

Warming in the Southern Ocean: Mechanisms and Implications

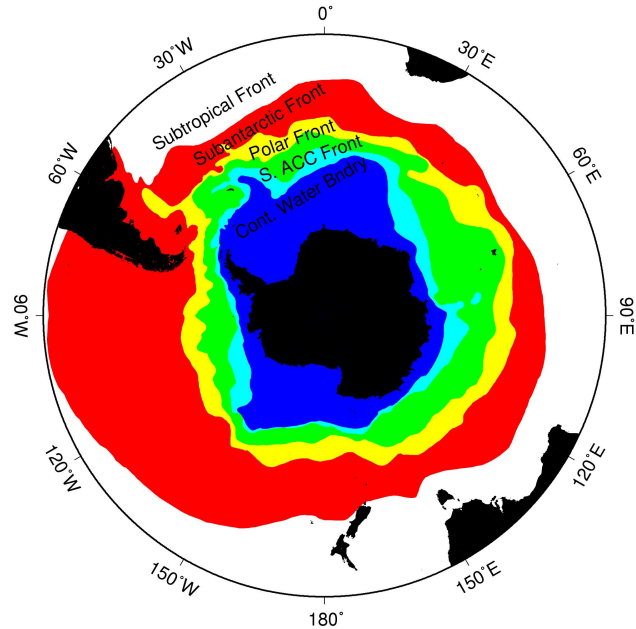
Sarah Gille

Angelica Gilroy

Matt Mazloff

Uriel Zajaczkovski

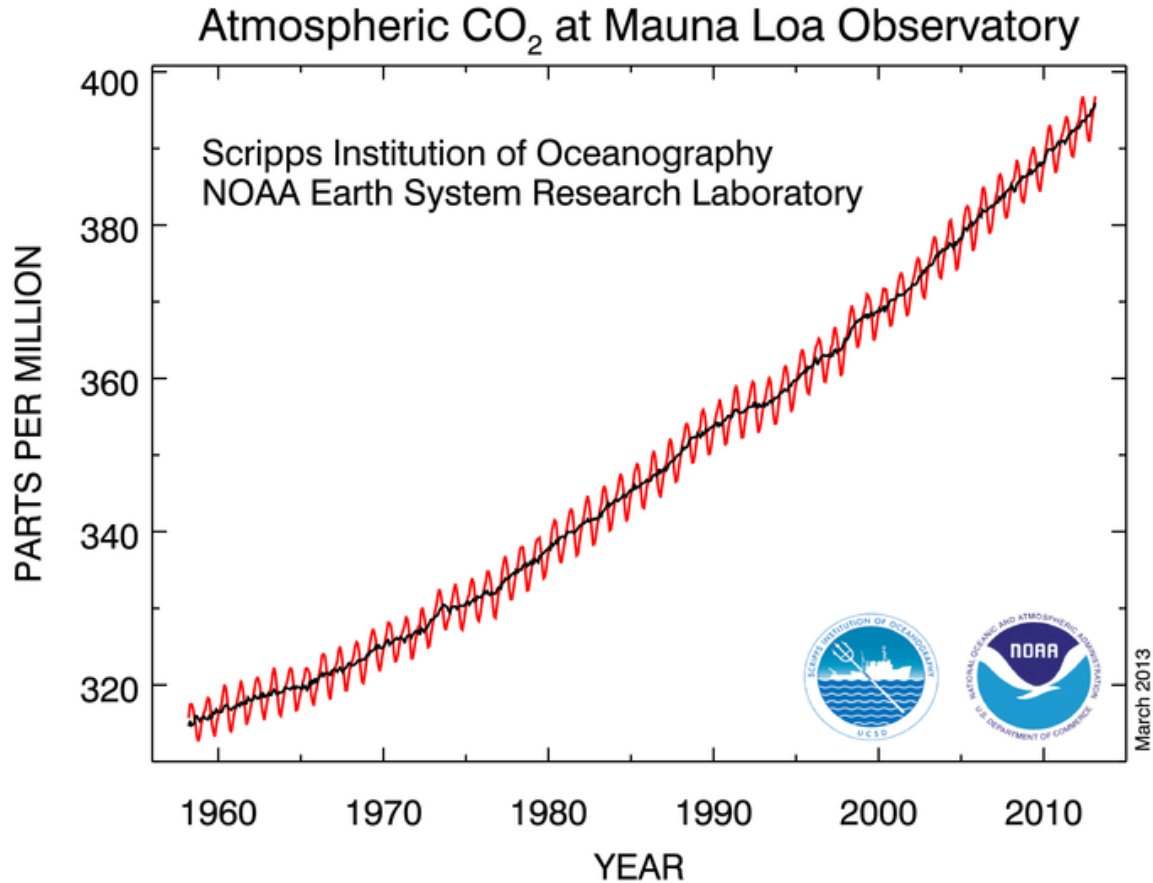
Nathalie Zilberman



(Orsi et al, 1995)

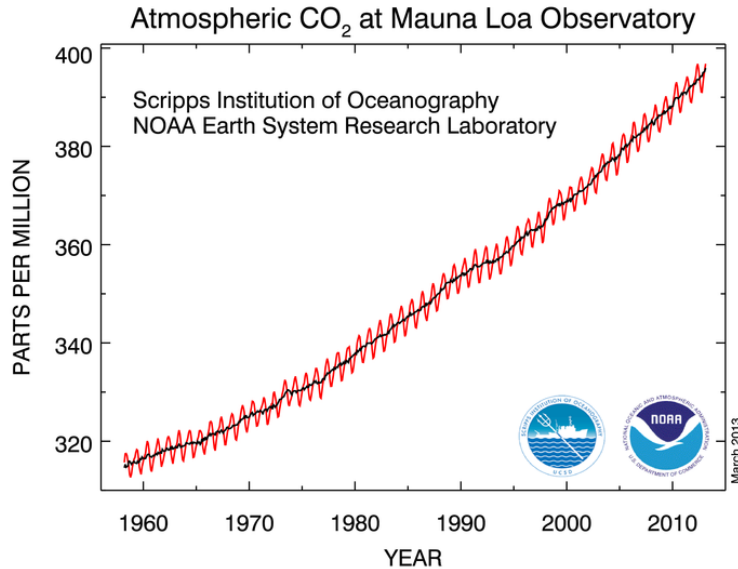
Scripps Institution of Oceanography
University of California San Diego

Observation 0: CO₂ concentrations rising



NOAA: <http://www.esrl.noaa.gov/gmd/ccgg/trends/>

What does rising CO_2 mean for the ocean?

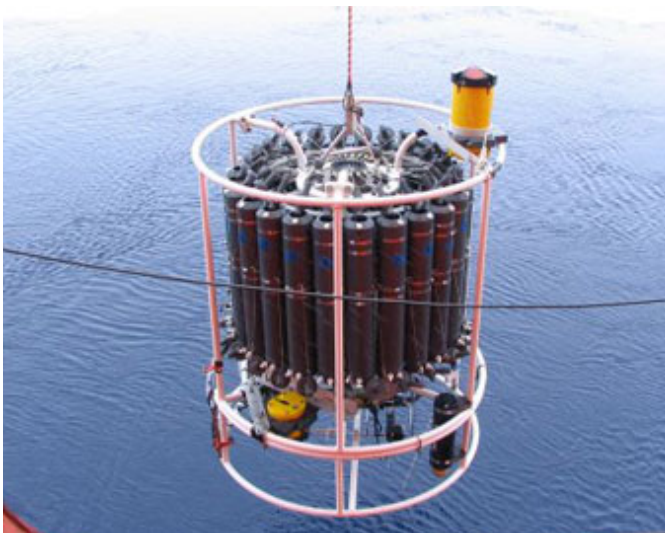


- If CO_2 is steadily rising, expect augmented greenhouse effect. How do we tell if ocean is warming? And if the ocean is warming, where is the warming?
- What mechanisms influence warming patterns?
- What are the implications of a warming ocean (in particular for Pine Island Glacier, Antarctica)?

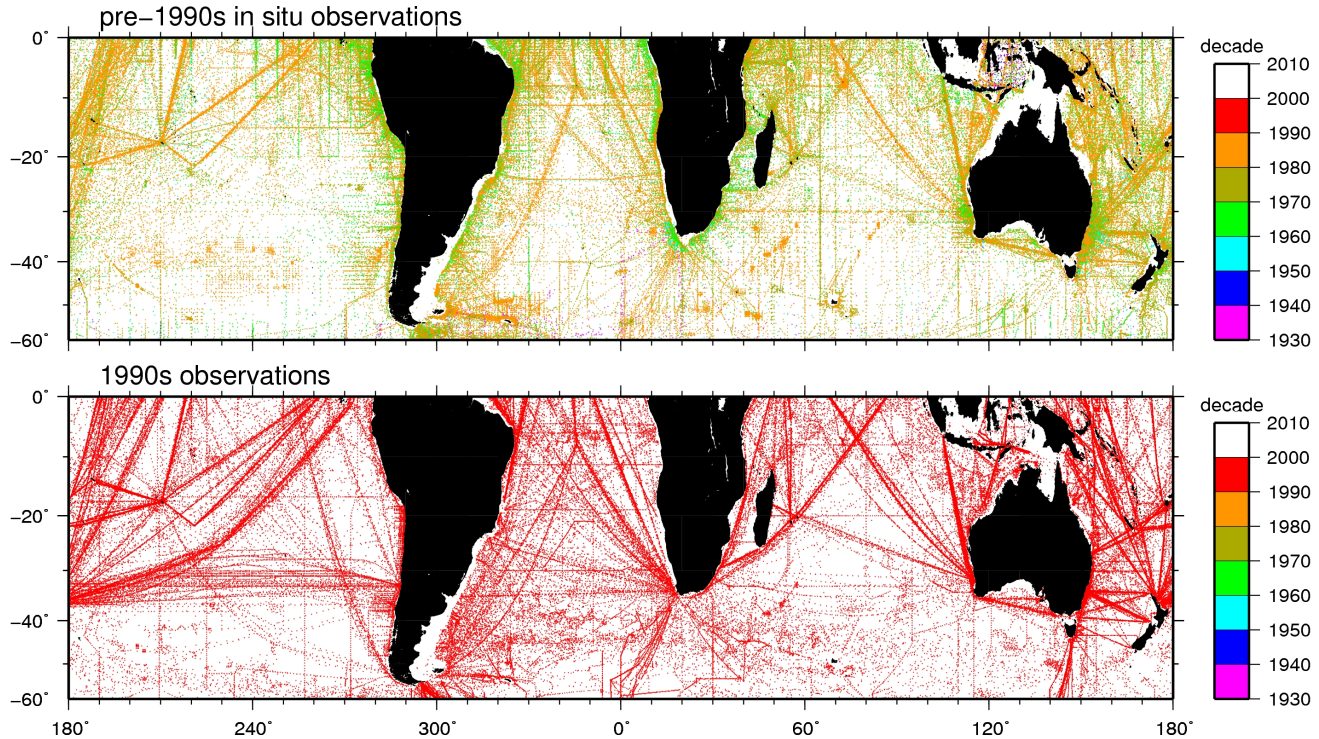
NOAA: <http://www.esrl.noaa.gov/gmd/ccgg/trends/>

