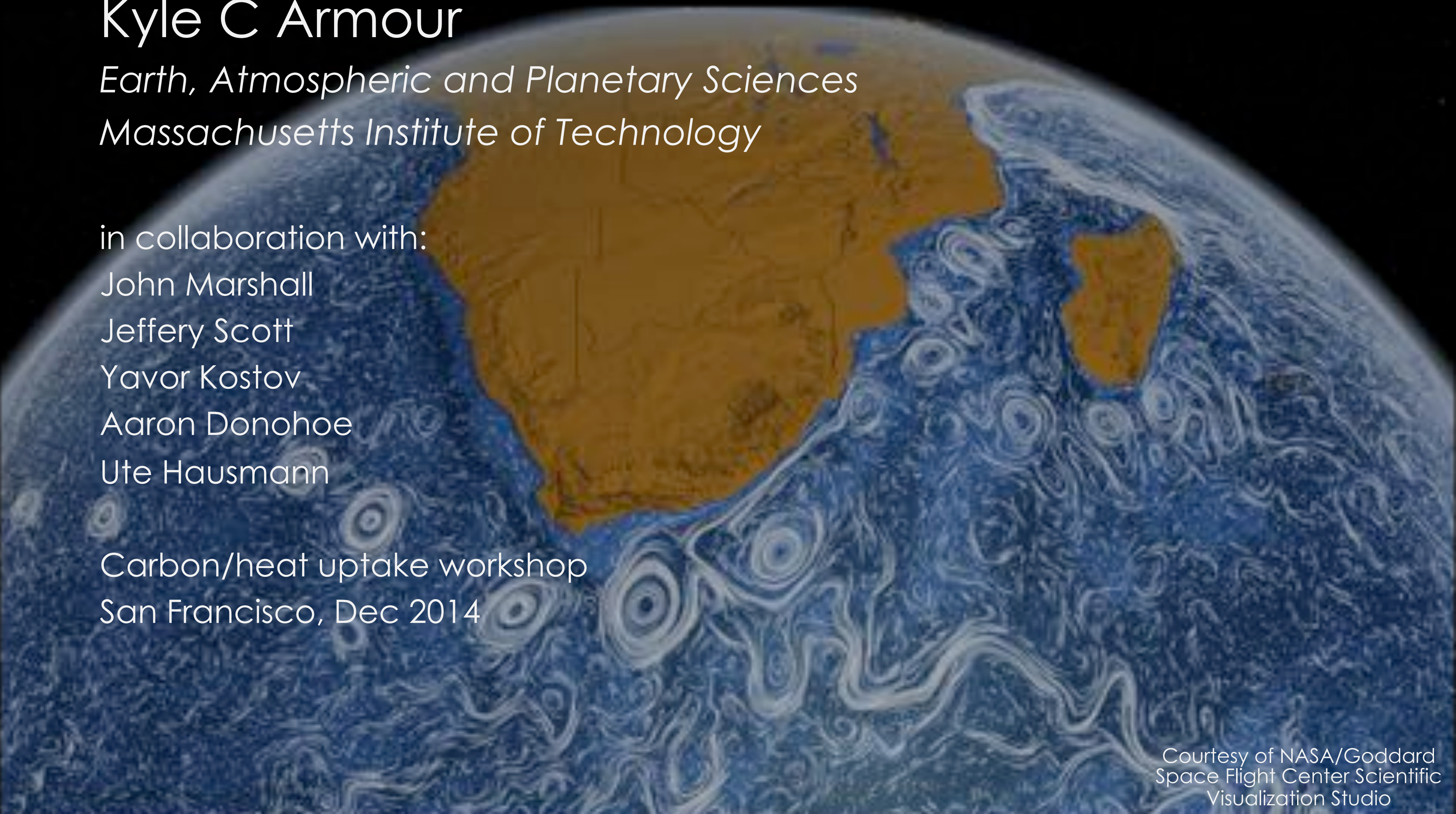
What sets patterns of Southern Ocean heat uptake and storage?

Kyle C Armour
Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology

in collaboration with:
John Marshall
Jeffery Scott
Yavor Kostov
Aaron Donohoe
Ute Hausmann

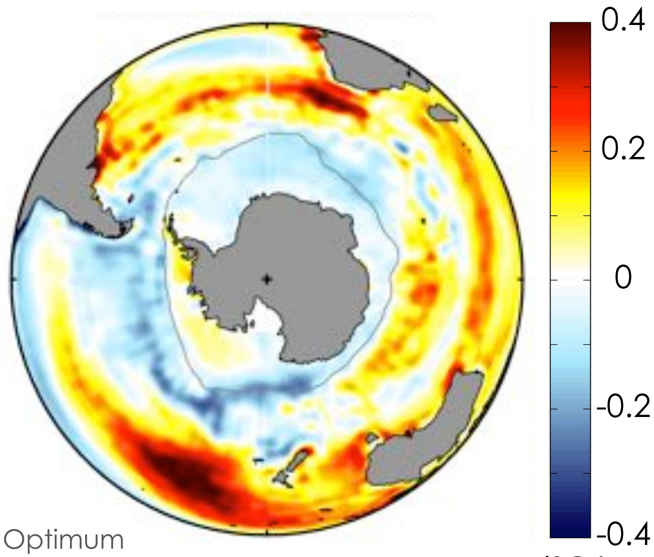
Carbon/heat uptake workshop
San Francisco, Dec 2014



Courtesy of NASA/Goddard Space Flight Center Scientific Visualization Studio

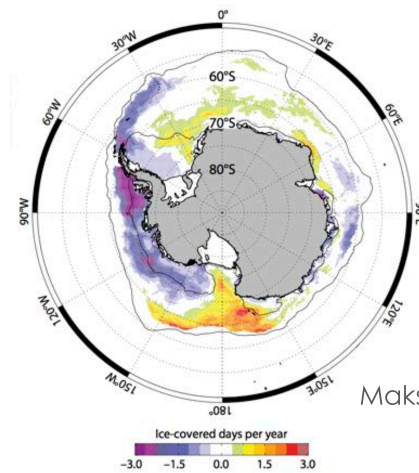
Observed Southern Ocean trends

1982-2012 sea-surface temperature trend

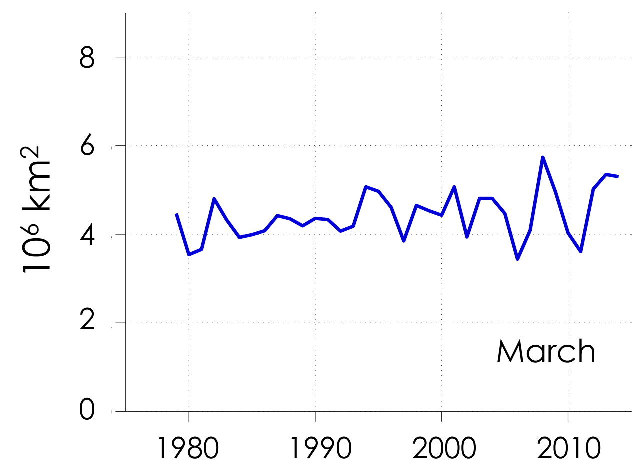


NOAA Optimum
Interpolation SST Version 2
(Reynolds et al 2002)

Antarctic sea-ice extent



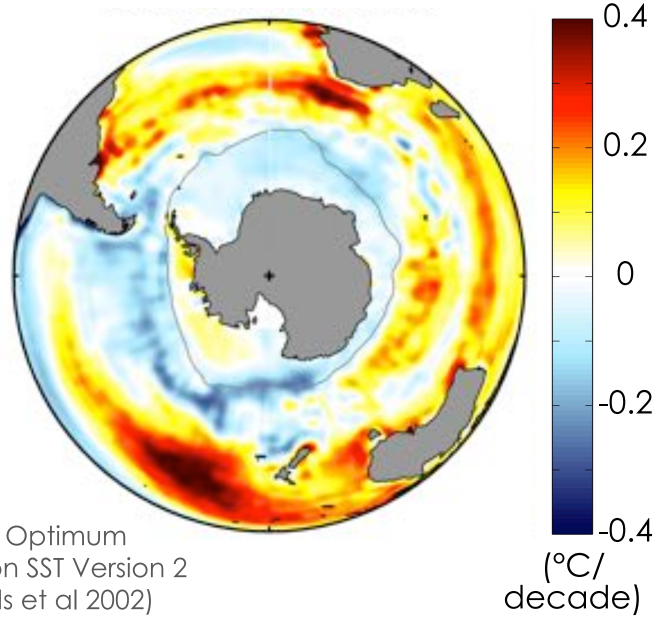
Maksym et al (2012)



From National Snow and Ice Data Center
http://nsidc.org/cryosphere/sotc/sea_ice.html

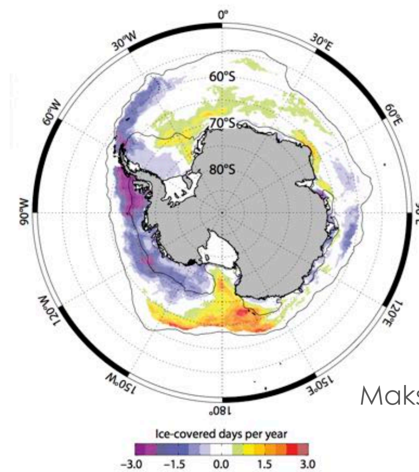
Observed Southern Ocean trends

1982-2012 sea-surface temperature trend



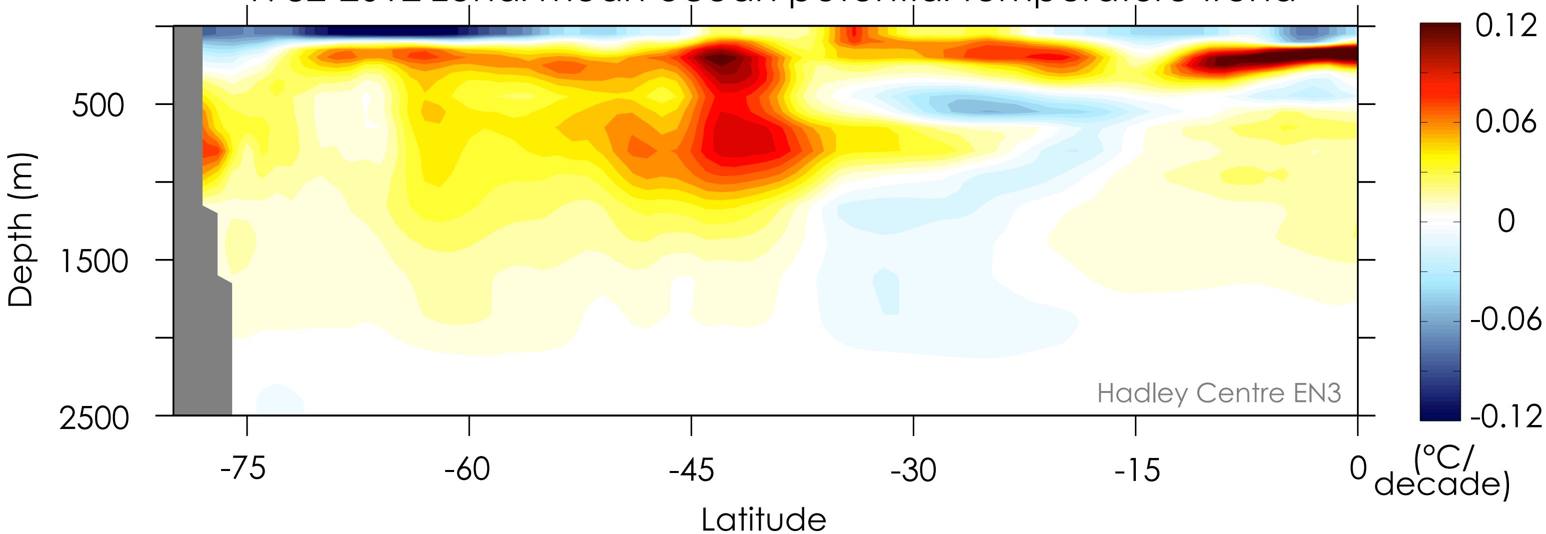
NOAA Optimum
Interpolation SST Version 2
(Reynolds et al 2002)

Antarctic sea-ice extent



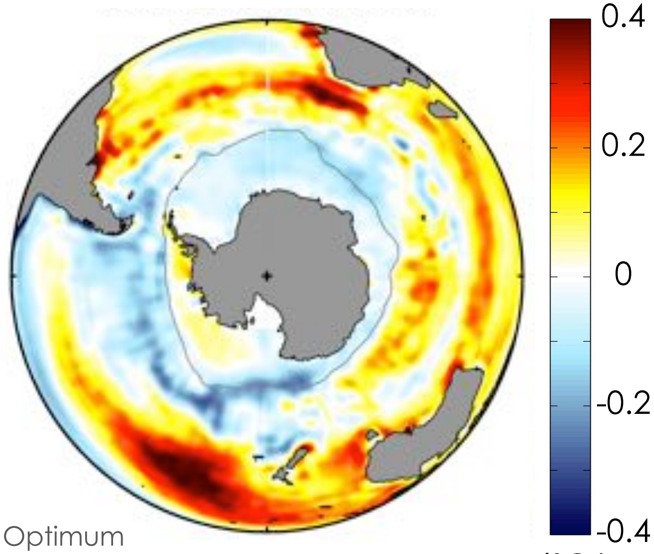
Maksym et al (2012)

1982-2012 zonal mean ocean potential temperature trend



A response to trends in surface winds?

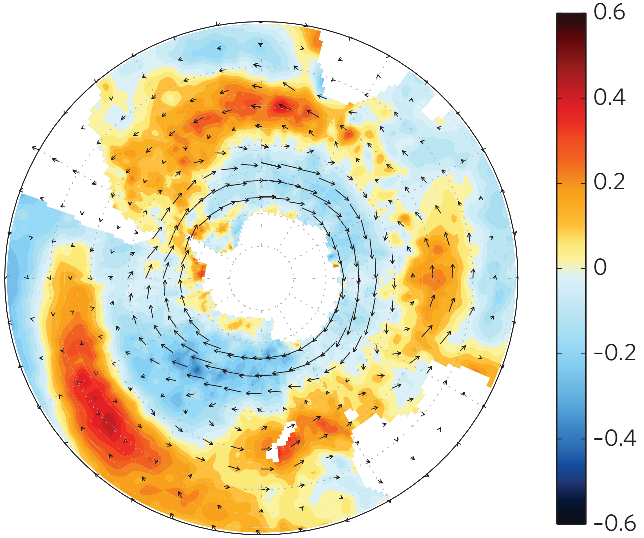
1982-2012 sea-surface temperature trend



NOAA Optimum
Interpolation SST Version 2
(Reynolds et al 2002)

(°C/
decade)

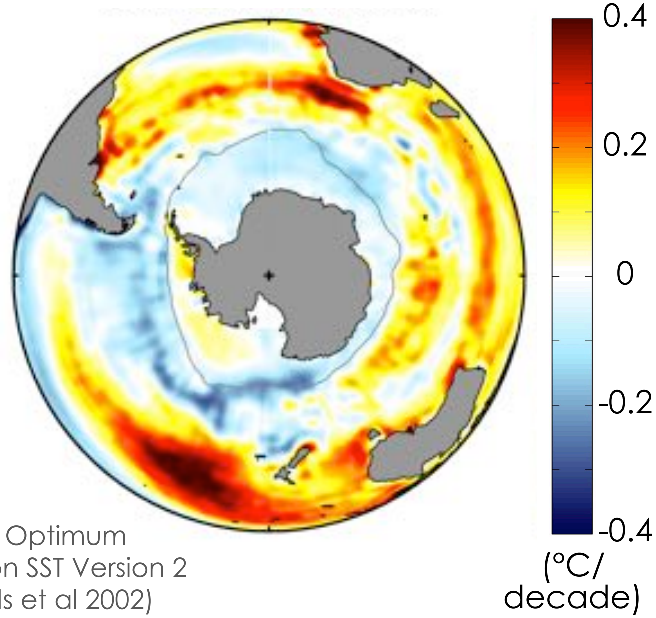
Observed SST/wind correlations with SAM



Thompson et al 2011

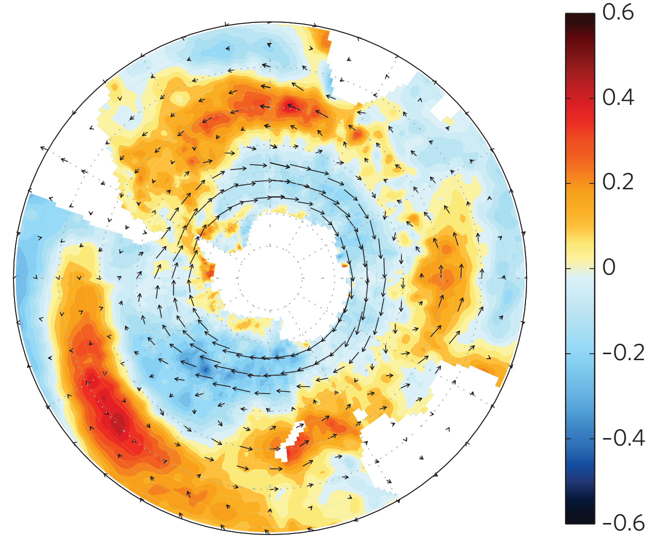
A response to trends in surface winds?

