An analysis of the Southern Ocean's barotropic response to the wind during the past 20 years.

Its contribution to SSH variations and to the ACC transport variability across the Kerguelen Plateau

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Motivations

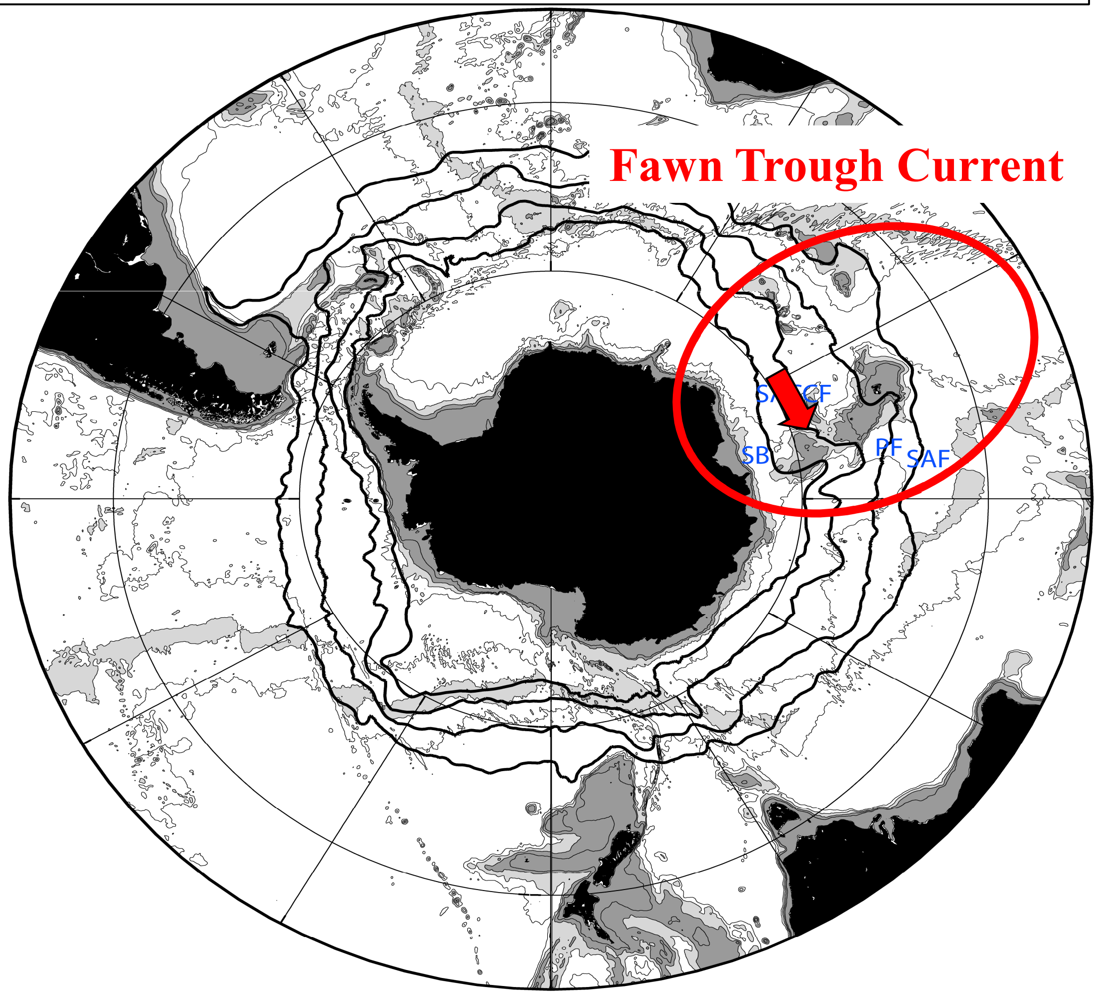
- Significant climatic signals have been detected in water masses formed in the Southern Ocean over the past decades.
- SSH from satellite altimetry is a key source of information to document heat/freshwater storage variations.
- But SSH is also impacted by convergence of mass (barotropic response to the winds) particularly at high latitude.
- The barotropic response is expected to be weaker at interannual time scales, but might still be significant.

- Here it is investigated over the past 20 years from a simple finite element barotropic model (Vivier et al, JGR, 2005), compared with GRACE data available since 2004.

Motivations: ACC dynamics

The 20 year long simulation is also used to investigate the dynamics of the **Fawn Trough Current (FTC),** a major branch of the ACC crossing the Kerguelen Plateau.

- FTC transport was measured during one year from current meter moorings (*TRACK* program, 2009-2010)
- Transport estimates were extended for the period 1992-present from altimetry (Vivier et al, DSR, 2015)



A simple barotropic model

- 22 yr simulation (altimeter era), forced with ERAI weekly winds.
- <u>Model setting (Vivier et al, JGR 2005):</u>

Transport streamfunction ψ: $\mathbf{v}H = k \times \nabla\psi$

Vorticity: $$\nabla \cdot \frac{\nabla \partial_t \psi}{H} - \frac{f}{H}\partial_t \eta + J\left(\psi, \frac{f}{H}\right) + \nabla \cdot \left(\frac{r}{H^2}\nabla\psi\right) = \mathrm{curl}\left(\frac{\boldsymbol{\tau}}{\rho_0 H}\right)$$

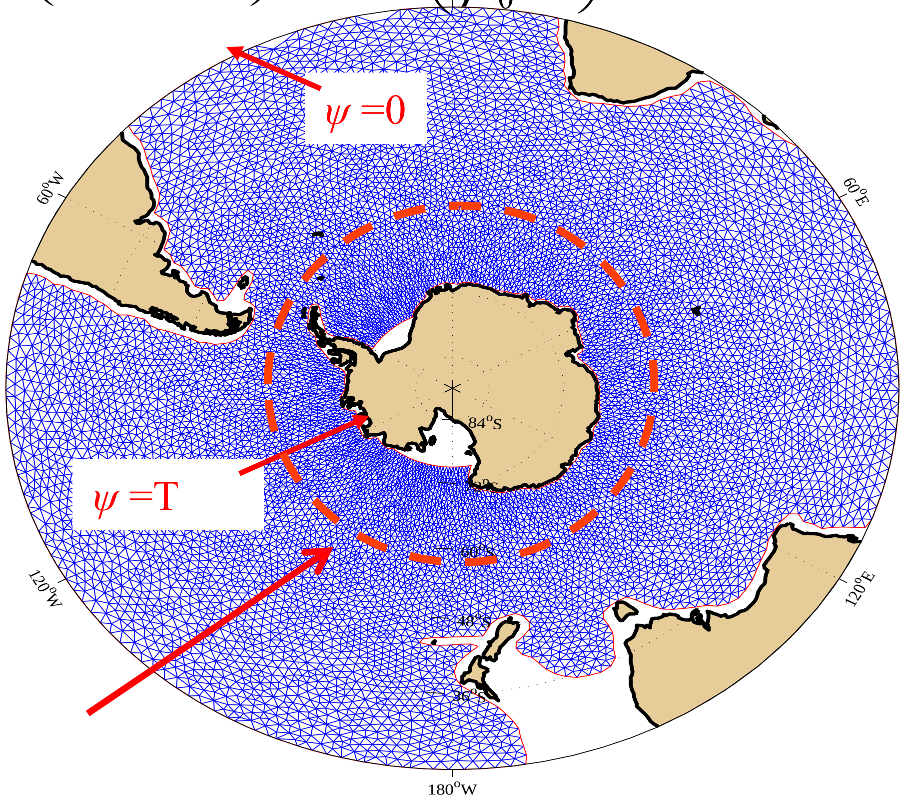
From geostrophy, $$\nabla^2 \eta = \nabla \cdot \left(\frac{f}{gH}\nabla\psi\right)$$

- Spectral in time: coupled set of elliptic PDEs.
- Finite elements.Resolution ~1°
- Periodic channel setting:

  ψ_N =0 and ψ_S =T

T: circumpolar transport.

-> T from zonally integrated momentum equation [eg *Krupitsky & Cane,1994]*

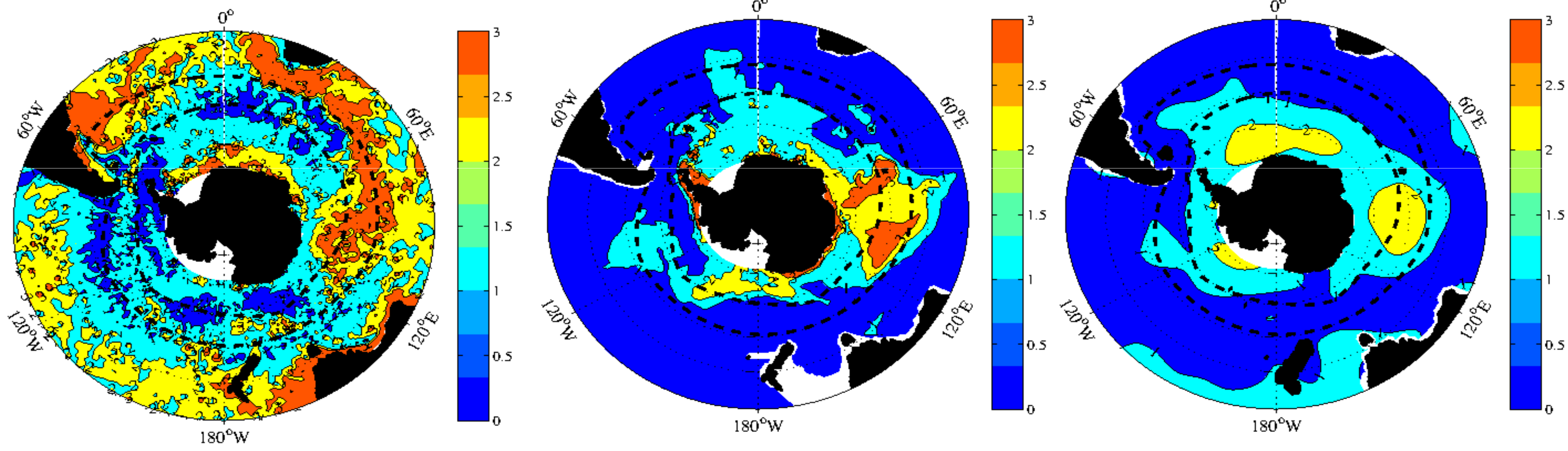


Monthly climatology

Comparison with AVISO SSH 1992-2014, and monthly GRACE data 2004-2014 (Tellus CSR rel 5, Chambers & Bonin, 2012)