Available Observations

- Data
 - World Ocean Database (2001): Conductivity-Temperature-Depth (CTD), bottle samples, expendable bathythermograph (XBT)
 - Argo floats

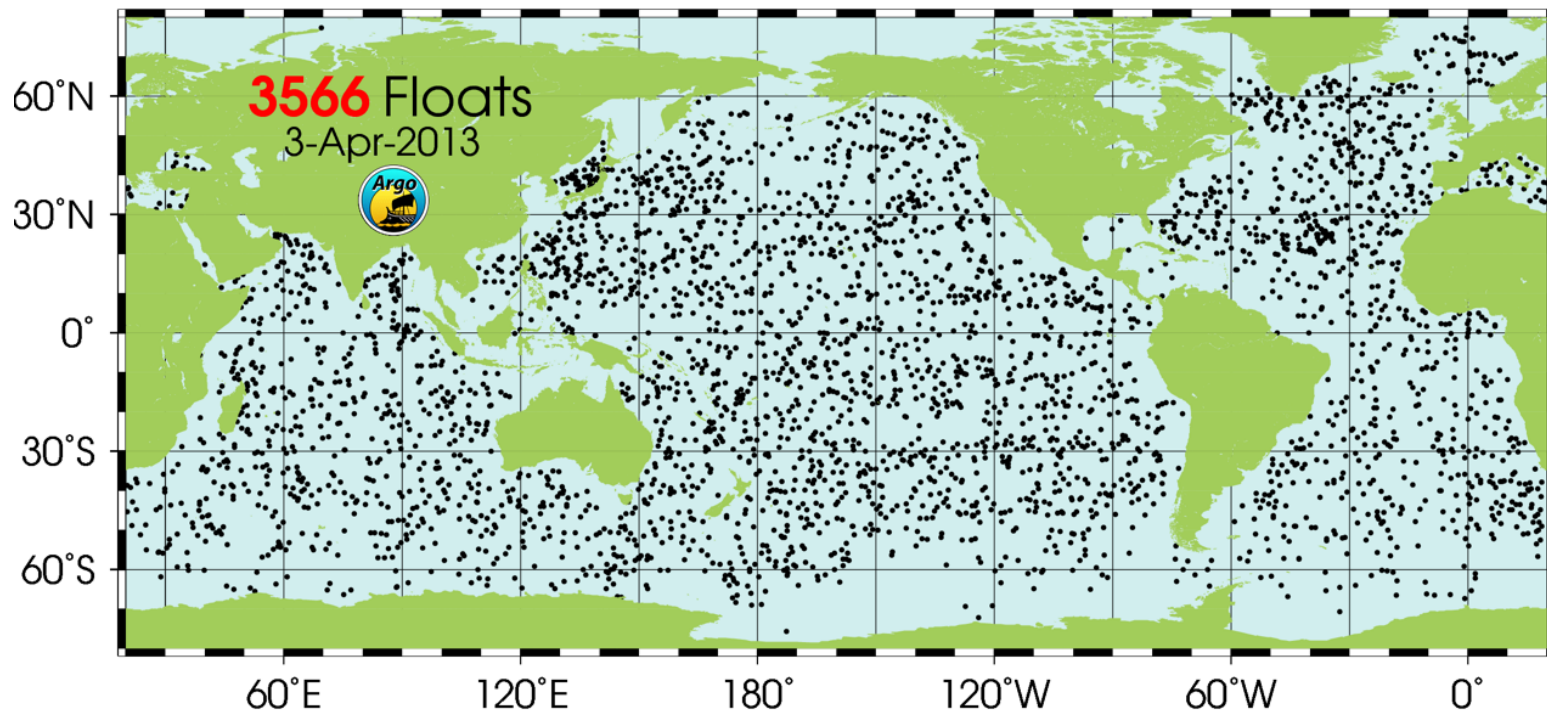


In situ observations: Sparse prior to floats



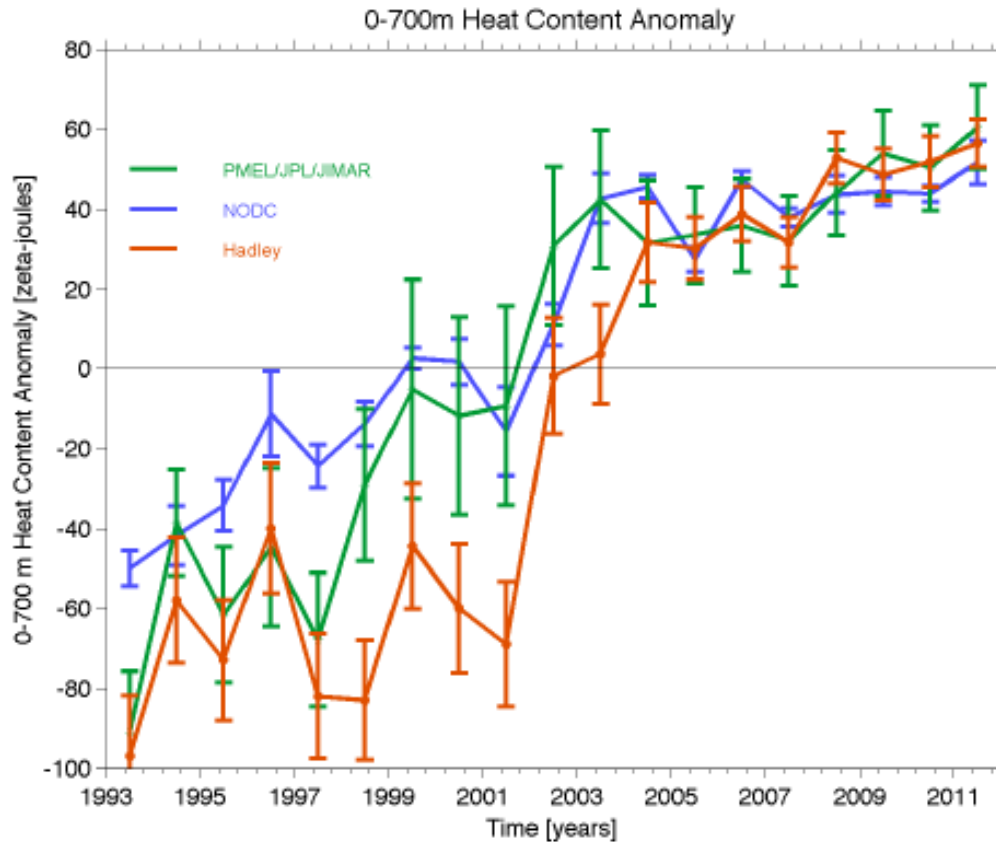
(Gille, J. Climate, 2008)

Argo: Profiling floats now monitor the upper ocean



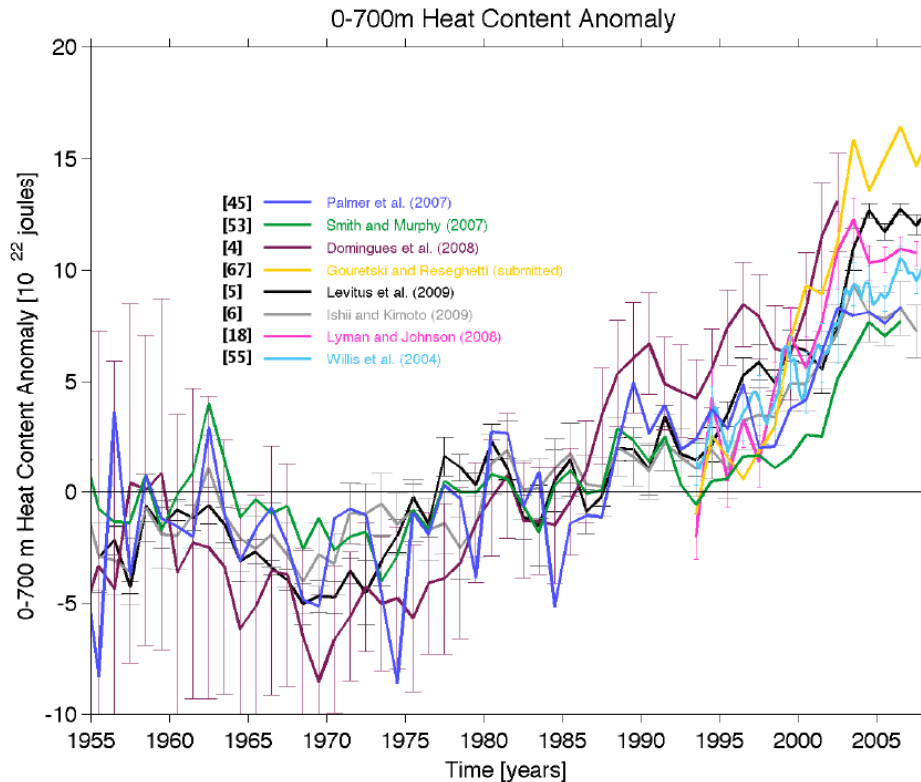
Floats reporting data in last 30 days: <http://www.argo.ucsd.edu/>

Ocean warming inferred from Argo floats + other data



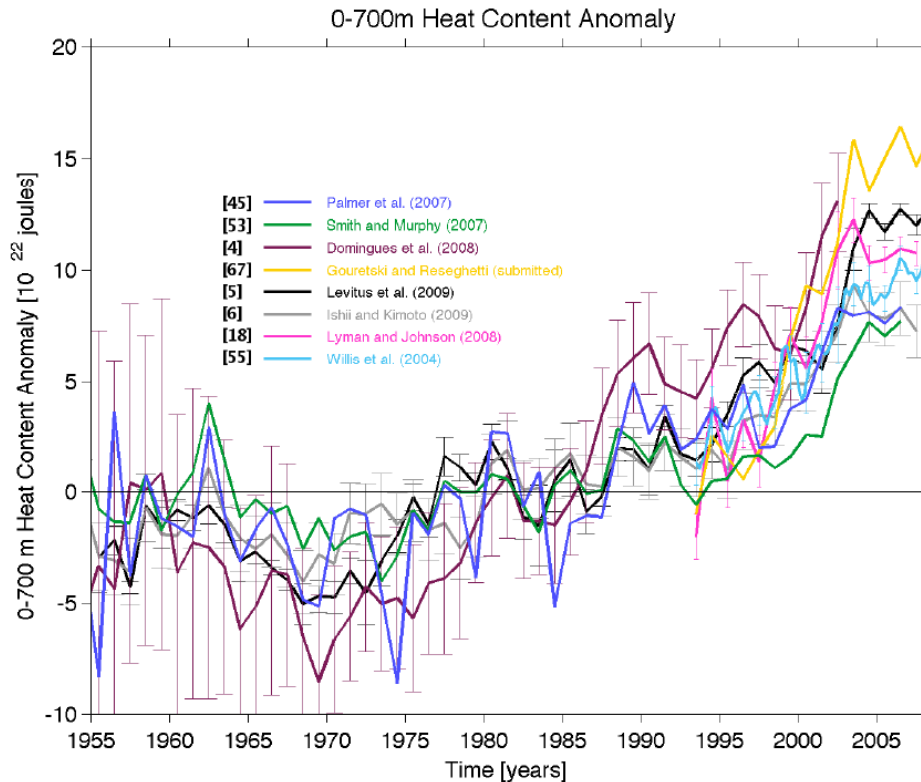
(Johnson et al., Bull. Amer. Met. Soc., 2012) 1 zeta Joule = 10^{21} J