1982-2012 sea-surface temperature trend



NOAA Optimum Interpolation SST Version 2 (Reynolds et al 2002)

Observed SST/wind correlations with SAM

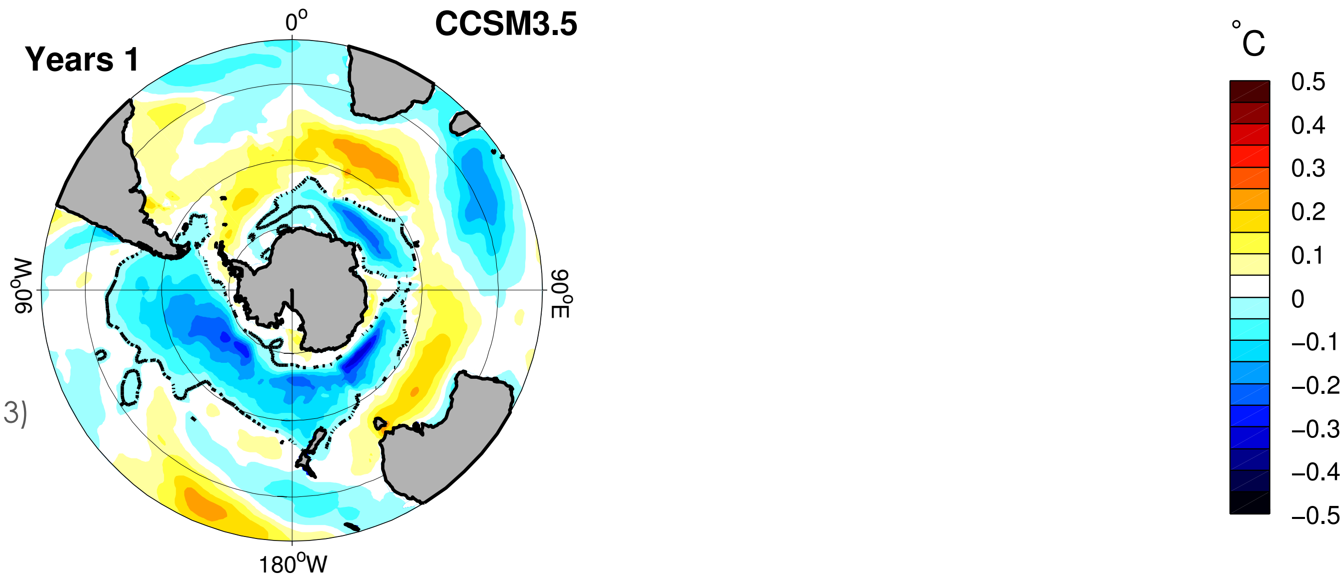


Thompson et al 2011

GCM response to sustained ozone depletion: two timescales

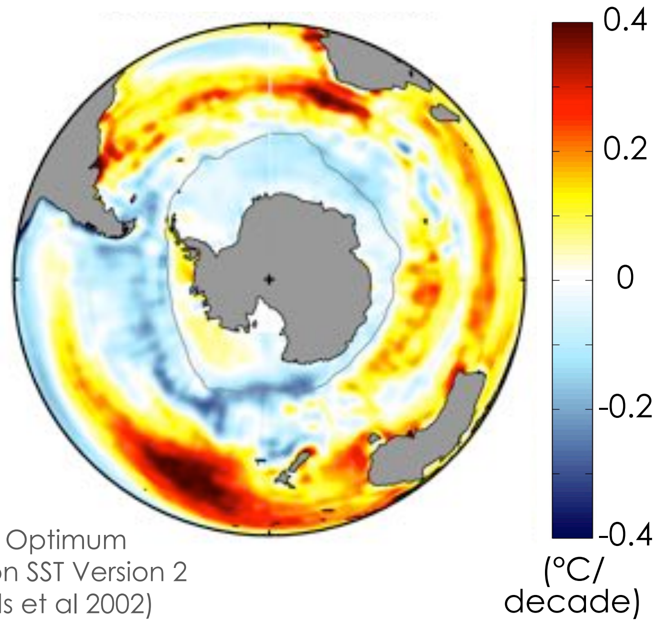
Ferreira et al 2014

see also:
Sigmond and Fyfe (2010,2013)
Bitz and Polvani (2012)
Smith et al (2012)
Marshall et al (2014)



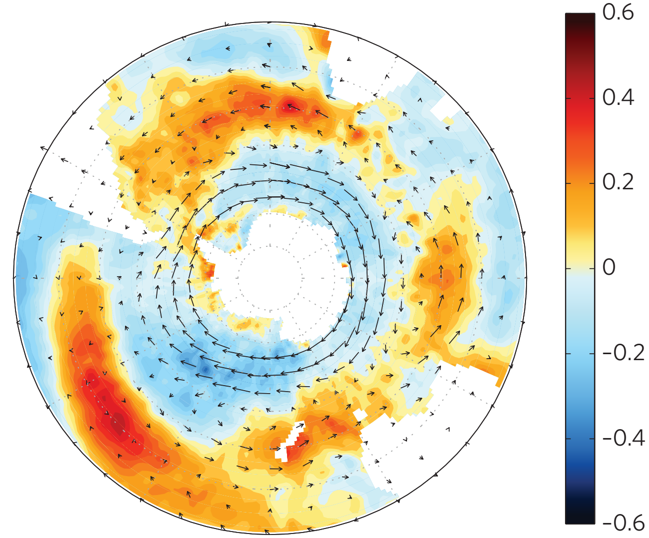
A response to trends in surface winds?

1982-2012 sea-surface temperature trend



NOAA Optimum
Interpolation SST Version 2
(Reynolds et al 2002)

Observed SST/wind correlations with SAM

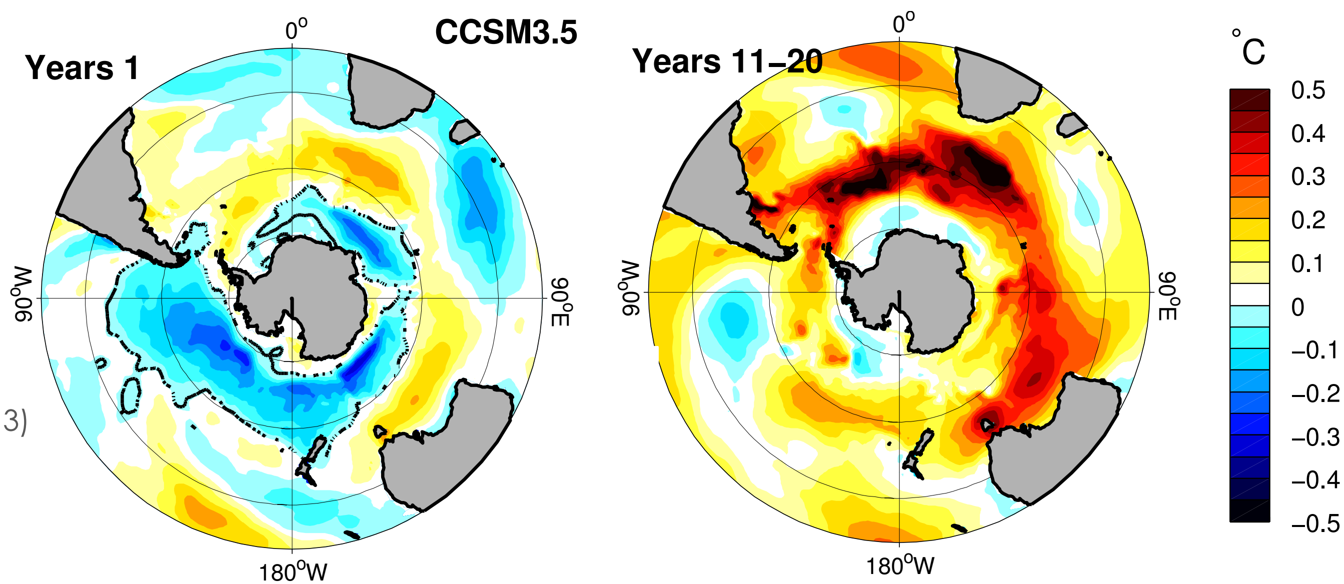


Thompson et al 2011

GCM response to sustained ozone depletion: two timescales

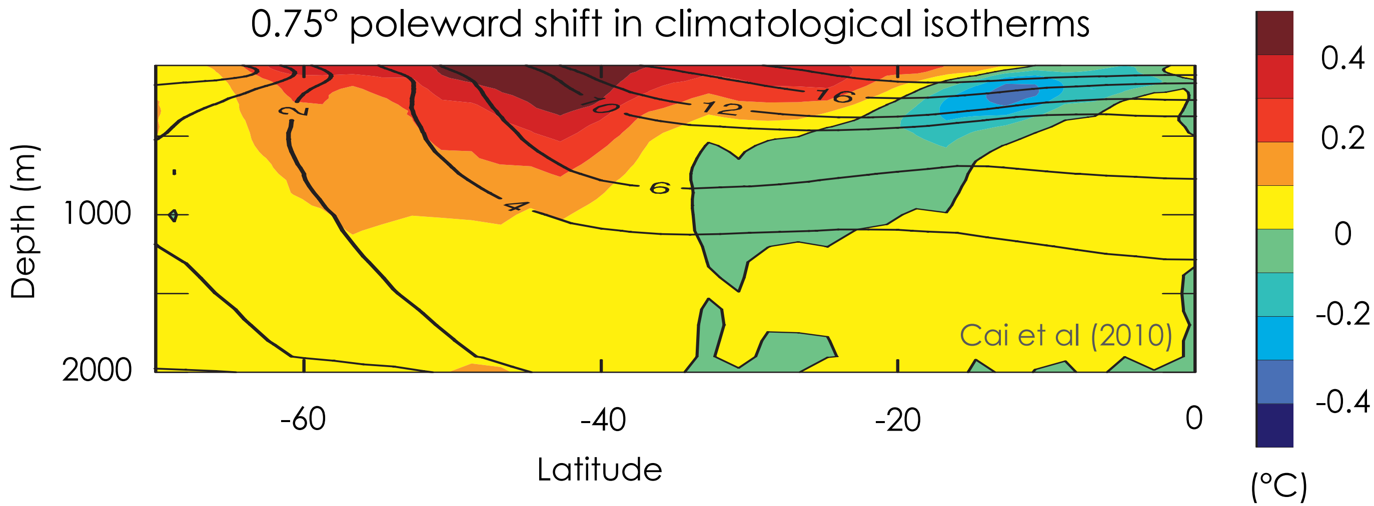
Ferreira et al 2014

see also:
Sigmond and Fyfe (2010,2013)
Bitz and Polvani (2012)
Smith et al (2012)
Marshall et al (2014)

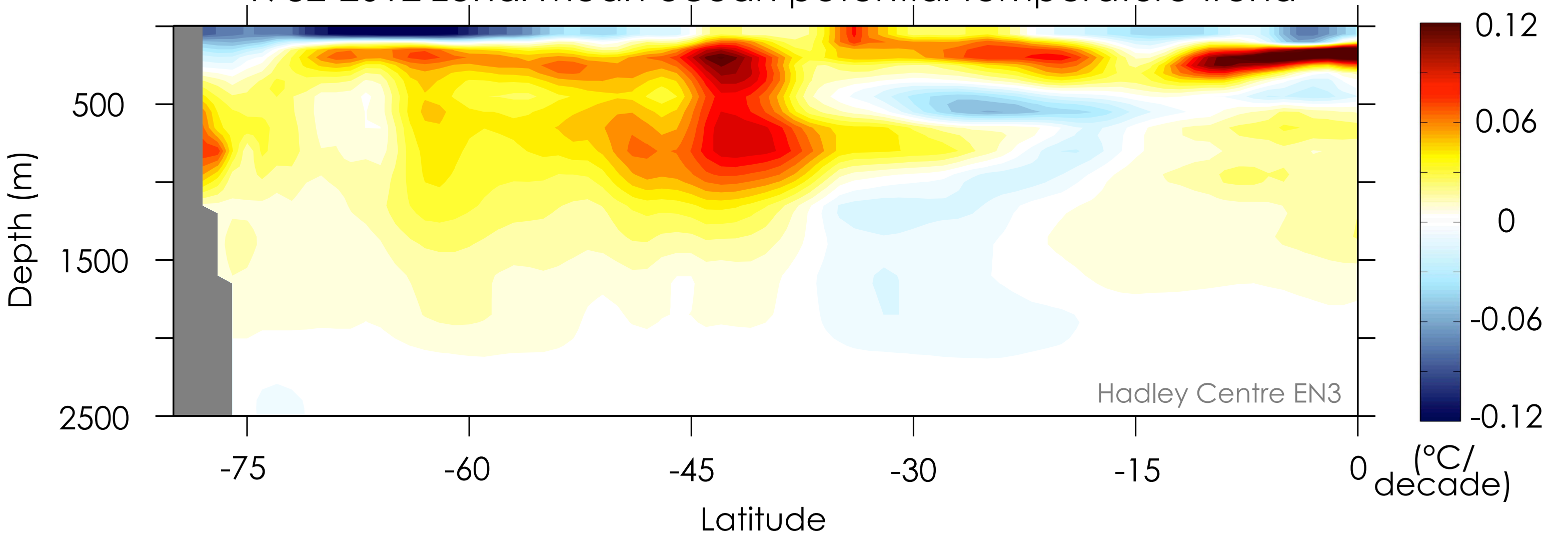


A response to trends in surface winds?

Pattern of temperature change associated with a (theoretical) 0.75° poleward shift in climatological isotherms

