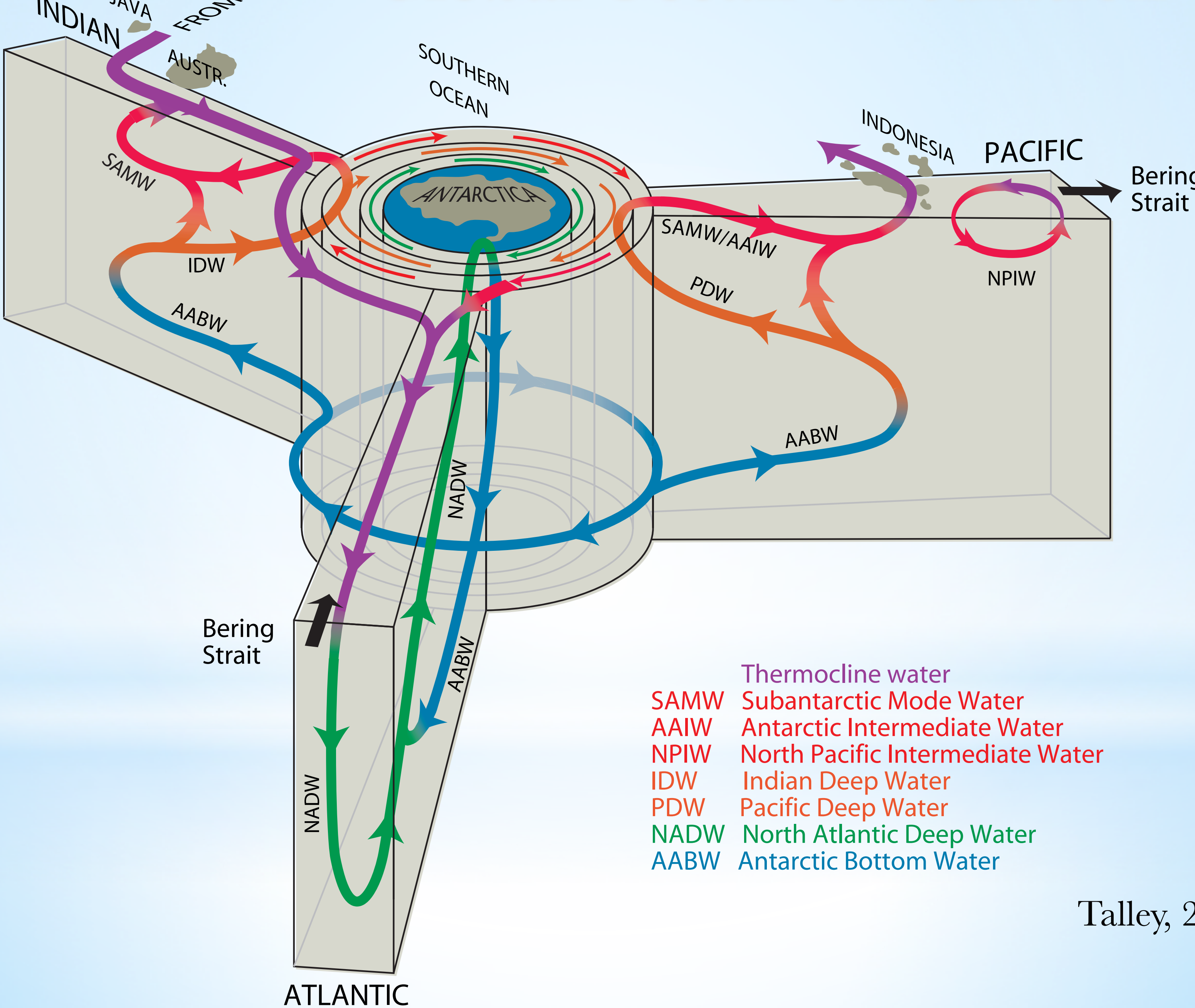
Heat and Carbon Uptake by the Southern Ocean:
Joint U.S. CLIVAR/OCB Working Group

Photo by O. Schofield

Co-Chairs: Joellen L. Russell (U. Arizona)

