Southern Ocean 4-D circulation: combining altimeter and Argo float data

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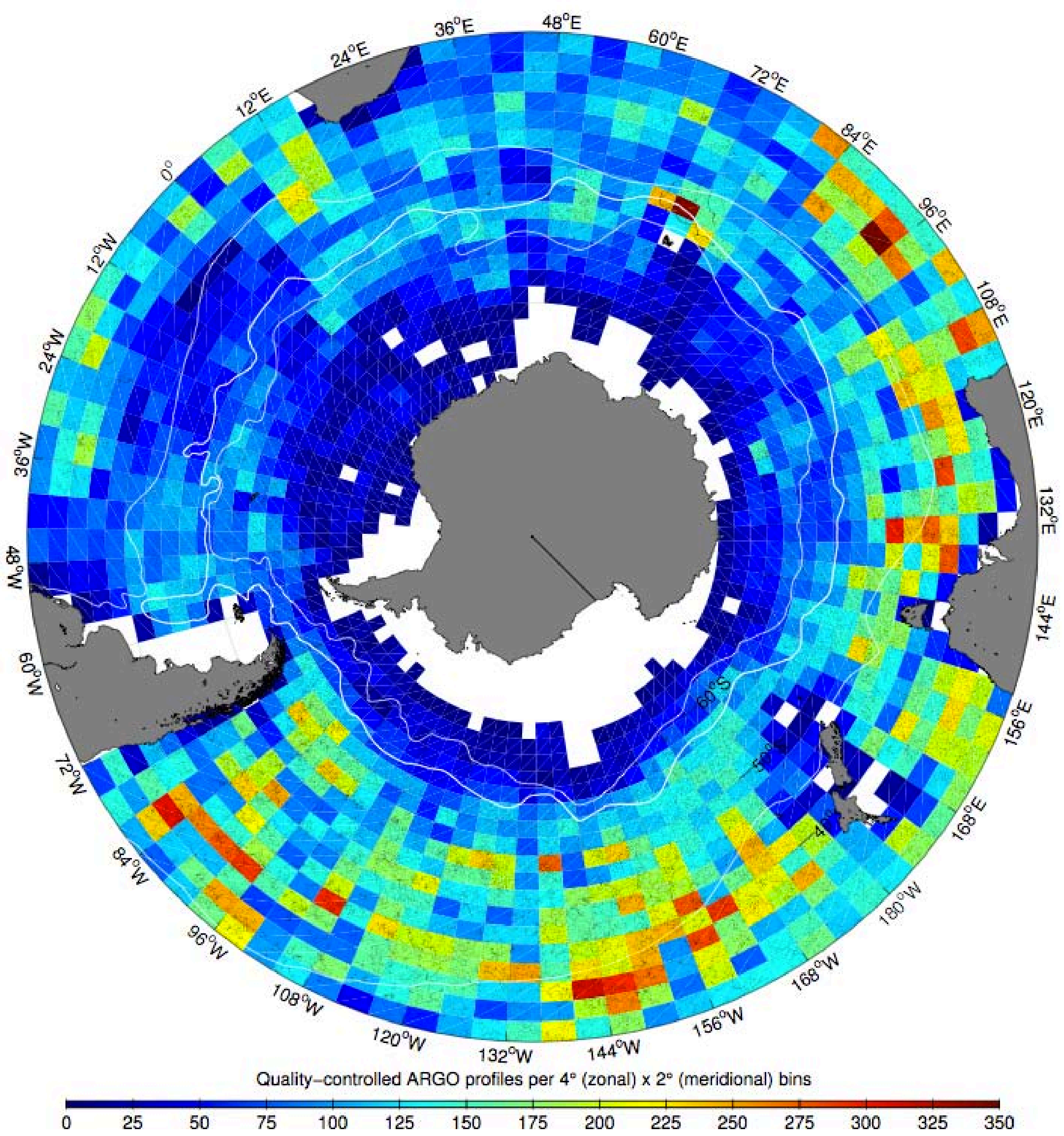
2012 Ocean Surface Topography Science Team Meeting
Venice-Lido, Italy - September 27-28, 2012

This work was supported by NASA Headquarters under the NASA Earth and Space Science Fellowship Program – Grant 'NNX11AL55H'

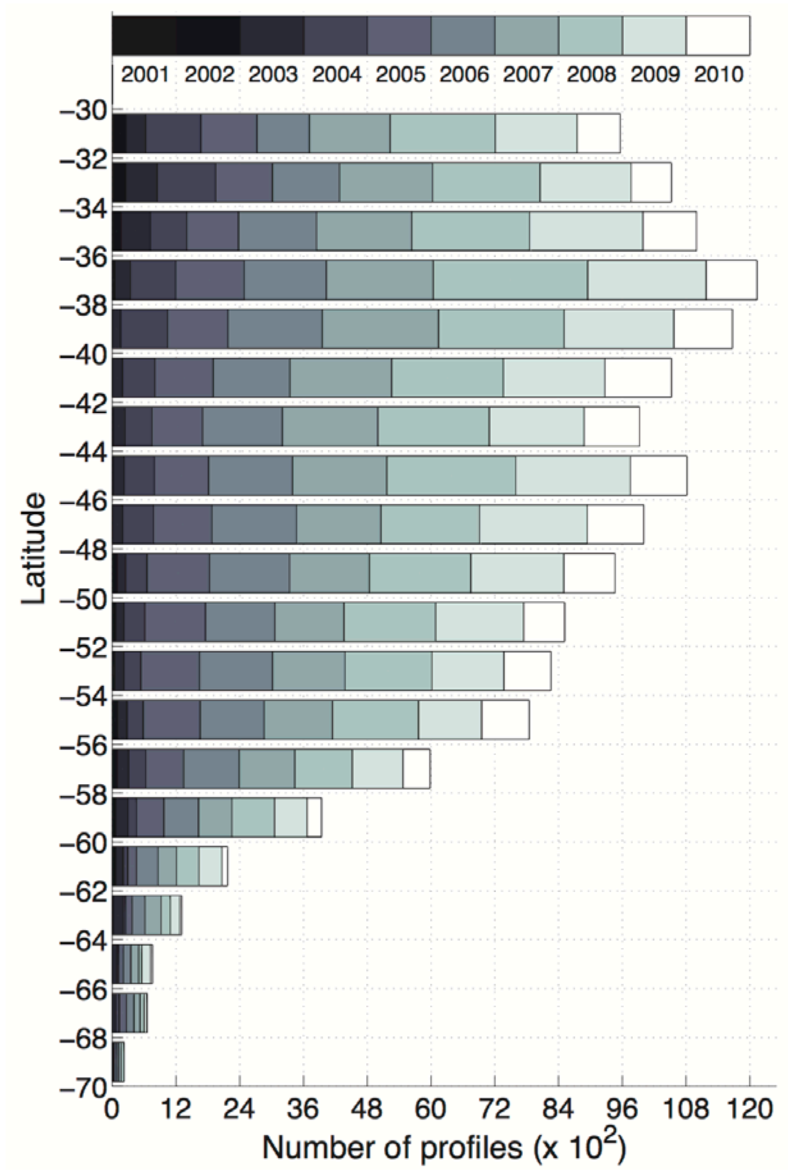
Motivation

Since the launch of the Argo program the number of observations in the Southern Ocean has steadily increase, however, some regions still remain poorly observed.

Quality controlled delayed-mode Argo profiles per 4° x 2° bins



Profiles per year and latitude band for 2001-2010



Motivation

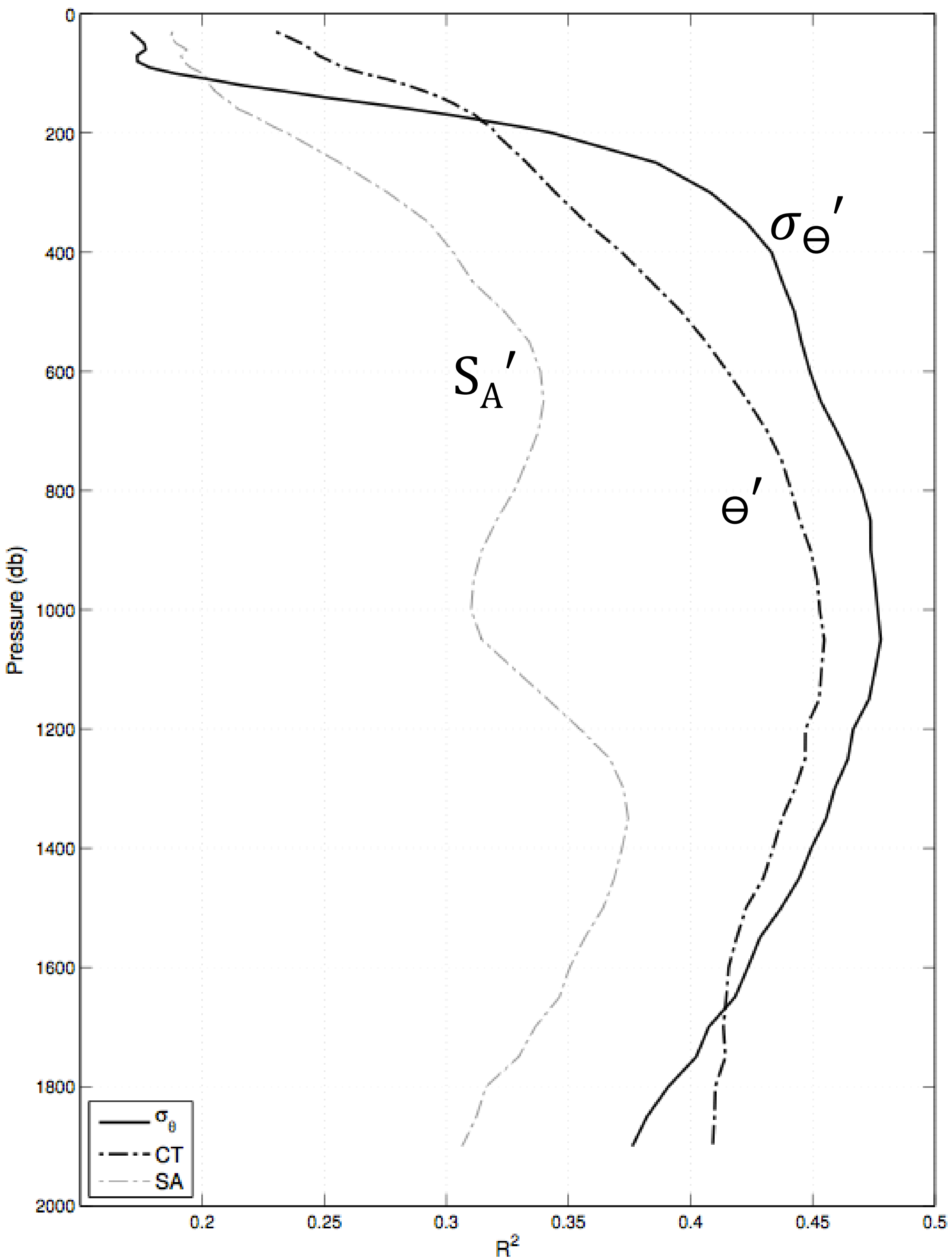
This relatively low resolution in space and time restricts the observational analysis of subsurface ACC variability to hydrographic sections, and basin or circumpolar scale studies of subsurface variability are largely model based.

Goal

Take advantage of the close relation between subsurface density profiles and surface proxies, such as dynamic height to extract information on the subsurface structure.

How much variance can be explained by the altimeter?

