Long-term Warming Trends in the Southern Ocean: Links to Winds and Frontal Migration

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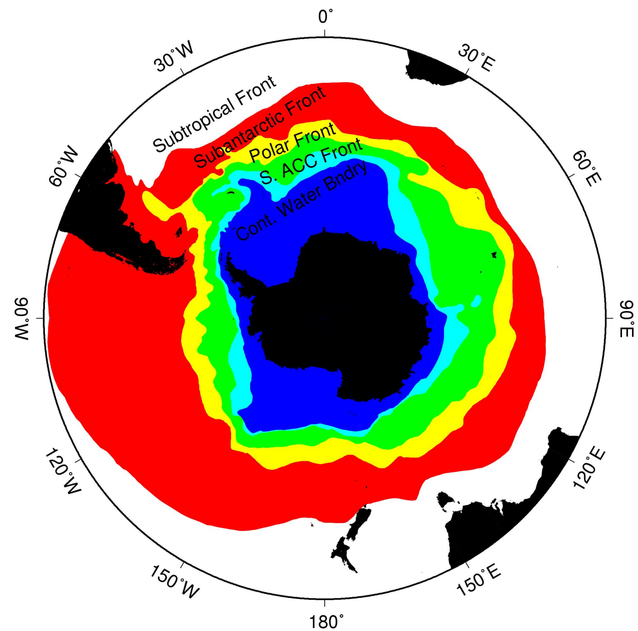
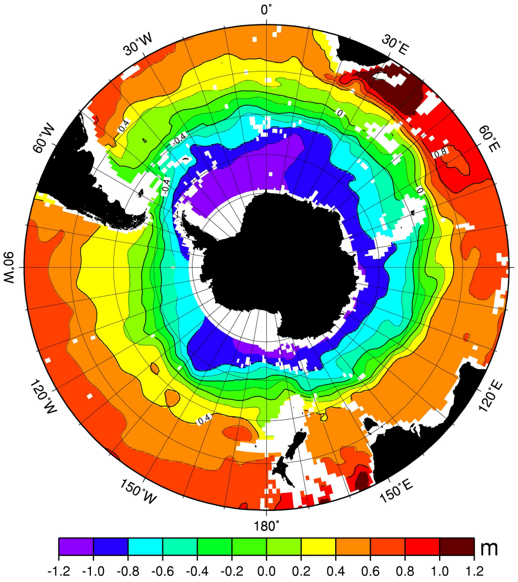
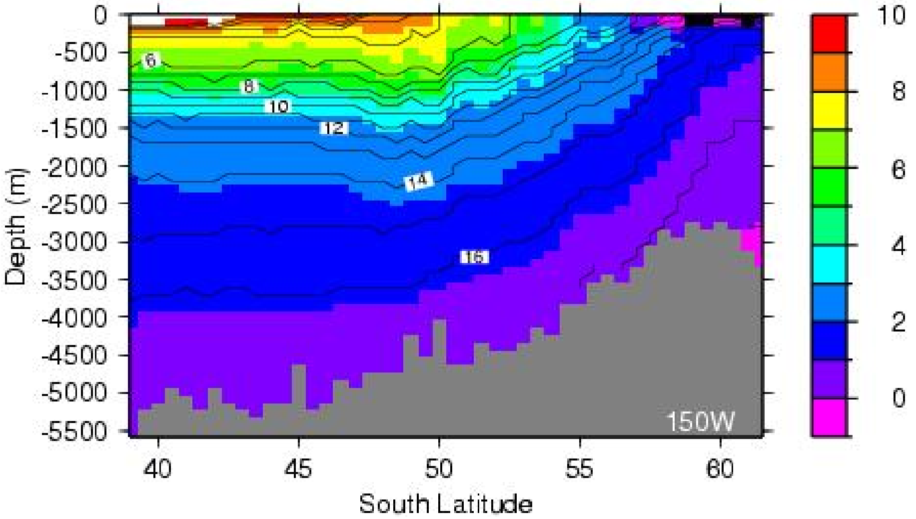


