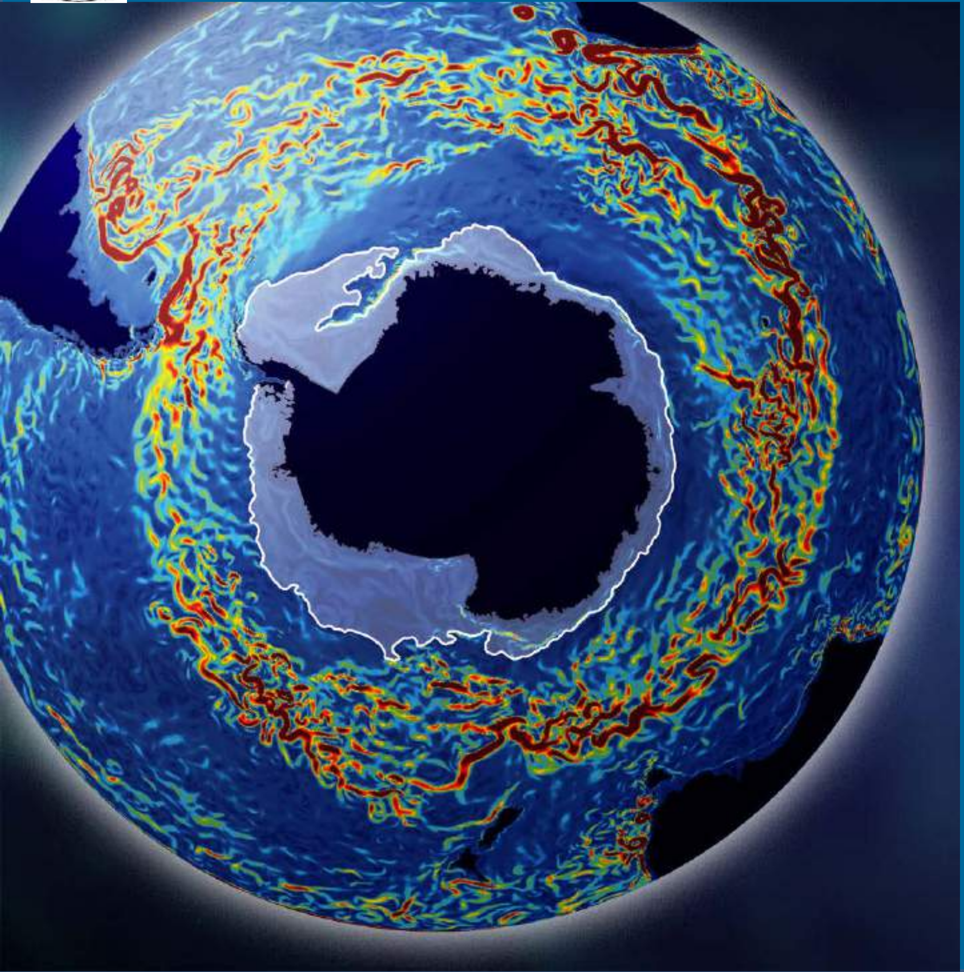
State Estimation for Analyzing Southern Ocean Budgets and Properties

Matt Mazloff

Scripps Institution of Oceanography

September 2017



Coauthors: this talk covers material from

Tamsitt, et al. Zonal variations in the Southern Ocean heat budget. *J. Climate*, 2016

Masich, et al. Topographic form stress in the Southern Ocean state estimate. *JGR*, 2015

Abernathey, et al. Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geoscience* , 2016

Rodriguez, et al. An oceanic heat transport pathway to the Amundsen Sea Embayment. *JGR,* 2016

Rosso, et al. Space and time variability of the Southern Ocean carbon budget. JGR, 2017

State Estimation for Analyzing Southern Ocean Budgets and Properties

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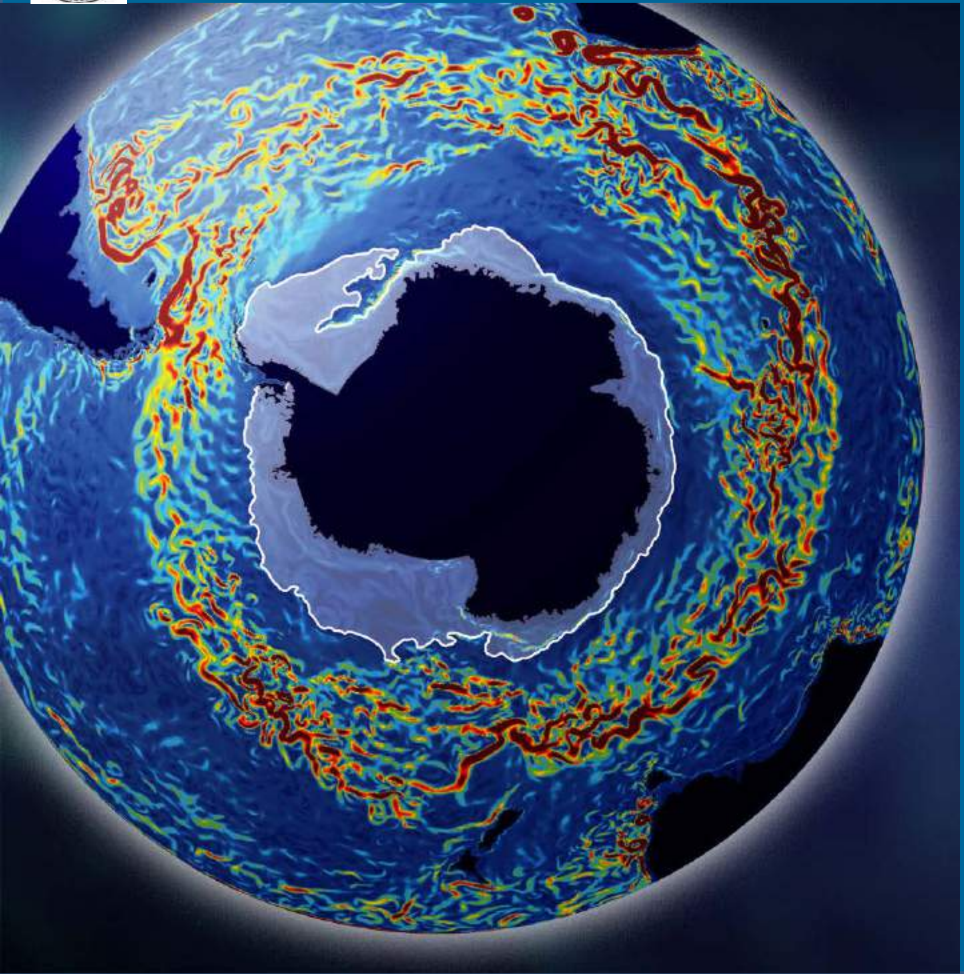


Talk summary:

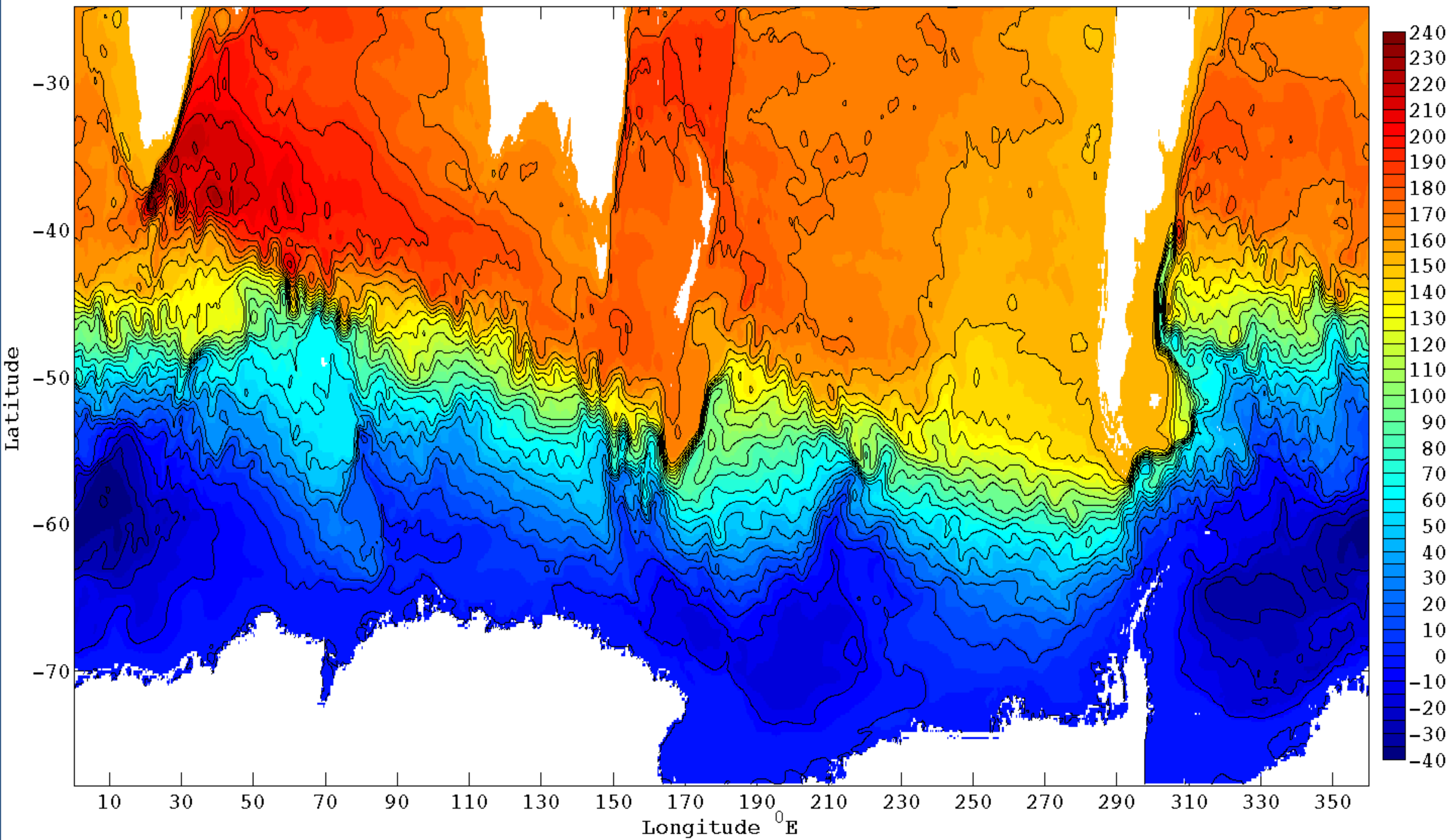
- The Southern Ocean is a windy, energetic, and complex region where schematics are major simplifications
- Synthesizing all available information into a state estimate allows quantification of budgets, bringing scientific understanding to the region
- An overview of the fundamental balances of the Southern Ocean is presented, relying heavily on work led by SIO students and post-docs

SOSE: A 2005 to 2010 physical state estimate.

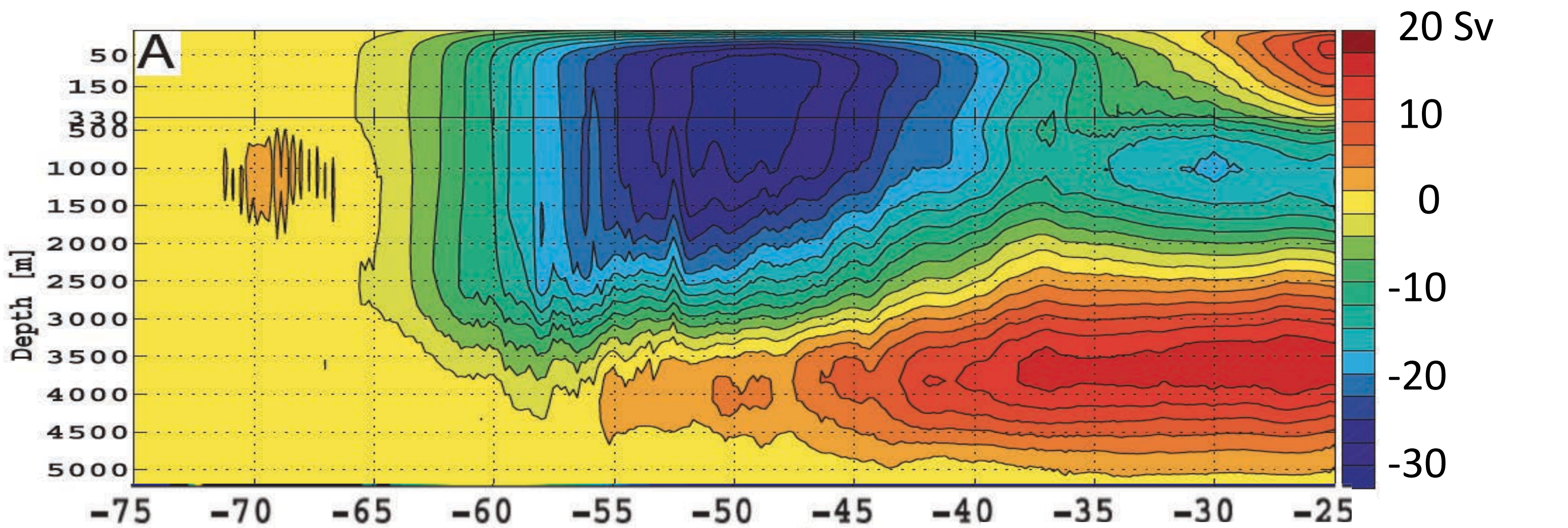
BSOSE: A 2008 to 2017 BGC state estimate.

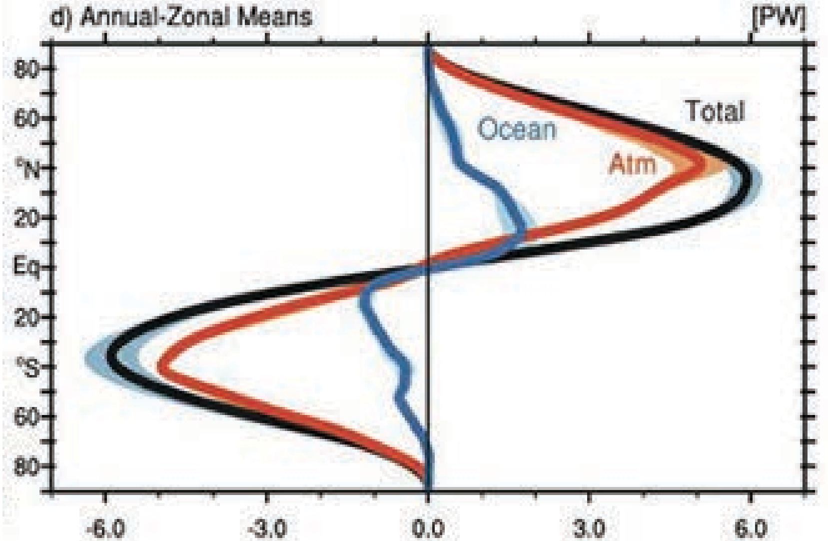
More than 75 publications have used this resource.

The vertically integrated transport streamfunction of the Southern Ocean



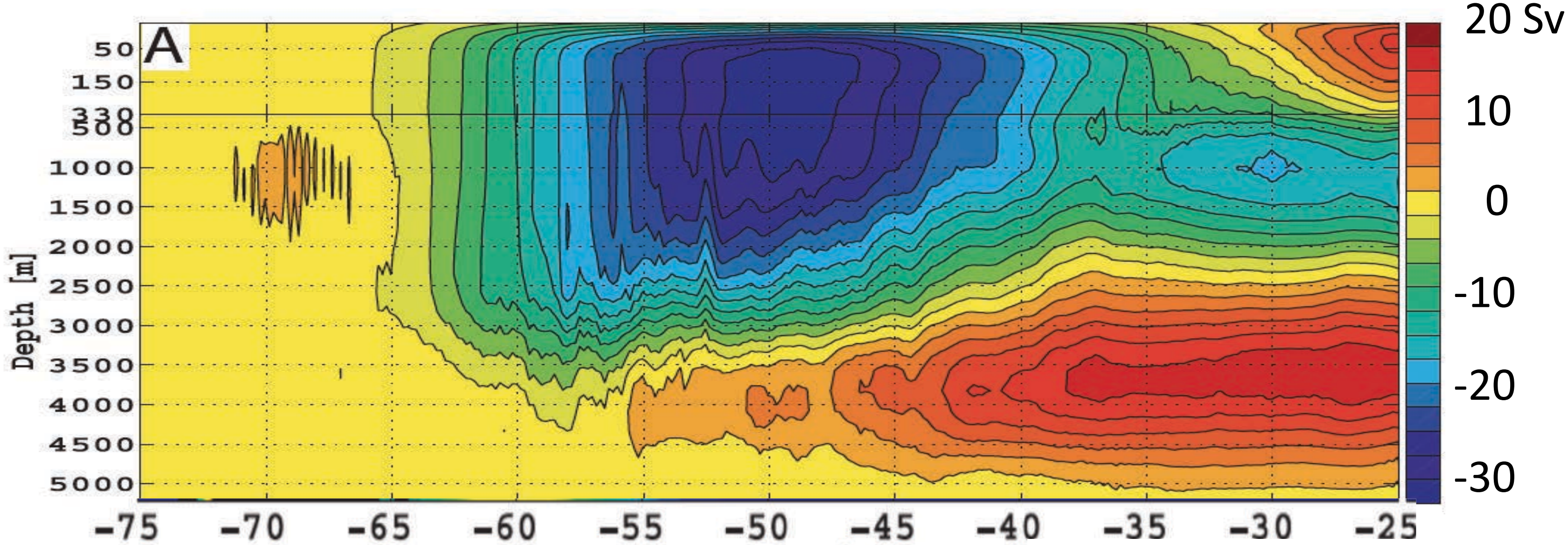
The meridional overturning streamfunction of the Southern Ocean

