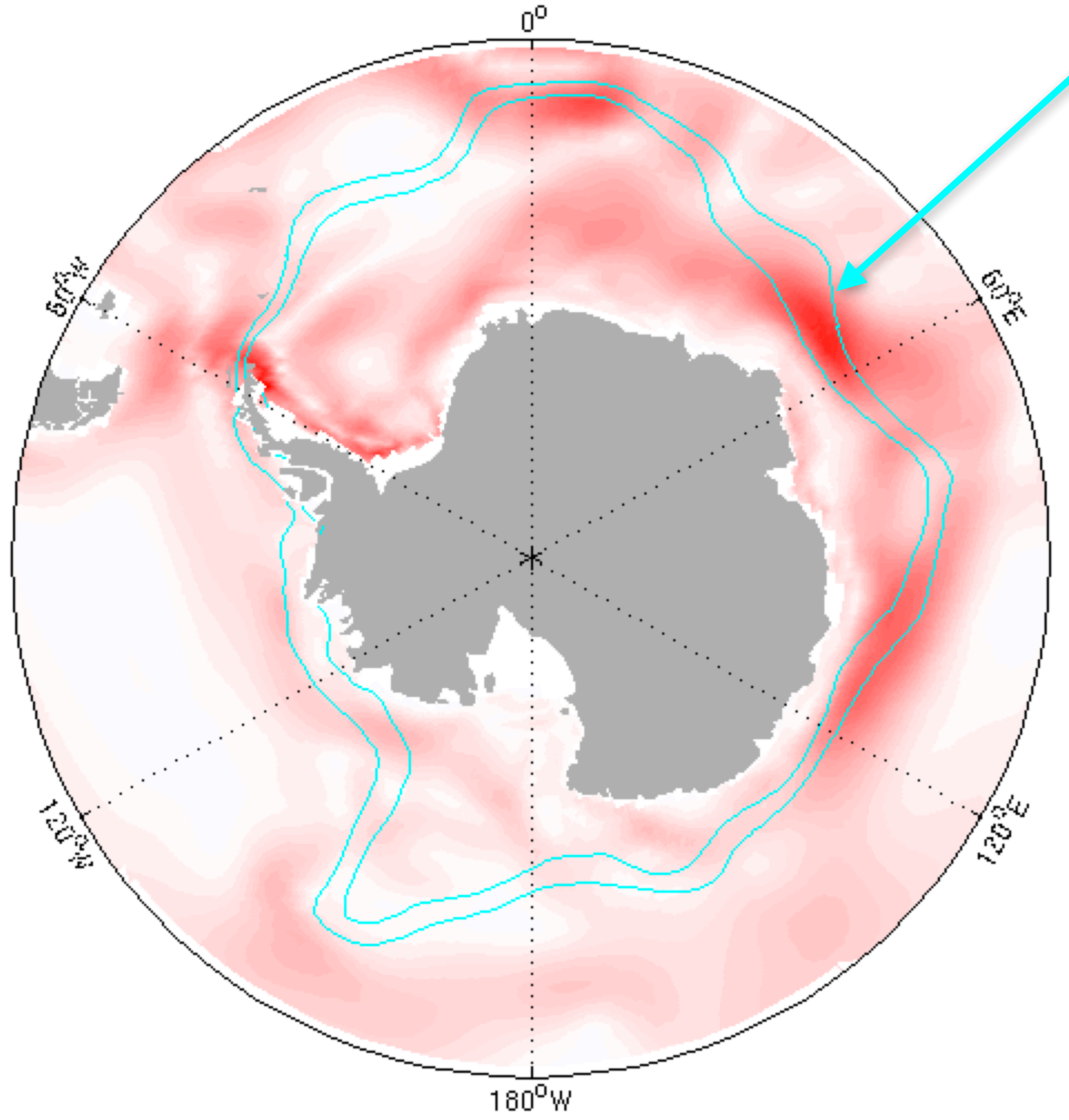

The Drake Passage Effect
(Toggweiler and Samuels 1994)

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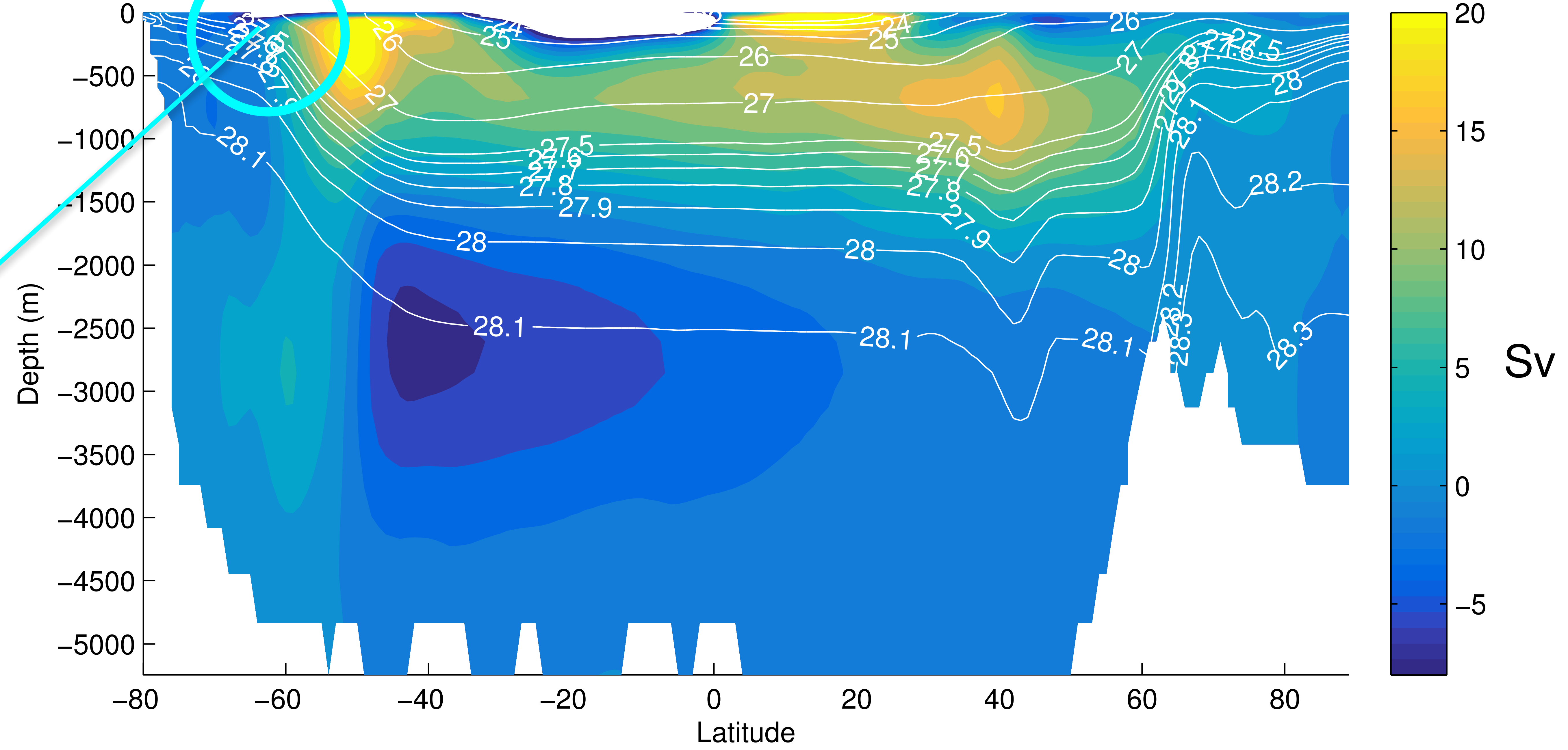