The ACC: connector and barrier

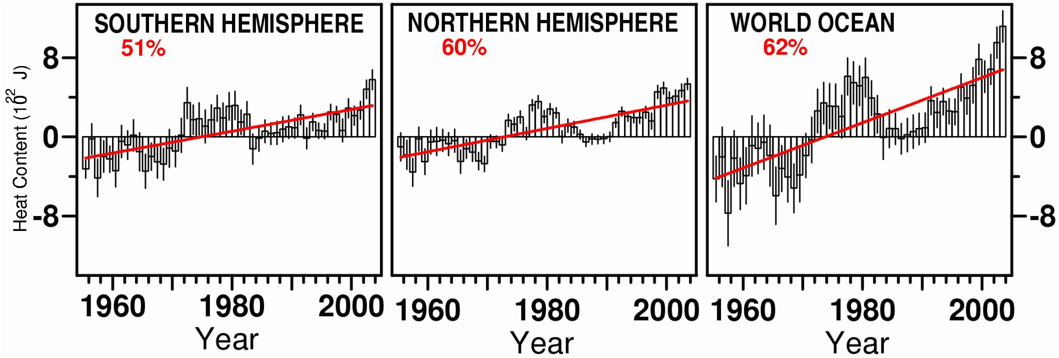


Dynamic Topography



Potential Temperature and Isopycnals

Warming in the Southern Hemisphere

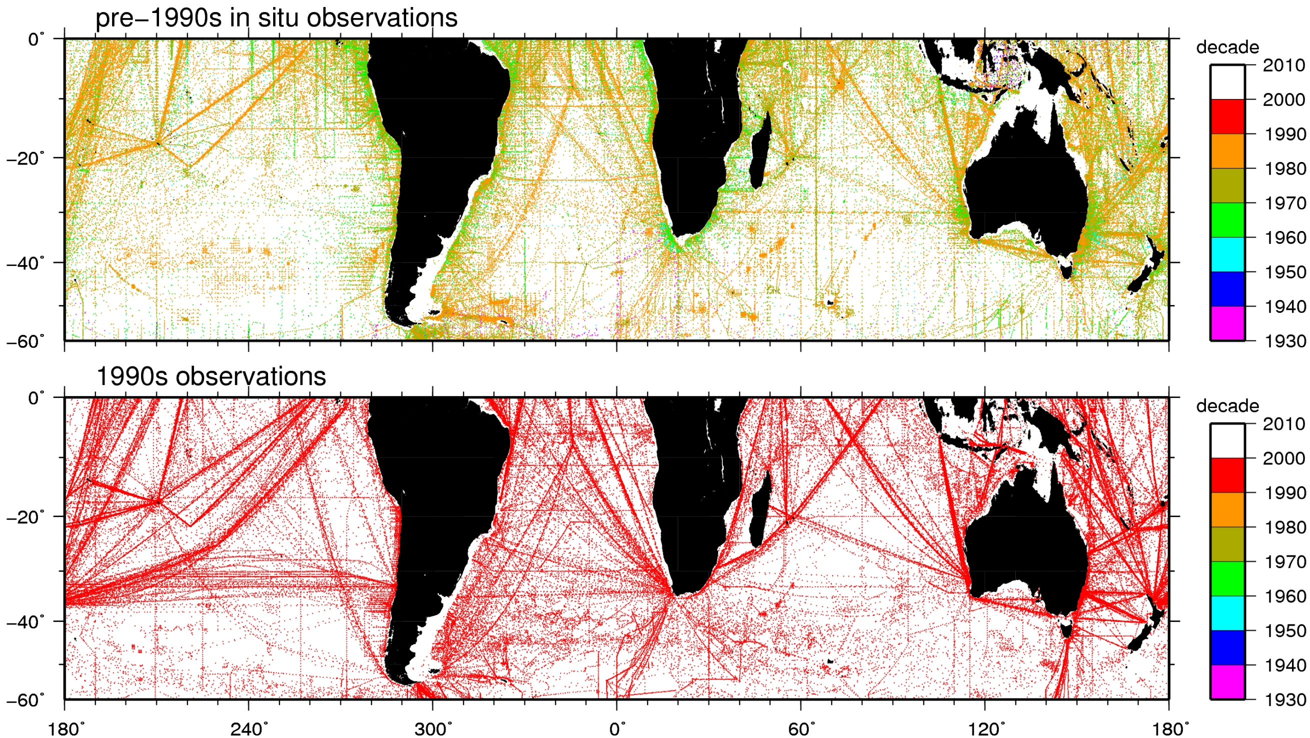


(Levitus et al., GRL, 2005)

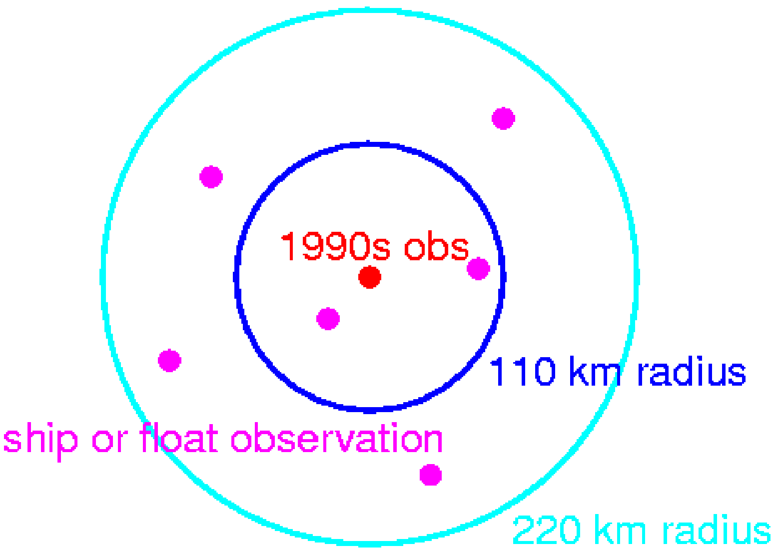
Objectives today:

- Revisit Southern Hemisphere warming trends in regional context: Results suggest Southern Hemisphere heat content rise large and 90% south of 30°S.
- Consider mechanisms underlying trends—in particular the role of fronts, wind, and eddies.
- Suggest some open questions.

In situ observations: Sparse prior to floats

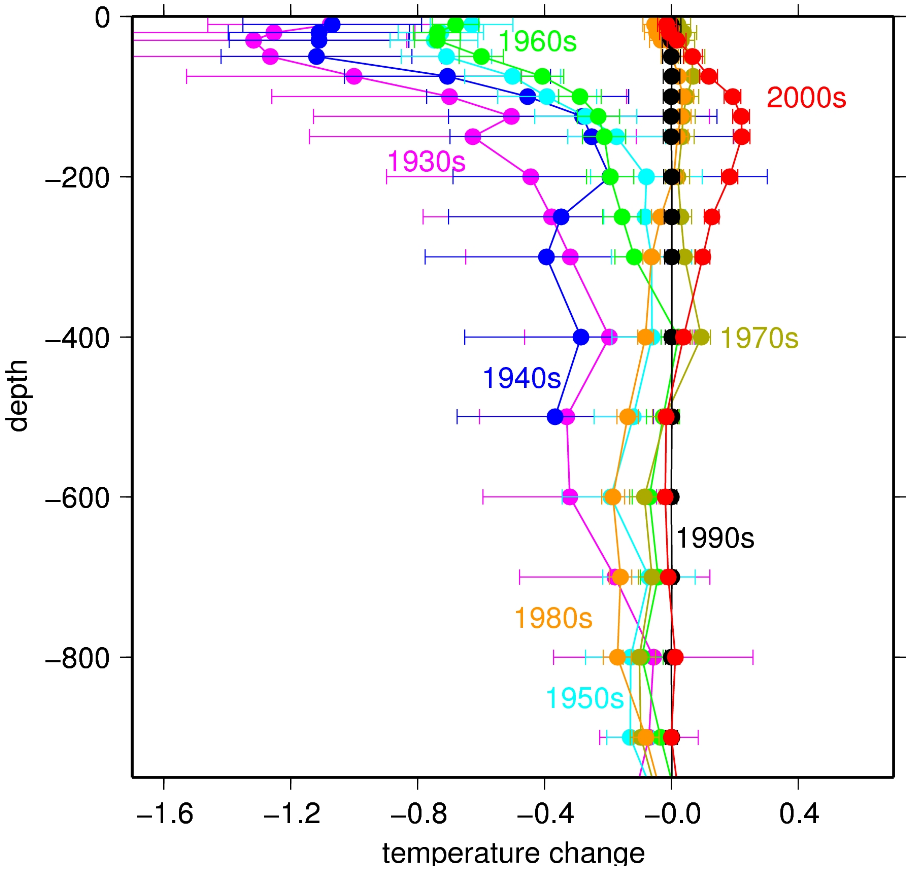


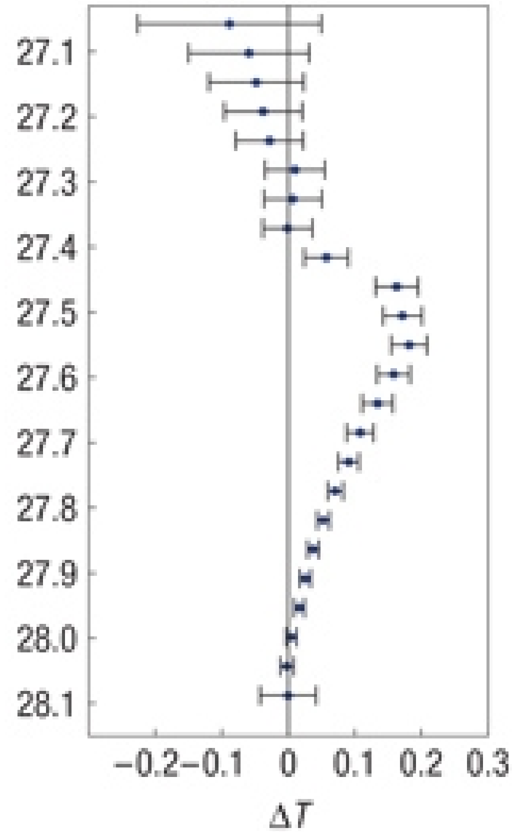
Nearest neighbor comparisons



- WODB standard levels, 10 to 1000 m
- Pairs
  - ~150,000 1990s profiles
  - ~202,000 non-1990s profiles
  - up to 143×10^6 pairs
- 1990s biases appear minimal
  - PALACE, CTD, OSD slightly cooler than XBT and Argo.
  - Not significant below mixed layer.
- Bin average data pairs by depth, decade, and geographic region to produce mean trends.