Domain-averaged variance vs pressure



$S_A{}'$: Absolute Salinity anomaly

Θ': Conservative Temperature anomaly

$\sigma_\Theta{}'$: Potential Density anomaly

$$\phi' = \phi - \hat{\phi}$$

Local mean

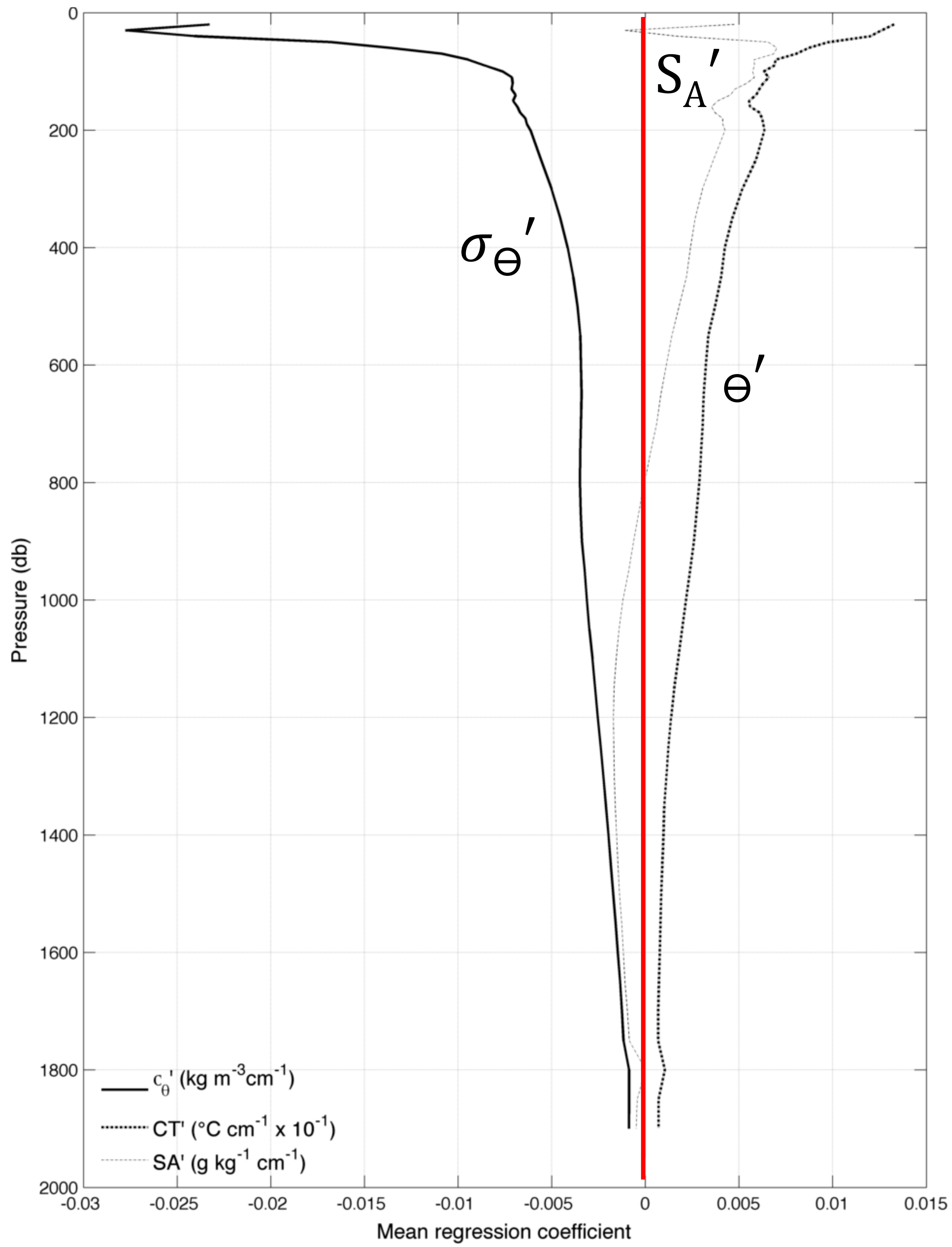
Single ARGO profile

$$\phi^* = \alpha \,.\, SSH'$$

Regression coefficient between ø′and SSH′

Regression analysis: average vertical structure

Domain-averaged regression coefficient ($\bar{\alpha}$) per pressure level



Positive SSH′ values indicate a depression of the isopycnals, which can in turn be driven by positive Θ' or negative S_A'.

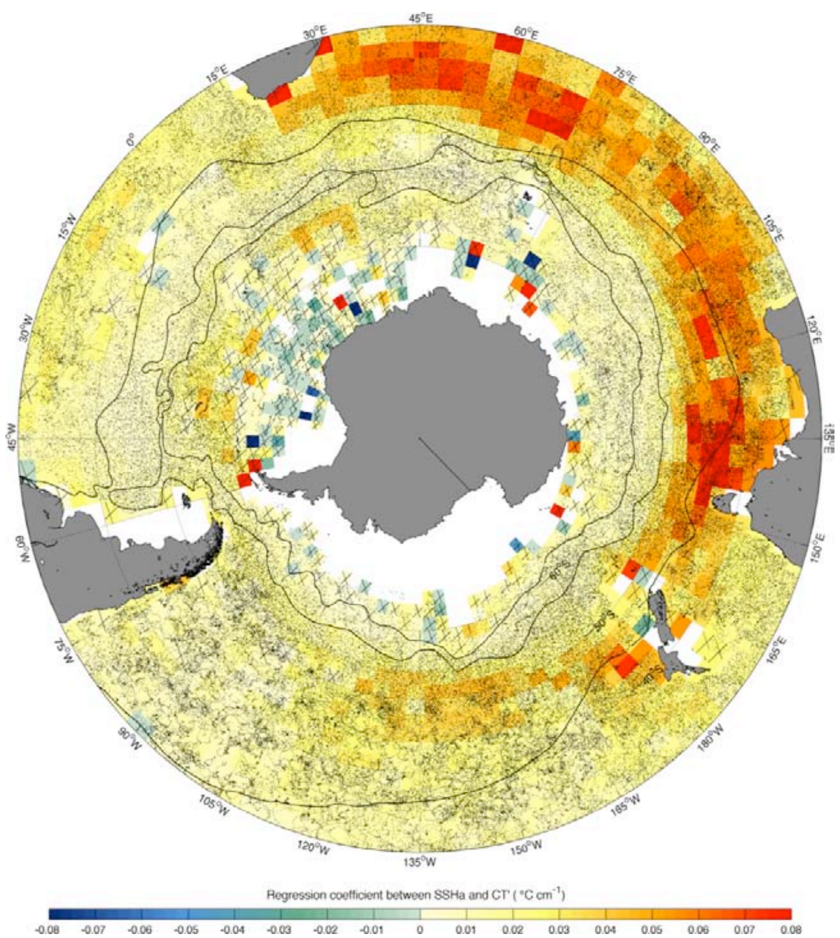
↓

Therefore negative regression slopes are expected for S_A' and σ_θ' and positive slopes for Θ'.

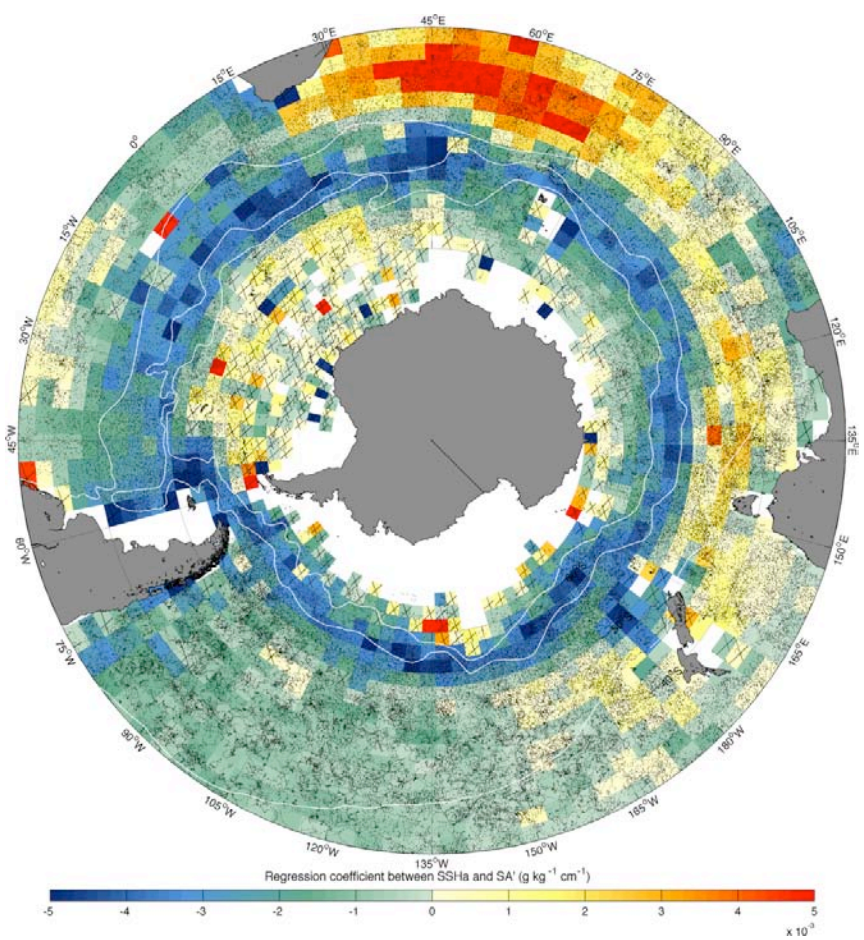
Mean regression coefficients for σ_θ' and Θ' have the expected signs, however a sign reversal occurs for S_A' at 800 db.

Regression analysis: slice at 1000db

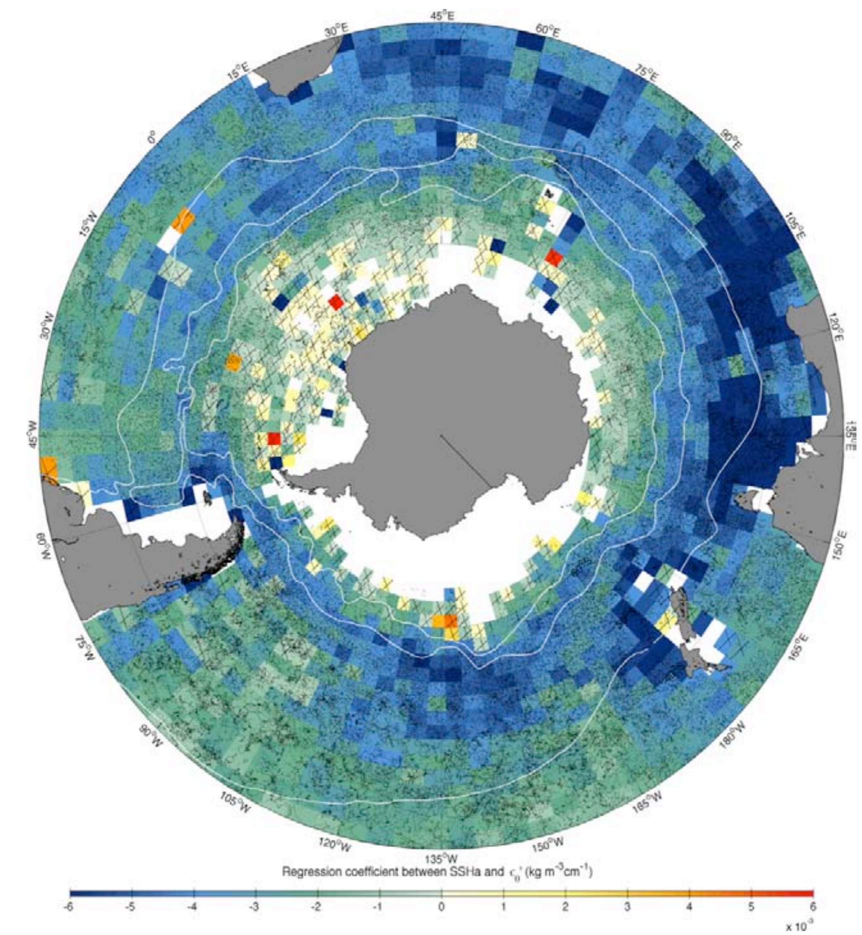
$\alpha(\Theta)$: SSH′ vs Θ'



$\alpha(S_A)$: SSH′ vs S_A'



$\alpha(\sigma_\theta)$: SSH′ vs σ_θ'