Ocean warming in top 700 m, since 1940s



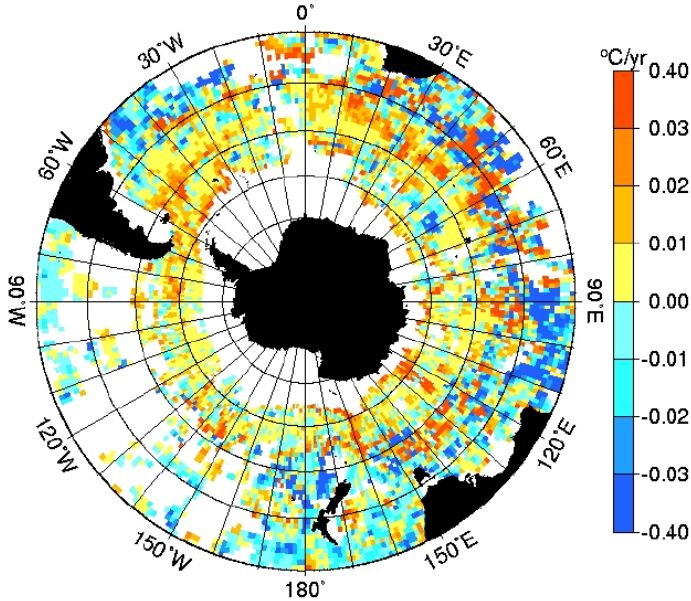
- About 0.1°C warming over 700 meters of ocean.
- Warming of upper ocean (8×10^{22} J in 50 years = 50 TW) roughly quadruple current energy usage by people (13 TW).

Ocean warming in top 700 m, since 1940s

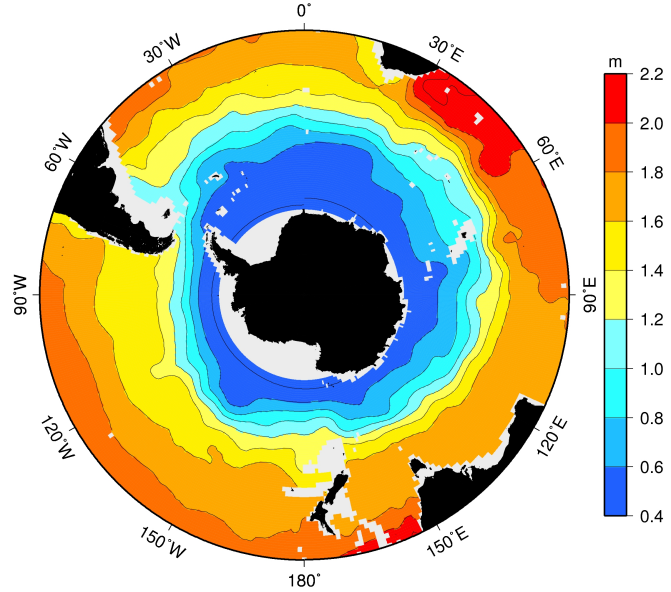


- About 0.1°C warming over 700 meters of ocean.
- Warming of upper ocean (8×10^{22} J in 50 years = 50 TW) roughly quadruple current energy usage by people (13 TW).
- Energy added to top 700 m of ocean equivalent to about 2 billion Hiroshimas...

Where does warming occur?



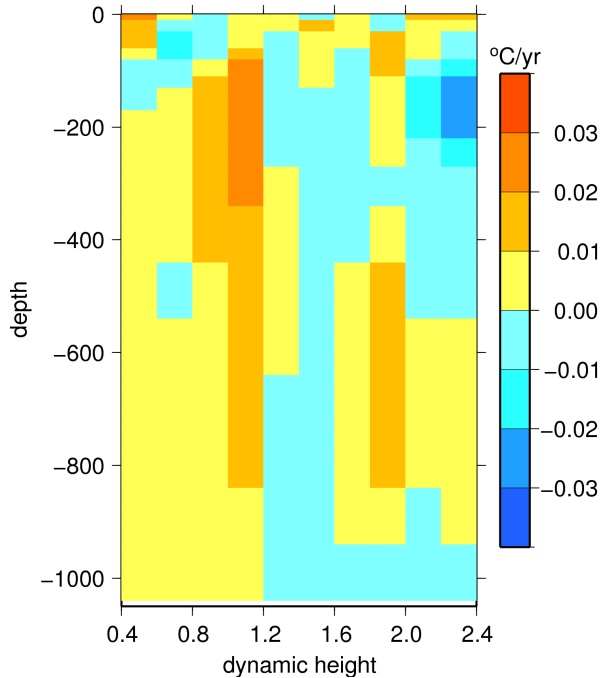
Temperature trends at ~900 m, (Gille, Science, 2002)



Dynamic topography

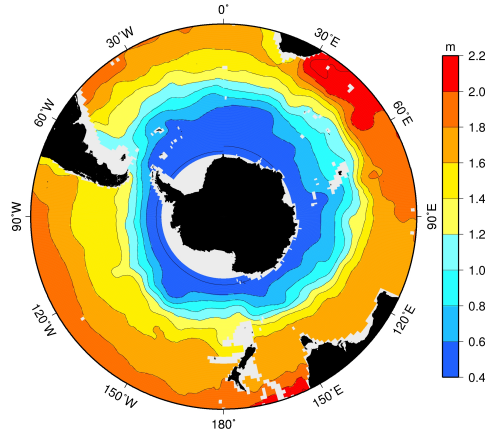
- Warming concentrated in Antarctic Circumpolar Current.

Observation 1: Southern Ocean warming throughout Antarctic Circumpolar Current

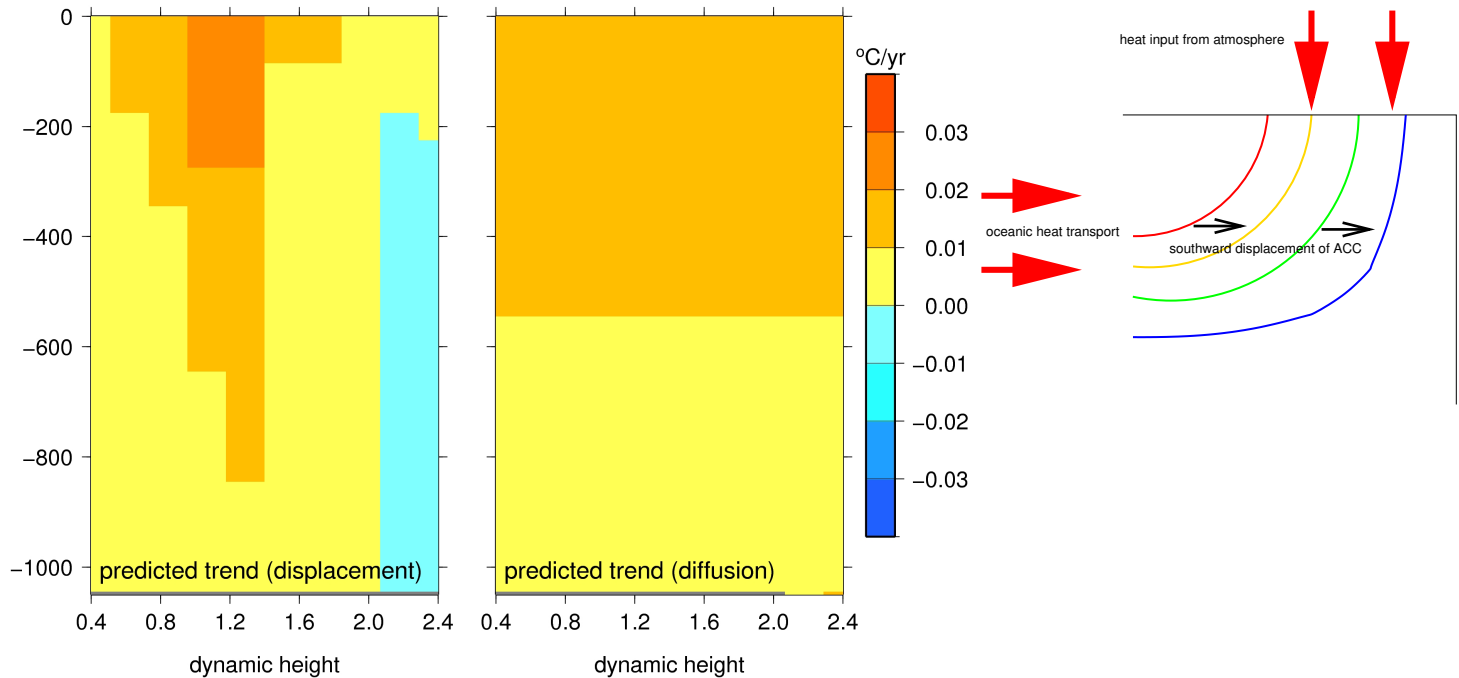


(Gille, J. Climate, 2008)

- Warming in Antarctic Circumpolar Current throughout top 1000 meters over last 50-60 years.
- Warming in top 100 m north of Antarctic Circumpolar Current.
- Surface cooling in Southern Ocean possibly residual seasonal bias.

