Southern Ocean overturning compensation in an eddy-resolving climate simulation

Stuart P. Bishop
North Carolina State University

Collaborators:
Peter Gent, **Frank Bryan**, **Matt Long** (NCAR)
Andy Thompson (Caltech)
Ryan Abernathey (Columbia)

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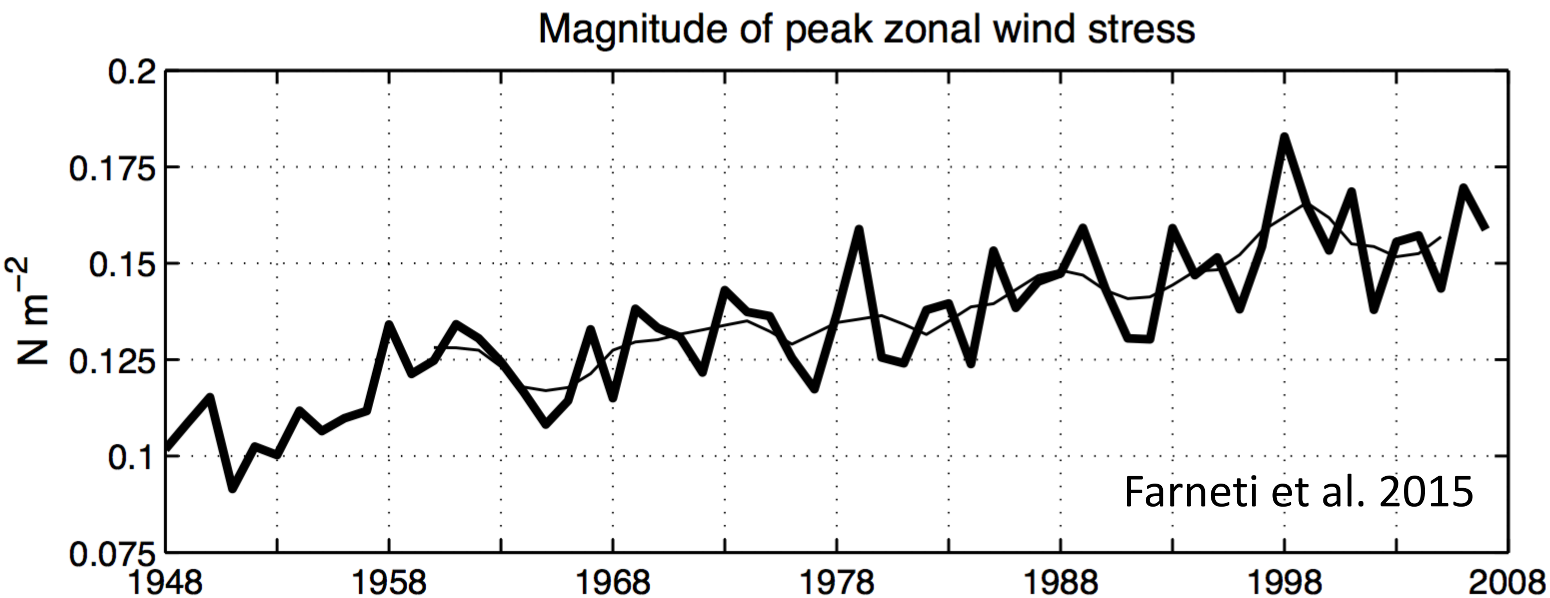
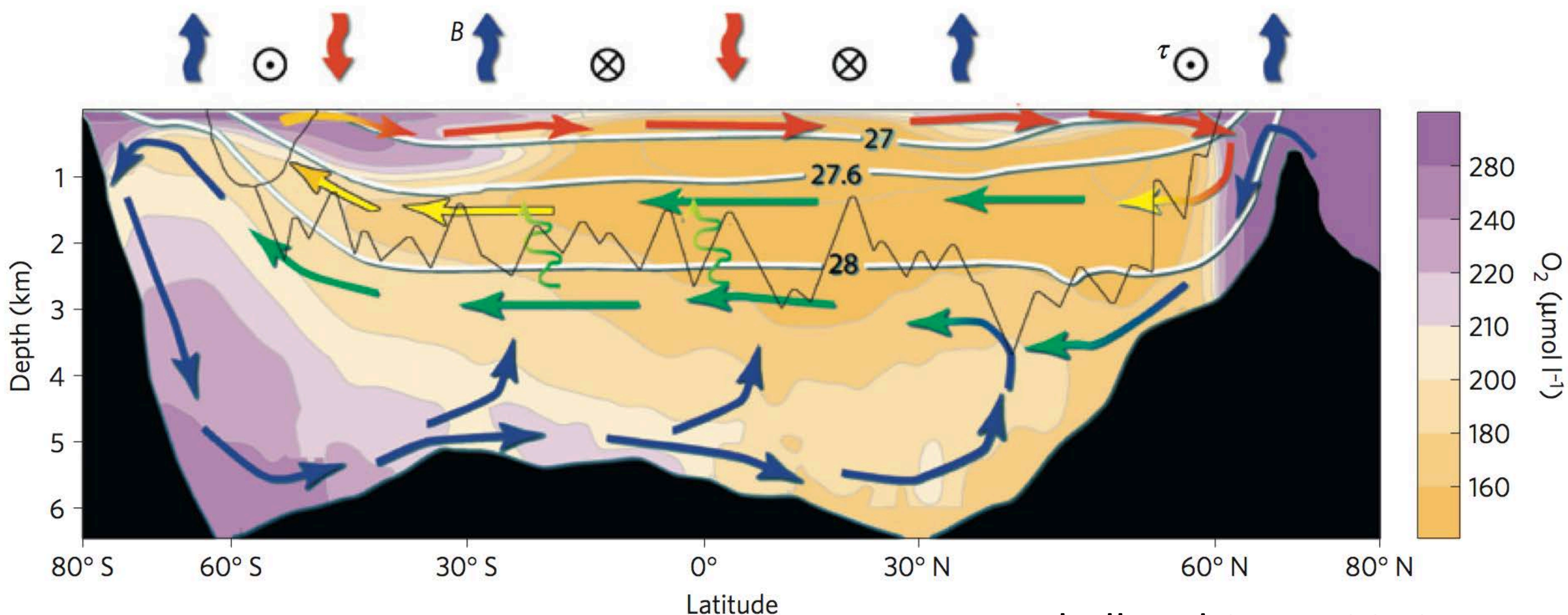
Southern Hemisphere Winds



- Southern Hemisphere winds have increased ~50% and shifted poleward.
- Wind changes are attributed to anthropogenic forcing.
- Paleo records suggest the SO winds are the strongest they have been in the past 1000 years (Abram et al. 2014).
- Past climates have indicated slower winds (Toggweiler and Russell 2008).
- **Key Questions: How has and will the Southern Ocean respond to changes in winds and what are the implications for climate change?**