SSH′>0 $\longleftrightarrow$ Θ'>0

$\longrightarrow$ $\alpha(\Theta) > 0$

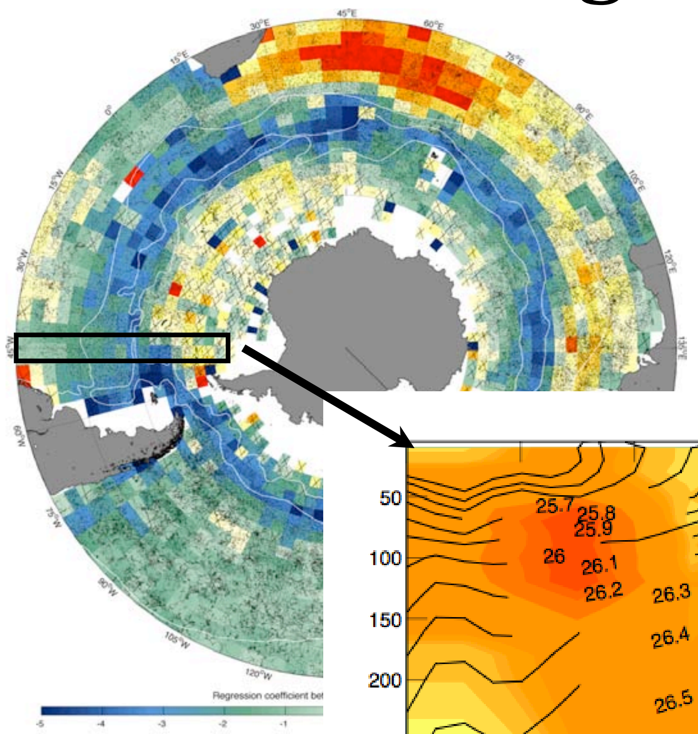
SSH′> 0 $\longleftrightarrow$ S_A'<0

$\longrightarrow$ $\alpha(S_A) < 0$

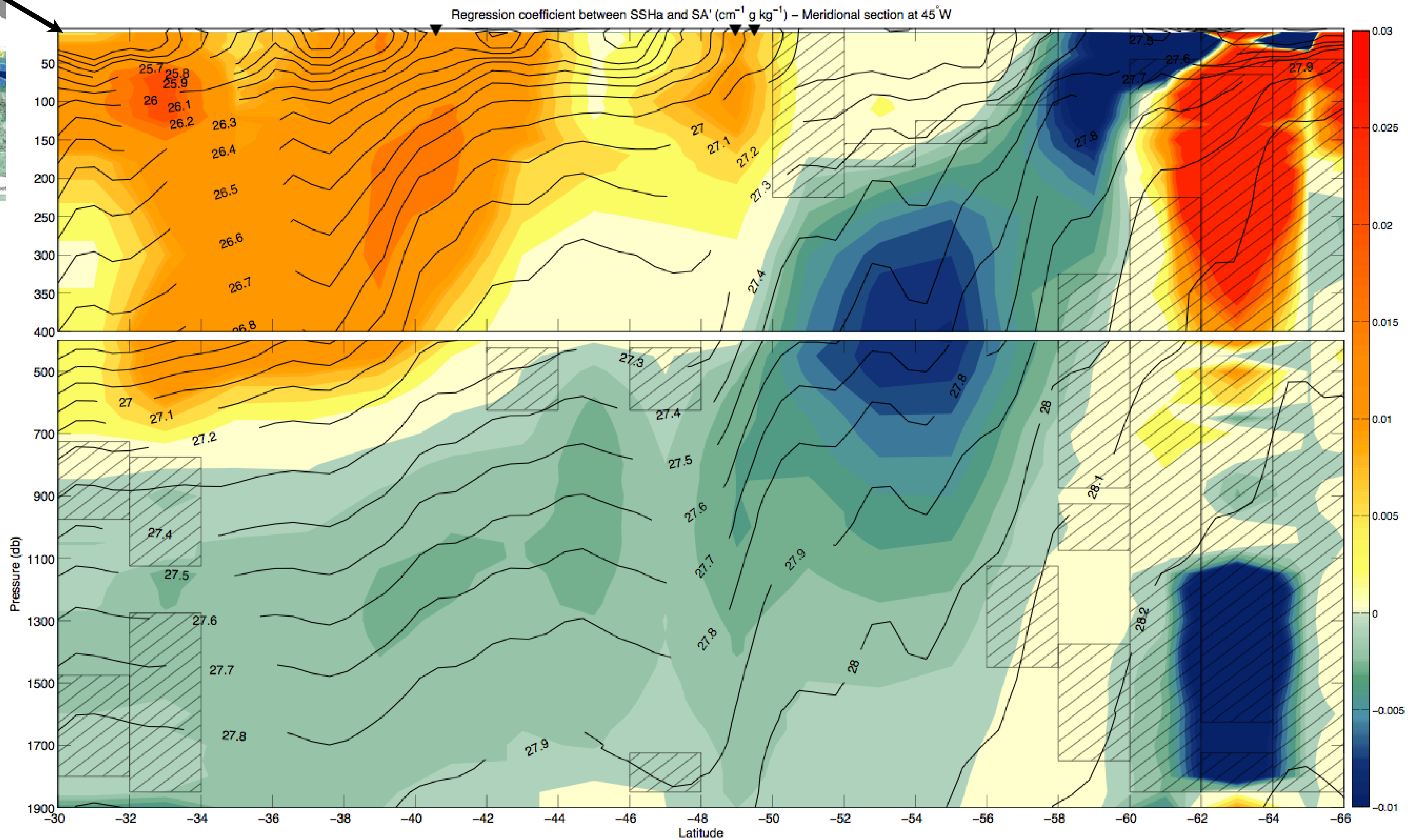
SSH′>0 $\longleftrightarrow$ σ_θ'<0

$\alpha(\sigma_\theta) < 0$

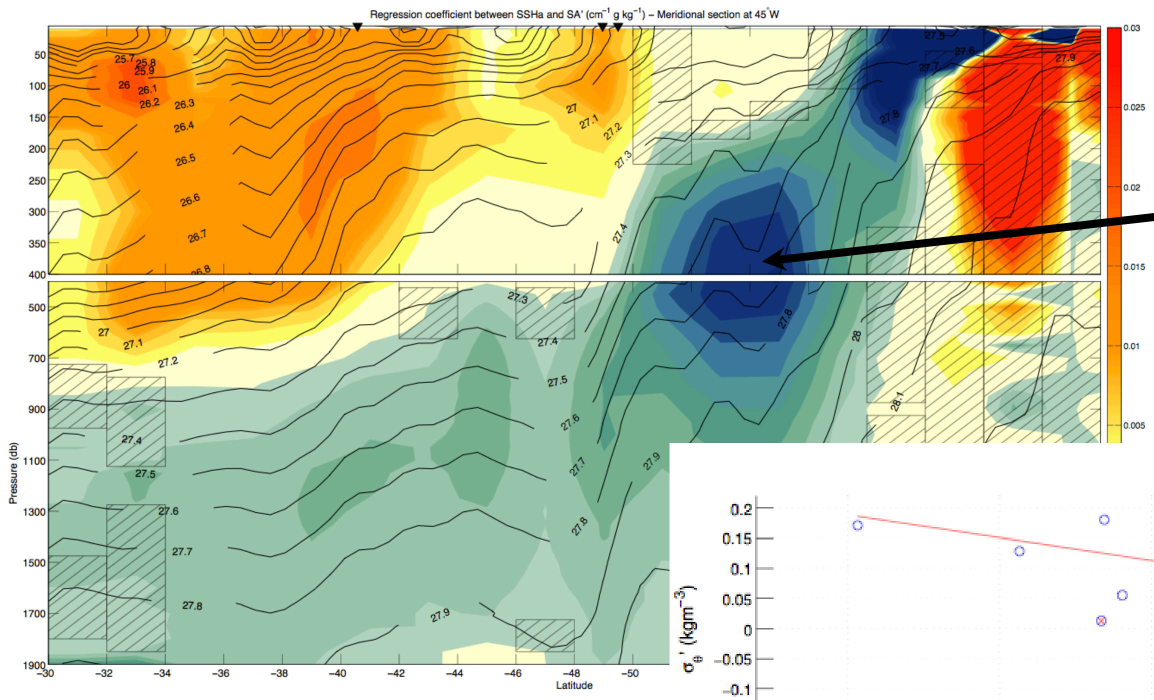
Regression analysis: meridional sections



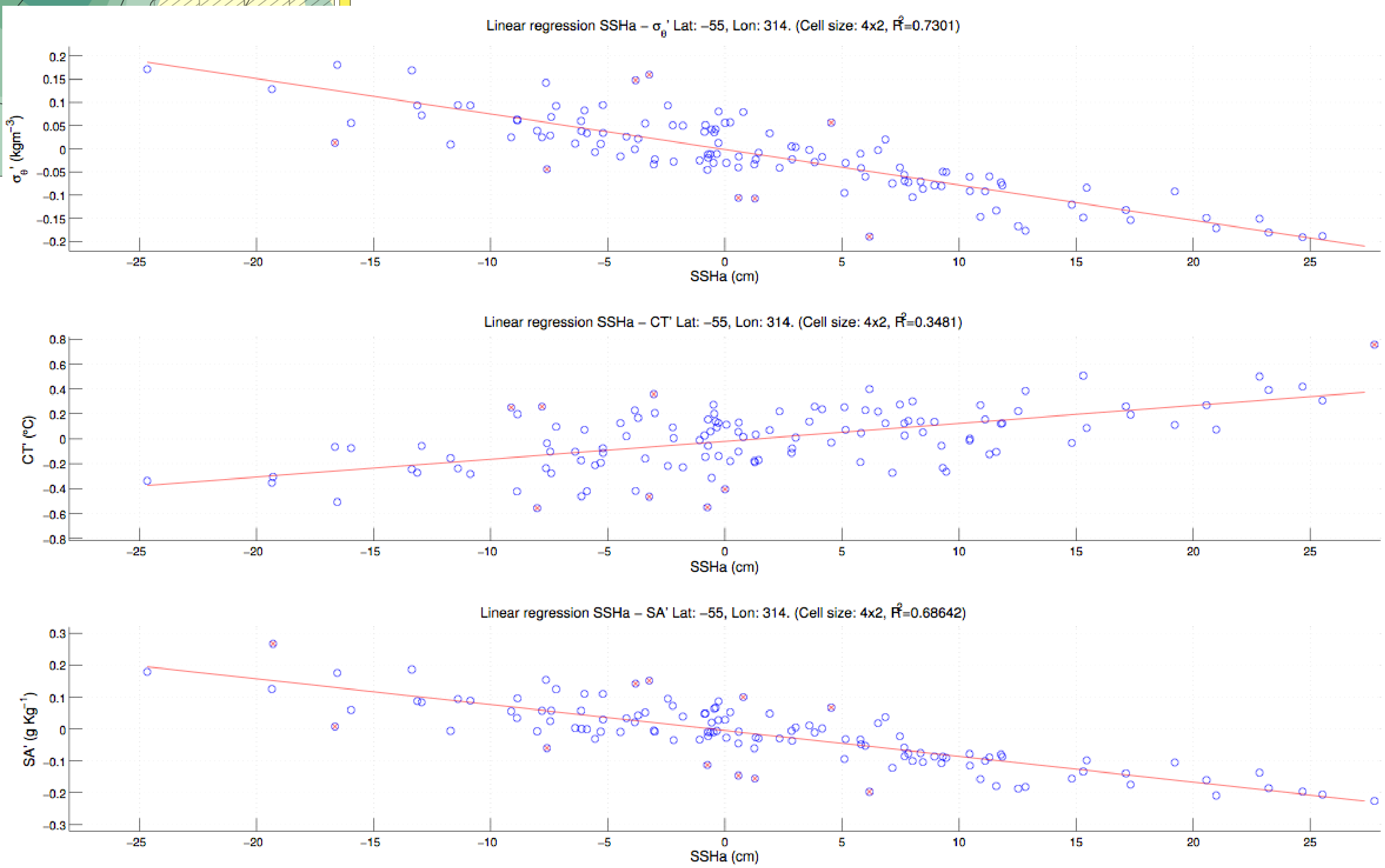
Regression between SSH′ and S_A′- Meridional section at 45° W



Example of regression analysis

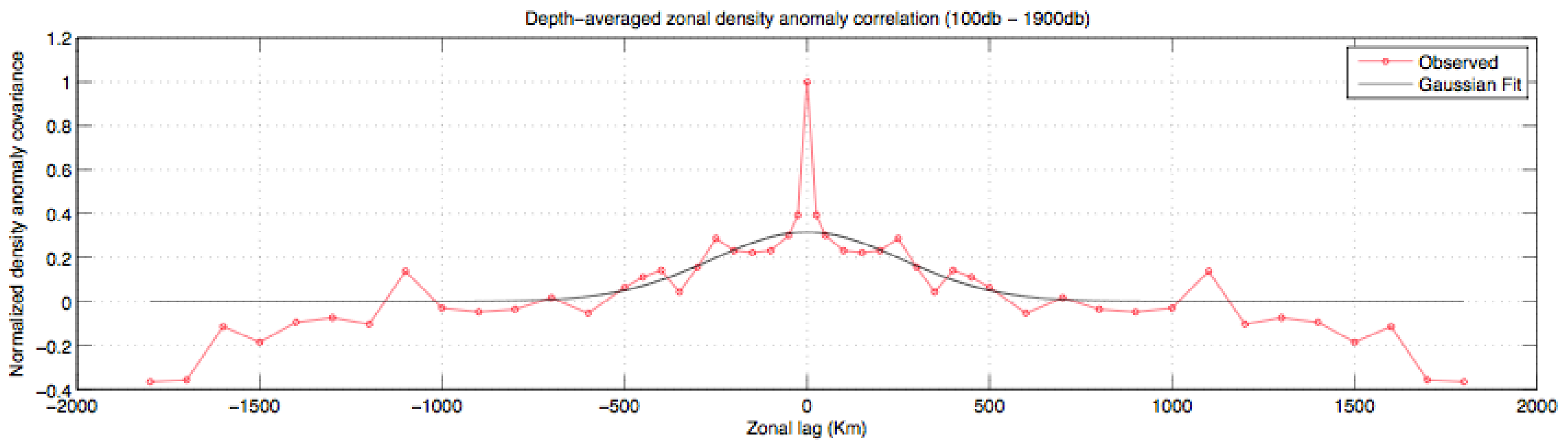


Example of regression analysis from previous section (45° W) at 55° S and 400 db

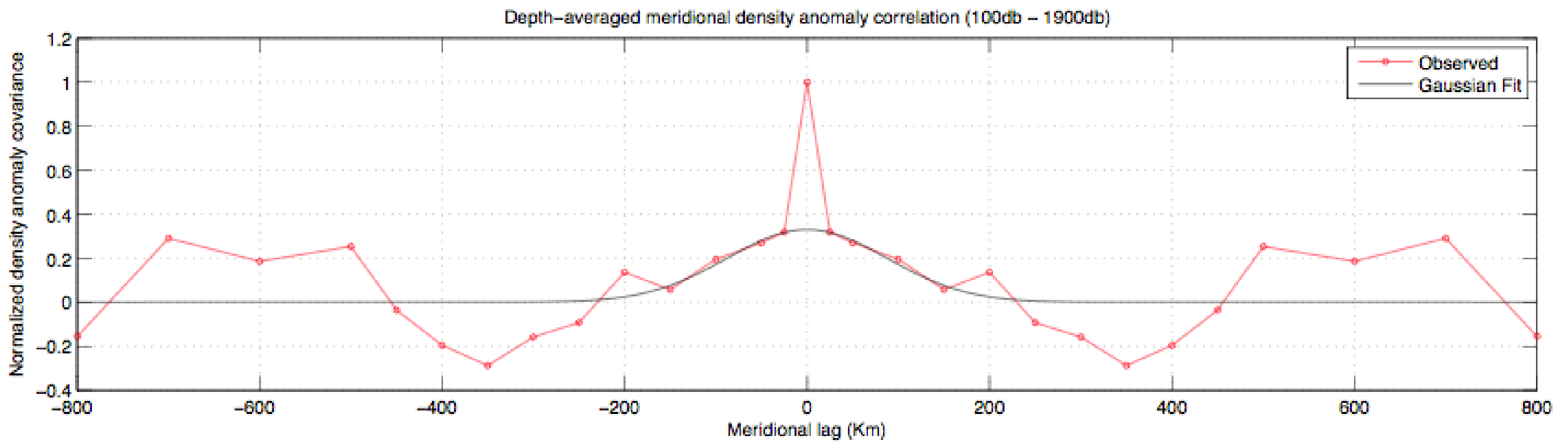


Objective mapping
Estimation of the covariance matrix

Depth-averaged (100-1900db) σ_θ' correlation (red) and Gaussian fit (black).