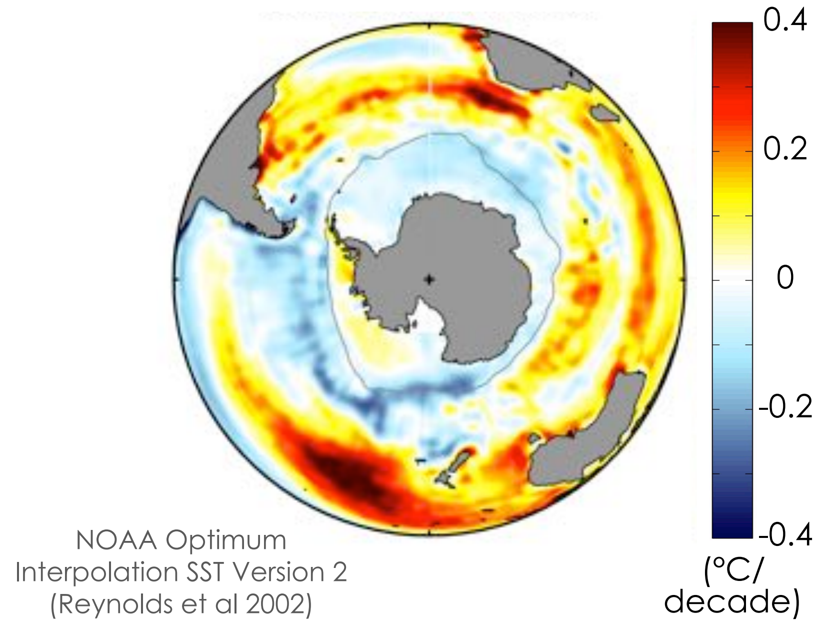


1982-2012 zonal mean ocean potential temperature trend

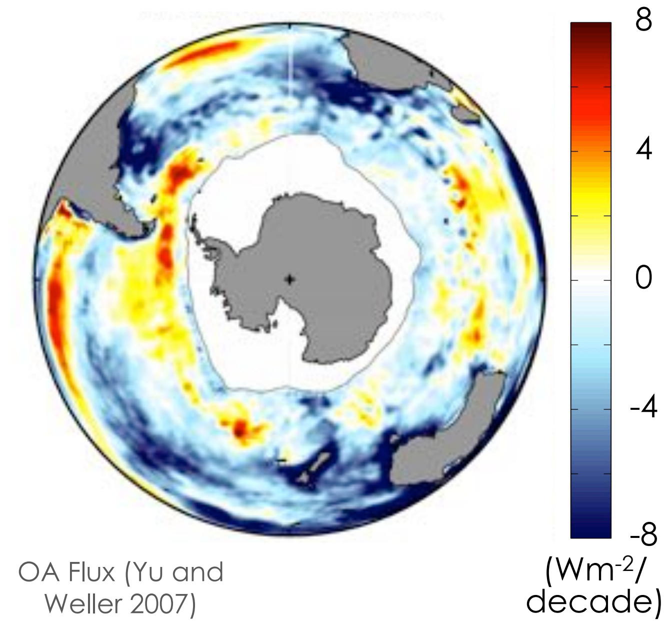


Observed Southern Ocean trends

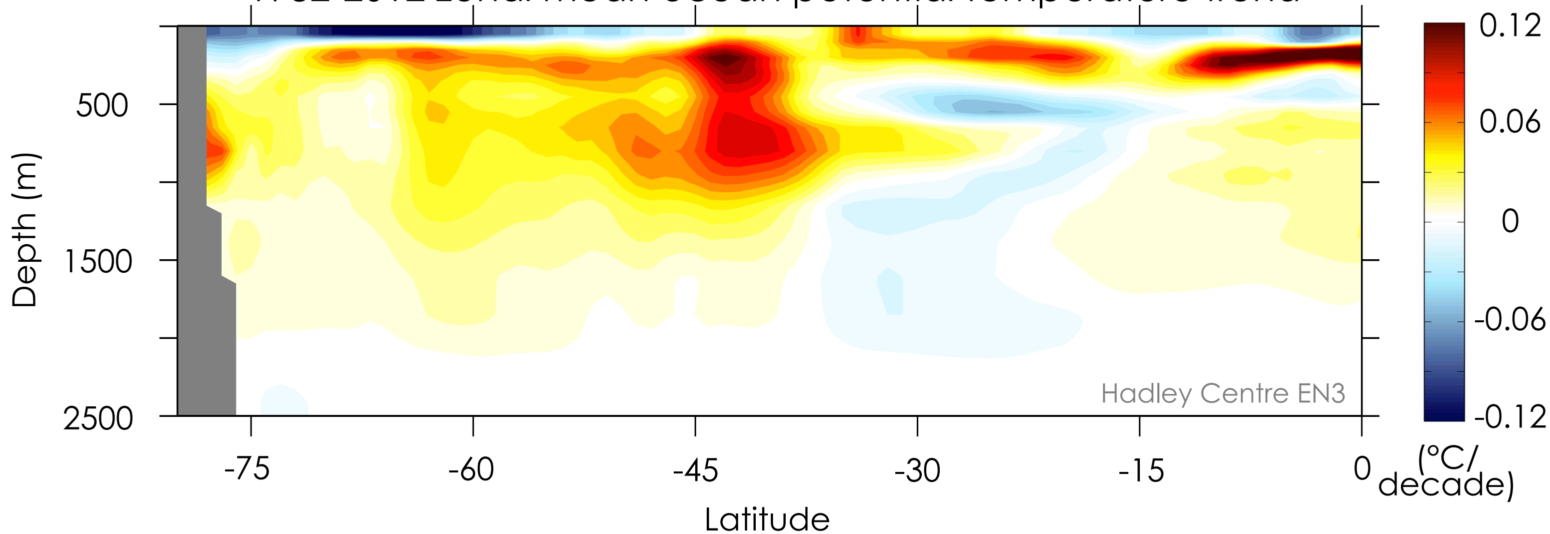
1982-2012 sea-surface temperature trend



1984-2009 surface heat flux trend

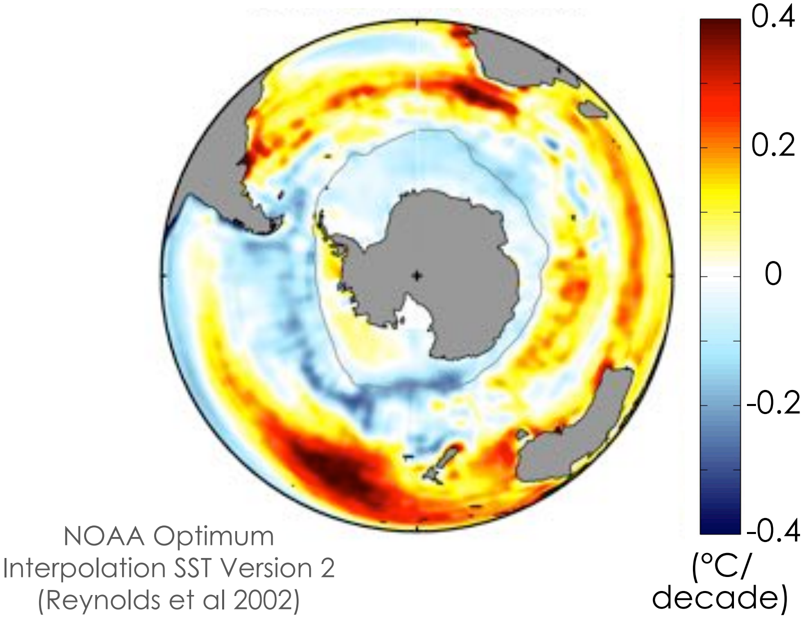


1982-2012 zonal mean ocean potential temperature trend

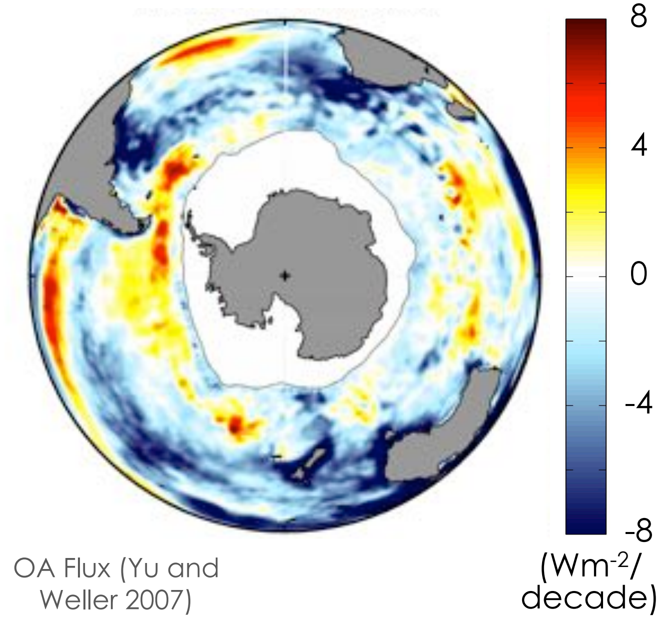


Observed Southern Ocean trends

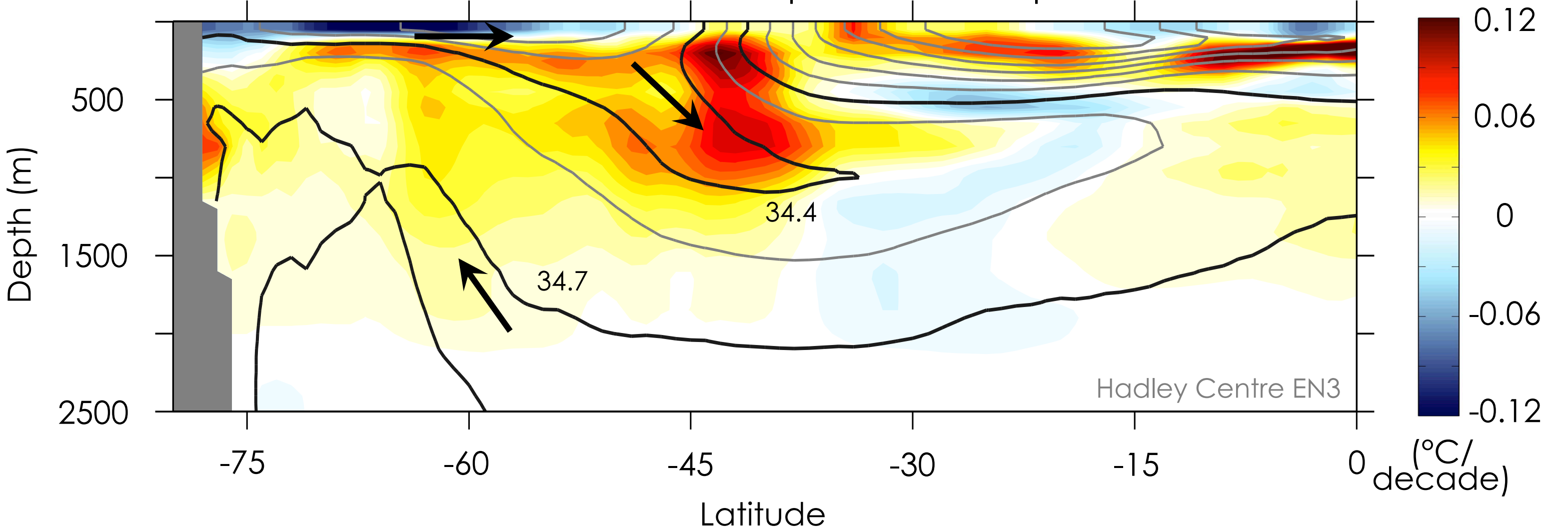
1982-2012 sea-surface temperature trend



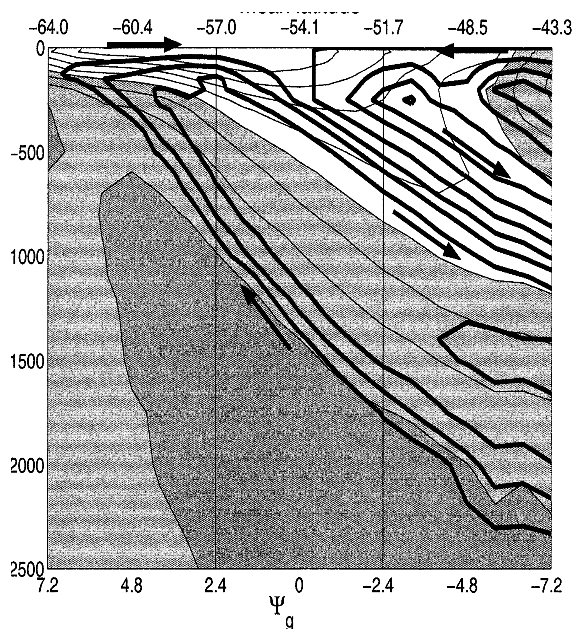
1984-2009 surface heat flux trend



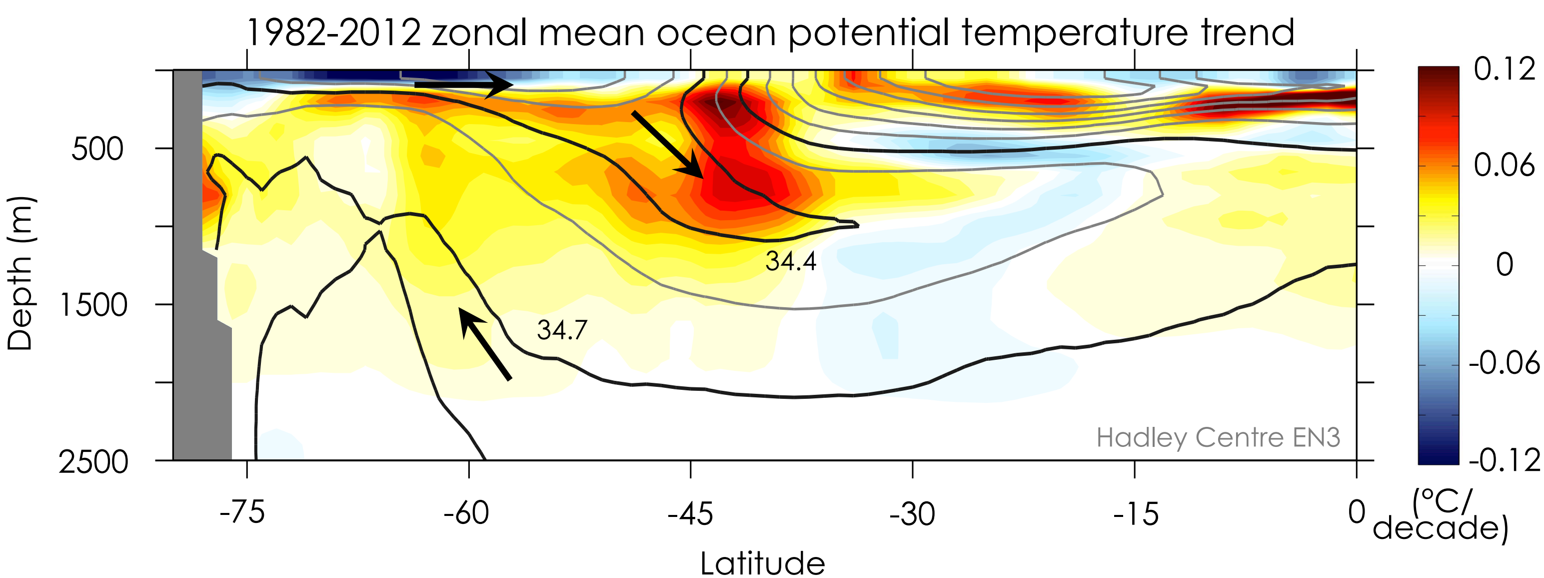
1982-2012 zonal mean ocean potential temperature trend



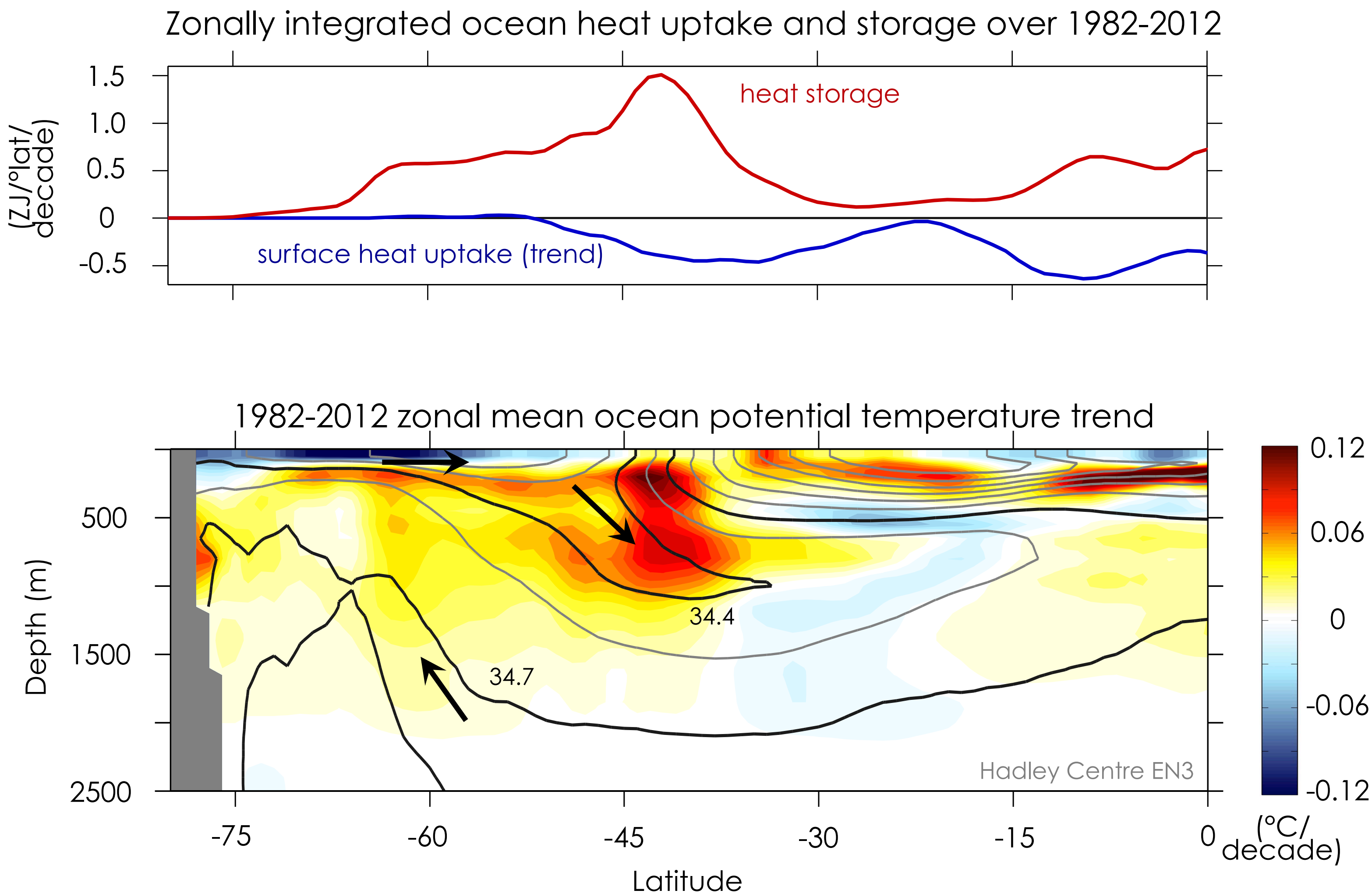
Observed Southern Ocean trends



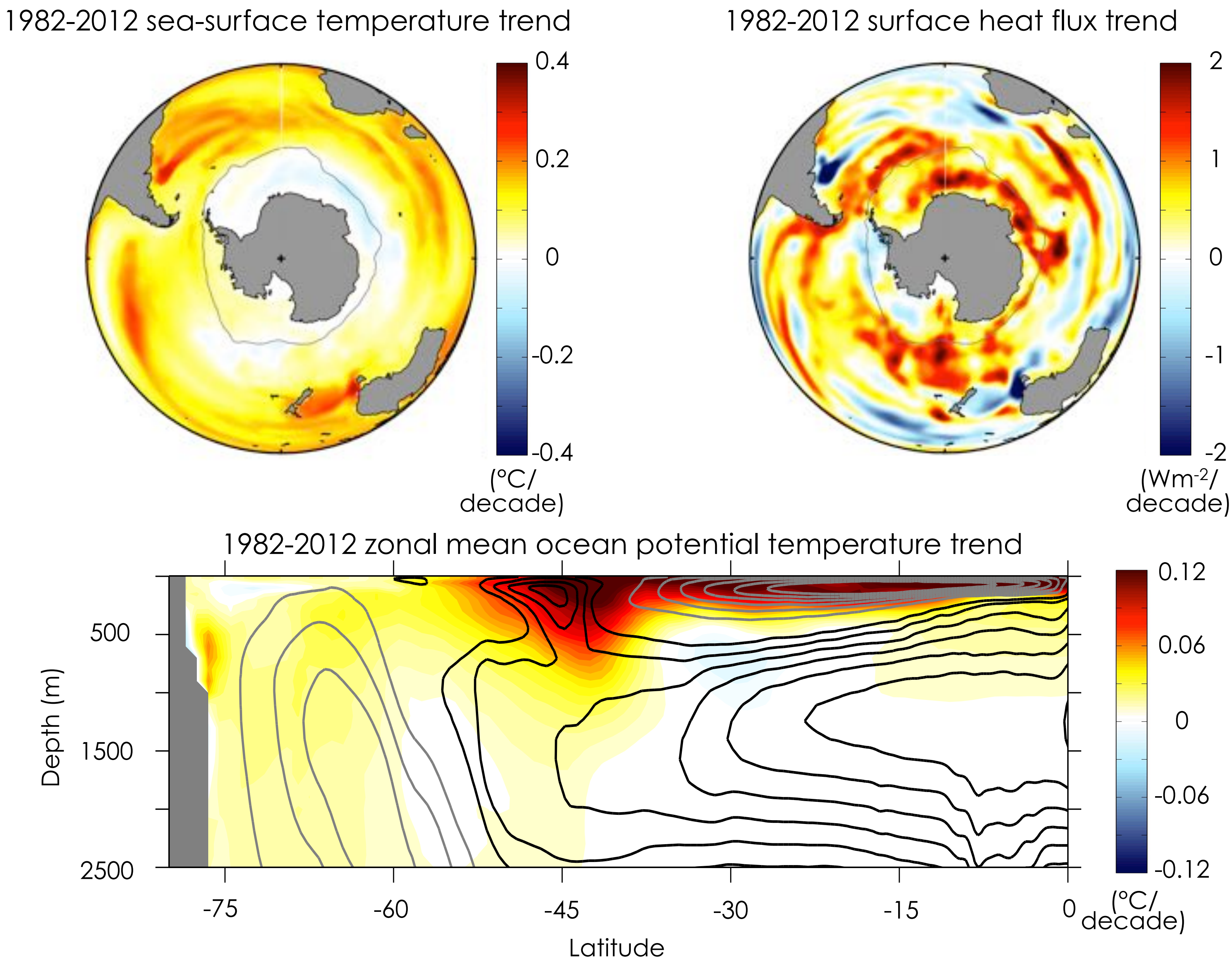
Karsten and Marshall (2002)