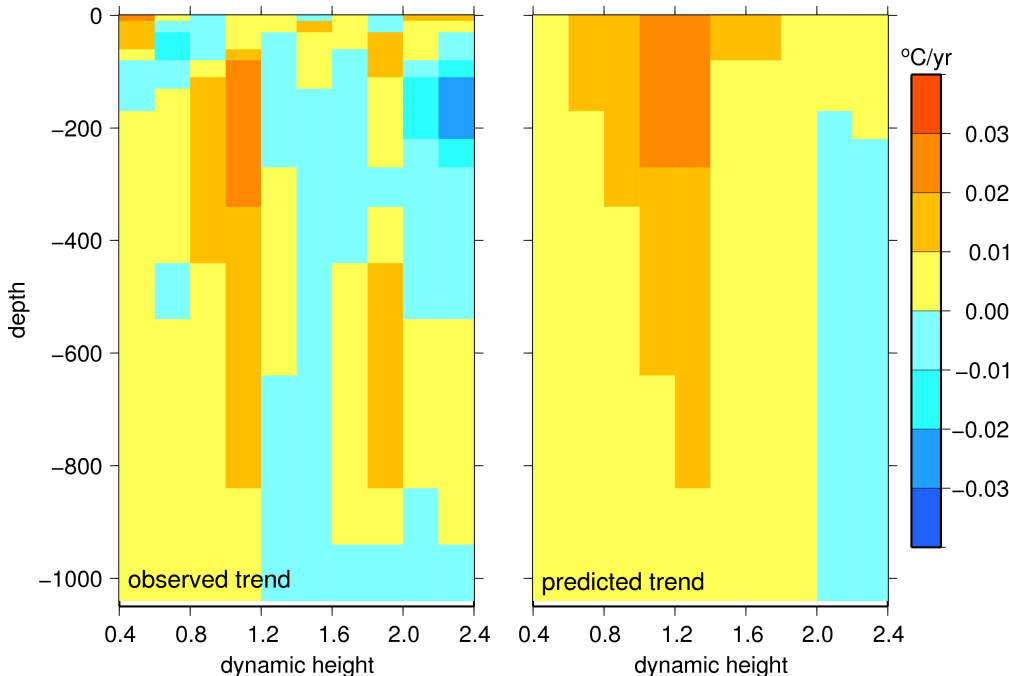


Explaining long-term trends in heat content



(Gille, J. Climate, 2008)

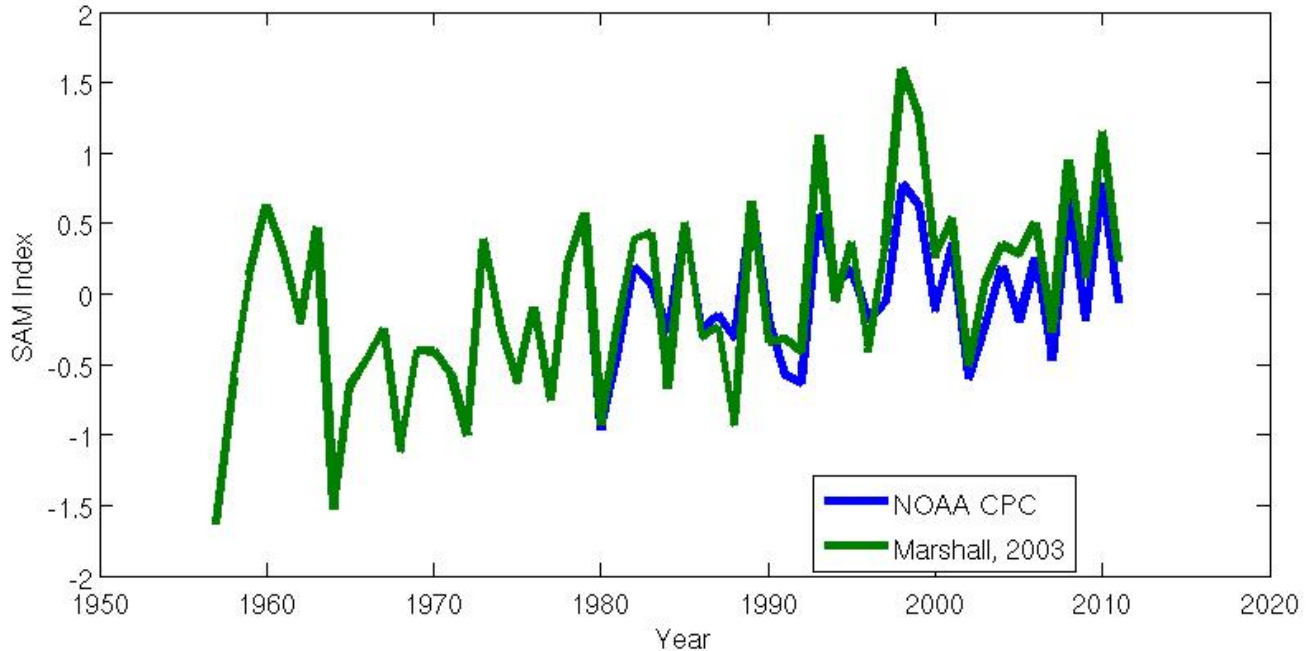
Long-term trends in Southern Ocean heat content



(Gille, J. Climate, 2008)

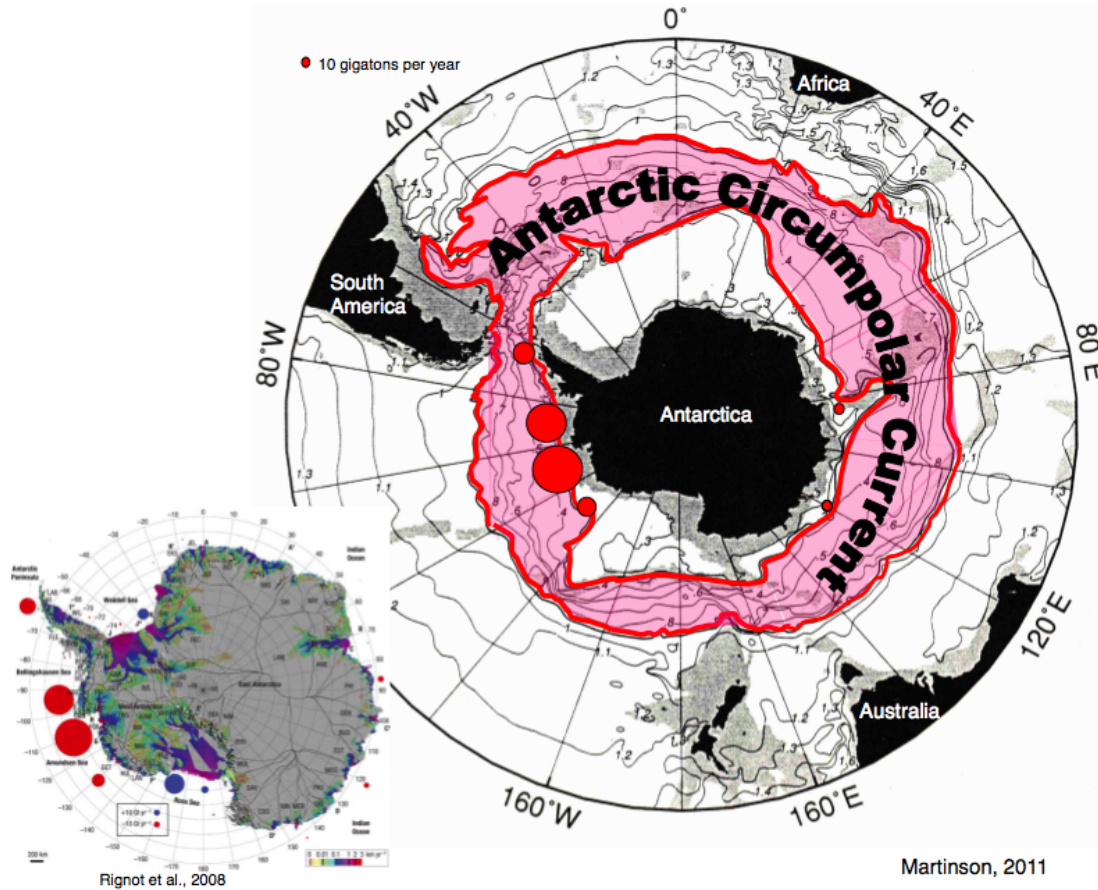
- In Southern Hemisphere ocean, 90% of net heat content increase is south of 30°S.
- Warming consistent with poleward migration of background temperature. by 1° latitude every 35 years (Gille, 2008; Sprintall, 2008; Morrow et al, 2008).

Observation 2: Southern Annular Mode (SAM) has trended upward over past 50+ years



- Implies stronger winds, further south

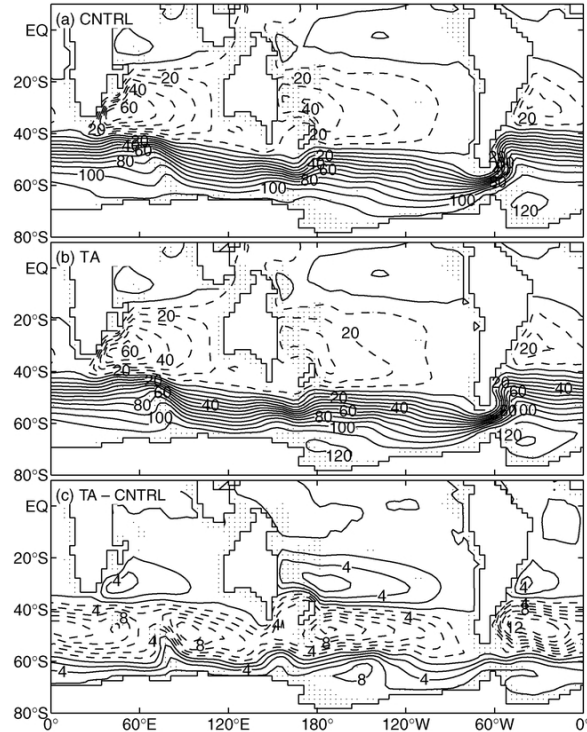
Observation 3: Antarctic glacial mass loss occurs where Antarctic Circumpolar Current approaches continent



Linking the observations

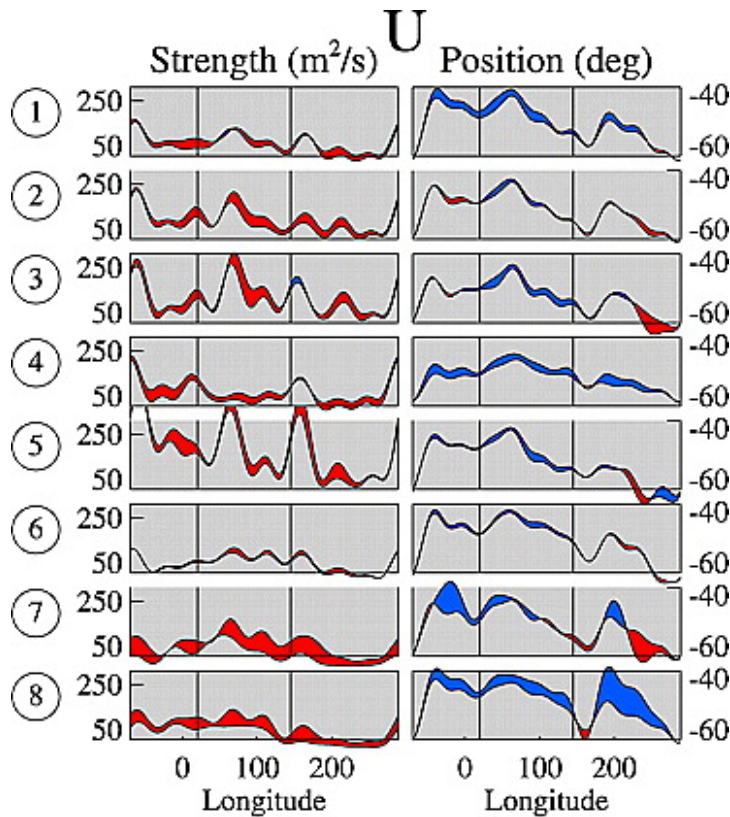
Hypothesis: An increasing Southern Annular Mode drives the Antarctic Circumpolar Current southward (and in turn helps to inject warm Circumpolar Deep Water under the ice.)