Zonal component
Lx = 400 Km



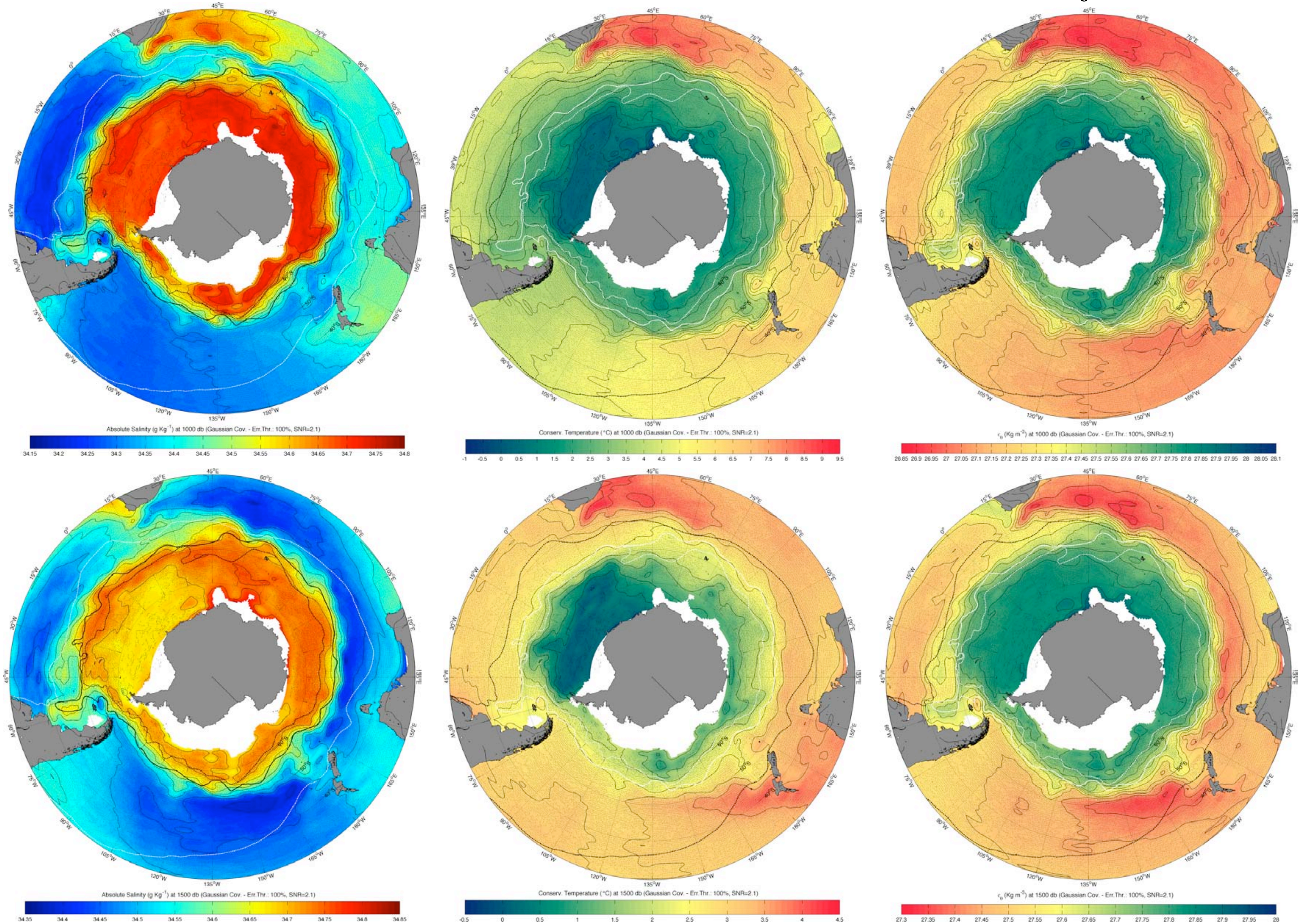
Meridional component
Ly = 120 Km

Objective mapping
Mean fields at 1000 and 1500db

S_A' | Θ' | σ_θ'

1000db

1500db



Reconstructing the 4-D fields

Each variable can be objectively mapped after removing the altimeter signal:

$$\hat{\phi} = \{\phi - \alpha(\phi) * SSH'\}$$

Using the regression coefficients α(ø) and SSH′ as a proxy, each variable can then be mapped in space and time:

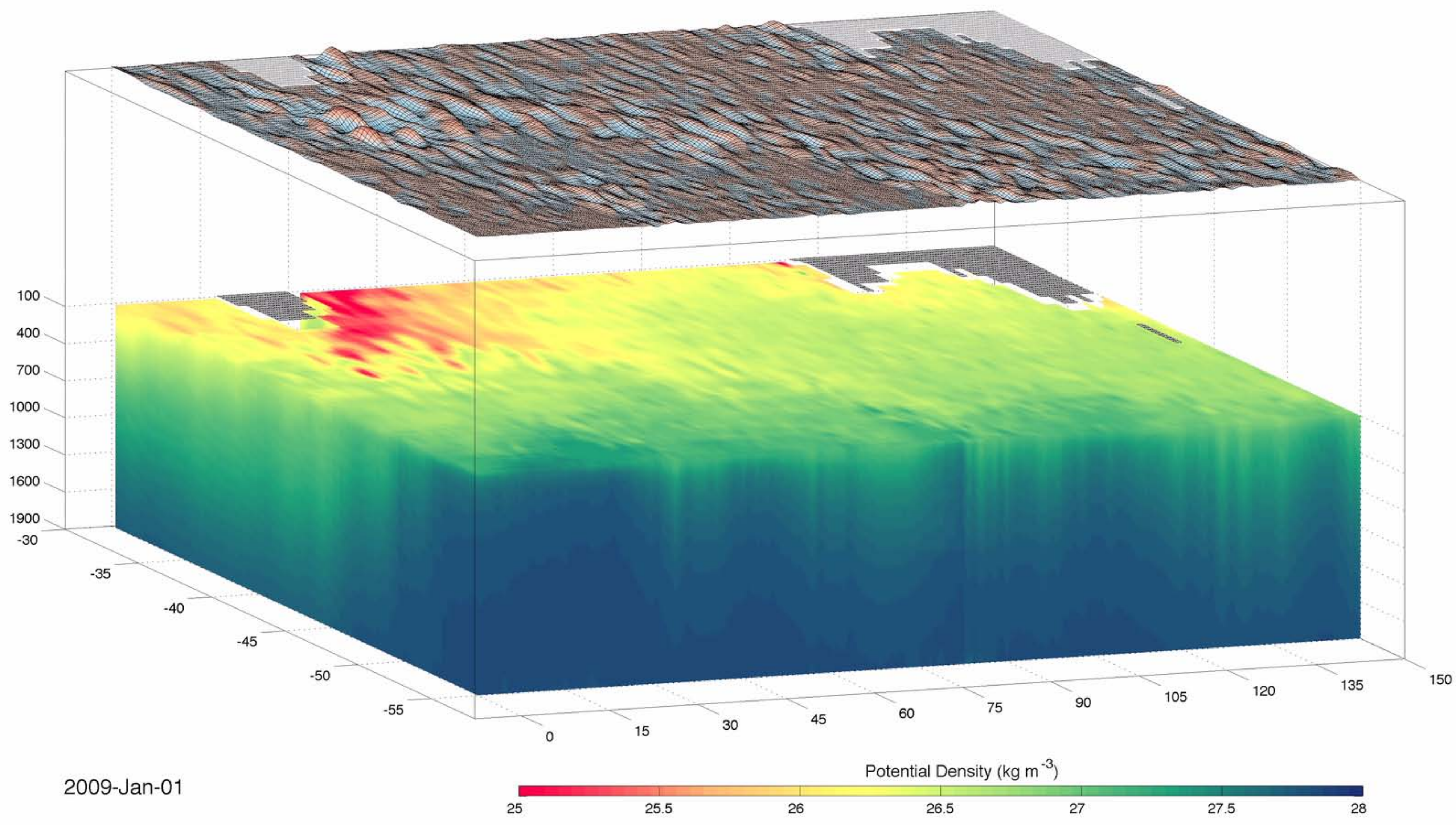
$$\phi_M(x, y, z, t) = \alpha(\phi(x, y, z)) * SSH'(x, y, t)$$

The full 4-dimensional field can be reconstructed by adding the objectively mapped mean field to the mapped variable:

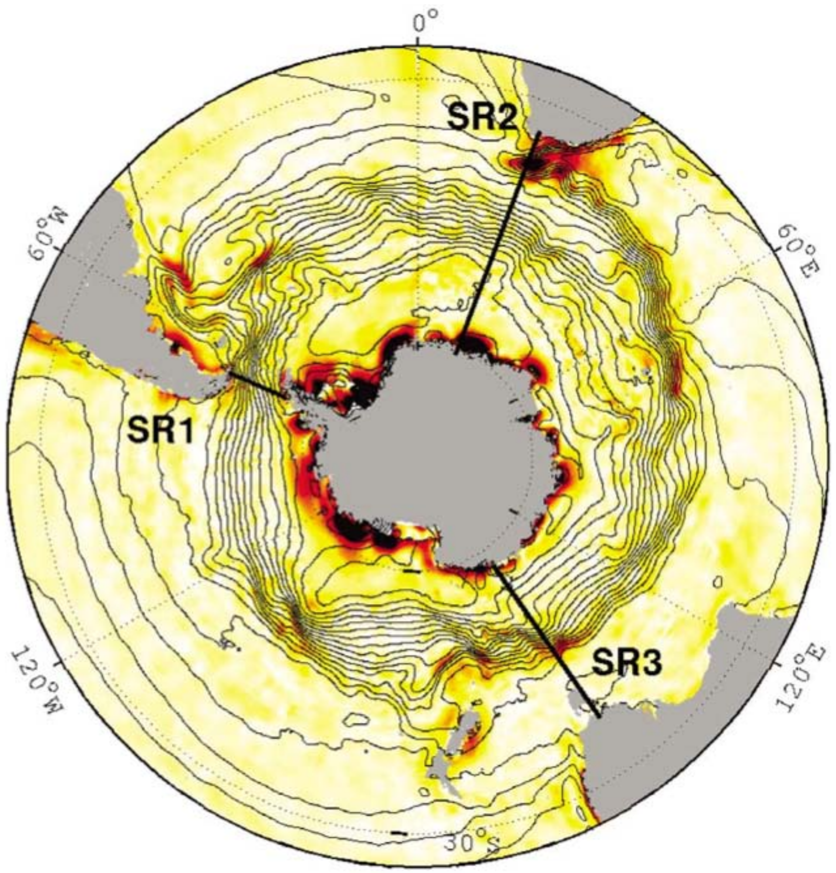
$$\Phi(x, y, z, t) = \hat{\phi}(x, y, z) + \phi_M(x, y, z, t)$$

Reconstructing the 4-D fields

Indian Ocean SSH and potential density field for 2009-2010



Dynamically constrained MDT



	SR1 Drake	SR2 Africa	SR3 Tasmania	SR1-SR2
CNES-CLS09	172 ± 6 (224)	135 ± 31 (169)	164 ± 4 (188)	37 (55)
EGM08	151 ± 3 (205)	136 ± 13 (166)	167 ± 4 (194)	15 (39)
GGM02C	142 ± 2 (182)	188 ± 23 (219)	175 ± 3 (200)	46 (37)
MN05	159 ± 4 (211)	98 ± 18 (133)	187 ± 7 (213)	61 (78)
SOSE	147 ± 5	145 ± 15	159 ± 3	2