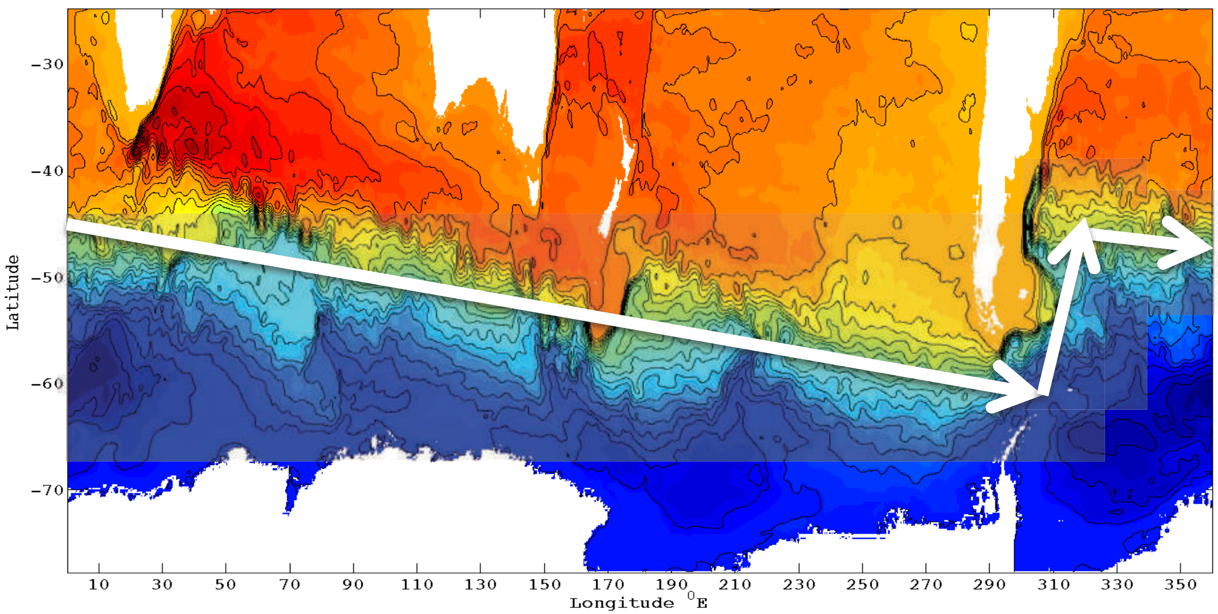


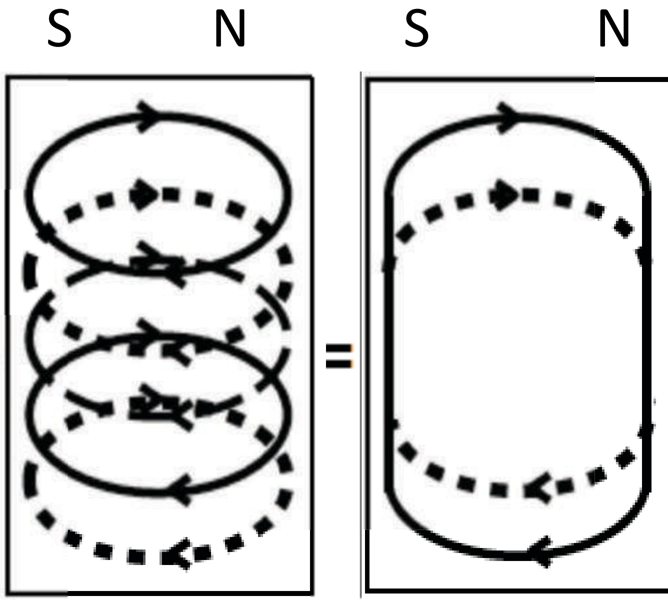


Fasullo and Trenberth 2008

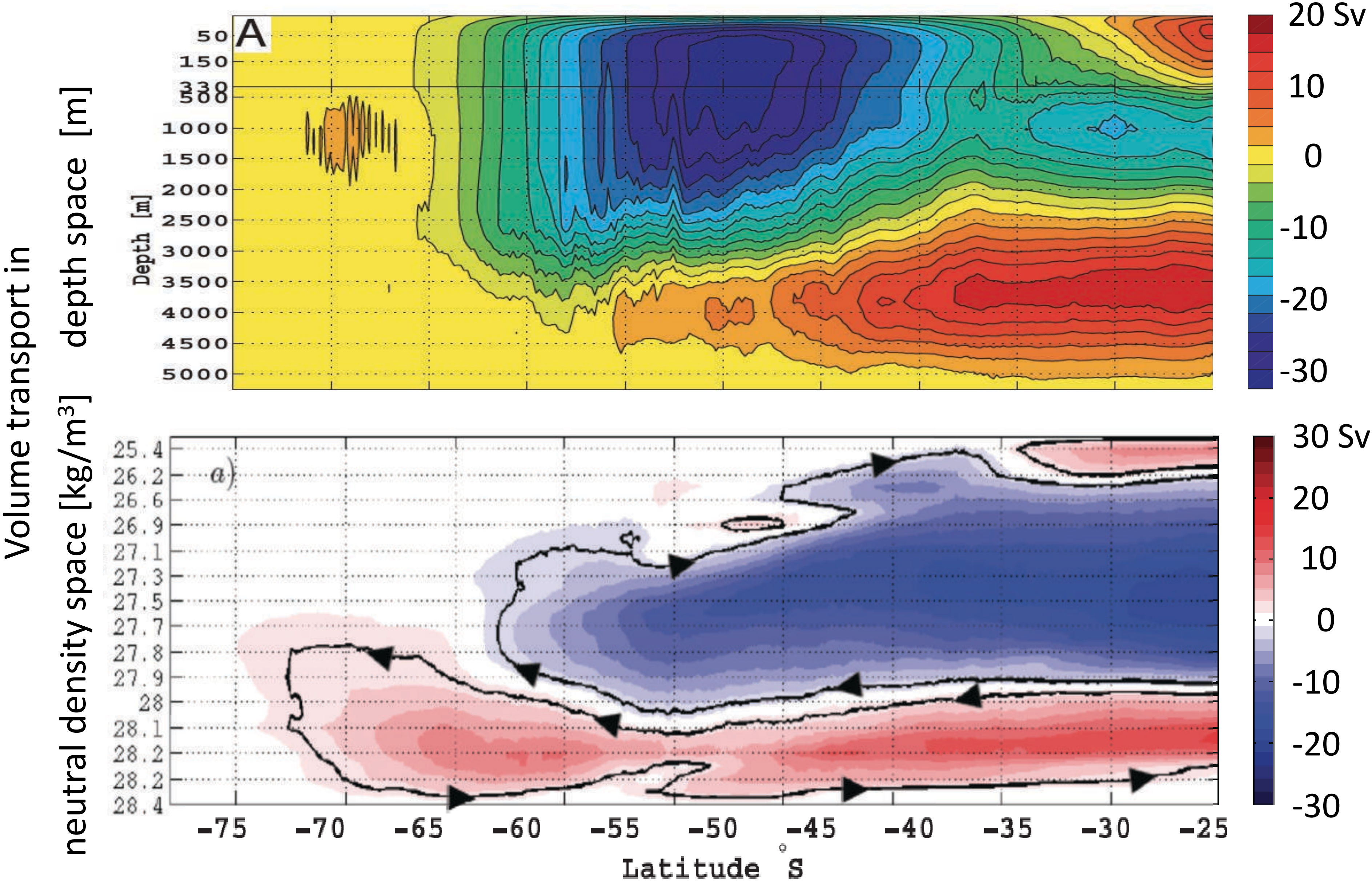
The meridional overturning streamfunction of the Southern Ocean



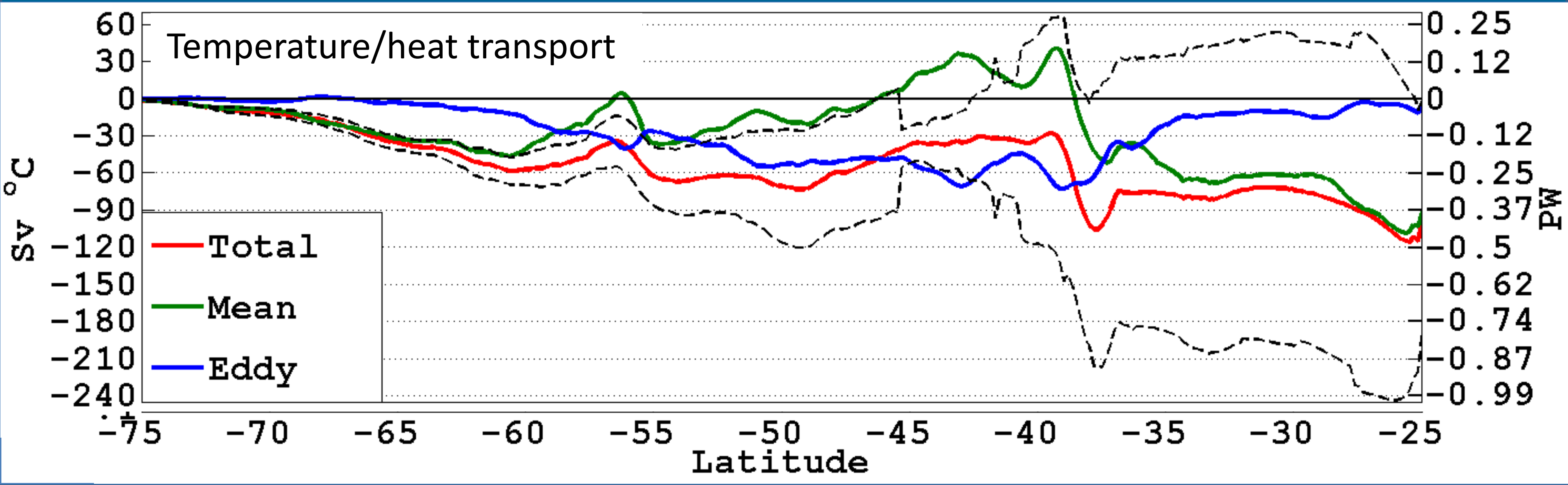




The meridional overturning streamfunction of the Southern Ocean

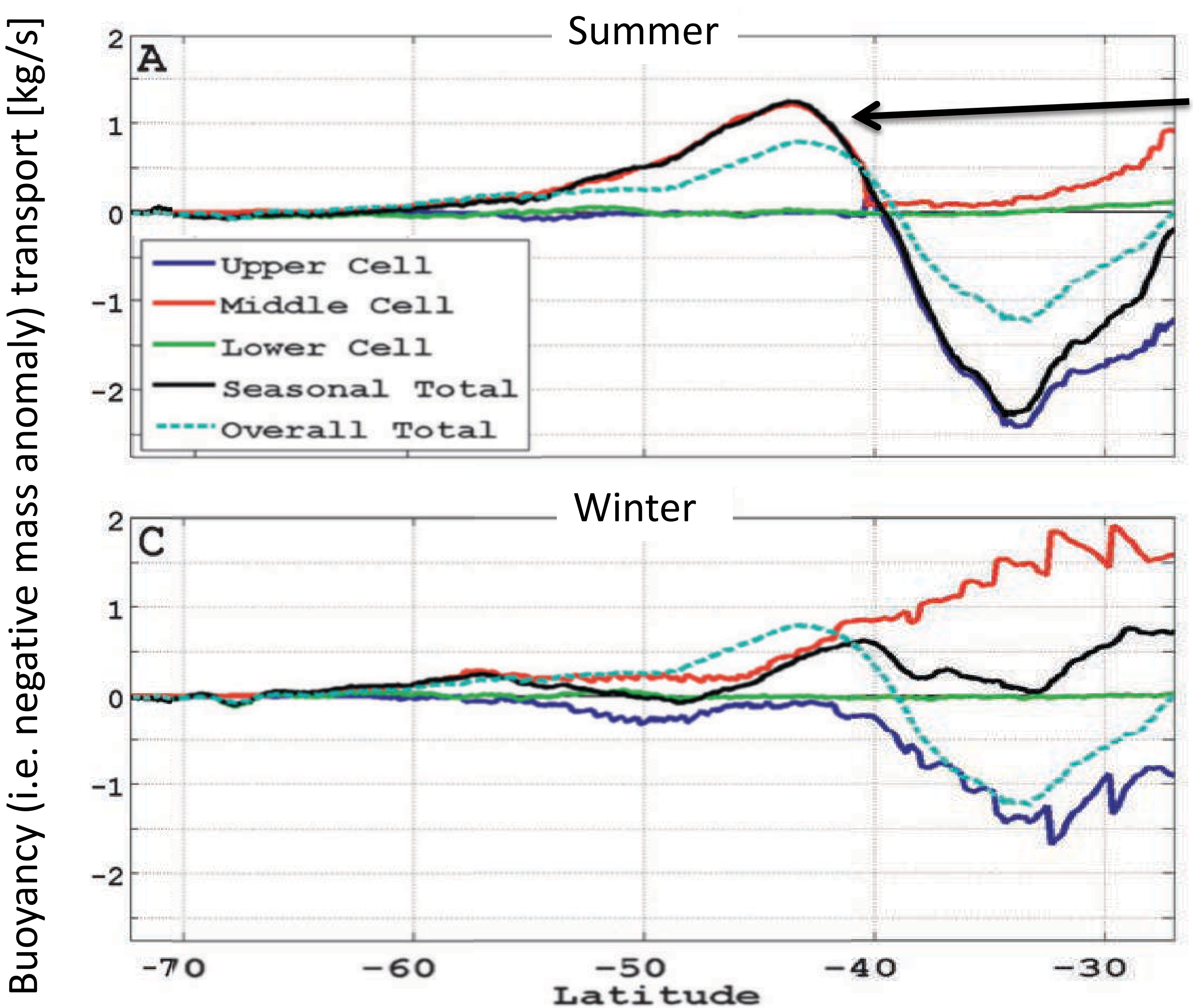


The meridional heat transport of the Southern Ocean



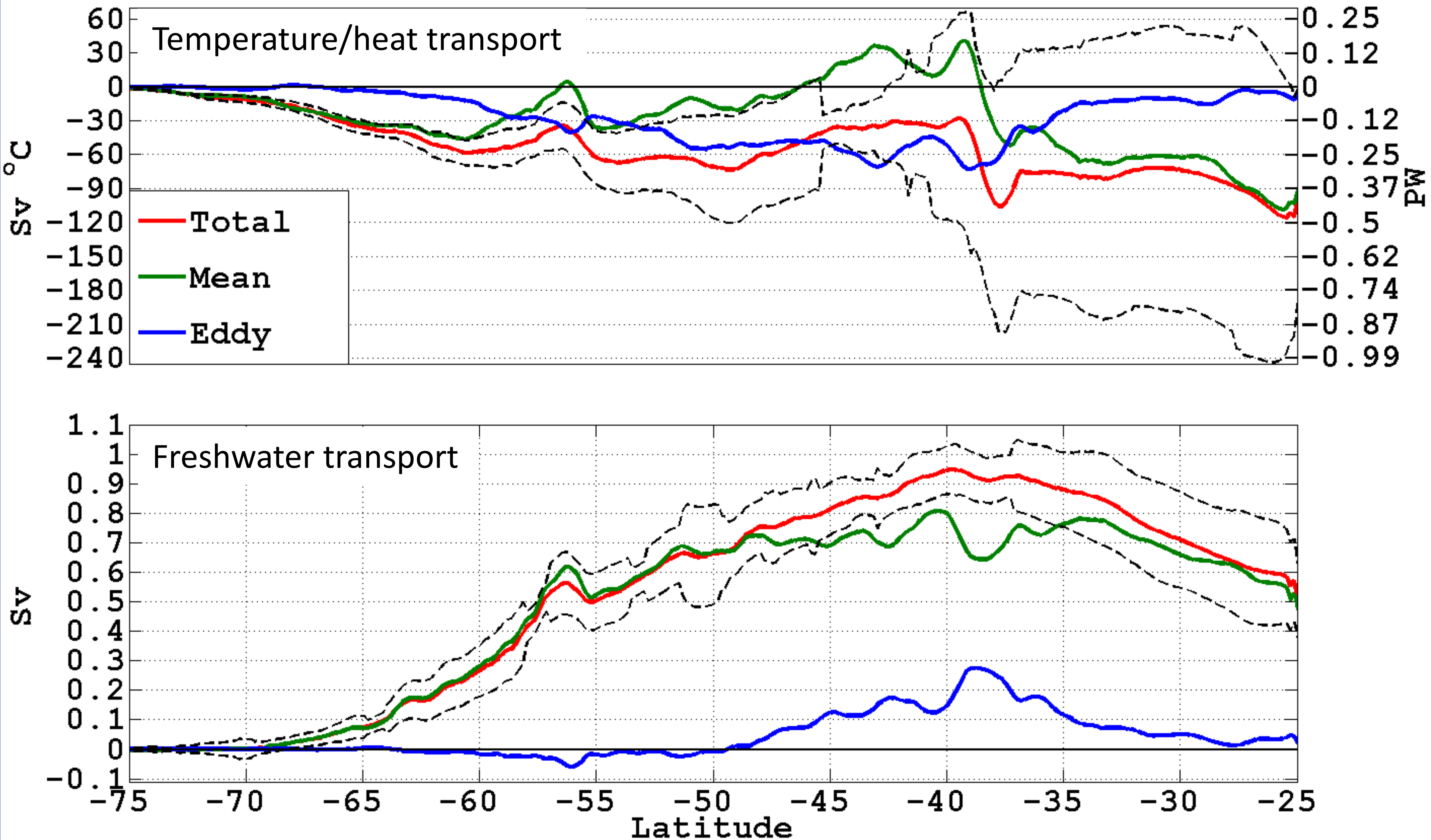
We find a poleward total heat transport at all latitudes (red line)

The meridional buoyancy transport of the Southern Ocean



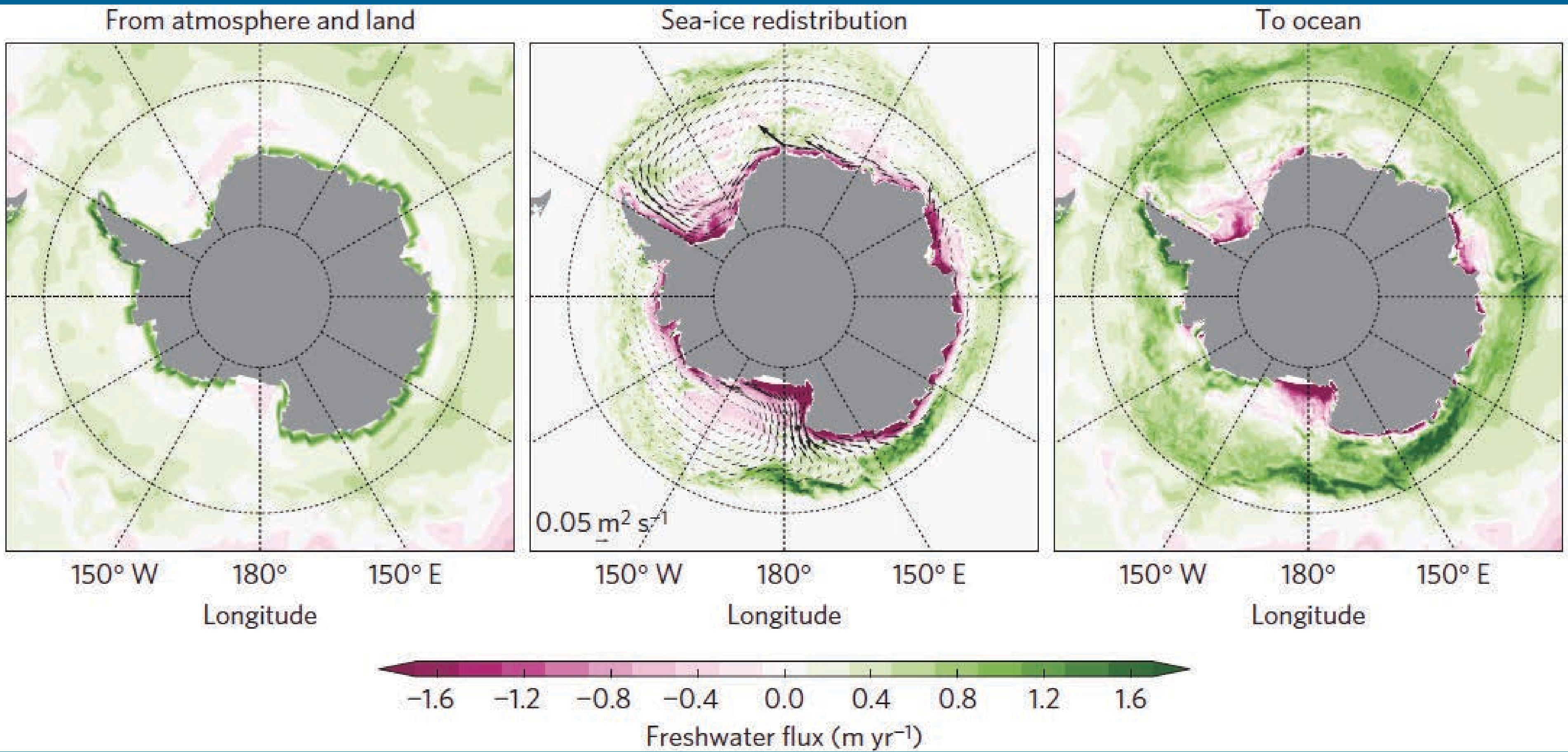
Total buoyancy transport (black line) is positive indicating equatorward buoyancy transport