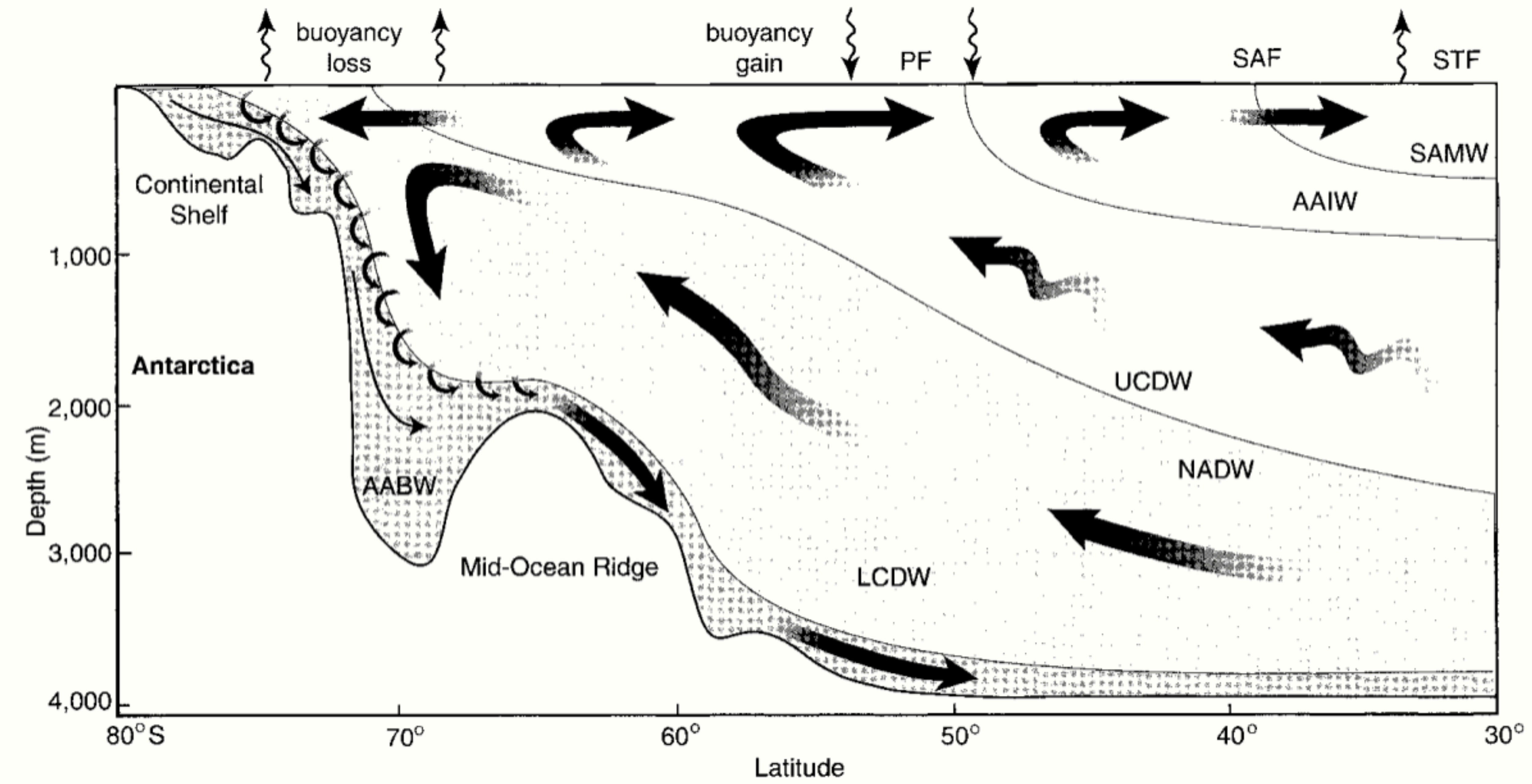

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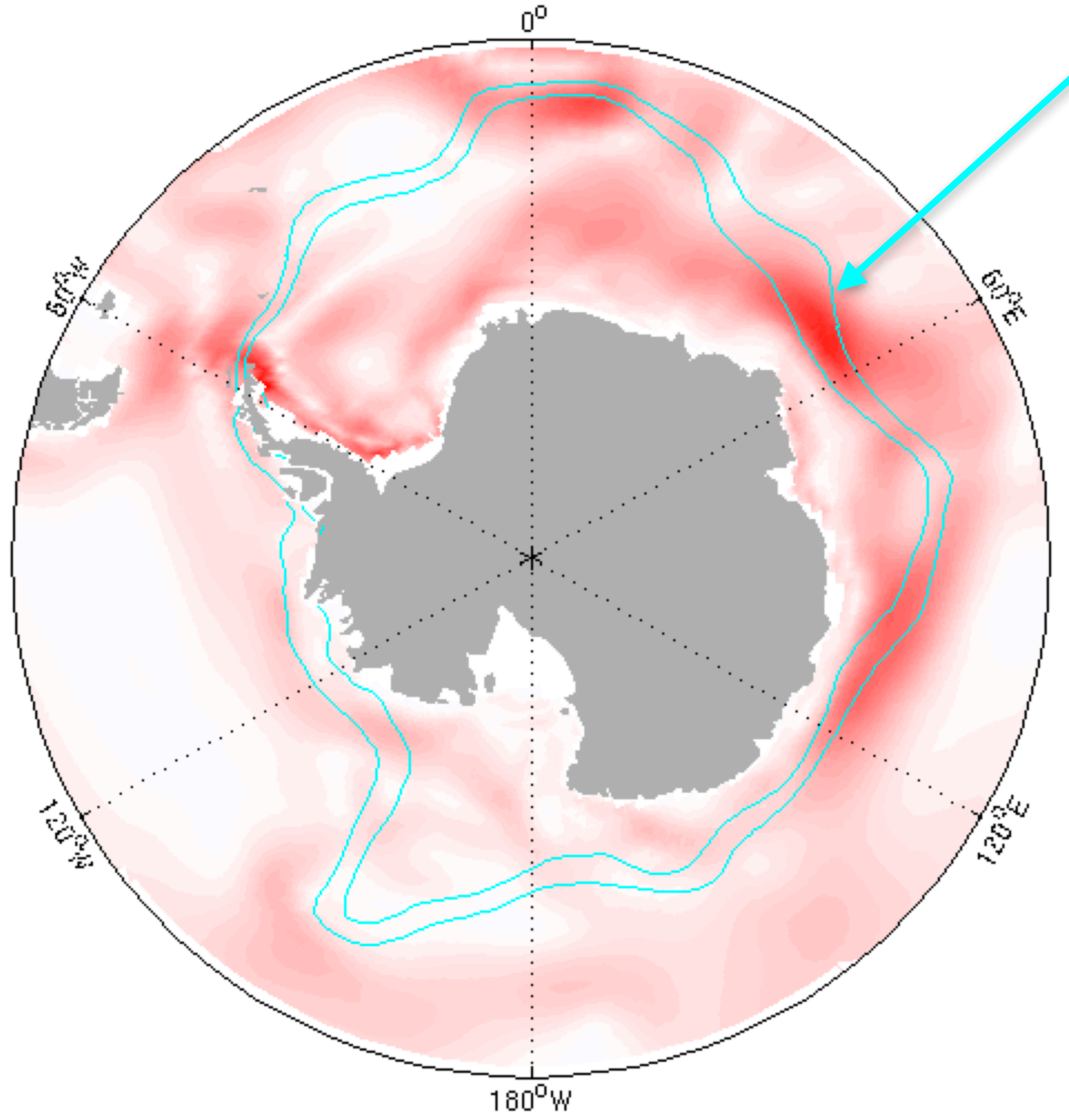

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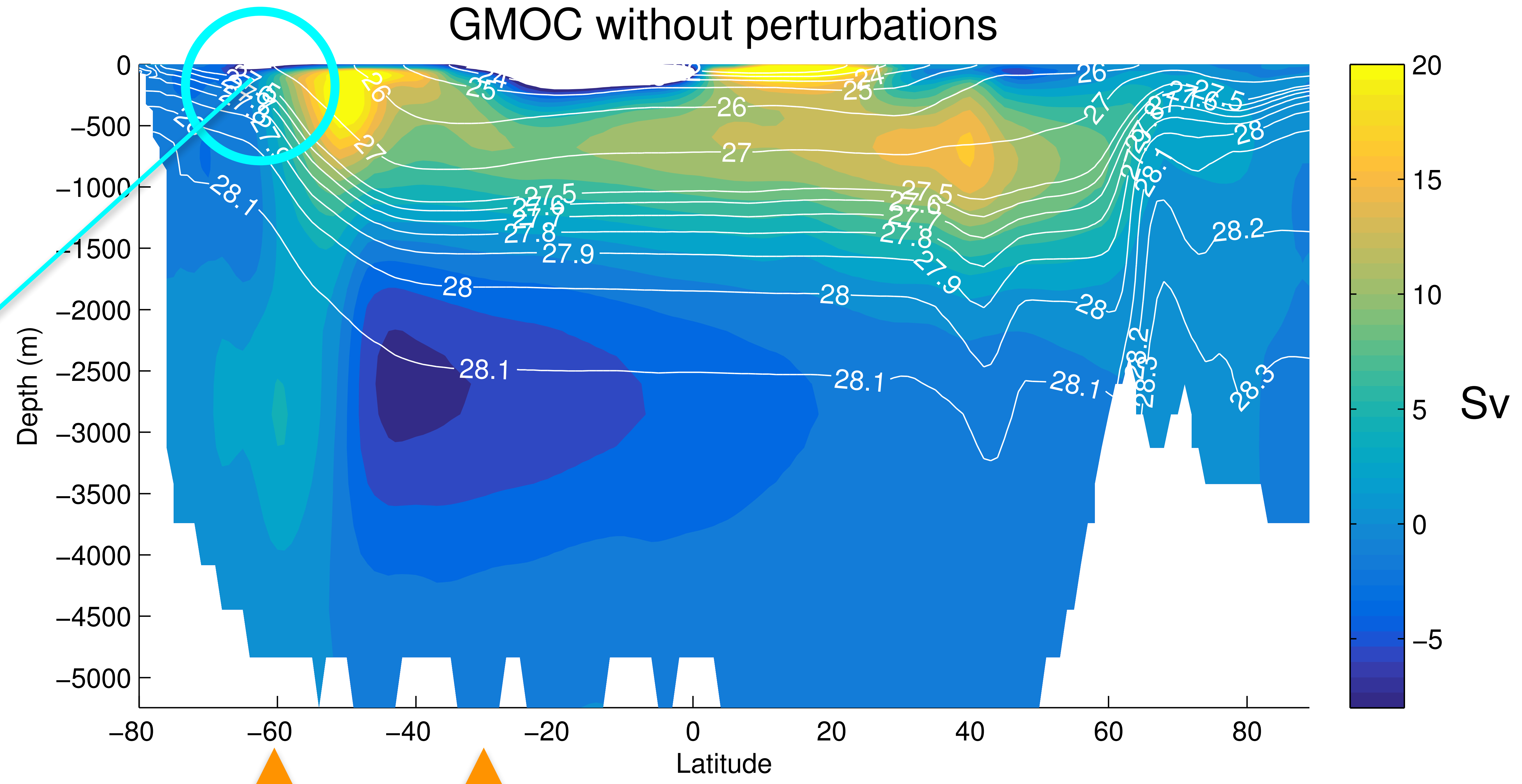
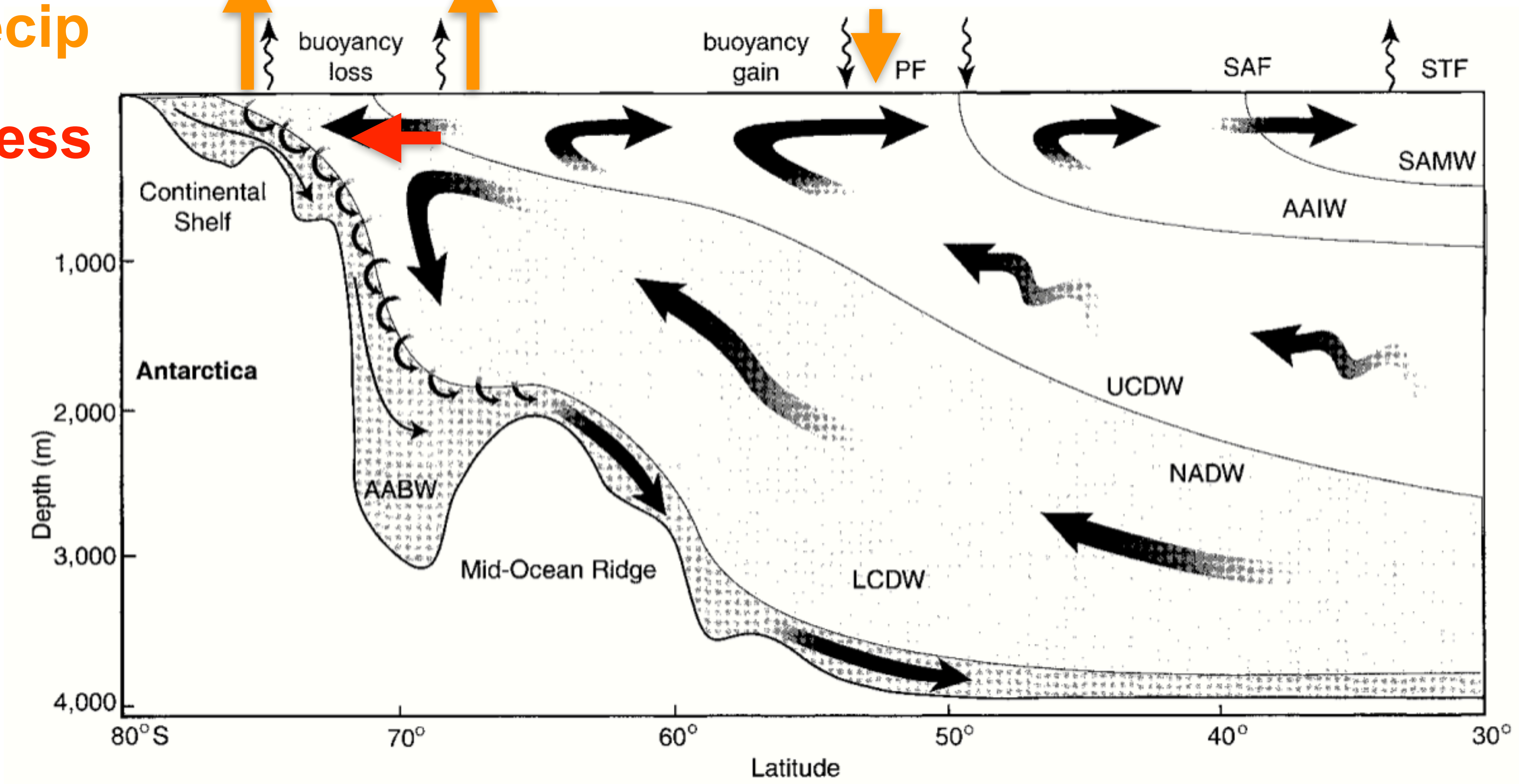