Coarse-resolution climate models support this concept.



(Oke and England, J. Climate, 2004.)

Climate Model Intercomparison Project Models: Strong Antarctic Circumpolar Current with Poleward Shift

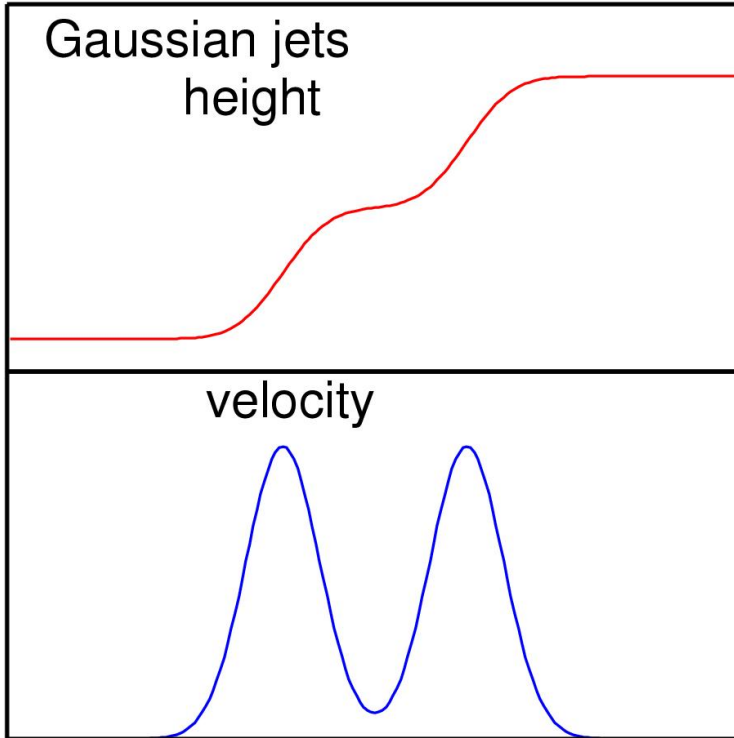


Antarctic Circumpolar Current strengthens (left) and shifts poleward (right).

(See also Fyfe and Saenko, 2005; Cai, 2005)

Fyfe and Saenko, GRL, 2006: 8-models.

Do Antarctic Circumpolar Current fronts move in response to shifting winds?



Radar altimeters have measured sea surface elevation for > 20 years. Will that tell us about Antarctic Circumpolar Current changes?

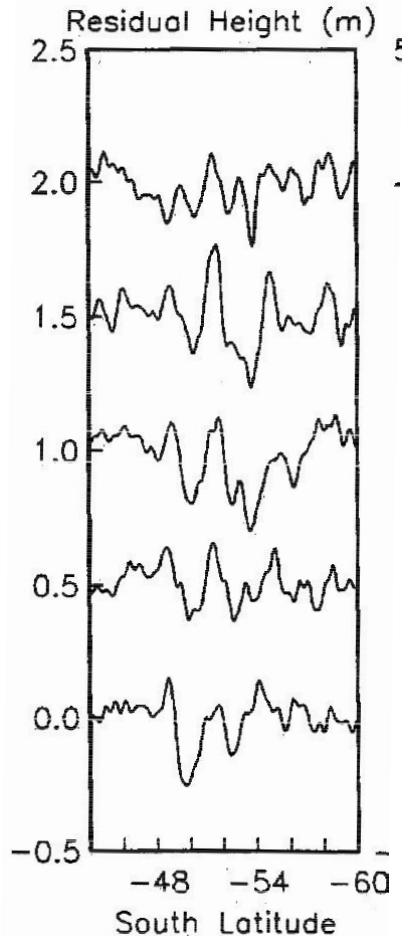
- Antarctic Circumpolar Current has multiple (more or less) Gaussian jets.
- Sea surface height is error function.
- But

Challenges to identifying front position (1)

Altimeter measures only anomaly.

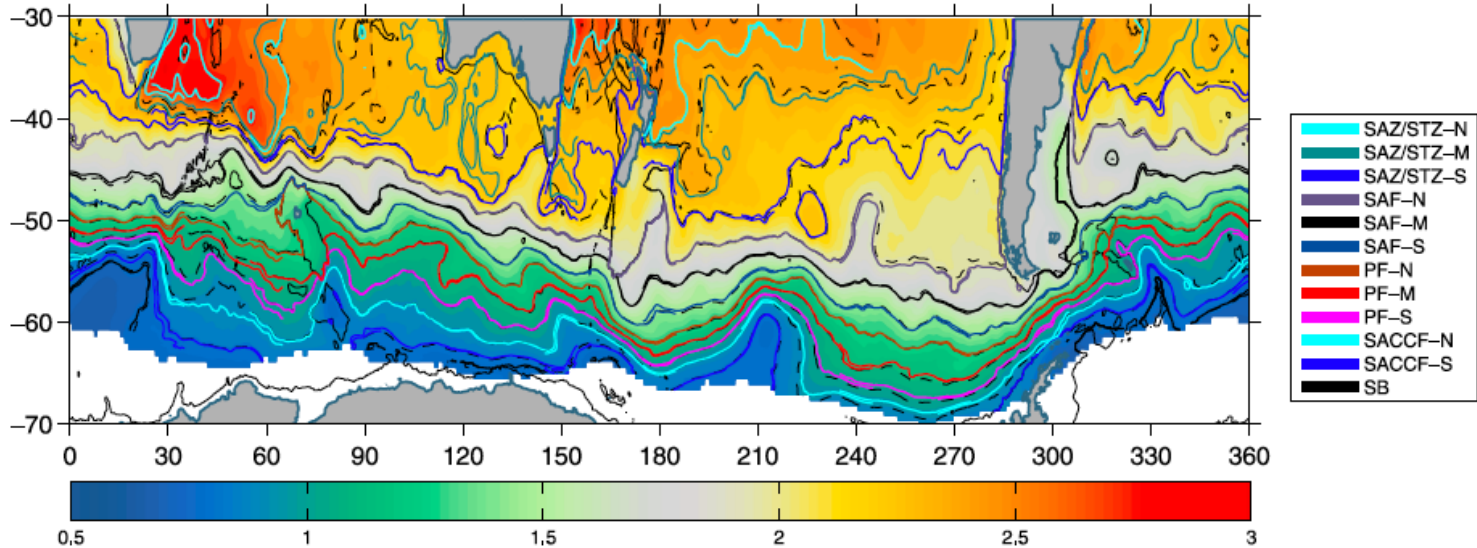
Strategies

- Study only variability of geostrophic currents. (e.g. Gille, 1994; Thompson and Demirov, 2006)
- Use an independent mean dynamic topography.



Challenges to determining front position (2)

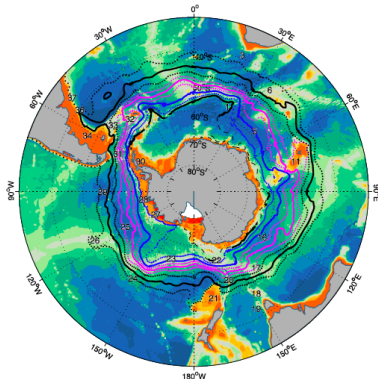
Not always clear how many fronts the Antarctic Circumpolar Current has at any given time.



Sokolov and Rintoul, 2009

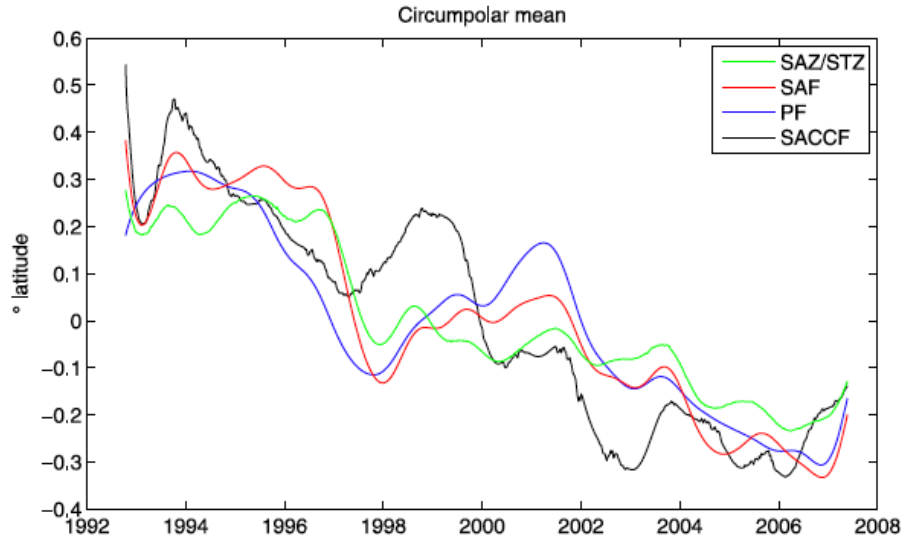
- Close inspection of sea surface height gradients imply multiple positions for each front.
- Positions reported quasi-stationary, stable in sea surface height.
- Transport shifts between fronts.

Antarctic Circumpolar Current jet displacements from radar altimetry: Long-term 60 km migration in 15 years



Gradients used to identify height contours

Sokolov and Rintoul, JGR, 2009

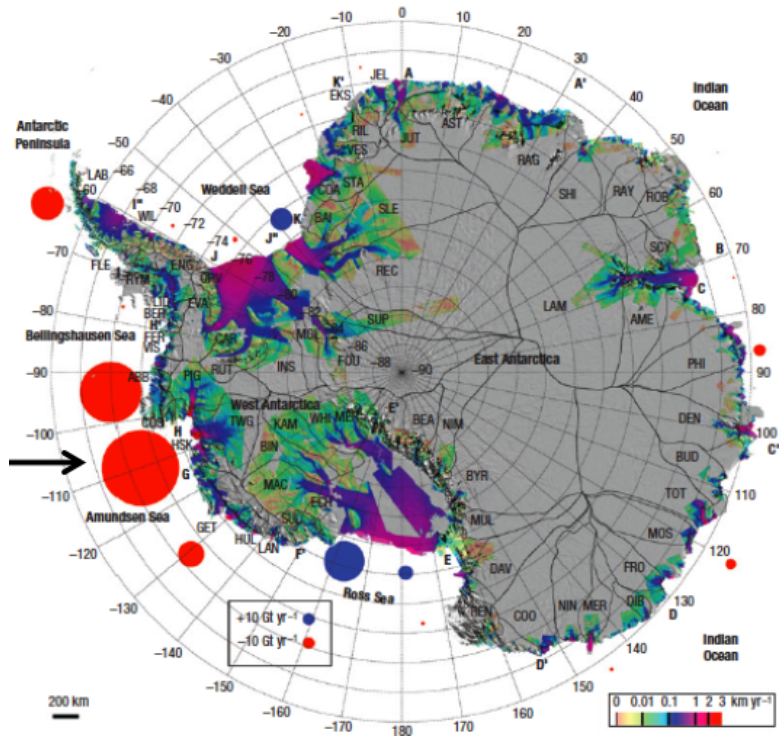


Do changes in wind drive poleward heat transport in ocean and lead to glacial melt?