From Griesel et al. (JGR, 2012)

Find a MDT that is consistent with the available products and some dynamical constraint by minimizing a cost-function that is the sum over all space of:

$$J = \sum_{i=1,N_{\mathrm{MDT\ products}}} (\eta - \eta_{product\ i})^2 \sigma_{product\ i}^{-2} + (\eta - \eta_{vort})^2 \sigma_{vort}^{-2}$$

Dynamically constrained MDT

QG linear vorticity balance:

$$\beta v + u_H . \nabla \zeta = f \frac{\partial w}{\partial z} \qquad (1)$$

From geostrophy and hydrostatic balance:

$$v = \frac{g}{f \rho_0} \int_z^0 \frac{\partial \rho}{\partial x} \, dz' + \frac{g}{f} \frac{\partial \eta}{\partial x} \qquad (2)$$

Replacing (2) in (1) and integrating between the surface and some level H:

$$\frac{\beta g H}{f} \frac{\partial \eta}{\partial x} + \frac{\beta g}{f \rho_0} \int_{-H}^0 \int_z^0 \frac{\partial \rho}{\partial x} \, dz' dz = \frac{1}{\rho_0} \nabla \times \tau - f w(z = -H)$$

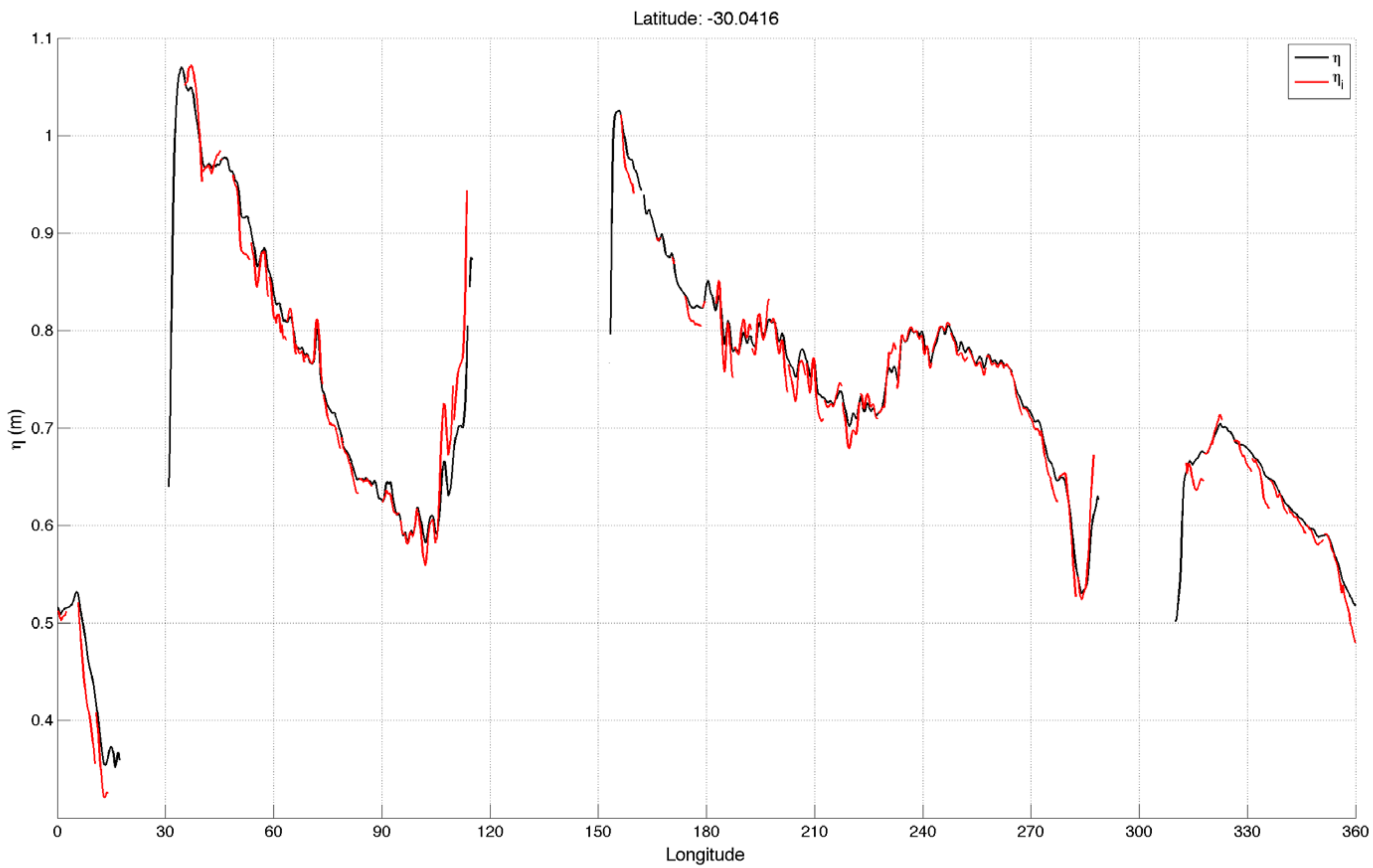
$\frac{\partial \rho}{\partial x}$: SOSE (next: Argo)

$\frac{1}{\rho_0} \nabla \times \tau$: ECMWF

$f w(z = -H)$: SOSE

Dynamically constrained MDT

$$\eta(x,y) = \eta(x_0,y) \; + \; \frac{f}{\beta g H \rho_0} \int_{x_0}^{x} \nabla \times \tau \, dx \; - \; \frac{f^2}{\beta g H} \int_{x_0}^{x} w_{-H} \, dx \; - \; \frac{1}{\rho_0 H} \int_{x_0}^{x} \int_{-H}^{0} \int_{z}^{0} \frac{\partial \rho}{\partial x} \, dz' dz dx$$



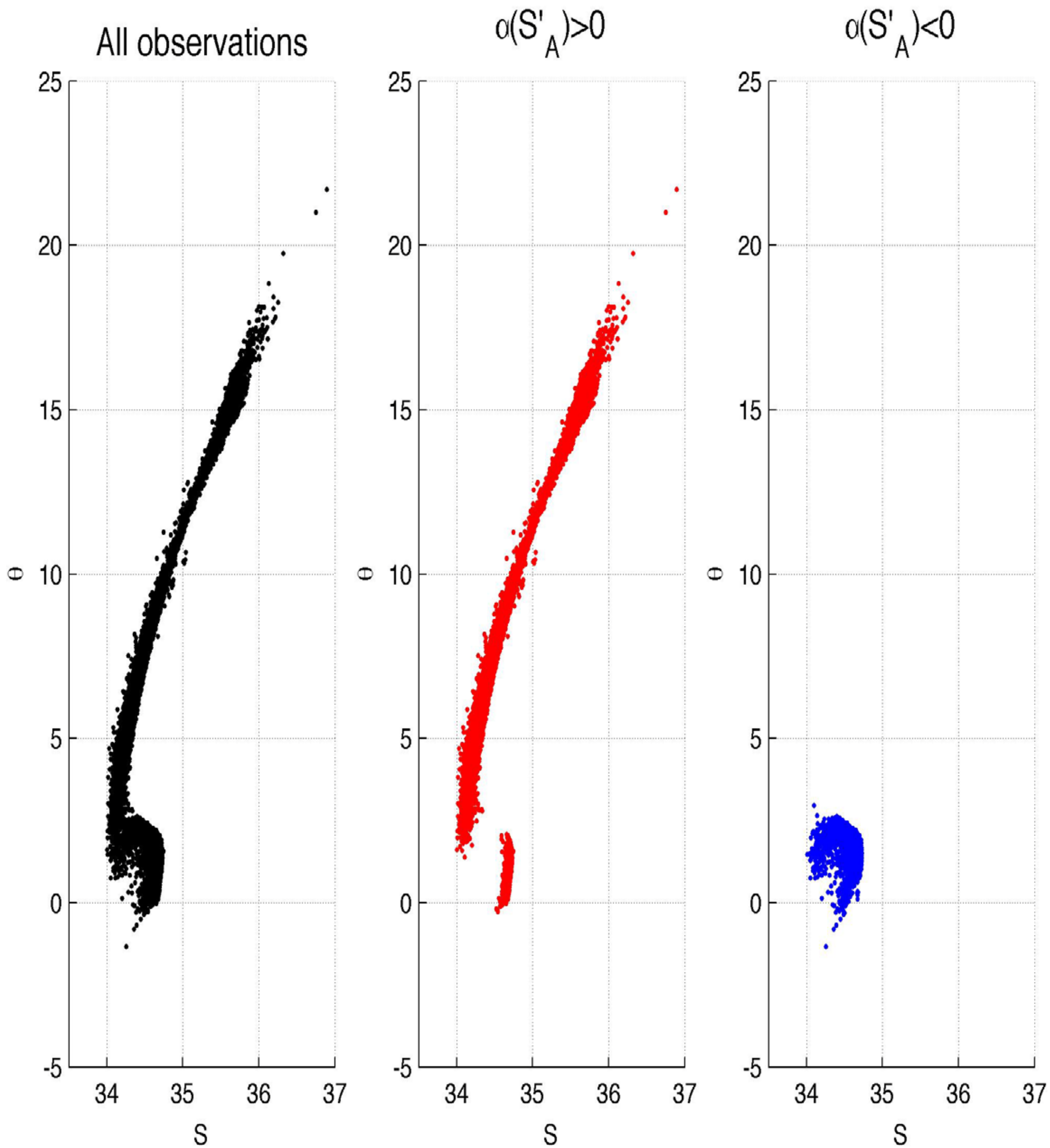
Summary

Due to the strong vertical coherence and equivalent barotropic nature of the ACC, it is possible to extract substantial information on the subsurface structure by using SSH as a proxy to infer T, S and σ_θ anomalies.

The correlation between SSH with T, S and σ_θ is significant (95% level) on ~75% of the 3.6 million grid cells of the domain. An improvement of the signal to noise ratio is achieved, on average the anomaly variance is reduced by 40%.

The removal of the altimeter signal from T, S and σ_θ produces more stable and less noisy estimates of the mean fields of the Southern Ocean.

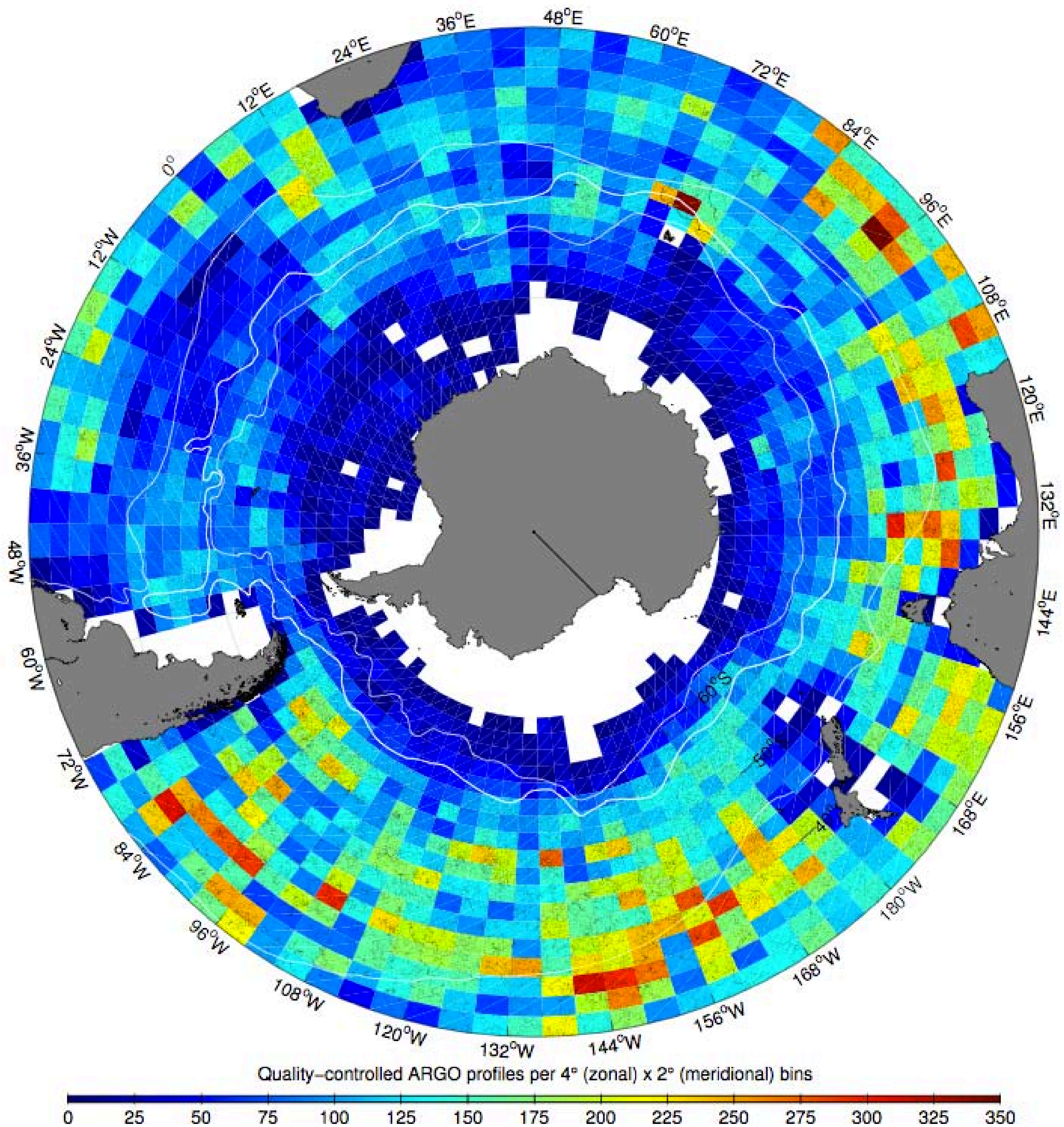
QG linear vorticity budget seems to be enough to infer SSH. Further work would prove if this dynamically constrained SSH helps improve the available MDT products and a close mass balance is reached.