Meridional Overturning Circulation

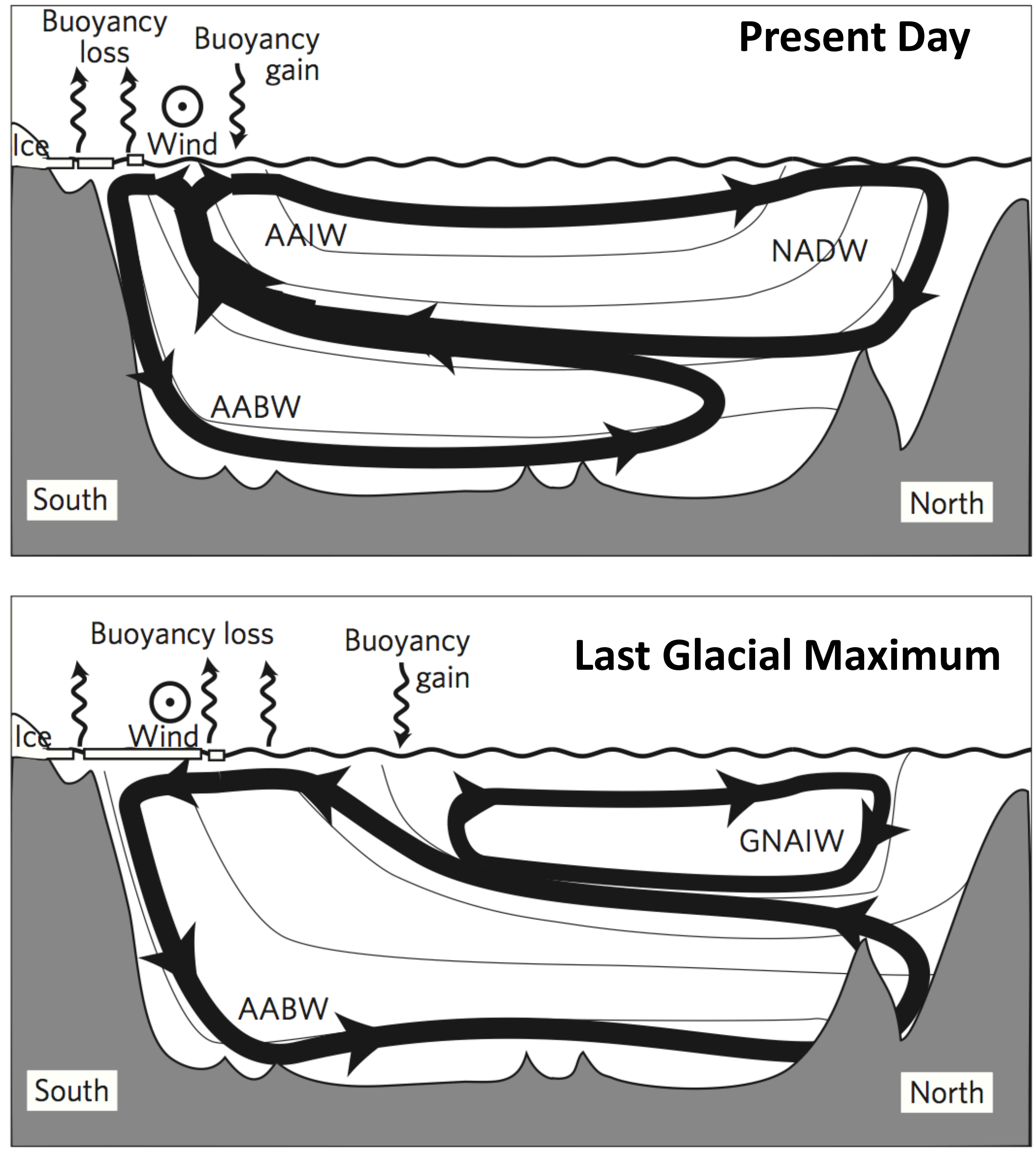


Marshall and Speer 2012

- Zonally-averaged meridional circulation
- Southern Ocean's importance in climate and variability:
  - >40% of ocean uptake of CO_2 takes place south of 40° S (Sallée et al. 2012).
  - Strength of MOC and upwelling branch controls outgassing rates of CO_2.
  - **How will the MOC respond in a changing climate?**

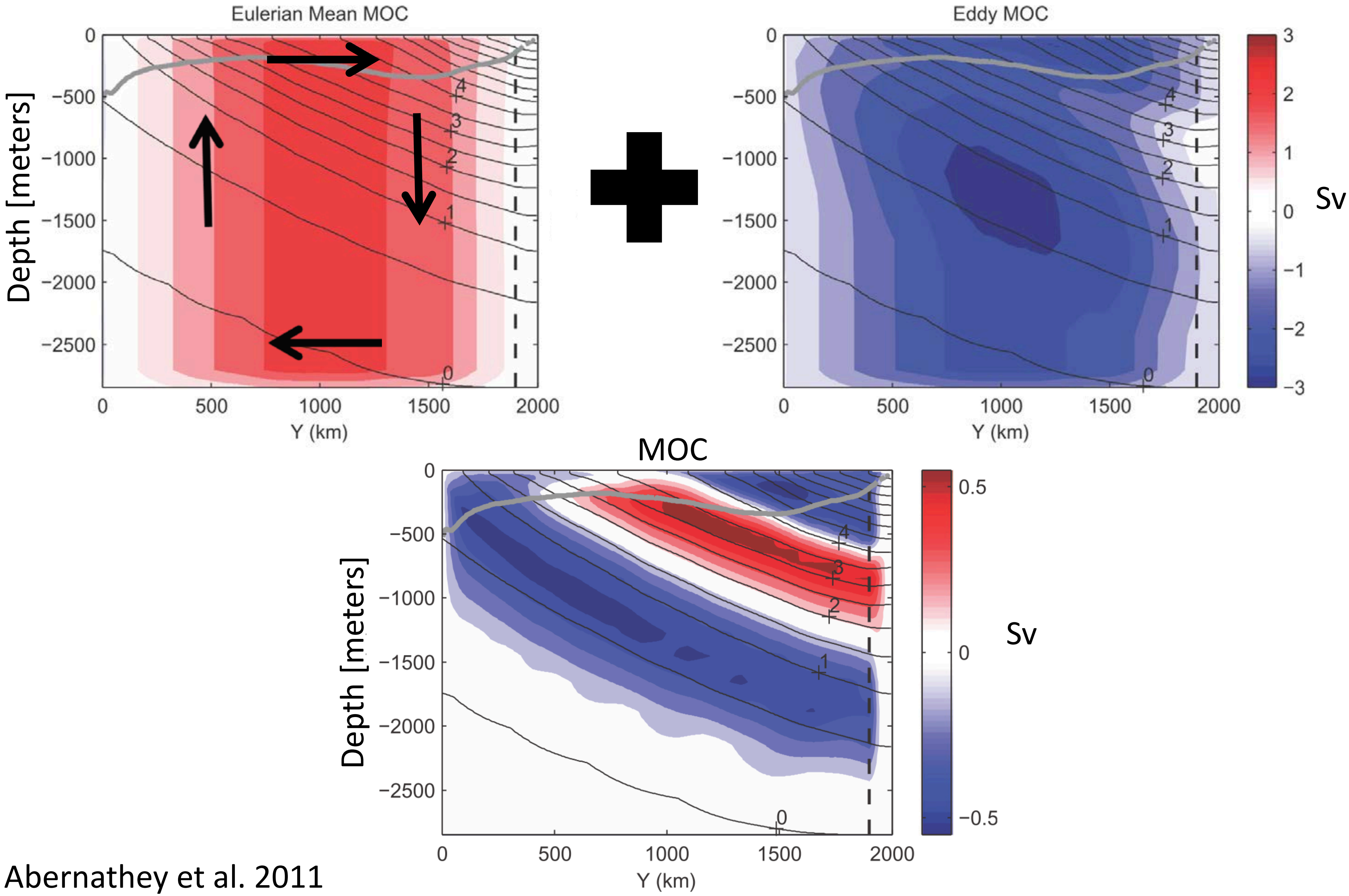
MOC in Past Climates

- LGM (Last Glacial Maximum)
  - 30,000 years ago.
  - Ice was at a maximum.
  - Sea level was between 120-135 meters (396-446 ft) lower than today.
- The northern location of upwelling results in reduced CO2 outgassing and stronger carbon sequestration in the deep ocean.
- The shift to this glacial-style circulation can draw down 30 to 60 ppm of atmospheric CO2.



