Antarctic Circumpolar Current response to the Southern Annular Mode: Changes in mixed-layer depth and jet position

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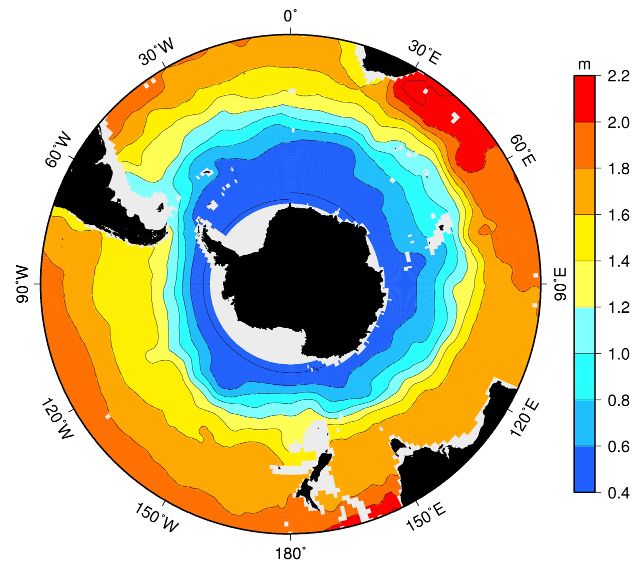
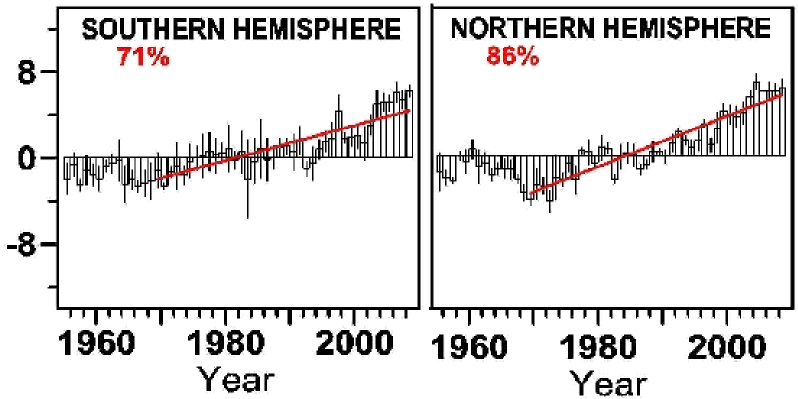


Dynamic topography

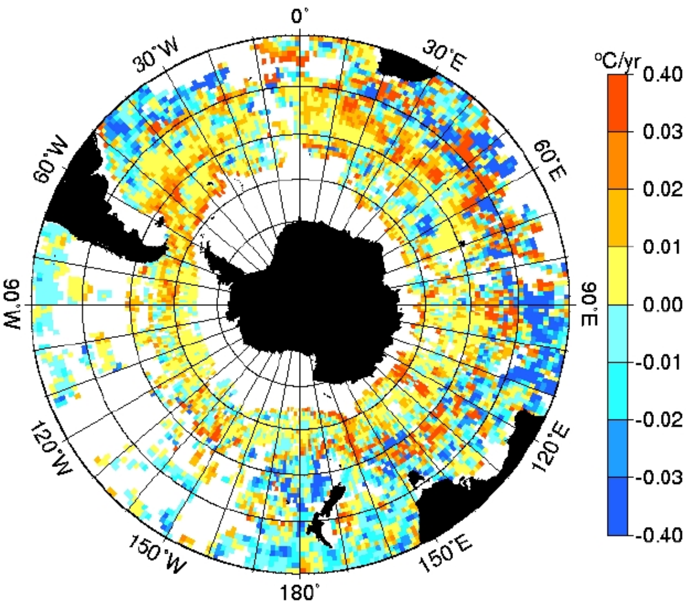
Multi-decadal changes in ocean heat content



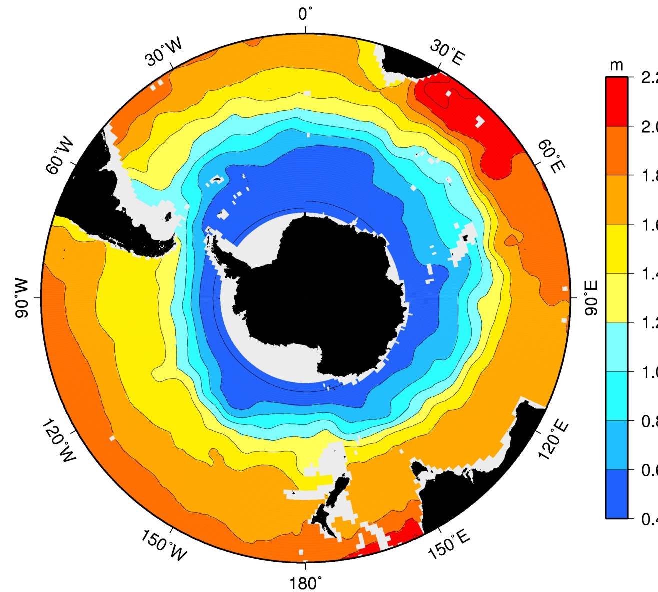
(Levitus et al., GRL, 2009; see also Ishii and Kimoto, 2009, etc.)

- Where specifically does warming occur?
- What mechanisms account for observed warming?

Where does warming occur?