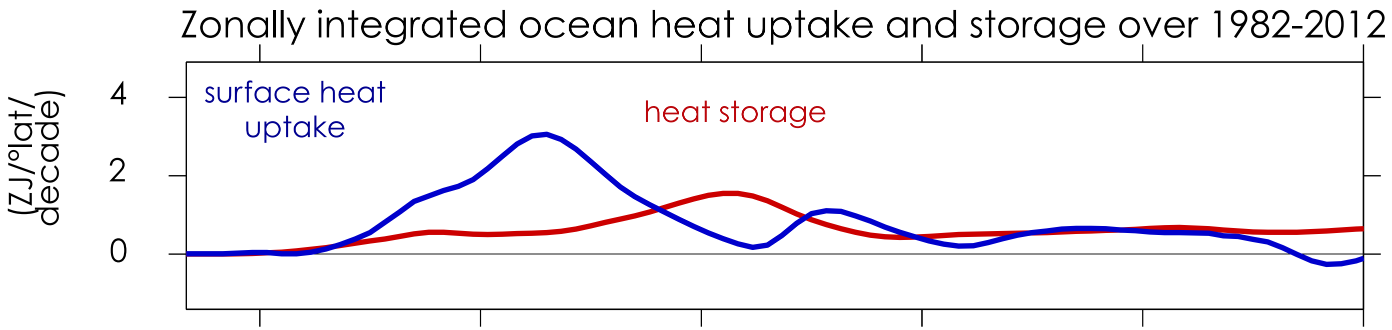
Observed Southern Ocean trends

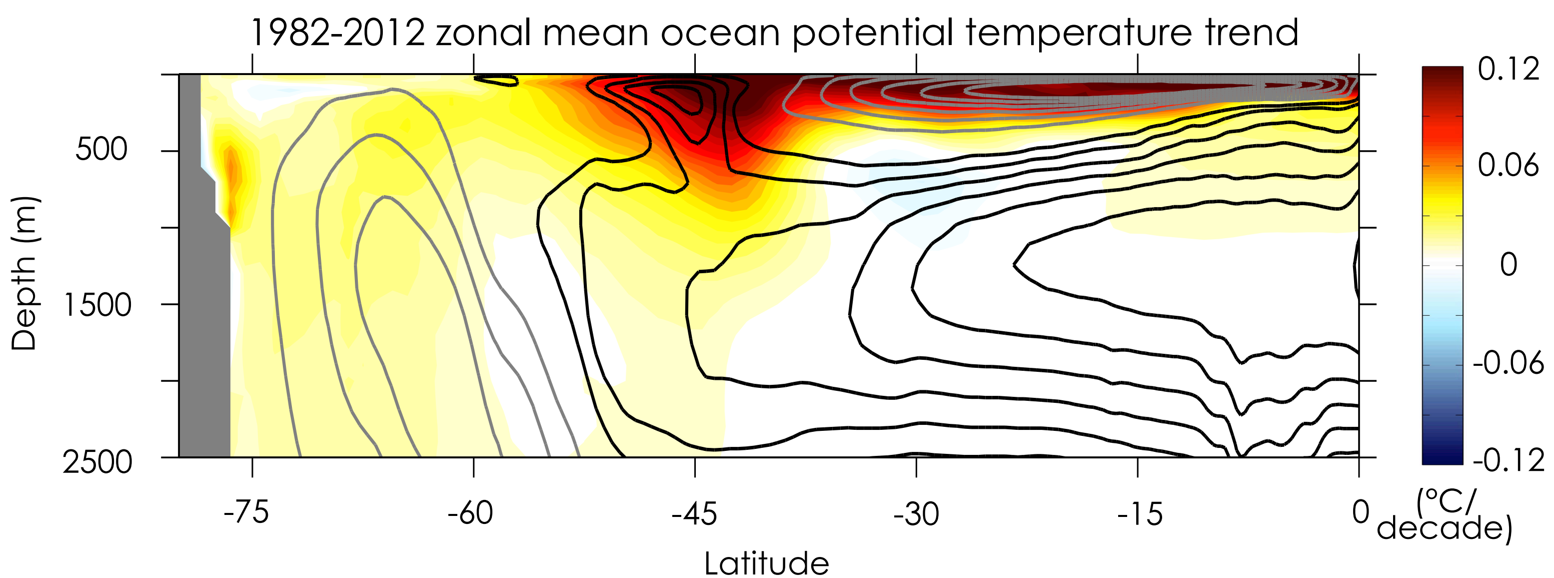


CMIP5 historical Southern Ocean trends

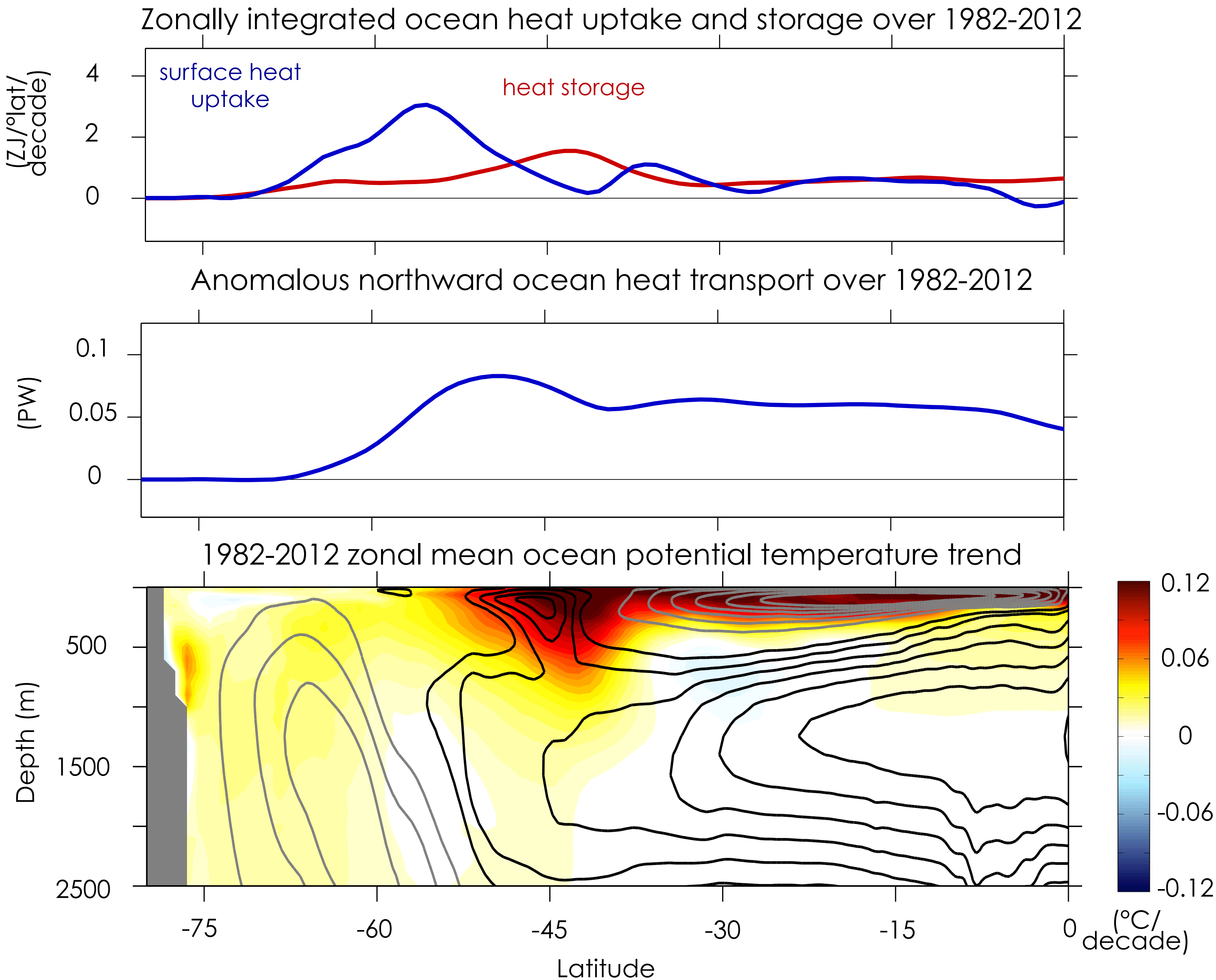


CMIP5 historical Southern Ocean trends

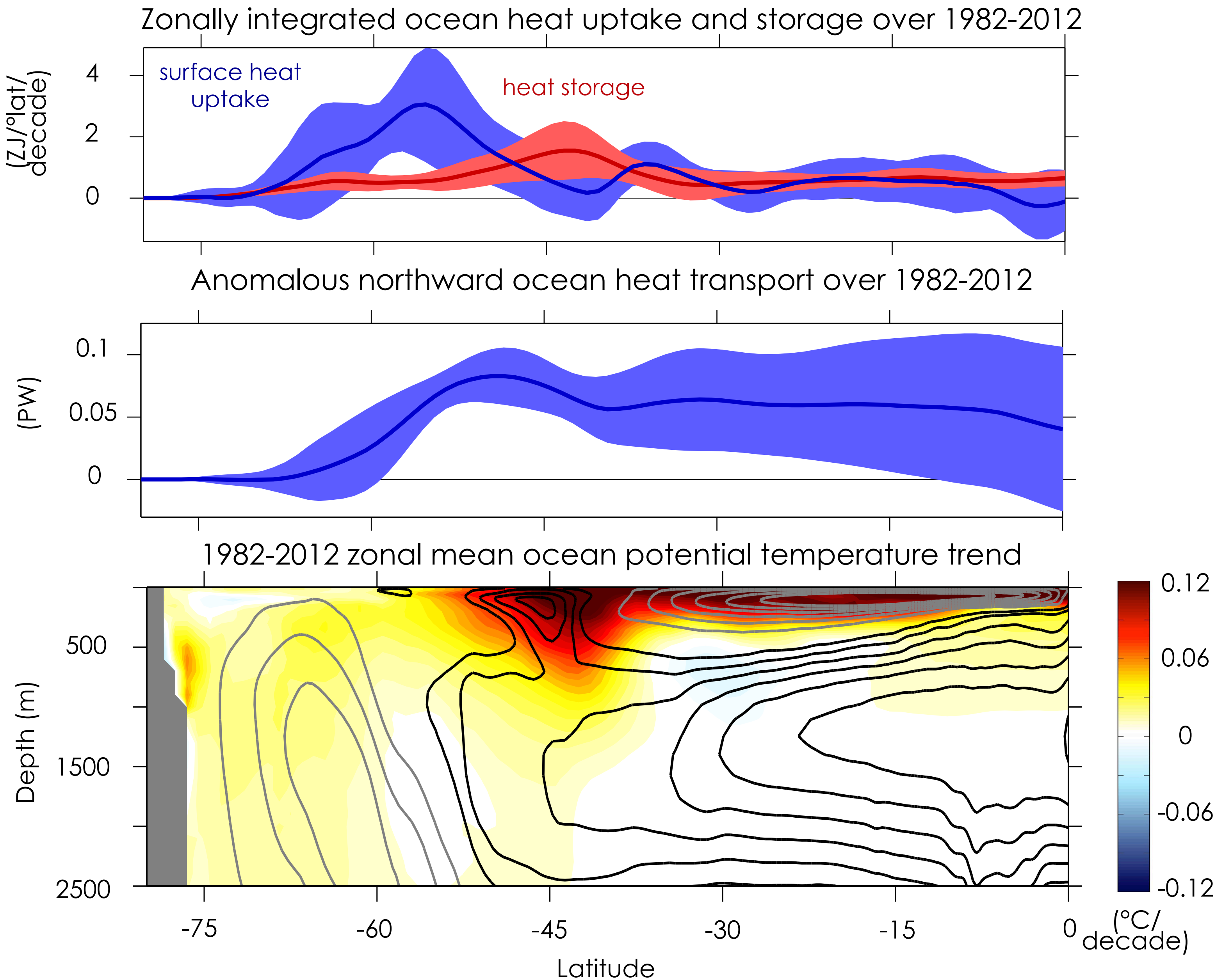




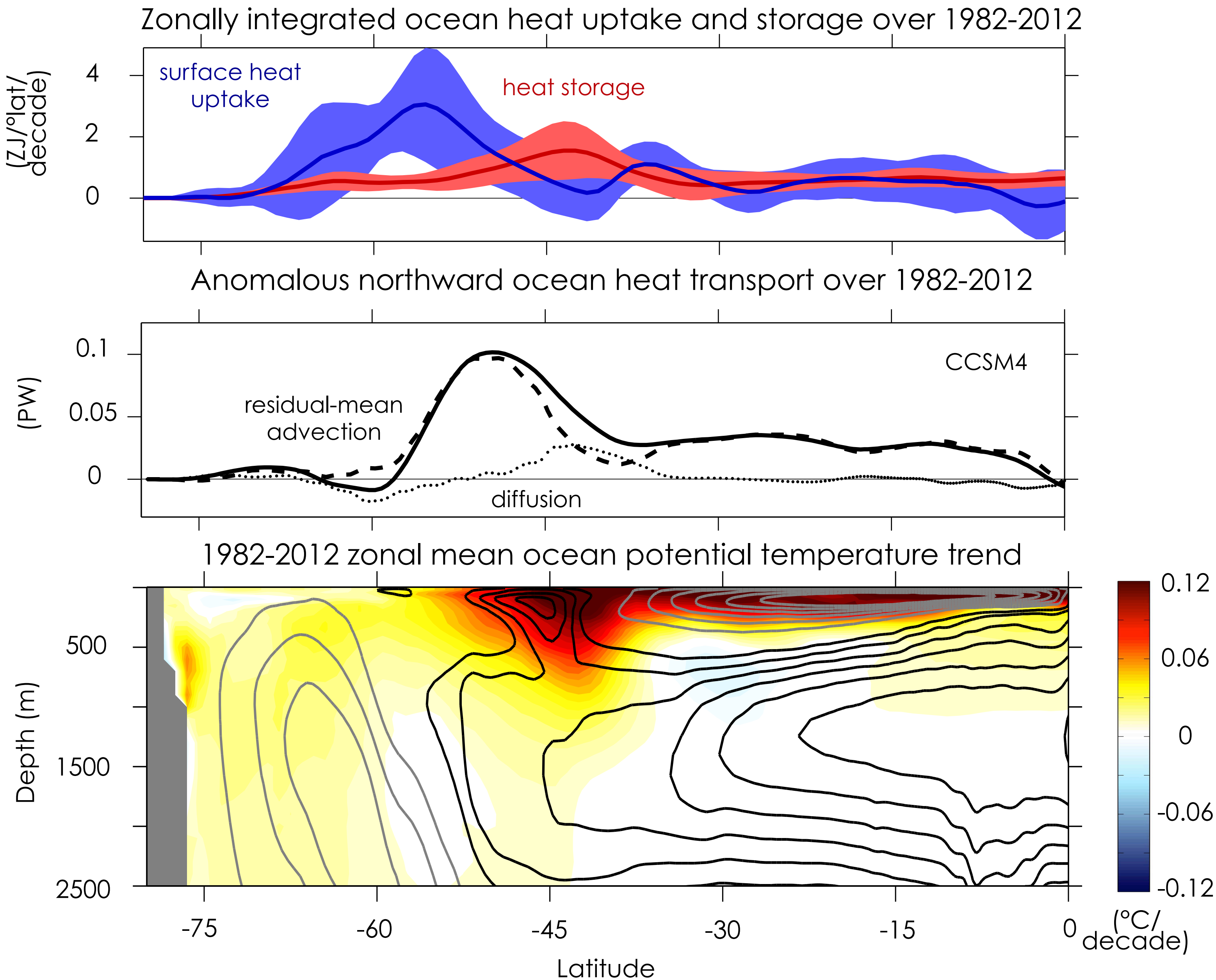
CMIP5 historical Southern Ocean trends



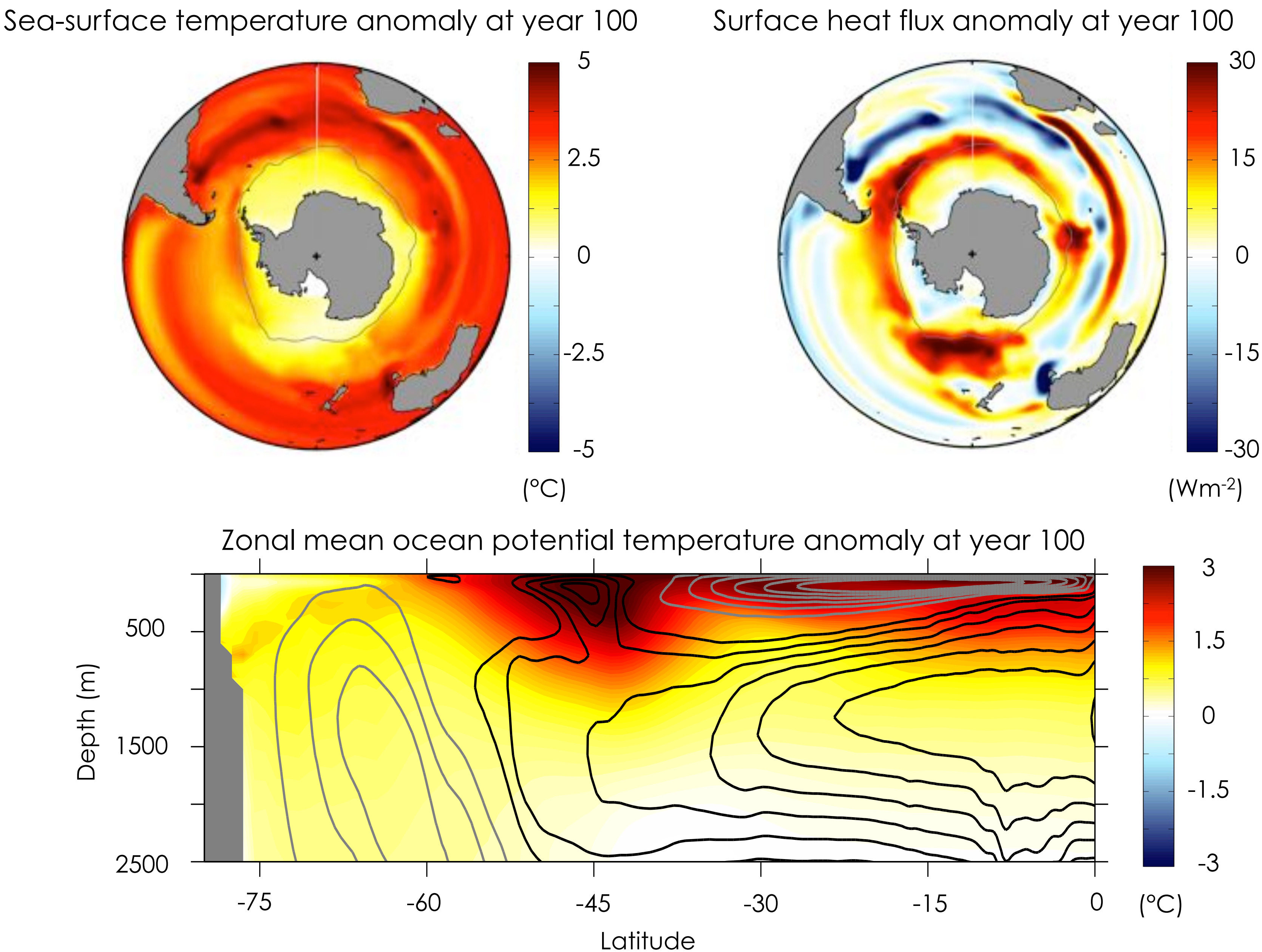
CMIP5 historical Southern Ocean trends



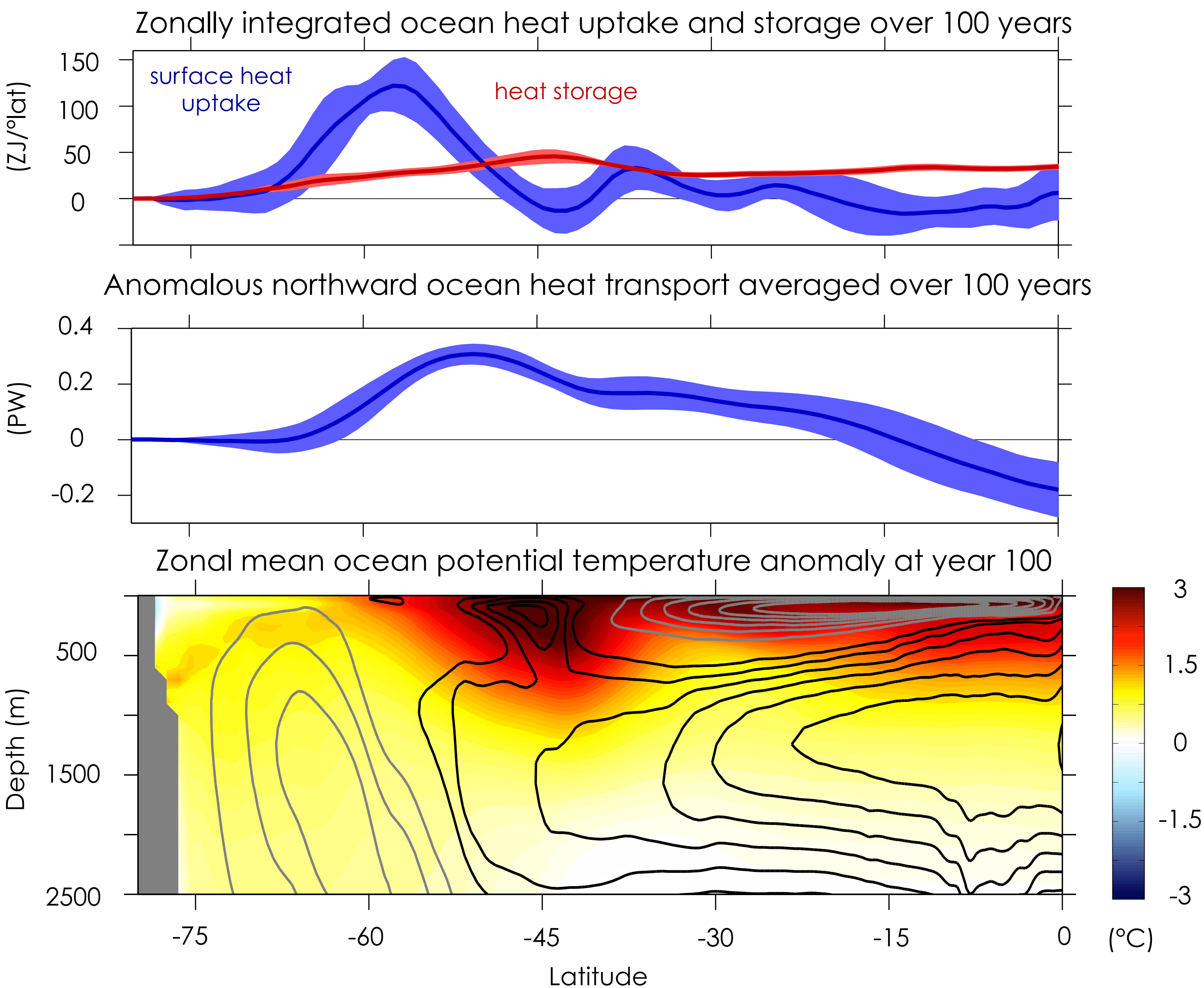
CMIP5 historical Southern Ocean trends



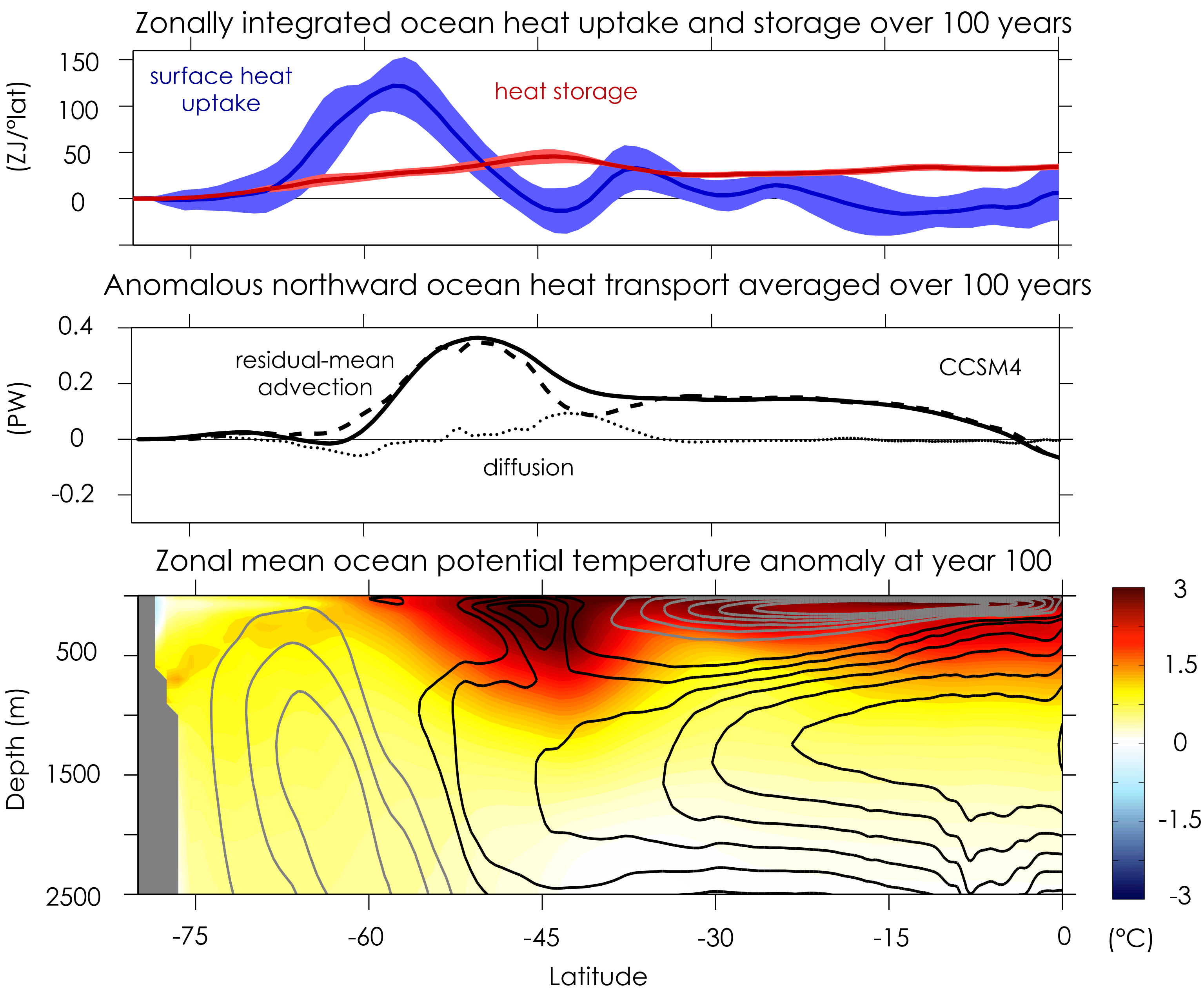
CMIP5 response to abrupt CO_2 forcing



CMIP5 response to abrupt CO_2 forcing



CMIP5 response to abrupt CO_2 forcing



Ocean-only MITgcm simulation

- Ocean-only simulation with the MITgcm
  - global ocean with realistic land geometry, 1° resolution
  - no atmosphere

- Model run to equilibrium with air-sea fluxes prescribed through bulk formulae -- CORE protocol of Griffies et al (2009), with an annually repeating cycle

Ocean-only MITgcm simulation

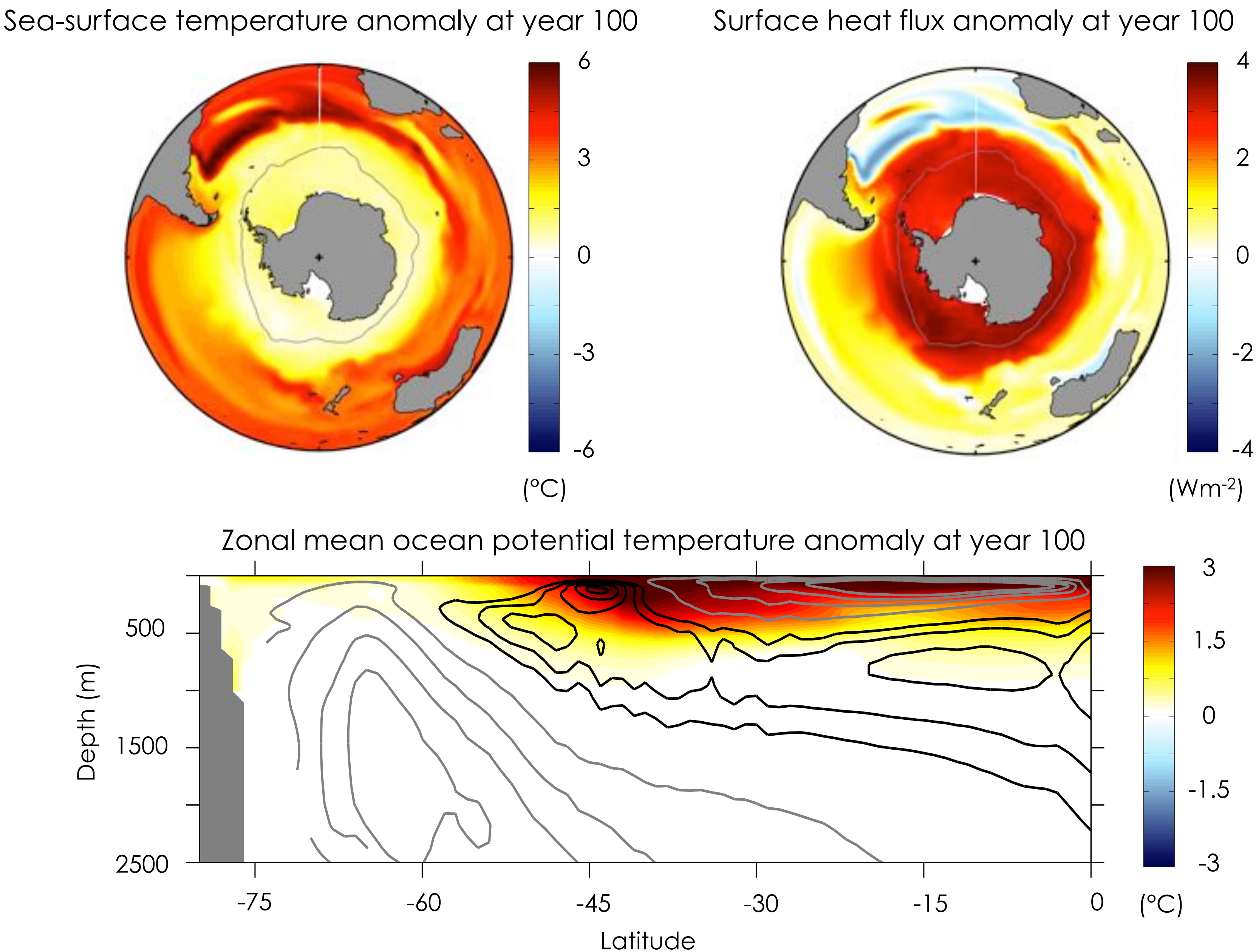
- Ocean-only simulation with the MITgcm
  - global ocean with realistic land geometry, 1° resolution