Watson et al. 2015

Theoretical Understanding of MOC

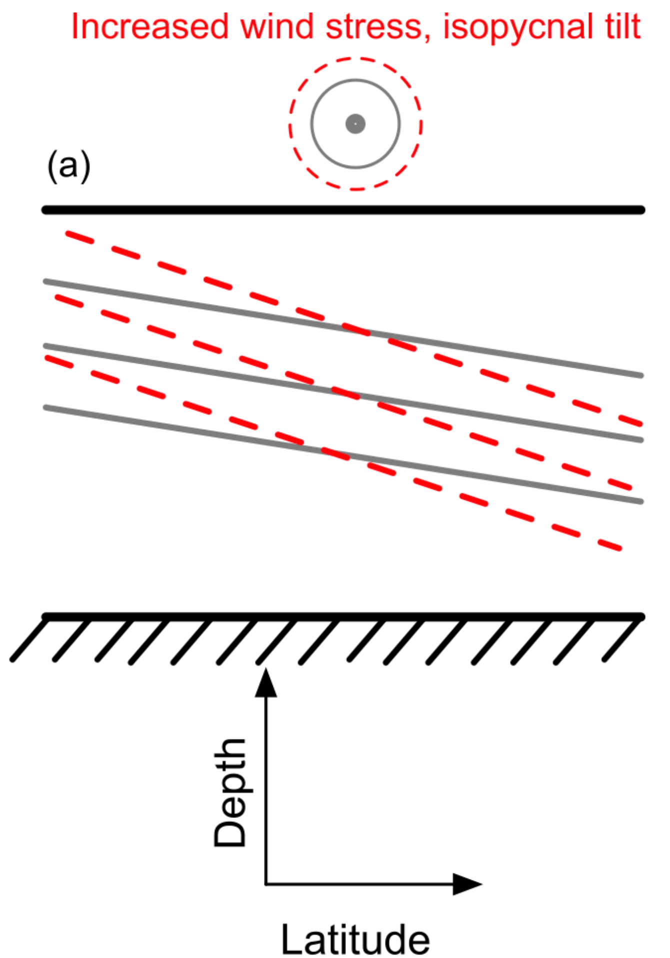


Abernathey et al. 2011

Hypotheses

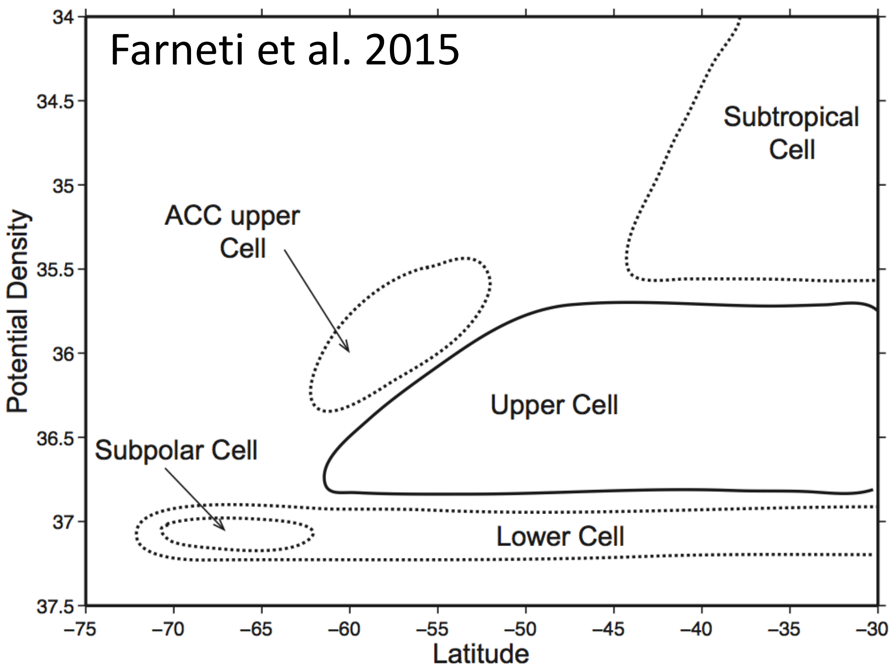
- ***Eddy Saturation***: ACC Transport
  - Increased wind tilts isopycnals
  - Baroclinic instability flattens isopycnals back
  - No net increase in transport
  - More widely accepted

- ***Eddy Compensation***: MOC
  - Increased wind drives a larger mean overturning
  - Larger tilt in isopycnals drives larger eddy overturning (baroclinic instability)
  - No net increase in residual MOC
  - The jury is still out (no direct measurements of MOC)