SAT, precip

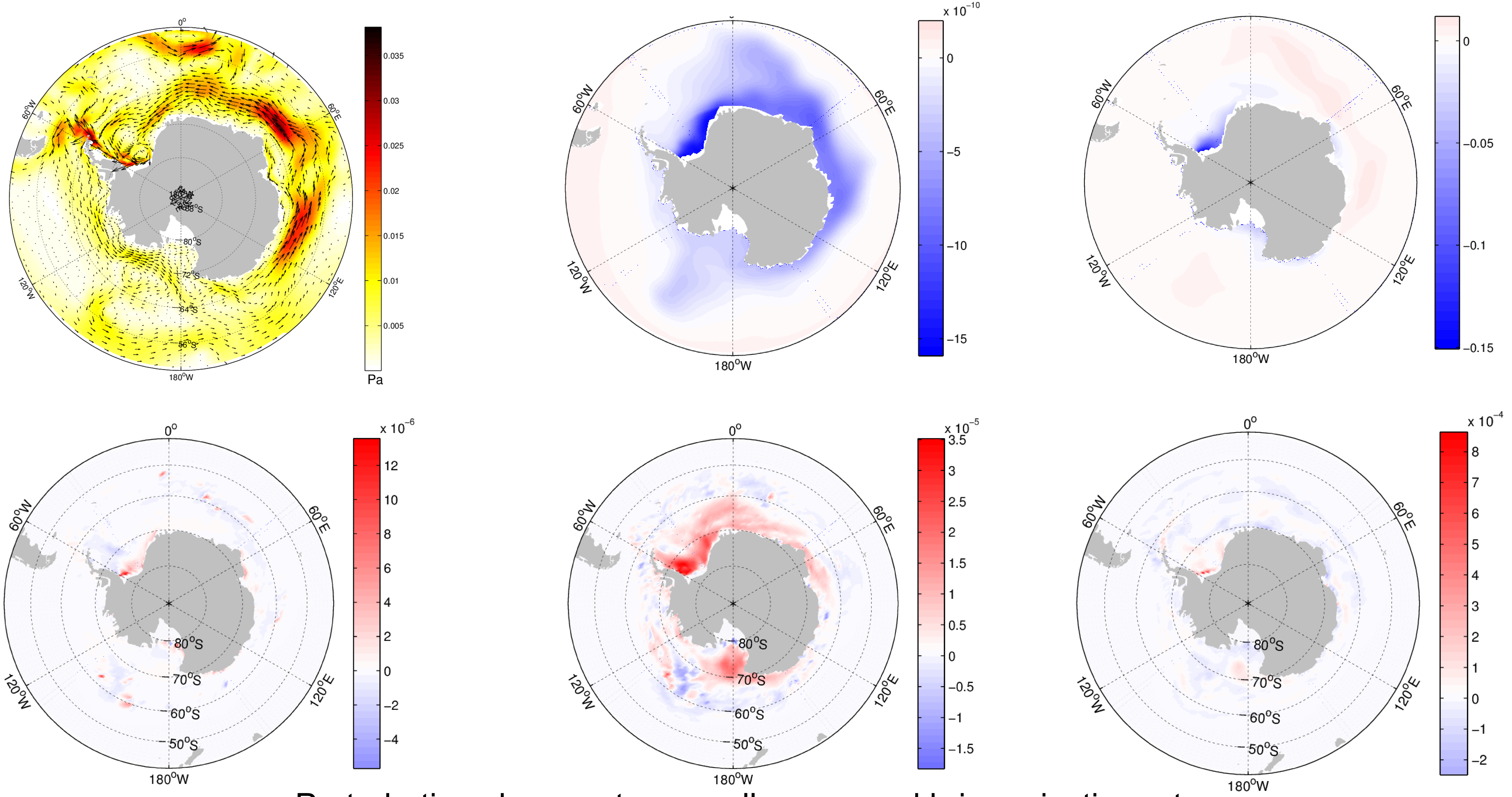
Wind stress



Speer (2000)

An intermediate role for sea ice

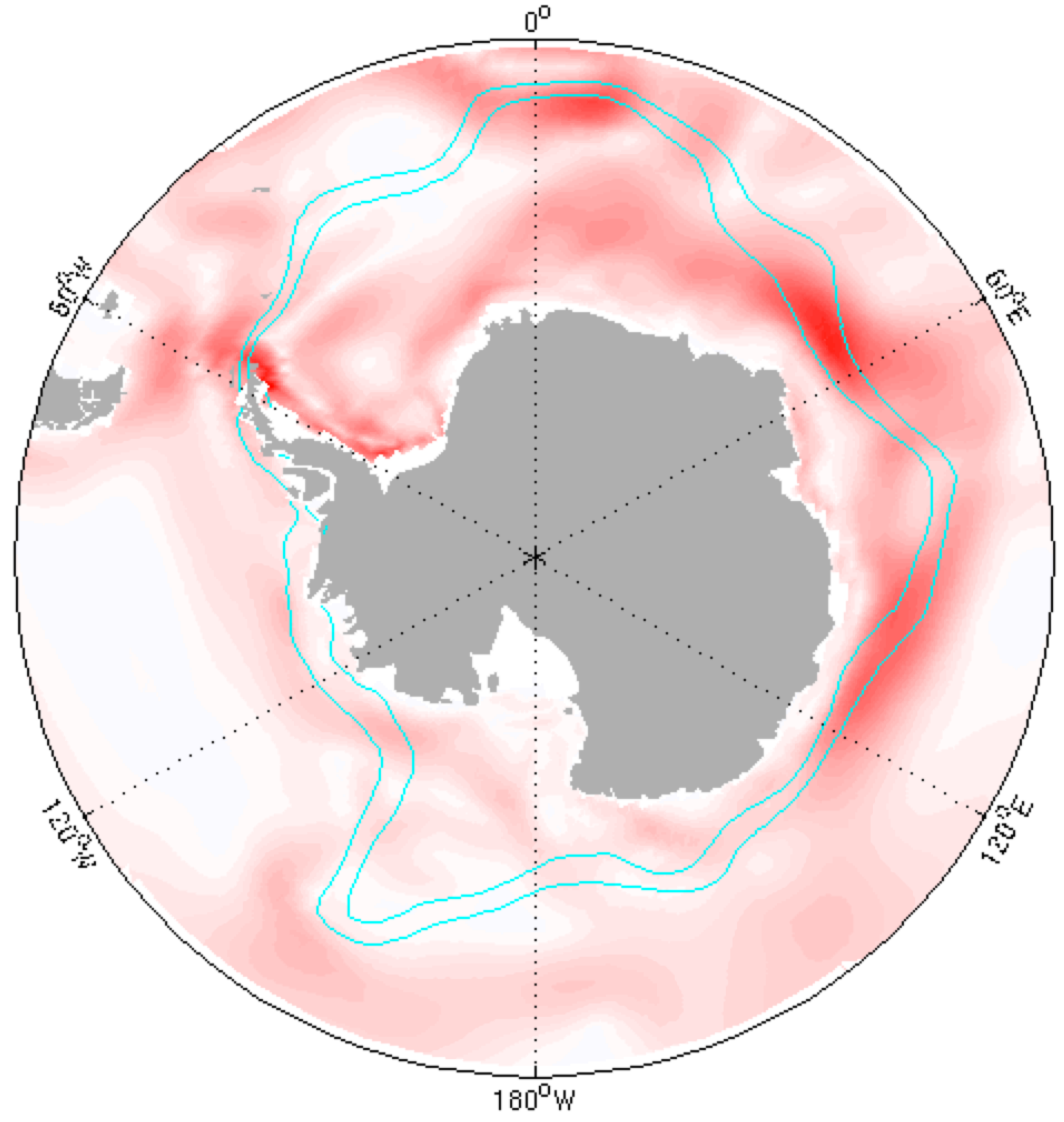
Wind stress | Precipitation | Atmos. temp



Perturbation changes to annually-averaged brine rejection rates

Conclusions

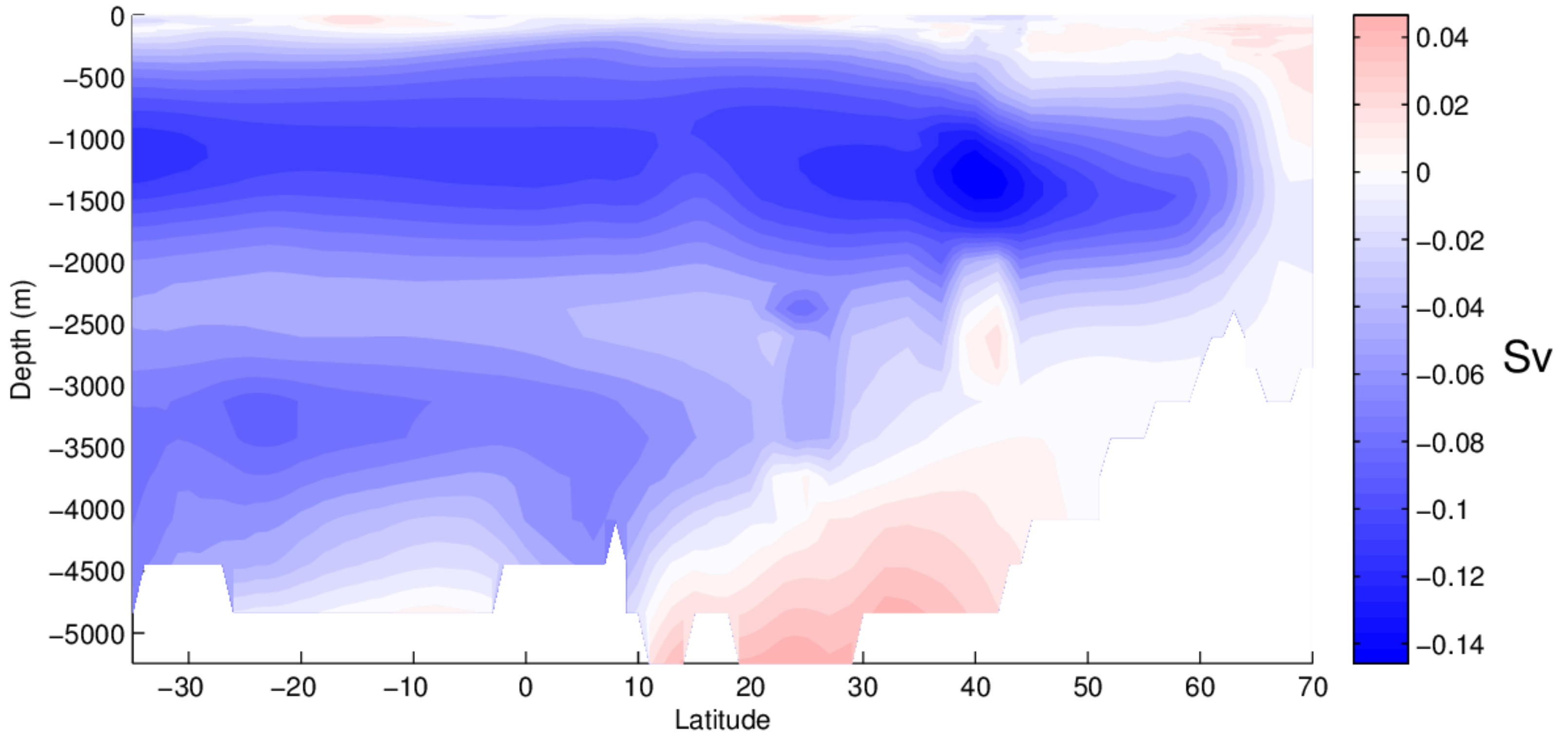
We used the MITgcm adjoint to derive changes to winds, air temperature, and precipitation that increased the presence of southern-source waters in the Atlantic.



Conclusions

We used the MITgcm adjoint to derive changes to winds, air temperature, and precipitation that increased the presence of southern-source waters in the Atlantic.

AABW increase is associated with decreased upper AMOC cell transport and increased lower cell transport, evidently caused by changes in surface water density.