RMS SSH (or eqH2O for GRACE) in cm

T/P-Jason (1993-2014) **Model (1993-2014)** **GRACE (2005-2014)**

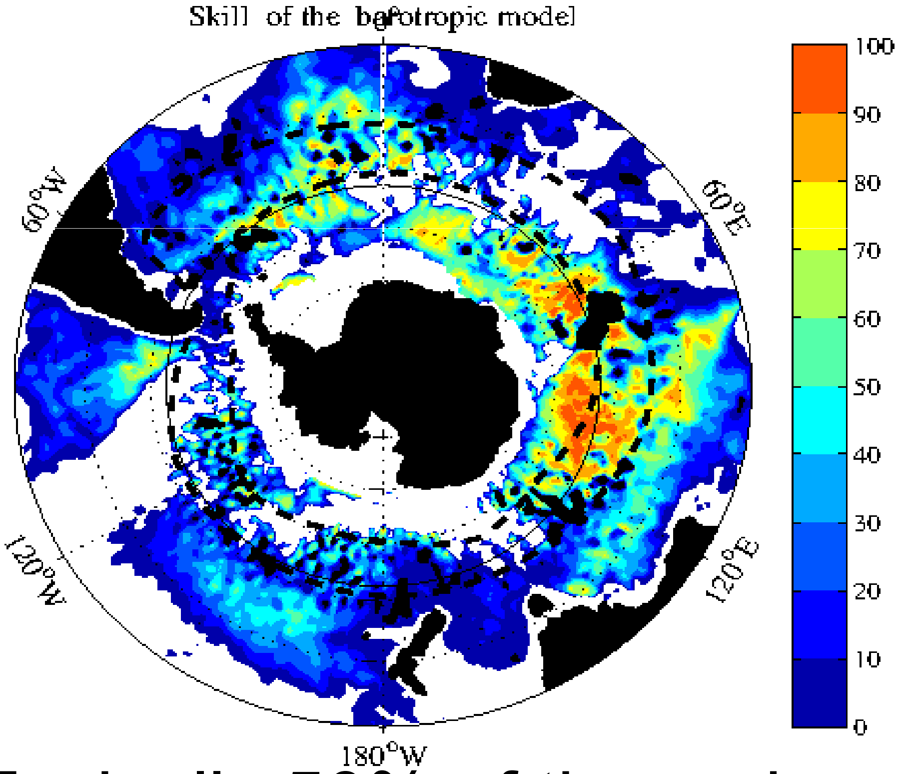


- Barotropic response enhanced at high latitude.
- Resonant basins (Australia-Antarctic & Bellingshausen Basin; Fu, 2003)
- T/P-J SSH variance comparable to barotropic SSH south of 50°S
- Far larger further north: other processes dominate

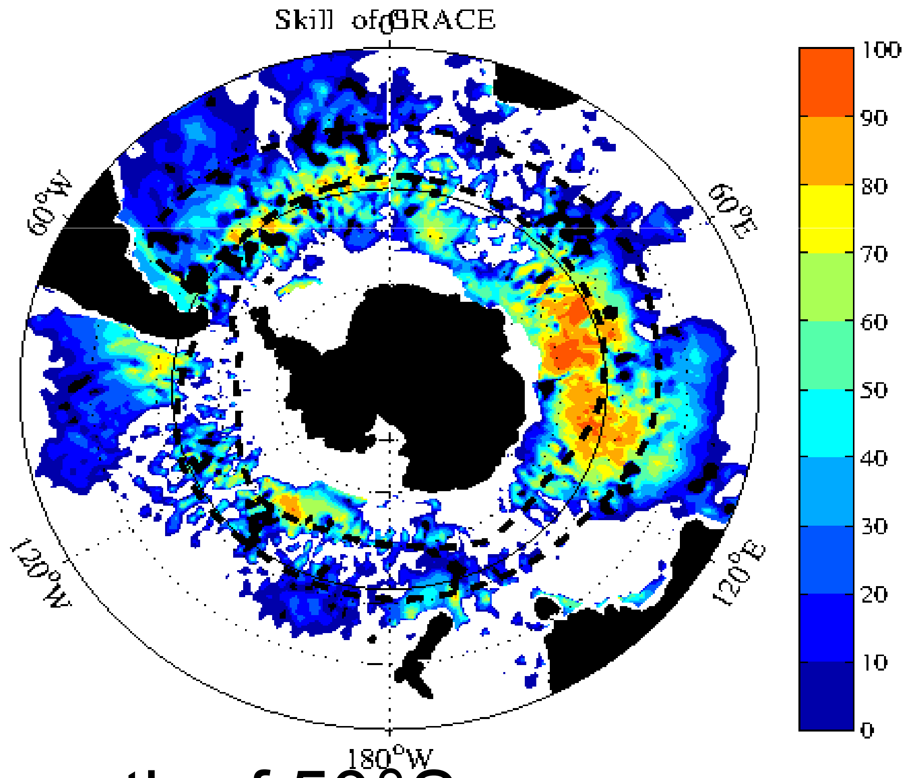
Monthly climatology

Where and to what extent does the batropic response account for the T/P-Jason SSH variance?

Skill Model



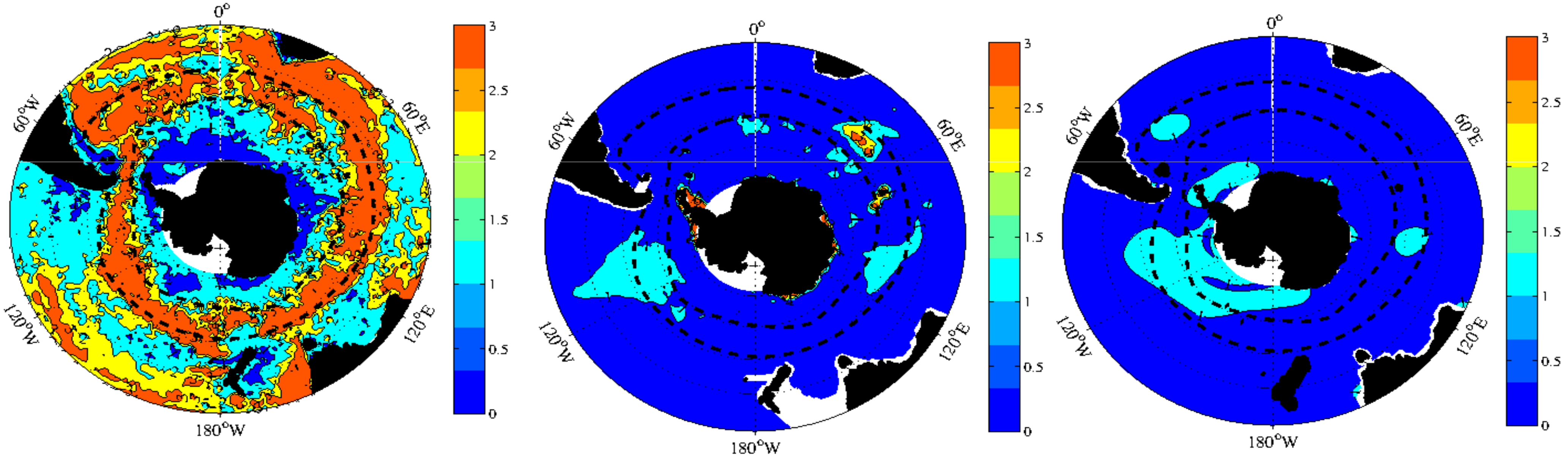
Skill GRACE



- Typically 50% of the variance south of 50°S
- > 90% in some regions (Australian-Antarctic Basin...)

RMS SSH **Interannual** (trends removed)

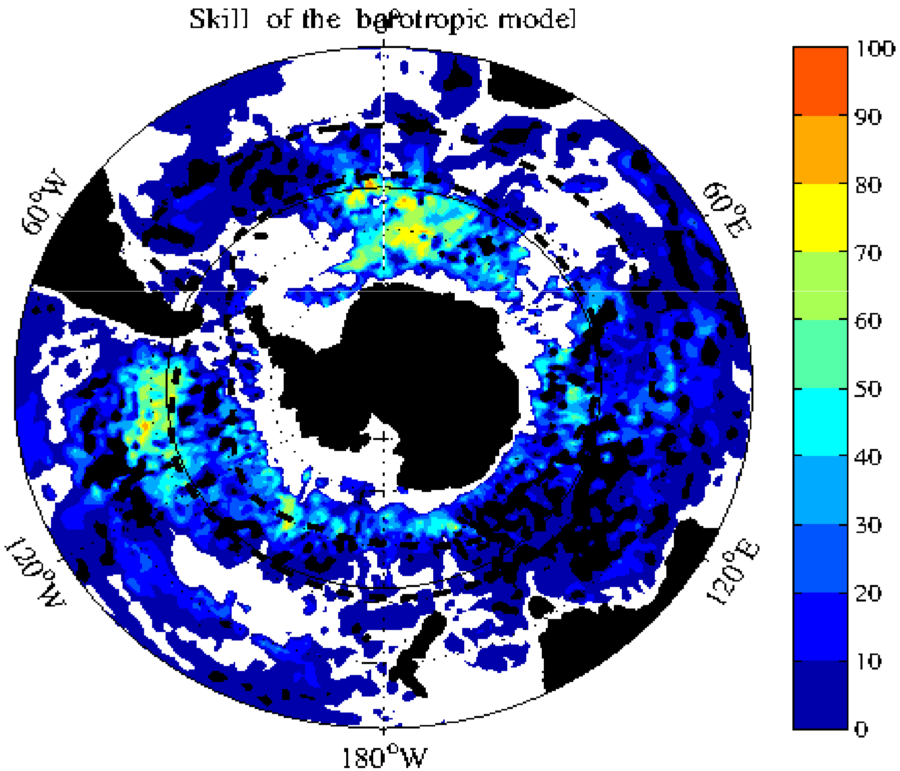
T/P-Jason **Model** **GRACE**



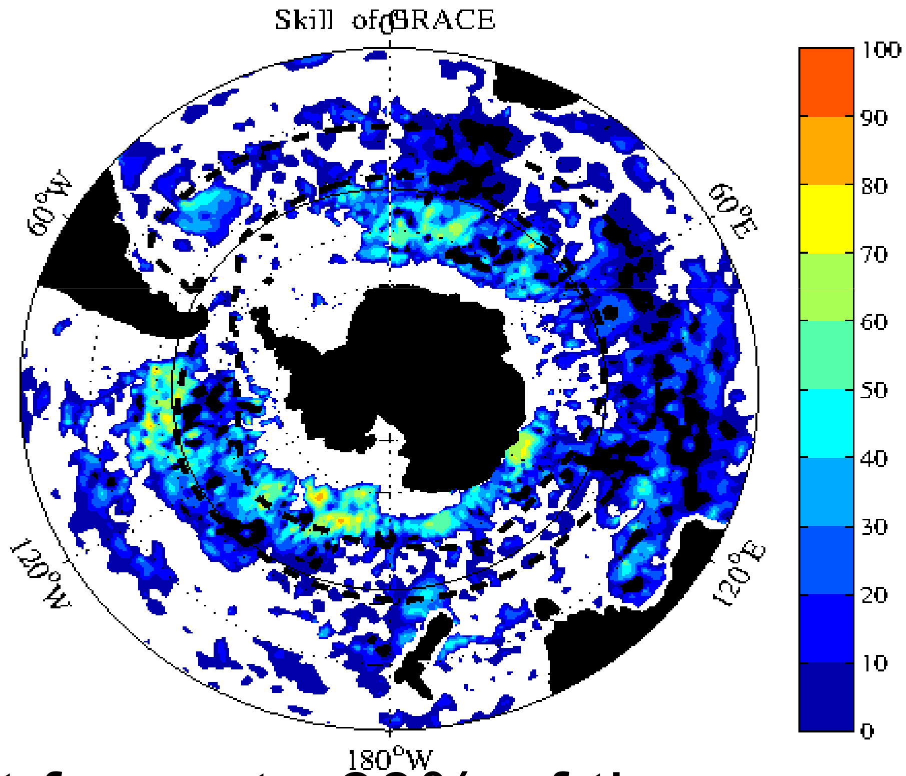
- Barotropic contribution up to 1cm RMS (Australian-Antarctic and Belligshausen basins..)