Temperature trends at ~900 m, (Gille, Science, 2002; See also Gille, J. Climate, 2008)

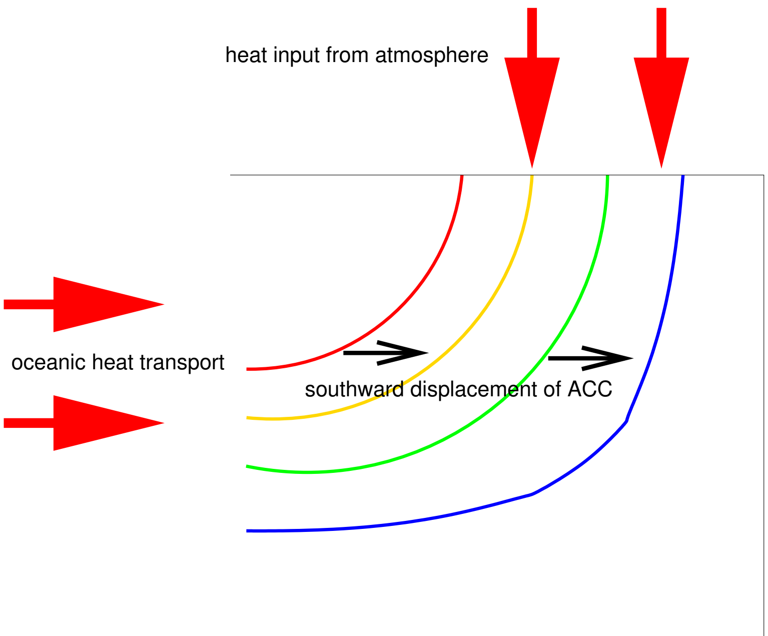


Dynamic topography

- Warming concentrated in Antarctic Circumpolar Current (ACC) throughout top 1000 m.
- 90% of net heat content increase south of 30°S.
- Warming consistent with poleward migration of background temperature. by 1° latitude every 35 years (Gille, 2008; Sprintall, 2008).

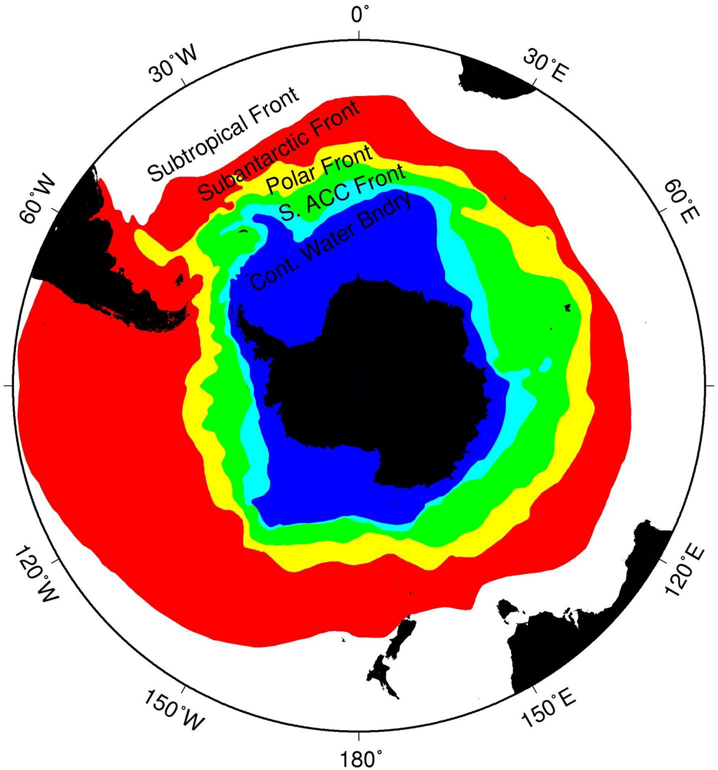
Mechanisms: What Controls Change?

$$\overline{\frac{\partial T}{\partial t}} + \nabla \cdot (\overline{\mathbf{u}}\overline{T}) + \nabla \cdot (\overline{\mathbf{u}'T'}) = \text{forcing}$$