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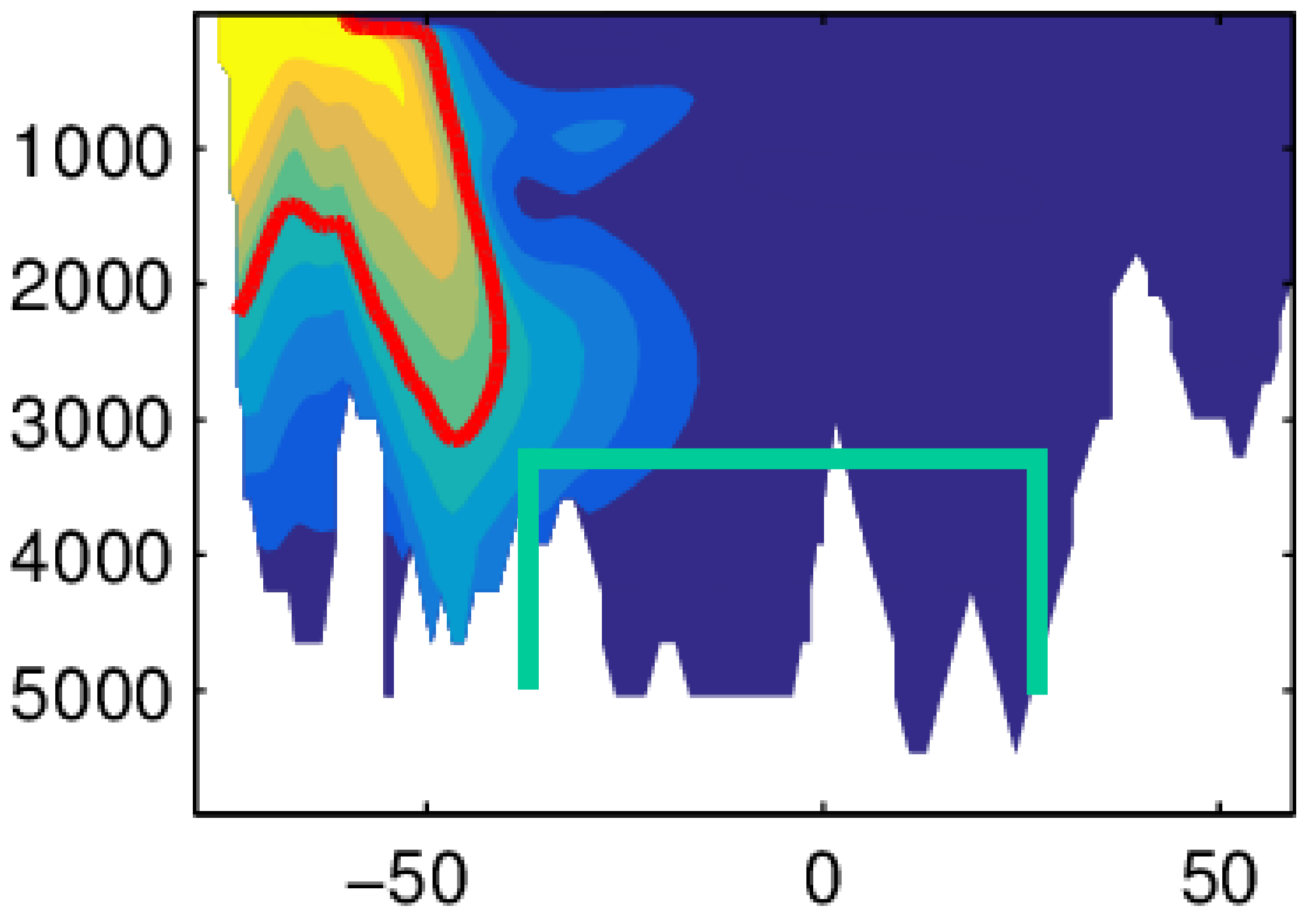
This generic approach can be applied to other paleotracers.



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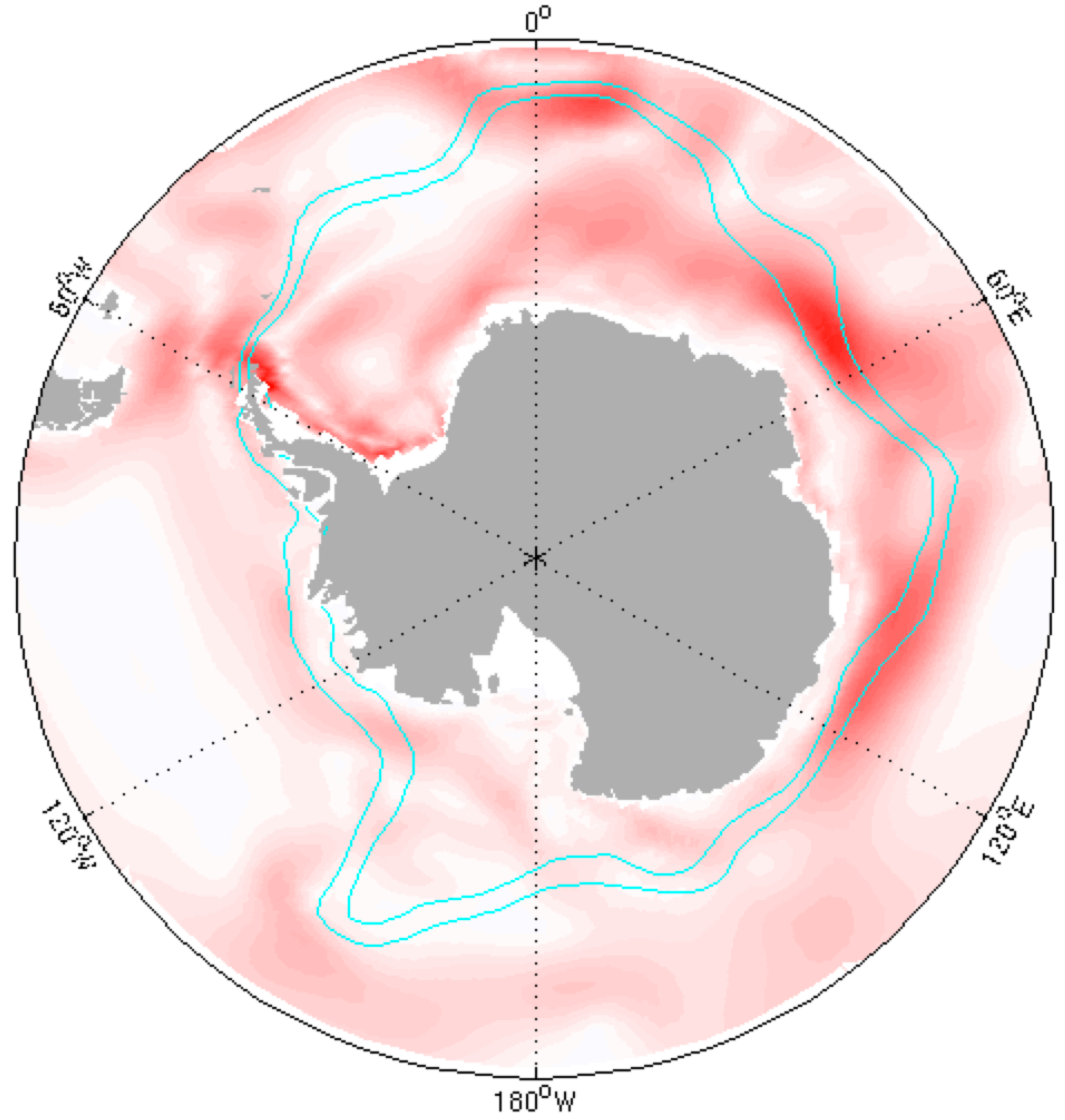
Caveats: Parameterized AABW formation, non-uniqueness, model biases



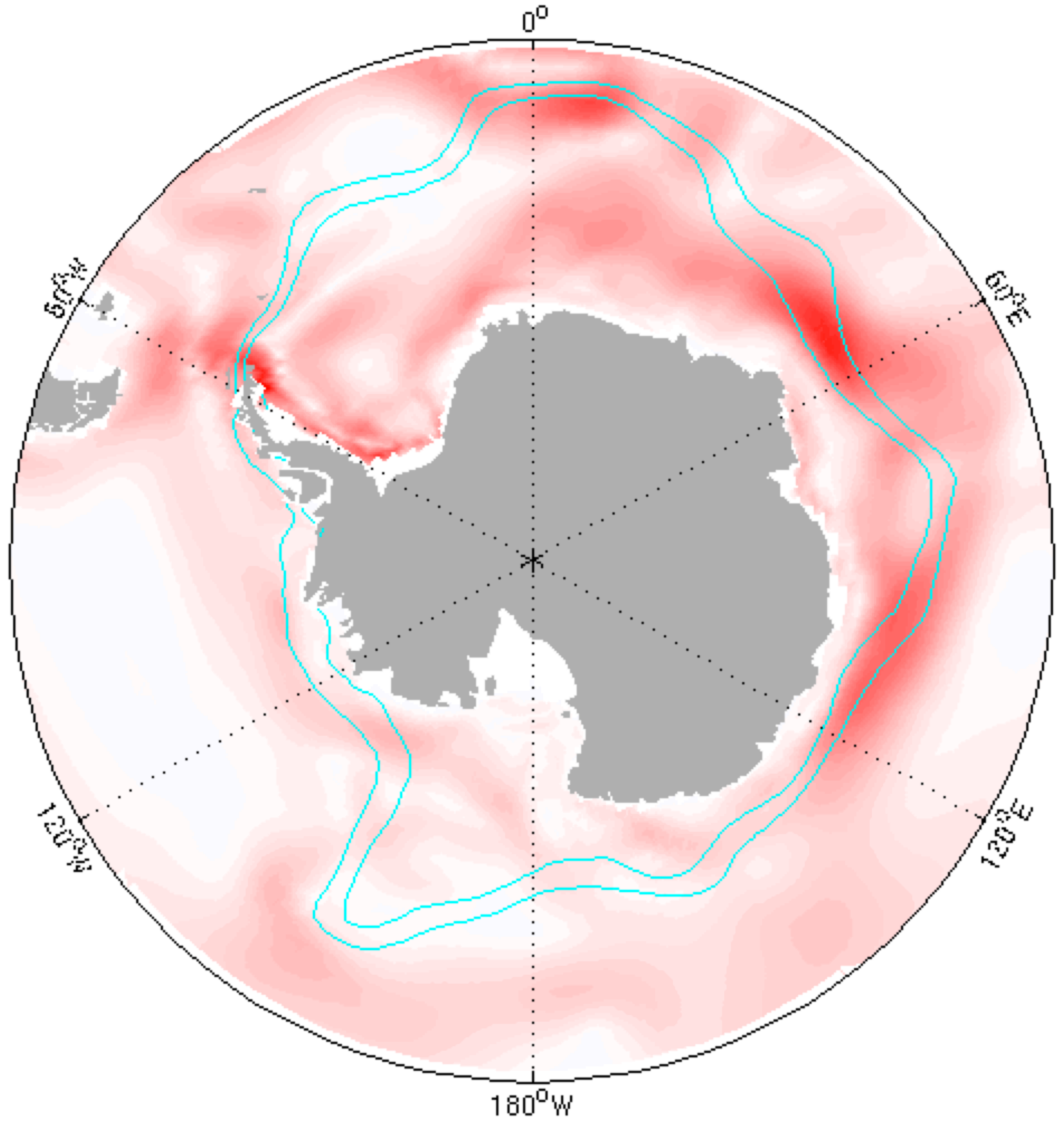
Next steps

Assess zonal asymmetries in wind and temperature sensitivities

How might an LGM atmosphere project onto these patterns?

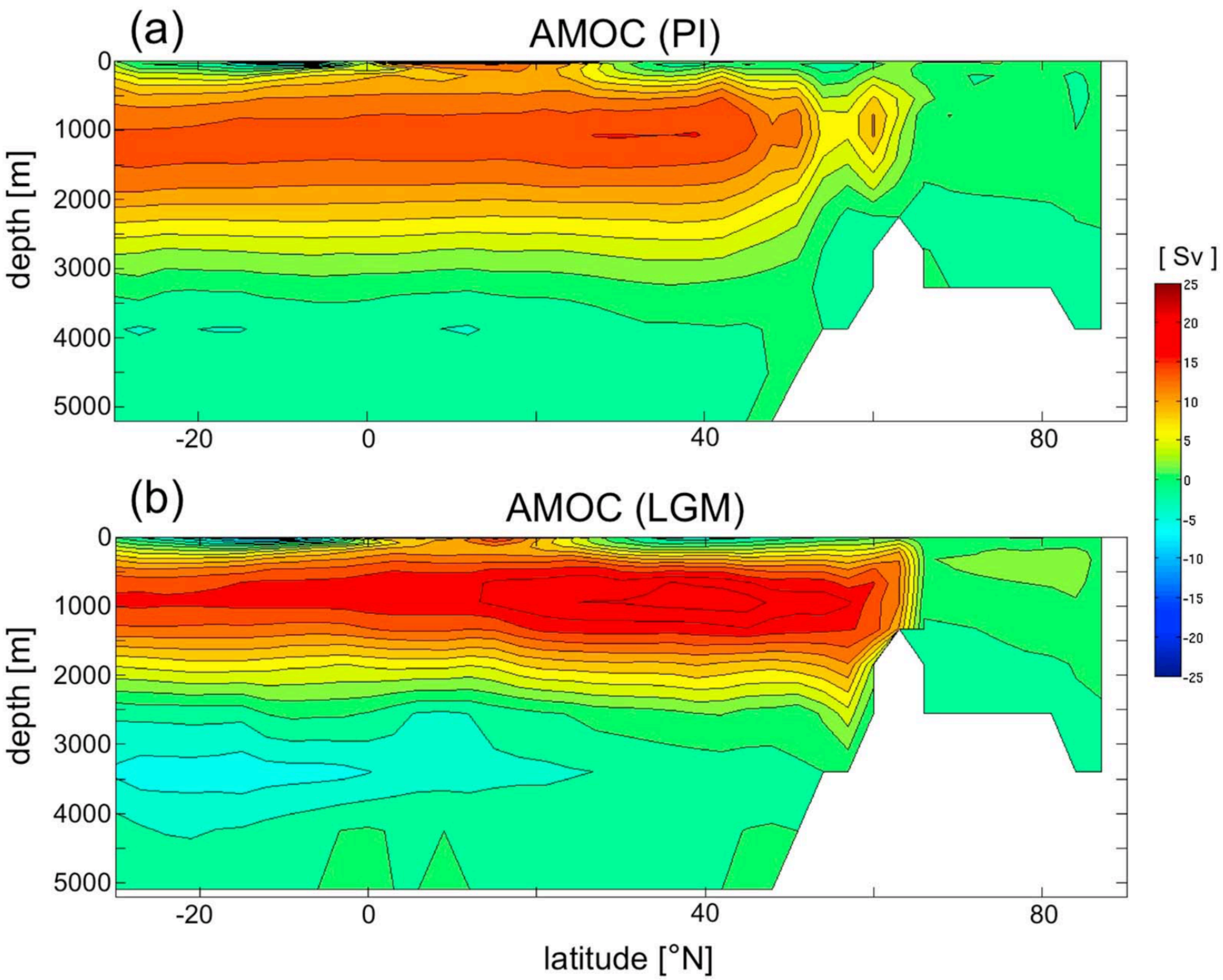
How can we distinguish between mechanisms of southern-source water shoaling at the LGM? (Why does it matter?)