Igor Kamenkovich (U. Miami)

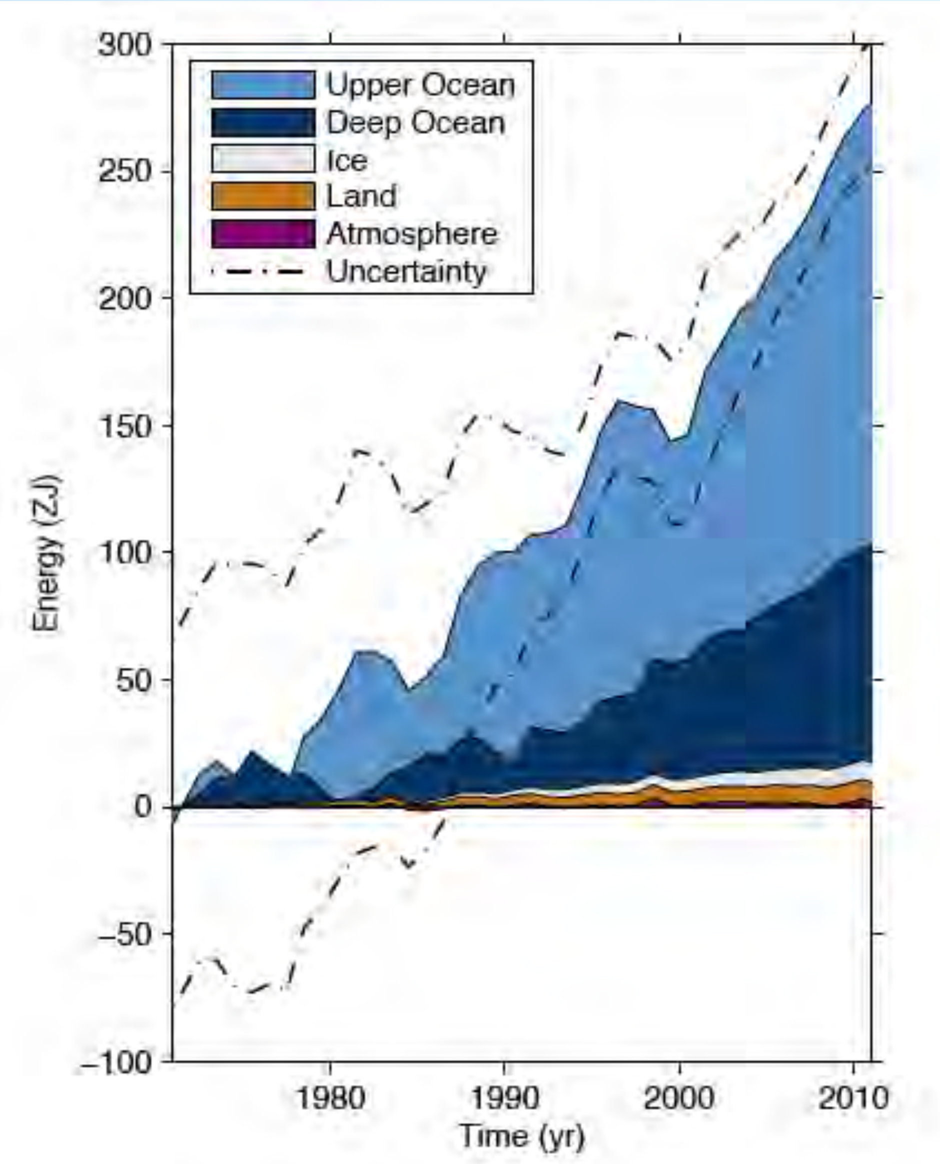
Global Ocean Circulation



Talley, 2013

What is the role of the Southern Ocean (SO) in the global climate system?