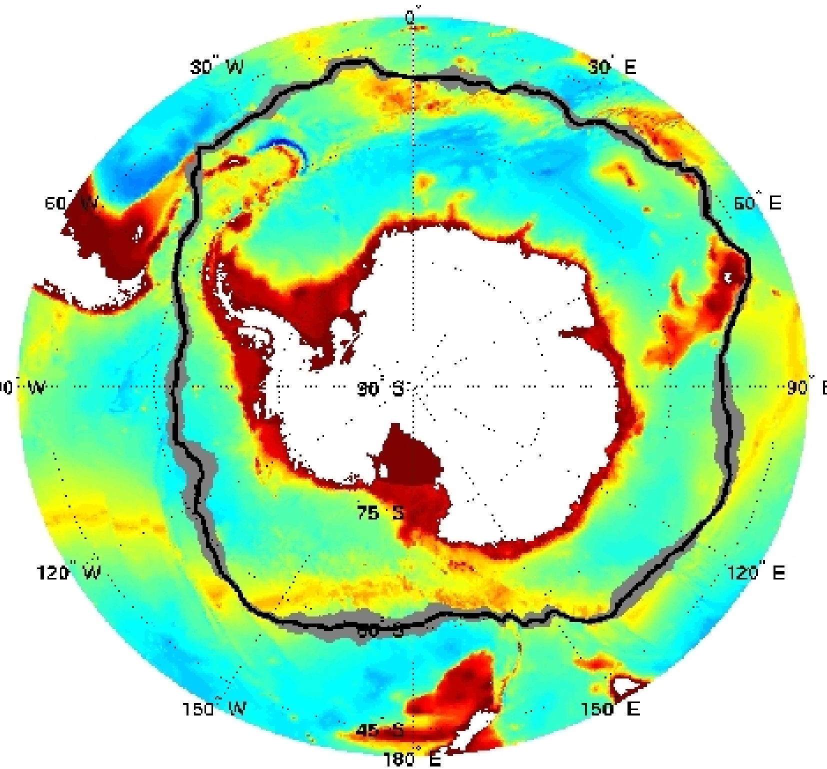


- Mean Advection: poleward shift in ACC frontal features? *Assess frontal migration from satellite observations of SST and sea surface height.*
- Eddy Advection: changes in poleward eddy heat transport?
- Surface Forcing: increases in air-sea heat exchange and heat input to upper ocean. *Consider changes in mixed-layer and upper ocean heat content.*

Background: Multiple meandering fronts of the ACC



(Orsi et al. 1995)

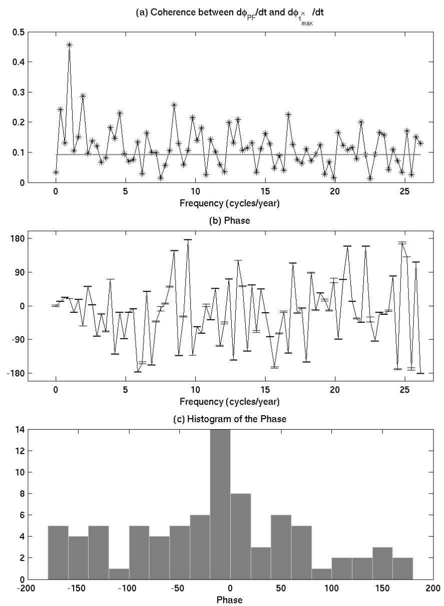


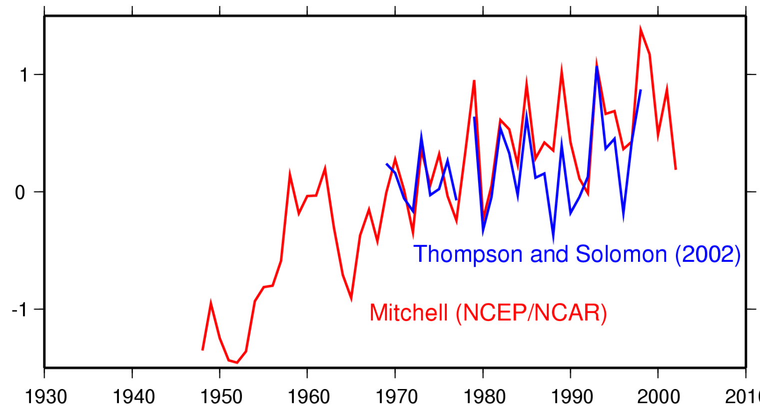
Polar Front from AMSRE-E microwave SST.
(Dong et al., JPO, 2006)

Meandering fronts are top-to-bottom features.

Can Southern Annular Mode drive frontal migration?

Southern Annular Mode intensification implies poleward shift in wind.



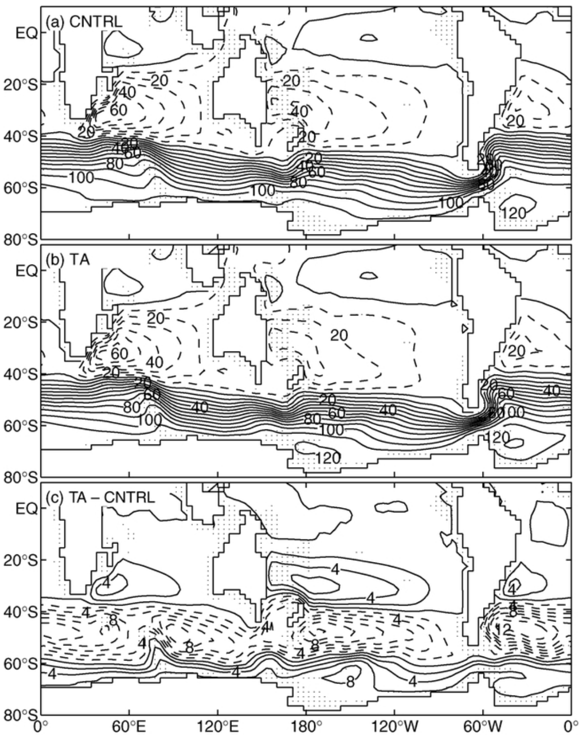


Poleward shift in wind implies poleward shift in ACC at least on time scales <1 year (Dong et al., JPO, 2006)

$$\phi_{PF} \propto \phi_{\tau}$$

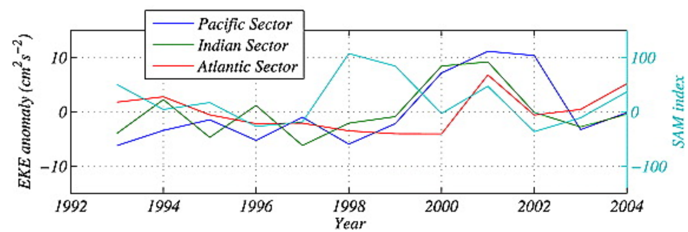
Dynamics Governing Observed Long-Term Trends