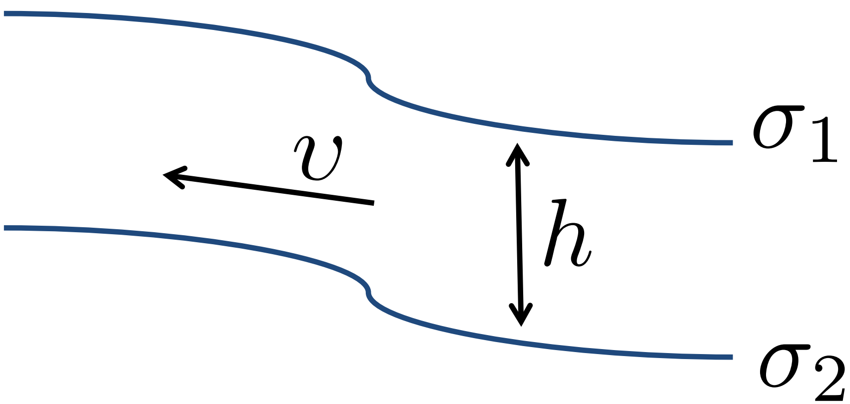


Thompson and Garabato 2014

Calculating the MOC

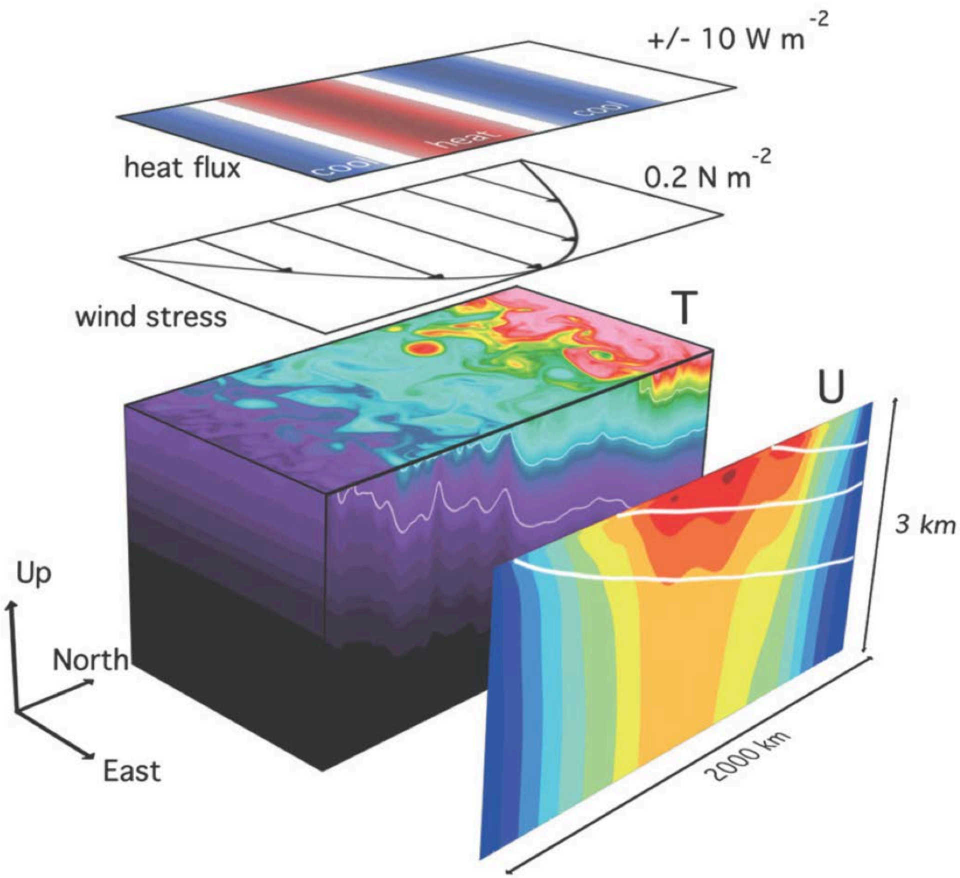


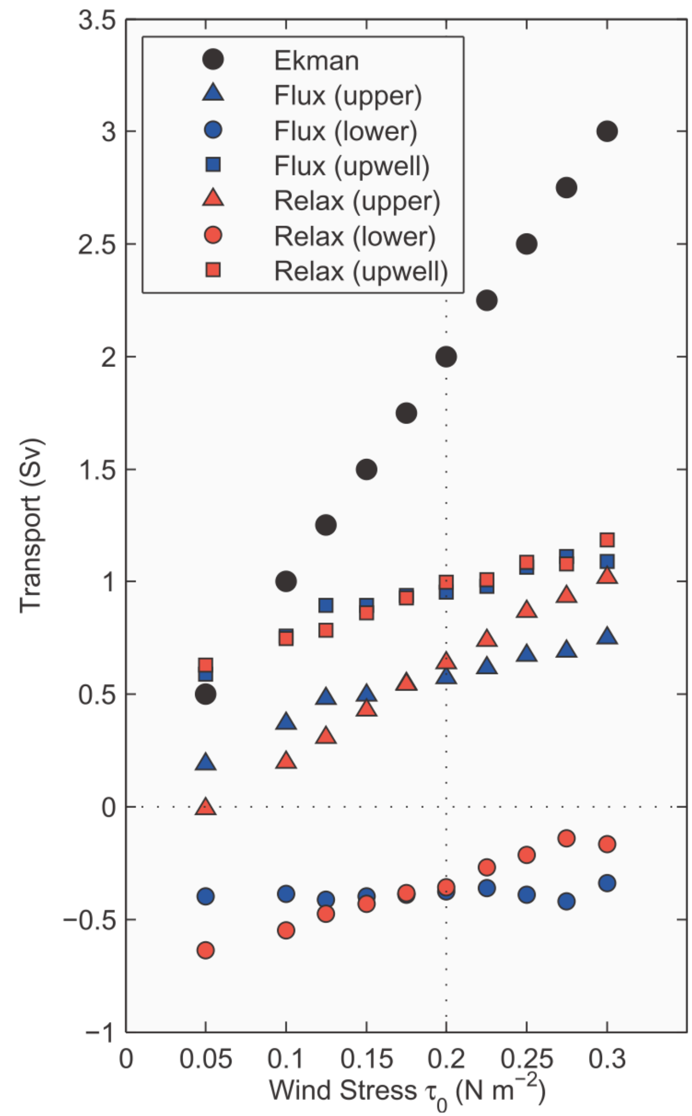
$$\psi_{moc} = \overline{\oint \int_{\sigma} vh\mathrm{d}\sigma\mathrm{d}x}$$



- **MOC** = meridional transport between density surfaces.
- MOC is made up of several clockwise and counterclockwise circulation cells.
  - **Upper cell**: wind-driven cell, clockwise circulation.
  - **Lower cell:** counterclockwise circulation nearest Antarctica (not necessarily lower than Upper cell).
- Outcropping isopycnals feel changing winds.

Idealized Experiments

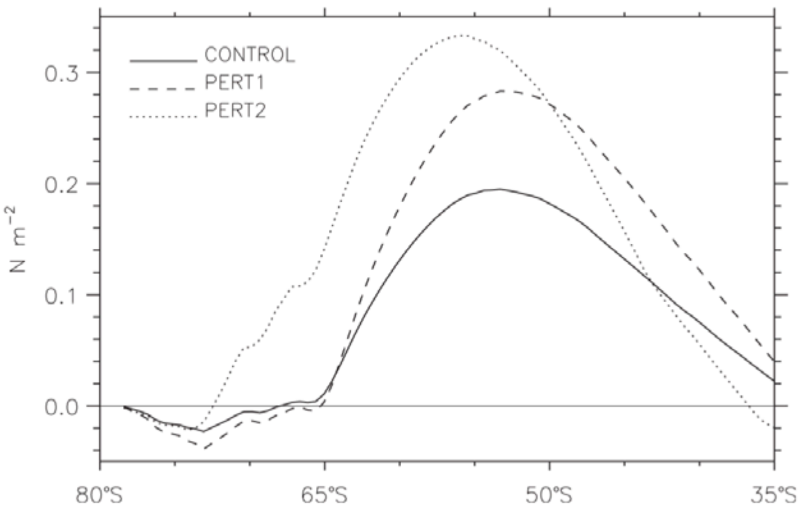




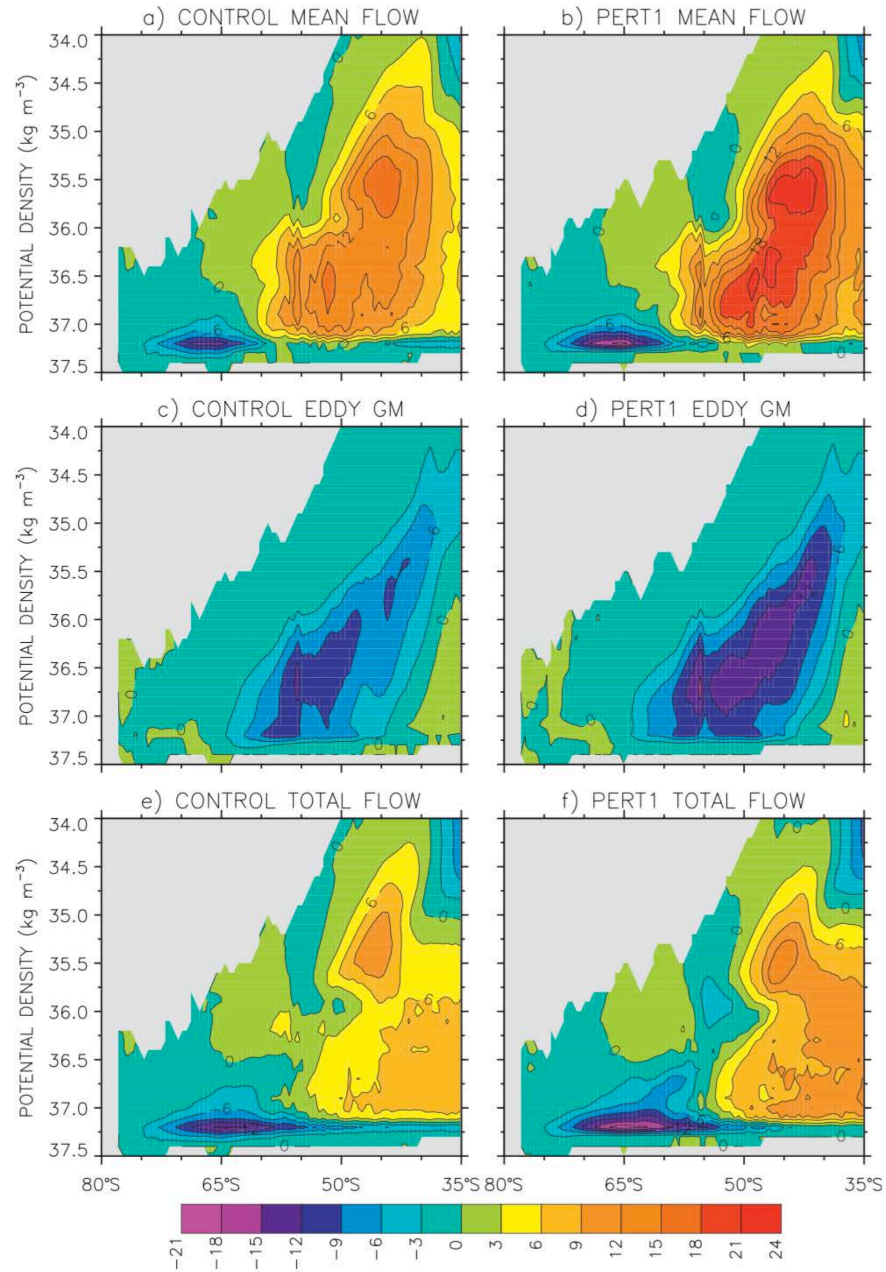
Abernathey et al. 2011

Wind Perturbation Experiments

$$\psi_{moc} = \overline{\psi} + \psi^*$$



- Gent & Danabasoglu (2011)
- 1^o CCSM4
- 20-yr experiments
- Winds increased 50% (PERT1)
- GM coefficient increased for compensation