  - no atmosphere

- Model run to equilibrium with air-sea fluxes prescribed through bulk formulae -- CORE protocol of Griffies et al (2009), with an annually repeating cycle

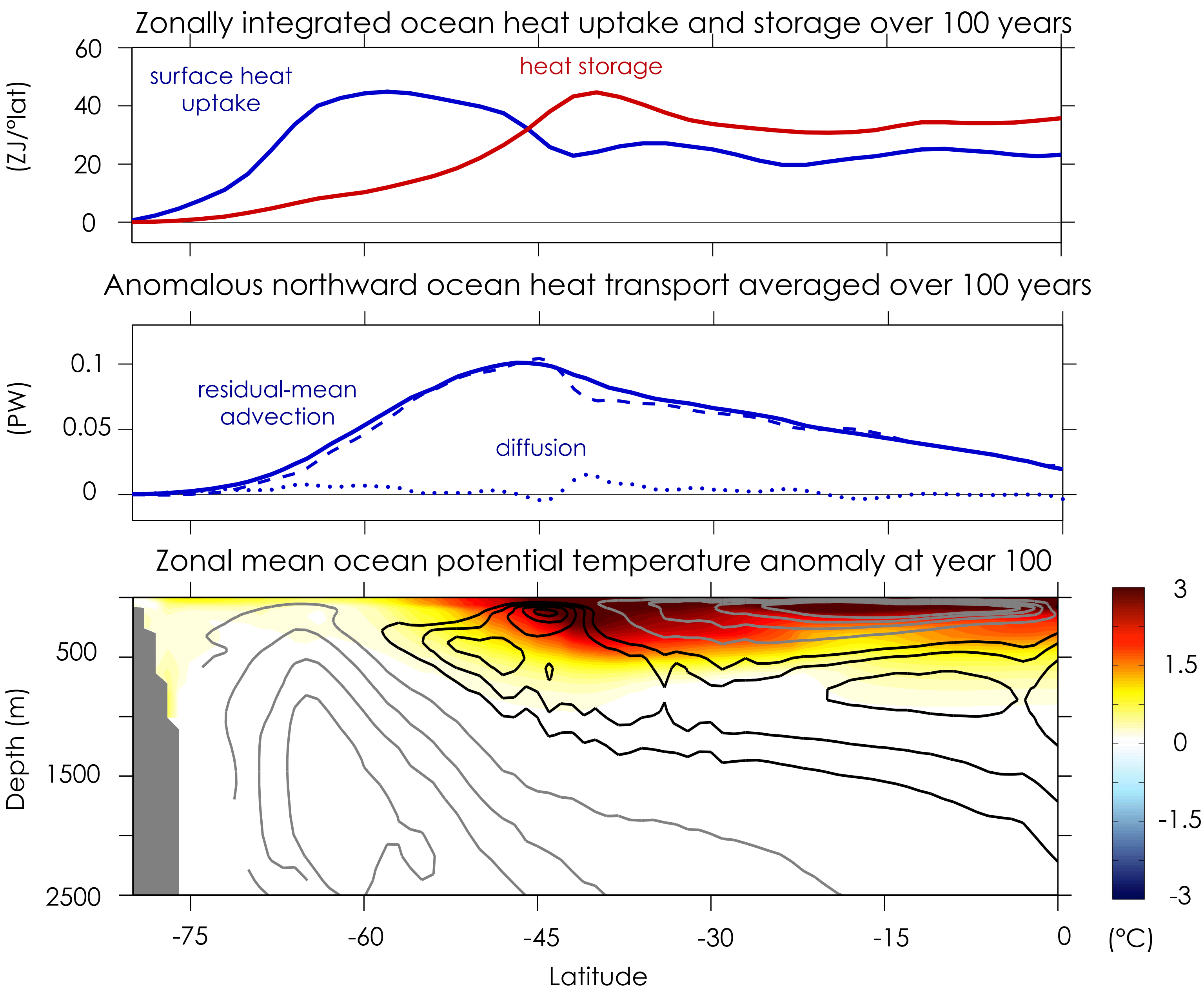
- Greenhouse gas forcing experiment:
  - Abrupt, uniform surface forcing of R = 4 Wm^{-2}
  - Uniform radiative feedback of equal to -1 $Wm^{-2}K^{-1}$
  - No other surface flux changes (wind, fresh water, etc)

→ *Any spatial structure in warming must arise from ocean circulation*

MITgcm response to abrupt CO_2 forcing



MITgcm response to abrupt CO_2 forcing



Ocean-only MITgcm simulation

- Ocean-only simulation with the MITgcm
  - global ocean with realistic land geometry, 1° resolution
  - no atmosphere

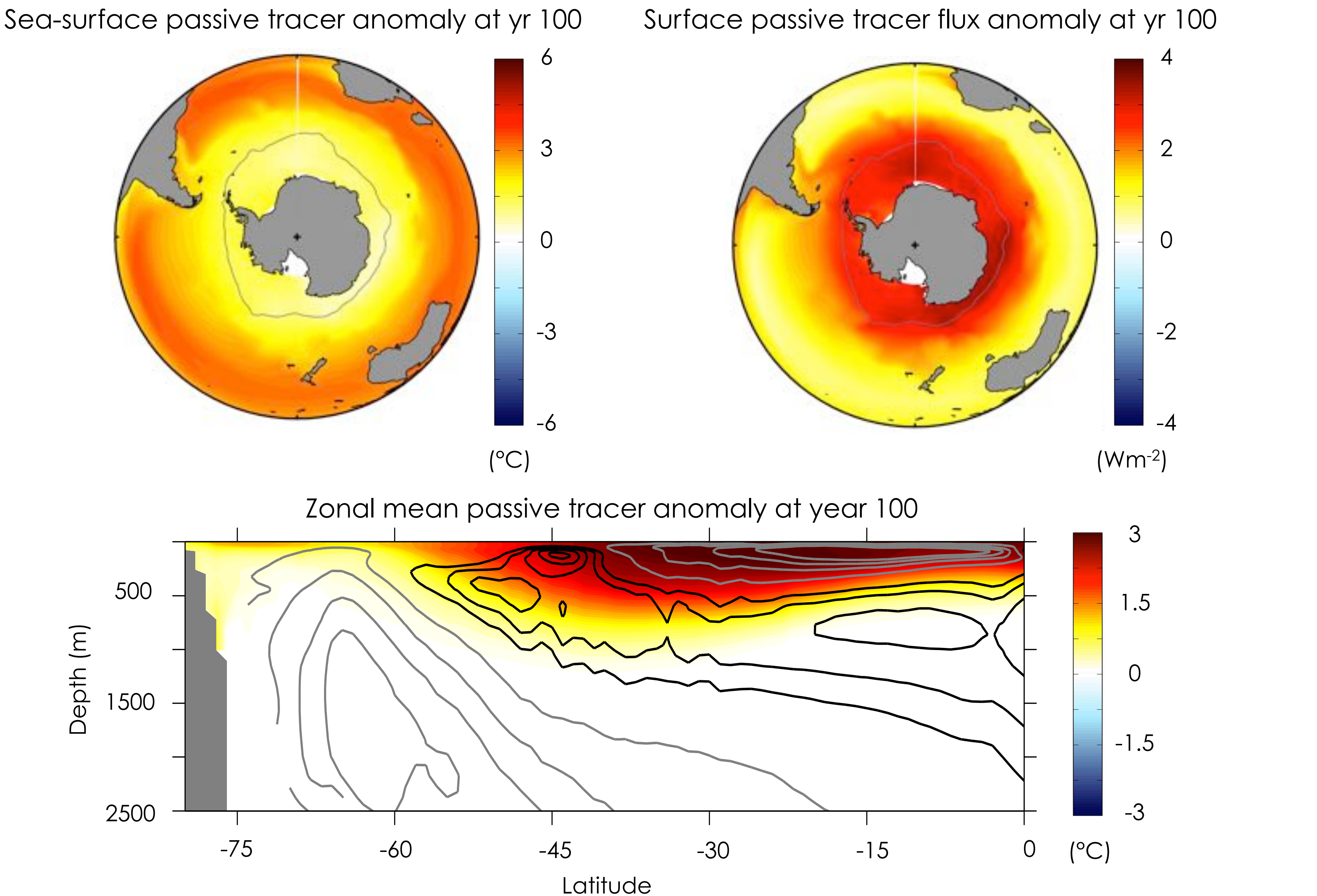
- Model run to equilibrium with air-sea fluxes prescribed through bulk formulae -- CORE protocol of Griffies et al (2009), with an annually repeating cycle

- Greenhouse gas forcing experiment:
  - Abrupt, uniform surface forcing of R = 4 Wm^{-2}
  - Uniform radiative feedback of equal to -1 $Wm^{-2}K^{-1}$
  - No other surface flux changes (wind, fresh water, etc)