- Hypothesis A: Shifts in SAM drive shifts in ACC fronts



(Oke and England, J. Climate, 2004. See also Fyfe and Saenko, 2005; 2006, etc; Cai, 2005)

- Hypothesis B: Changes in SAM imply changes in EKE, which can increase eddy heat transport

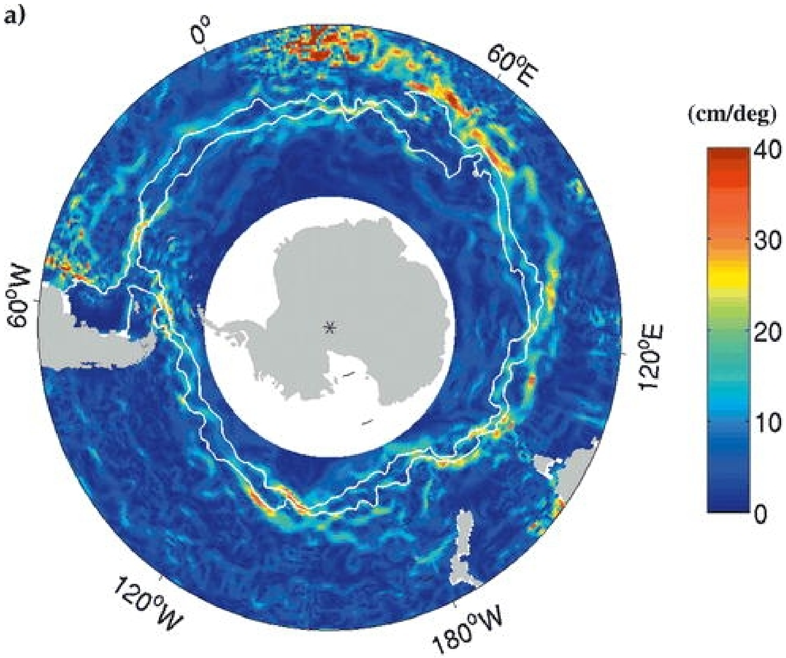


(Meredith and Hogg, JGR, 2006)

- Böning et al (2008) suggested no change in tilt of isopycnals, implying no long-term transport change.
- Farneti et al. (2010) find models that resolve eddies buffer ACC transport response to atmospheric changes.

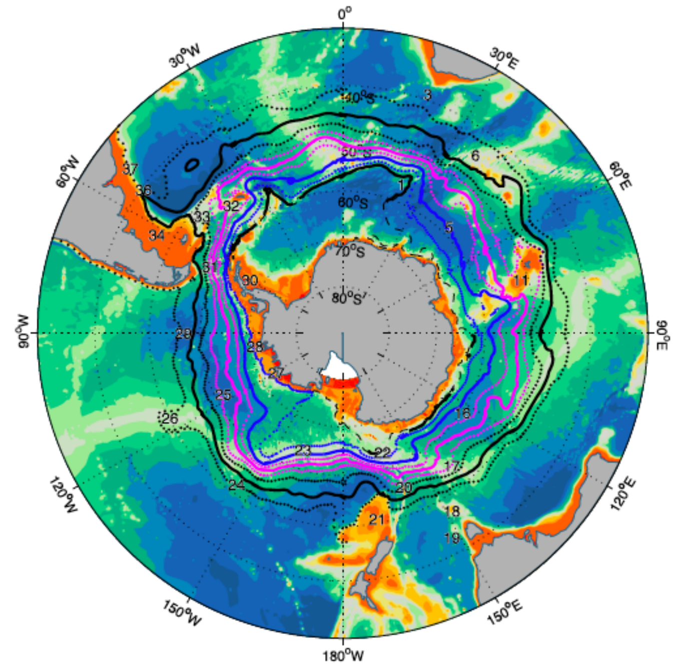
Can we track ACC jet displacements over longer timescales from altimetry?

From fixed height contours:



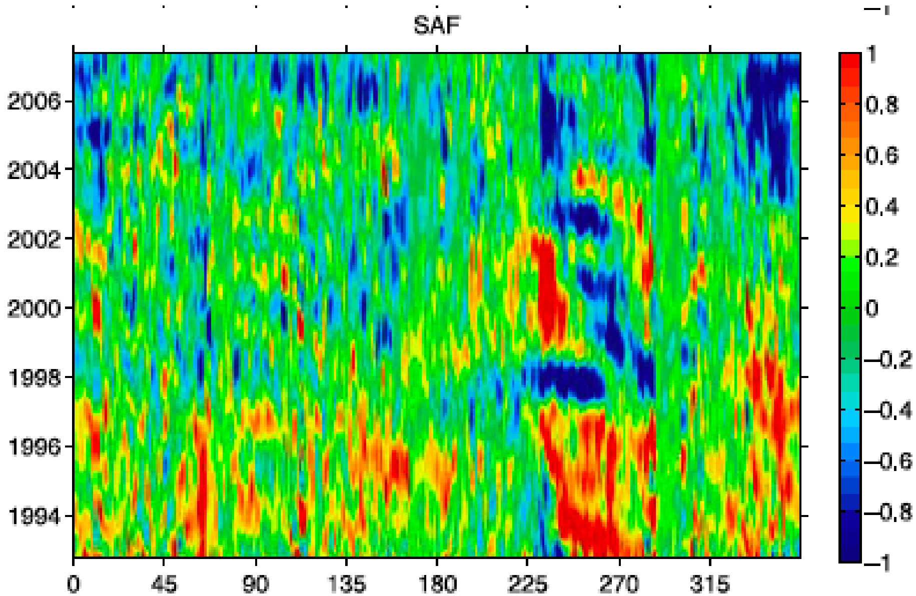
(Sallée et al, J. Climate, 2008: PF = 0.95 m, SAF = 1.20 m)