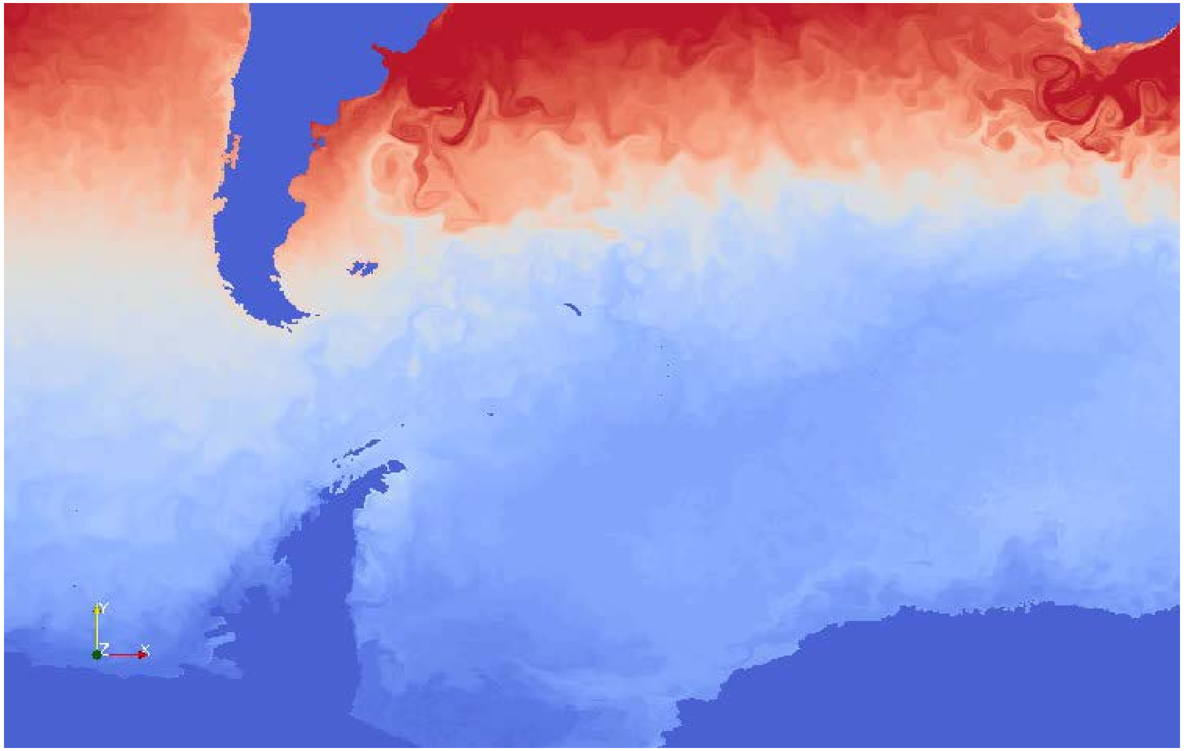


Mean

Eddy

MOC

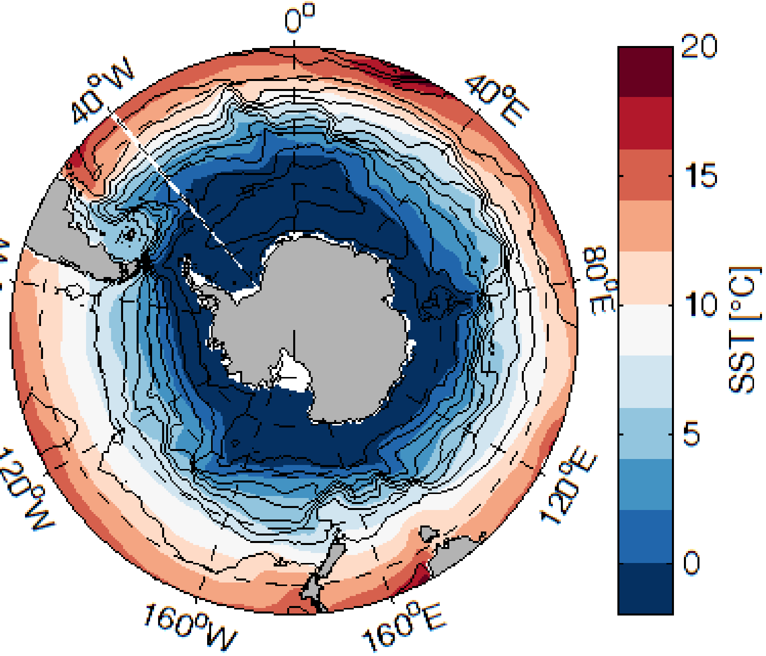
Eddy-Resolving CESM



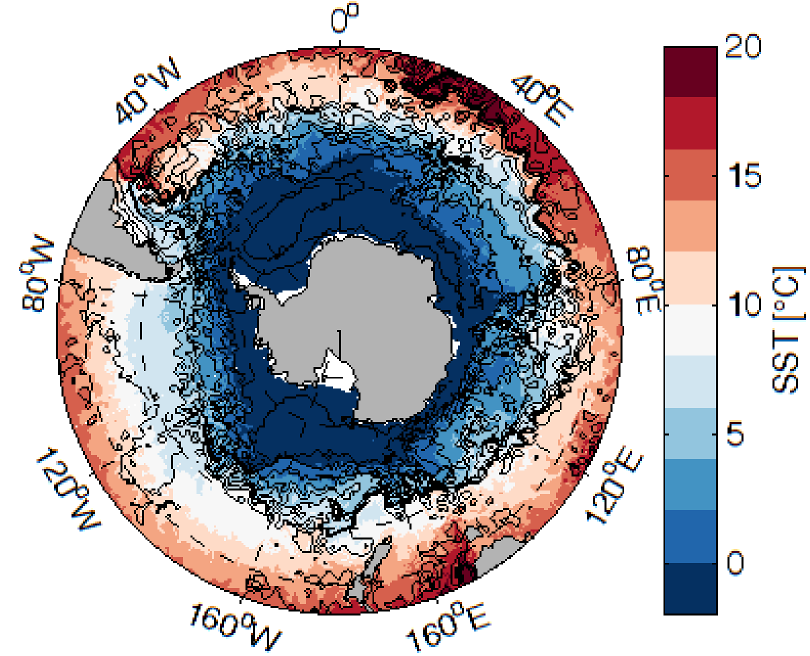
- Eddy-resolving Community Earth System Model (CESM-H)
- Fully-coupled ocean-atmosphere model
  - POP ocean, CAM5 atmosphere
- Resolution: Ocean 0.1^o, atmosphere 0.25^o
  - No dependence on parameterization for mesoscale eddies
- 100 year simulation with present day CO_2 forcing

Southern Ocean Snap Shot

Typical Climate Model (coarse resolution)