All observations
σ(S'_A)>0
σ(S'_A)<0
θ
S
25
20
15
10
5
0
-5
34
35
36
37

Distribution of Argo profiles II

Quality controlled delayed-mode Argo profiles per 4° x 2° bins



Rapid decay of available profiles south of the PF.

Energetic regions are the least well sampled (ACC core, BFC, Agulhas recirculation).

Pacific and Eastern side of the Indian Ocean are the most well sampled regions (Southern limb of subtropical gyres).

Distribution of Argo profiles I

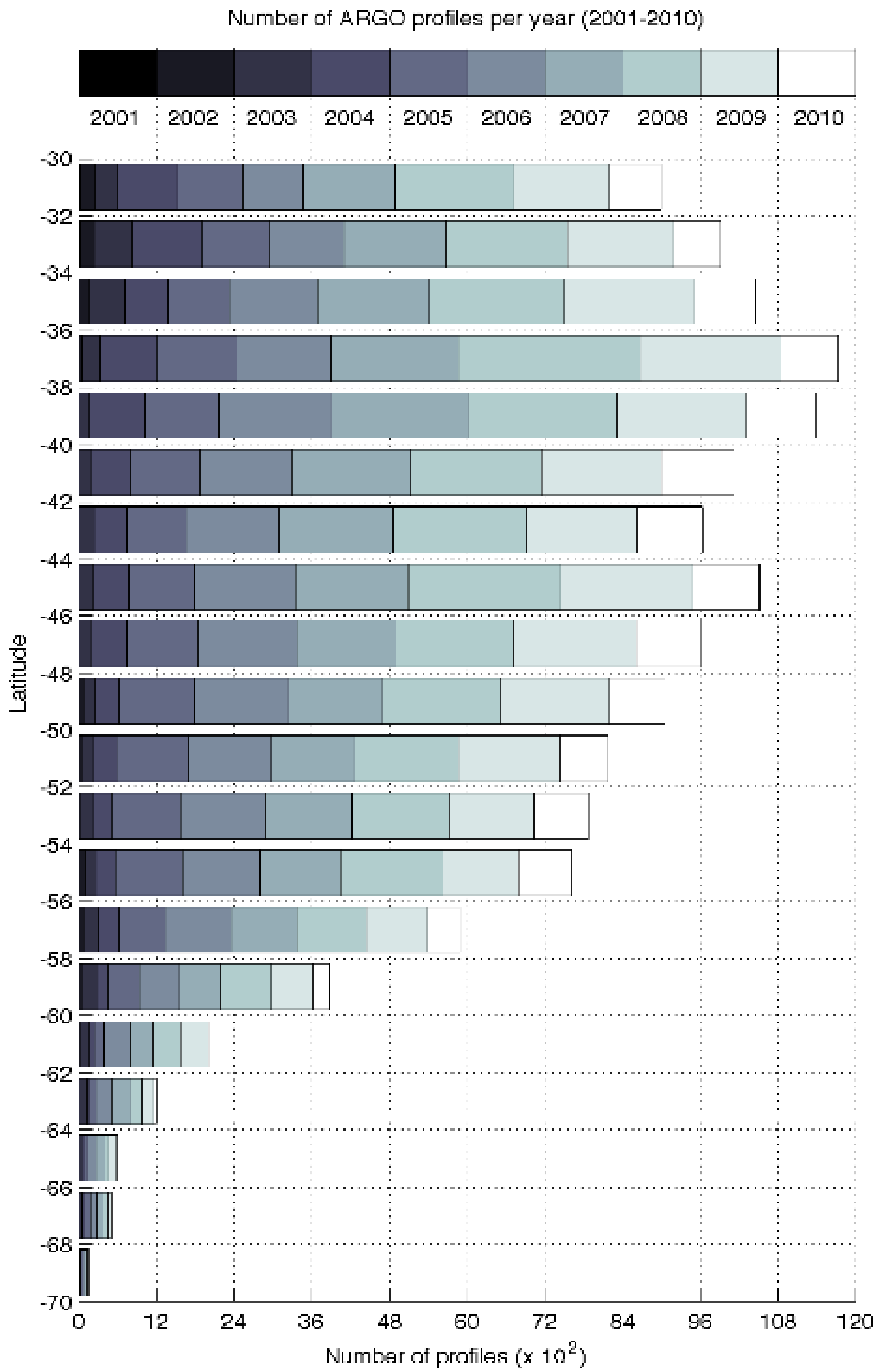
Delayed-mode Argo profiles south of 30° S from 2001-2010: +152500 profiles

Around 9% of the profiles were removed after further quality control.

Significant bias towards the second half of the record (2006-2010).

The delayed in the quality control of the Argo profiles is reflected in the number of profiles available for 2010.

