The Southern Ocean Meridional Overturning Circulation as Diagnosed from an Eddy Permitting State Estimate

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(modified by P. Heimbach)

MIT-WHOI Joint Program

Now @ SIO/UCSD

ECCO-GODAE's contribution to ECCO2

- Proposal, section 4.2.2:
  - "*1. Cubed-sphere adjoint: Development of cubed-sphere adjoint will first take place on a global, coarse-resolution setup that includes Arctic Ocean and sea-ice. Each face of the cube comprises 32 by 32 grid cells, …* "

    ➔see later talk on C.S. adjoint

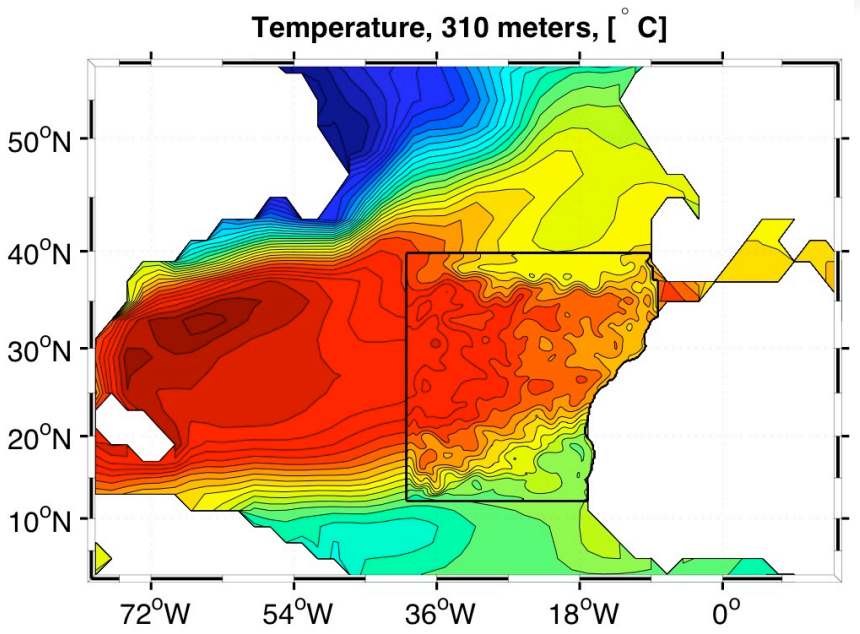
  - "*2. Exact high-resolution adjoint: The full high-resolution adjoint will be attempted for the global, 18-km cubed-sphere configuration and for two regional application, one in the North-Atlantic and one in the Southern Ocean.* "

    (Atlantic was left up to now to our German partners)

Preliminary and parallel work on high-resolution adjoint

- Gebbie (Ph.D. thesis, 2004)
  - Estimation at 1/6º resolution i the subduction region of the subtropical North Atlantic

    (Gebbie et al., JGR, 2006)



- Hoteit & Cornuelle
  - Estimation at 1/3º resolution in the tropical Pacific (now extended to forward 1/6º)

    (Hoteit et al., Q.J.Roy.Met.Soc., 2006)

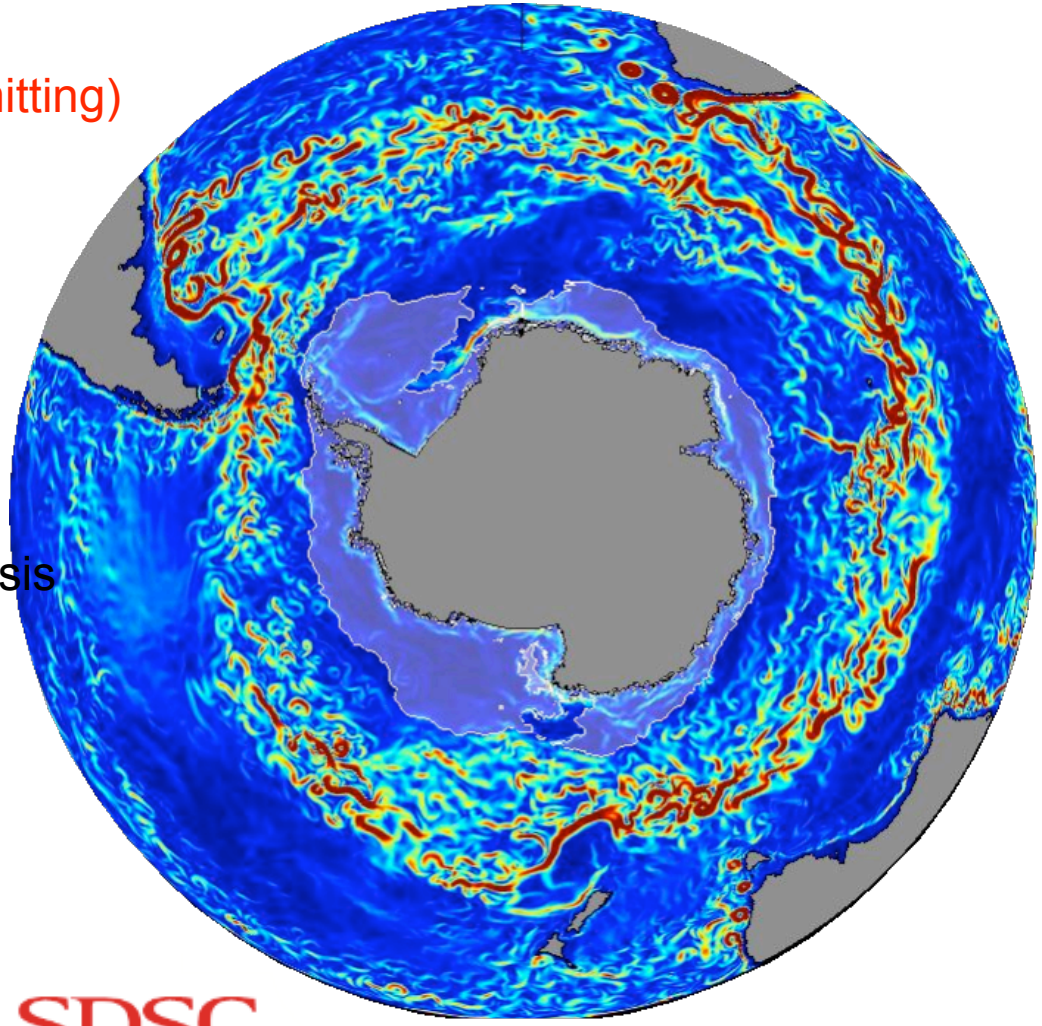
Matt Mazloff's Thesis Questions

- Small scale (eddy) dynamics are thought to play an essential role in the Southern Ocean dynamics. Can we find an eddy permitting model solution of the Southern Ocean that is consistent with the observed ocean?