Changes in upper ocean temperature (°C)



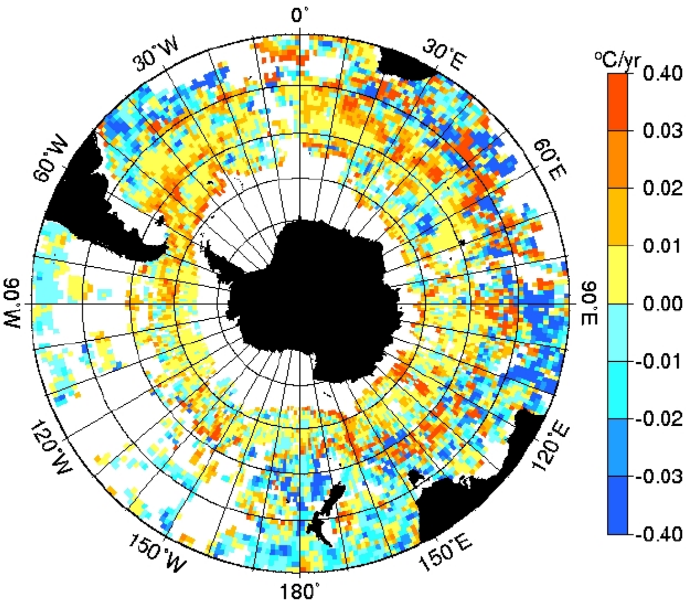


Gille, J. Climate, 2008

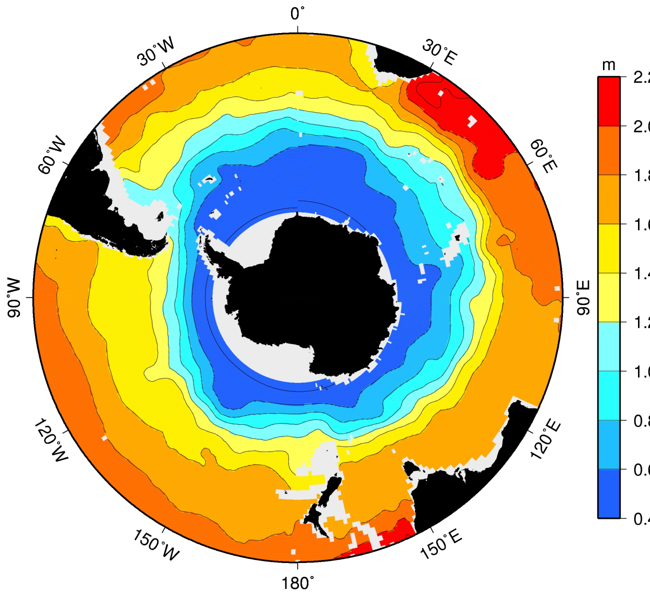
Böning et al, Nature Geosciences, 2008

Decadal trend for Polar Front

Where does warming occur?



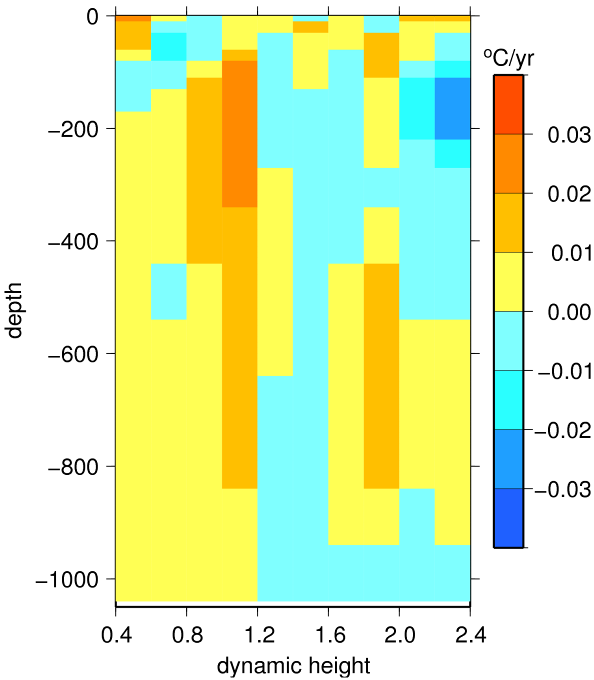
Temperature trends at ∼900 m, Gille, Science, 2002



Dynamic topography

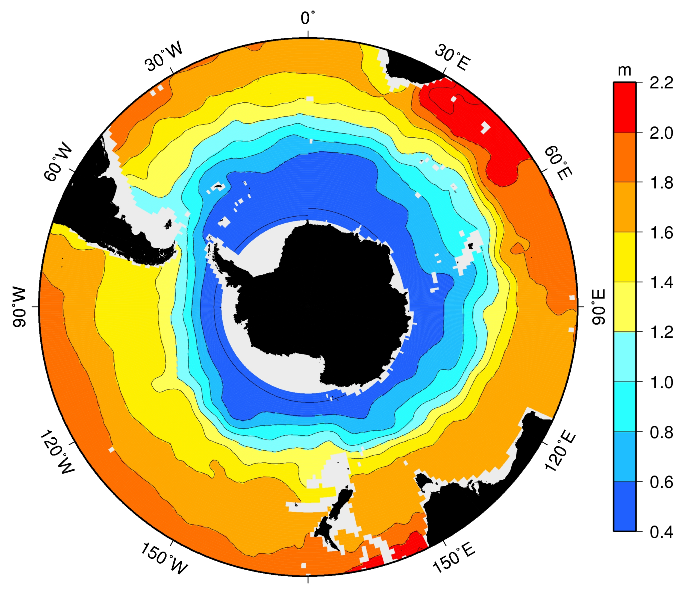
- Warming concentrated in ACC.
- 90% of net heat content increase south of 30°S.

Long-term trends in Southern Ocean heat content

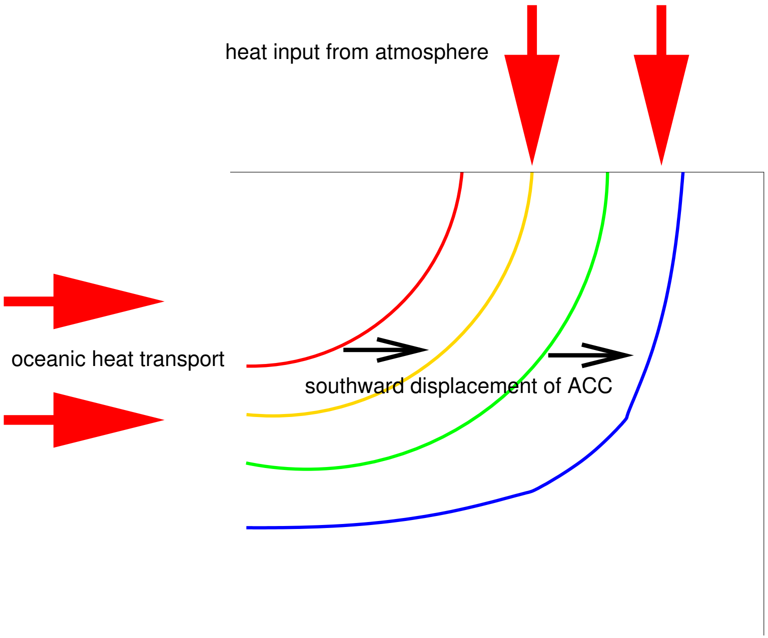


Gille, J. Climate, 2008

- Sparse hydrographic record indicates ACC has warmed at all depth levels over last 50 years.