From satellite gravity data:

- Red: Glacial melting
- Blue: Glacial mass increase

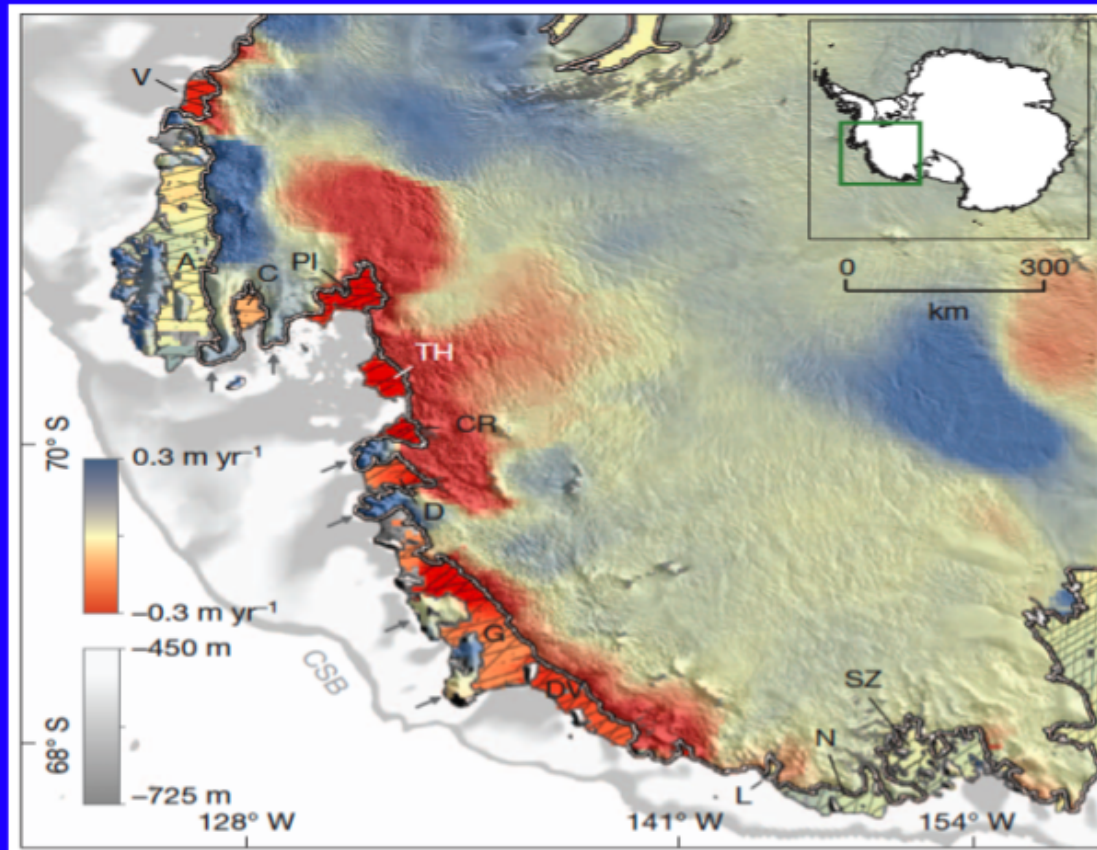
Focus on Pine Island Glacier



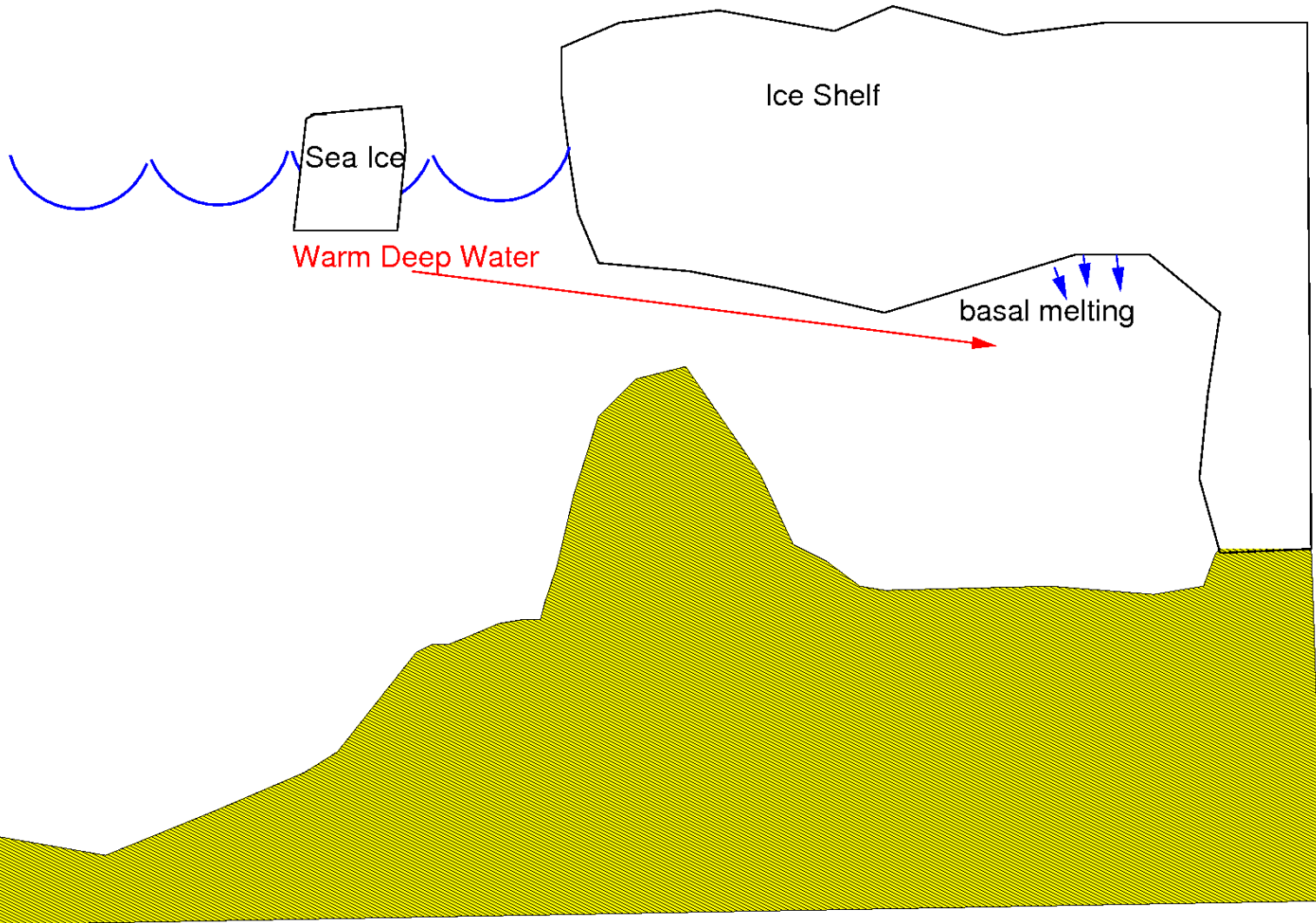
Rignot et al, 2008

Pritchard *et al*, 2012 attribute accelerated melting of PIG to increased oceanic heat supply:
“We deduce that it is caused by increased basal melt driven by ocean interaction.”

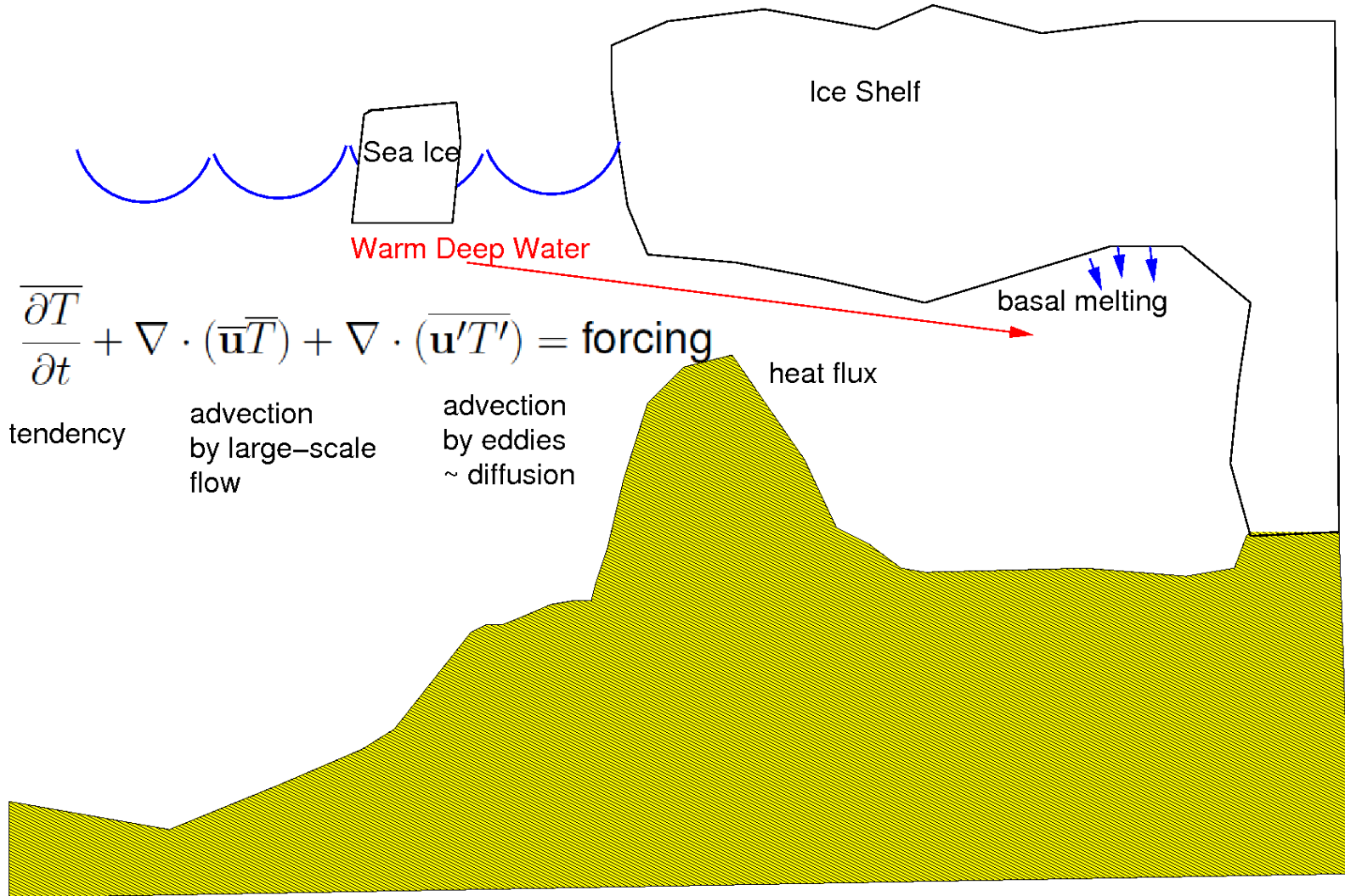
Thickness change
rate 2003-2008
from Pritchard *et al*, 2012



Why does the ocean matter for glacial melt?