The meridional heat and freshwater transport of the Southern Ocean



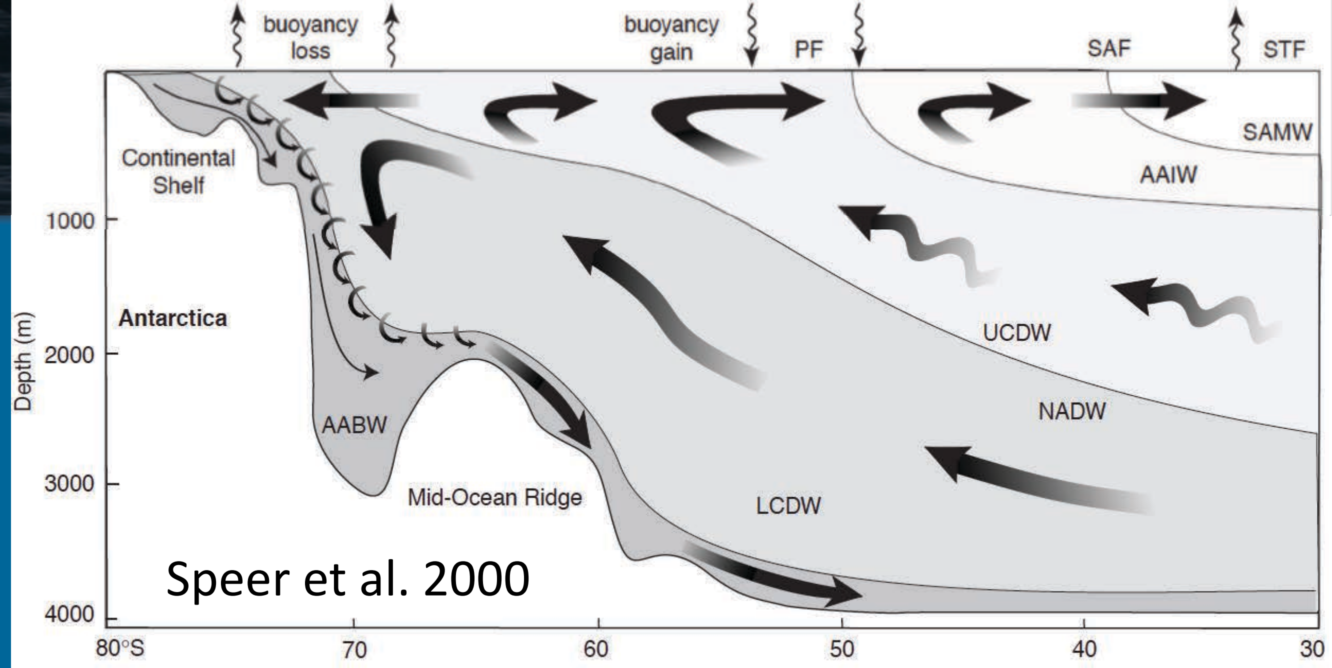
Sea ice redistributes freshwater

Precipitation plus run off | Sea ice redistribution | Net flux into the ocean



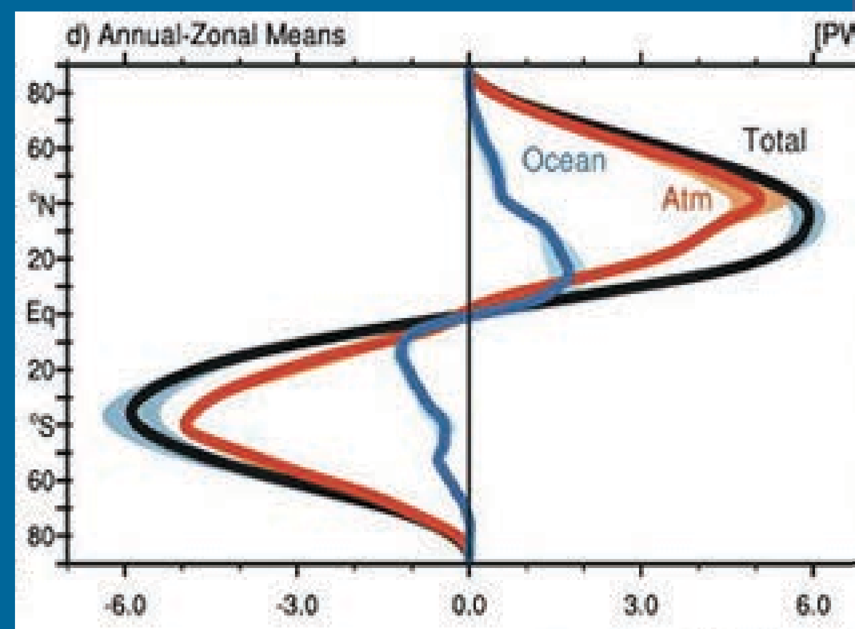
Abernathy et al. 2016

Southern Ocean Fundamentals Summary #1



Speer et al. 2000

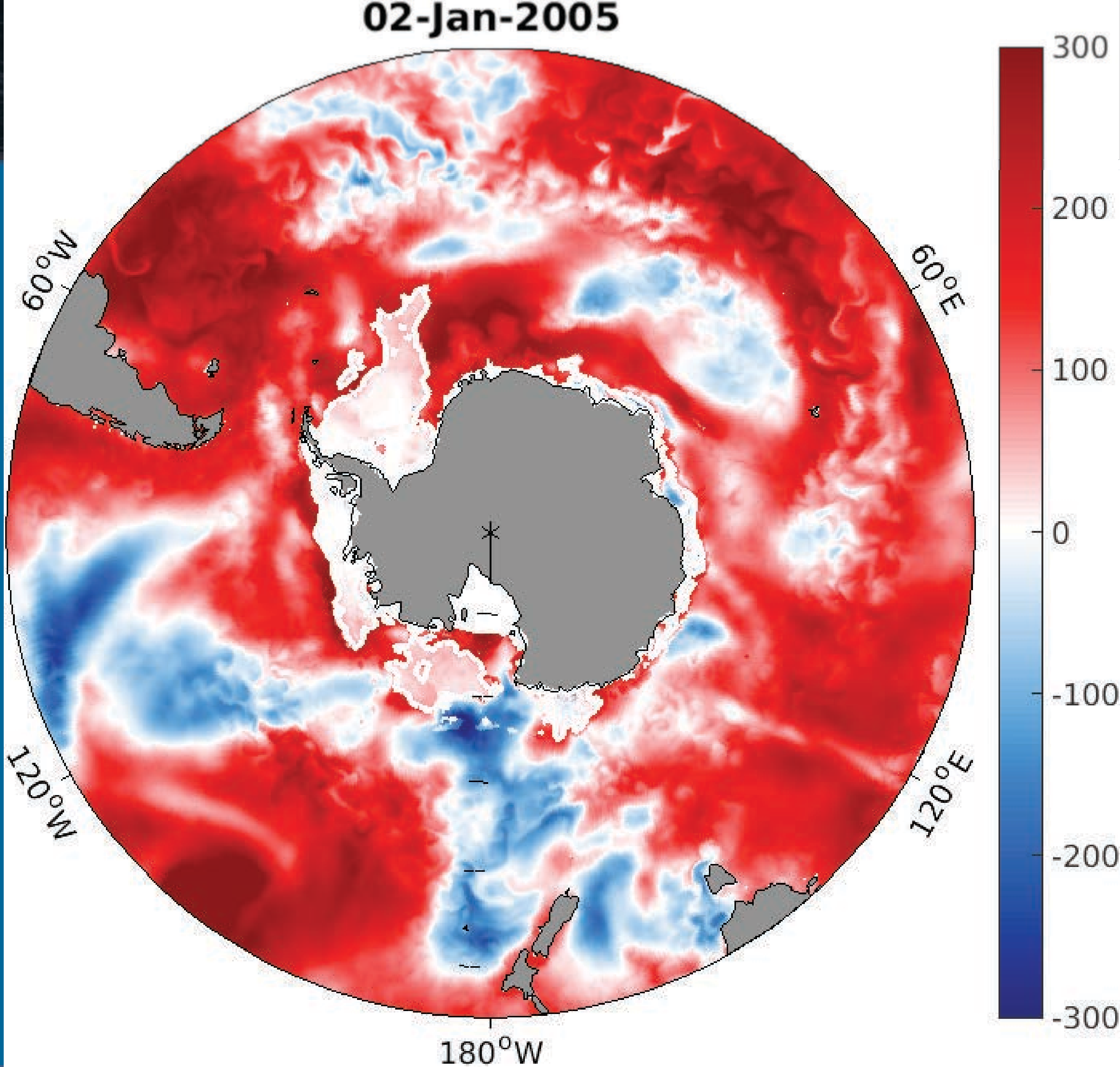
- ~30 Sv *equatorward* Ekman transport
- ~0.3 PW *poleward* heat transported
- Stability achieved via equatorward freshwater transport (~1 Sv), maintained via freshwater redistribution by sea ice
- Water mass exchange:
  - Warm waters move poleward
  - Fresh waters move equatorward



Fasullo and Trenberth 2

The heat budget of the Southern Ocean

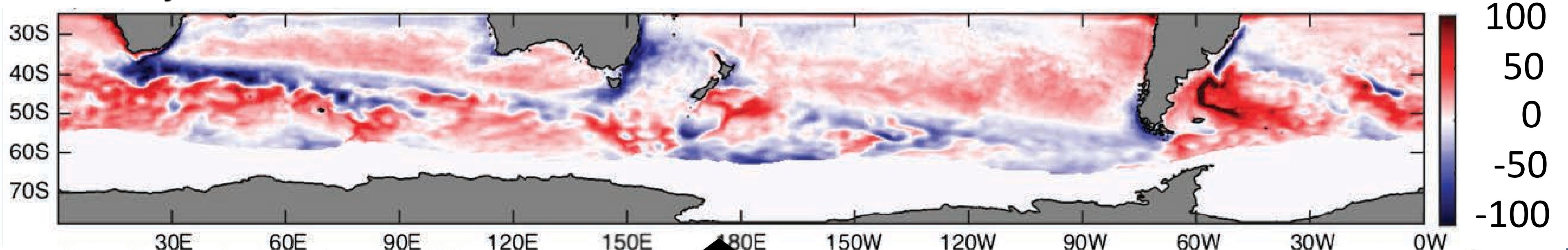
The zonal mean heat flux [Wm^{-2}] is small residual of a complex 4-D structure



The heat budget of the Southern Ocean

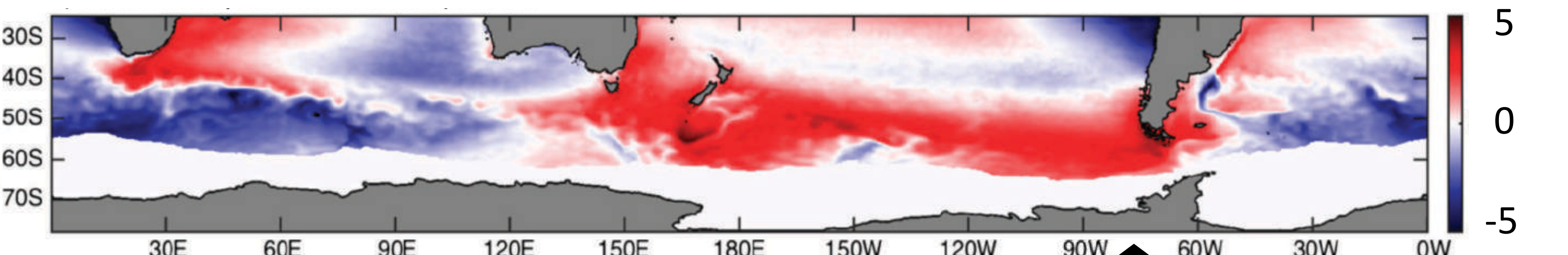
$$\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho c_p dz} - \mathbf{u_g} \cdot \nabla_H T - \mathbf{u_a} \cdot \nabla_H T - w \frac{\partial T}{\partial z} + \kappa_H \nabla_H^2 T + \kappa_z \frac{\partial^2 T}{\partial z^2} + K_T^{turb}$$

Temperature tendency | air-sea flux | geostrophic advection | Ekman advection | vertical advection | diffusion



Net air-sea heat flux [Wm^{-2}]:

Mean heat flux is small residual of a highly *temporally* variable field

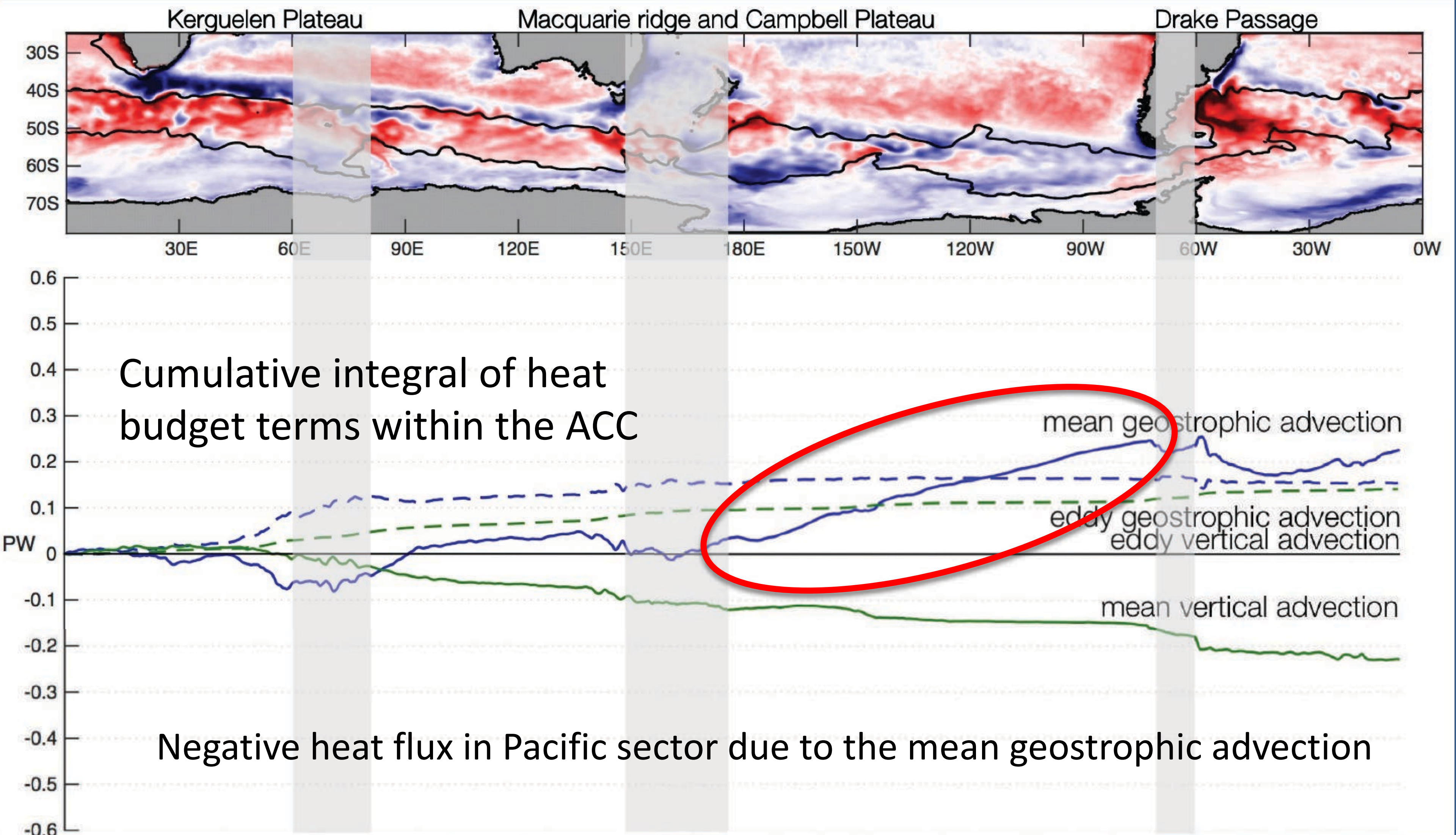


Zonal anomaly of sea surface temperature [^oC]:

Mean heat flux is a small residual of a highly *spatially* variable field

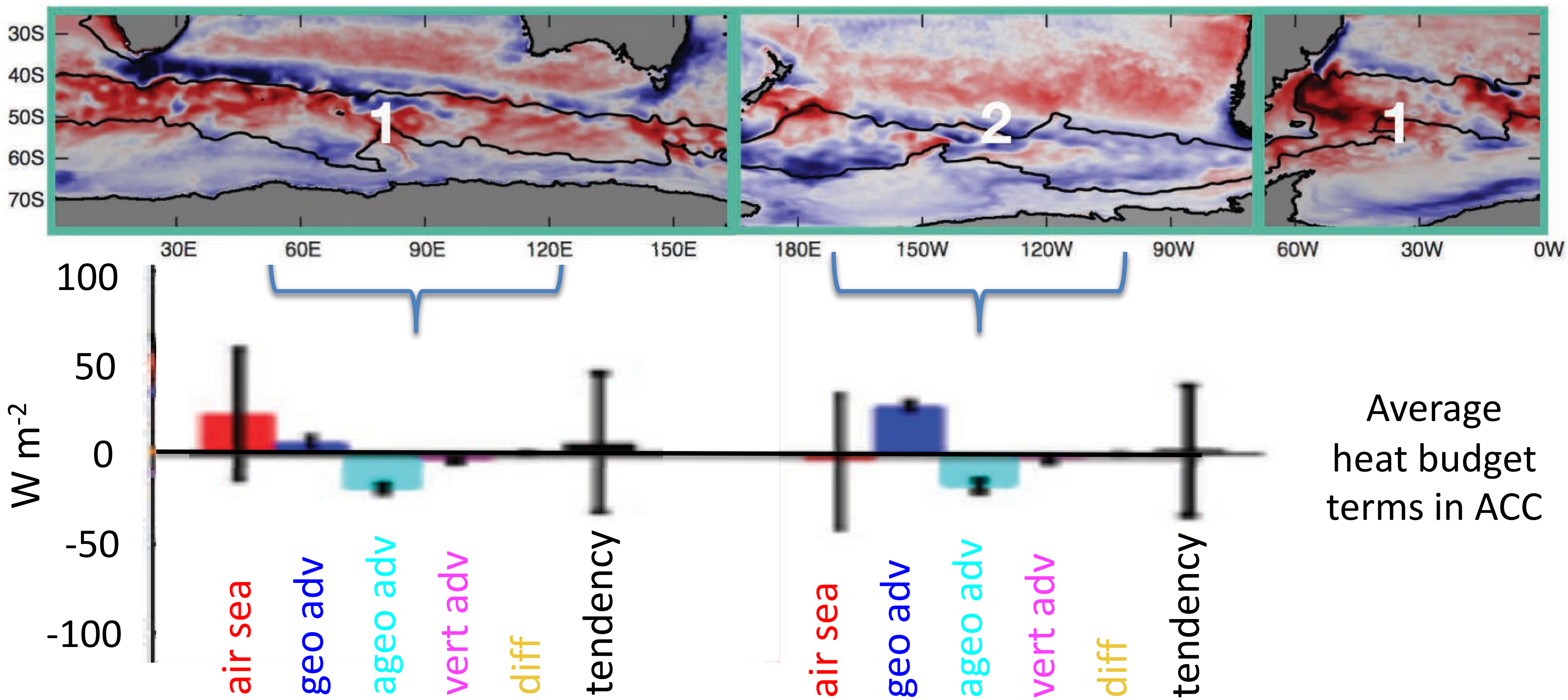
The heat budget of the Southern Ocean

Net air-sea heat flux: asymmetry accounted for with mean geostrophic advection



$$\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho c_p dz} - \mathbf{u}_g \cdot \nabla_H T - \mathbf{u}_a \cdot \nabla_H T - w \cdot \frac{\partial T}{\partial z} + \kappa_H \nabla_H^2 T + \kappa_z \frac{\partial^2 T}{\partial z^2} + K_T^{turb}$$

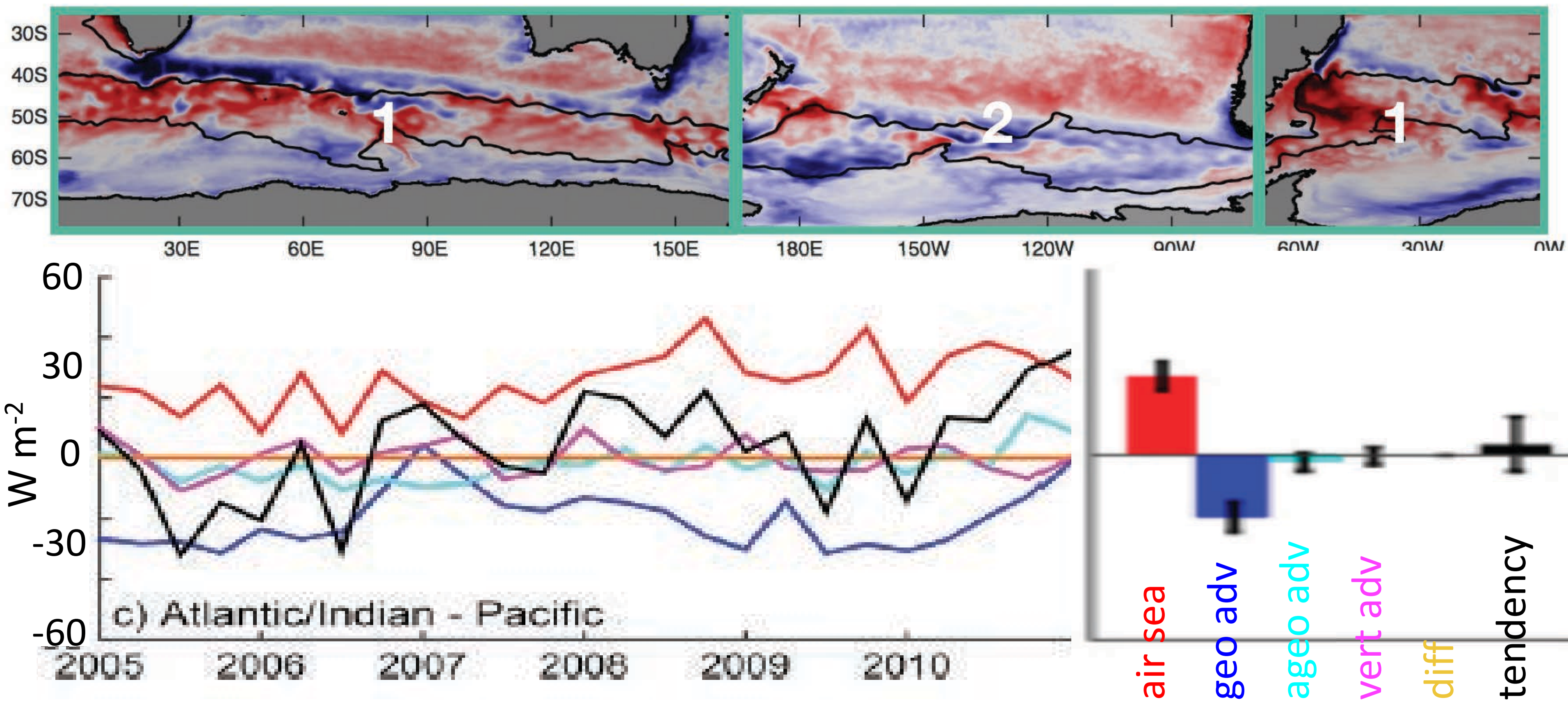
Temperature tendency	air-sea flux	geostrophic advection	Ekman advection	vertical advection	diffusion



Atlantic and Indian sectors | Pacific sector

$$\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho c_p dz} - u_g \cdot \nabla_H T - u_a \cdot \nabla_H T - w \frac{\partial T}{\partial z} + \kappa_H \nabla_H^2 T + \kappa_z \frac{\partial^2 T}{\partial z^2} + K_T^{turb}$$

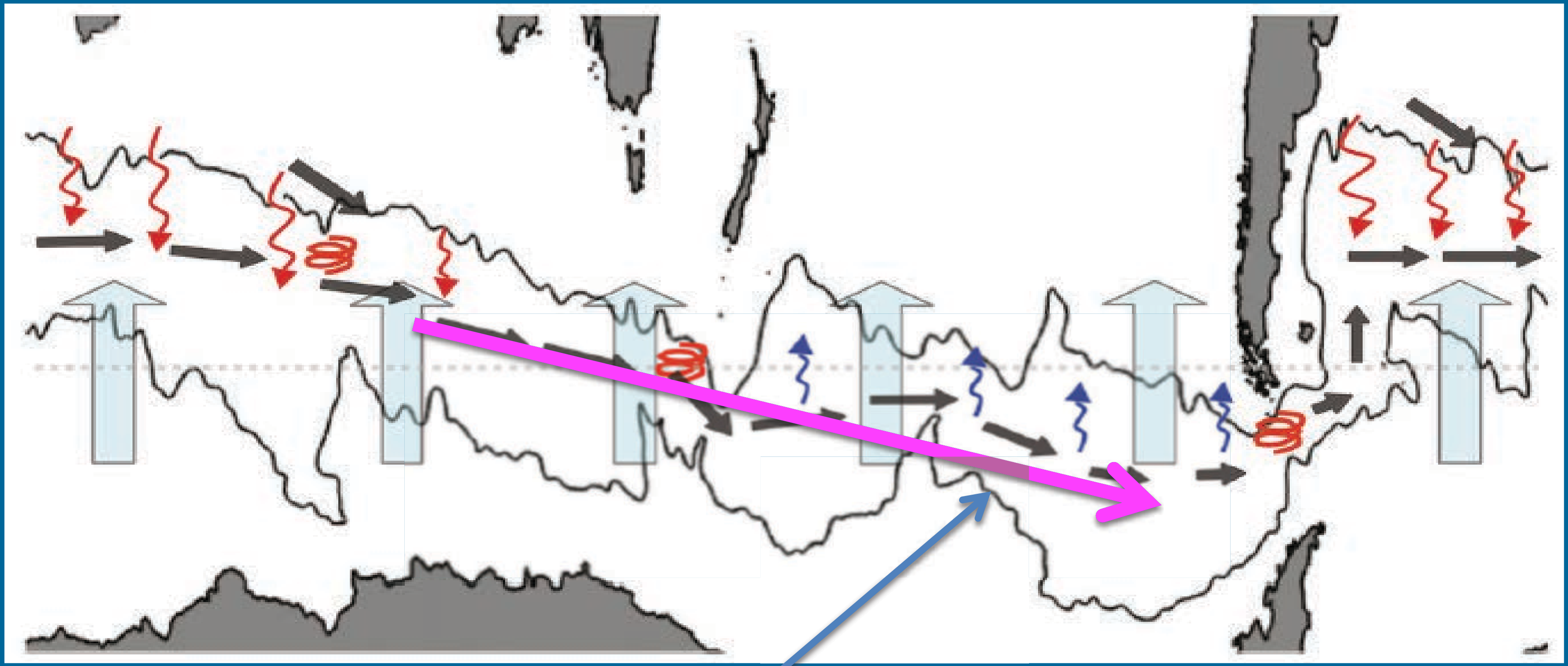
Temperature tendency	air-sea flux	geostrophic advection	Ekman advection	vertical advection	diffusion



Atlantic and Indian sectors minus Pacific sector

The heat budget of the Southern Ocean

- Asymmetry in air-sea heat flux driven by geostrophic advection

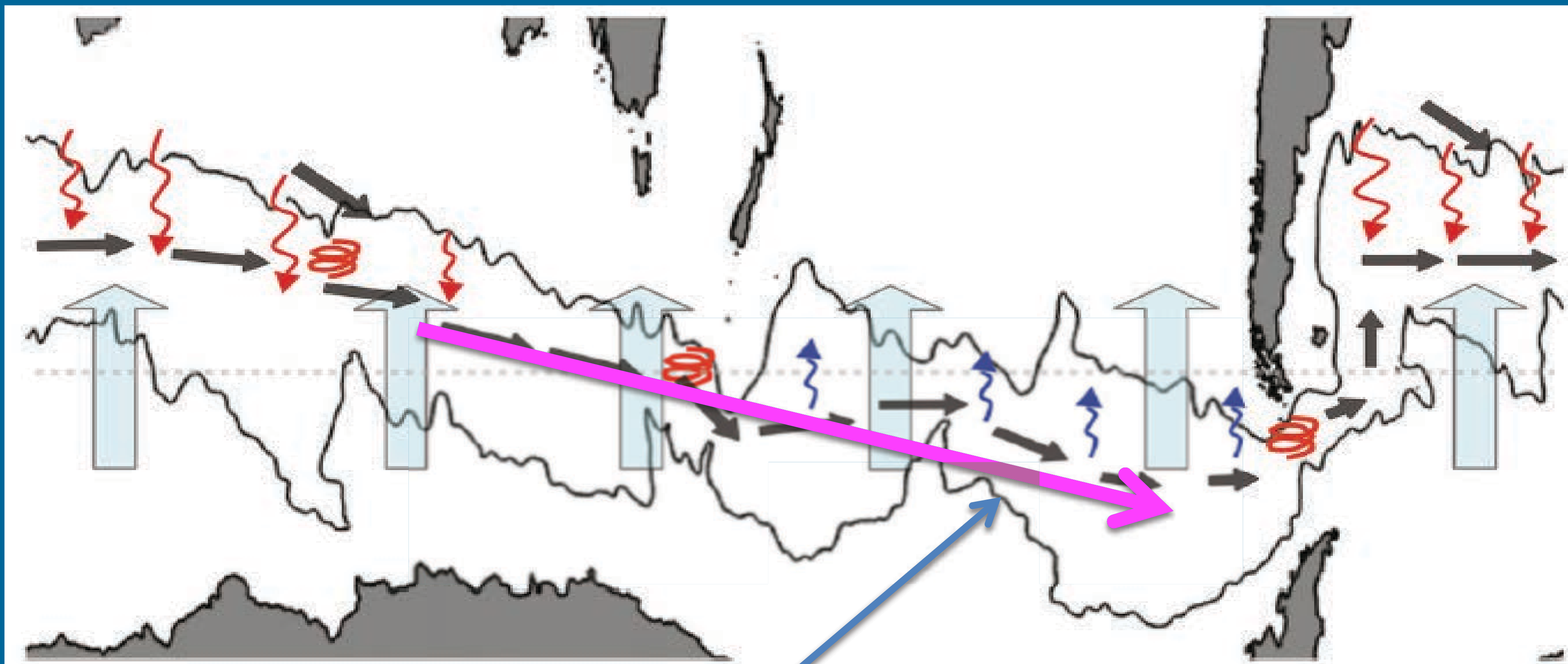


- How does one sustain a mean geostrophic heat transport across Drake Passage latitudes where no land boundaries exist?

$$\rho_\circ f \oint v_g dx = \oint p_x dx = 0,$$

The heat budget of the Southern Ocean

- Asymmetry in air-sea heat flux driven by geostrophic advection



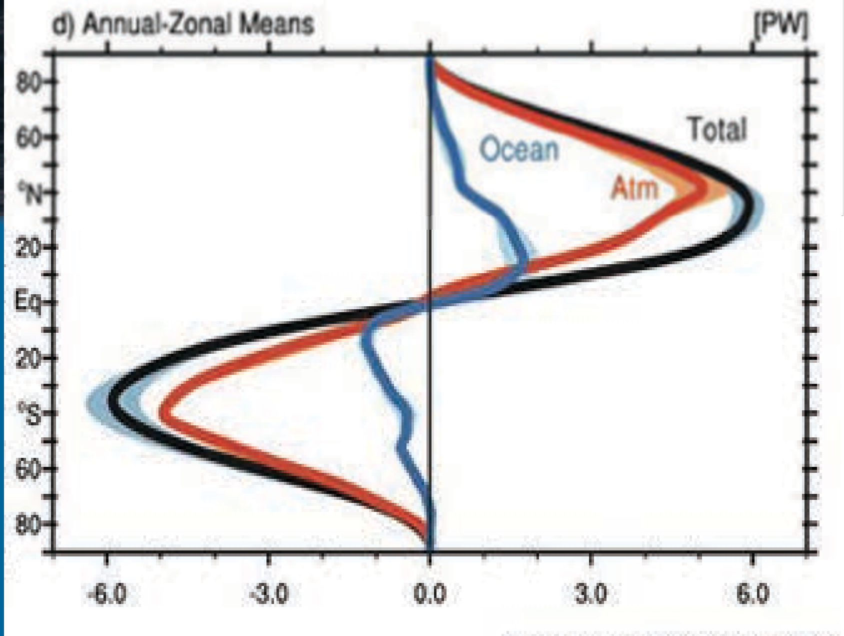
- How does one sustain a mean geostrophic heat transport across Drake Passage latitudes where no land boundaries exist?

$$\rho_\circ f \oint v_g dx = \oint p_x dx = 0, \qquad \rho_\circ f \oint \theta v_g dx \neq 0$$

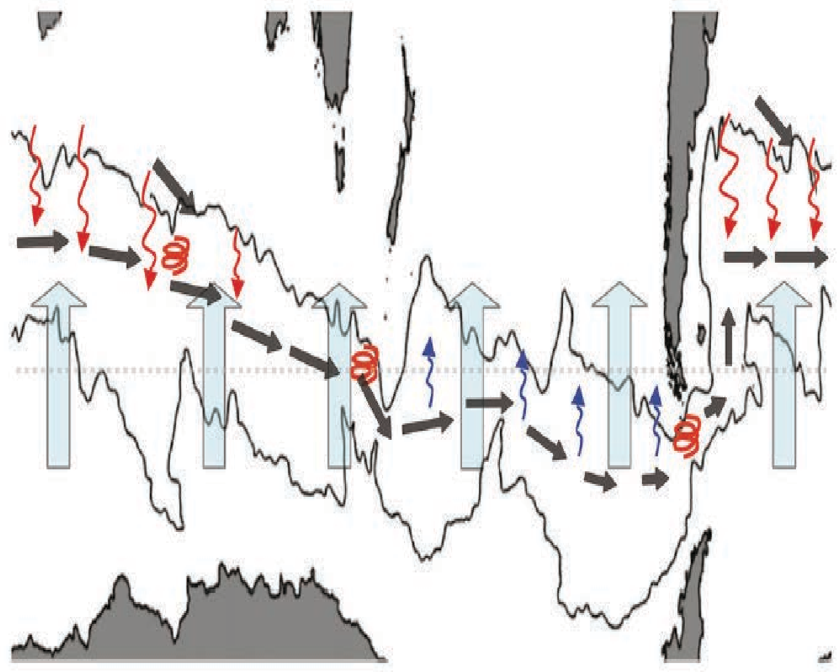
Exchange: warm/salty moves poleward and cold/fresh moves equatorward

Southern Ocean Fundamentals Summary #2

- ~30 Sv *equatorward* Ekman transport
- ~0.3 PW *poleward* heat transported
- Stability achieved via equatorward freshwater transport, maintained via freshwater redistribution by sea ice
- Implies exchange of warm/salty and cold/fresh waters
- Upper ocean geostrophic volume transport across Drake Passage latitudes is negligible.
- Warm salty poleward transport is accomplished by zonal asymmetries in the mean geostrophic flow

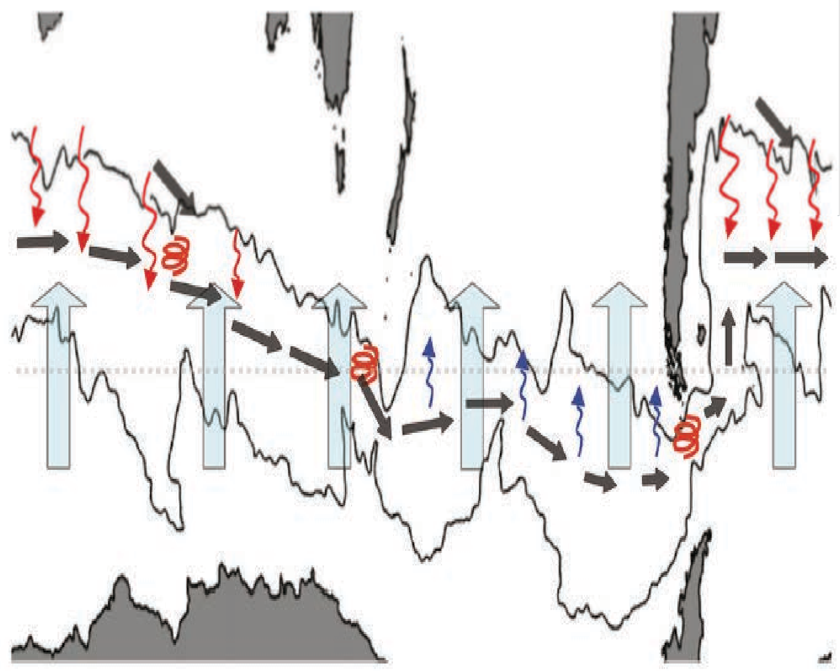


Fasullo and Trenberth 2008



Southern Ocean Fundamentals Summary #2

- Warm salty poleward transport is accomplished by water mass exchanges via zonal asymmetries in the *mean* geostrophic flow