From height contours at maxima in sea surface slope:



(Sokolov and Rintoul, JGR, 2009)

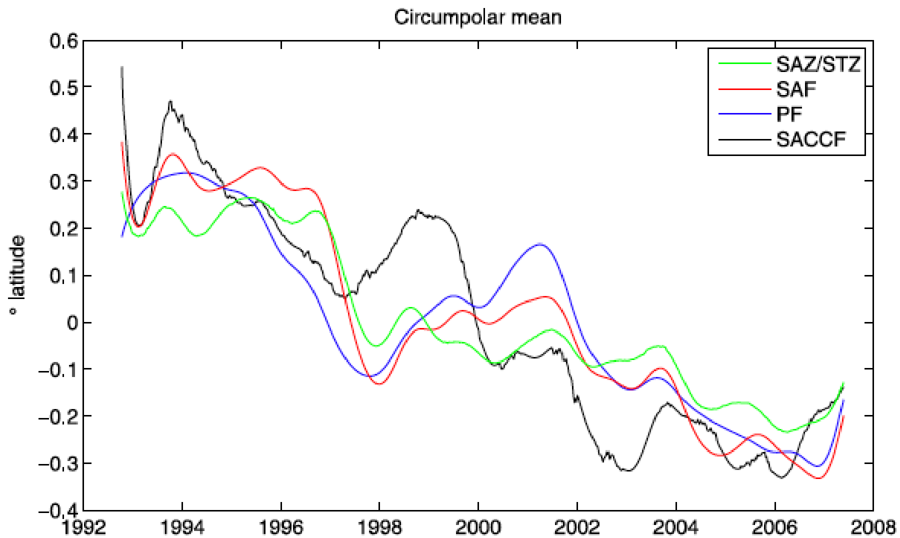
Altimetry imply steady poleward migration of ACC



Subantarctic Front moves southward from 1992 to 2007

Sokolov and Rintoul, JGR, 2009

Overall migration about 60 km in 15 years

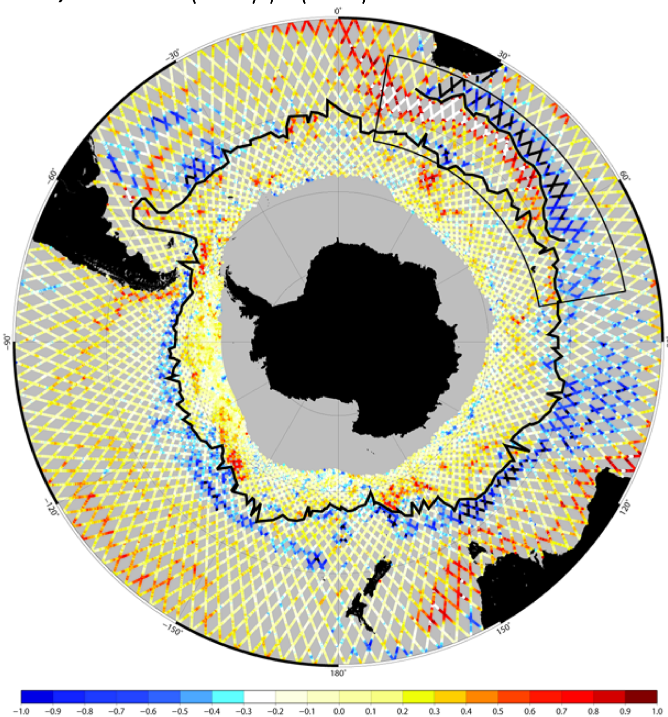


Sokolov and Rintoul, JGR, 2009

- Steric warming would also yield apparent poleward migration
- But Sokolov and Rintoul (2009) report that gradients do migrate.

Alternative methods: Skewness or transport shifts

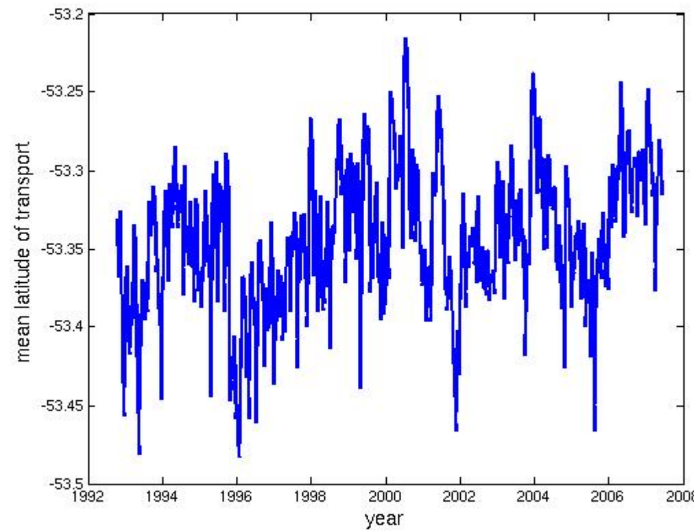
Skewness from AVISO altimetry (following Thompson and Demirov, JGR, 2006): $s = \langle h'^3 \rangle / \langle h'^2 \rangle^{3/2}$