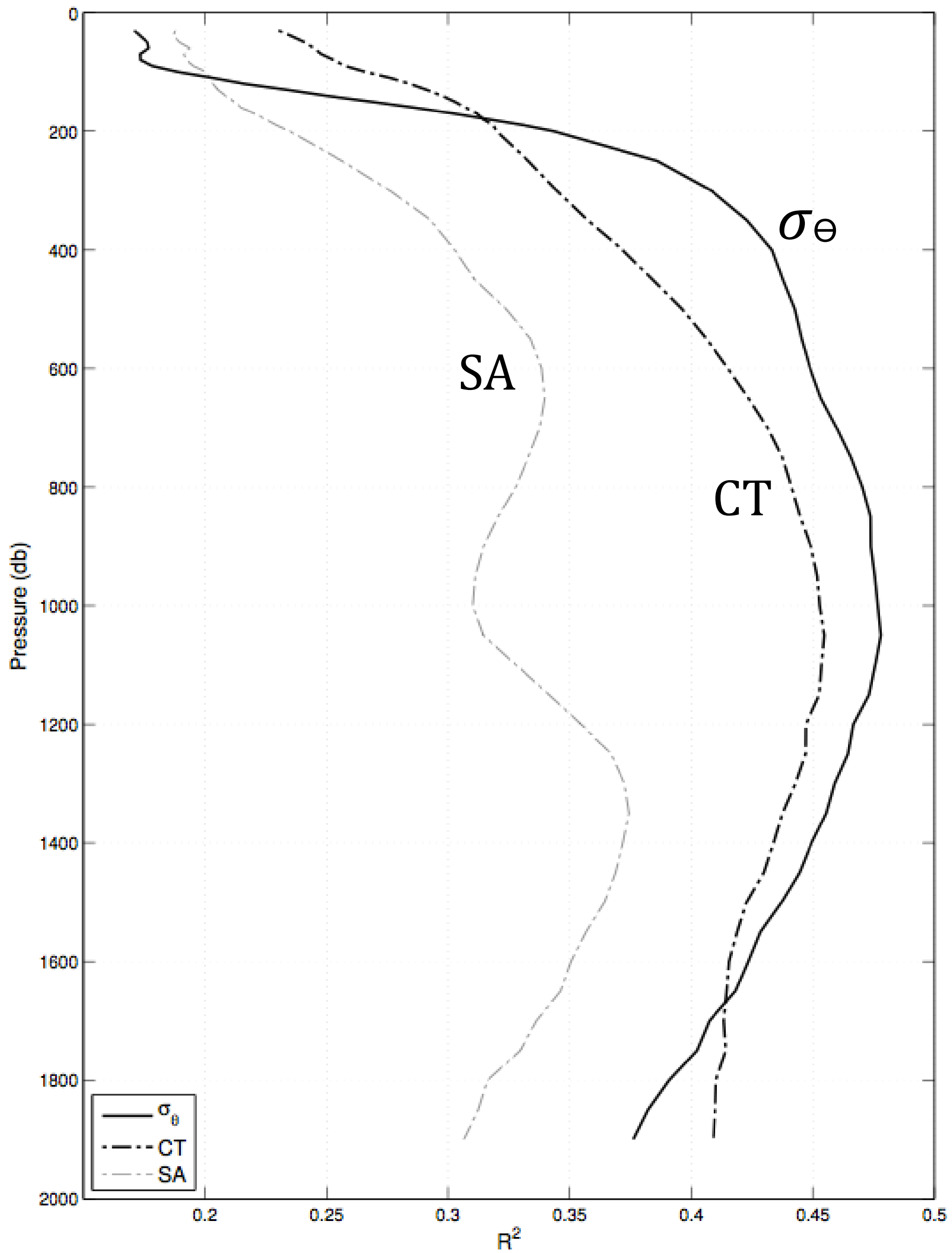
Profiles per year and latitude band



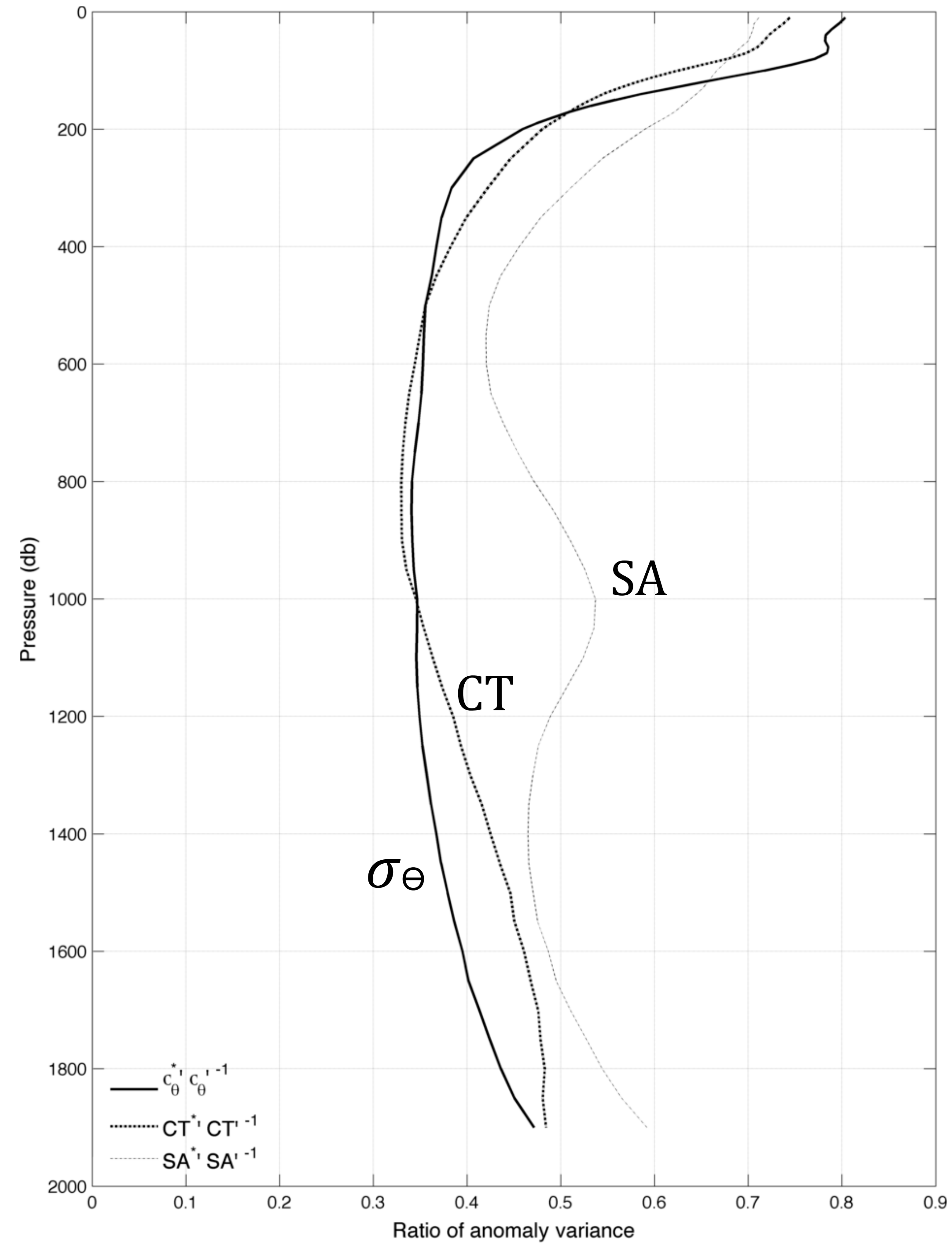
Removing the altimeter signal

$$\hat{\vartheta} = \{\vartheta - \alpha\ .\ SSH\} + \overline{\alpha\ .\ SSH}$$

Variance explained by the altimeter

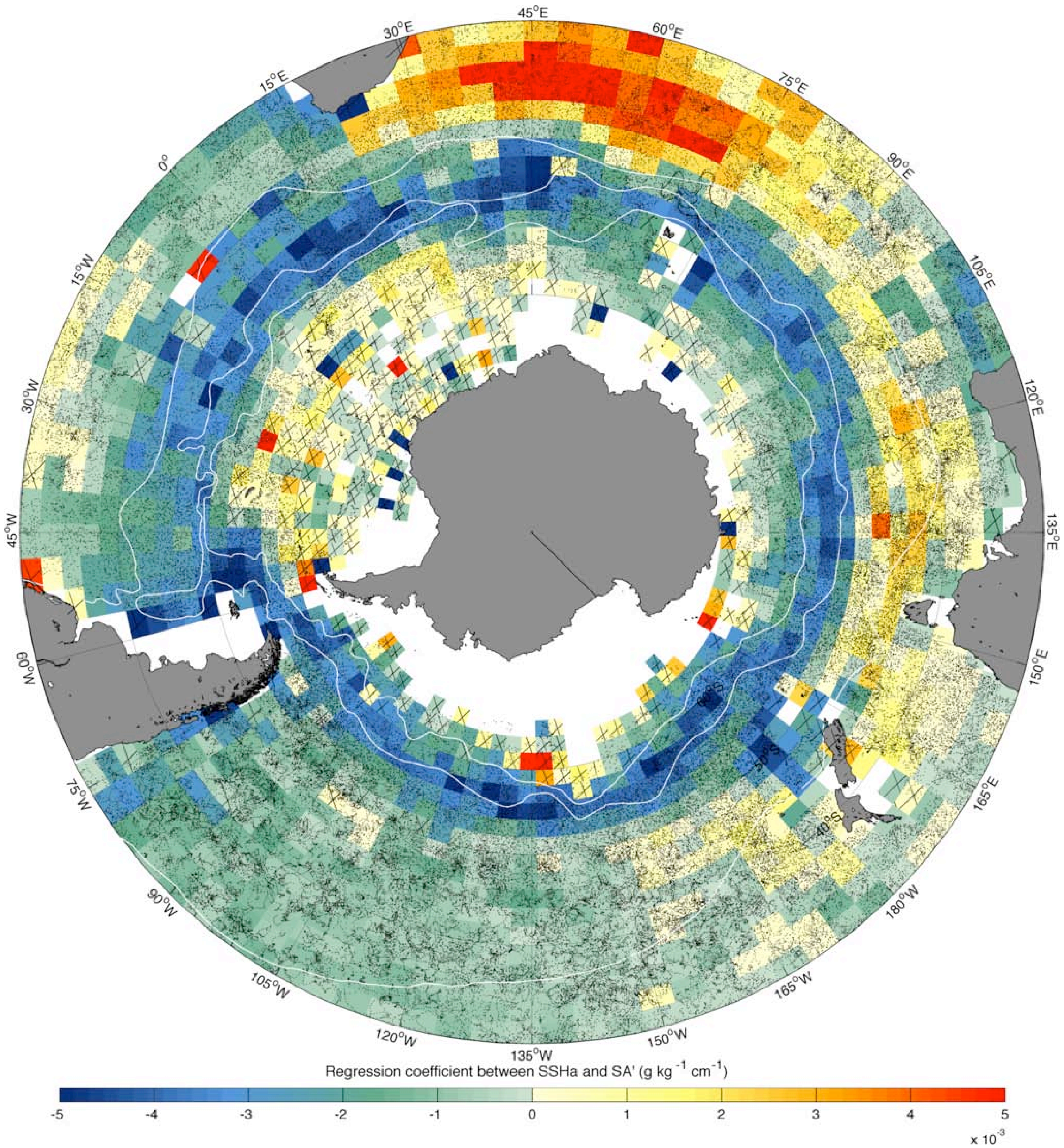


Ratio of anomaly variance



Regression analysis: SSHa-SA'

Regression coefficient between SSHa and SA' at 1000db



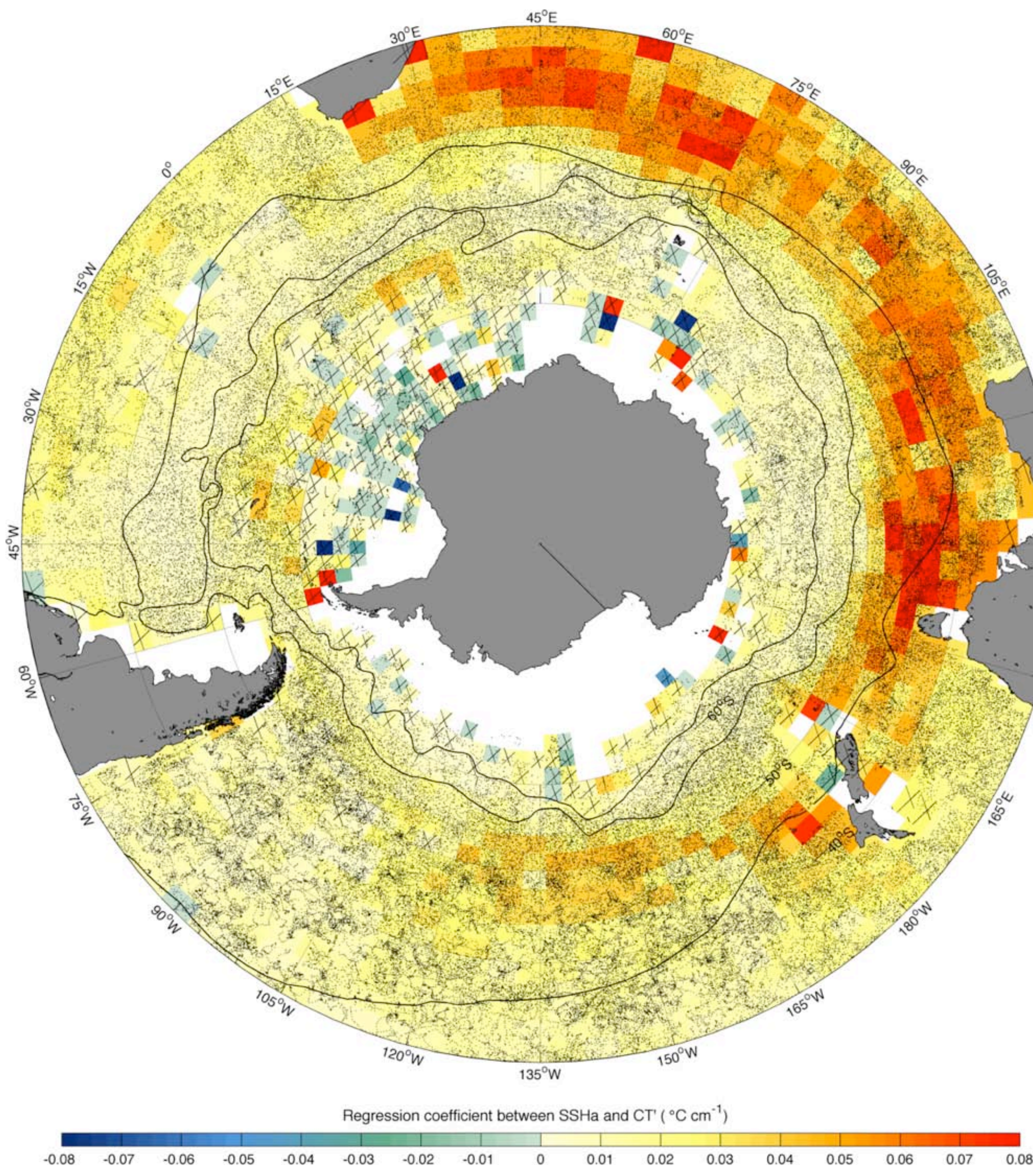
Slope of linear regression between SSHa and SA′ in 4° x 2° bins at 1000db.

Hatched bins are not significant at the 95% level.

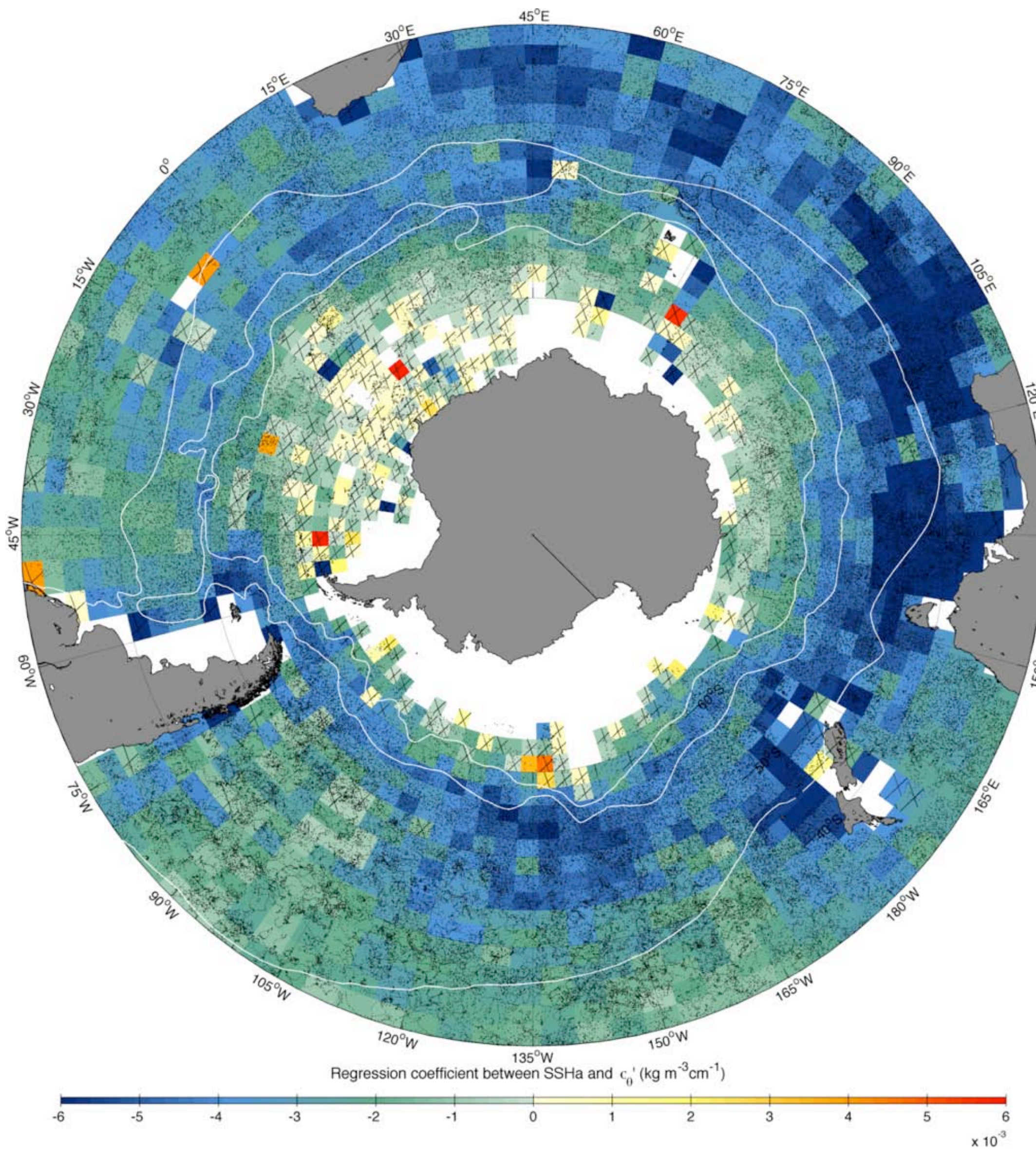
Mean positions of fronts is shown in white and black dots show the available observations.