- What is the force balance of the Southern Ocean meridional overturning circulation (MOC)? Is the balance assumed in current theories of the MOC representative of the true Southern Ocean?

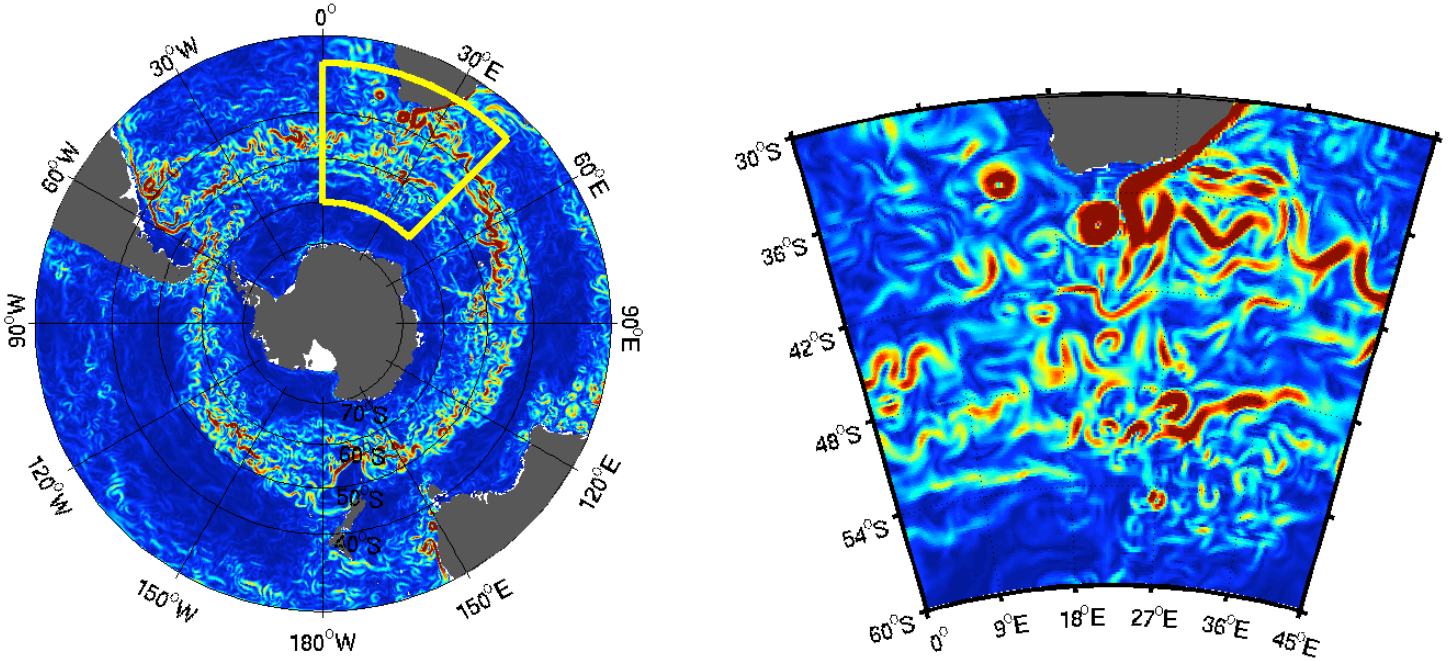
Southern Ocean State Estimate Configuration

- 78^0 South to 24.7^0 South
- $1/6^0$ Horizontal resolution (eddy permitting)
- 42 depth levels (partial cells)
- initial conditions and open boundary conditions derived from, and constrained to, G. Forget's 1^o resolution global state estimate (OCCA)
- atmospheric boundary layer scheme
- constrained to NCEP/NCAR re-analysis atmospheric state
- adjoint generated via AD tool TAF
- sea-ice model
- KPP, GM/Redi parameterizations
- currently optimizing years 2005-06
- 600 processor adjoint on SDSC's DataStar (IBM SP4) supercomputer



SDSC
SAN DIEGO SUPERCOMPUTER CENTER

The 2-year solution (iter. 22)