Skill in accounting for altimeter SSH variance at interannual time scales (detrended SSH)

Skill SSH Model



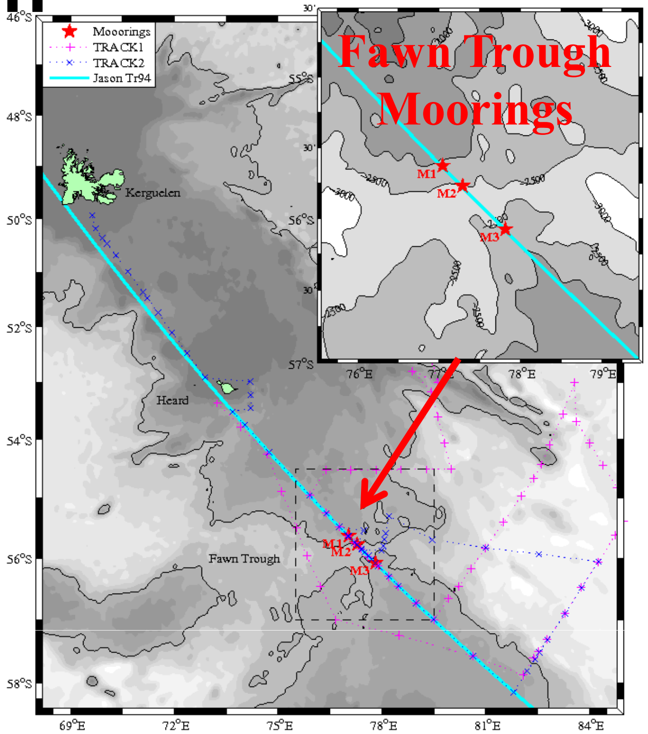
Skill SSH GRACE

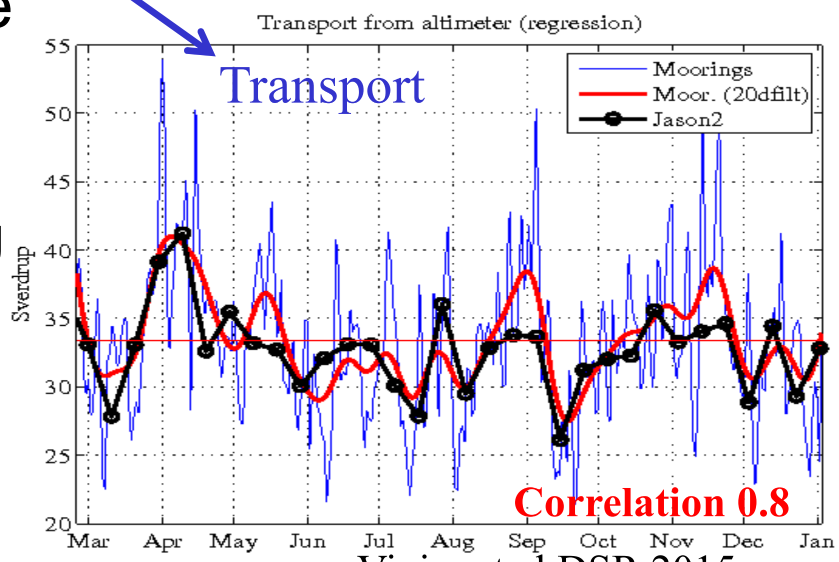


- Barotropic processes account for up to 60% of the altimeter SSH variance in some regions (see also Ponte and Piecuch, 2014)

ACC transport accross the Kerguelen Plateau (Fawn Trough Current)

- Monitored during the 2 *TRACK* cruises (2009-2010): roughly a third of the ACC (35-40 Sv) engulfs the Fawn Trough (Park et al GRL 2009)
- An array of current meter enabled to estimate the volume transport for 1yr
- Along track Jason data used to estimate the transport:
  - « Canonical » method developed for the Malvinas Current (Vivier & Provost 99), using the vertical structure inferred from CM data did not work so well here.
  - « Adhoc » method (excluding the southern part of the section) works well.

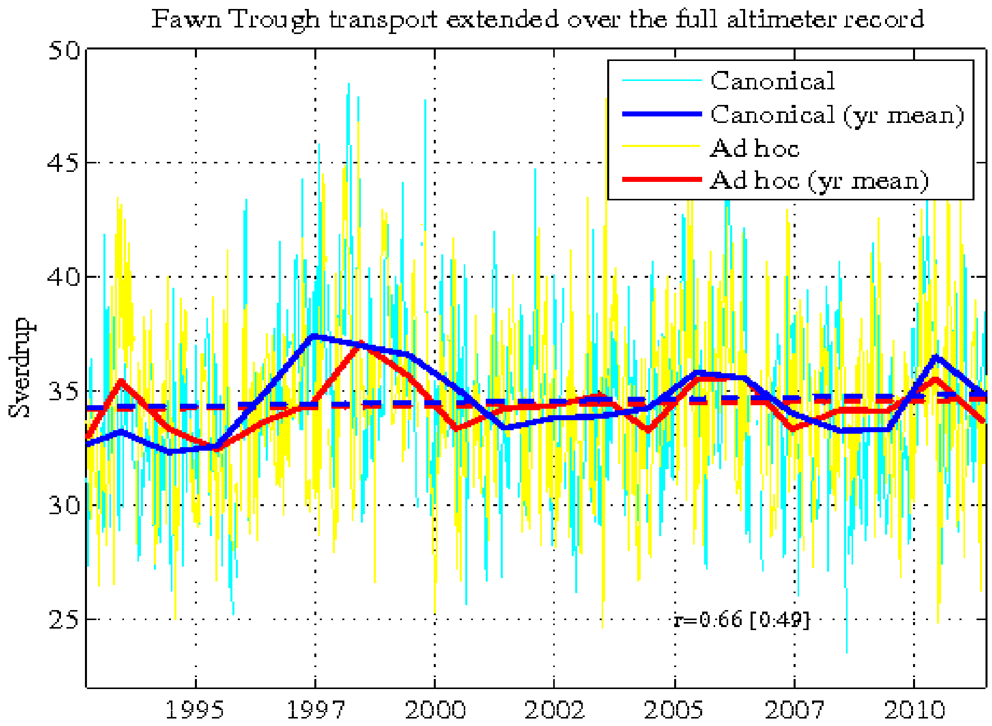


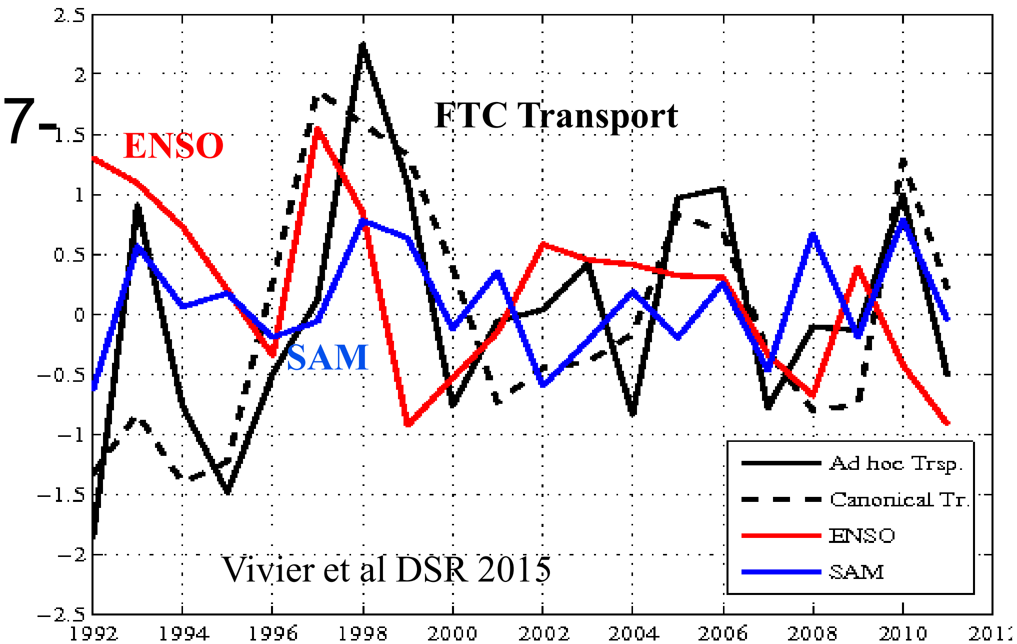


Vivier et al DSR 2015

Variability of the Fawn Trough Current from 20 years of altimetry

- Canonical and ad-hoc methods yie consistent transport variations at **interranual time scales**:
- Slight positive trend of 0.25 Sv per decade**: not significant.**
- Strongest transport anomaly (3Sv) coincides with the outstanding 1997-98 ENSO.
- Besides this event, no correlation with the ENSO index.
- Statistically significant correlation (0.6) with the SAM index.