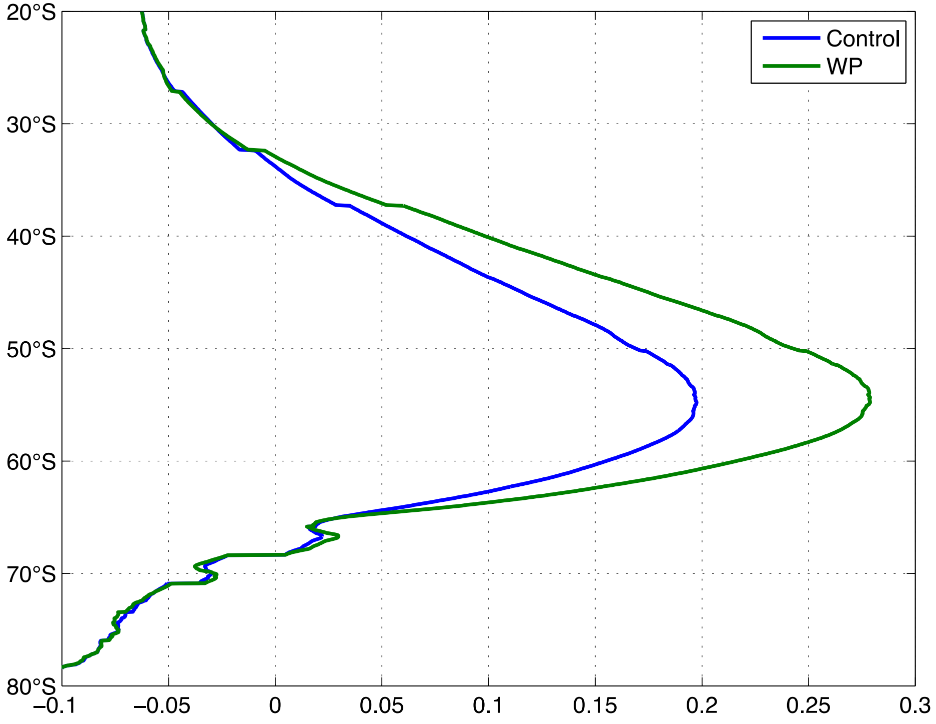


Eddy-Resolving Climate Simulation



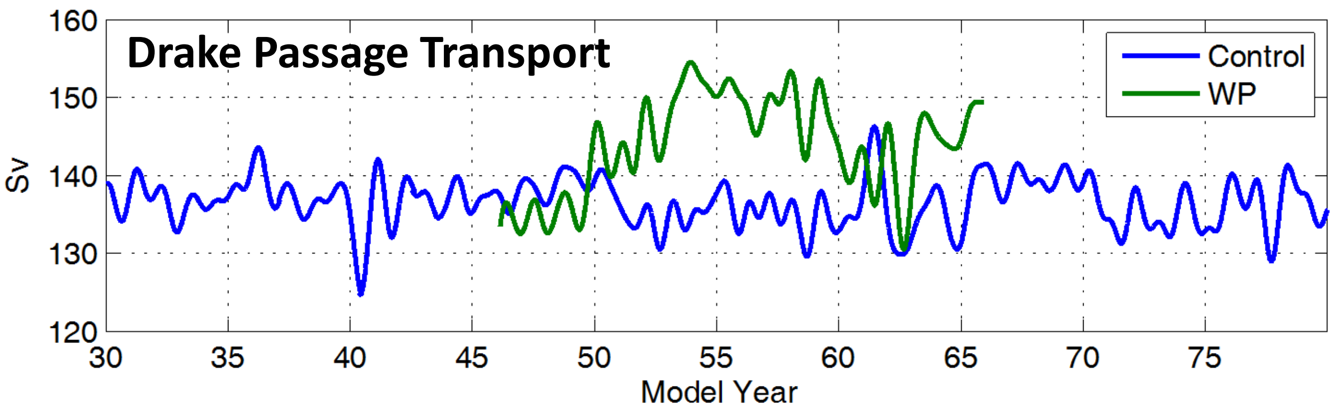
Wind Perturbation Experiment

Time and Zonally Averaged Zonal Wind Stress



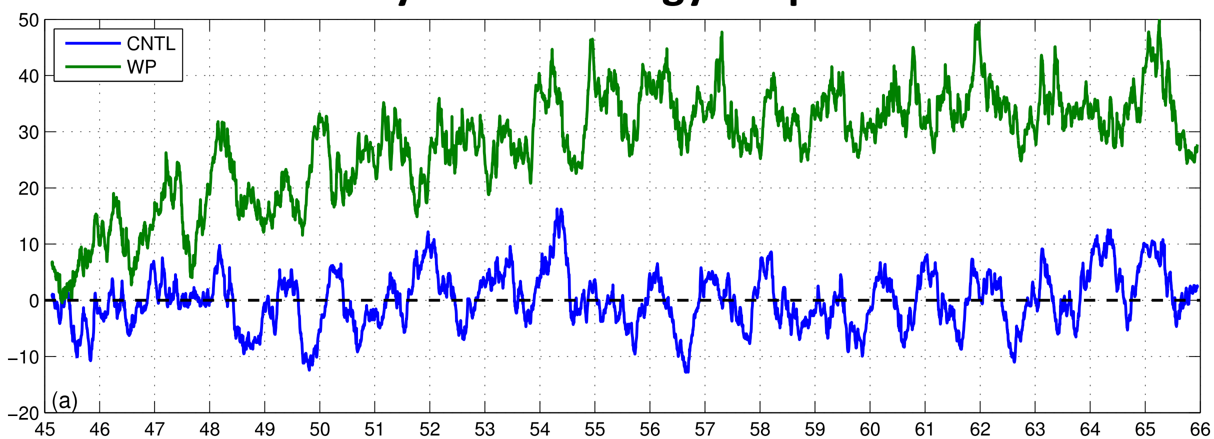
- 20 year experiment (Repeat of Gent and Danabasoglu 2011 at eddy-resolving resolution).
- Surface wind stress increased 50% south of 35^{o} S.
- Increased winds not used to calculate heat and freshwater surface fluxes.
- Indirect effect in coupled system through SST changes.
- Averages over the last 10 years of simulation (56-65).

ACC Transport Response

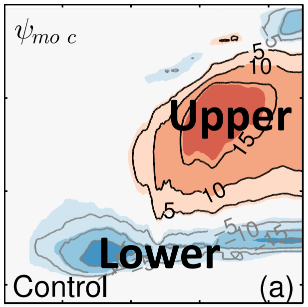


- Mean Transport through Drake Passage
  - Control: 136±3 Sv (Sv = 10^6 m^3 s^{-1})
  - WP: 144±6 Sv
- Mean transport only increased by 6% in WP.

Eddy Kinetic Energy Response



MOC Response

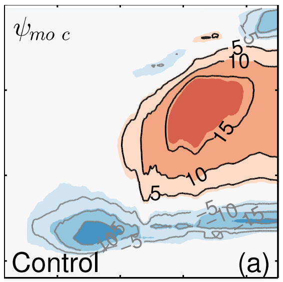


- MOC cells do increase with wind forcing:
  - Upper cell maximum increased 7.7 Sv (**39%** increase over Control)
  - Lower cell maximum increased 12.6 Sv (**63%** increase over Control)
- Are eddies responsible for the partial compensation?

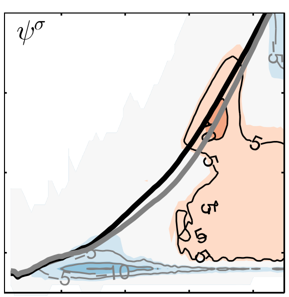
Low vs. High MOC Response

High Resolution

Control | **WP** | **WP minus Control**



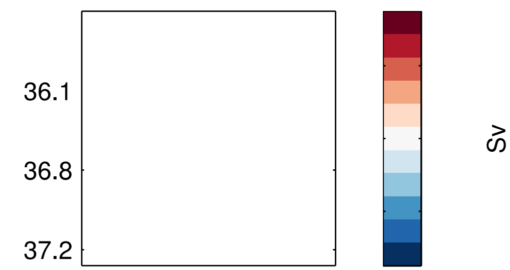
Low Resolution



Mean and Eddy Response

$$\psi_{moc} = \overline{\psi} + \psi^*$$

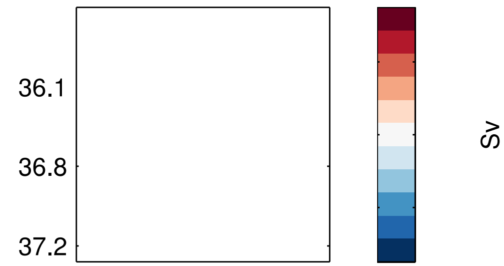
Mean



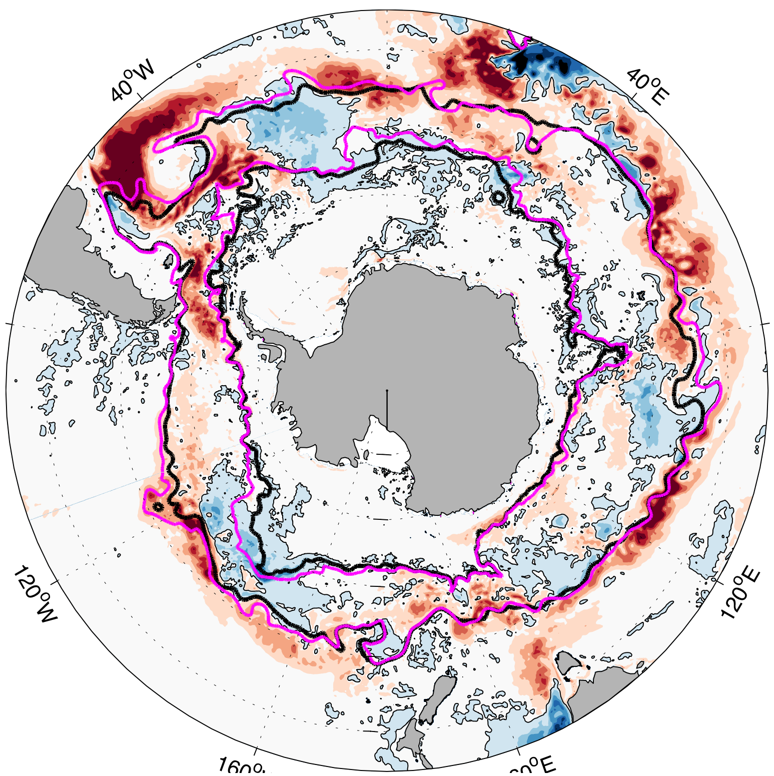
Eddy

- Changes in Mean overturning 5-10 Sv.
- Change in eddy overturning is small
- Most of the compensation takes place by mean overturning.