Regression analysis: SSHa-CT' and SSHa-σ_θ'

Regression coefficient between SSHa and CT' at 1000db

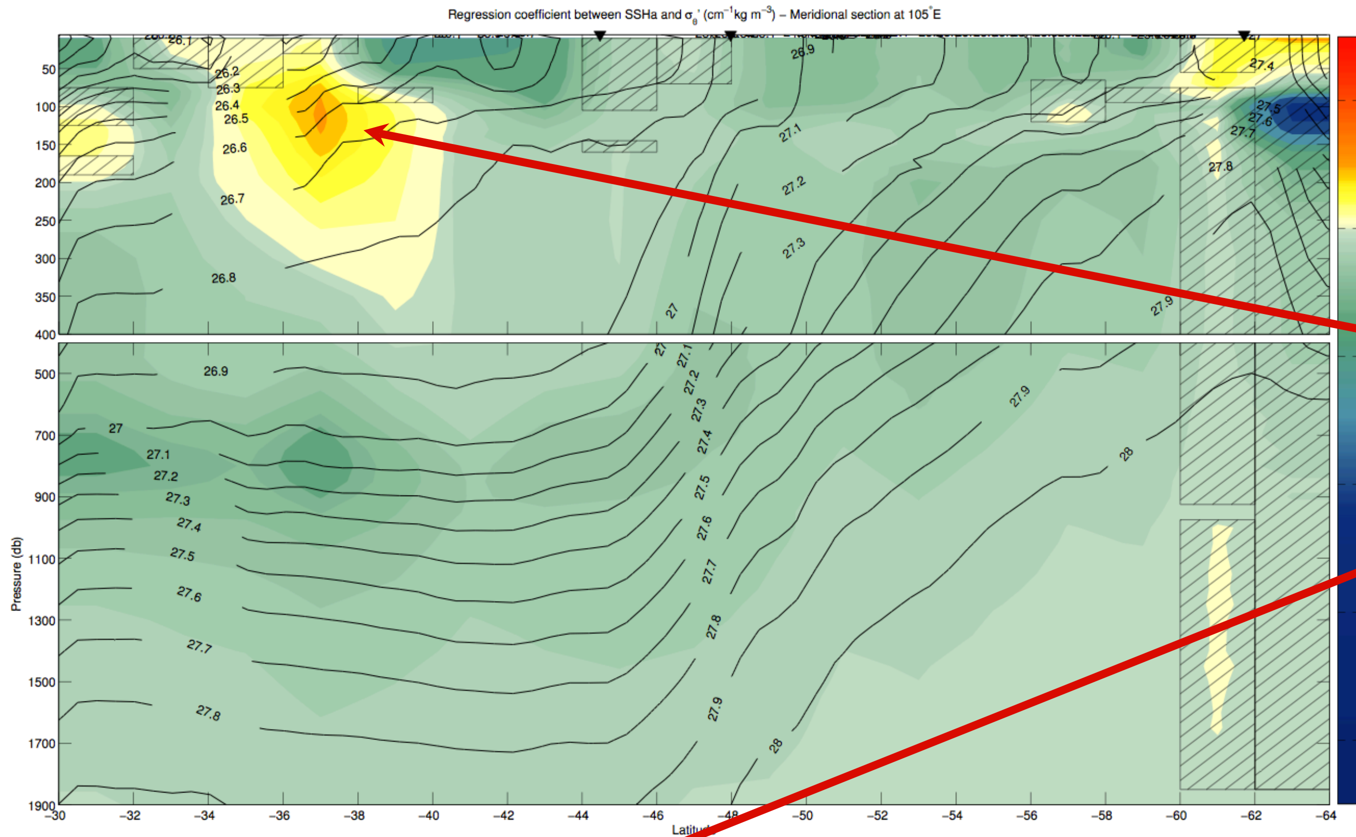


Regression coefficient between SSHa and σ_θ' at 1000db

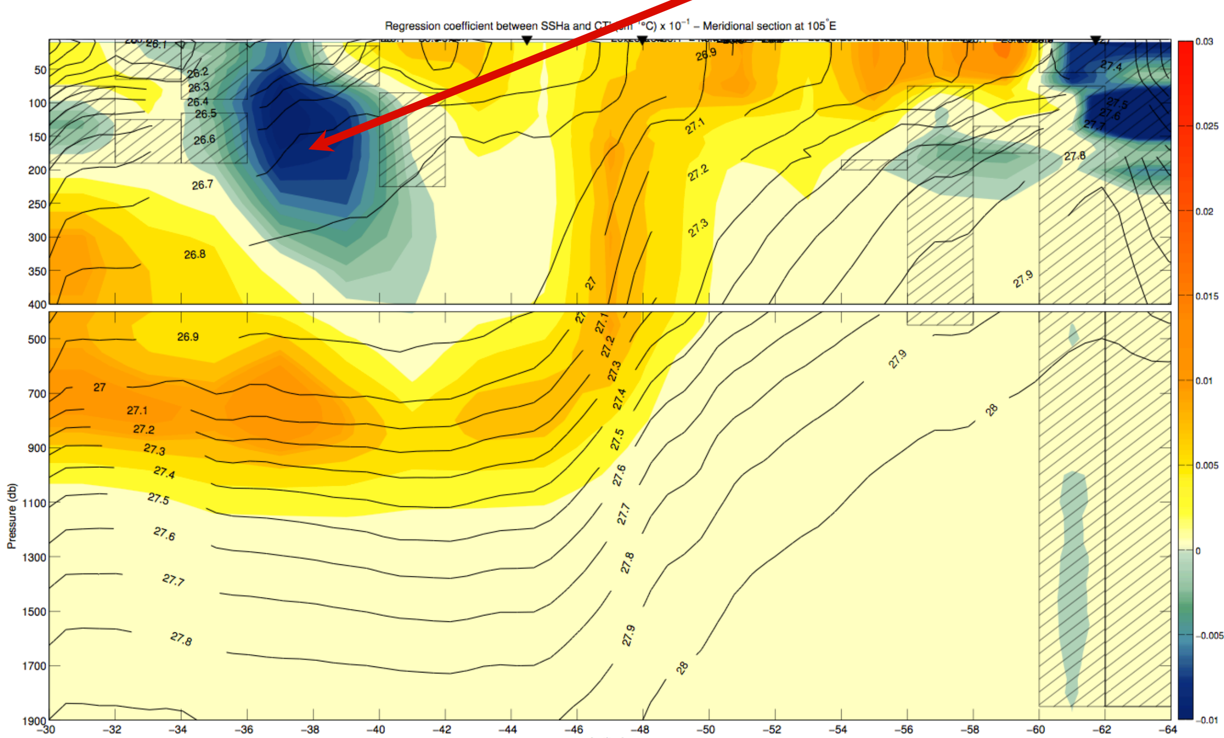


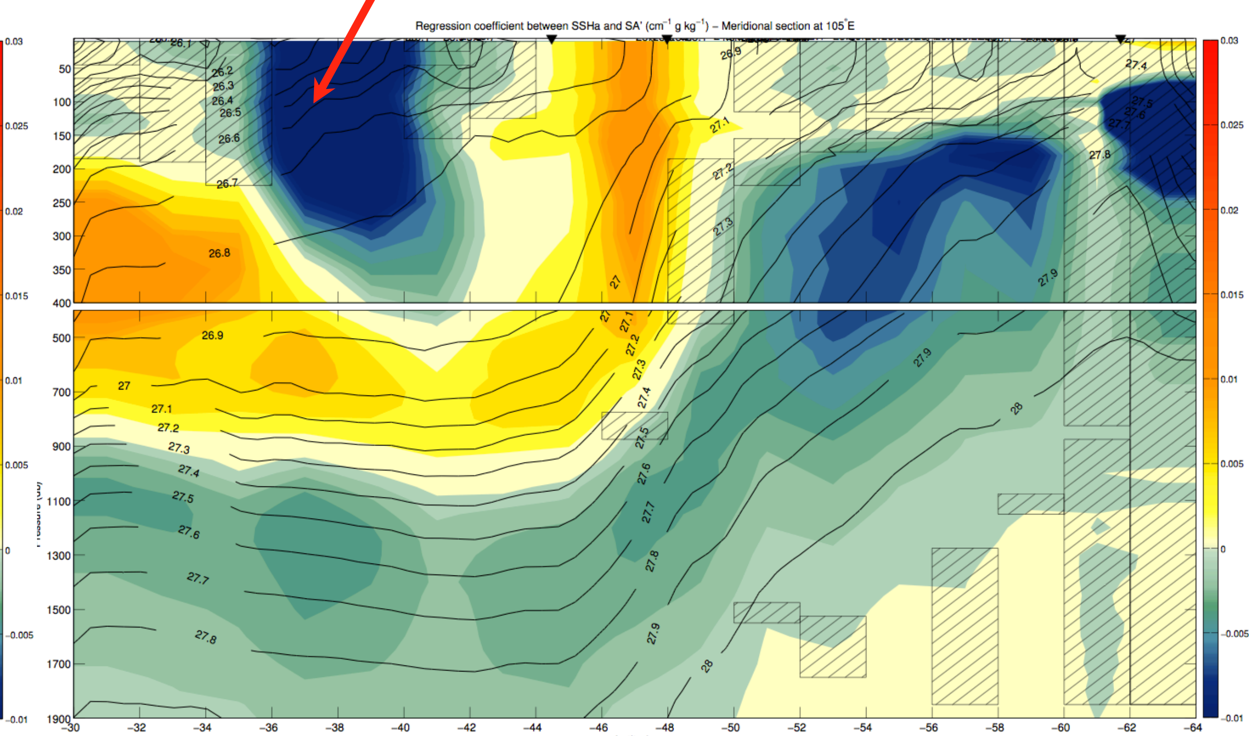
Example of regression analysis II

Regression between SSHa and σ_θ' - Meridional section at 105° E



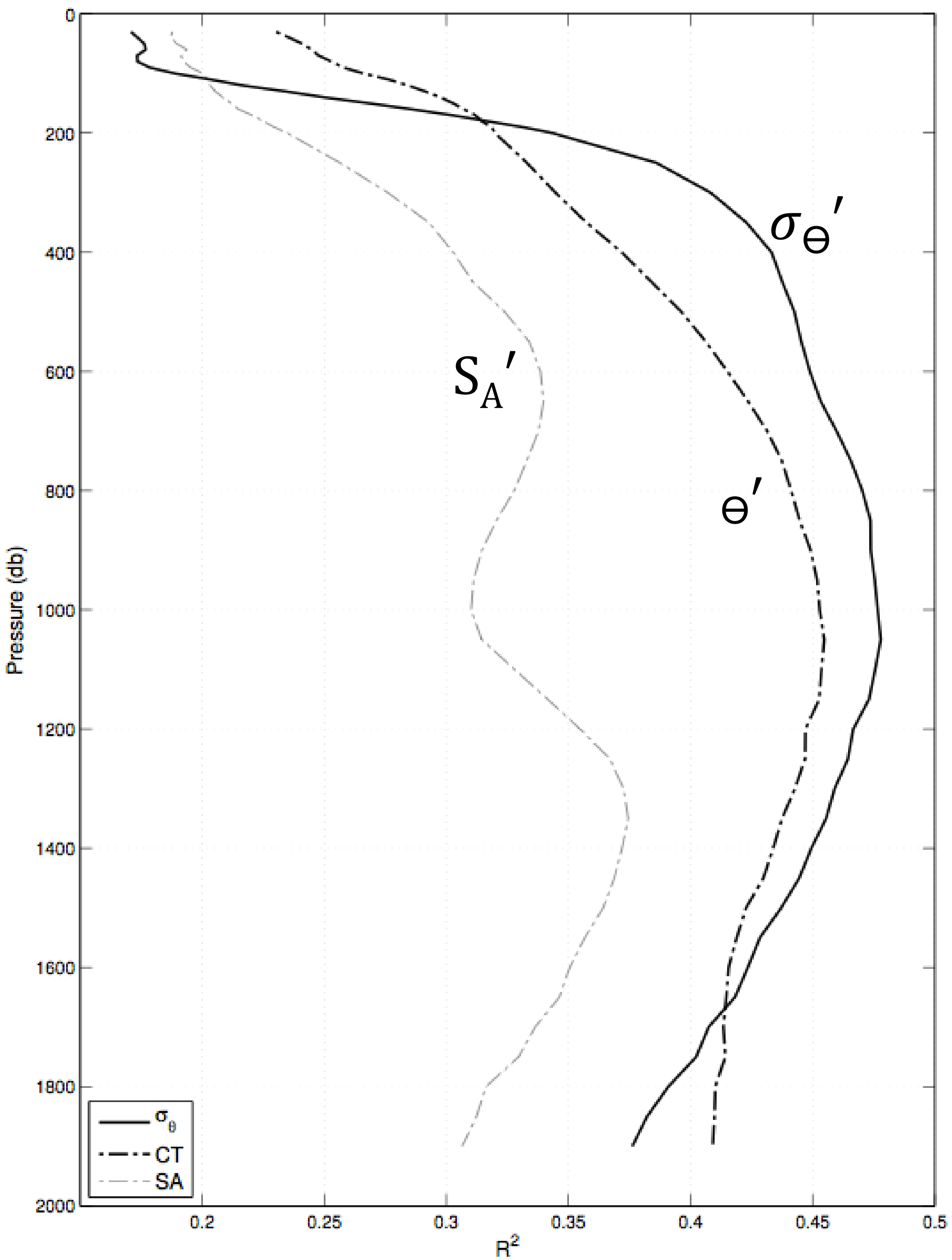
Positive regression for σ_θ ' due to negative regression slope in CT' (note that SA' < 0)





How much variance can be explained by the altimeter?

Domain-averaged variance vs pressure



S_A': Absolute Salinity anomaly

Θ': Conservative Temperature anomaly

σ_Θ': Potential Density anomaly

{ } denotes objective mapping

< > denotes times average

$$\hat{\phi} = \{\phi - \alpha \,.\, SSH'\} - < \alpha \,.\, SSH' >$$

$$\phi' = \phi - \hat{\phi}$$

Regression coefficient between Ø ′and SSH′

Regression analysis: structure of zonal average

Fraction of cells with significant regression at the 95% level