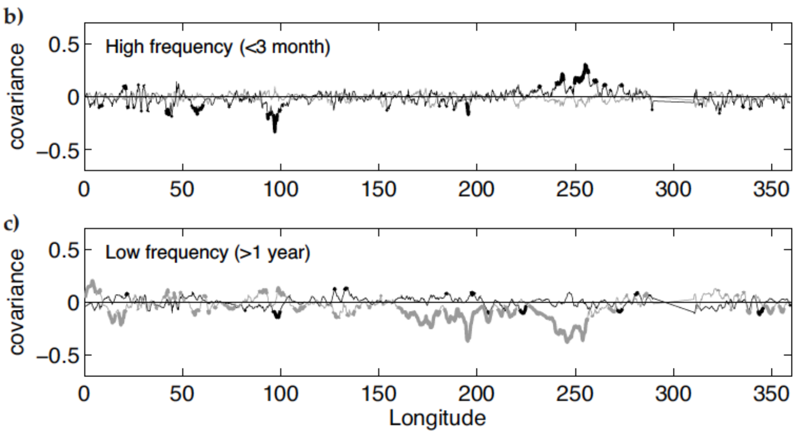
(Shao and Gille, in preparation))

- Velocity-weighted jet position.

$$\overline{\theta(t,\phi)} = \frac{\int_{\theta_S}^{\theta_N} \theta \Delta h d\theta}{\int_{\theta_S}^{\theta_N} \Delta h d\theta}$$



Subantarctic Front (and Polar Front) response to SAM and ENSO

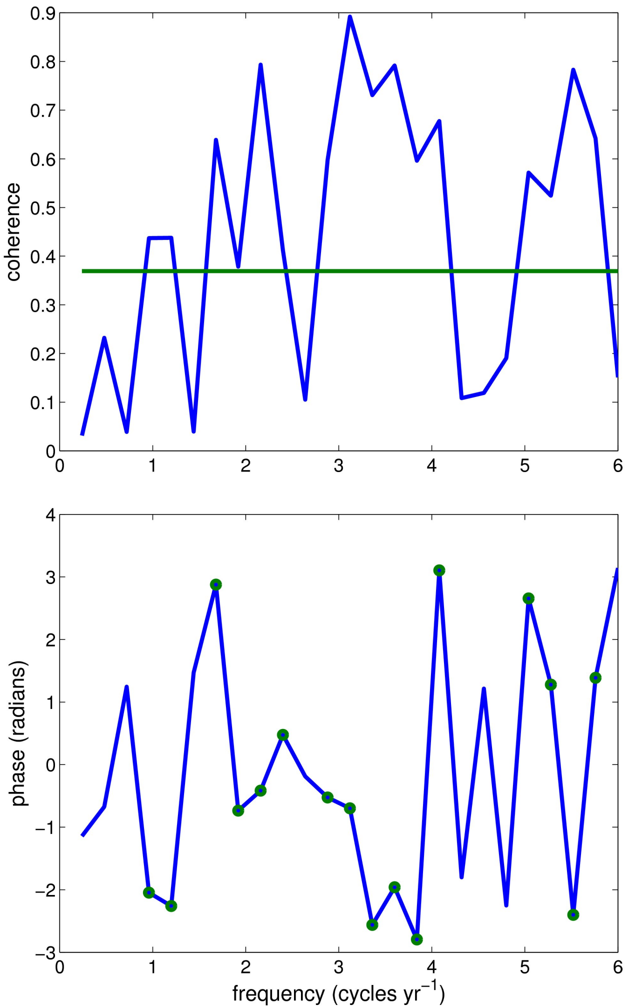


Black: correlation with SAM
Gray: correlation with ENSO

Sallée et al., J. Climate, 2008

- Top: Time scales $<$3 months: strong links to SAM.
- Bottom: Time scales $>$1 year: strong links to ENSO.
- Spatial variability in response.
- From skewness, Shao and Gille (in preparation) show similar relationship (albeit without resolving frequency dependence.)

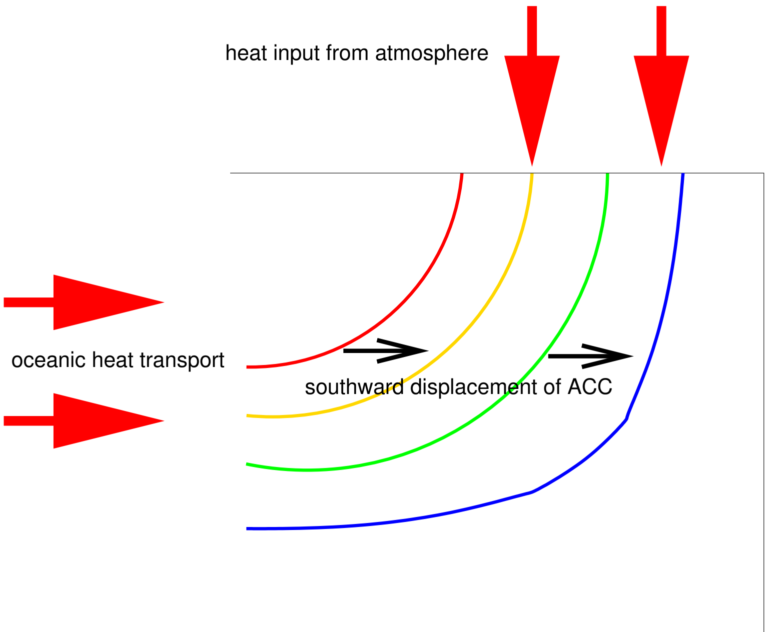
Coherence of monthly mean "jet" positions with SAM



- Significant coherence at sub-annual cycle frequencies.
- No simple phase relationship between -SAM and jet position.
- Suggests either that SAM may not capture wind variability ...
- ... or "transport" shifts may not capture ACC meridional shifts.