current speed at 53m [m/s] : day =5

0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50

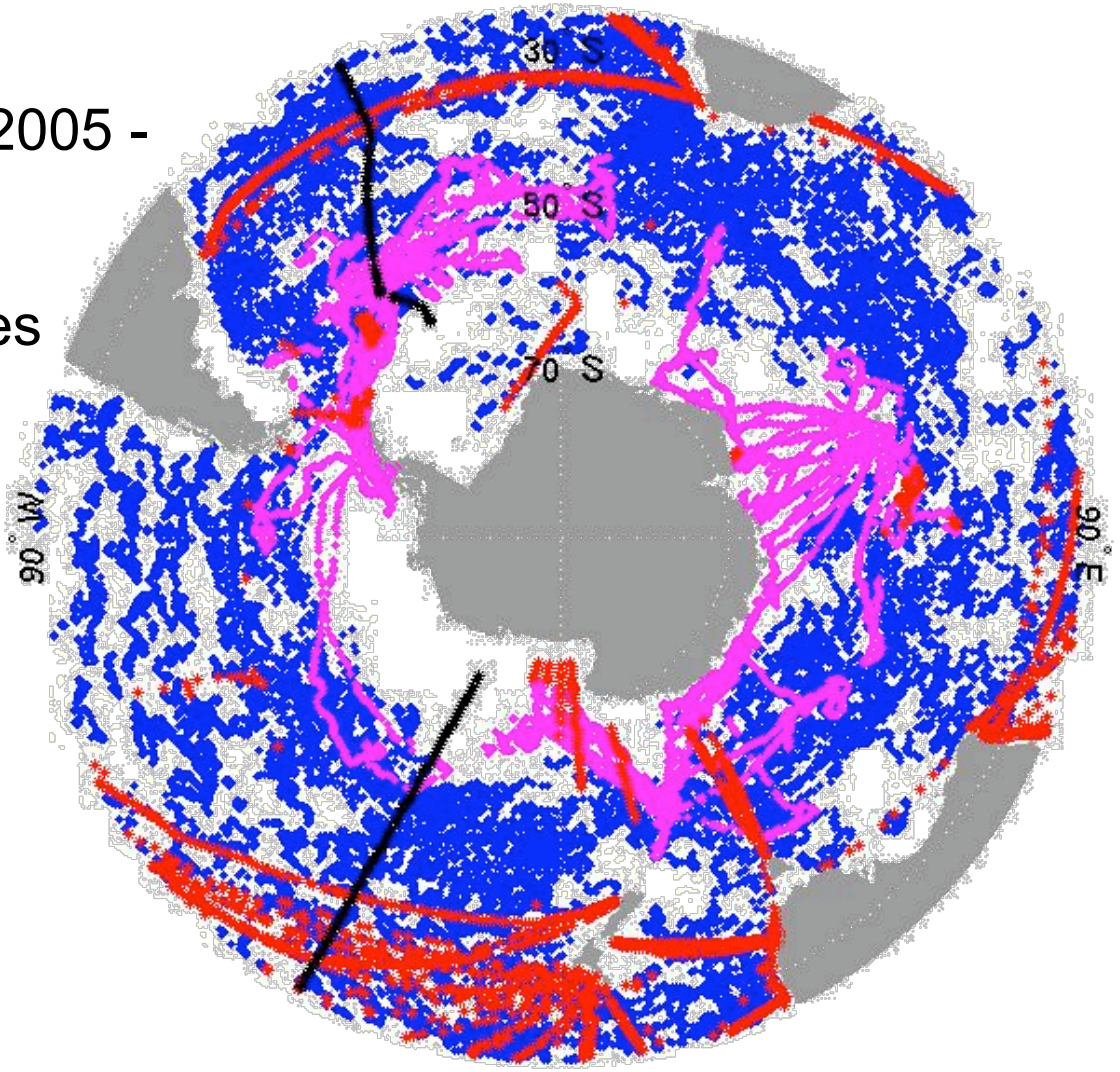
Observational Constraints

observation	*instrument*	*product*	*#*
Mean dynamic topography (MDT)	•GRACE SM004-GRACE3	CLS/GFZ (A.M. Rio)	1.1×10^7
Sea level anomaly (SLA)	• Jason • ENVISAT • GFO	PO.DAAC AVISO NOAA, USN	4.3×10^7 7.3×10^6 3.9×10^6
SST	• AVHRR • TMI AMSR-E	NOAA/Reynolds Remote Sensing System	1.3×10^7 1.1×10^7
In-situ T, S	• Argo • XBT • CTD • SEaOS	Ifremer S. Behringer (NCEP) Various SMRU & BAS (UK)	4.2×10^6 4.7×10^4 6.2×10^4 3.8×10^5
Climatological T,S	• WOA01 (upper 300 m) • WOCE	Conkright et al., 2002 Gouretski & Koltermann, 2004	2.5×10^7

Observational Coverage

In situ profile coverage for 2005 - 2006. Total number of observations in parentheses

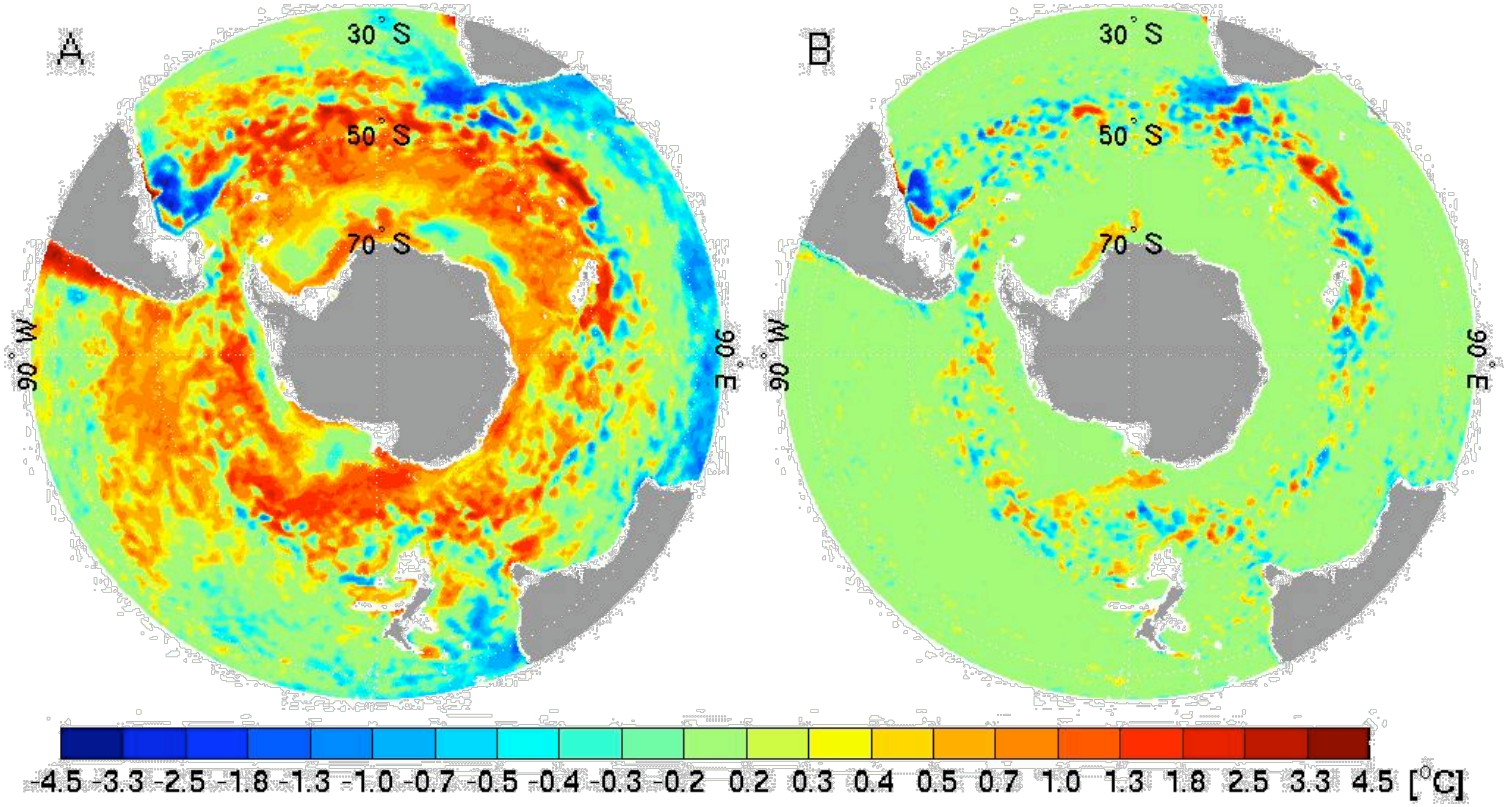
- SEaOS (3.8×10^5)
- ARGO (4.2×10^6)
- XBT (1.2×10^4)
- CTD (2.5×10^4)