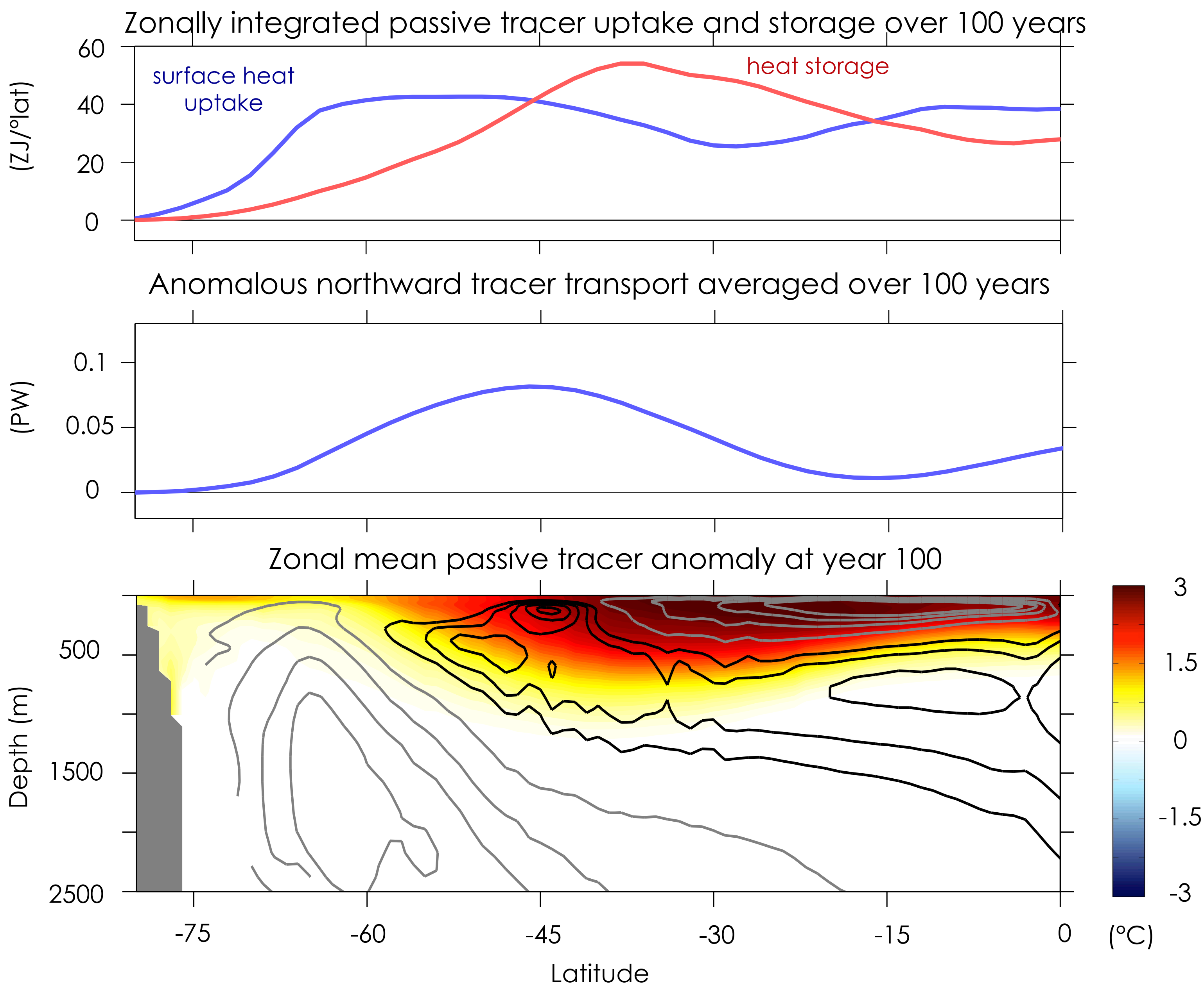
→ *Any spatial structure in warming must arise from ocean circulation*

- Compare to passive tracer uptake (units of temperature, initialized to background temperature distribution, forced and damped at the surface as in the greenhouse gas forcing experiment)

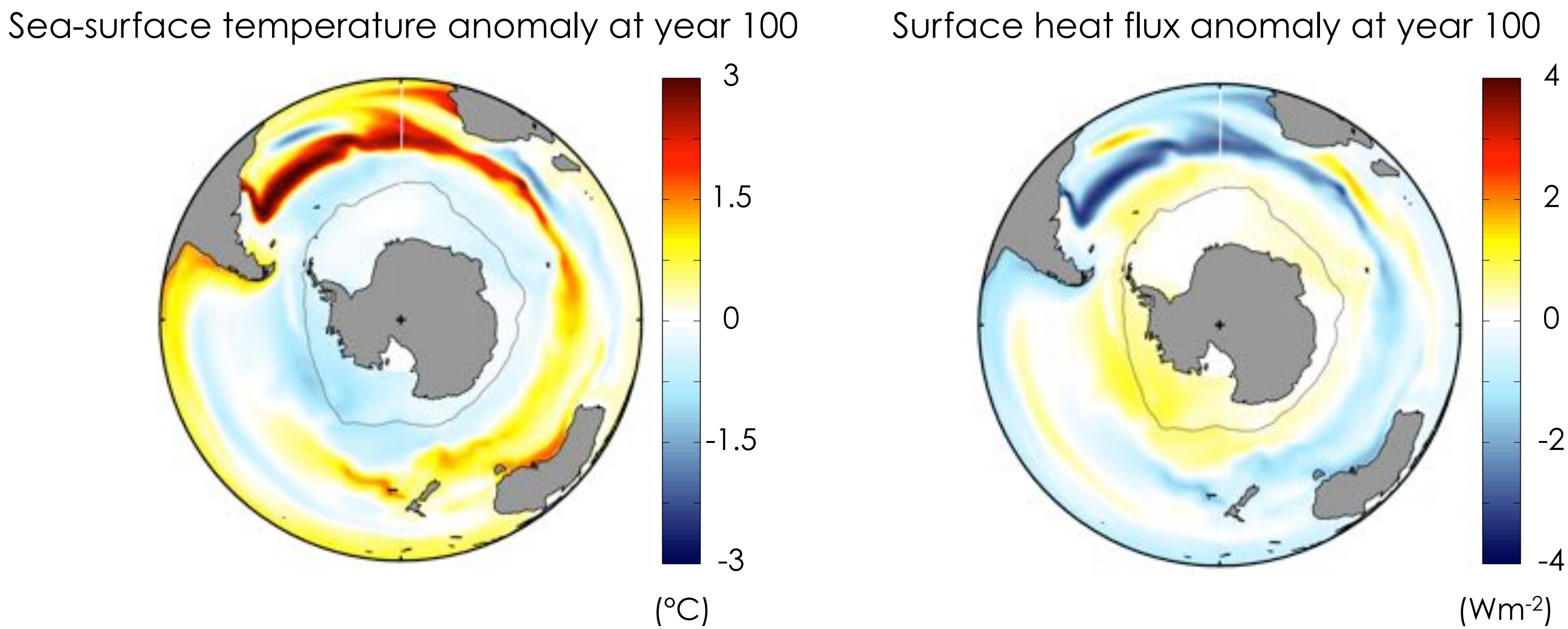
MITgcm passive tracer response to abrupt CO_2 forcing

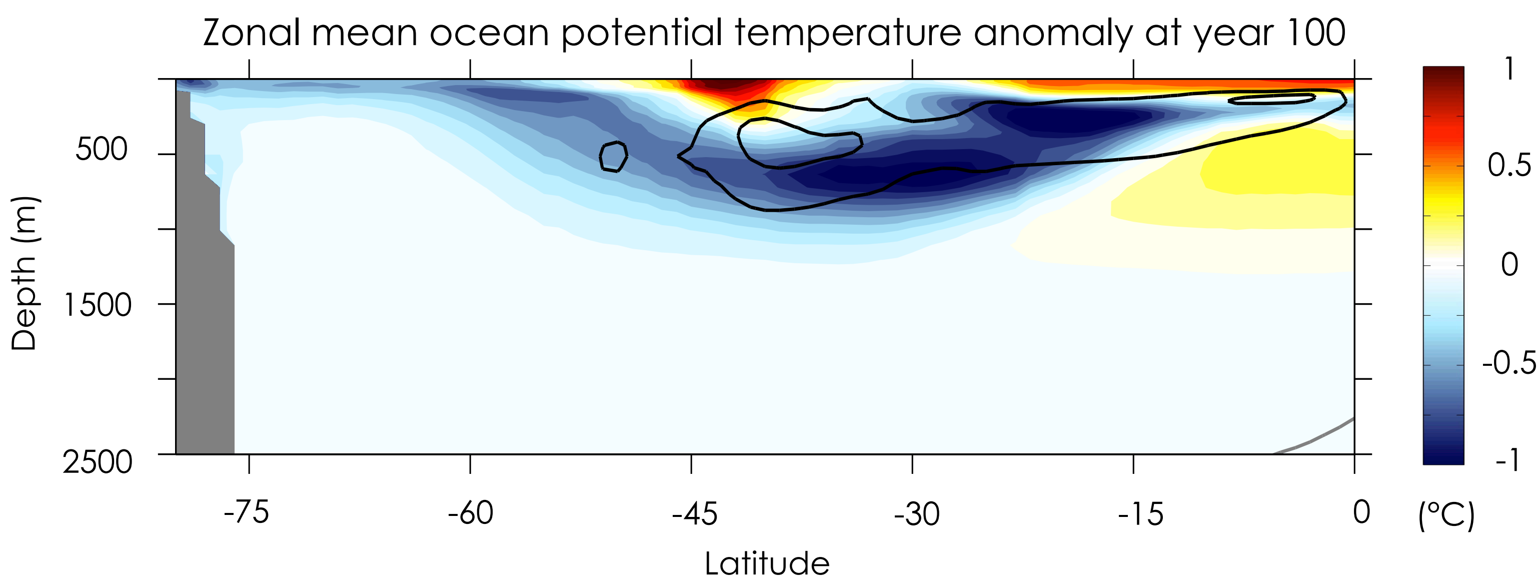


MITgcm passive tracer response to abrupt CO_2 forcing



MITgcm difference in response between active and passive heat uptake





Ocean-only MITgcm simulation

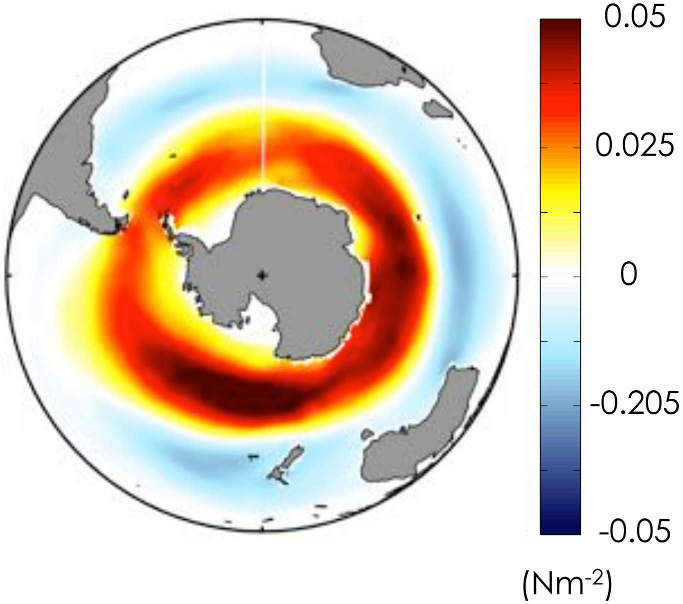
- Ocean-only simulation with the MITgcm
  - global ocean with realistic land geometry, 1° resolution
  - no atmosphere

- Model run to equilibrium with air-sea fluxes prescribed through bulk formulae -- CORE protocol of Griffies et al (2009), with an annually repeating cycle

- Wind forcing experiment
  - Abrupt perturbation to Southern Ocean surface winds (response to a step change in the Southern Annular Mode)
  - Wind stress on ocean only, no direct heat flux forcing, but uniform radiative feedback of equal to -1 $Wm^{-2}K^{-1}$

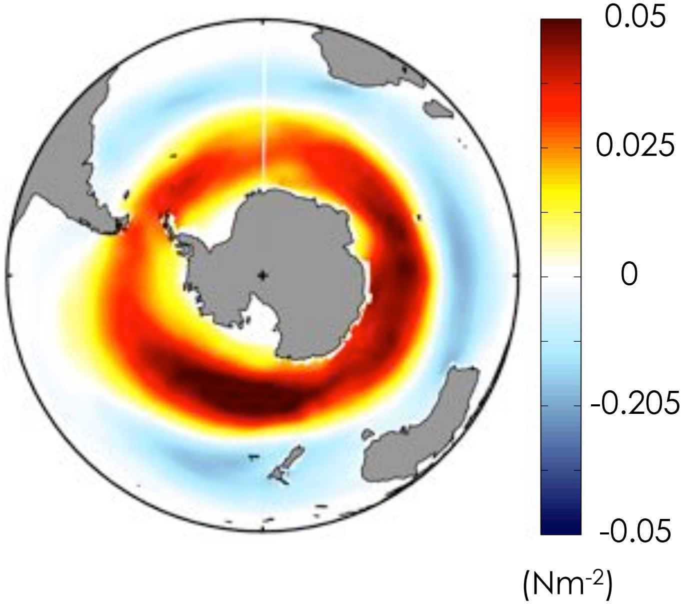
MITgcm response to abrupt wind forcing

SAM-like perturbation to surface wind stress

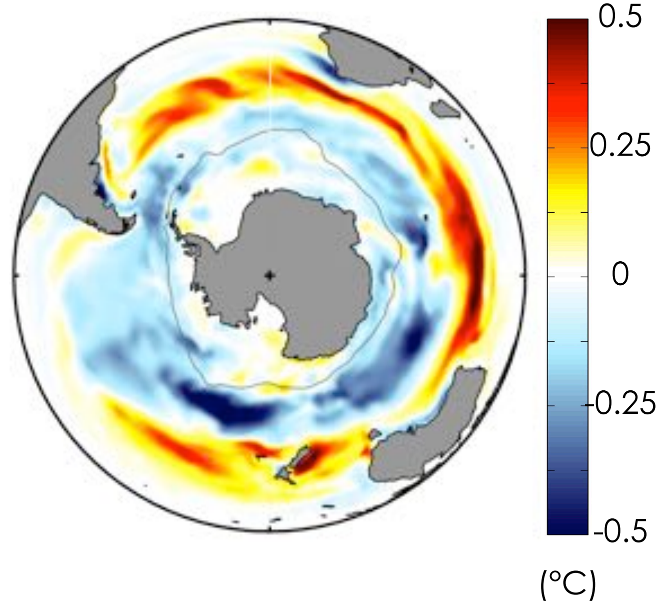


MITgcm response to abrupt wind forcing

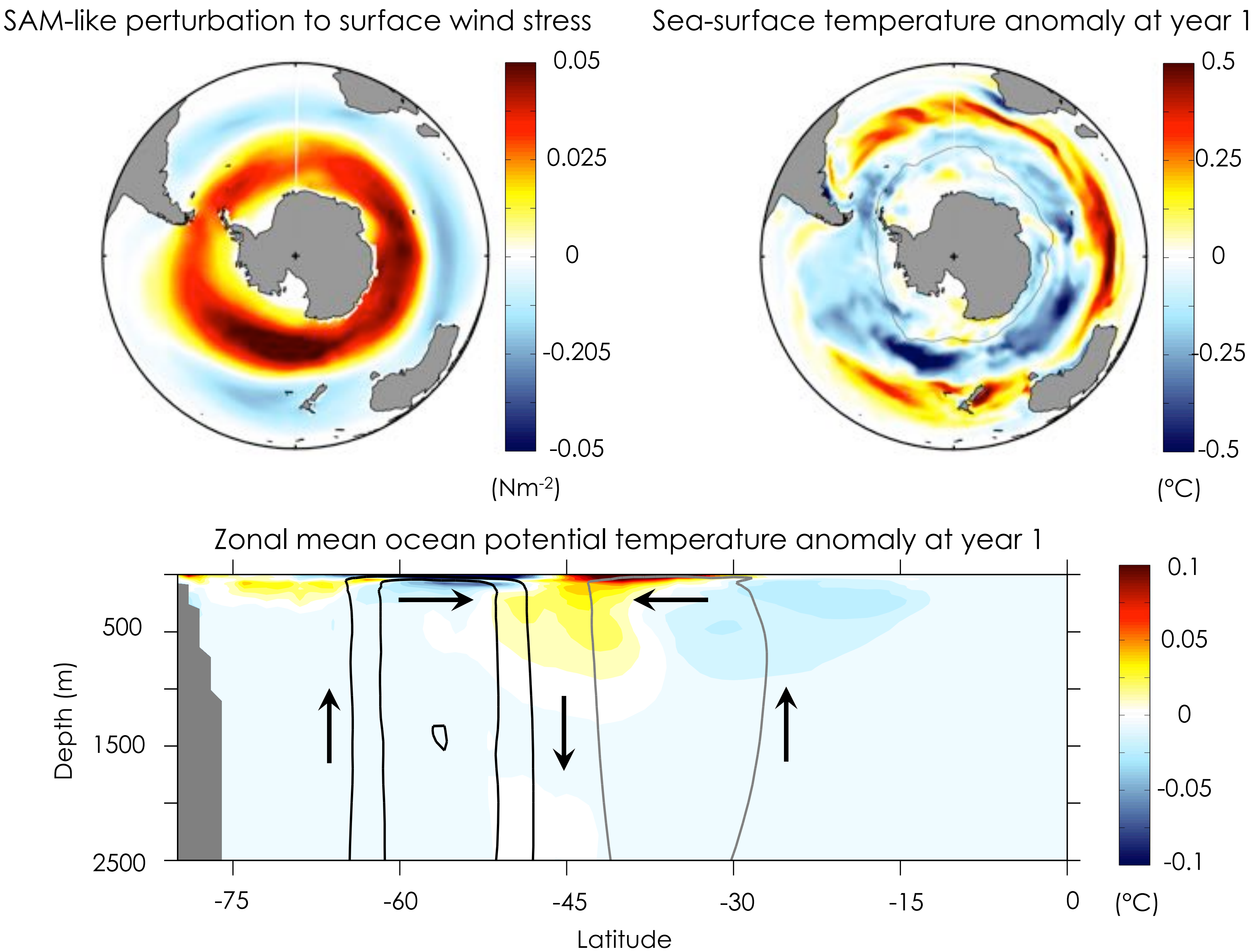
SAM-like perturbation to surface wind stress