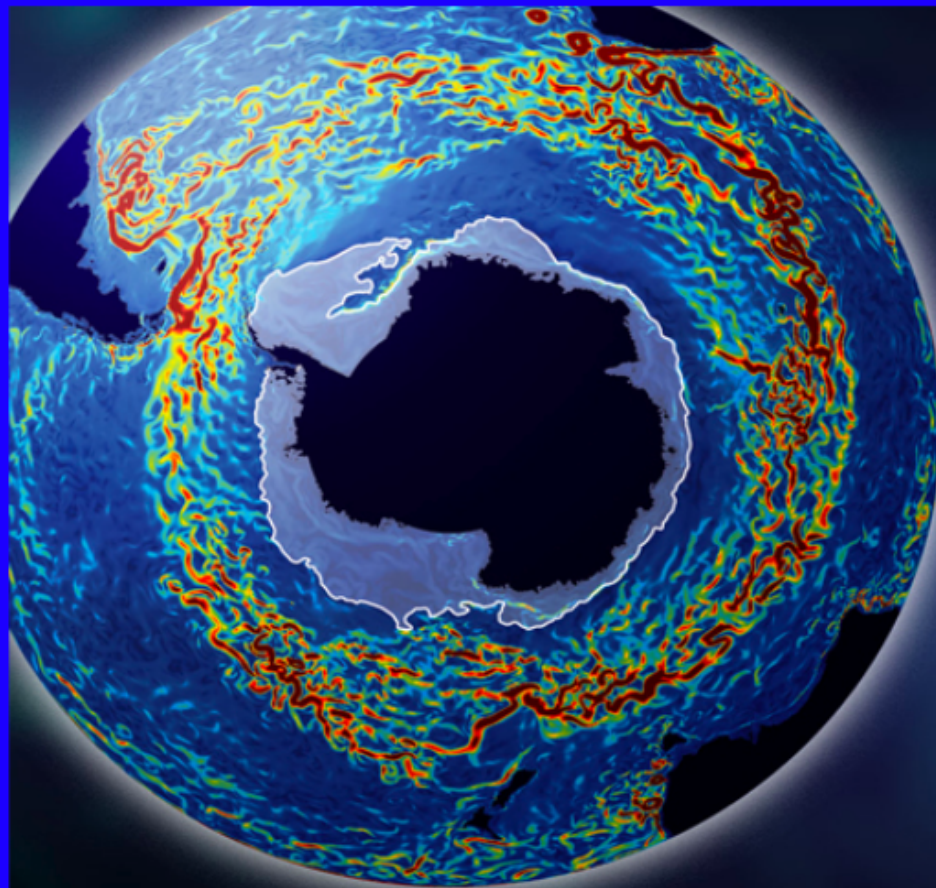
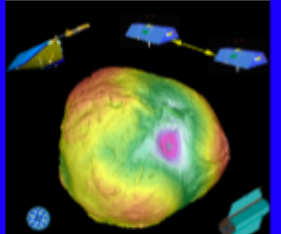
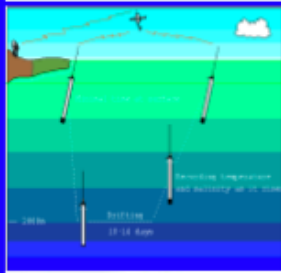
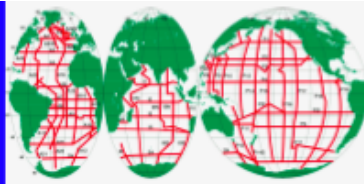


Why does the ocean matter for glacial melt?

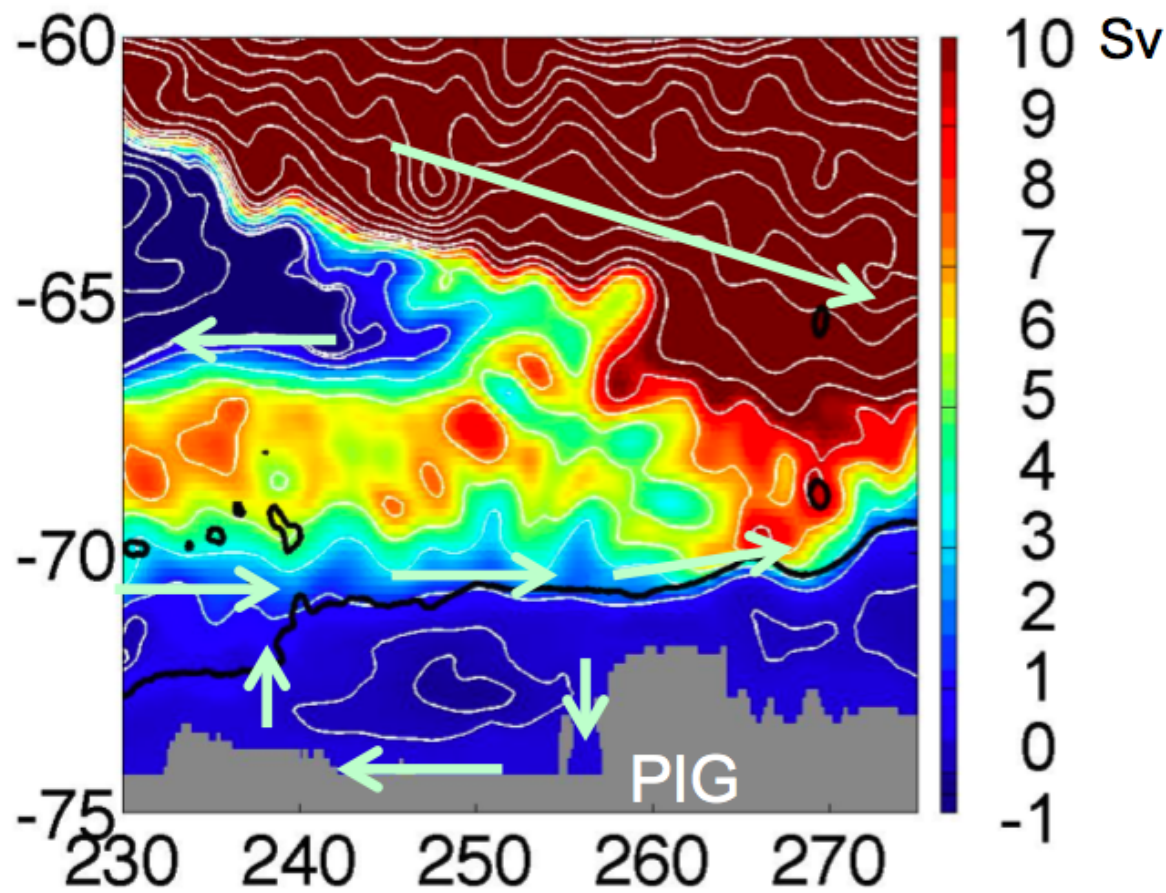
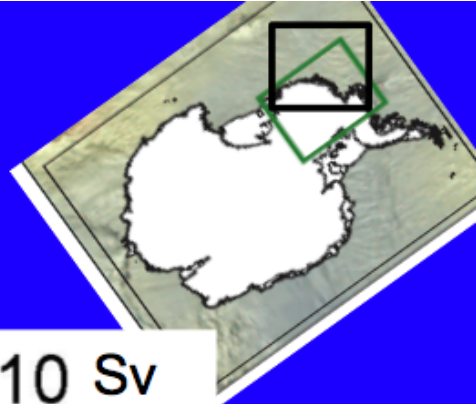


Southern Ocean State Estimate (SOSE)

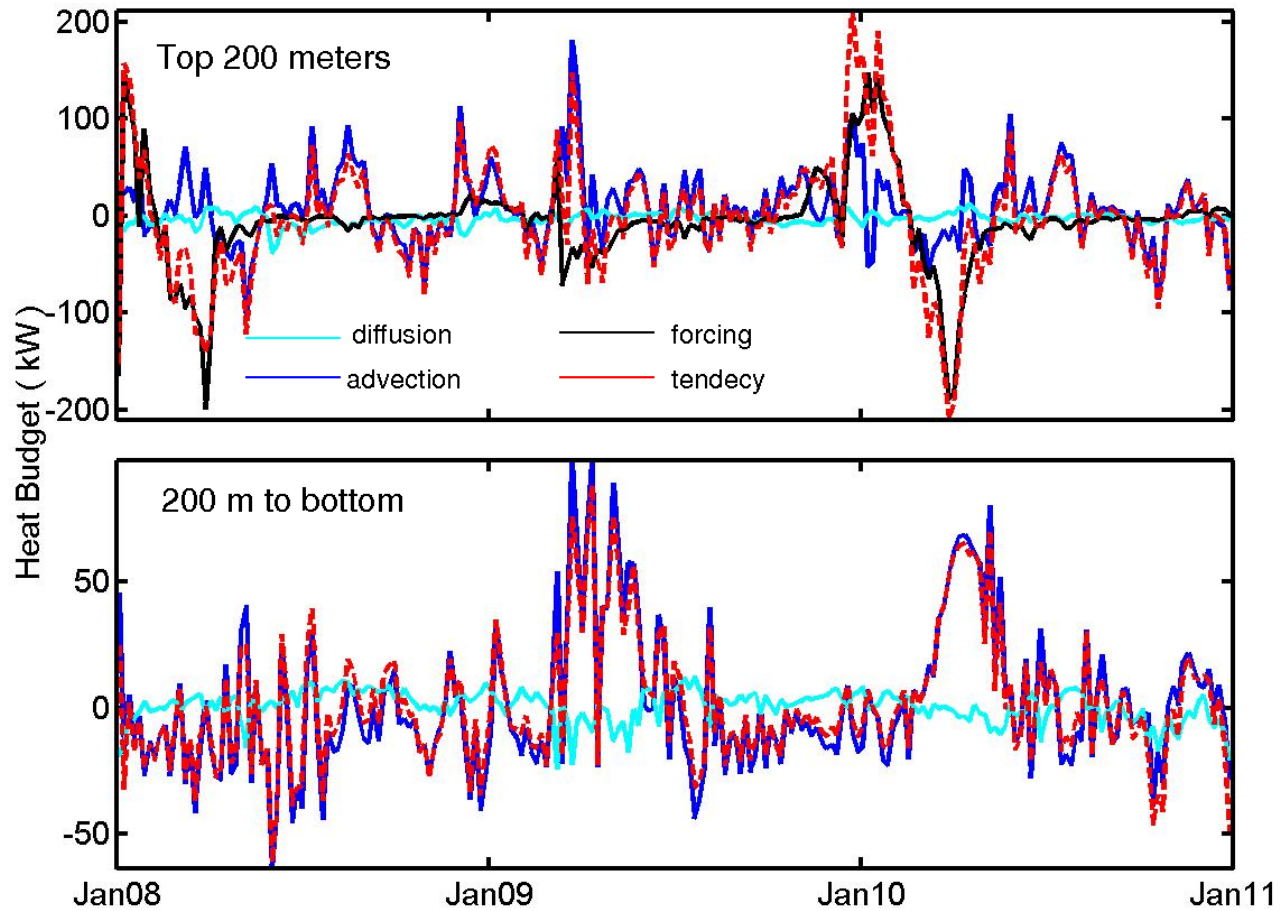
MITgcm-ECCO adjoint method
optimization for years 2008-2010. $1/6^\circ$,
42 depth levels. <http://sose.ucsd.edu>