Mechanisms: What Controls Change?



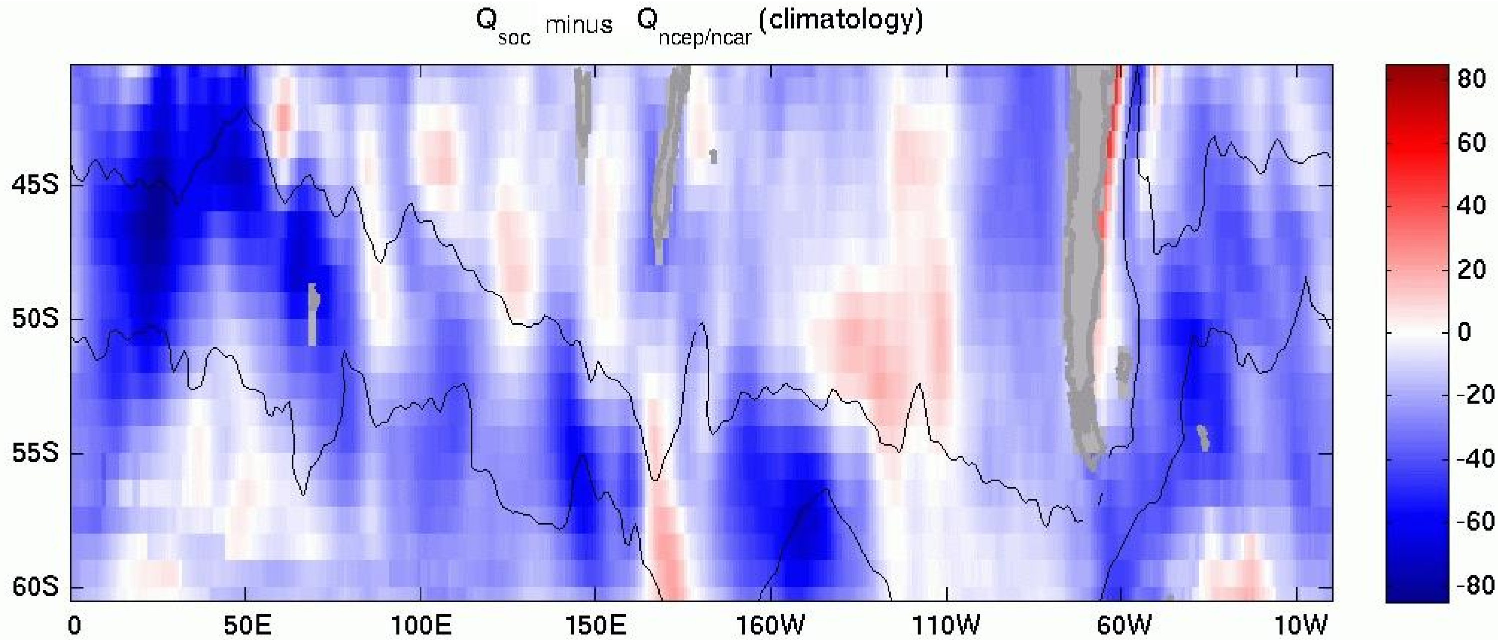
- Advection in ocean: 0.1×10^{15} W across equator
- Surface forcing into ocean: explains combined NH and SH trends

— These results: 0.5 to 0.7 W m^{-2}

— Hansen et al. (2004): 0.85 W m^{-2} global imbalance

South of 30°S: advection or surface forcing both possible

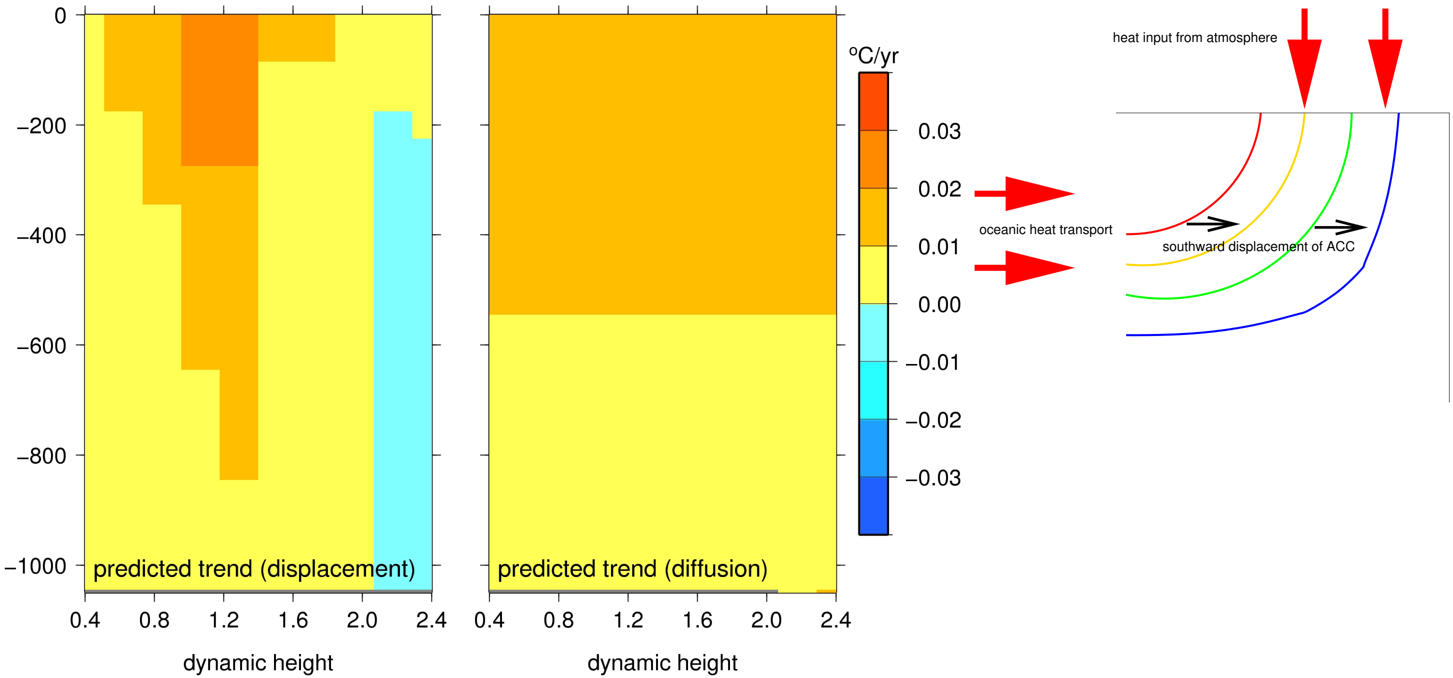
Surface flux products differ enormously



Heat budget imbalance about 1 W m^{-2}.