Change in SST misfit

Iteration 0 (Control run)

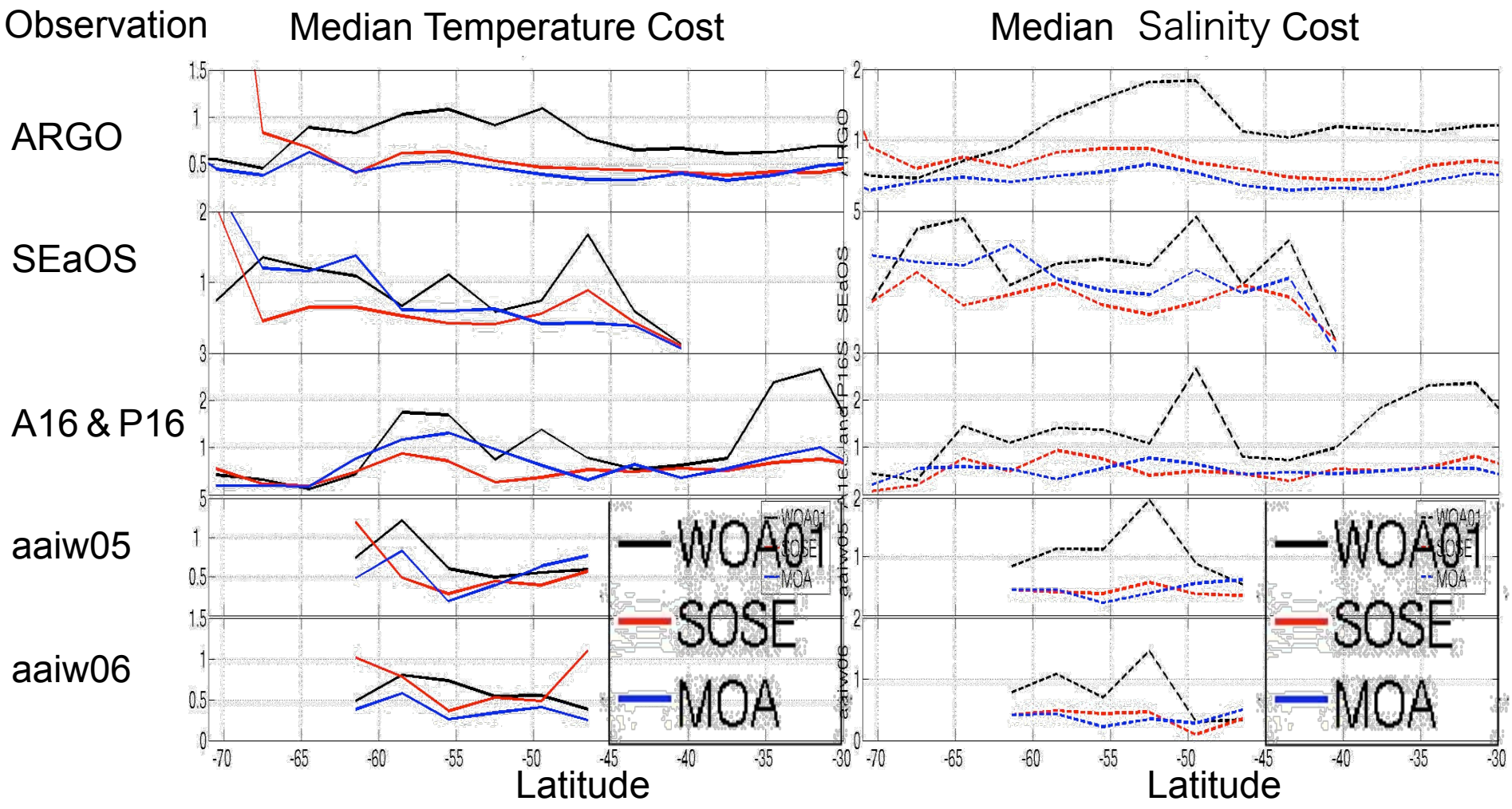
Iteration 23



Time average of model solution minus observations [°C]
Observations are combined mean from infrared (AVHRR) and microwave (TMI AMSR-E) radiometers
Exponential color axis