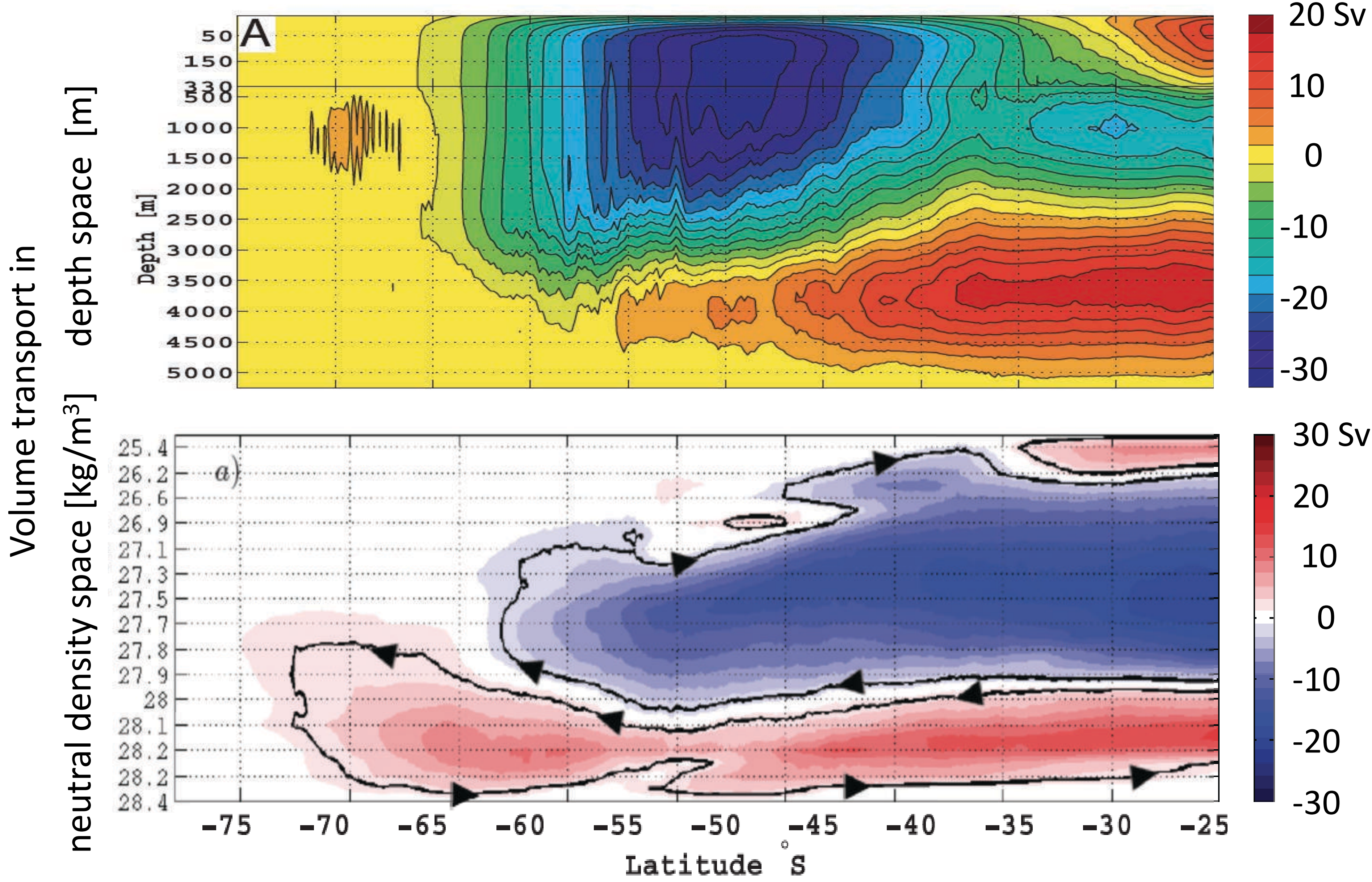


Executive summary of Southern Ocean dynamics:

"water pushes on water sometimes, land other times"

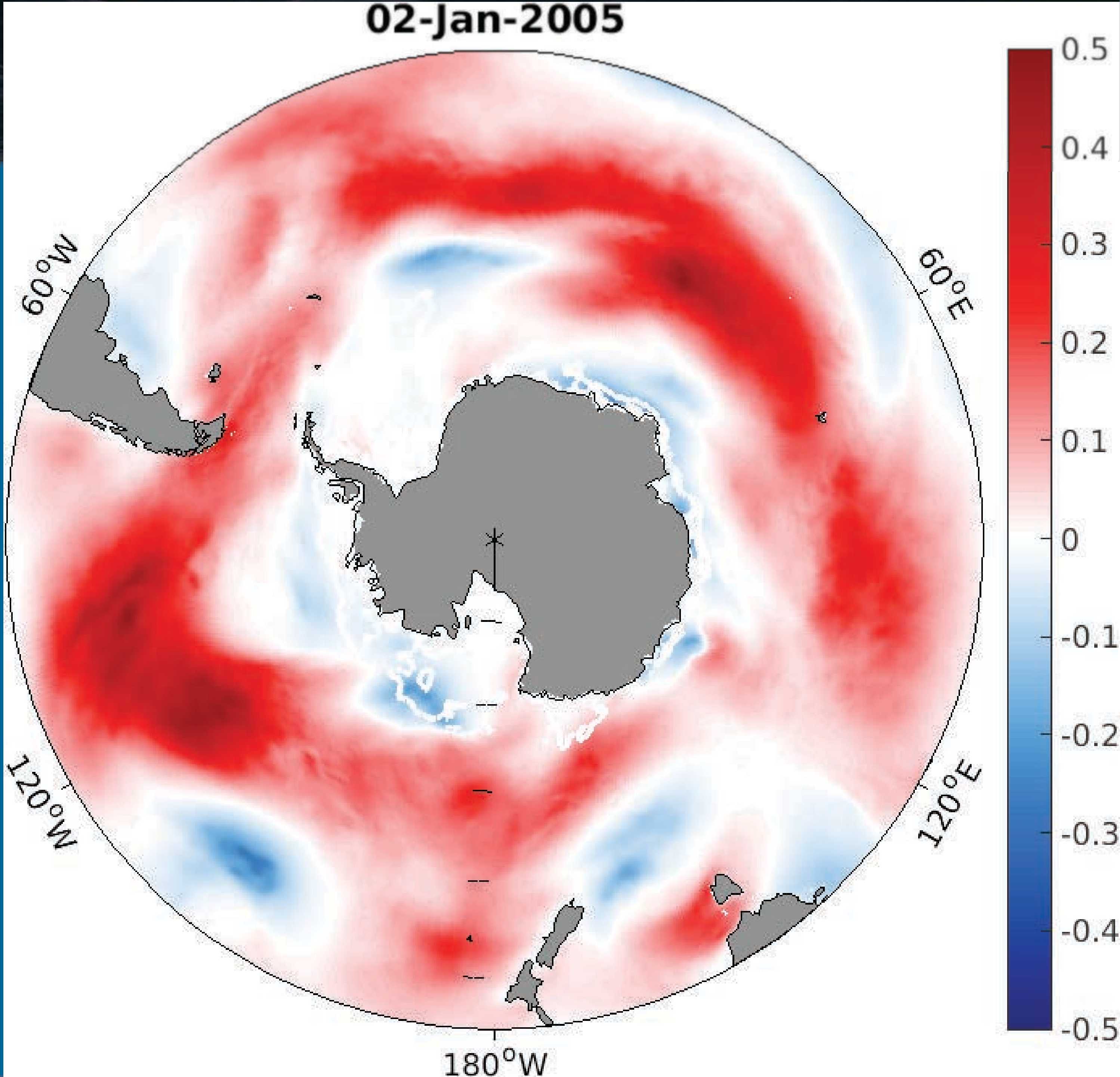
-Jessica Masich, Ph.D., UCSD

The meridional overturning streamfunction of the Southern Ocean

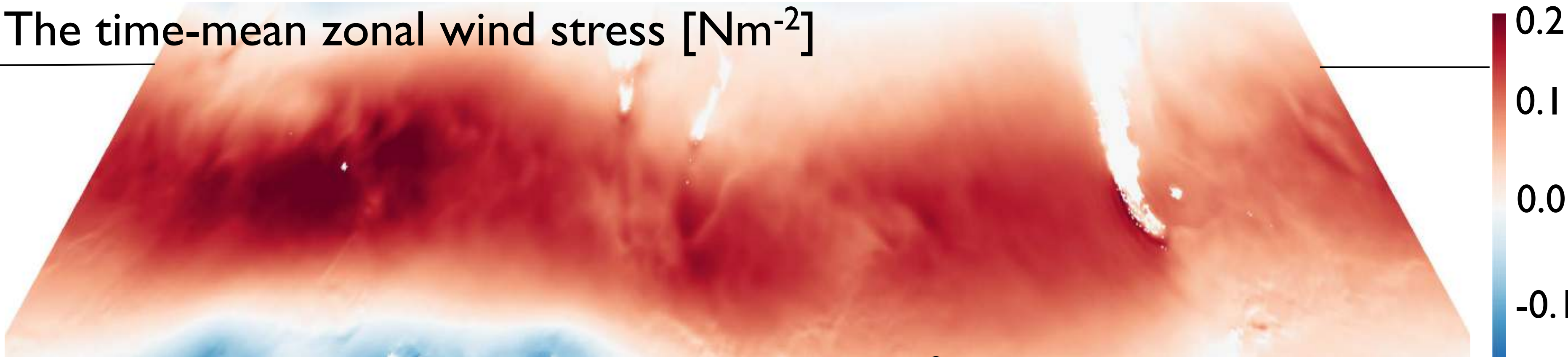


Zonal wind stress [Nm^{-2}]

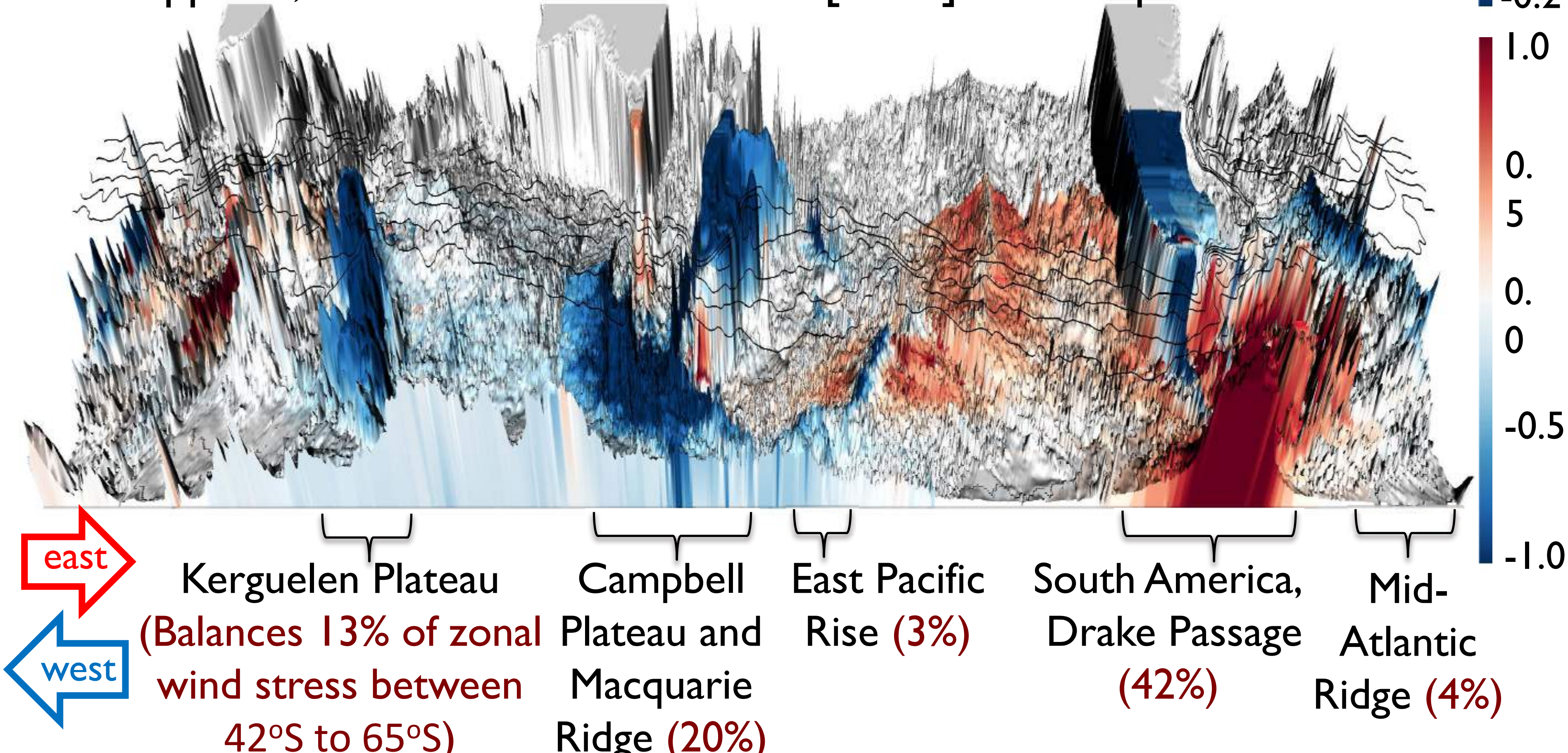
The mean momentum input is the residual of a complex 4-D structure.



The time-mean zonal wind stress [Nm^{-2}]

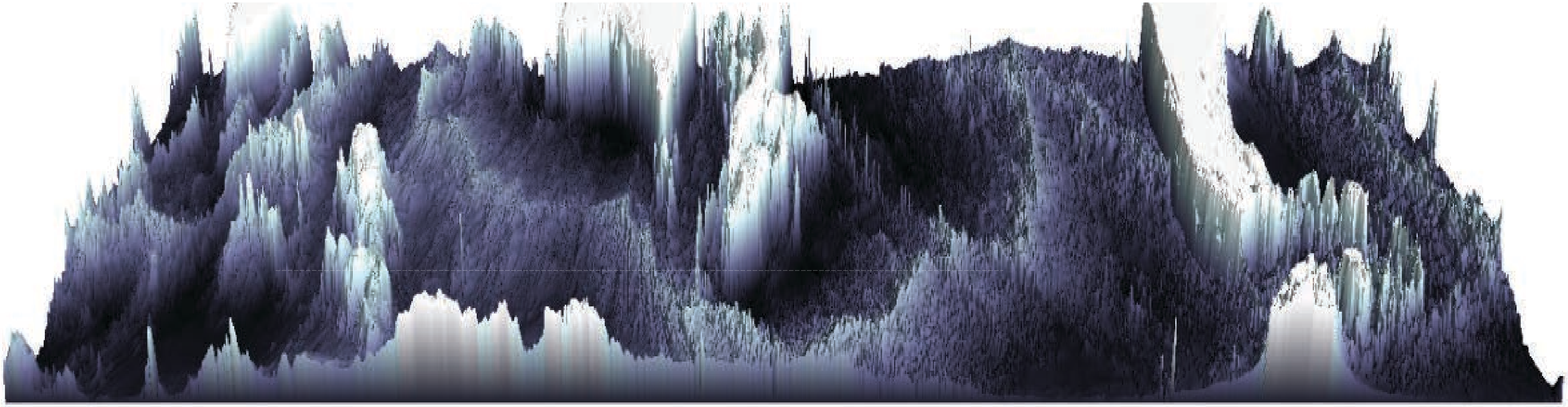


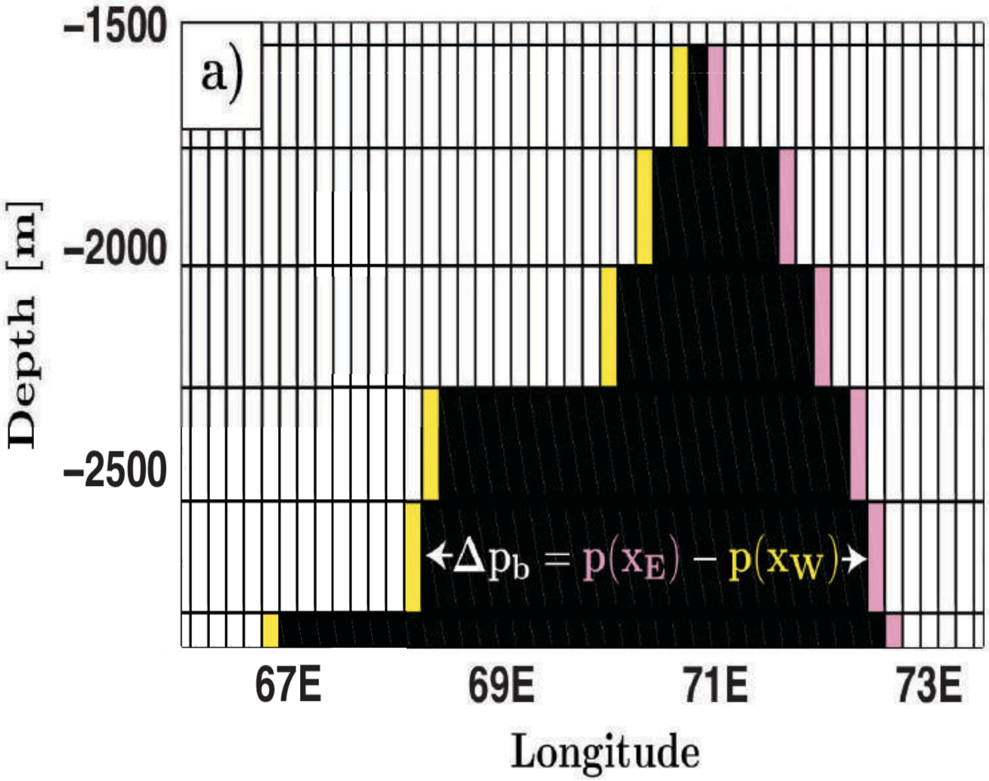
Mean upper 3,700m bottom form stress [Nm^{-2}]: “water push on land”