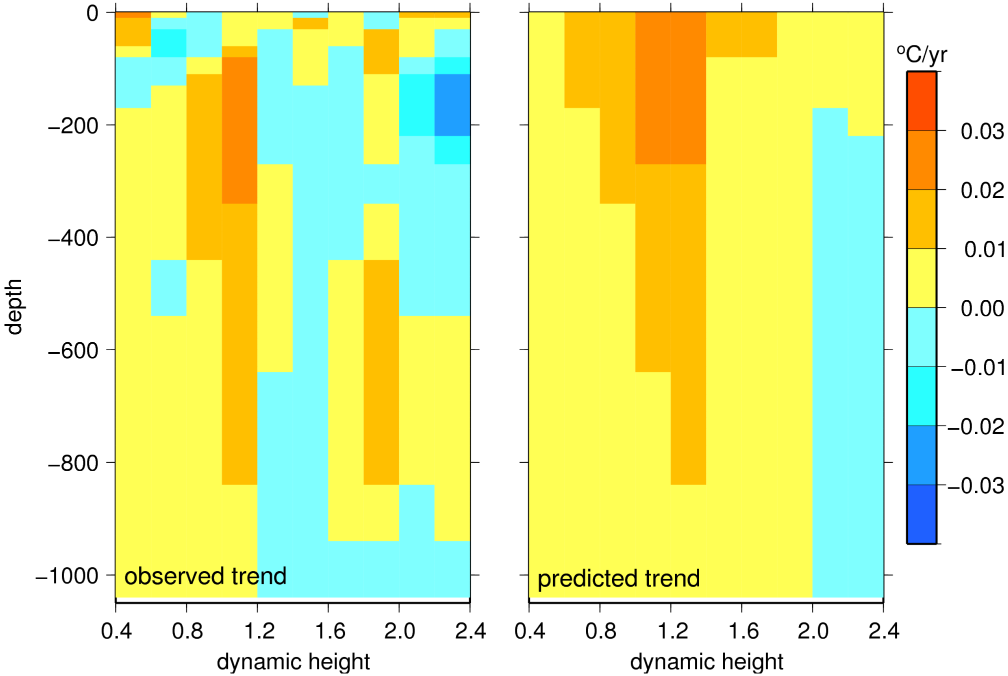
Flux difference in W m^{-2}, courtesy of Shenfu Dong

Explaining long-term trends in heat content



Gille, J. Climate, 2008

Long-term trends in Southern Ocean heat content

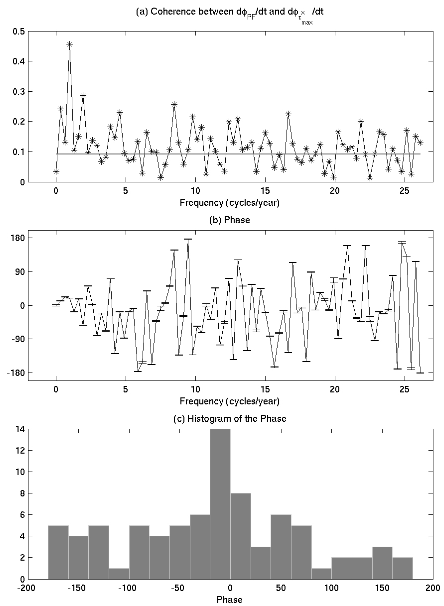


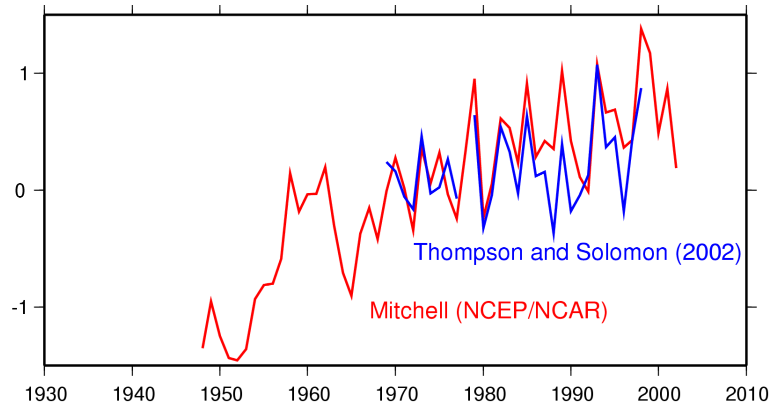
- Sparse hydrographic record indicates ACC has warmed at all depth levels over last 50 years.
- In ACC below 200 m depth, ∼95% of profile trend explained as poleward migration of current at 1° latitude/35 years.

Gille, J. Climate, 2008

Latitudinal shift in ACC?

Southern Annular Mode intensification implies poleward shift in wind.



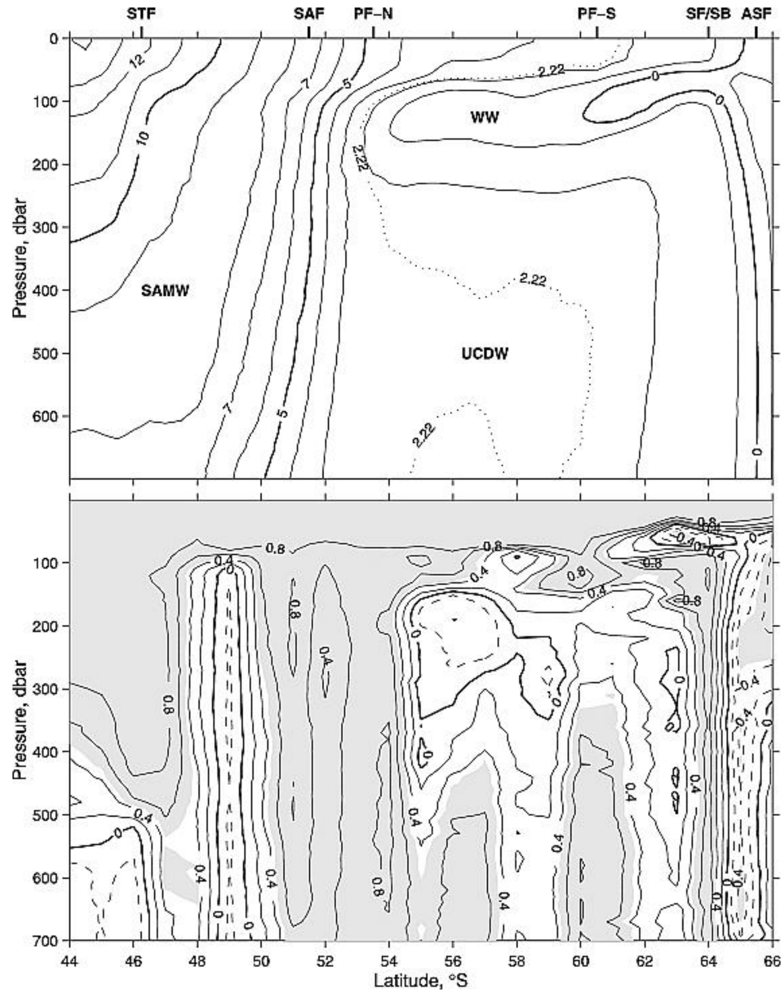


Poleward shift in wind implies poleward shift in ACC (at least on some time scales; Dong et al., JPO, 2006)