Binned cost: WOA01, MOA, SOSE (iter26)

Binned median cost (weighted product - observation squared) at each longitude

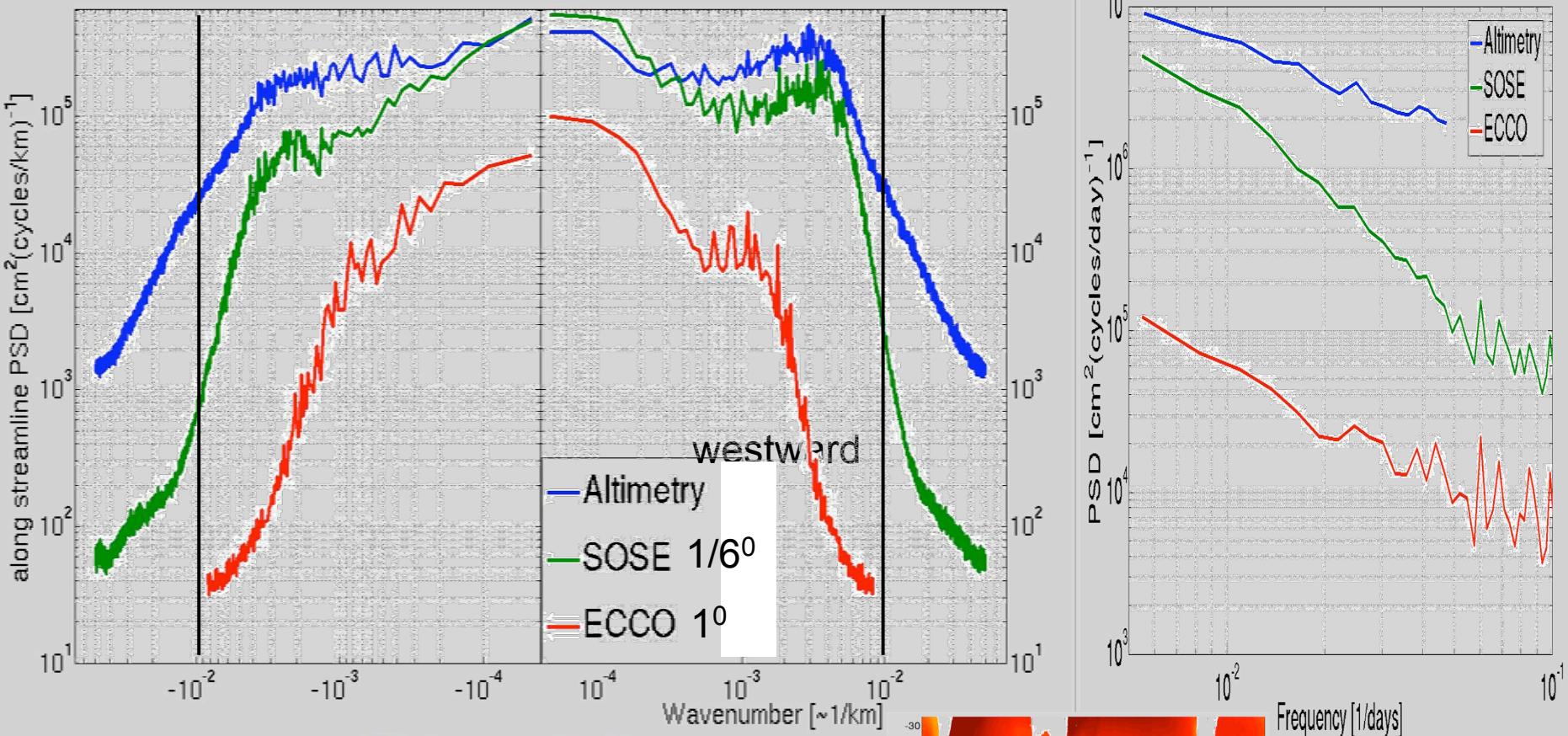


SOSE Results

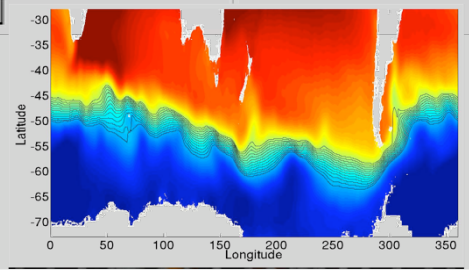
- The adjoint method optimization is converging towards consistency at eddy permitting resolution
- Perturbations to input variables similar to those found in coarse state estimates
- Largely consistent with all individual observations and previous static inverse models
- A better fit to the 2005-2006 *in situ* observations than the WOA01, and with realistic dynamics

SSH power spectra density (from Iter 5)

Along streamline spectra vs. wavenumber (left) and frequency (right)