Some form of coupled ocean-atmosphere inverse modeling is ultimately essential for paleo problems.



Abyssal circulation: Stronger, deeper upper AMOC cell at LGM?

LGM state estimate
(Kurahashi-Nakamura et al. 2017)



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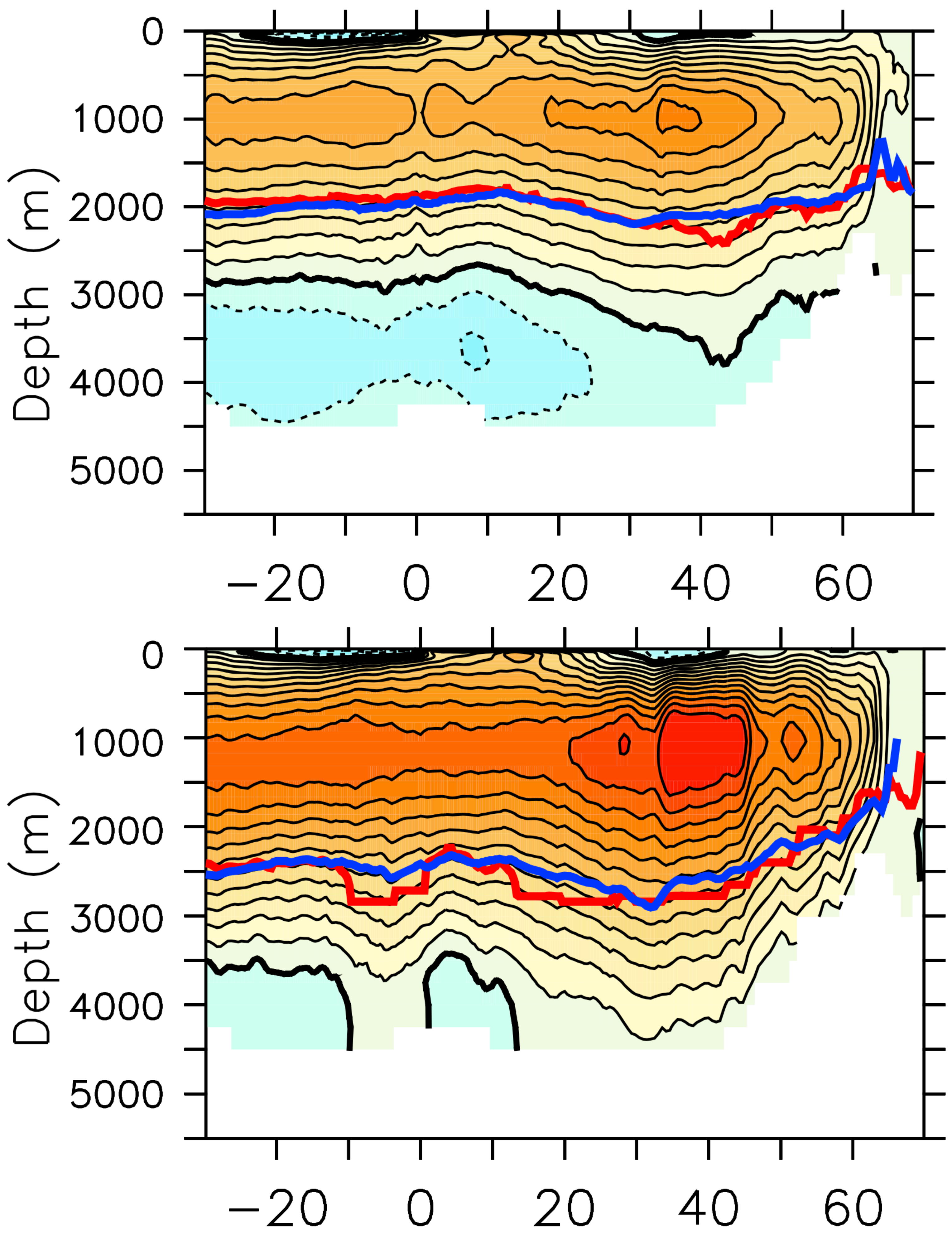
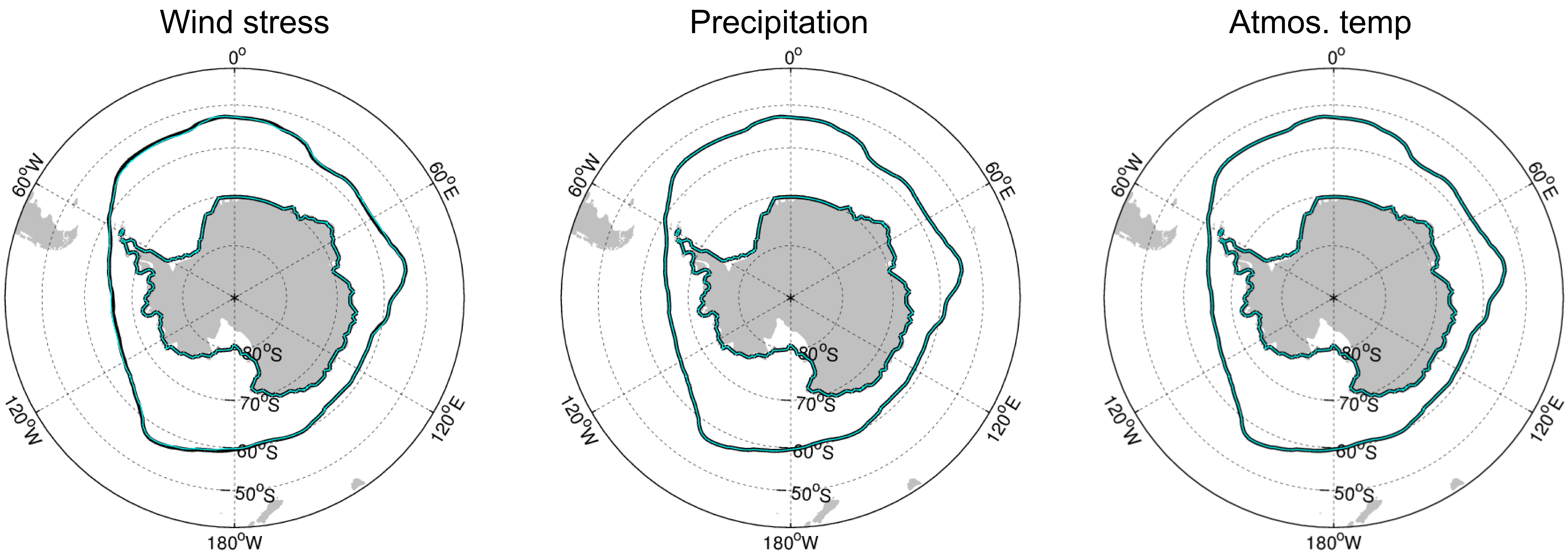


Muglia and Schmittner (2015)

Sea ice extent changes



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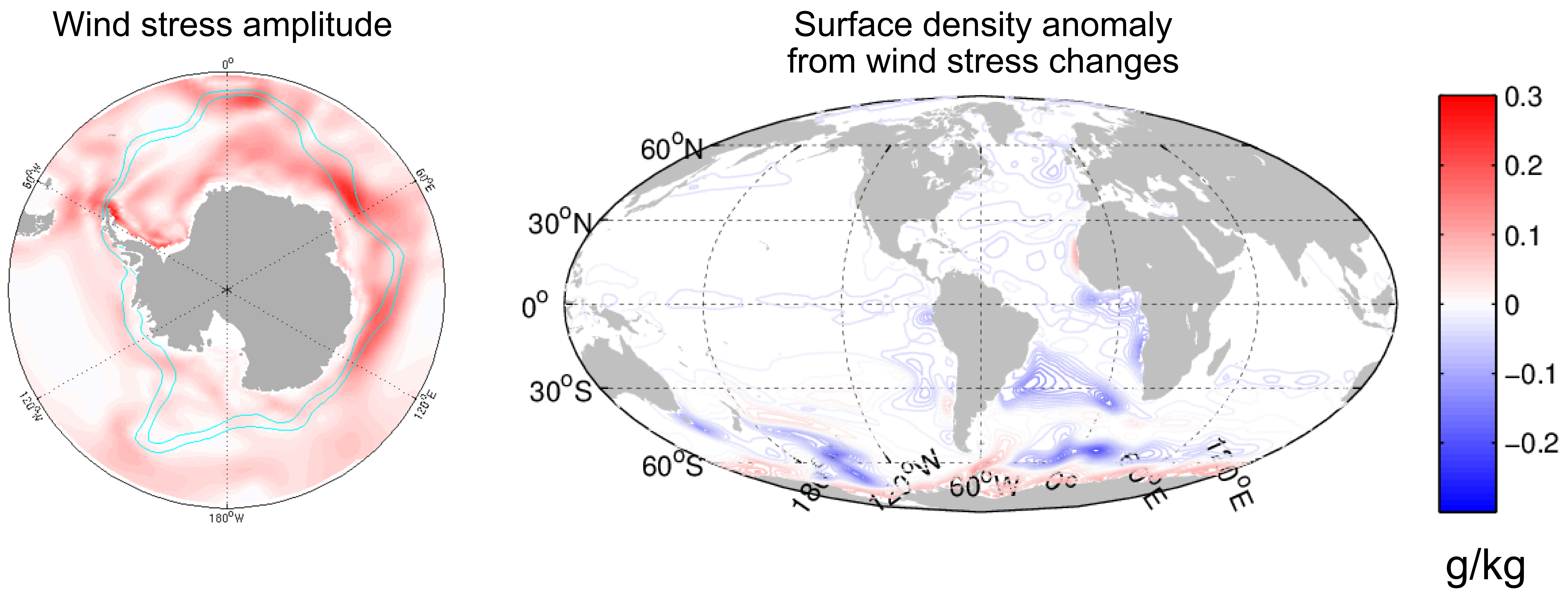
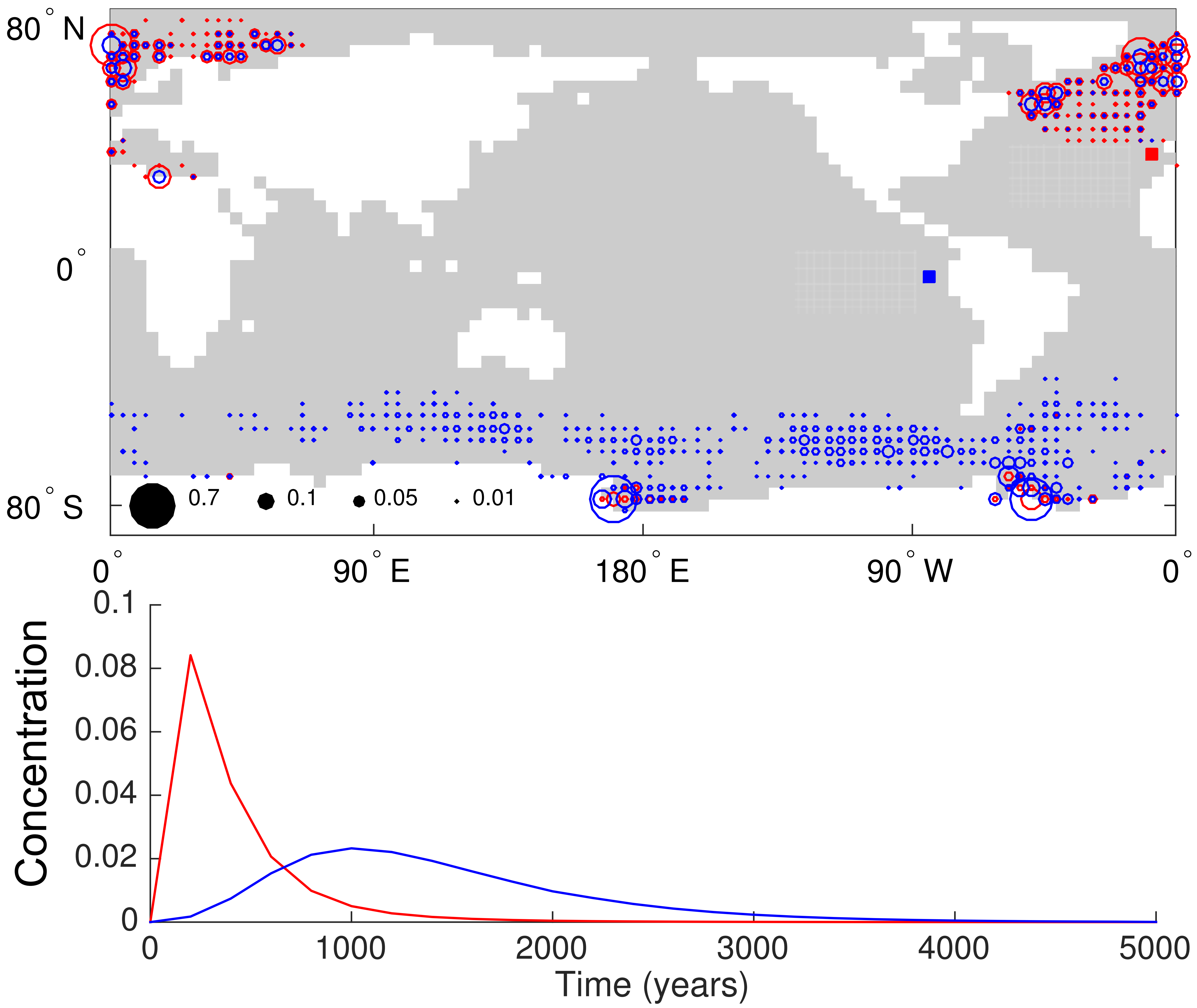