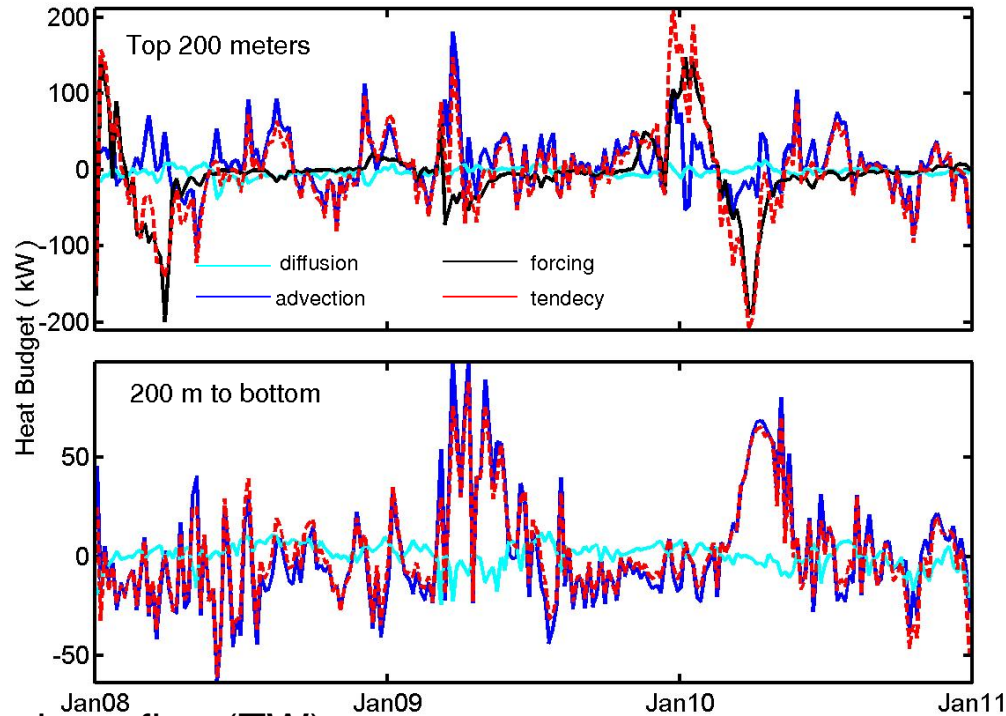
Transport streamlines [Sv]
2600m bathymetry contour in black



Pine Island Bay heat budget



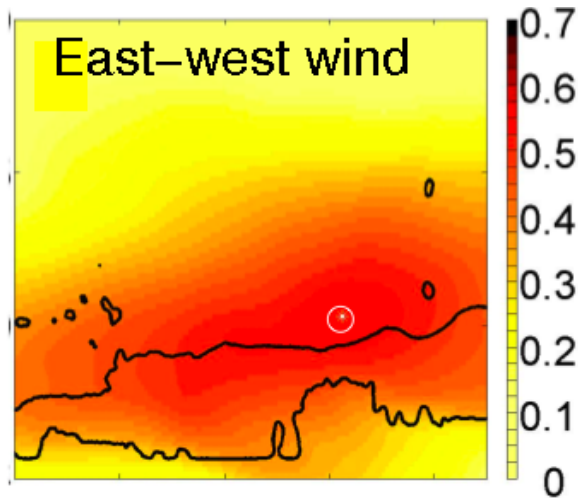
Pine Island Bay heat budget



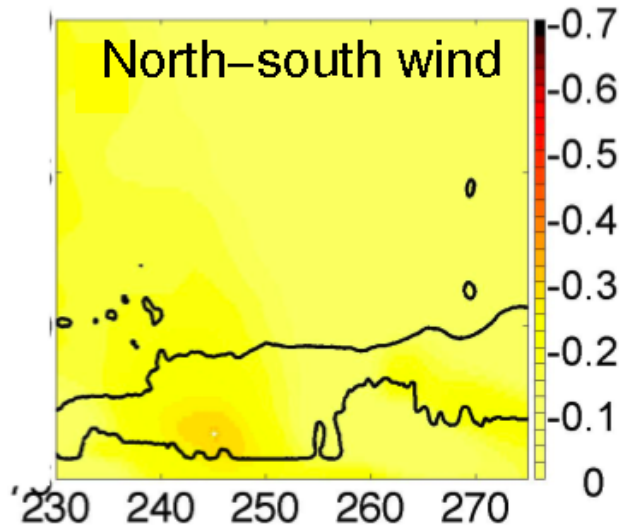
Net advective heat flux (TW):

| year | top 200 | bottom |
|------|---------|--------|
| 2008 | -0.05 | 0.22 |
| 2009 | 0.51 | 1.01 |
| 2010 | 1.39 | 2.80 |

Winds and warm water

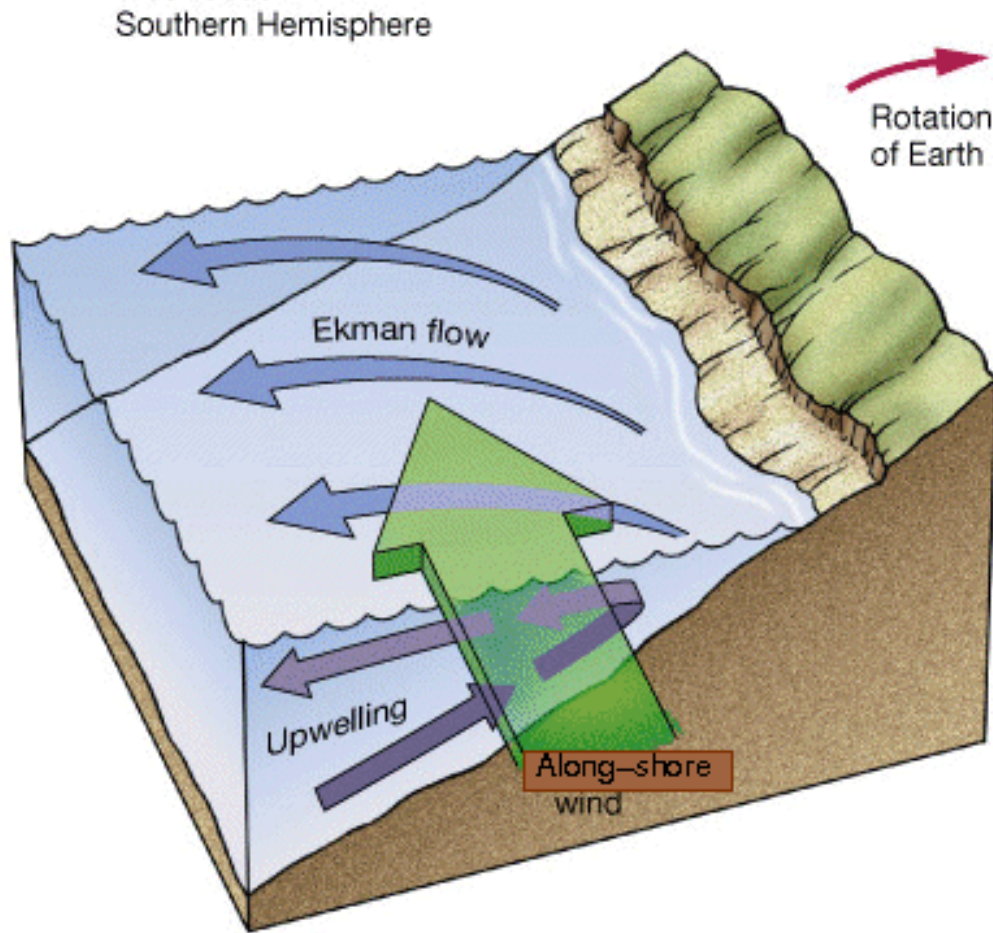


- Zonal (east-west) wind more strongly correlated than meridional (north-south) wind.
- Significant correlation with zonal winds: wind driving heat transport into Pine Island Bay.



Gilroy, Mazloff, Gille, in prep

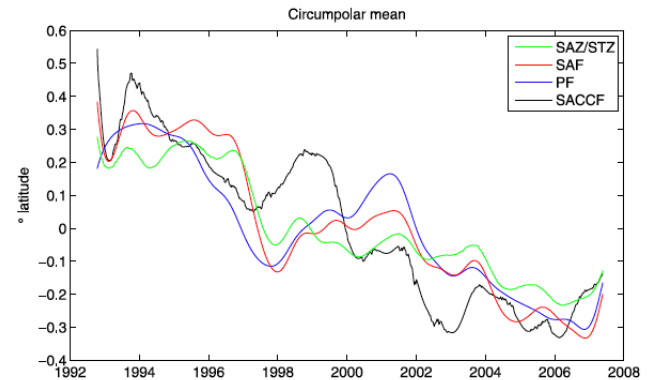
Schematic circulation: Classic coastal upwelling



Adapted from http://wps.prenhall.com/wps/media/objects/374/382993/Fg07_11.gif

Summary

- Southern Ocean and global ocean have warmed significantly since 1950s.
- Warming consistent with poleward shift of Antarctic Circumpolar Current, linked to poleward shift in winds.
- Hypothesized to enhance transport of warm water into space under ice shelves.
- Data-constrained model supports this: greater wind at shelfbreak implies greater net poleward heat transport into Pine Island Bay.
- Do the large-scale winds (i.e. Southern Annular Mode) drive local changes in wind?



Sokolov and Rintoul, 2009