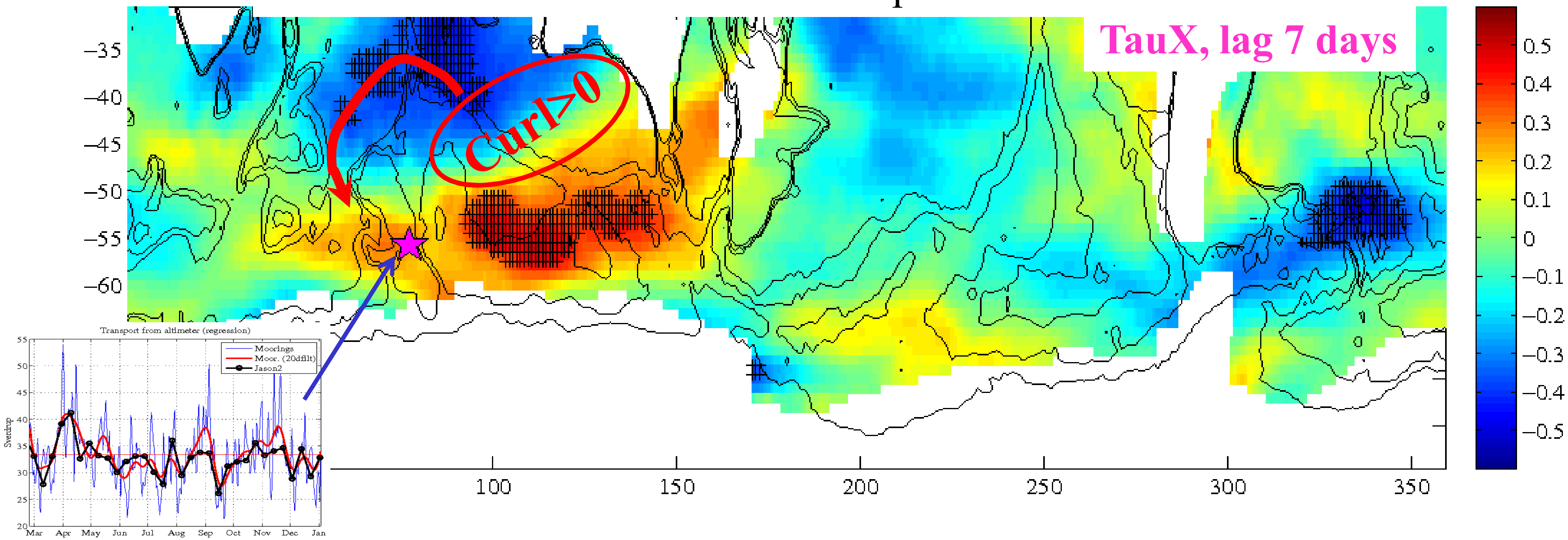




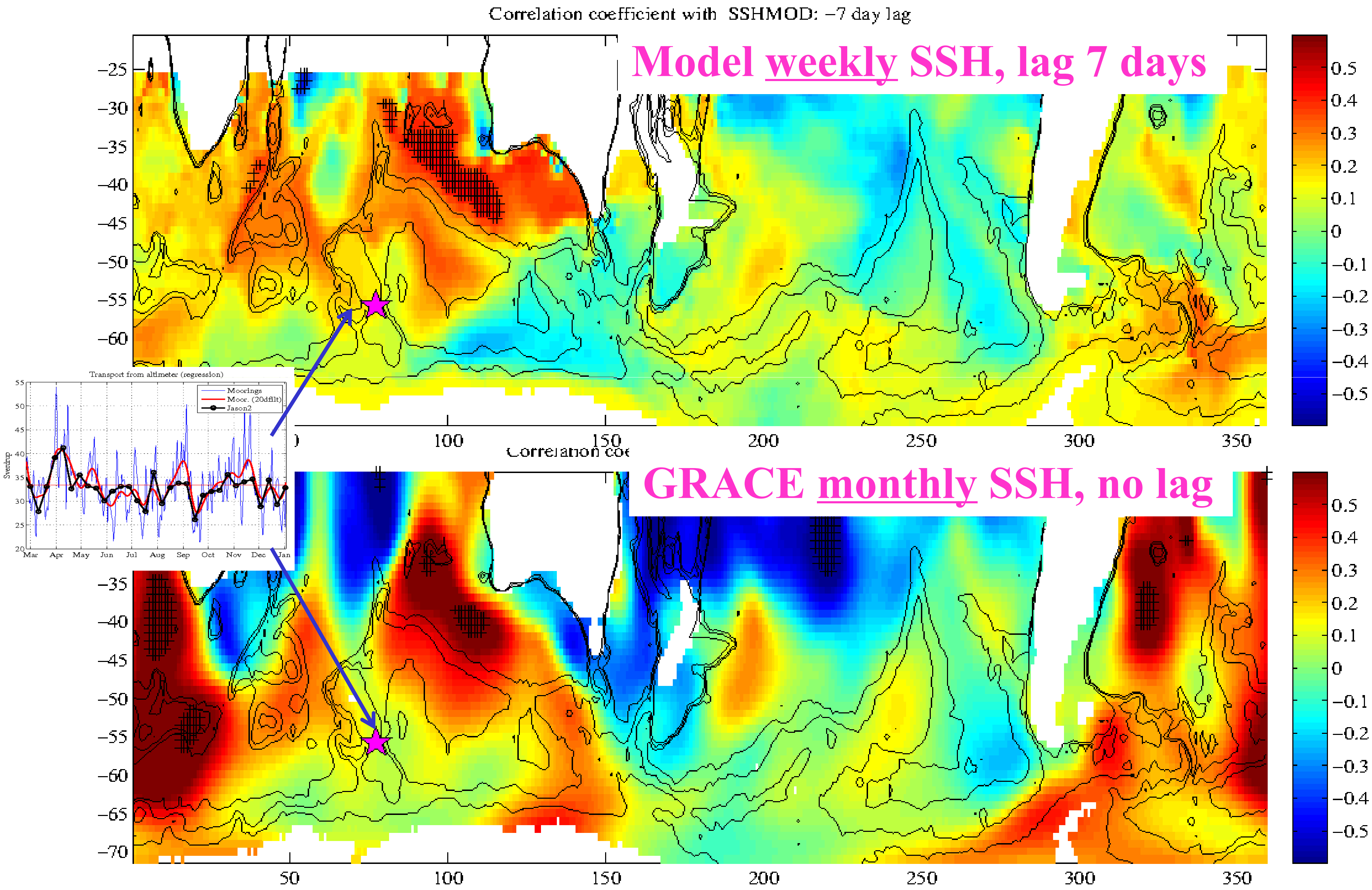
(How) does the current respond to winds?
Part 1: subannual scales

- Systematic lagged correlation analysis between 1yr in situ transport and zonal wind stress: significant correlations with a short lag
- Interestingly f/H contours connect with the South Australian basin and to the exit of the Australian-Antarctic basin, a region of enhanced barotropic variability (resonant basin, Fu 2003 , Weijer et al, 2005…)
- Response mediated by topographic Rossby waves along SE Indian ridge?

Correlation coefficient between transport and windstress



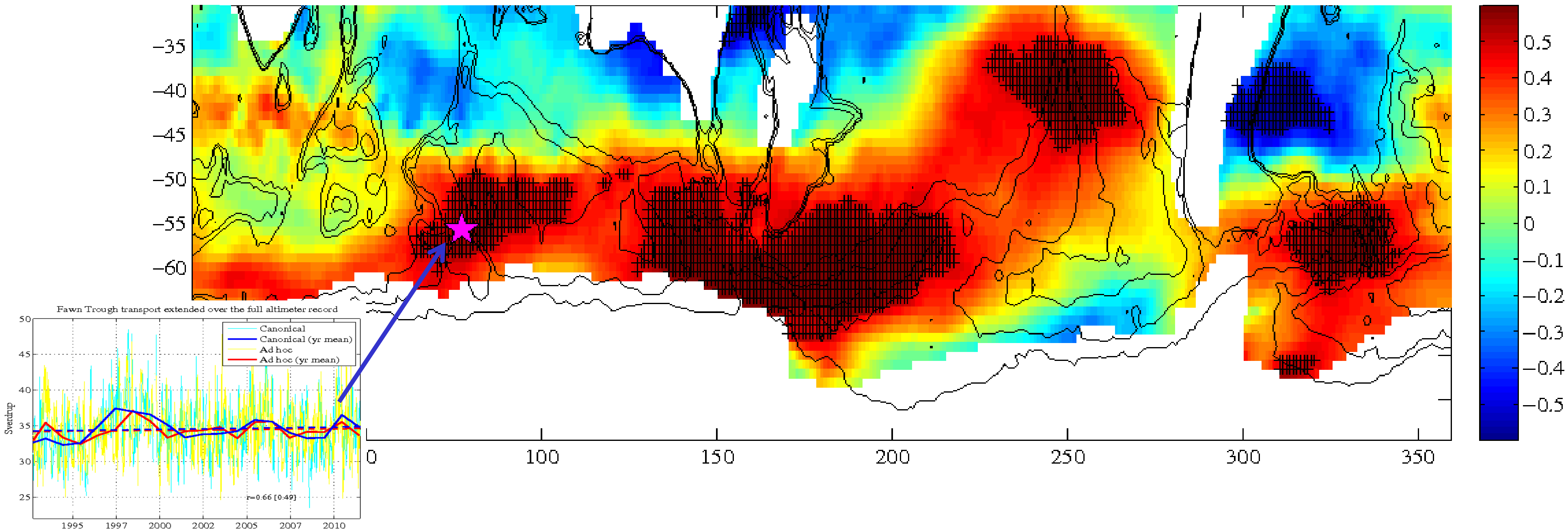
Correlation between Transport and SSH



(How) does the FTC respond to the wind : Part 2: **Interannual** time scales

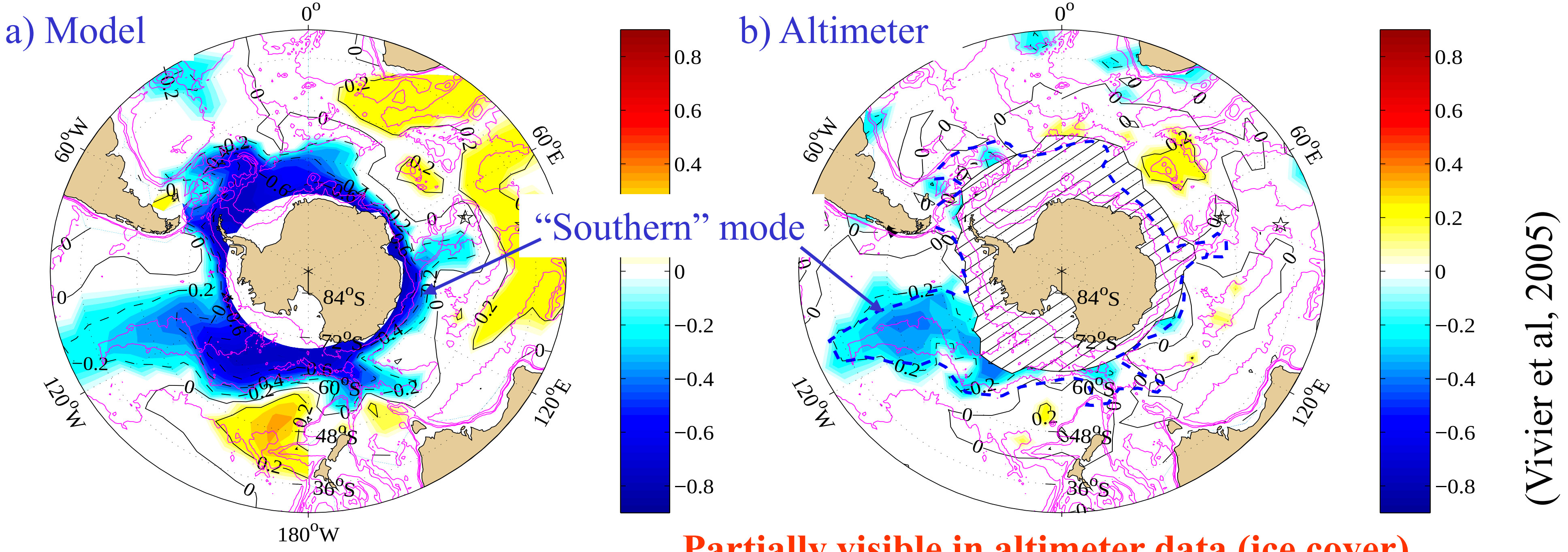
- Systematic correlation between the 20yr long series of transport from altimetry and wind, then SSH.
- Correlation with the zonal wind stress at zero lag
- The loci of significant correlations are aligned along circumpolar f/H contours: hints at the “Southern Mode”

Correlation between transport and annually averaged TauX (lag 0 year)



« Southern » mode (Hughes et al 1999)