Figures from J. Masich

Bottom form stress: methodology

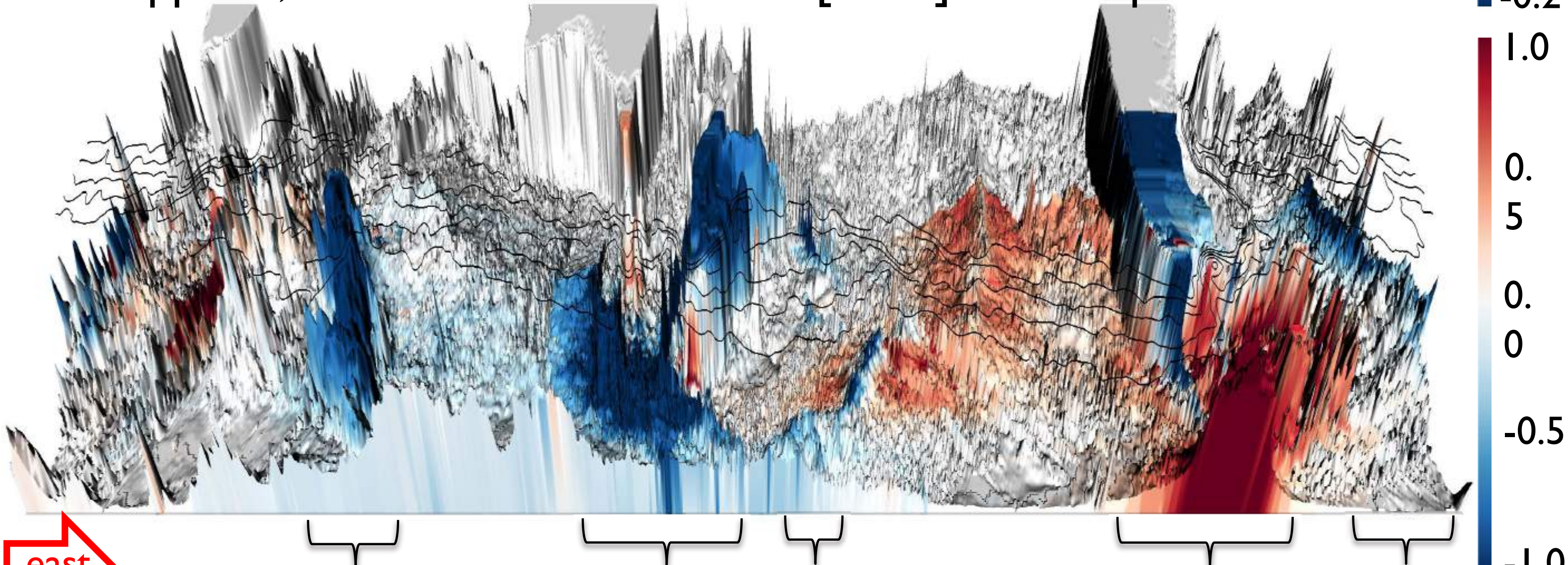




Slide from J. Masich

The time-mean zonal wind stress [Nm^{-2}]

Mean upper 3,700m bottom form stress [Nm^{-2}]: “water push on land”



east

west

Kerguelen Plateau (Balances 13% of zonal wind stress between 42°S to 65°S)

Campbell Plateau and Macquarie Ridge (20%)

East Pacific Rise (3%)

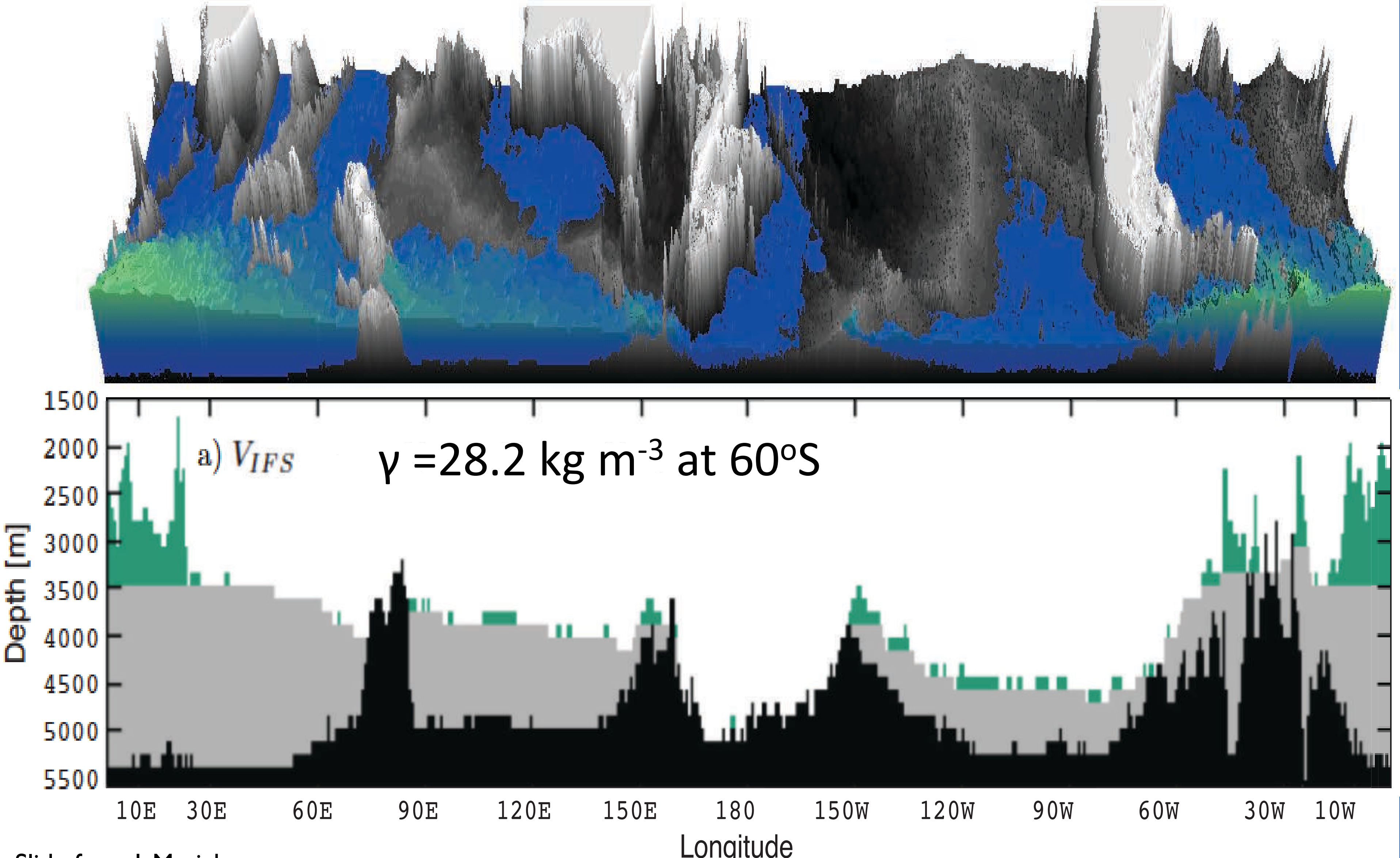
South America, Drake Passage (42%)

Mid-Atlantic Ridge (4%)

Figures from J. Masich

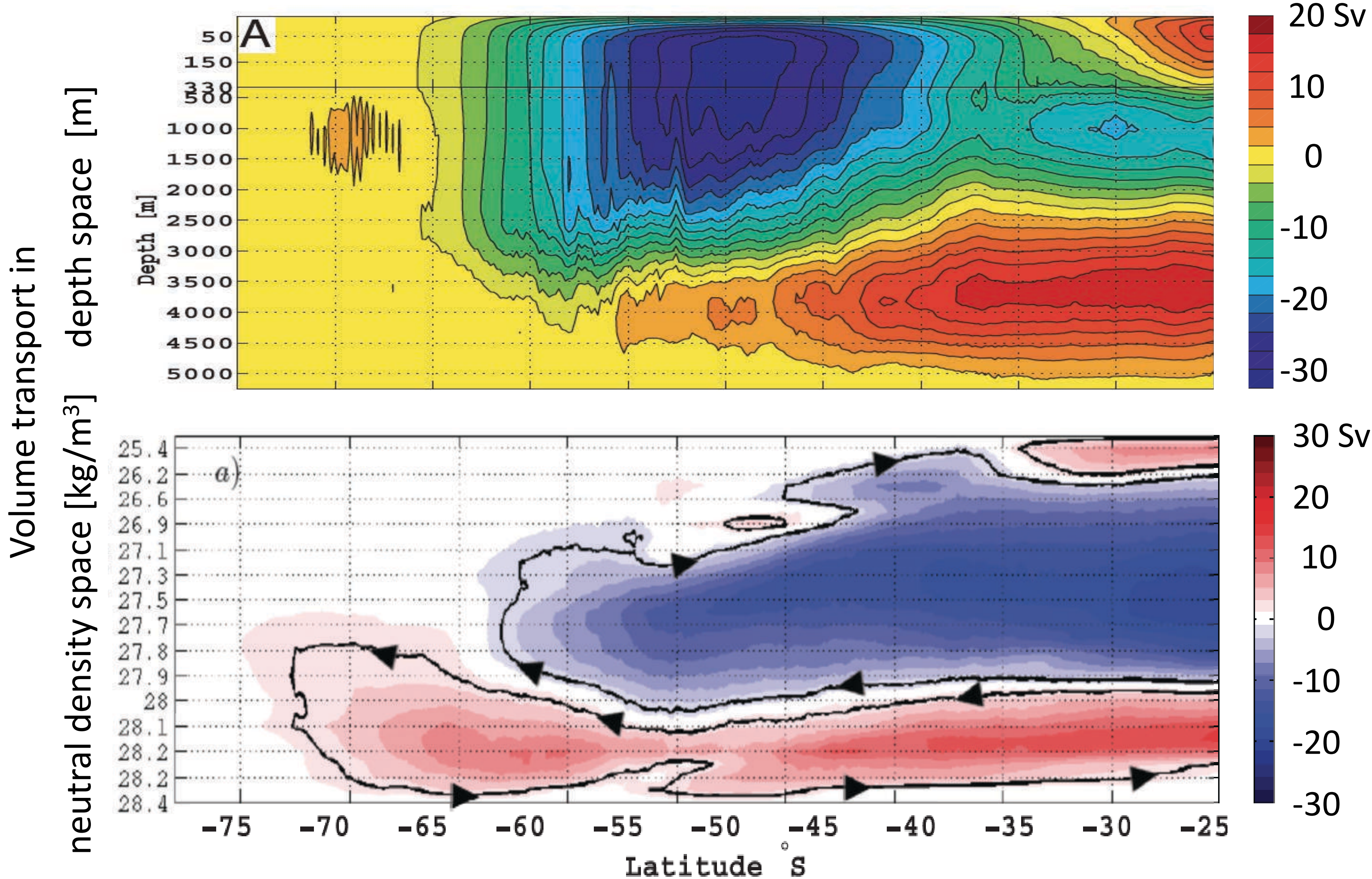
Interfacial form stress: "water push on water"

Consider the layer bound by 28.2 kg/m³ and the seafloor, on 1 Dec 2007:

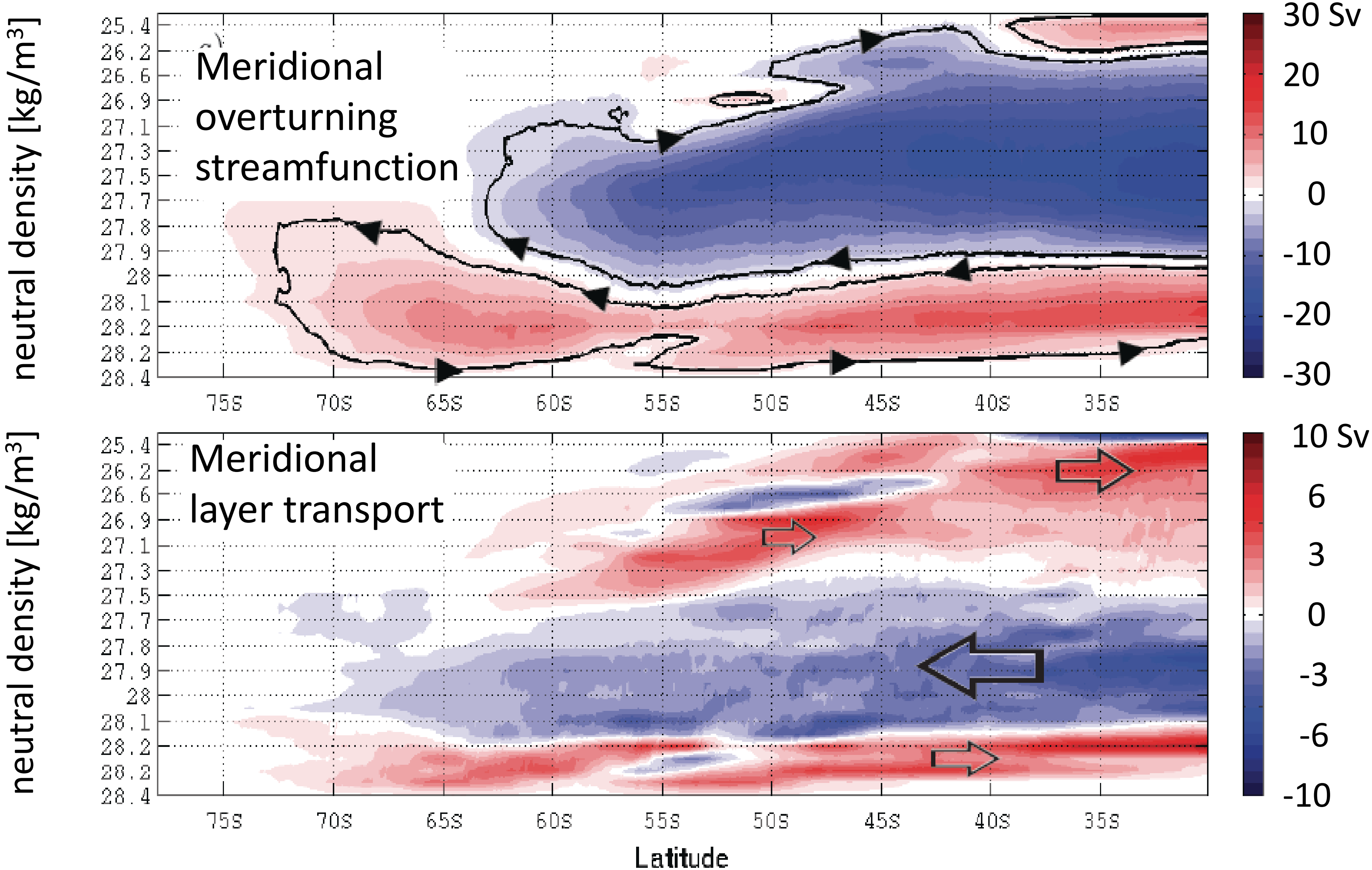


Slide from J. Masich

The meridional overturning streamfunction of the Southern Ocean



IFS and BFS reveal the meridional overturning circulation (MOC)