Mechanisms: Forcing and the SAM

$$\overline{\frac{\partial T}{\partial t}} + \nabla \cdot (\overline{\mathbf{u}}\overline{T}) + \nabla \cdot (\overline{\mathbf{u}'T'}) = \text{forcing}$$



- Surface Forcing: depends on wind, sea surface temperature, air temperature, humidity, atmospheric composition, surface albedo, etc.

Surface flux products differ enormously and fluxes vary on scales that match variability of wind

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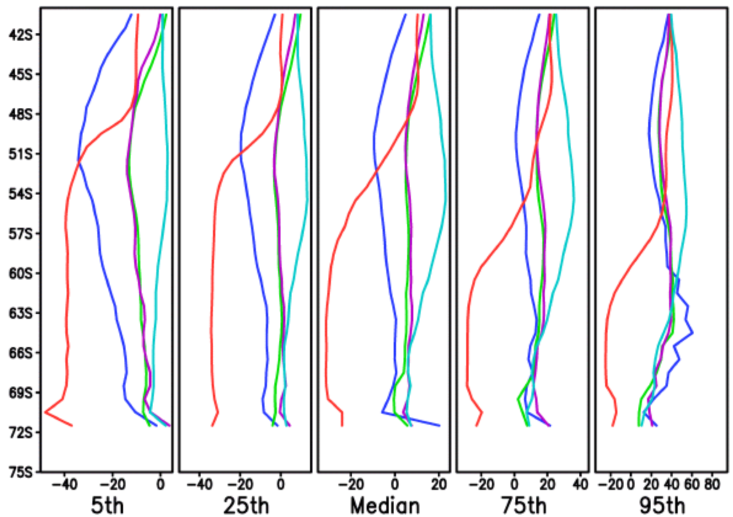
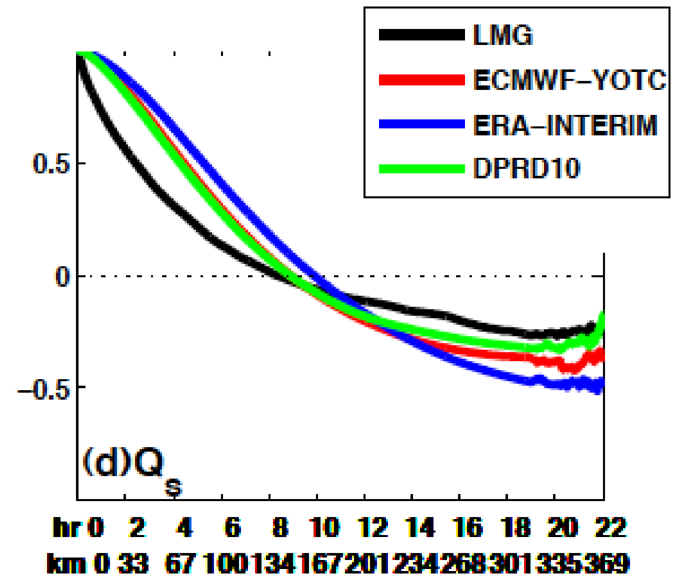


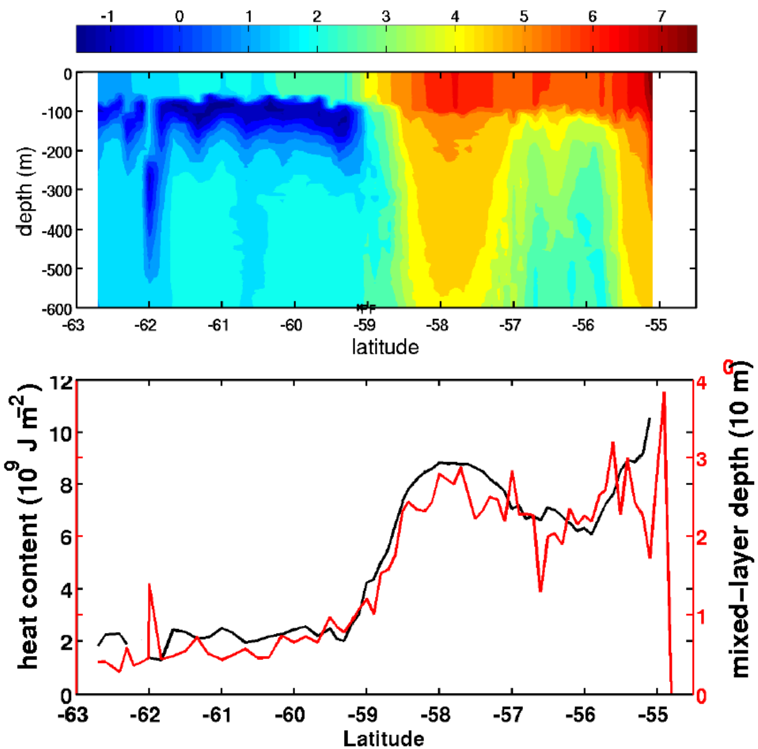
Sensible heat fluxes: blue (NCEP2), JMA (green), ERA40 (purple), IFREMER (red), HOAPS (cyan).