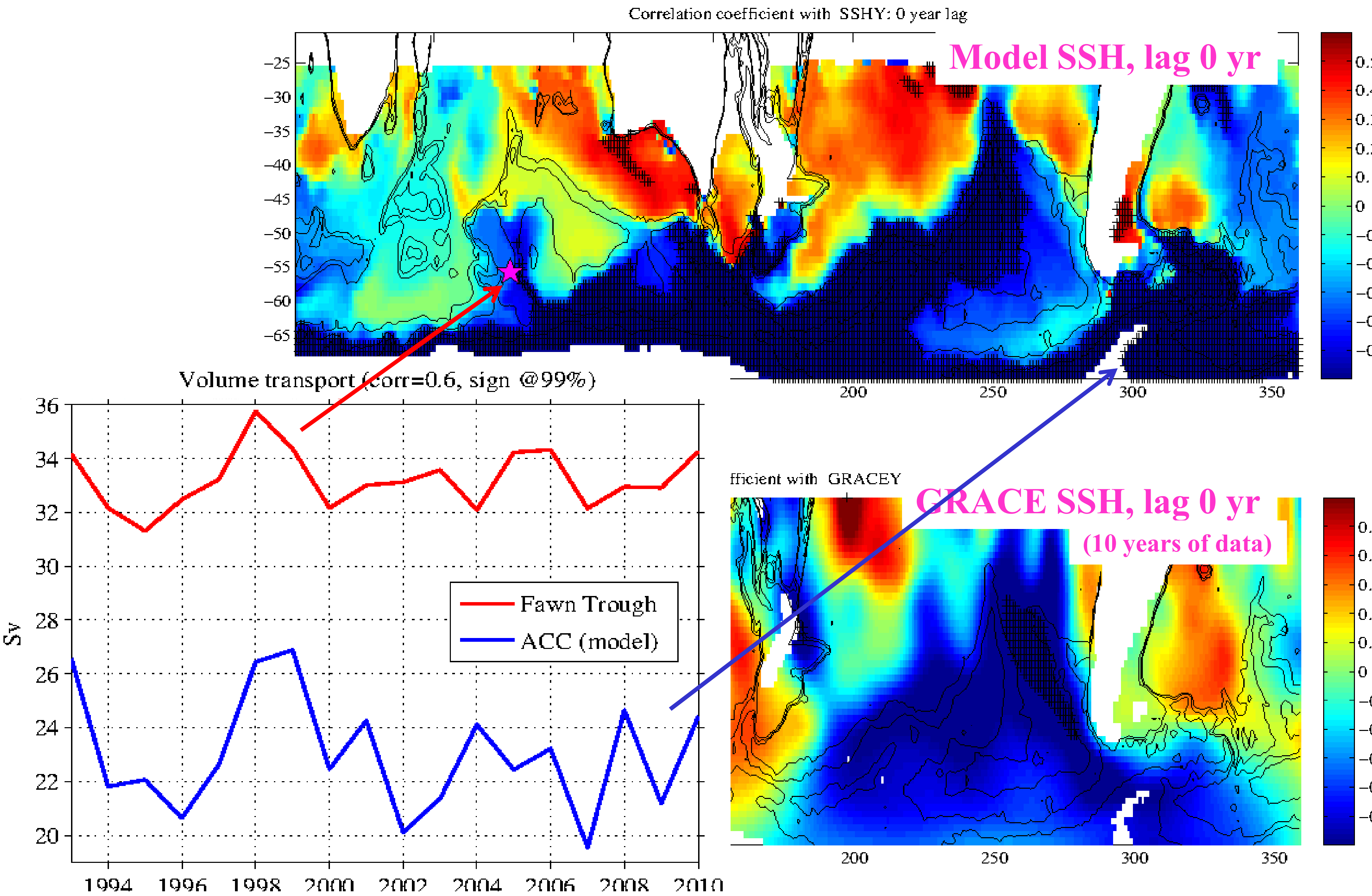
Correlation coefficient between   SSH and zonal integral of eastward Wind Stress



Partially visible in altimeter data (ice cover).

- Increase of $\int\tau$ $\rightarrow$ decrease of SSH along Antarctica ($\uparrow$ Transport)
- Circumpolar transport responds to zonal integral of eastward wind stress
- Free mode response along bundle of   f/H contours that circle Antarctica.
- Evidenced from BPR data at subannual timescales (Hughes et al , 1999; Gille et al 2001, Aoki, 2002; Hughes et al 2003)
- Extends to midlatitudes over the East Pacific Rise. Intensified on eastern flank of ridges, including Kerguelen

Correlation between transport and SSH



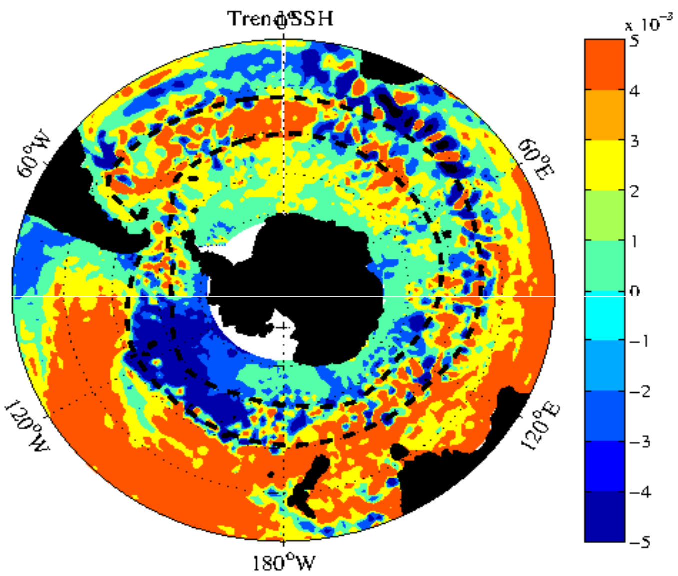
Conclusions

- Barotropic response to the winds at interannual times scales is generally small but exceeds 1cm RMS in resonant basins. Explains up to 60-70% of the altimeter SSH variance south of 50°S: far from negligible.
- Transport of the Fawn Trough Current (FTC) is successfully monitored from altimetry. No significant long term trend from 20 years series (Vivier et al DSR 2015).
- At subannual timescales, FTC transport variations connected to the wind forced variability in the South Australian Basin – North AAB, mediated by Topographic RW along the SE Indian Ridge
- At interannual timescales FTC transport variations are consistent with a “Southern Mode” response (correlated and correct order of magnitude),   primarily barotropic.
- “Southern Mode” thus still important at interannual timescales: Observations of the FTC confirm works by Olbers & Lettmann 2007 and Hughes et al 2014, based on numerical models.

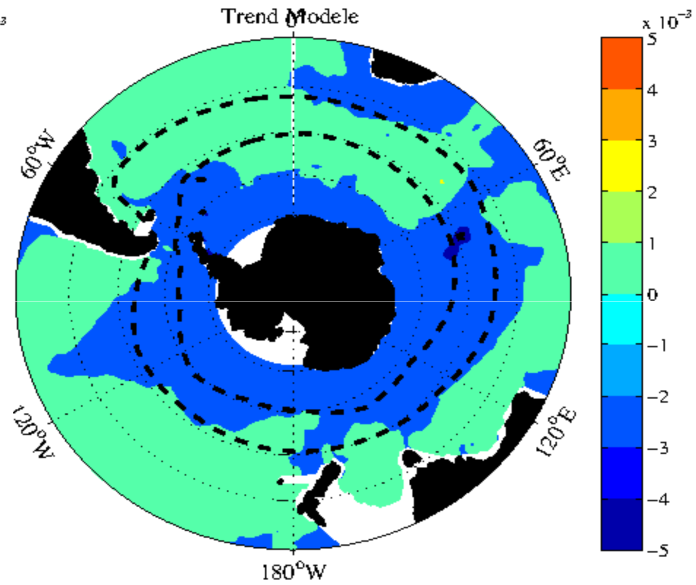
Extra slides

Trends from the time series of annual means

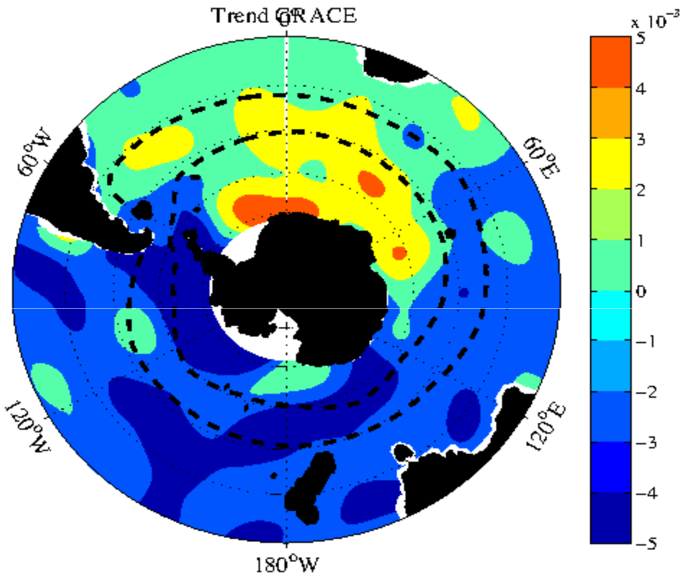
Trend T/P Jason



Trend model

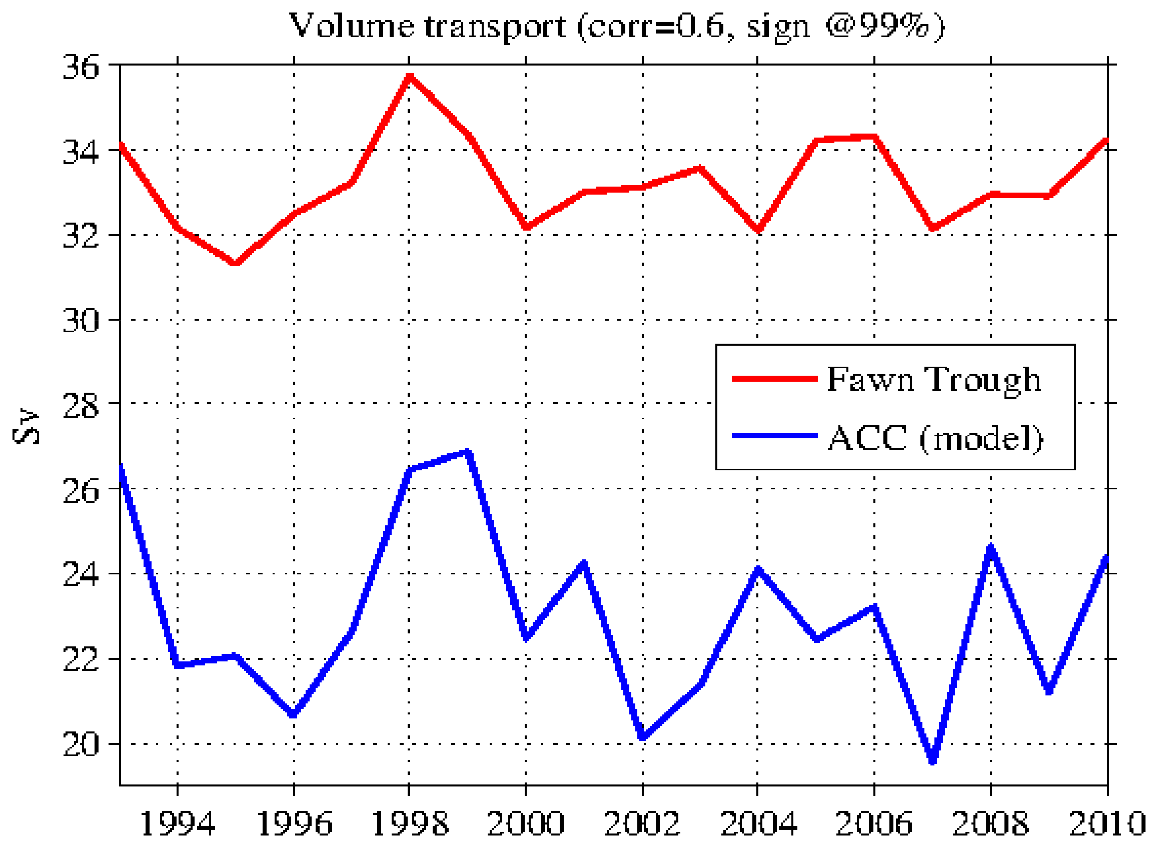


Trend GRACE



- Trends reaching 2mm/y in GRACE (see Purkey et al 2014)
- Smaller in the model, different pattern.
- Much larger trends in altimeter data (Steric changes).
- Time series detrended hereafter.