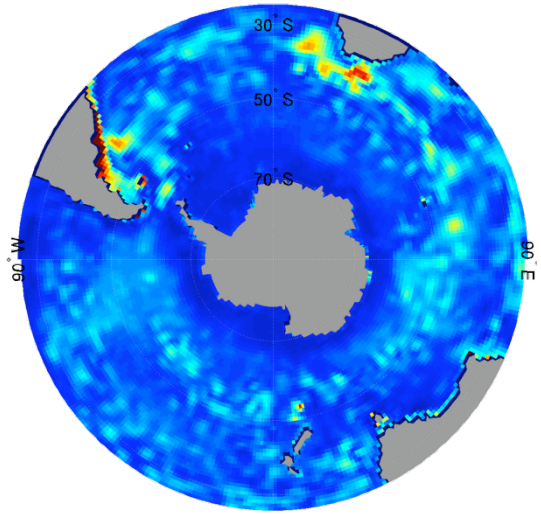
westward | eastward



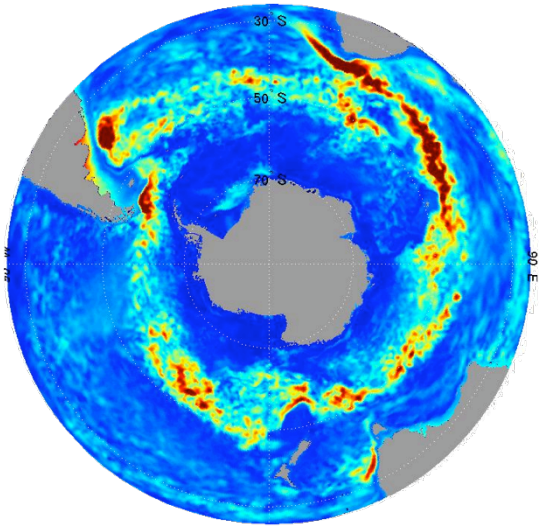
streamlines

rms sea surface height anomaly [cm]

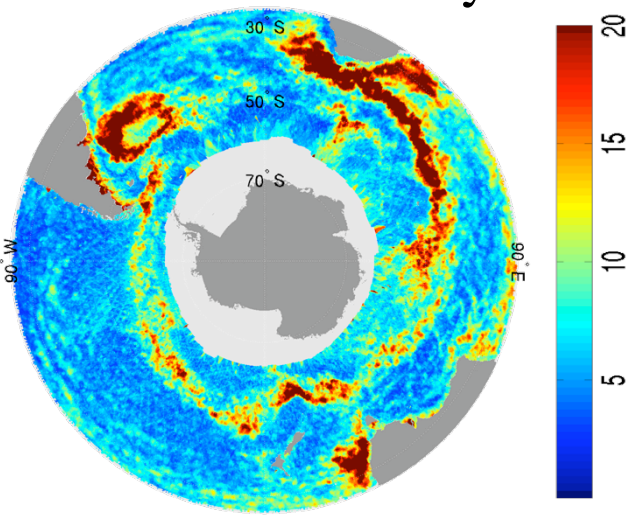
ECCO-GODAE



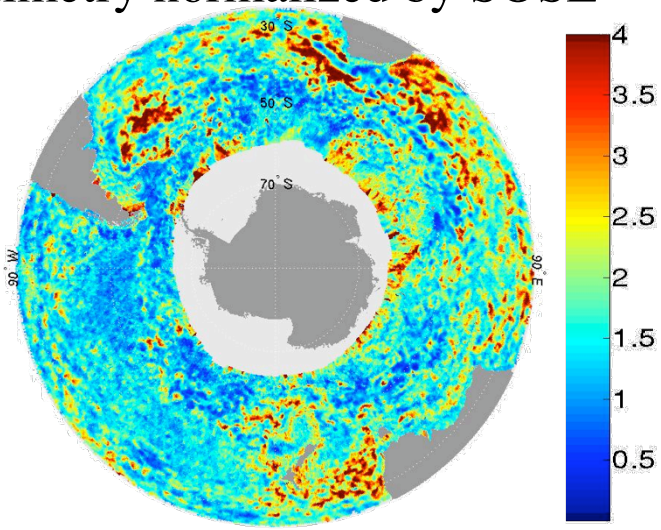
SOSE (I16)