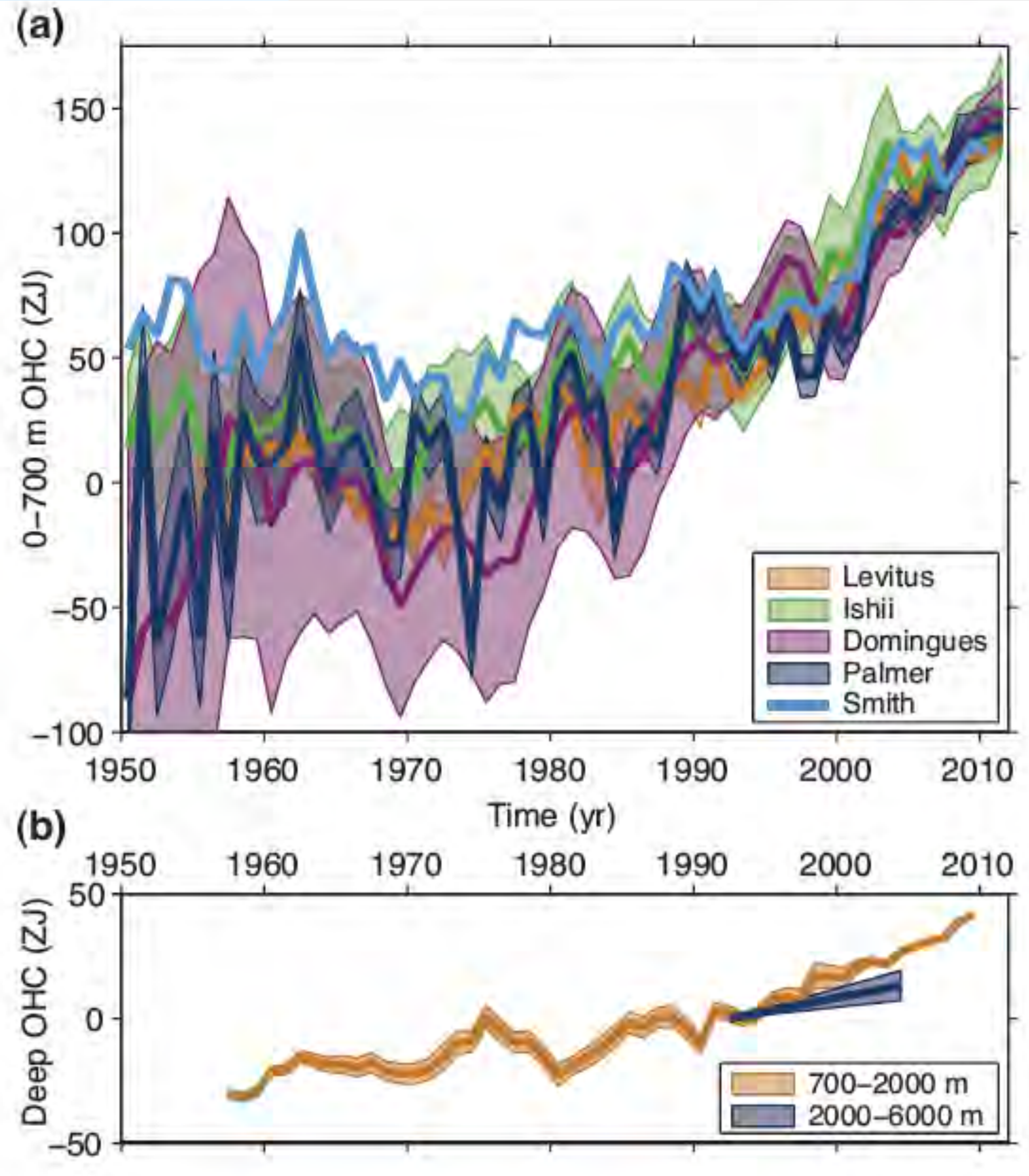
1. SO may account for up to half of the annual oceanic uptake of anthropogenic carbon dioxide from the atmosphere (*Gruber et al.*, 2009)
2. Vertical exchange in SO is responsible for supplying nutrients that fertilize three-quarters of the biological production in the global ocean north of 30°S (*Sarmiento et al.*, 2004)
3. SO may account for up to 70 ± 30% of the excess heat that is transferred from the atmosphere into the ocean each year (analysis of IPCC AR4 models)
4. SO winds and buoyancy fluxes (both surface and eddy-induced) play a key role in the global meridional overturning circulation throughout the ocean (e.g., *Toggweiler and Samuels*, 1998; *Marshall and Speer*, 2012)