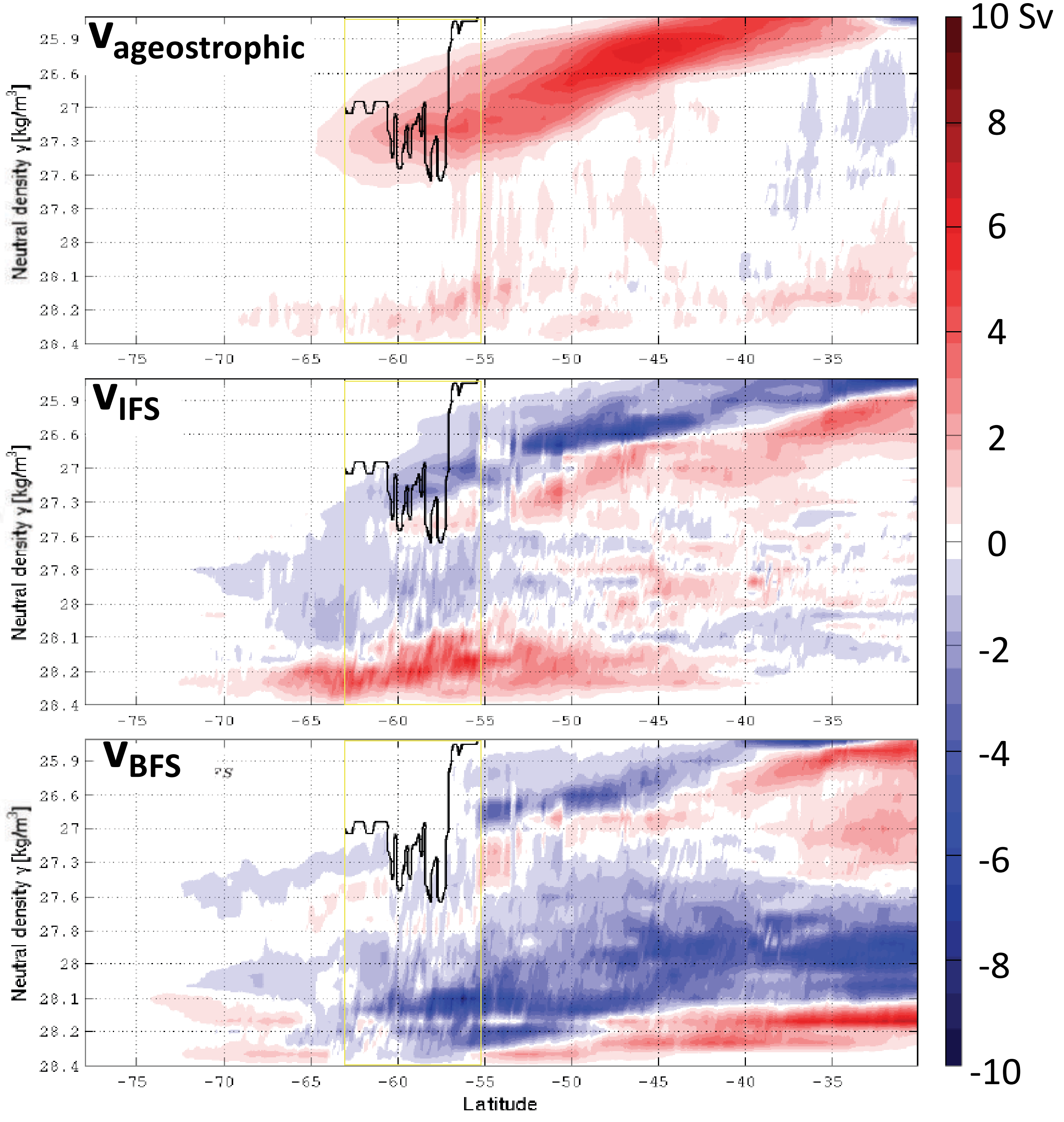


Components of the MOC

Air pushes on water

Water pushes on water

Water pushes on land



Components of the MOC

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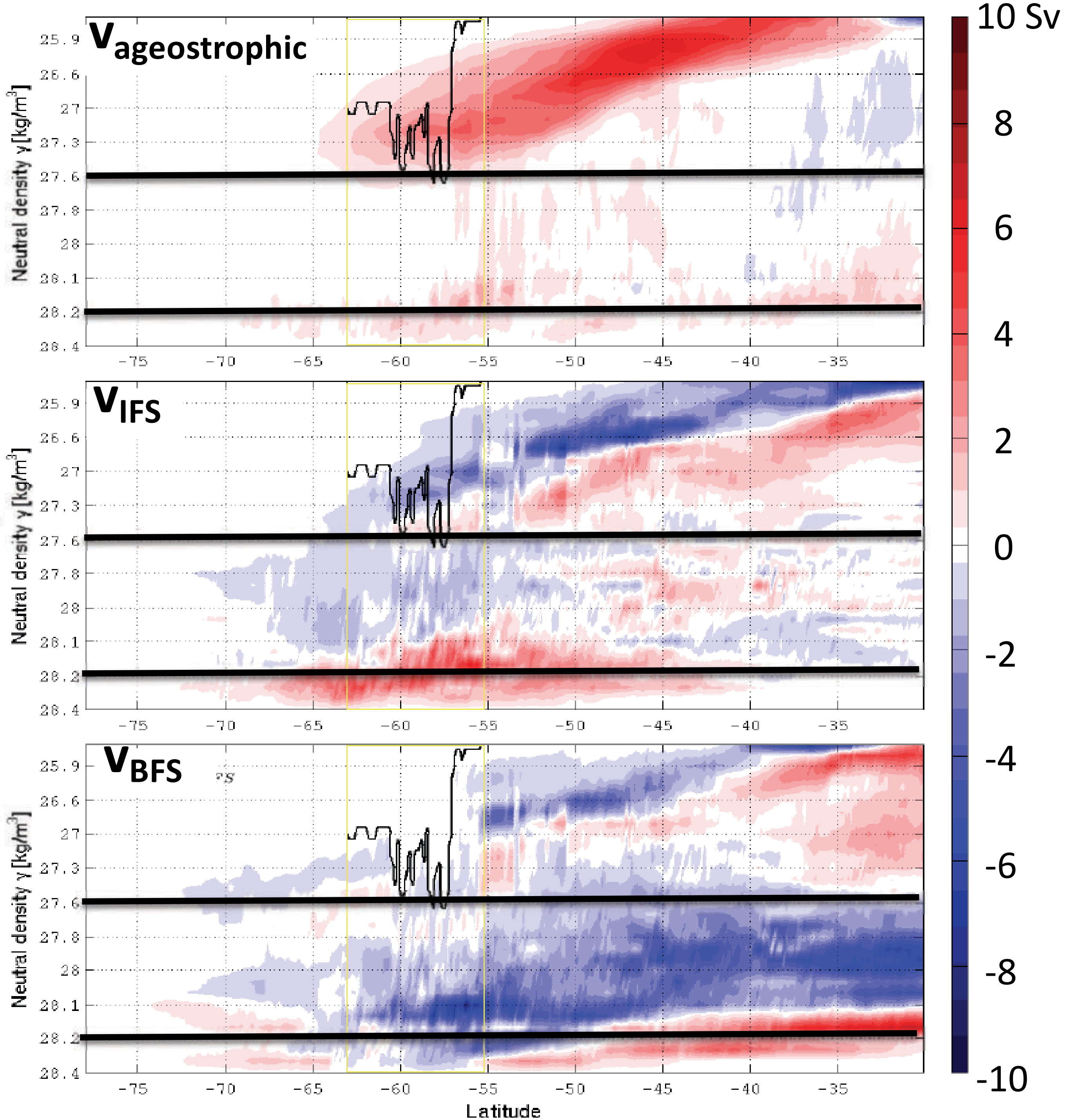
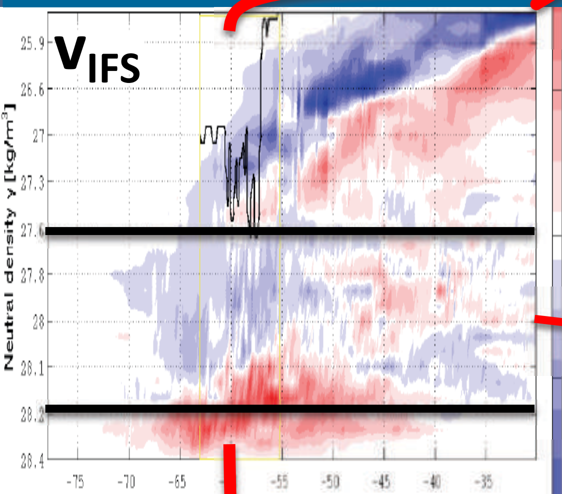


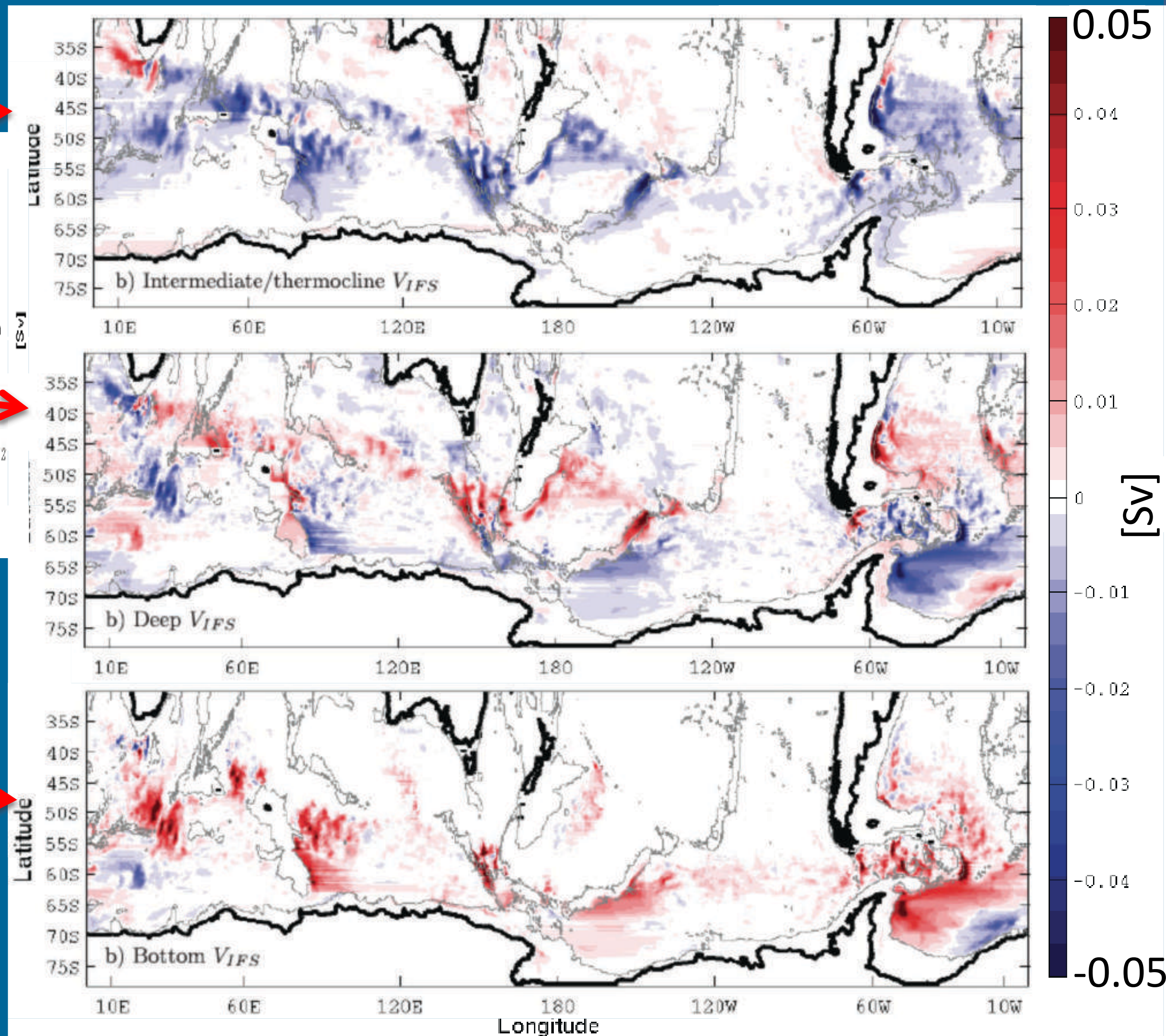
V_{IFS} in layers

Light

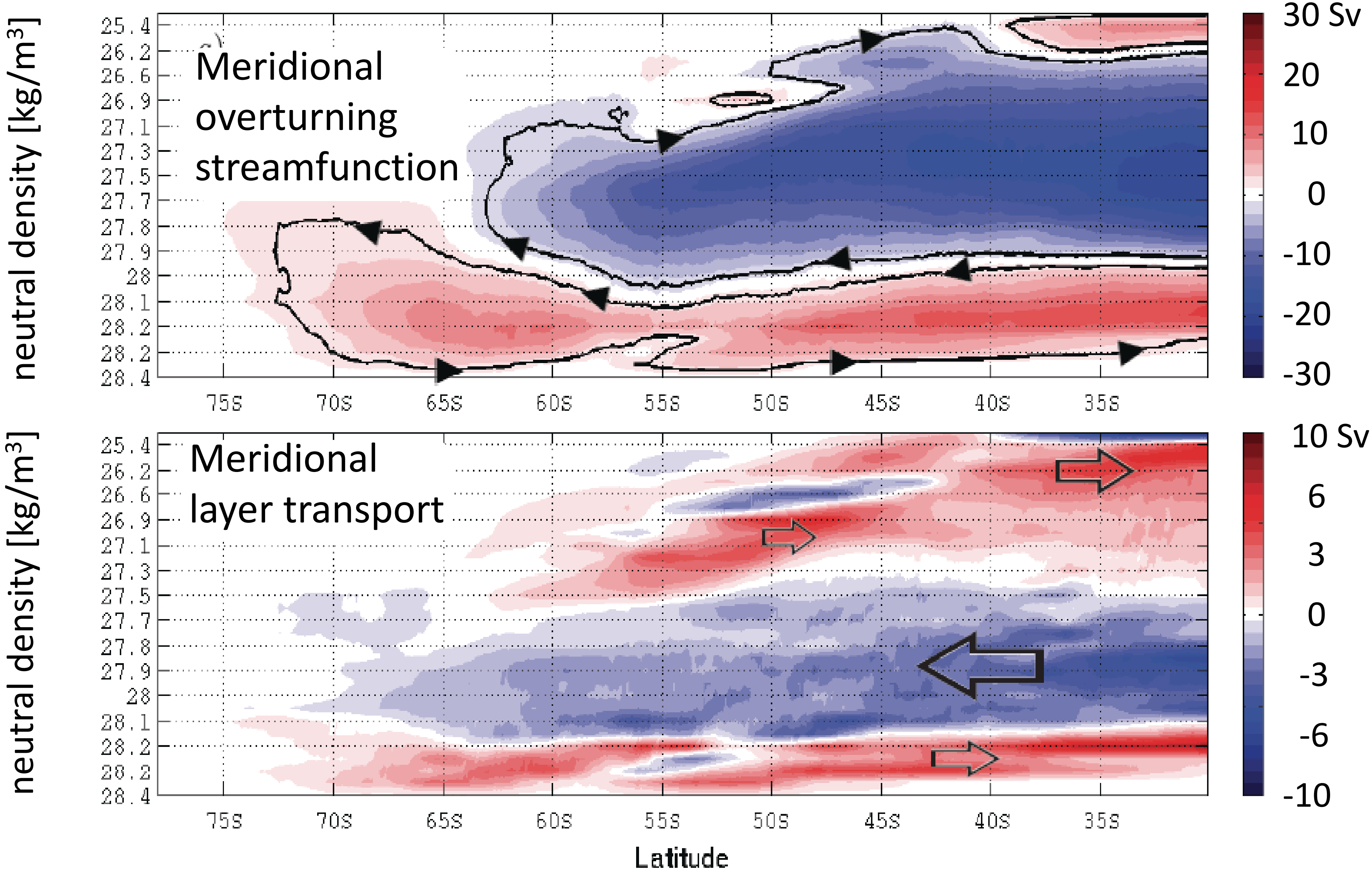
Deep

Bottom





IFS and BFS reveal the meridional overturning circulation (MOC)

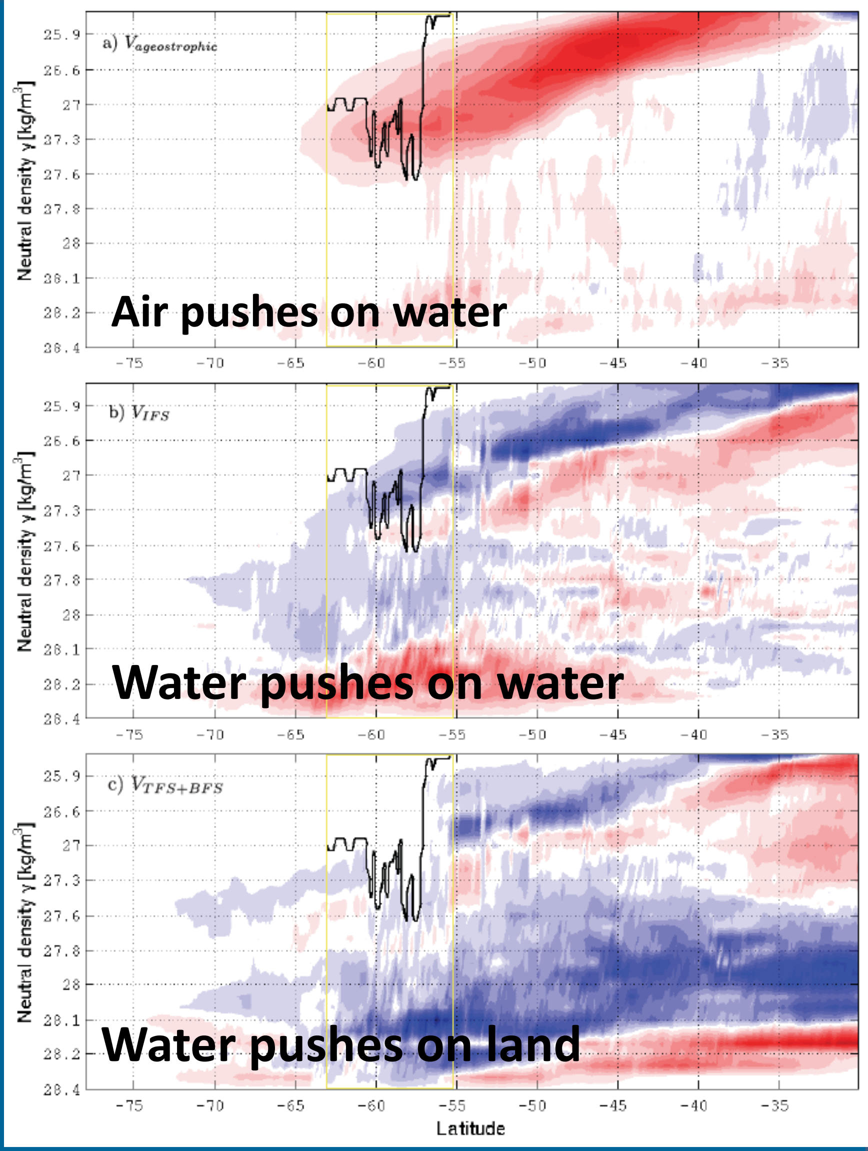


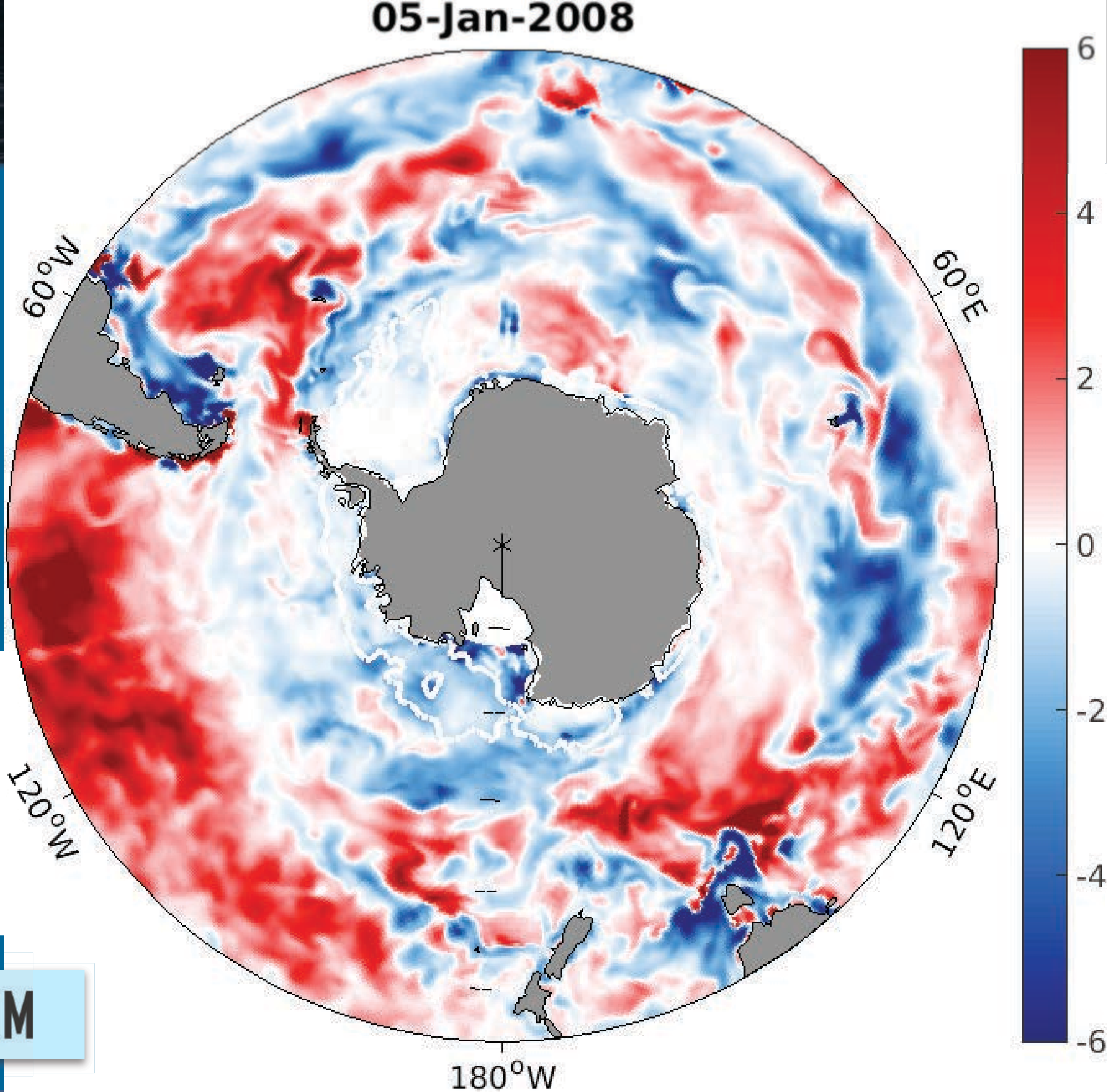
Southern Ocean Fundamentals
Summary #3

- Warm/salty and cold/fresh exchange is accomplished by zonal asymmetries in the mean geostrophic flow
- Vertical integral of momentum budget is

air pushes water + water pushes land = air pushes land

- Water pushes on water component on momentum budget (i.e. interfacial form stress; IFS) allows buoyancy constraints to be satisfied.
- In doing so IFS sets overturning strength