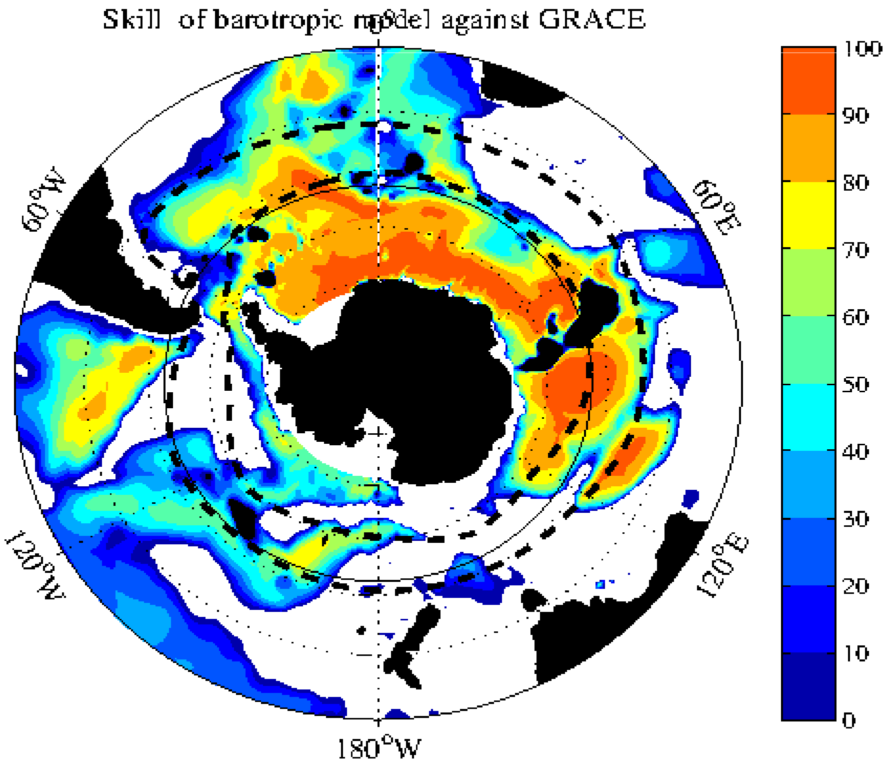
Volume transport



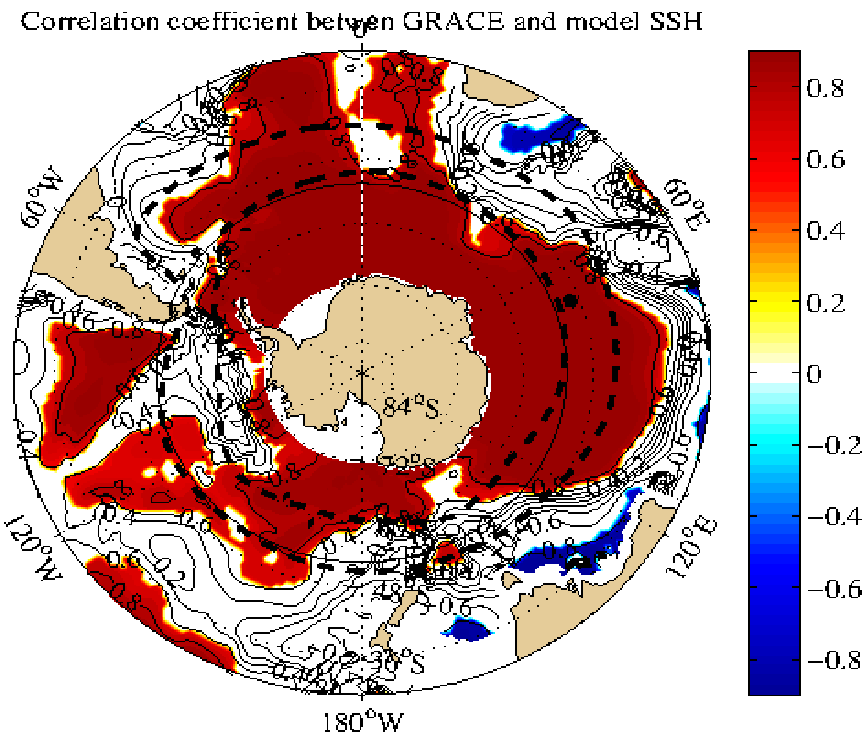
Monthly climatology

Intercomparison model vs GRACE

Skill of the model in accounting for GRACE

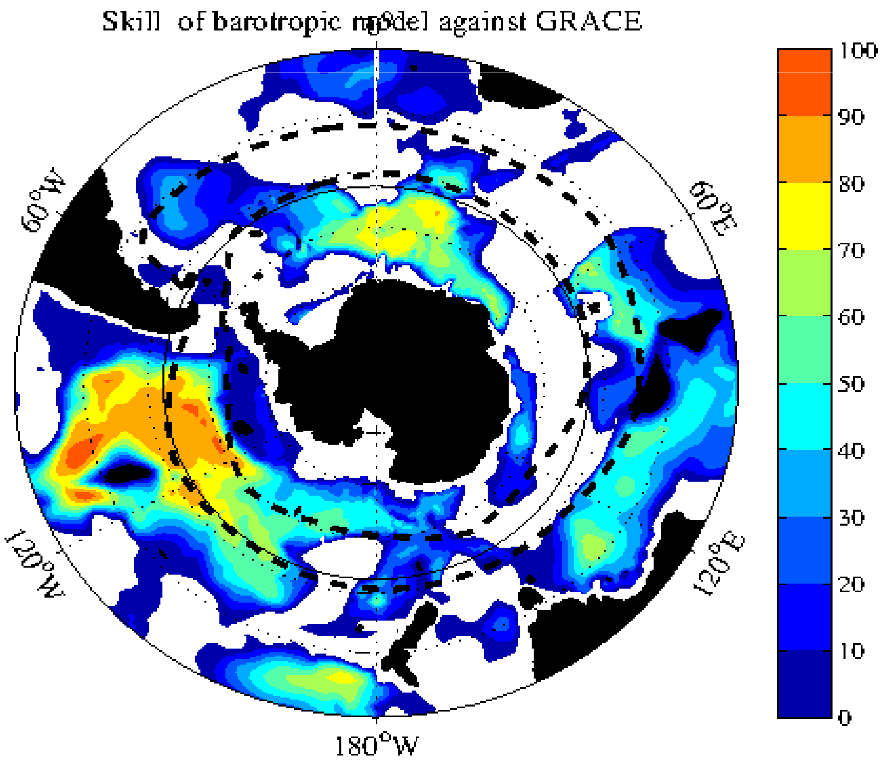


Correlation coefficient

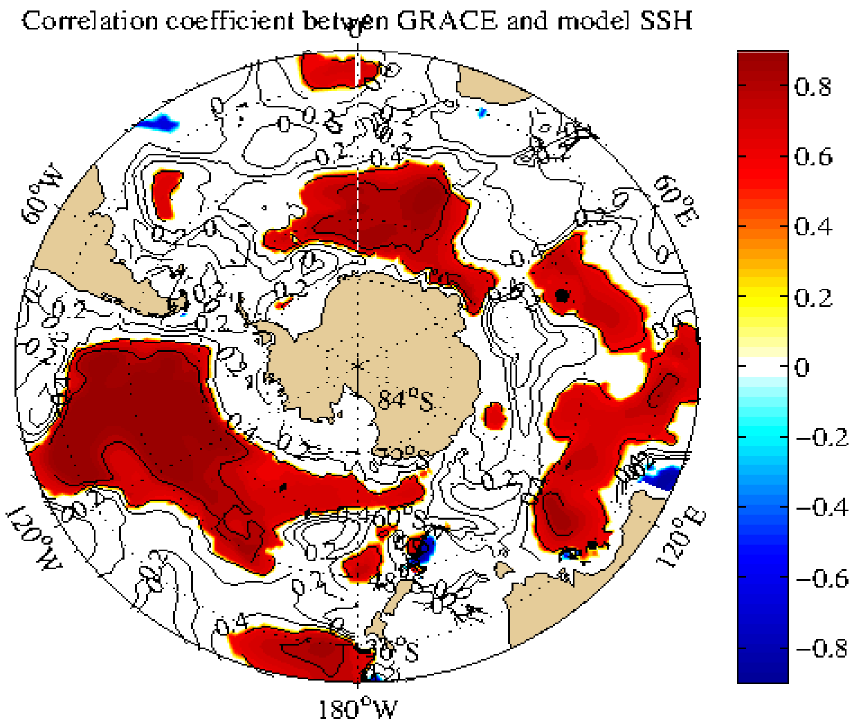


Intercomparison model vs. GRACE (Interannual)

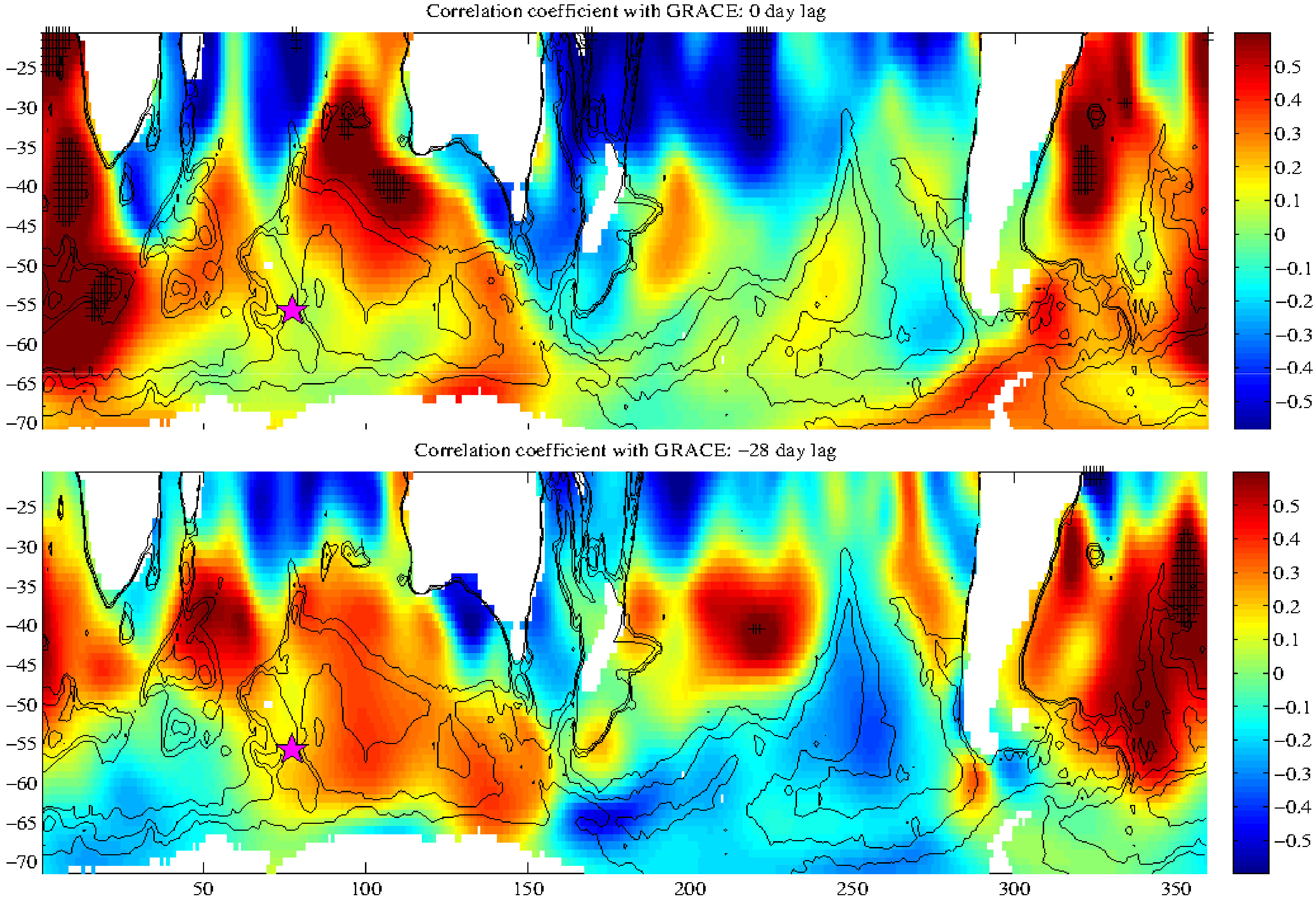
Skill of the model in accounting for GRACE