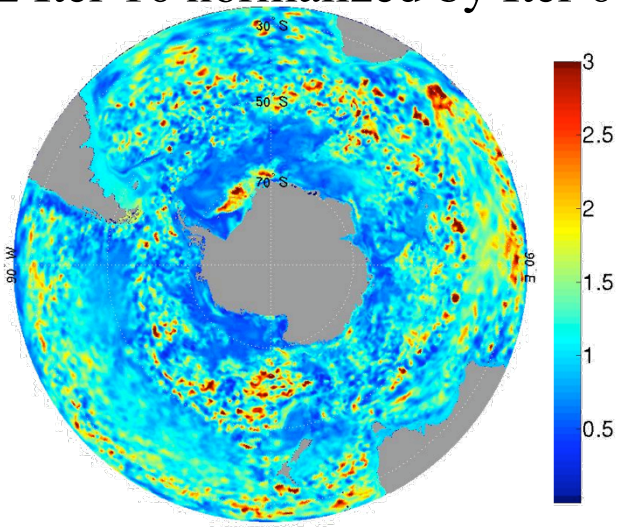
Altimetry



Altimetry normalized by SOSE

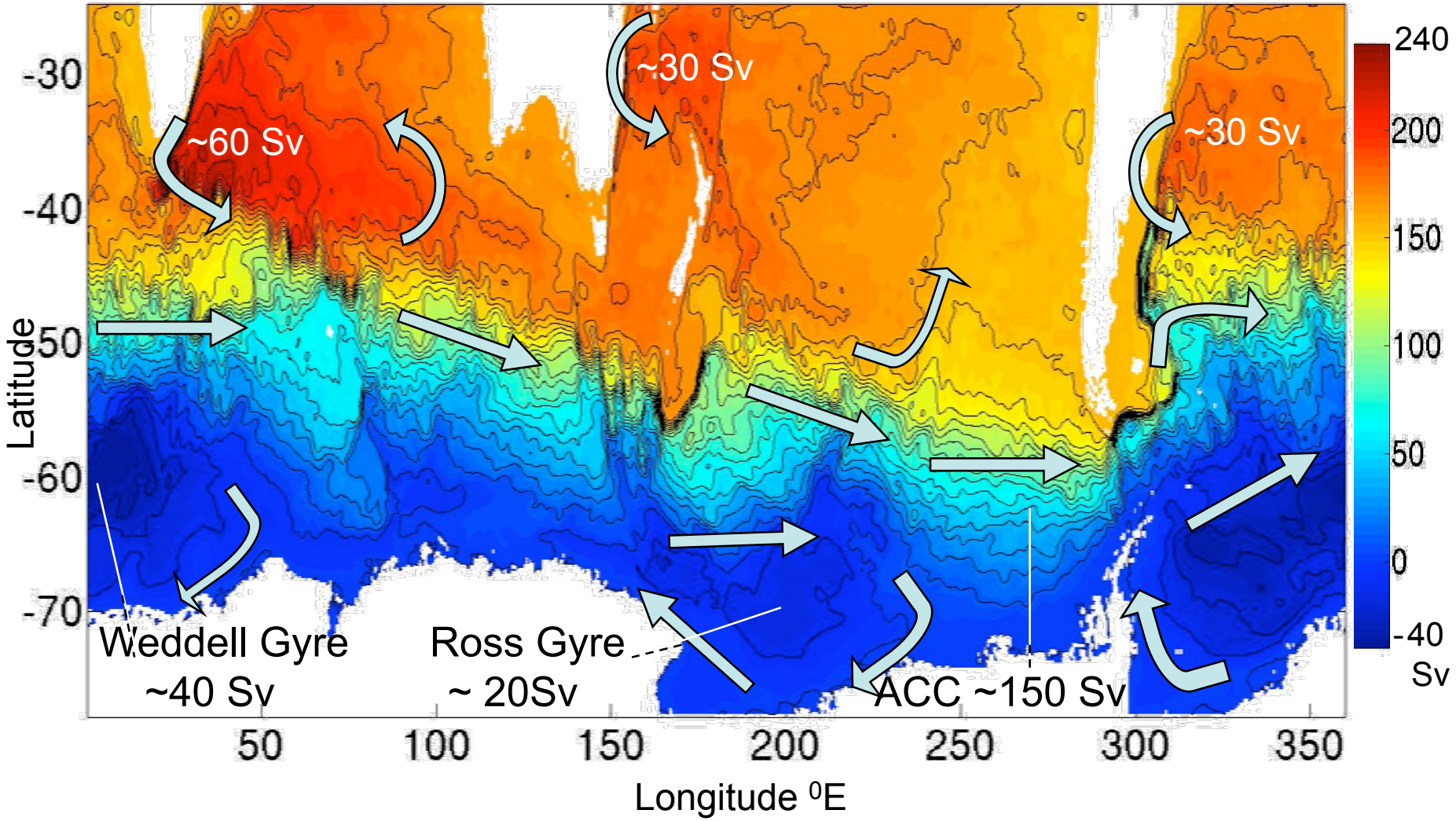


SOSE Iter 16 normalized by Iter 0



Mean Horizontal Transport in SOSE

Vertically integrated transport streamfunction [Sv]



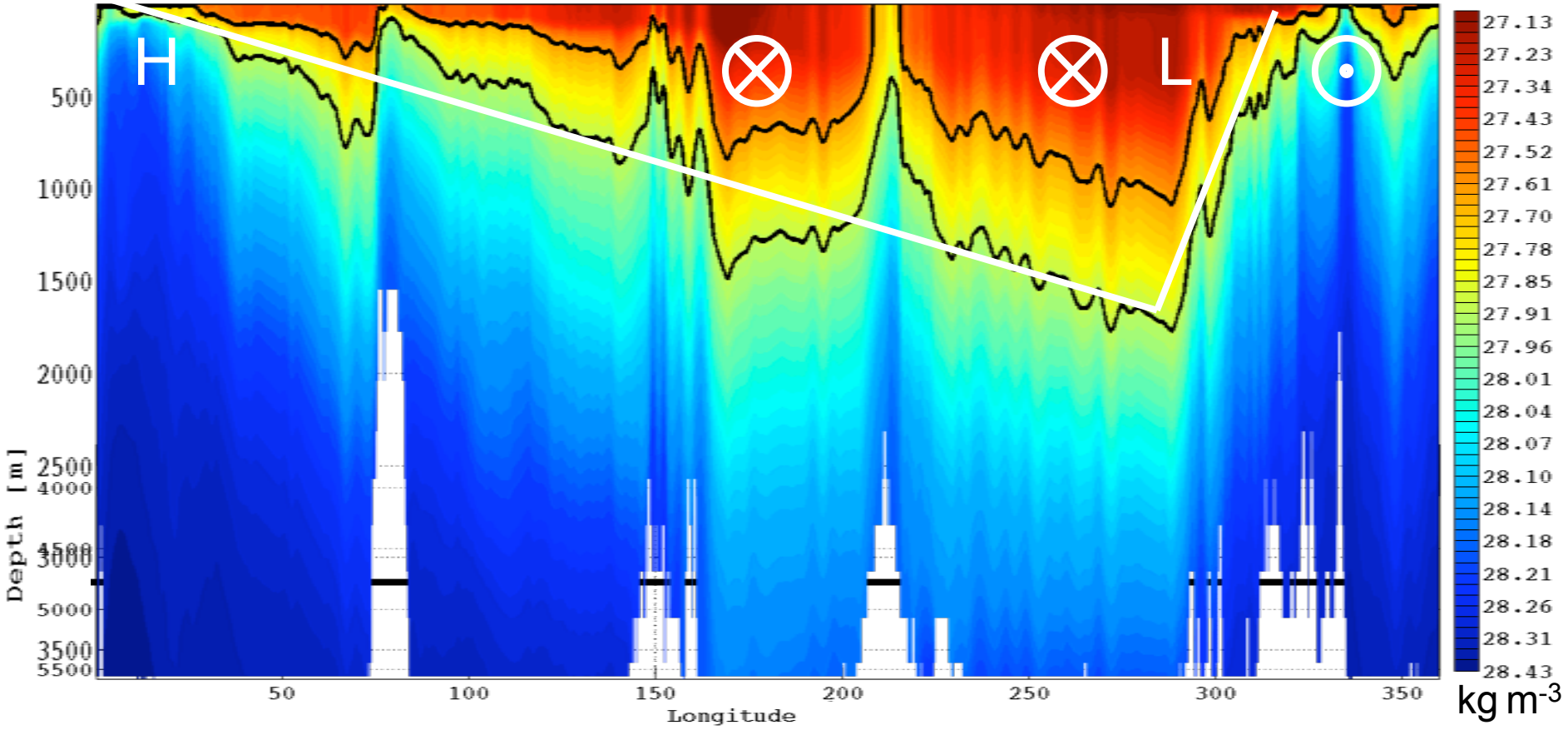
Current Theories of MOC

- Issues:
  - What is circulation in non-ventilated layers?
  - Are the assumptions made regarding the lowest order forcing relevant to actual Southern Ocean?
    - For near surface assume balance between eddies and wind stress
    - In abyss assume balance between eddies and pressure gradients
  - Rely heavily on eddy parameterizations; is the assumed eddy circulation realistic?
- To address these issues, the force balance of the MOC was analyzed in isopycnal (γ) coordinates using the Southern Ocean state estimate