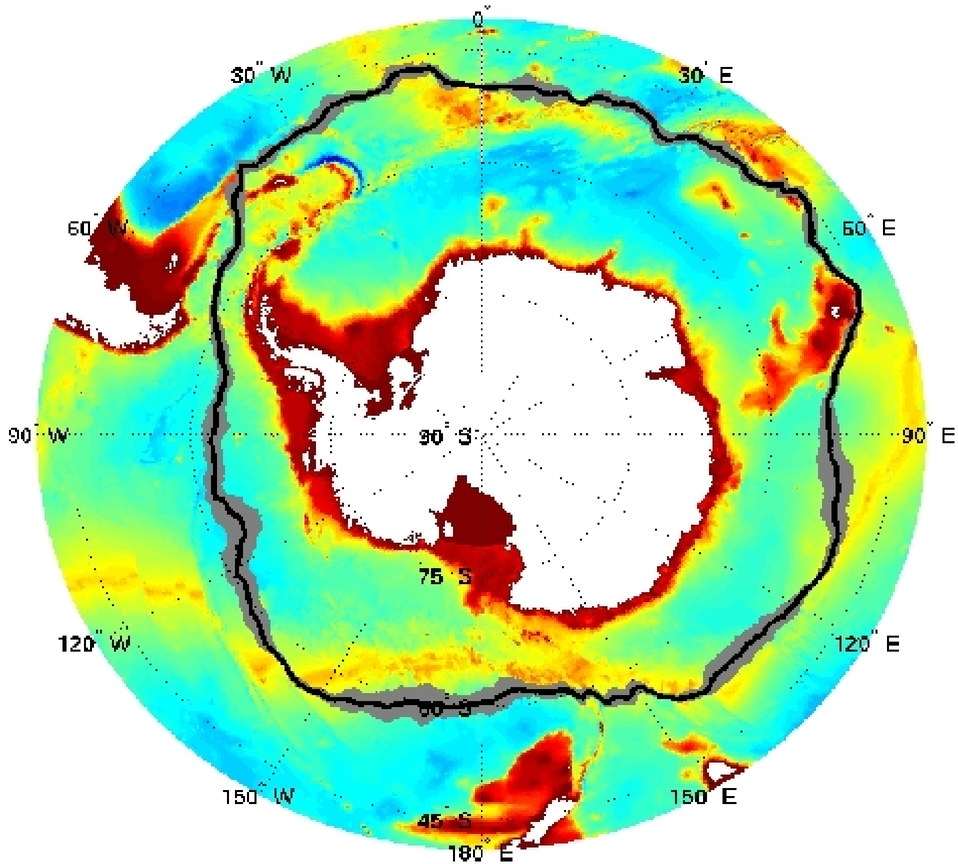
$$\phi_{PF} \propto \phi_{\tau}$$

Latitudinal shift in ACC? (2)

ACC displacement is top-to-bottom. (Sokolov and Rintoul, 2003)



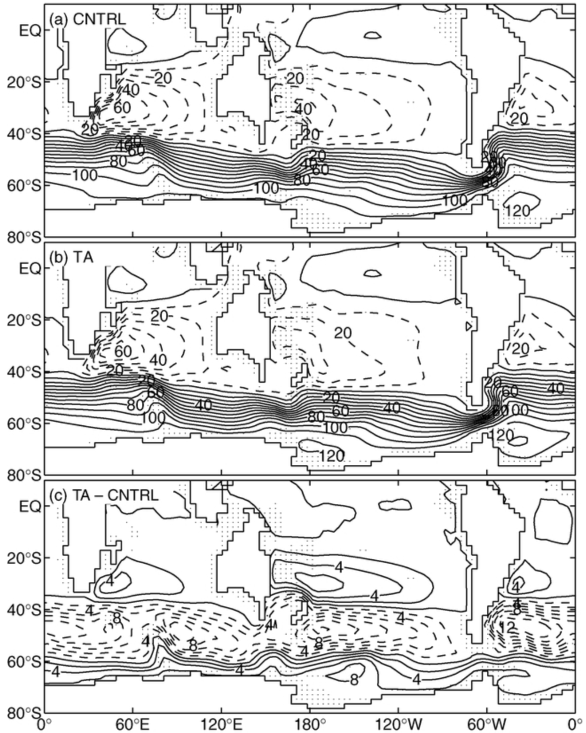
Frontal Variability Varies with Bathymetric Constraints



(Dong et al., JPO, 2006)

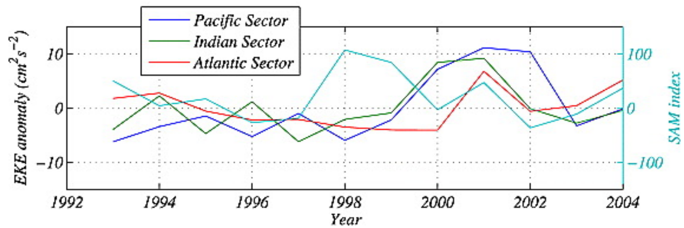
Dynamics Governing Observed Long-Term Trends

- Hypothesis: Shifts in SAM drive shifts in ACC fronts



Oke and England, J. Climate, 2004

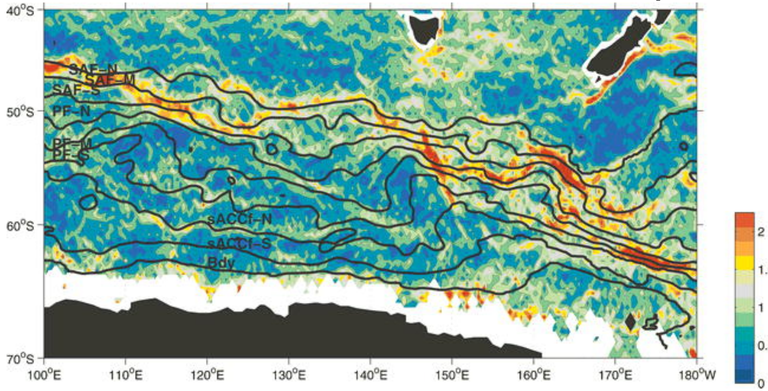
- Hypothesis: Changes in SAM imply changes in EKE, which can increase eddy heat transport



Meredith and Hogg, JGR, 2006

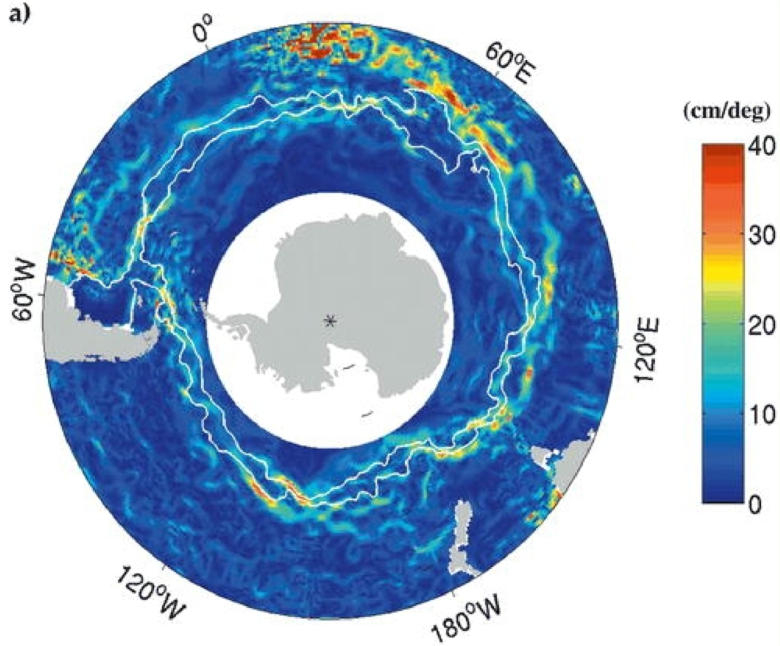
Can we track ACC jet displacements from satellite?