Bourassa et al., in preparation, BAMS, 2010



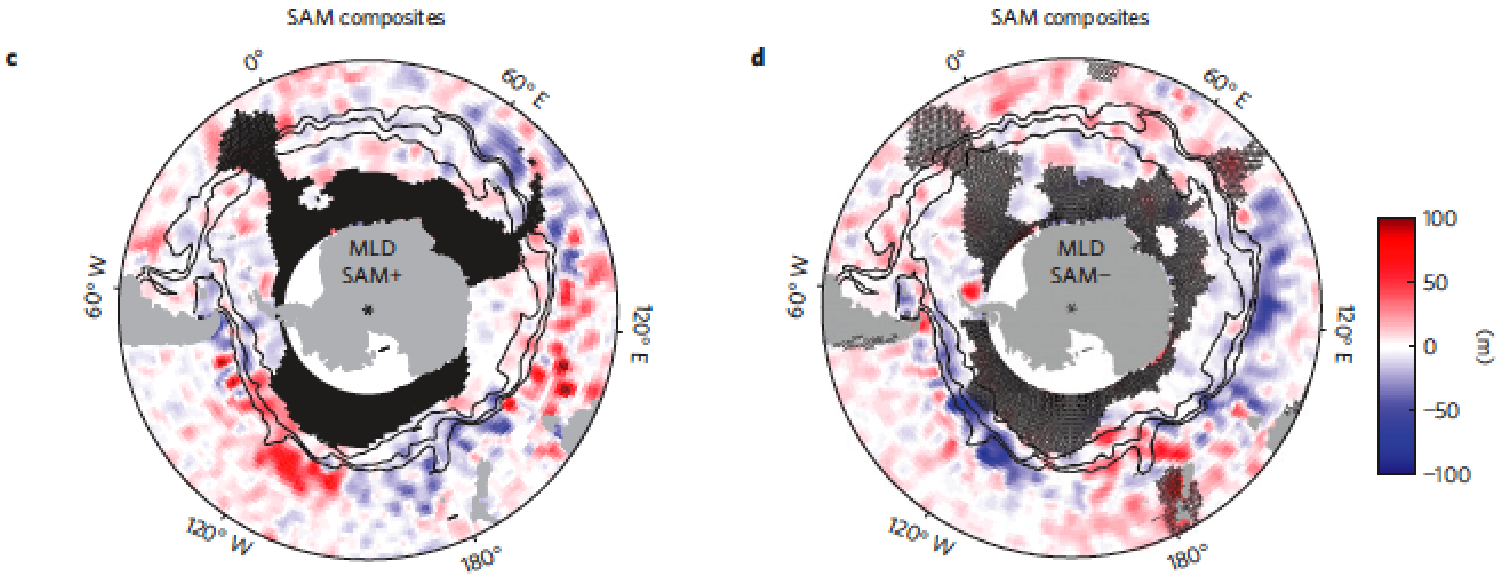
Jiang et al., J. Climate, submitted, 2010

Mixed-layer depth as a proxy for upper ocean air-sea exchange (but heat content is more robust)



Stephenson et al, in preparation, 2010. Caution: mixed-layer scale not correct

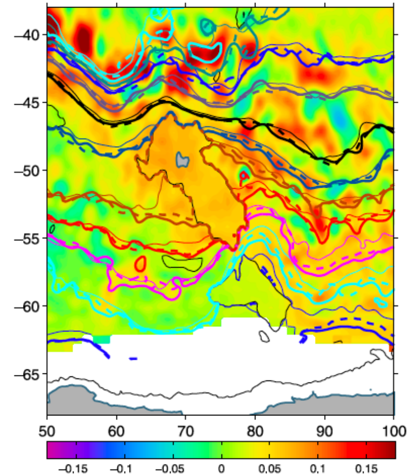
Changes in SAM imply changes in mixed-layer depth



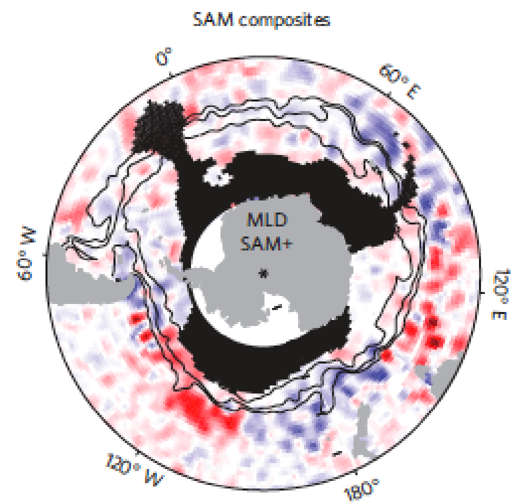
Sallée et al, Nature Geosciences, 2010

Summary

- Multi-decadal-scale warming in Southern Ocean consistent with a poleward shift in Antarctic Circumpolar Current temperature structure.
- Corresponding changes in ACC transport and eddy fluxes remain a topic of debate.
- On time scales $<$3-4 months, altimeter and SST data imply ACC shifts southward in response to strong SAM, but with strong regional variations. ENSO appears to be a factor on longer scales.
- Southern Ocean mixed-layer depth also shows strong regional response to SAM, with large deepenings in southeast Indian and Pacific basins (where mode or intermediate water forms.)



Sokolov and Rintoul, 2009. (thin: 1992-1997; dashed: 1998-2003; thick: 2004-2008)



Sallée et al, 2010