The global energy imbalance goes into the ocean

Energy accumulation within distinct components of Earth's climate system relative to 1971. (IPCC AR5)

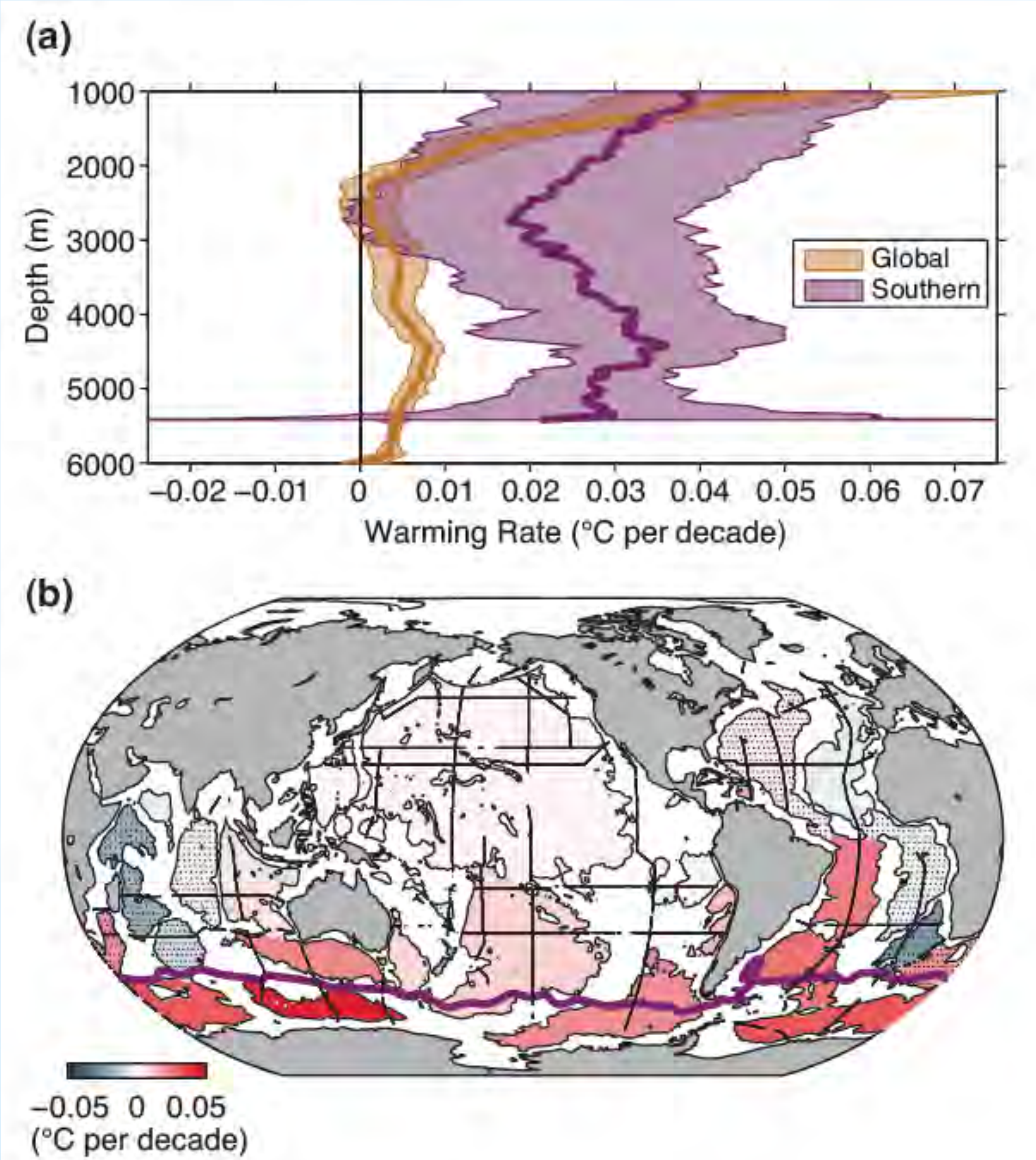
Ocean heat content is rising



Upper Ocean (0-700m) Heat Content (IPCC AR5)