From maxima in sea surface slope:



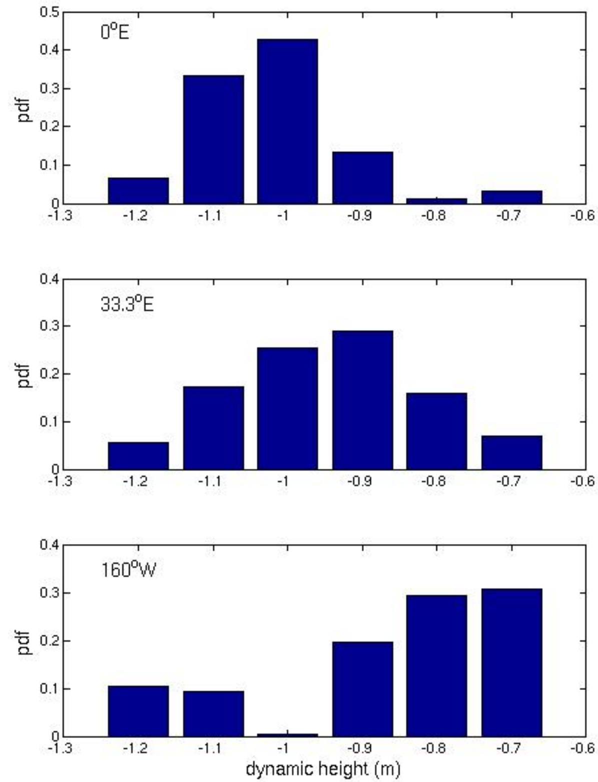
Sokolov and Rintoul, JPO, 2007

From height contours:



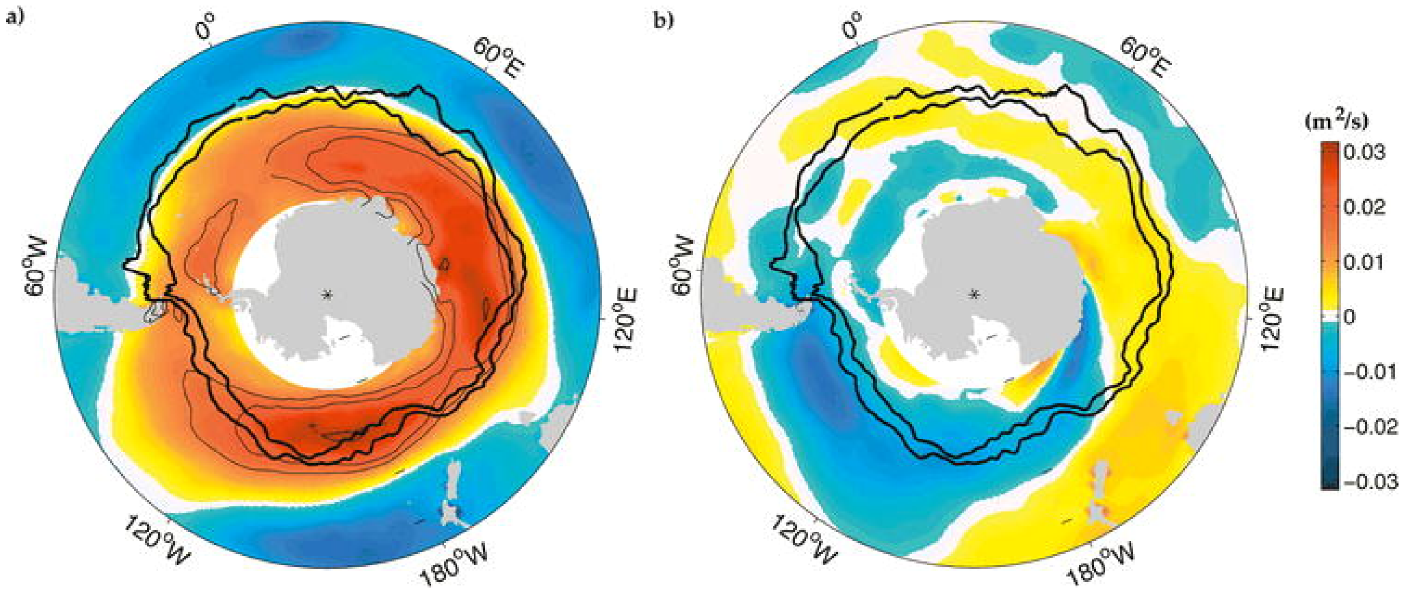
Sallée et al, J. Climate, 2008: PF = 0.95 m, SAF = 1.20 m

Strong Currents are not Consistently at Fixed SSH



- Compute sea surface slope at time-varying height contours separated by 10 cm.
- For each weekly field, find contour with steepest slope (e.g. max velocity).
- Probability density functions show that no fixed contour consistently represents jet at all longitudes.
- Maximum velocity not always at same height contour.

Height Variations Linked to SAM and ENSO



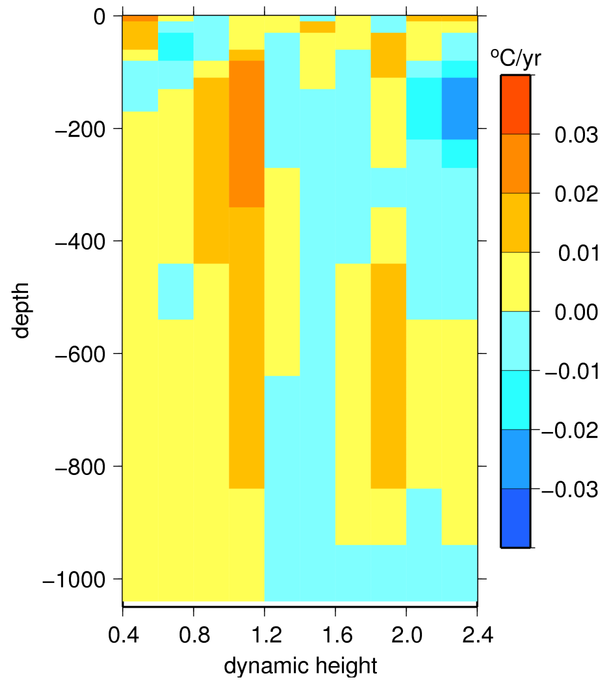
SAM vs $<$ 3 months

ENSO vs $>$ 1 yr

Sallée et al, J. Climate, 2008

Summary

- Southern Ocean has warmed significantly over last 50+ years, and warming is concentrated in ACC.
- Warming could imply migration of ACC, perhaps driven by changes in latitude of wind forcing.
- Dynamics underlying this imply either an increase in Ekman transport, intensification of the overturning circulation, and change in isopycnal slope OR a change in eddy energy (not seen in IPCC-class models).
- Local versus remote surface fluxes not easily diagnosed.
- Satellite altimetry should help unravel frontal migration and eddy kinetic energy.