Correlation coefficient

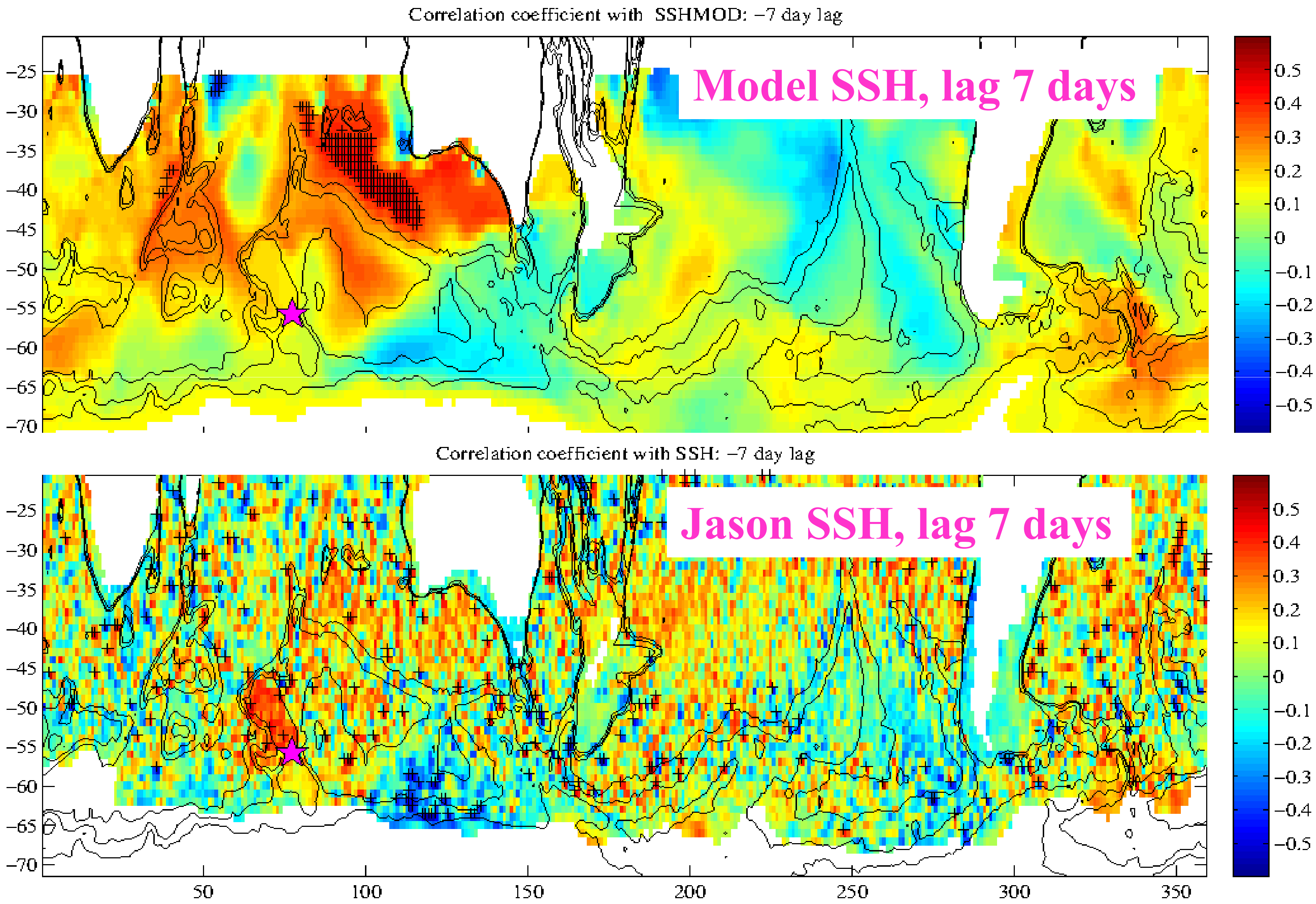


GRACE

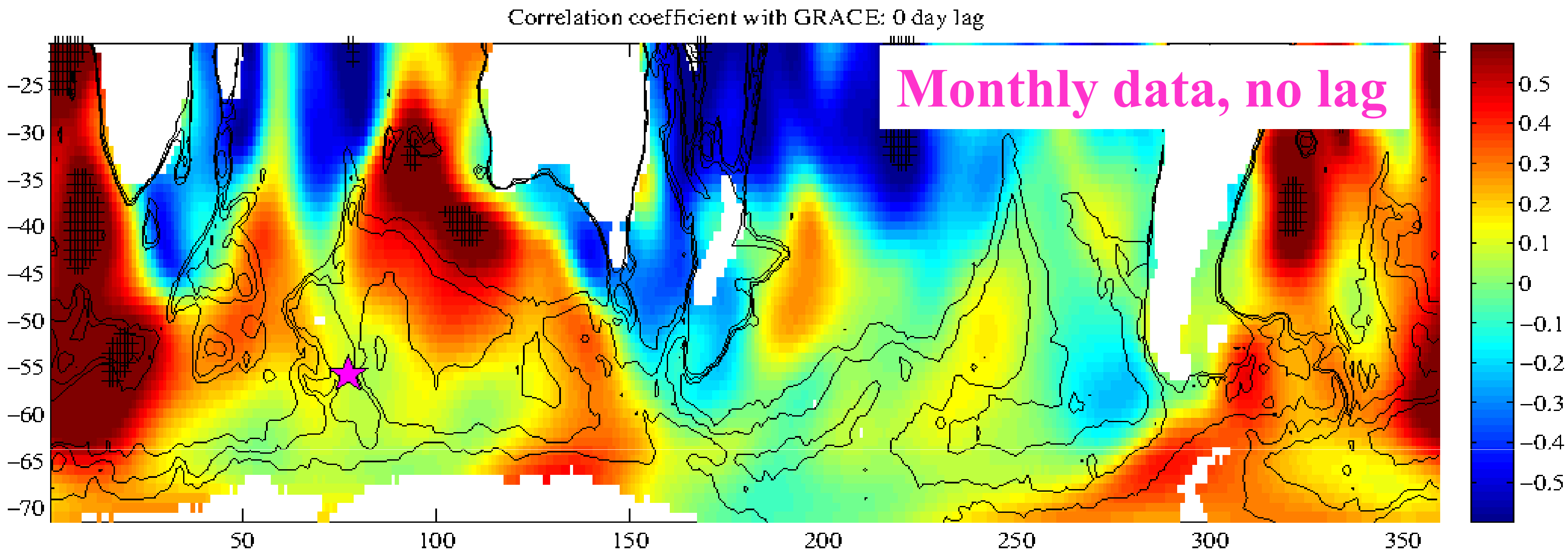


Correlation coefficient with GRACE: 0 day lag
Correlation coefficient with GRACE: −28 day lag
−25
−30
−35
−40
−45
−50
−55
−60
−65
−70
50
100
150
200
250
300
350
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5

Correlation between Transport and SSH



Correlation between FTC transport and GRACE



- At subseasonal time scale FT Current seems to be influenced by regions including South Australian Basin/ North AAB. Response mediated by barotropic Rossby waves along SE Indian ridge?
- What about interannual times scales?

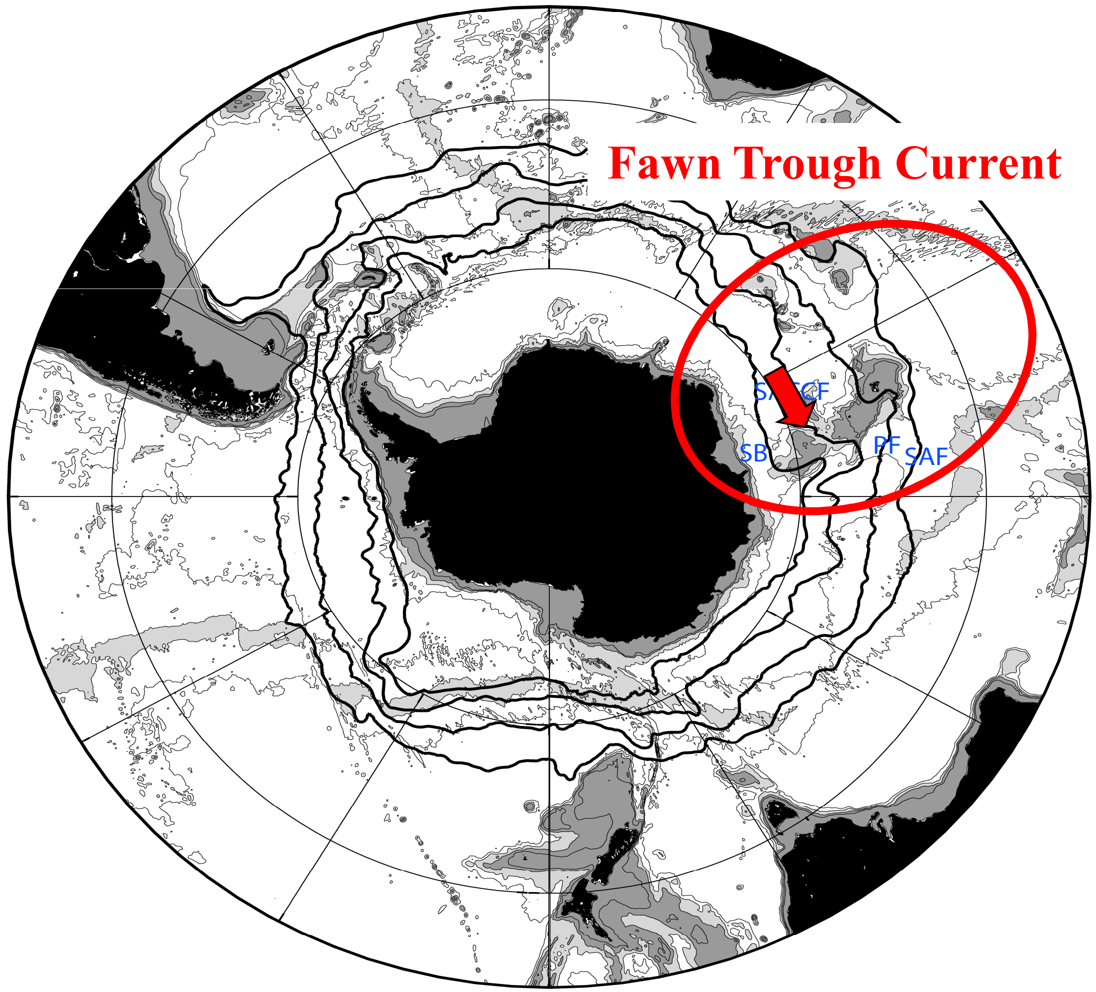
Motivations

- Large volumes of bottom, mode and intermediate waters are formed in the SO, which makes it a major compartment of the MOC.
- Significant climatic signals have been detected in water masses formed in the SO over the past decade.
- SSH from satellite altimetry is a key source of information to document heat/freshwater storage variations.
- But SSH is also impacted by convergence of mass (barotropic response to the winds) particularly at high latitude.
- The barotropic response is weaker at interannual time scales, but might still be significant.
- Here it is investigated over the past 20 years from a simple finite element barotropic model (Vivier et al, JGR, 2005), compared to GRACE data available since 2004.