Heat Content at:
Mid-depth (700-2000m)
Deep Ocean (>2000m)
(IPCC AR5)

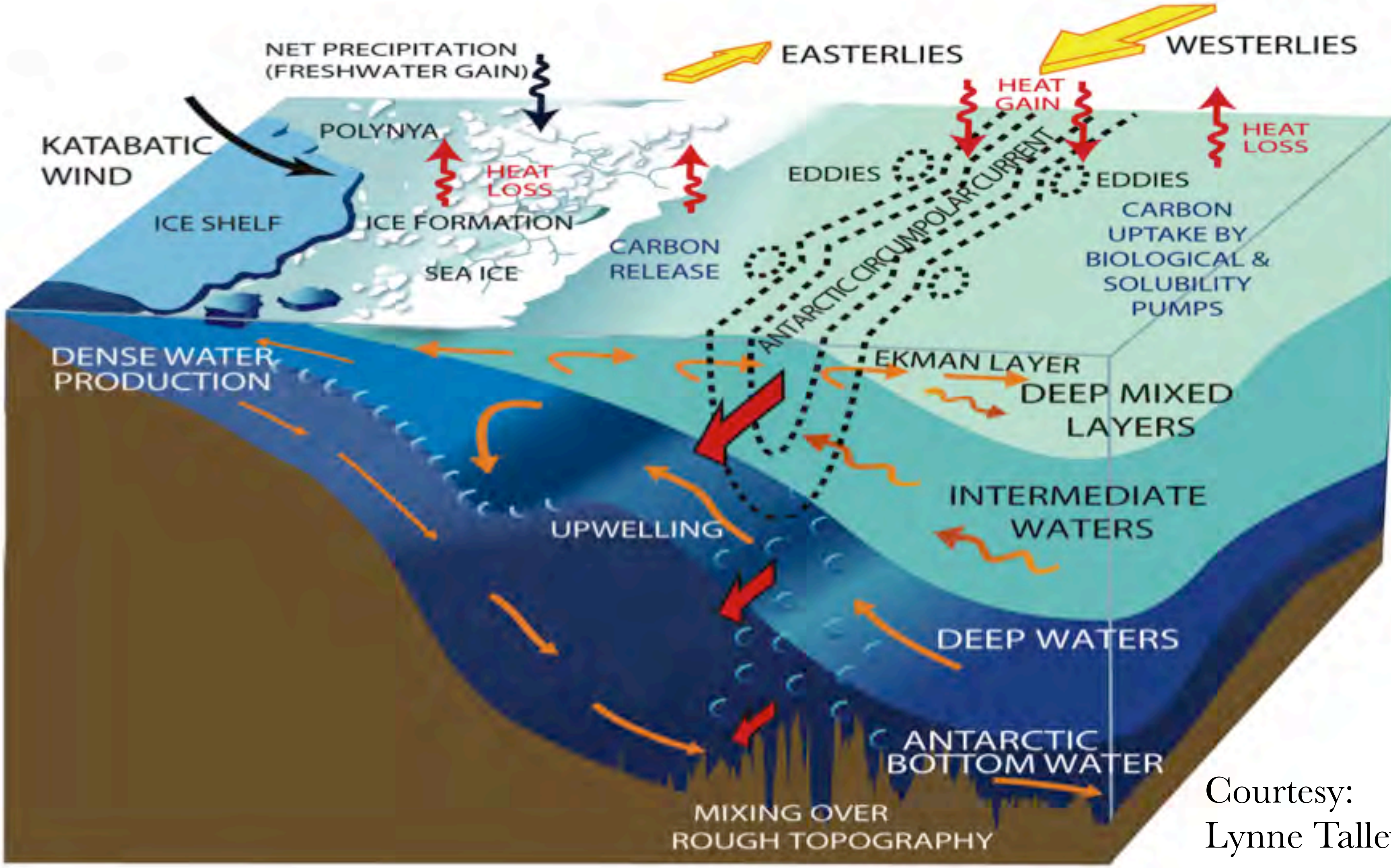
The Southern Ocean is warming at all depths