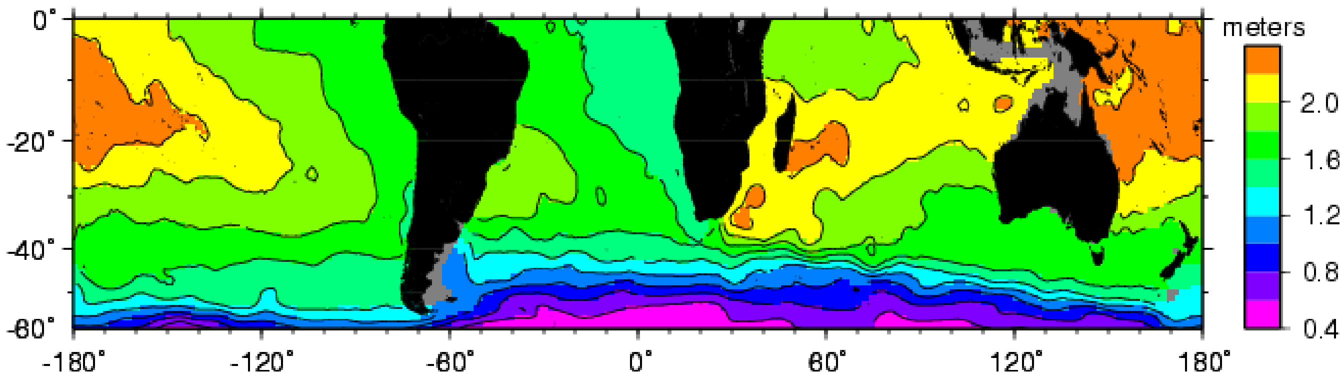
Unanswered Questions

- What are the respective roles of wind, eddies, and frontal migration in controlling observed warming trends?
- What is the role of air-sea heat exchange in all of this? On what scales does the ocean drive the atmosphere, and on what scales does the atmosphere drive the ocean?
- What are the long-term implications of the observed warming for ecosystems, CO_2 uptake, stability of ice around Antarctica?

Ways to Address Questions with Unlimited Budget

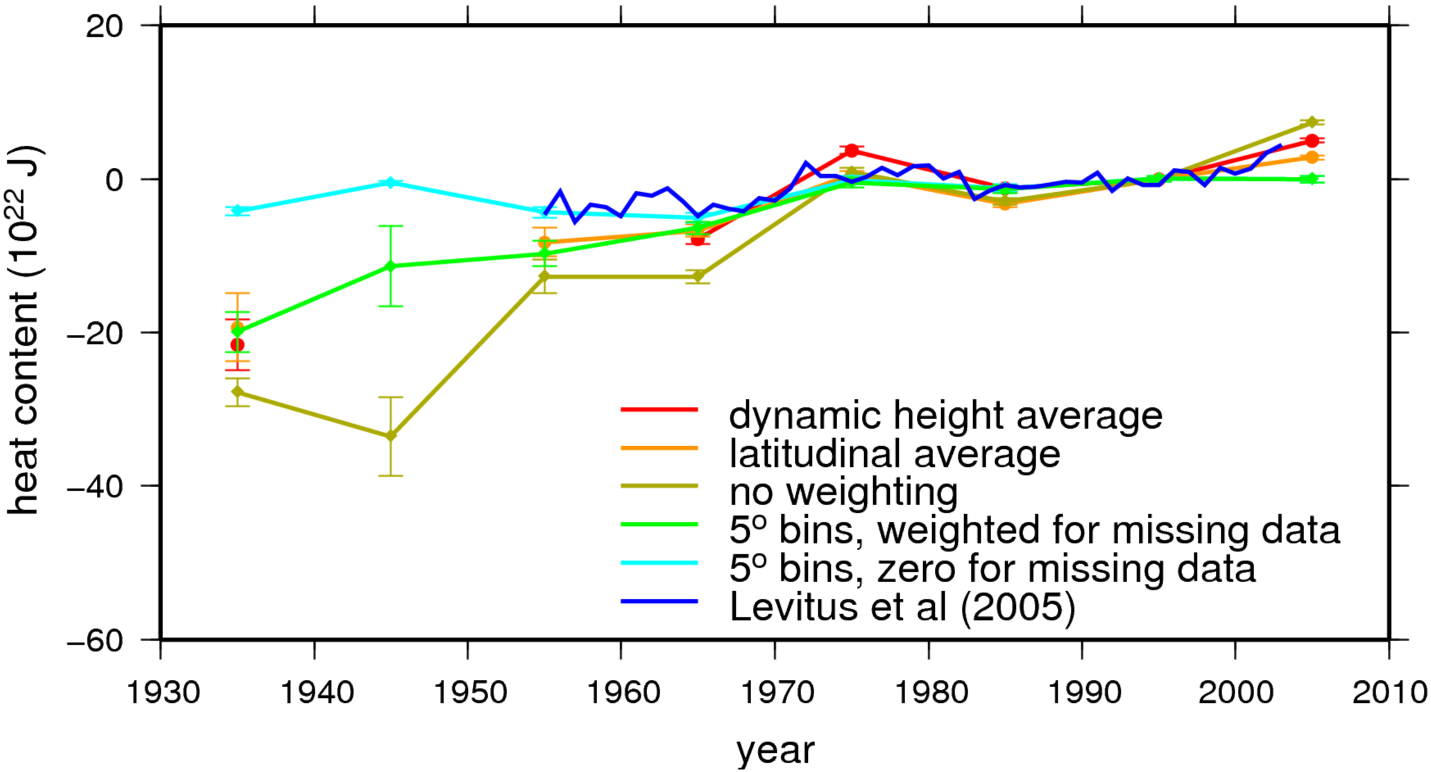
- What are the respective roles of wind, eddies, and frontal migration in controlling observed warming trends?
  High resolution numerical modeling that resolves fronts and eddies, needs to be supported with in situ observations. A better diagnosis of frontal migration (using a better mean dynamic topography) and better measurements of eddies (e.g. wide swath altimeter).
- What is the role of air-sea heat exchange in all of this? On what scales does the ocean drive the atmosphere, and on what scales does the atmosphere drive the ocean?
  To address air-sea heat exchange, more than anything we need good estimates of surface fluxes. This will require (a) flux moorings at several locations, (b) good use of existing satellite data (scatterometry, microwave SST, microwave/infrared atmospheric profiler data), (c) more satellite data (e.g. continued scatterometry, more attention paid to temporal sampling issues).
- What are the long-term implications of the observed warming for ecosystems, CO_2 uptake, stability of ice around Antarctica?
  Heat content in the mixed layer and the upper ocean is perhaps the critical quantity needed to address these long-term implication questions. Heavily seeding the ocean with high-vertical resolution Argo floats would help.

Uneven Coverage: Bin average by dynamic height



- Identify data pairs; sort by geographic bin (here dynamic height at surface relative to 1500 m), by depth, by decade.
- Compute average ΔT in bin.
- Sum bins, weighting by geographic area.

Heat content changes



- $O(25 \times 10^{22})$ J rise in heat content, regardless of averaging.
- Levitus et al (2005) shows smaller trend.
- Levitus trend duplicated if zero trend assumed for 5° bins with no data.