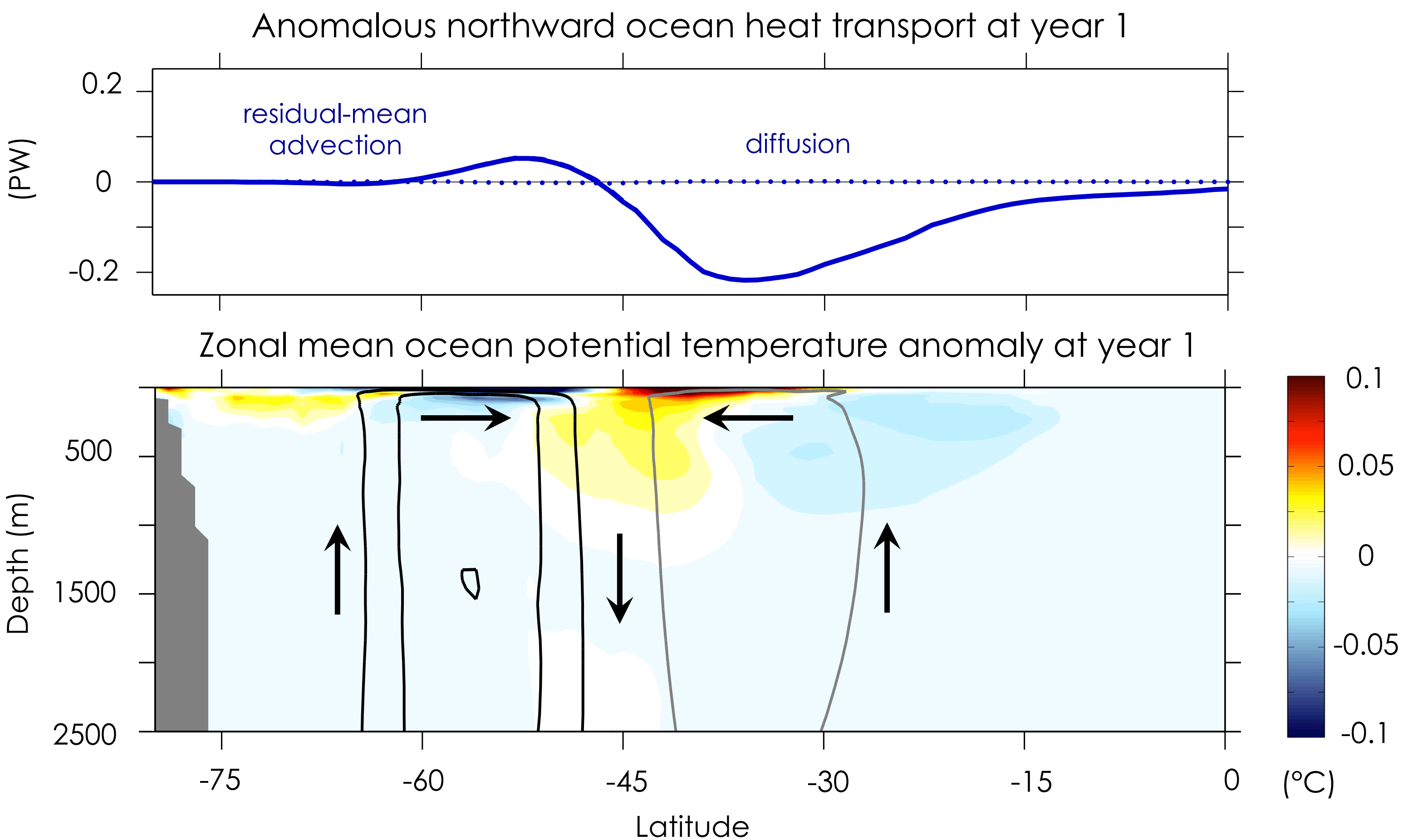
Sea-surface temperature anomaly at year 1



MITgcm response to abrupt wind forcing

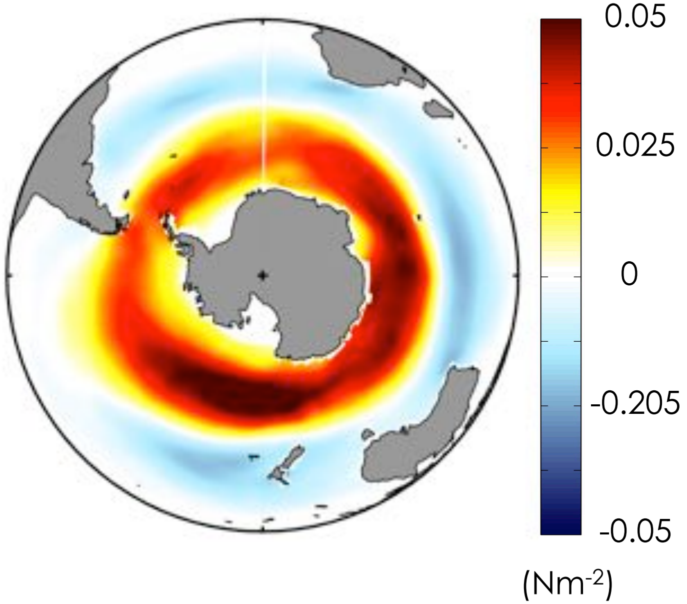


MITgcm response to abrupt wind forcing

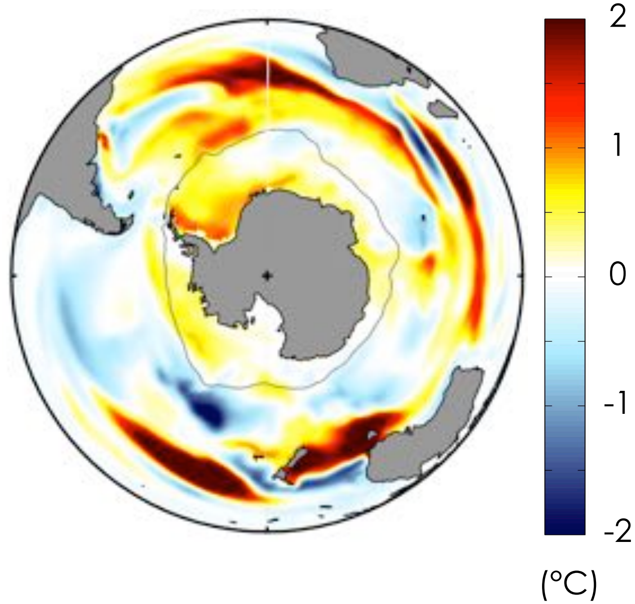


MITgcm response to abrupt wind forcing

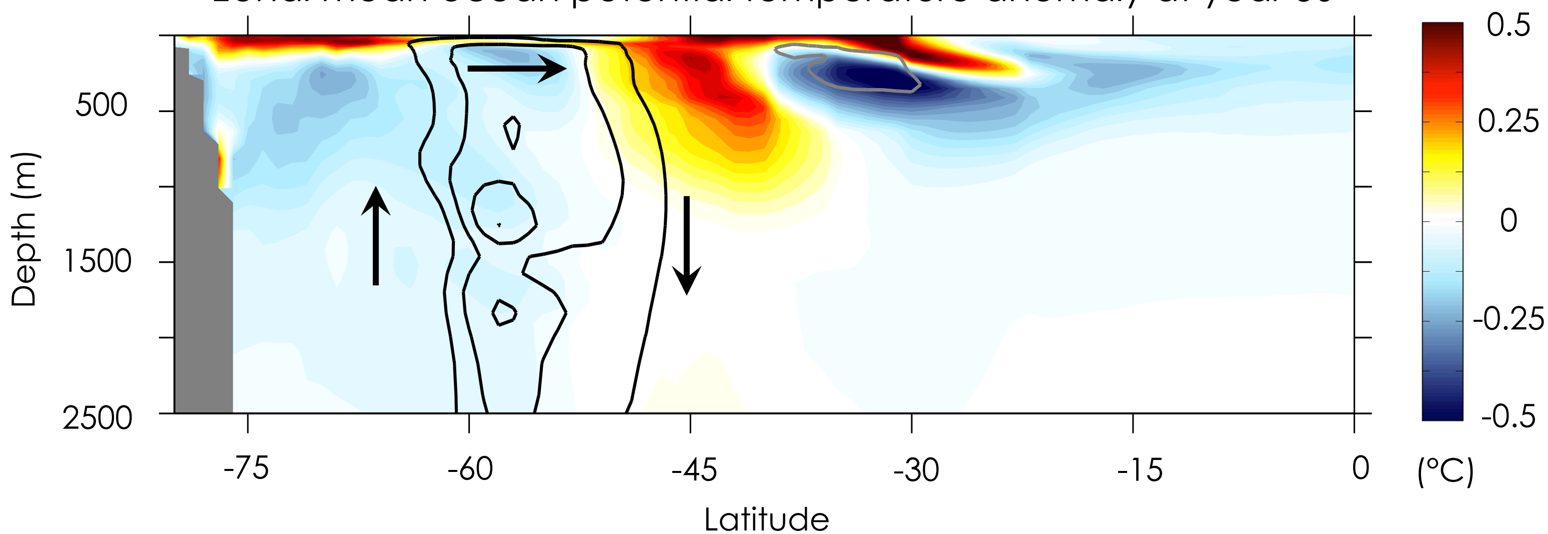
SAM-like perturbation to surface wind stress



Sea-surface temperature anomaly at year 30

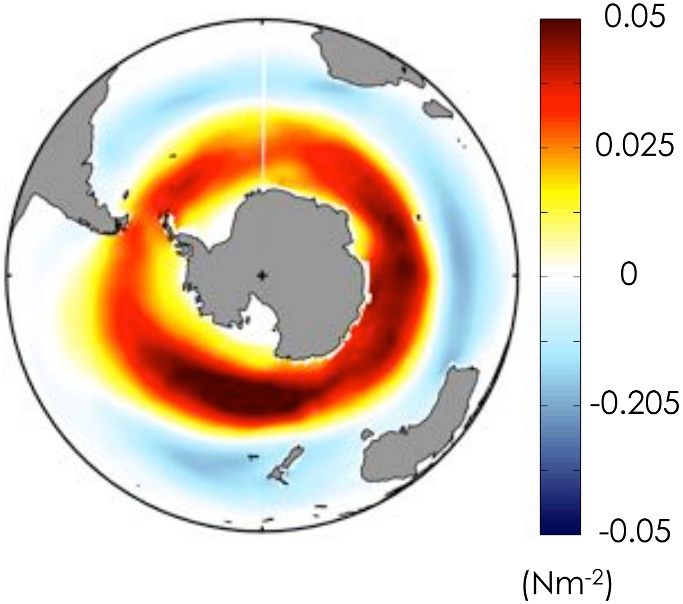


Zonal mean ocean potential temperature anomaly at year 30

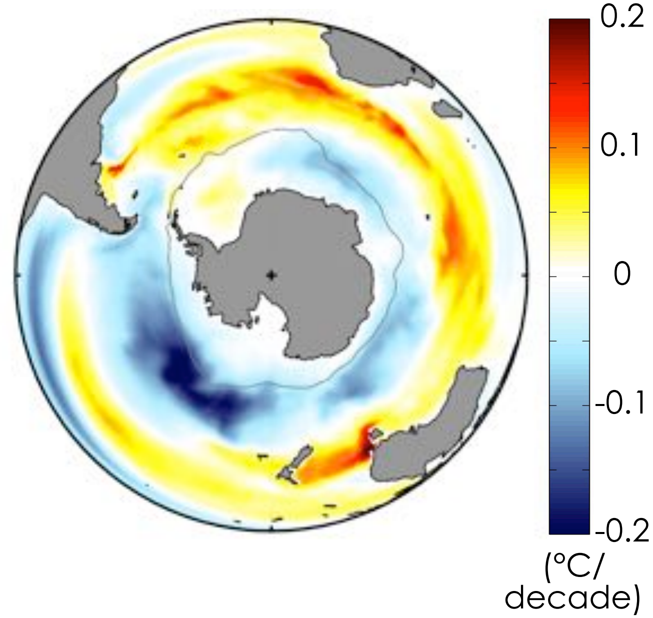


Internal variability in CMIP5 pre-industrial control simulations

Natural variations in surface winds



30-yr sea-surface temperature trend

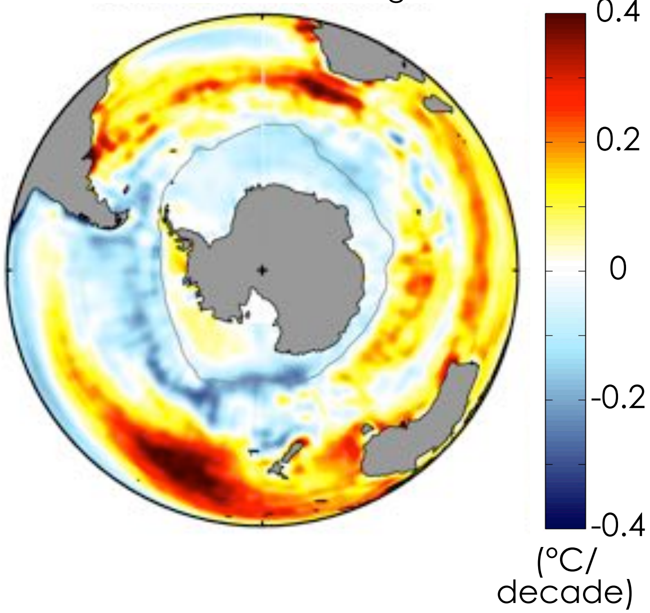


- Composite of 30 year sea-surface temperature trends congruent with large 30 year trends in surface winds (internal SAM variability), normalized to observed wind trend over last 30 years