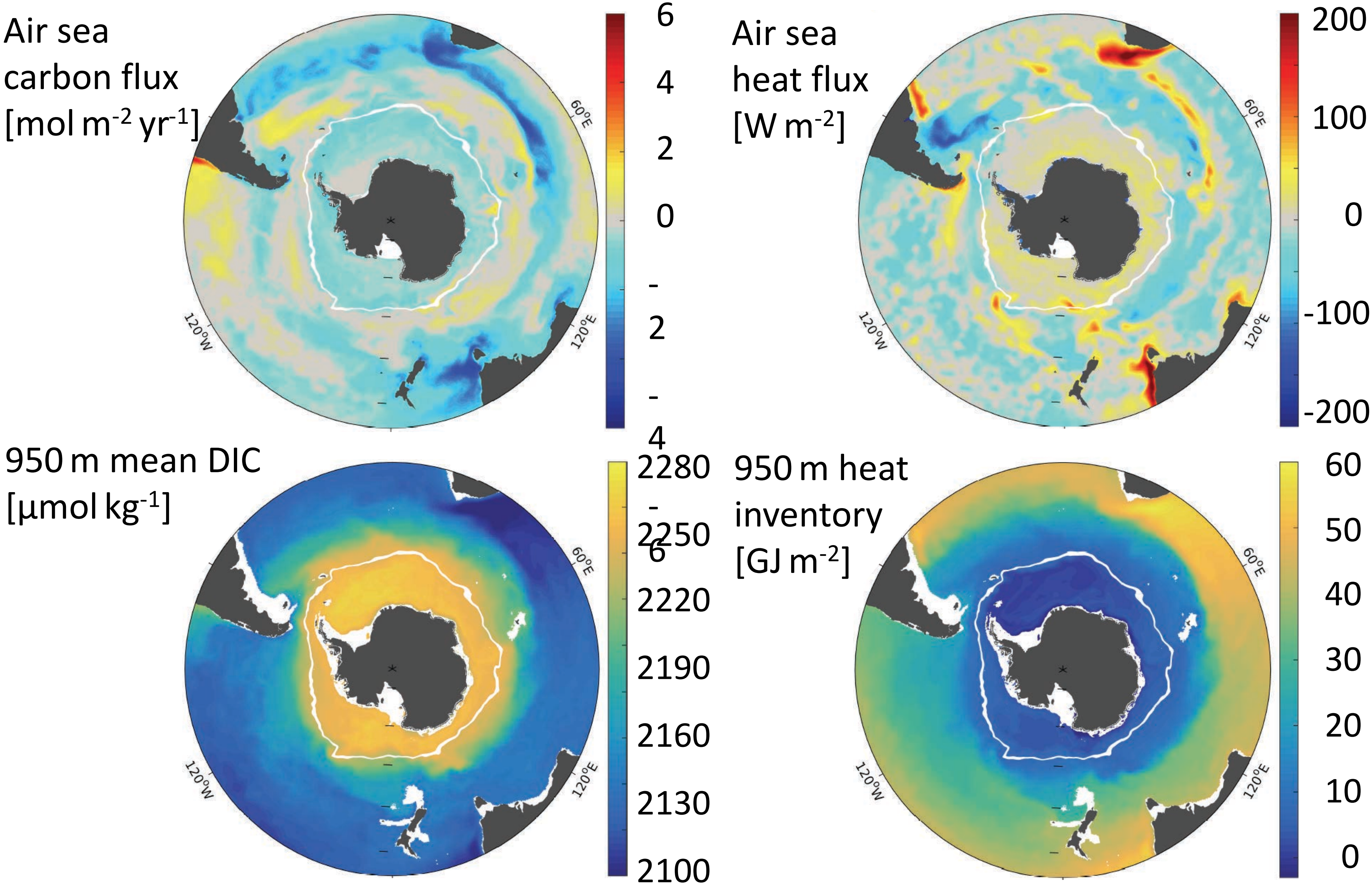




Air-sea CO_2 flux [mol m^{-2} yr^{-1}] from B-SOSE 2008 - 2012 solution

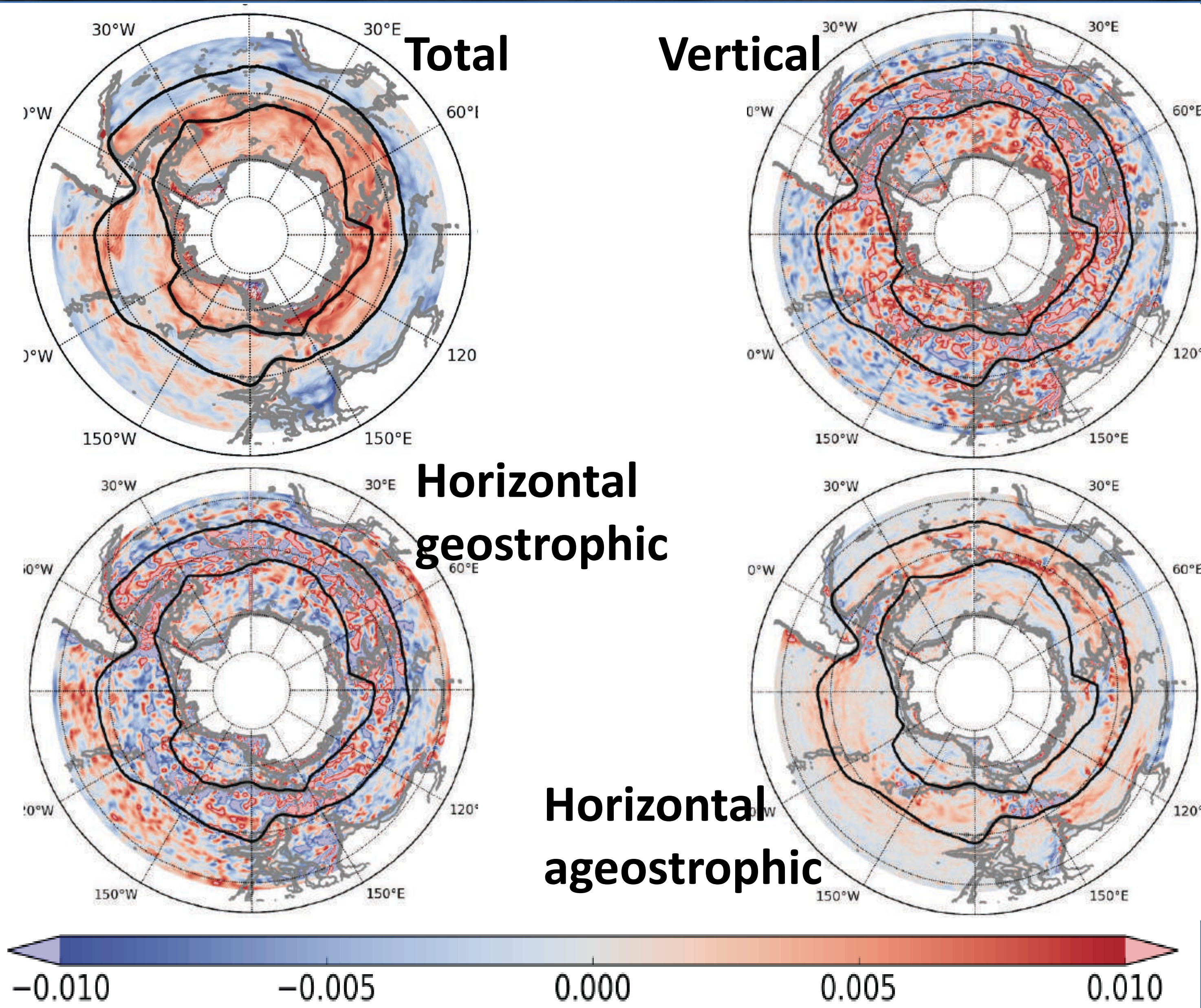
SOCCOM

Influence of the MOC on the dissolved inorganic carbon (DIC) budget
BSOSE mean fields:



Influence of the physical overturning circulation on the dissolved inorganic carbon budget

Components of advective transport divergence of DIC averaged over upper 650m [mol C m^{-3} y^{-1}]

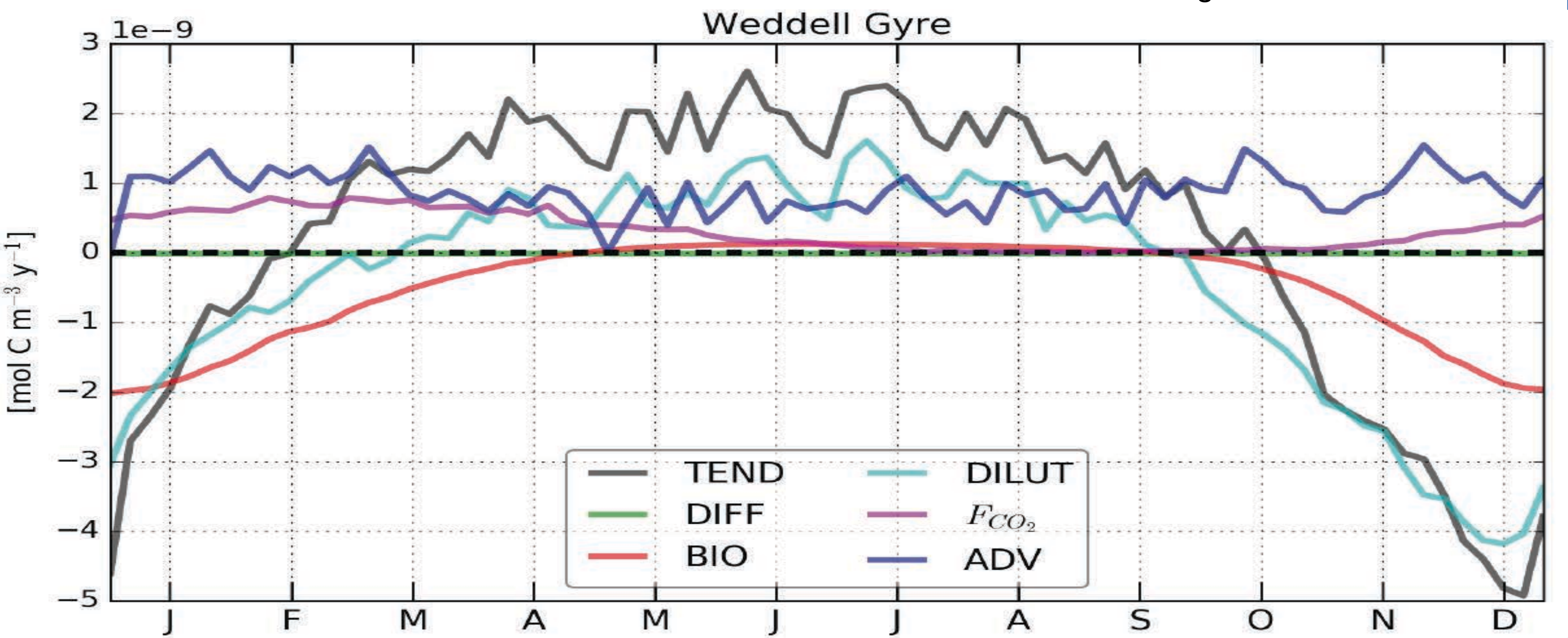


Figures from I. Rosso

Influence of the physical overturning circulation on the dissolved inorganic carbon budget

Seasonal DIC budget in Weddell Gyre

Figures from I. Rosso



Temporal change in DIC

Diffusive flux divergence

Biological processes

Dilution

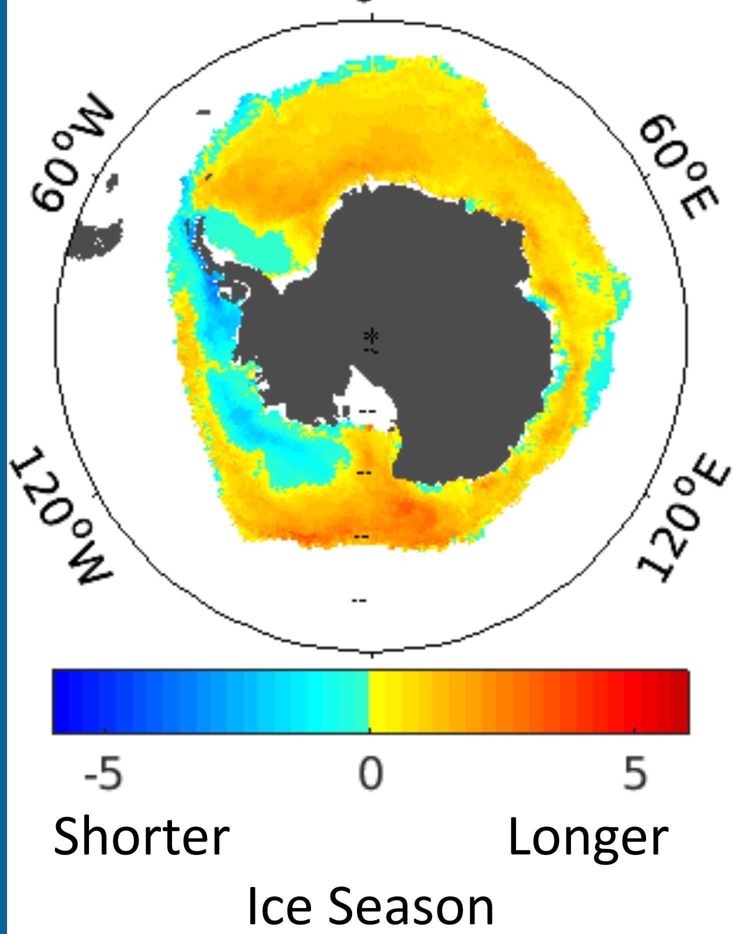
Air-sea flux

Advective transport divergence

Southern Ocean Fundamentals Summary #4

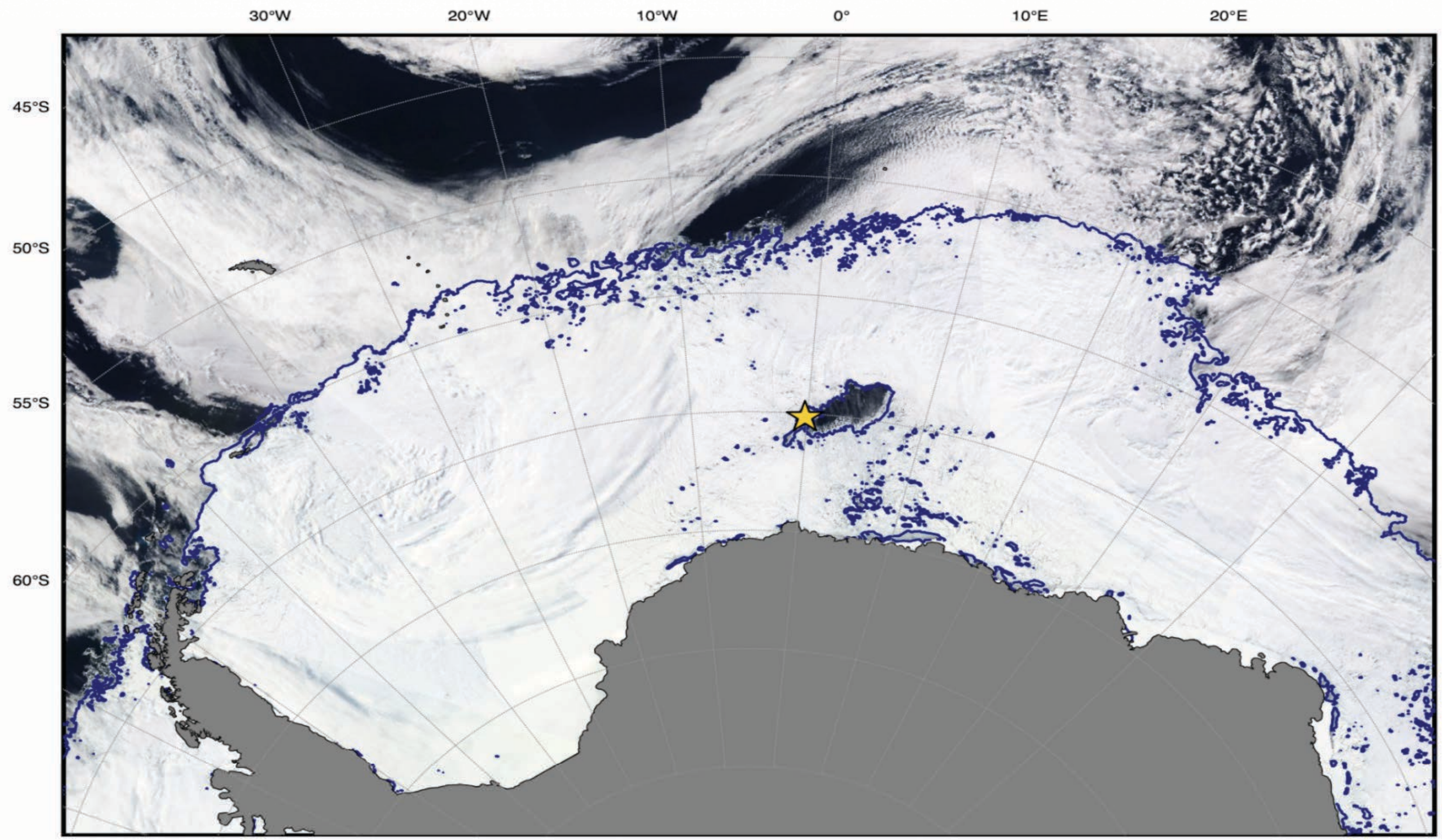
- Wind stress inputs momentum
- Bottom form stress removes momentum
- Interfacial form stress redistributes momentum throughout water column, allowing buoyancy constraints to be satisfied and setting the overturning strength
- The overturning strength regulates carbon and nutrient distributions
- Buoyancy constraints and carbon fluxes are both very sensitive to sea ice cover. And sea ice cover is changing!

Ice season duration trend 1979 to 2015



Calculated following the method of Stammerjohn et al. 2008

Weddell Sea Polynya Returns



Sea ice and clouds blanket the Weddell Sea around Antarctica in this satellite image from September 25, 2017. A SOCCOM float surfaced within the 60,000 km2 polynya (center) at the location marked in yellow. Image from MODIS-Aqua via NASA Worldview; sea ice contours from AMSR2 ASI via University of Bremen.

Contact: Ethan Campbell, University of Washington

Southern Ocean Talk Summary

- The Southern Ocean is a windy, energetic, and complex region
- Synthesizing all available information into a state estimate allows quantification of budgets, bringing scientific understanding to the region