Motivations: ACC dynamics

The 20 year long simulation is also used to investigate the dynamics of the Fawn Trough Current (FTC), a major branch of the ACC crossing the Kerguelen Plateau.

- FTC transport was measured during one year from current meter moorings (*TRACK* program, 2009-2010)
- Transport estimates were extended for the period 1992-present from altimetry (Vivier et al, DSR, 2015)



A simple barotropic model

Previously used in the SO to investigate seasonal variability (Vivier et al, JGR 2005)

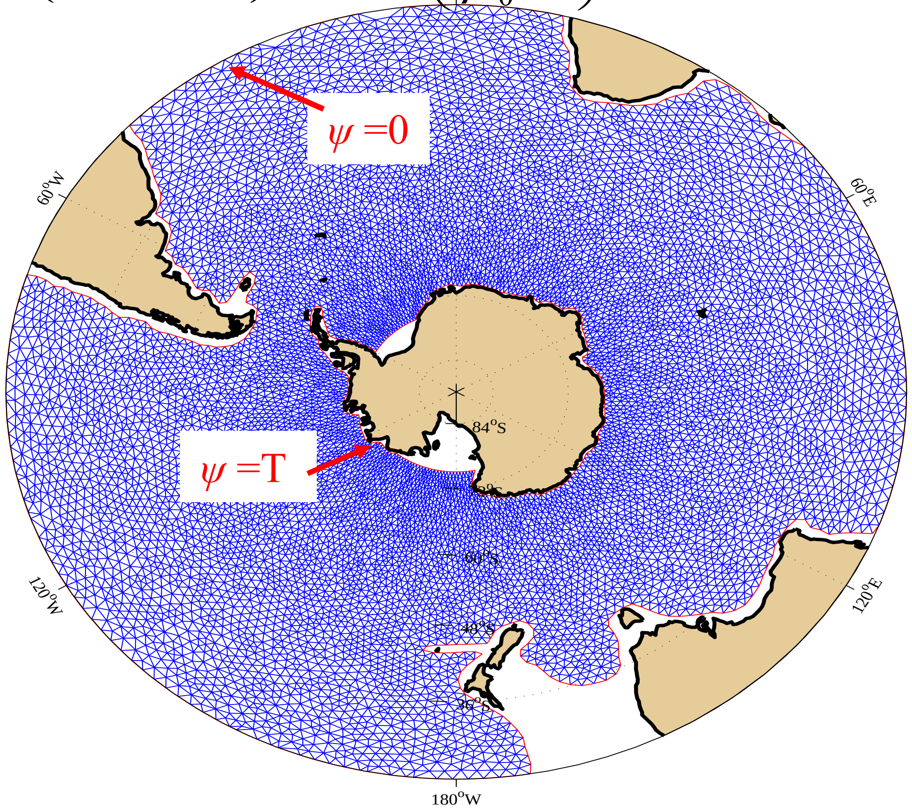
Transport streamfunction ψ: $\mathbf{v}H = \mathrm{k} \times \nabla\psi$

Vorticity: $$\nabla \cdot \frac{\nabla \partial_t \psi}{H} - \frac{f}{H}\partial_t \eta + J\left(\psi, \frac{f}{H}\right) + \nabla \cdot \left(\frac{r}{H^2}\nabla\psi\right) = \mathrm{curl}\left(\frac{\boldsymbol{\tau}}{\rho_0 H}\right)$$

From geostrophy, $$\nabla^2 \eta = \nabla \cdot \left(\frac{f}{gH}\nabla\psi\right)$$

- Spectral in time. Coupled set of elliptic PDEs.
- Finite elements.Resolution ~1°
- Periodic channel setting:
  ψ_N =0 and ψ_S =T

T: circumpolar transport



Determination of the Circumpolar Transport (southern boundary condition)

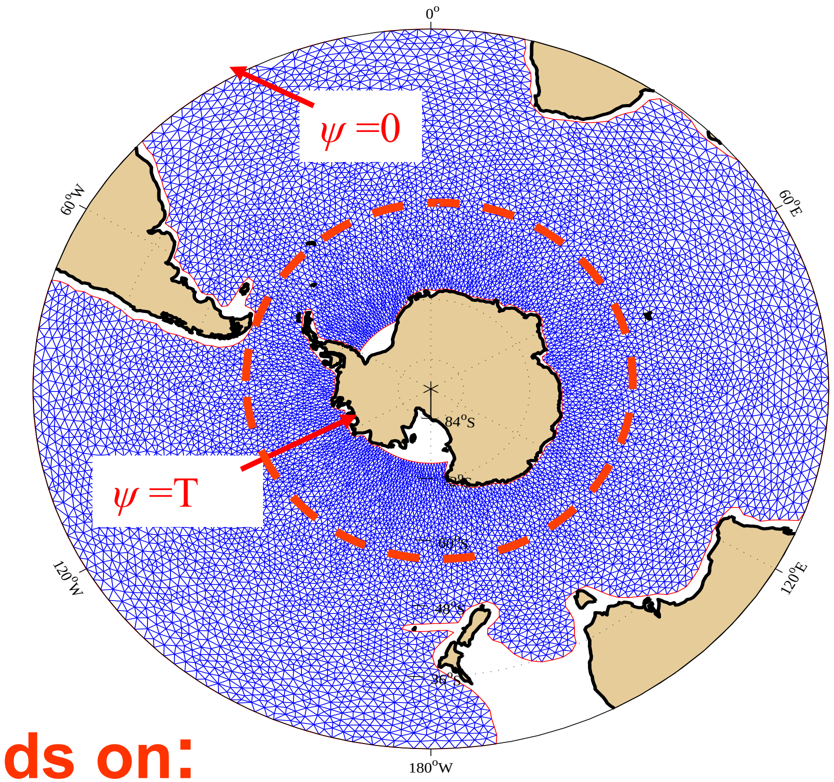
- à la *Krupitsky & Cane (1994):* Zonally integrated momentum equation $\frac{f}{H}\partial_x\psi = -g\partial_x\eta + \frac{r}{H^2}\partial_y\psi + \frac{\tau_x}{\rho_0 H}$

$\Psi = \Psi_F + T.\,\Psi_L$

Ψ_F forced solution (forcing; $\Psi_S = 0$)

Ψ_L "free" solution (no forcing; $\Psi_S = 1$)

$$T = \frac{\oint_{Drake}\left(\frac{\tau_x}{\rho_0 H} + \frac{f}{H}\partial_x\psi_F + \frac{r}{H^2}\partial_y\psi_F\right)dx}{\oint_{Drake}\left(\frac{f}{H}\partial_x\psi_L + \frac{r}{H^2}\partial_y\psi_L\right)dx}$$



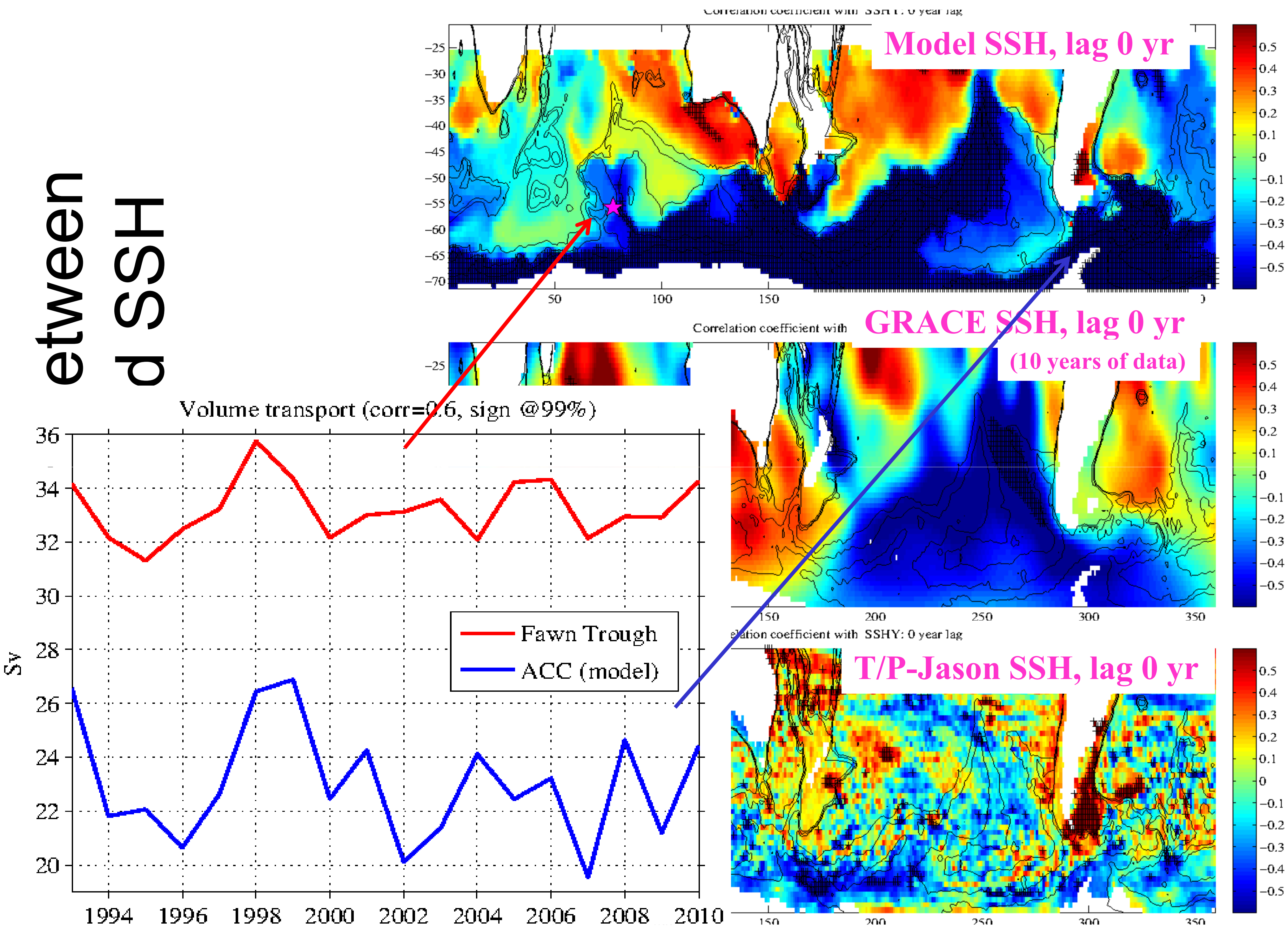
Barotropic circumpolar transport depends on:

- Zonal integral eastward wind stress

- Wind stress curl over the domain (via ψ_F).

- 22 yr simulation (altimeter era), forced with ERAI weekly winds.

etween
d SSH



Model SSH, lag 0 yr
GRACE SSH, lag 0 yr
(10 years of data)
T/P-Jason SSH, lag 0 yr
Correlation coefficient with
elation coefficient with SSHY: 0 year lag
Volume transport (corr=0.6, sign @99%)
Sv
Fawn Trough
ACC (model)