Extrapolating to tracer equilibrium: A motivating observation

Leading EOF / PC pairs representing two adjoint Green's functions capturing >90% of variance *(Amrhein et al. 2015)*

The relative contributions of surface locations to ventilating the abyss appear to be approximately constant.



Extrapolating to tracer equilibrium

$C(t)$	Tracer concentration
V	Total grid box volume
$v_v(t)$	Volume ventilated since t_0
$v_u(t)$	Volume not ventilated since t_0
$c_v(t)$	Concentration of ventilated volume
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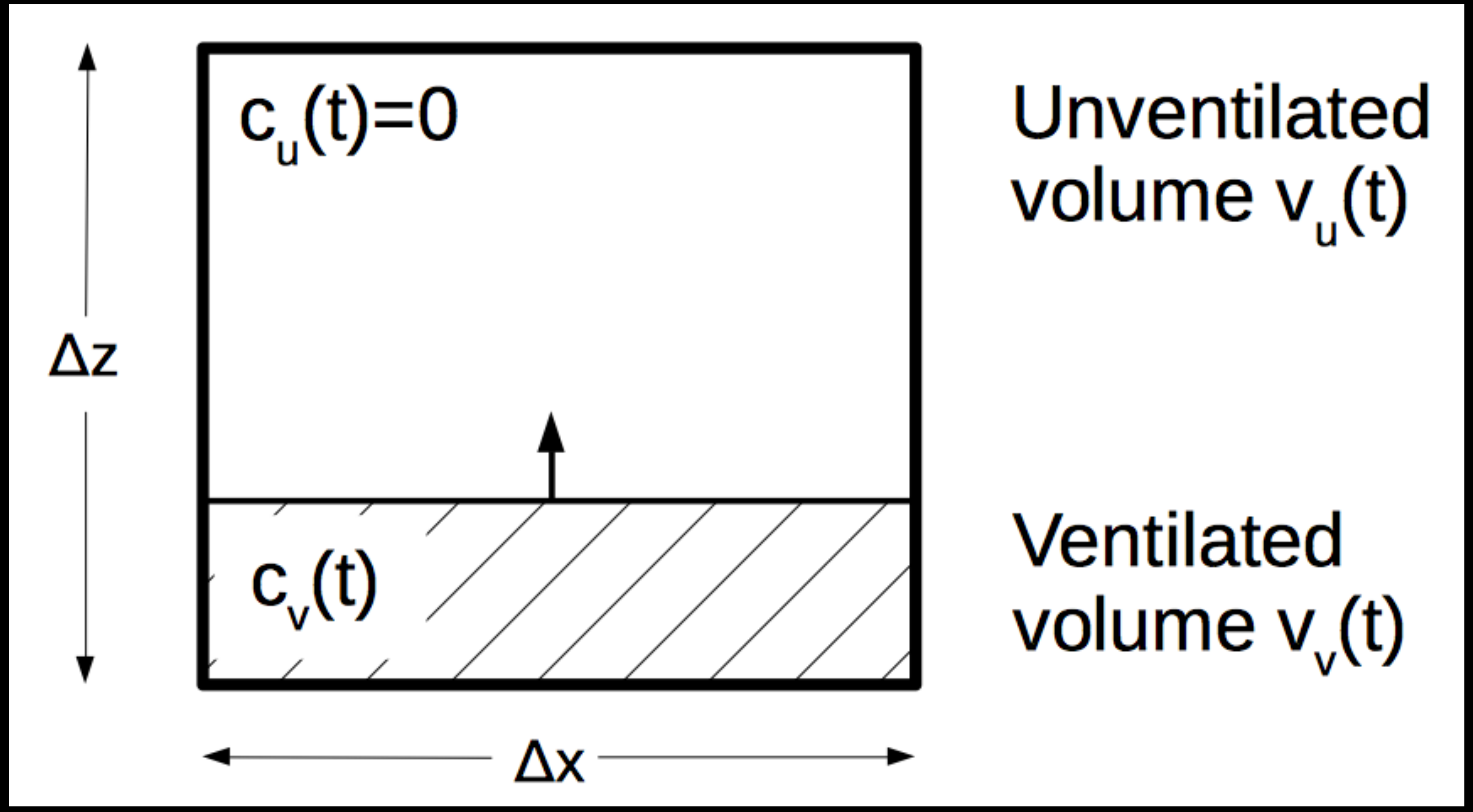

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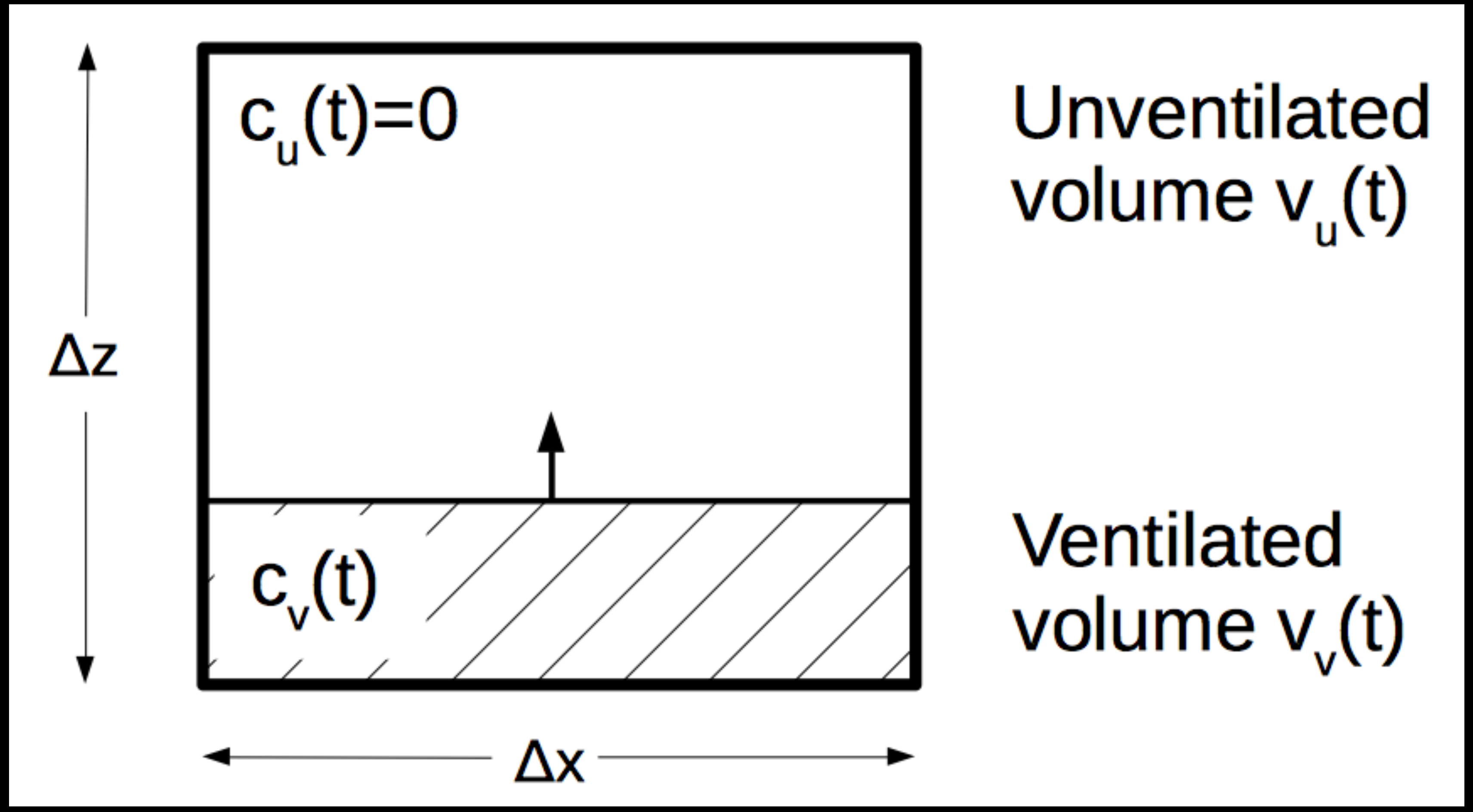

$$C\left(t\right)=\frac{v_v\left(t\right)c_v\left(t\right)+v_u\left(t\right)c_u\left(t\right)}{V}$$