Pressure Forcing in Unblocked Latitudes

Geostrophic transport, $v_g = (f\rho_o)^{-1} p_x$, vanishes when zonally integrated at constant depth, but not when integrated at constant γ, θ, or S. (AAIW moves equatorward while UCDW poleward)

Spring averaged γ at latitude 58^{0}S (γ contours: 27.63 & 27.9 kg m^3)

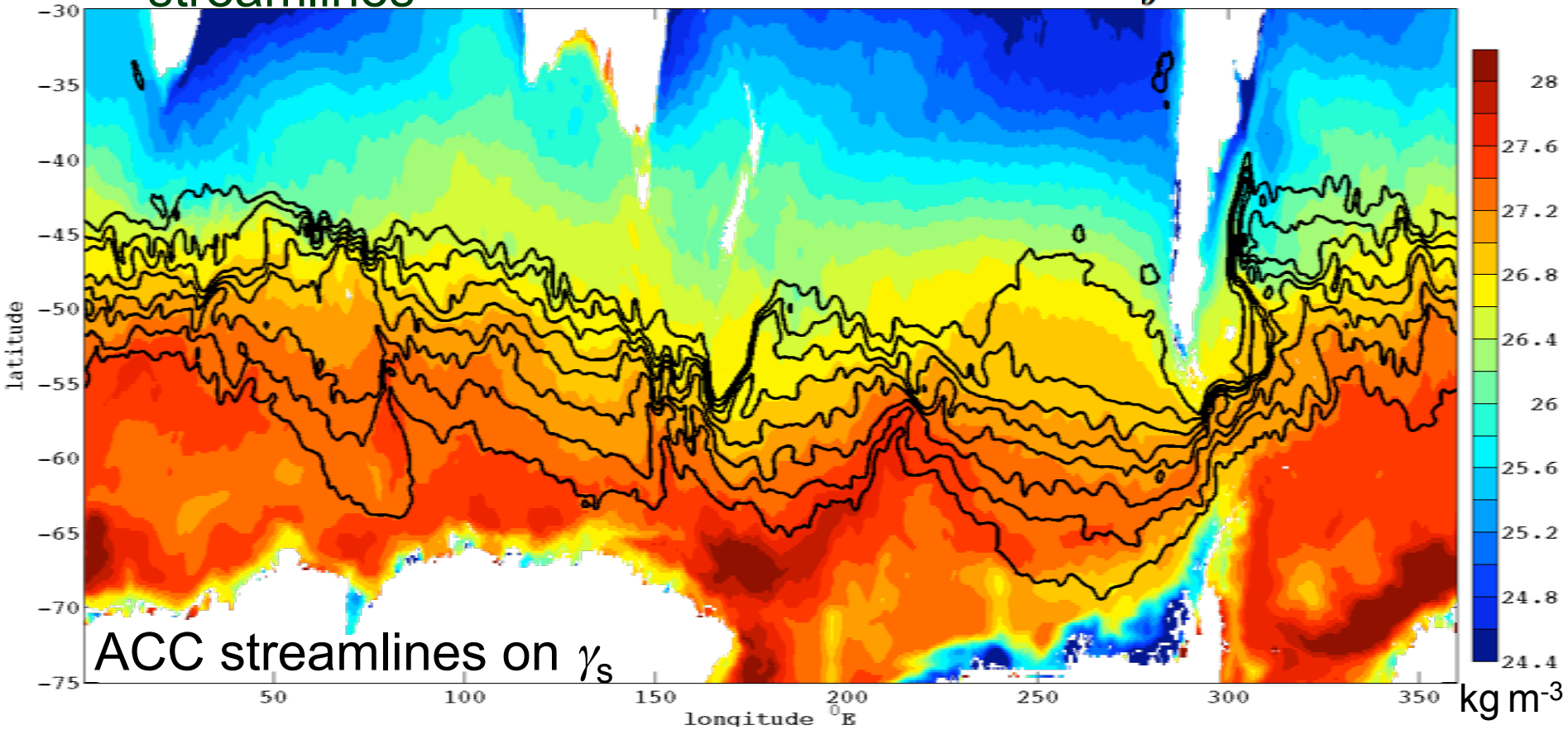


Pressure Forcing

- Pressure forcing is still significant for
  - Streamwise integration
  - Coordinate rotation into along and across streamlines

$$\oint p_x ds \neq 0$$

$$\oint \gamma p_s ds \neq 0$$



Conclusions

- A 2 year Southern Ocean state estimate (SOSE) was produced at eddy permitting resolution
  - A step towards goal of eddy resolving global state estimates
  - Provides a useful data set to study the Southern Ocean
- Eddy PV fluxes
  - drive an equator-ward flow in the most buoyant waters
  - derive part of their energy from direct wind stirring
  - are rather insignificant in the ocean interior
- Pressure forcing is lowest order everywhere in the Southern Ocean residual circulation force balance.

SOSE Users

- I. Cerovecki (SIO)
- L. Talley (SIO)
- R. Abernathy (next talk)
- T. Ito
- J. Ledwell

➔ The Southern Ocean community is taking notice of a useful product for science!