Eddy Kinetic Energy Response



Eddy



Changes in MOC

$$\delta\psi_{moc} \approx \delta\overline{\psi}$$

$\delta\psi_{moc}$ $\delta\overline{\psi}$

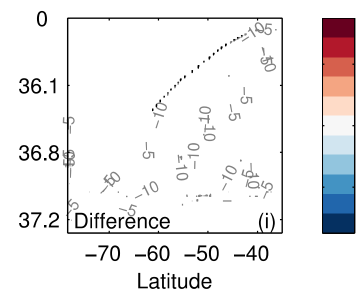
- The MOC is partially balanced by the mean flow rather than by eddy transport.
- **What part of the mean flow is compensating?**

Standing Wave Component of MOC

$$\overline{\psi} = [\overline{\psi}] + \psi^{\dagger}$$

Time & Zonal Mean **Standing Wave**

Time & Zonal Mean

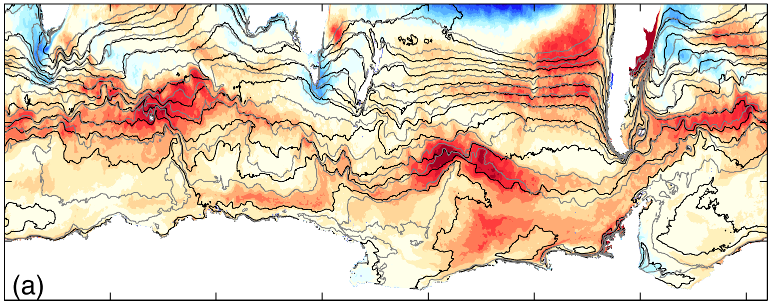


Standing Wave

- Stronger winds drive stronger meridional currents.
- Stronger currents have asymmetry in the zonal direction.
- Flow over major topography causes standing waves.

Sea Surface Density, SST, & SSS Response

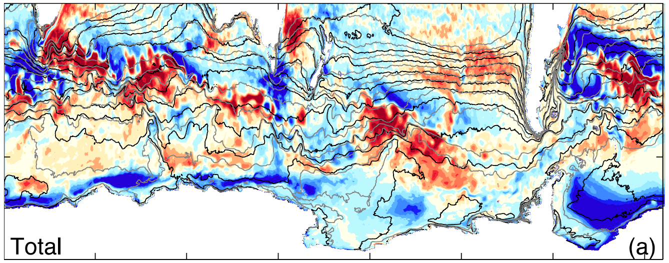
Sea Surface Density Difference

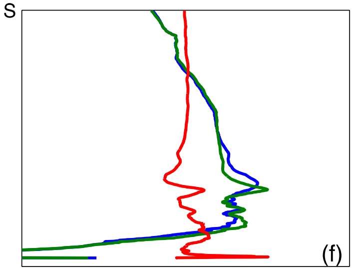


Zonal Average

Surface Buoyancy Flux Changes

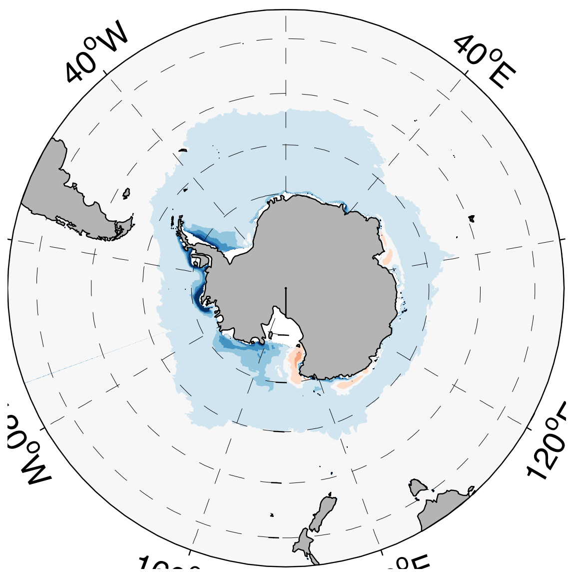
$$\mathcal{B} = \frac{\alpha_\theta g}{\rho_o c_p} Q_o - \frac{\alpha_S g}{\rho_{fw}} S_o (E - P - R)$$

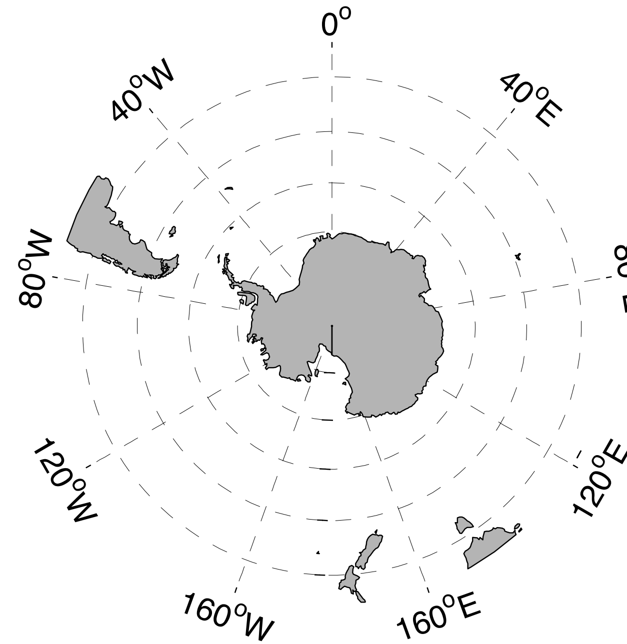




- Patchy Surface Buoyancy Flux (SBF) along ACC.
- Total SBF:
  - Gain north of 60°S
  - Loss south of 60°S
- Surface Heat Flux (SHF) dominates over Fresh Water Flux (FWF):
  - Warmer upwelled SSTs south of 60°S result in enhanced SHF to the atmosphere.
- FWF has a net gain near the coast of Antarctica.
- Increased sea ice melt?