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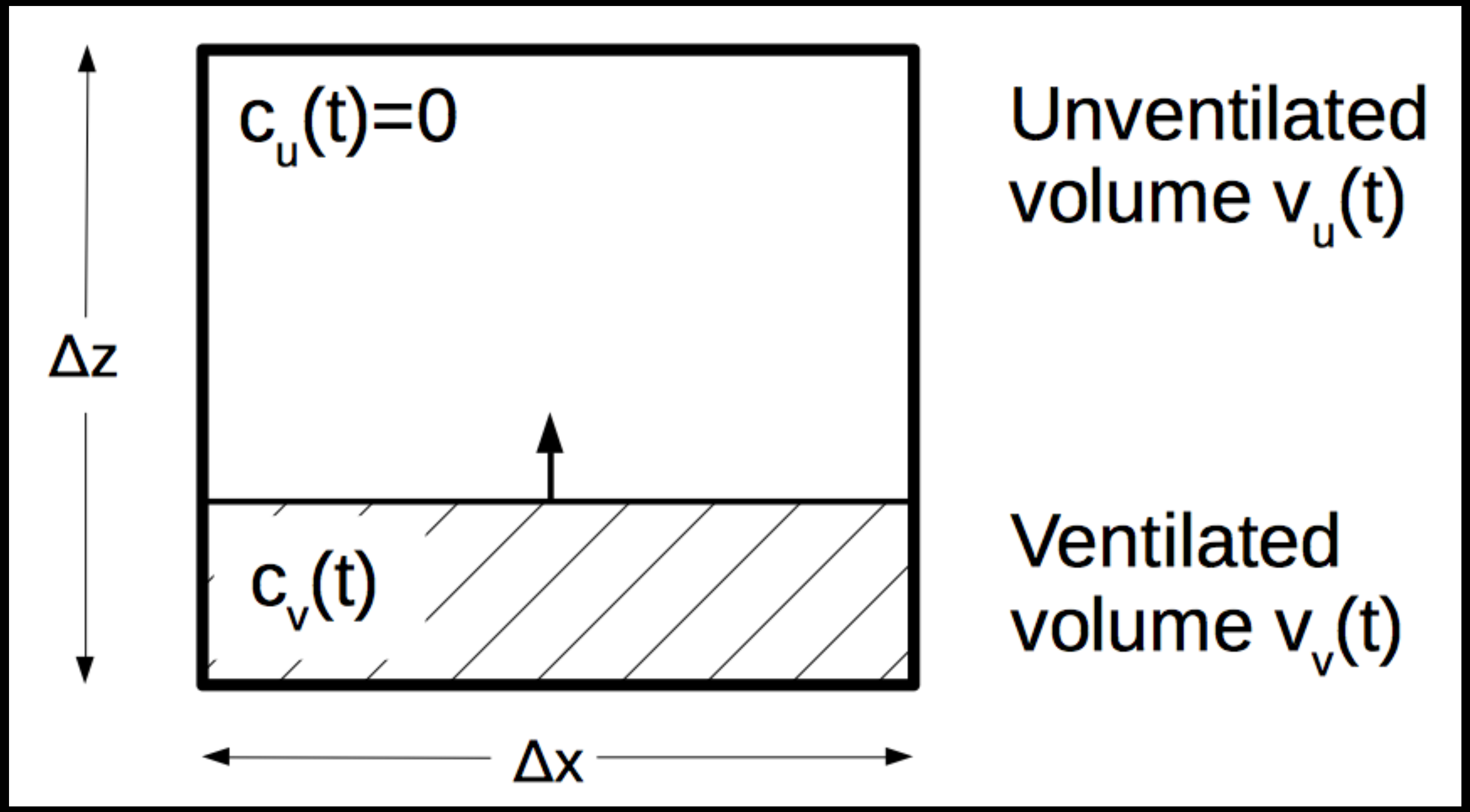

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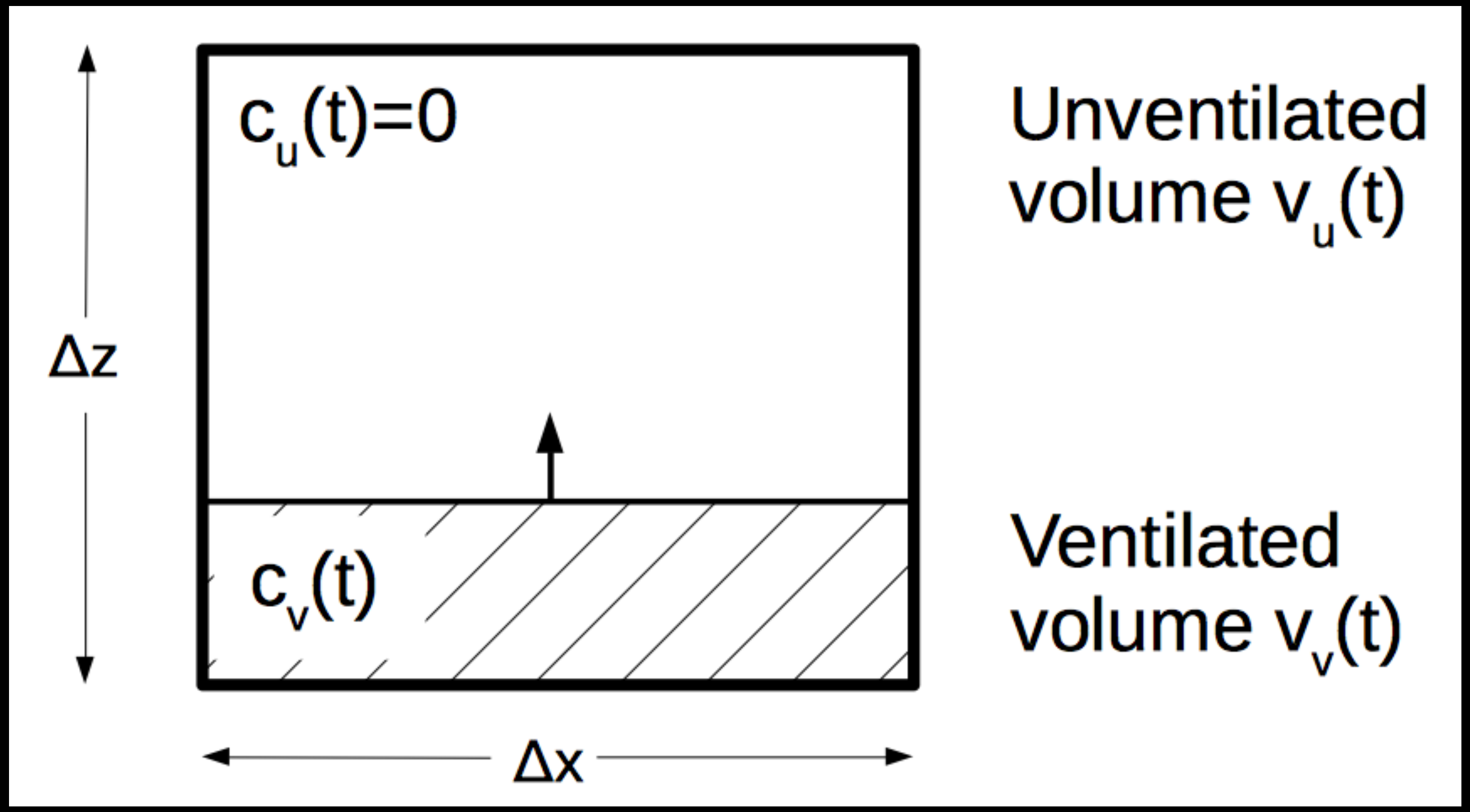

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$$c_v\left(t\right)=\frac{V}{v_v\left(t\right)}C\left(t\right)$$

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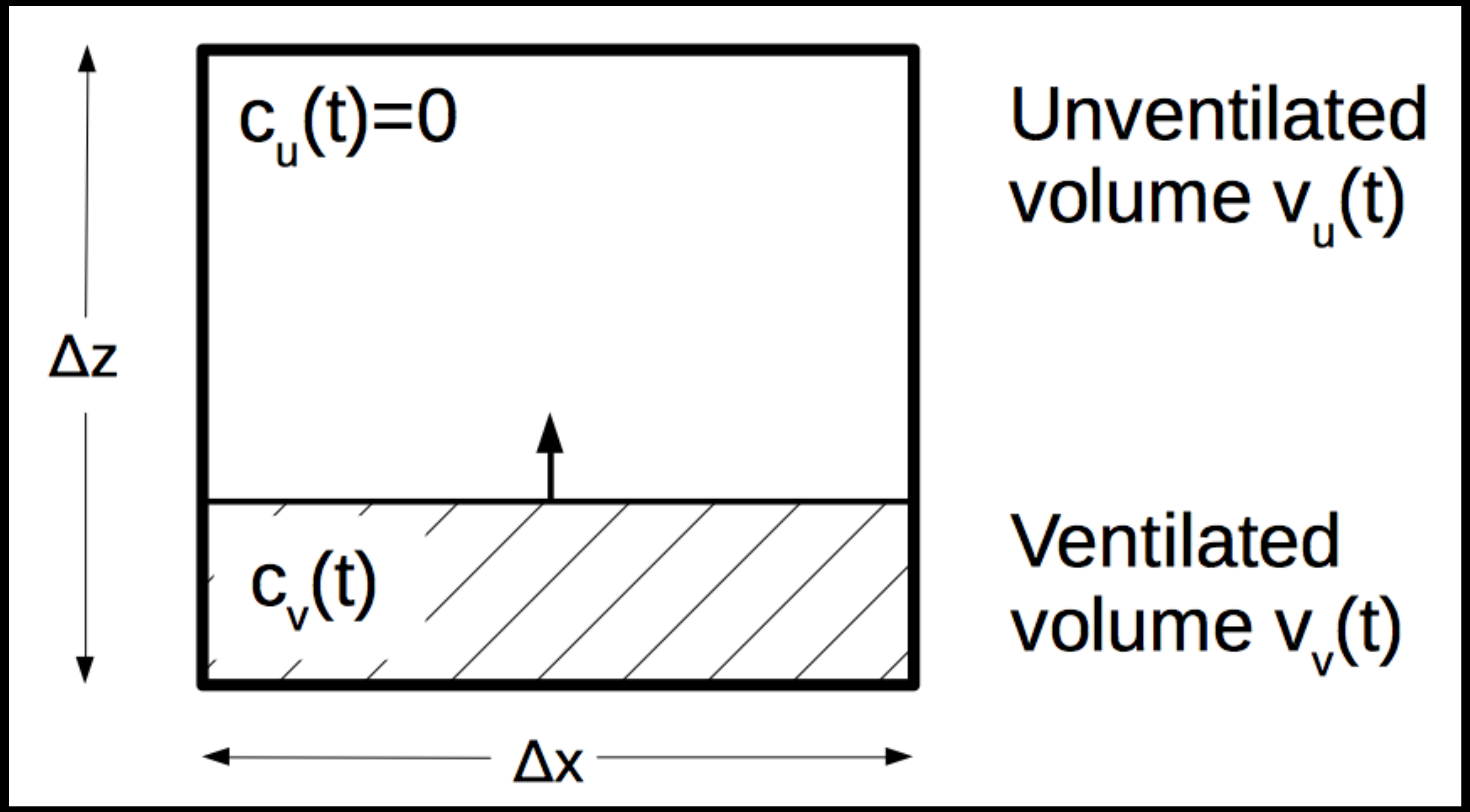

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$$\tilde{C}_\infty\left(t\right) = c_v\left(t\right) = \frac{V}{v_v\left(t\right)}C\left(t\right)$$