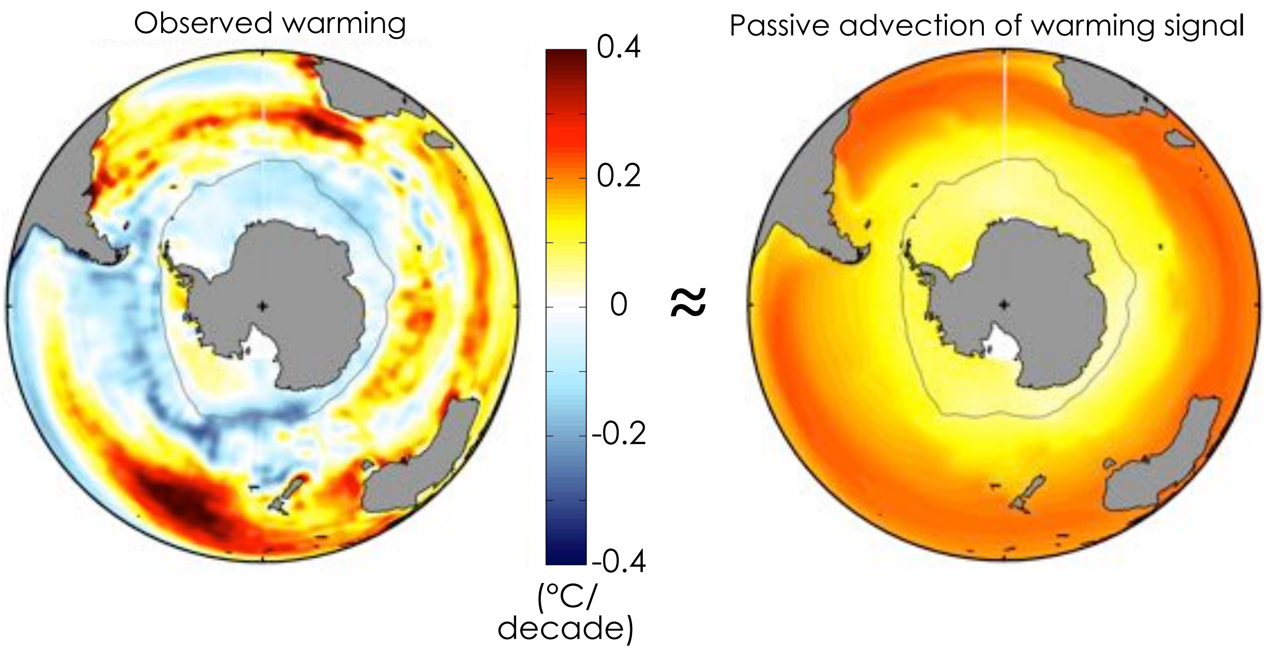
Kostov et al, in prep

Summary

Observed warming

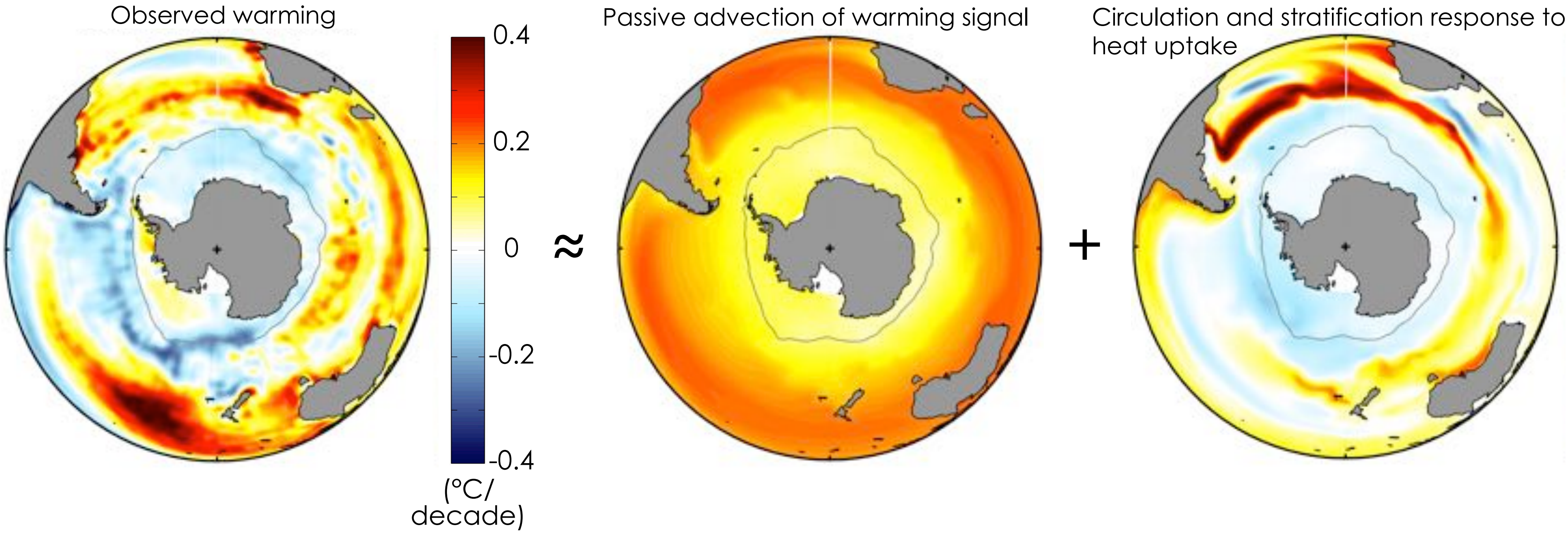


Summary



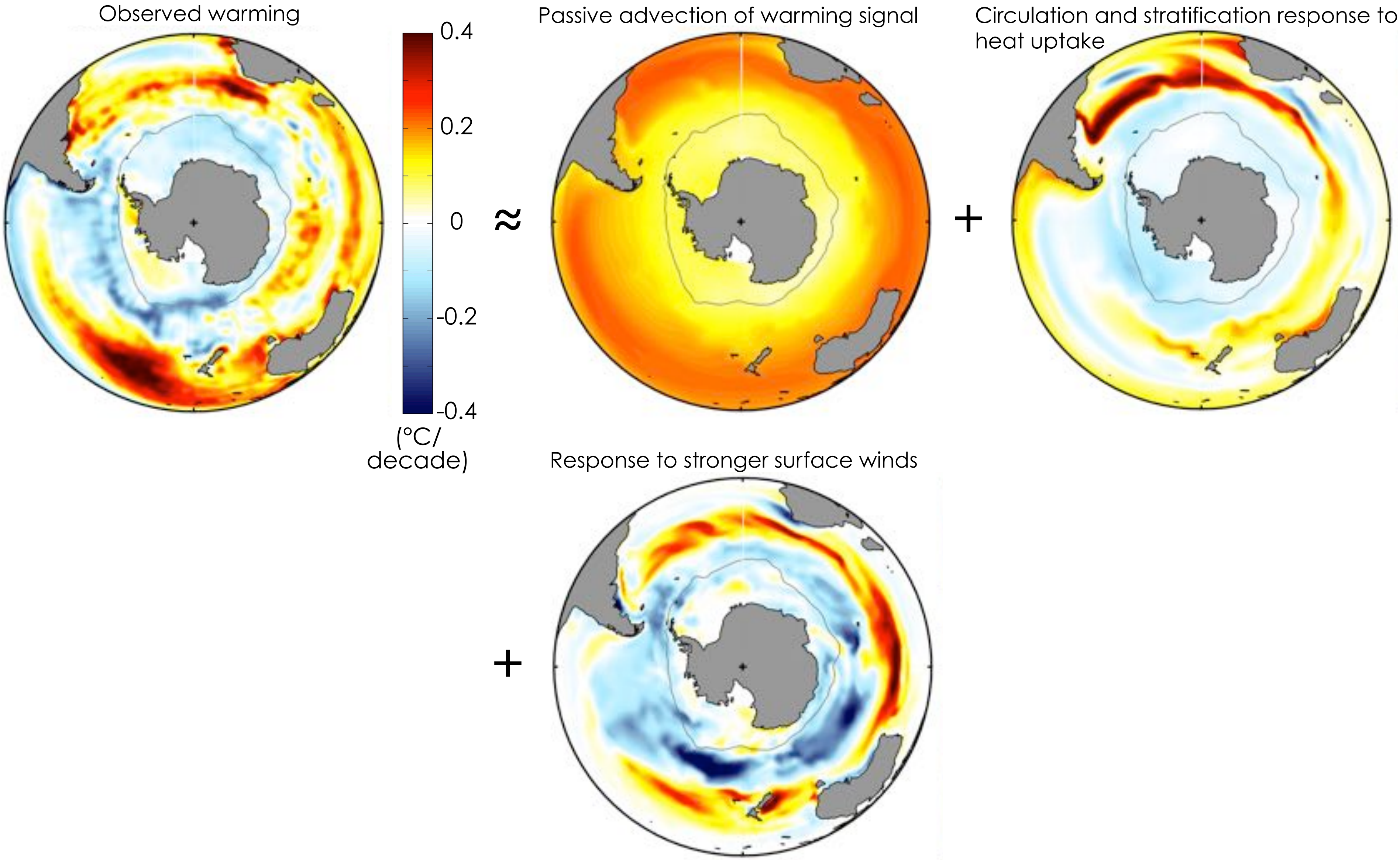
Observed warming
0.4
0.2
0
-0.2
-0.4
(°C/
decade)
≈
Passive advection of warming signal

Summary

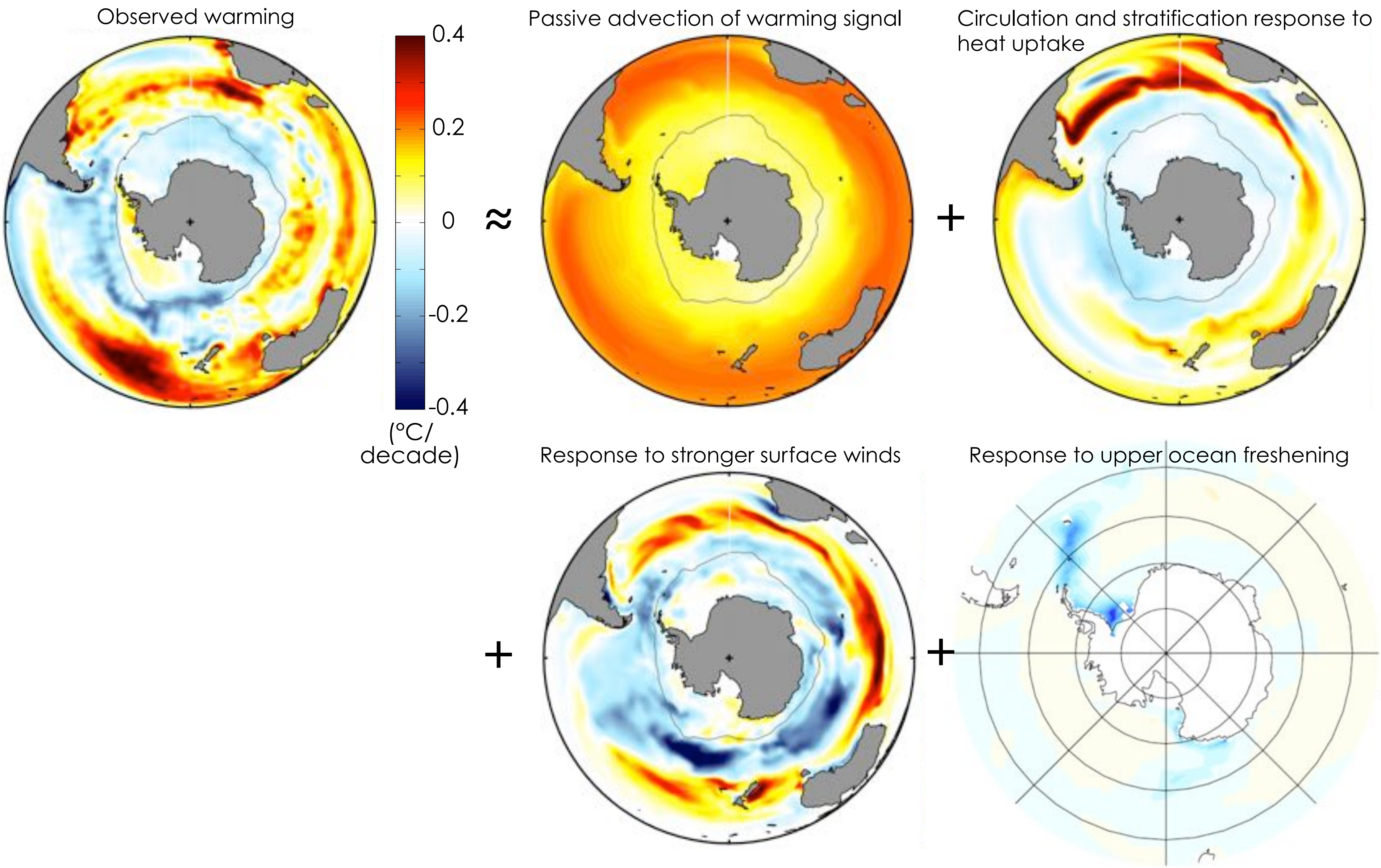


Observed warming
0.4
0.2
0
-0.2
-0.4
(°C/
decade)
≈
Passive advection of warming signal
+
Circulation and stratification response to
heat uptake

Summary


Observed warming
0.4
0.2
0
-0.2
-0.4
(°C/ decade)
≈
Passive advection of warming signal
+
Circulation and stratification response to heat uptake
+
Response to stronger surface winds

Summary

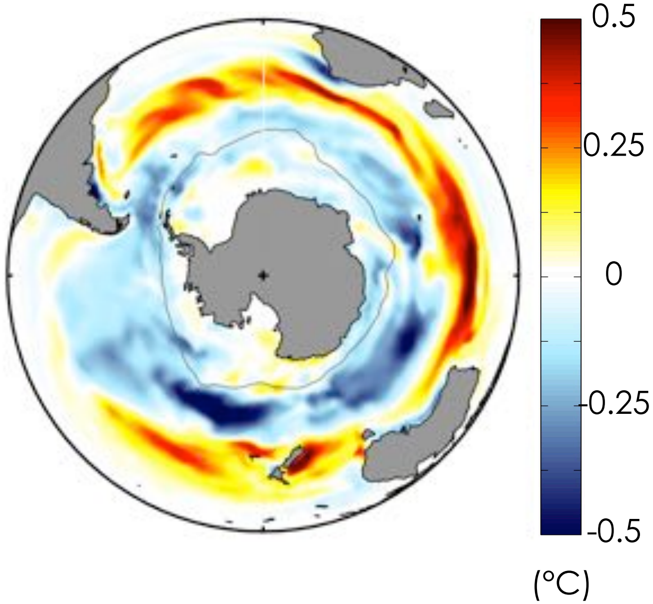


Bintanja et al 2013
(but see Swart and Fyfe 2013)

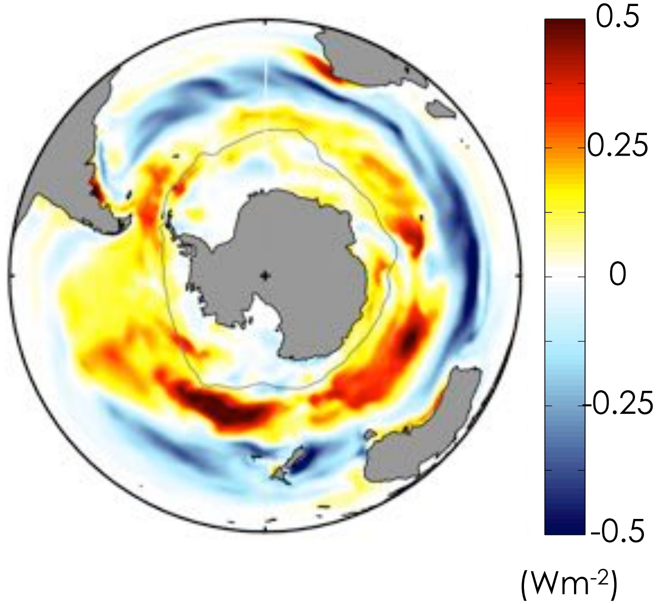
bonus slides

MITgcm response to abrupt wind forcing

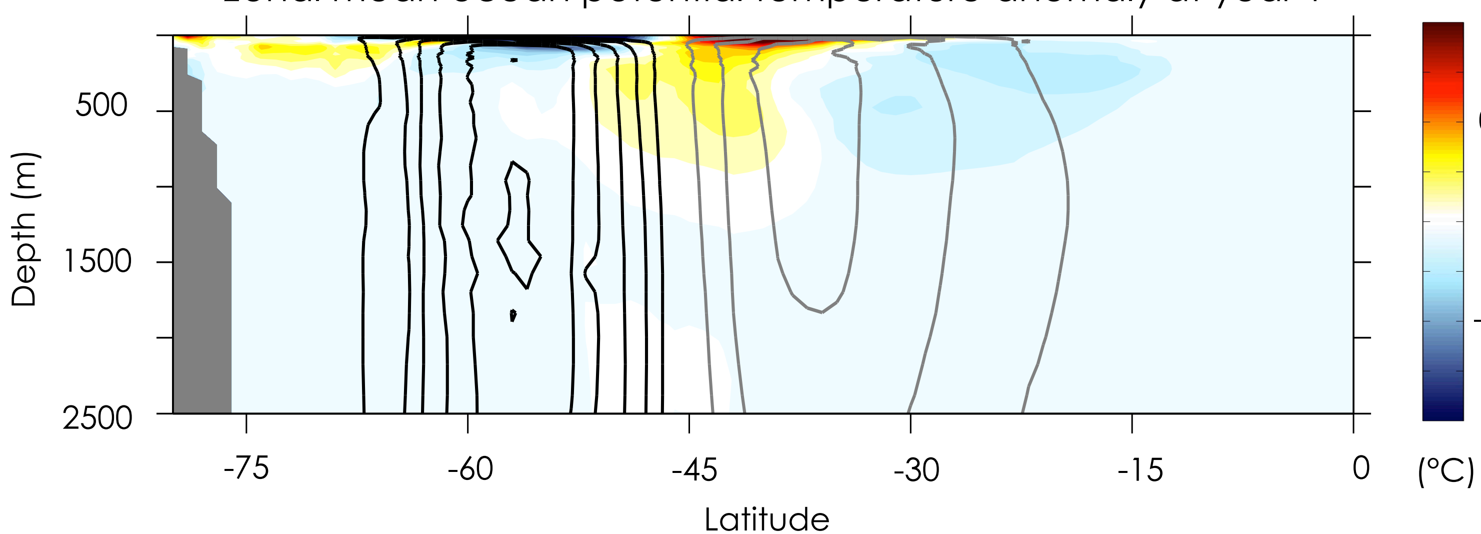
Sea-surface temperature anomaly at year 1



Surface heat flux anomaly at year 1

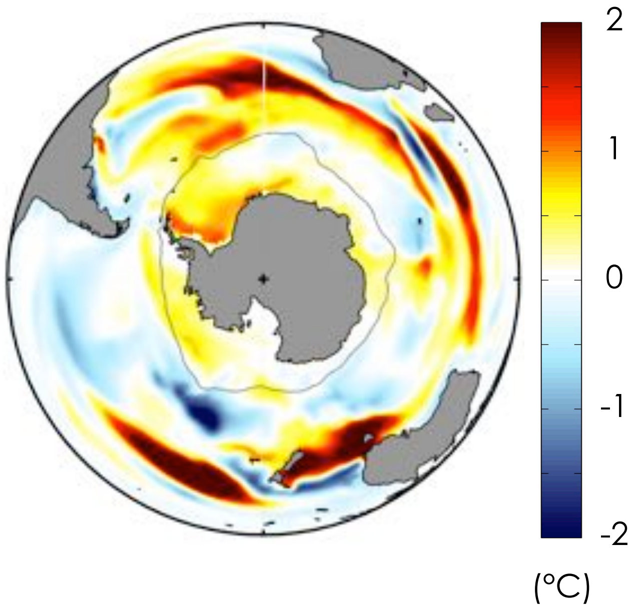


Zonal mean ocean potential temperature anomaly at year 1

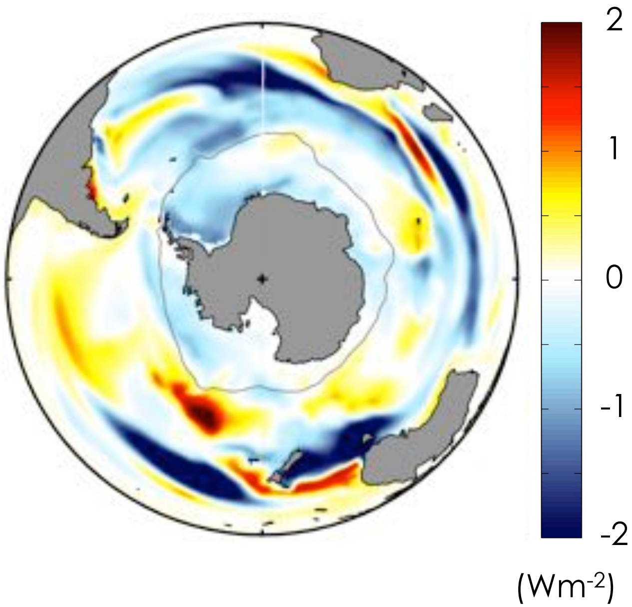


MITgcm response to abrupt wind forcing

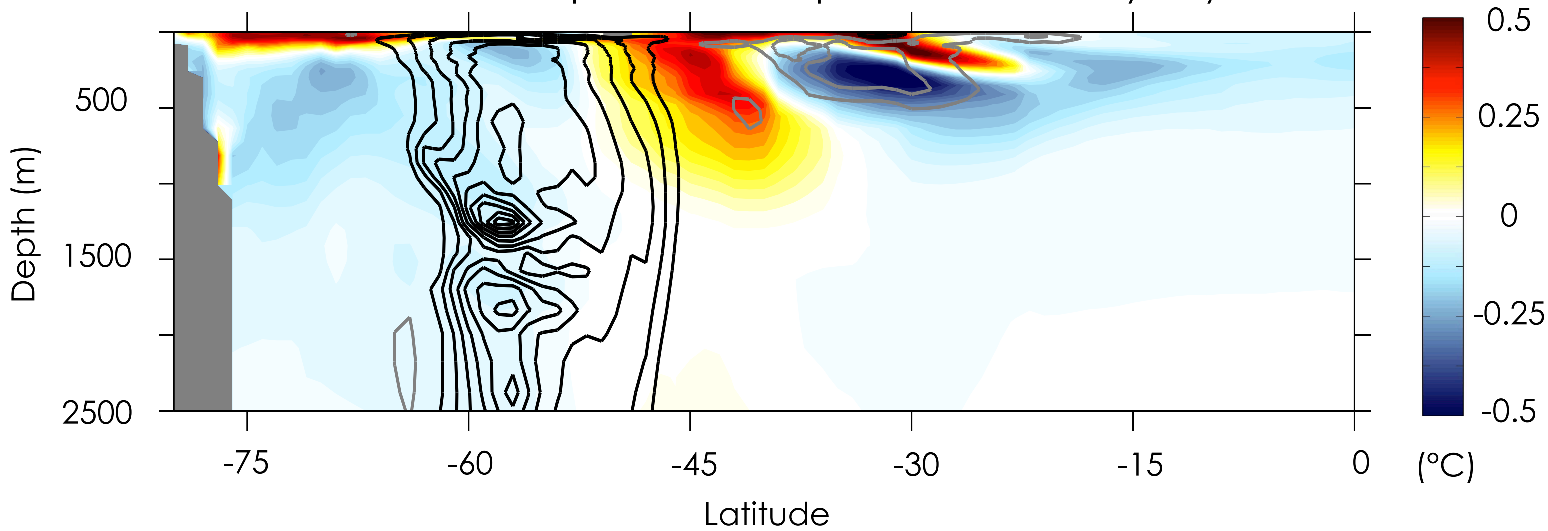
Sea-surface temperature anomaly at year 30



Surface heat flux anomaly at year 30



Zonal mean ocean potential temperature anomaly at year 30



MITgcm response to abrupt wind forcing