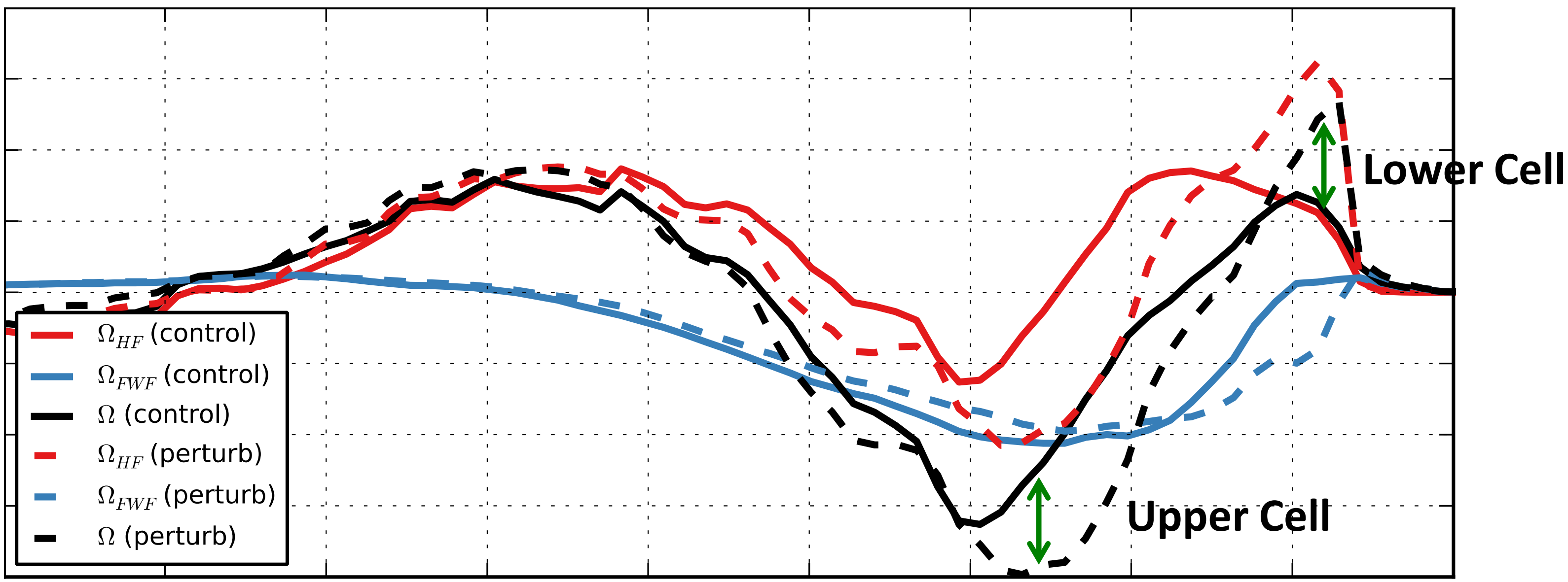
Sea Ice Melt





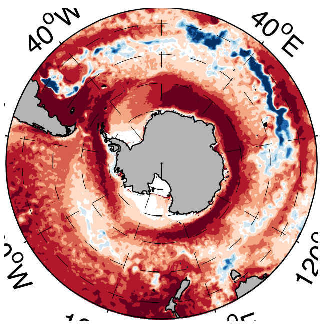
- Sea ice has a strong seasonal cycle.
  - JFM = January, February, March
  - JAS = July, August, September
- Sea ice thickness decreased in Austral winter and summer.
- In some places thickness decreased as much as 1 meter (3.3 ft).

Water Mass Transformation

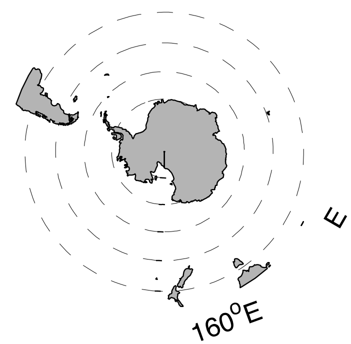


- Upper cell:
  - Net surface heat fluxes 36-36.8 σ_2 transformation account for ~10 Sv
- Lower cell
  - Net surface heat fluxes minus surface freshwater fluxes >37σ_2 transformation accounts for ~10-15 Sv

SST & Heat Flux Covariance



High

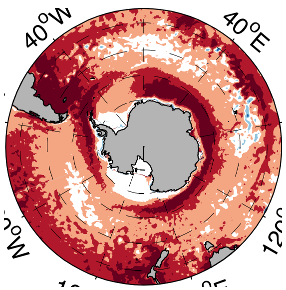


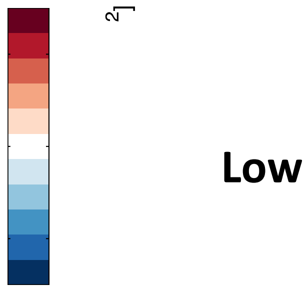
Low

- At high resolution:
  - – More negative covariance along ACC
  - – Higher positive covariance around Antarctica
    - Net cooling and heat loss are high in wind perturbation

SST & Heat Flux Covariance (Seasonal)

$$\overline{TQ} = \overline{T}\ \overline{Q} + \overline{T_s Q_s} + \overline{T'Q'}$$

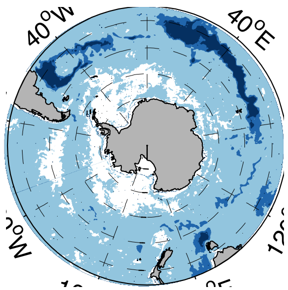




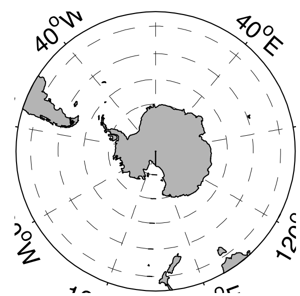
- At high resolution:
  - High positive covariance around Antarctica
    - Net cooling and heat loss are high in wind perturbation

SST & Heat Flux Covariance (Mesoscale)

$$\overline{TQ} = \overline{T}\ \overline{Q} + \overline{T_s Q_s} + \overline{T'Q'}$$



High



Low

- Transient response disappears around Antarctica
- Evidence that seasonal cooling & heat loss may be responsible for changes in lower cell

Conclusions

- In eddy-resolving CESM wind perturbation experiment:
  1. **ACC Transport** is approximately *eddy saturated.*
     - Only 6% increase with 50% increase in winds.

  1. **MOC** is not *eddy compensated* in the traditional sense.
     - Upper and lower cells increase with wind.
     - Compensation takes place by the strengthening standing waves in the lee of topography.

  2. **Stronger lower cell** drives more upwelling of warm and salty **Circumpolar Deep Water**:
     - Results in more melting of sea ice.
     - Increased winds today could already be having an effect on the strength of the MOC and subsequently melting of West Antarctica and draw down of anthropogenic CO_2.

  3. **Future**
     - Continue full energetics budget
     - Examine T'Q' in σ_2-space
     - Do seasonal decomposition with MOC: $\psi_{moc} = \overline{\psi} + \psi_s + \psi^*$
       - Do Seasonal and mesoscale overturning compensate?

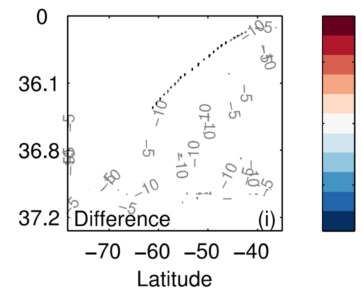
Thanks

- Advanced Study Program at the National Center for Atmospheric Research (NCAR).
- National Science Foundation for sponsoring NCAR.
- President and Director's Fund at the California Institute of Technology.
- Accelerated Scientific Discovery project at NCAR for making these numerical simulations possible.

Low vs. High Standing Wave Response

High Resolution

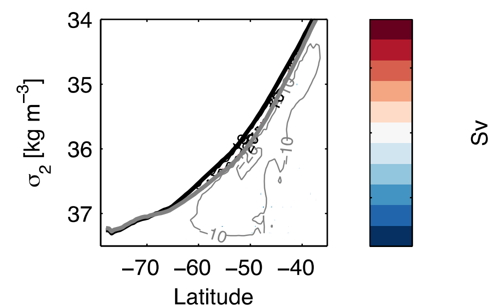
Time & Zonal Mean



Standing Wave

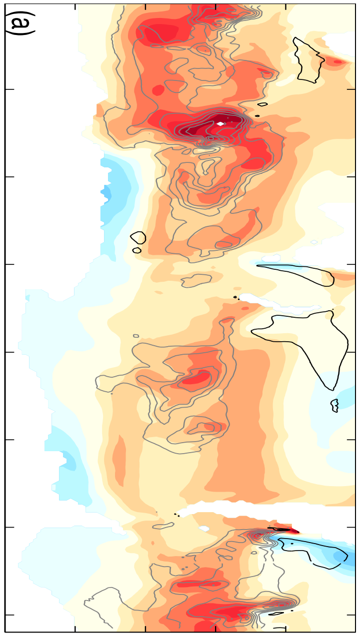
Low Resolution

Time & Zonal Mean



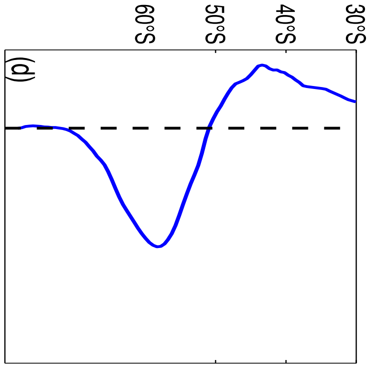
Standing Wave

Low Res Surface Density, Temperature, & Salinity



Density

Temperature



Salinity