Extrapolating to tracer equilibrium

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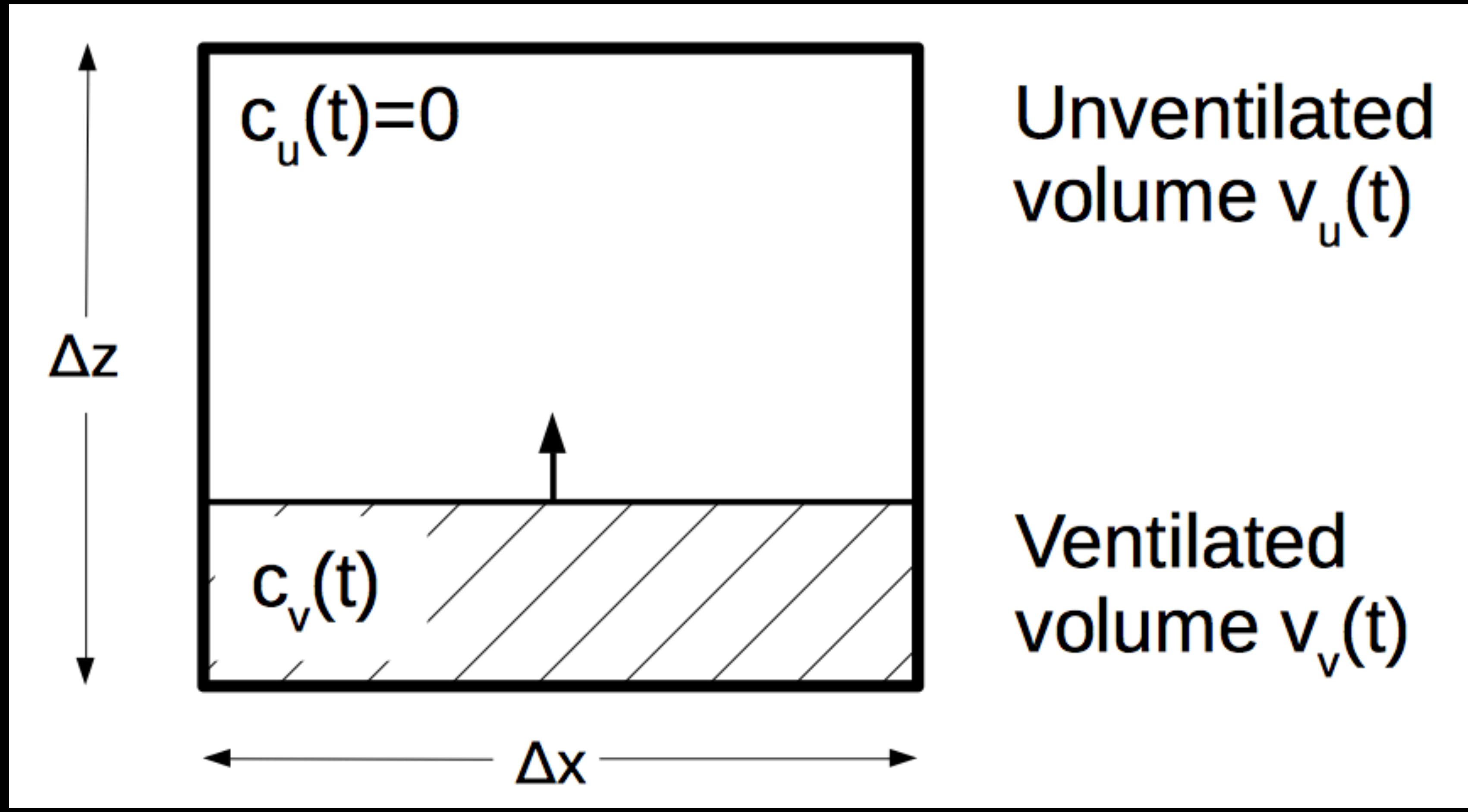
V	Total grid box volume
$v_v(t)$	Volume ventilated since t_0
$v_u(t)$	Volume not ventilated since t_0
$c_v(t)$	Concentration of ventilated volume
$c_u(t)$	Concentration of unventilated volume



$$C(t) = \frac{v_v(t)\, c_v(t) + \cancel{v_u(t)\, c_u(t)}}{V}$$

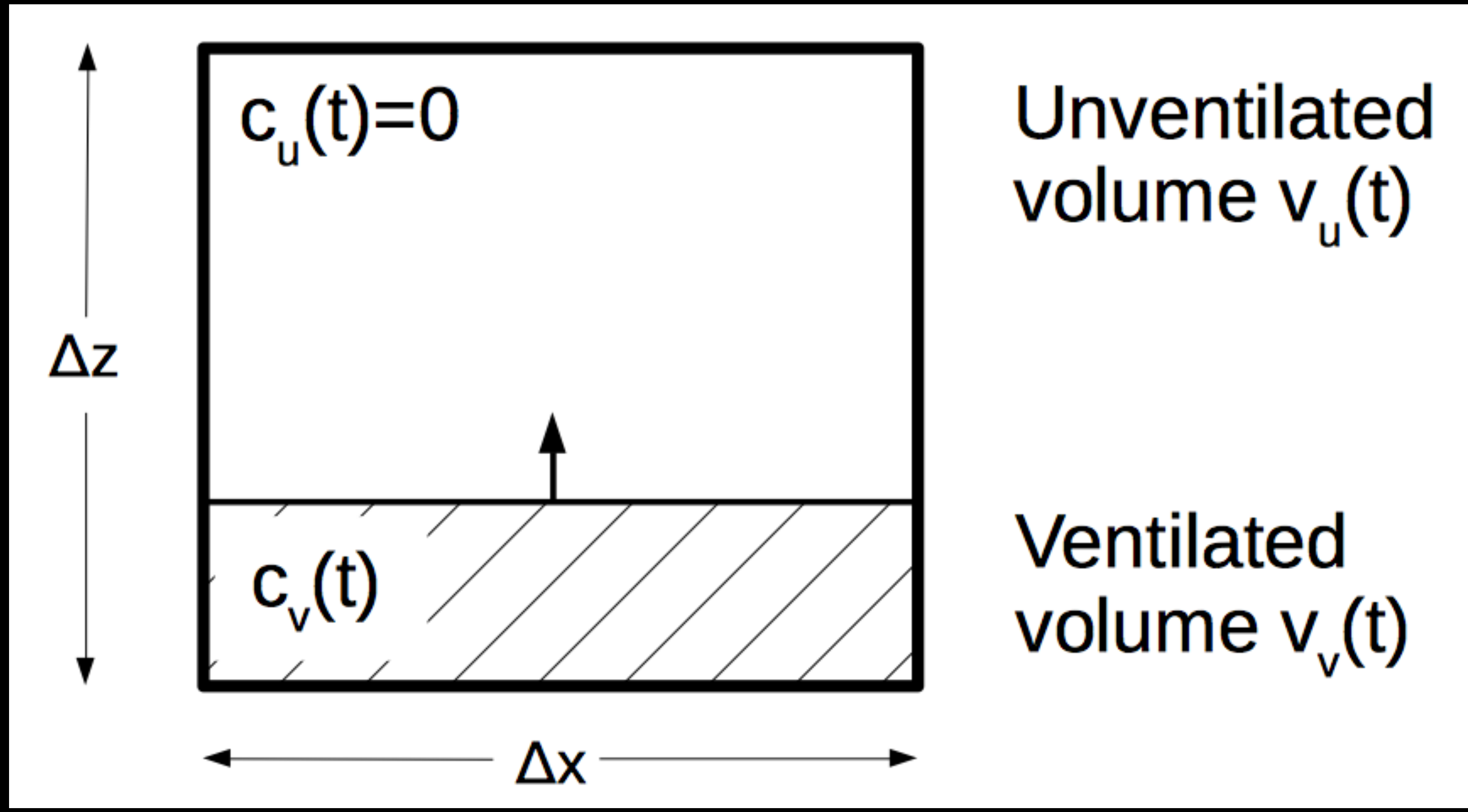
$$\tilde{C}_\infty(t) = c_v(t) = \frac{V}{v_v(t)} C(t)$$

C^h Concentration of “helper” tracer with the property $c_v(t) = 1$

$$C^h(t) = \frac{v_v(t)}{V}$$

Extrapolating to tracer equilibrium

$C(t)$	Tracer concentration
V	Total grid box volume
$v_v(t)$	Volume ventilated since t_0
$v_u(t)$	Volume not ventilated since t_0
$c_v(t)$	Concentration of ventilated volume
$c_u(t)$	Concentration of unventilated volume



$$C\left(t\right) = \frac{v_v\left(t\right) c_v\left(t\right) + \cancel{v_u\left(t\right) c_u\left(t\right)}}{V}$$

$$\tilde{C}_\infty\left(t\right) = c_v\left(t\right) = \frac{V}{v_v\left(t\right)} C\left(t\right)$$

C^h Concentration of "helper" tracer with the property $c_v(t) = 1$

$$C^h\left(t\right) = \frac{v_v\left(t\right)}{V}$$

Estimate of equilibrium concentration made at time *t*

$$\tilde{C}_\infty\left(t\right) = c_v\left(t\right) = \frac{C\left(t\right)}{C^h\left(t\right)}$$

Extrapolating to tracer equilibrium

$C(t)$	Tracer concentration
V	Total grid box volume
$v_v(t)$	Volume ventilated since t_0
$v_u(t)$	Volume not ventilated since t_0
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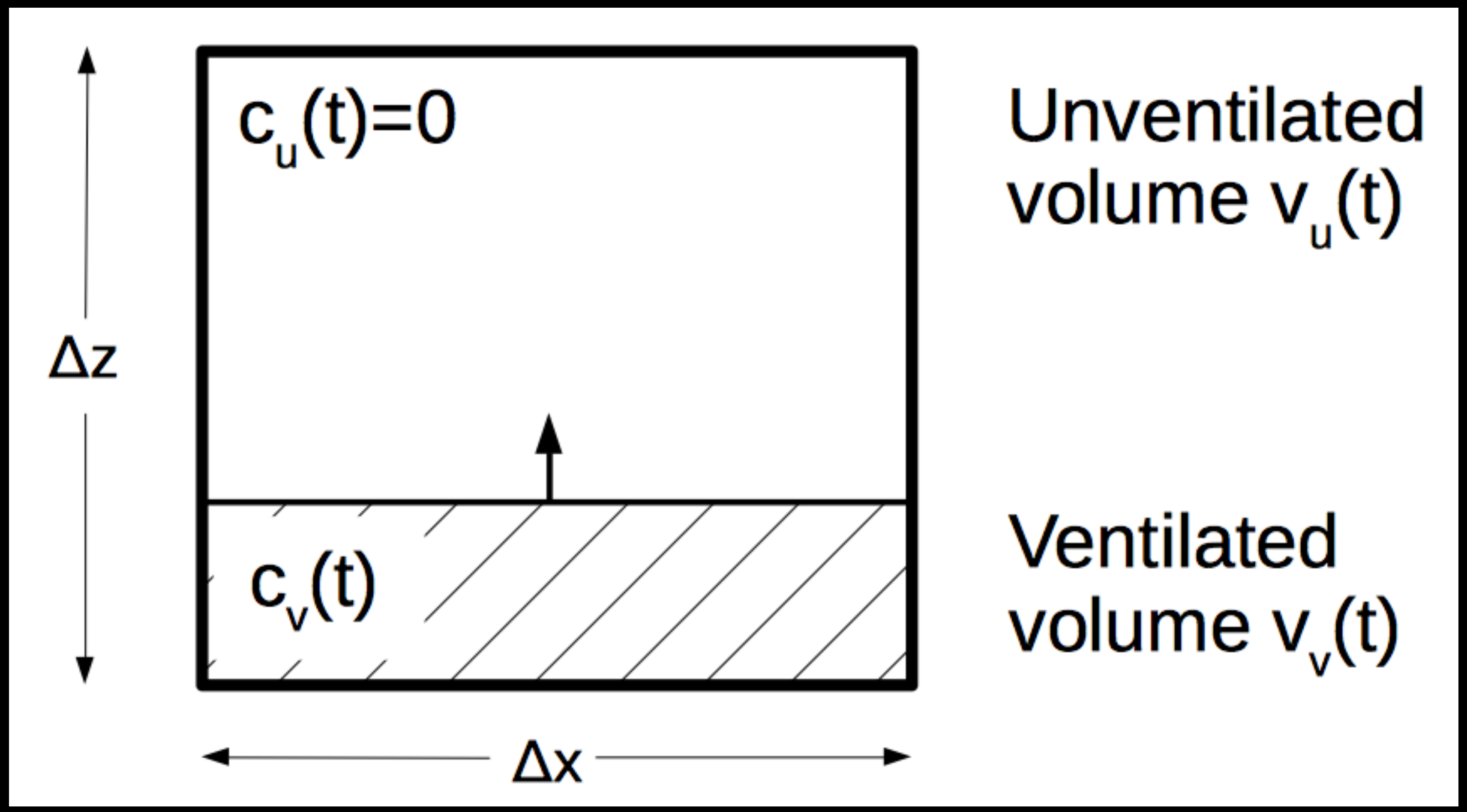

$$C\left(t\right) = \frac{v_v\left(t\right) c_v\left(t\right) + \cancel{v_u\left(t\right) c_u\left(t\right)}}{V}$$

$$\tilde{C}_\infty\left(t\right) = c_v\left(t\right) = \frac{V}{v_v\left(t\right)} C\left(t\right)$$

C^h Concentration of “helper” tracer with the property $c_v(t) = 1$

$$C^h\left(t\right) = \frac{v_v\left(t\right)}{V}$$

$$\lim_{t \to \infty} C^h\left(t\right) = 1$$

Asymptotic convergence

$$\Longrightarrow \lim_{t \to \infty} \tilde{C}_\infty\left(t\right) = C(t)$$