Warming rate of the Southern Ocean (purple) and global ocean (orange) (IPCC AR5)

Warming Rate of deep ocean (>4000m)
(IPCC AR5)

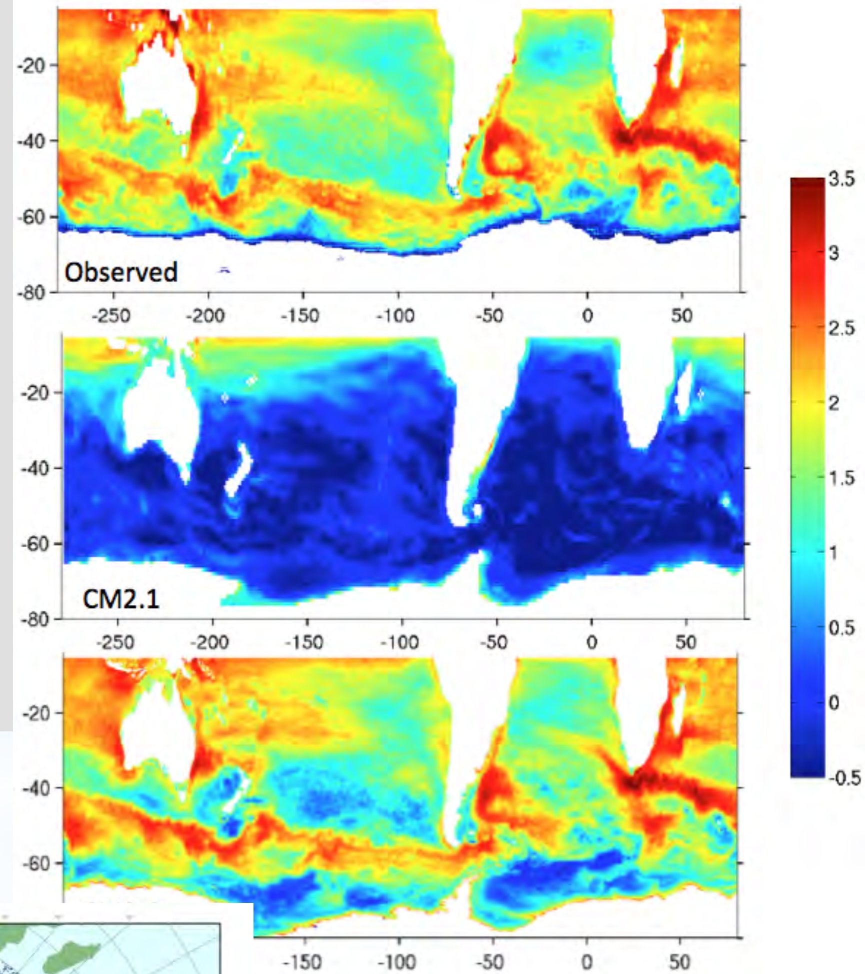
The Antarctic Circumpolar Current System



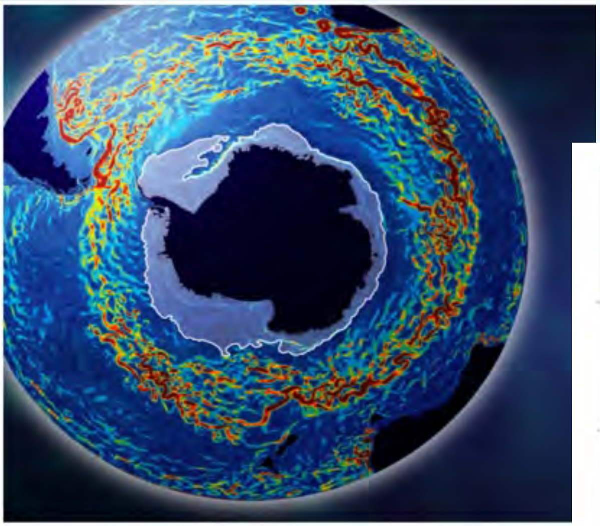
Courtesy:
Lynne Talley

New Tools:

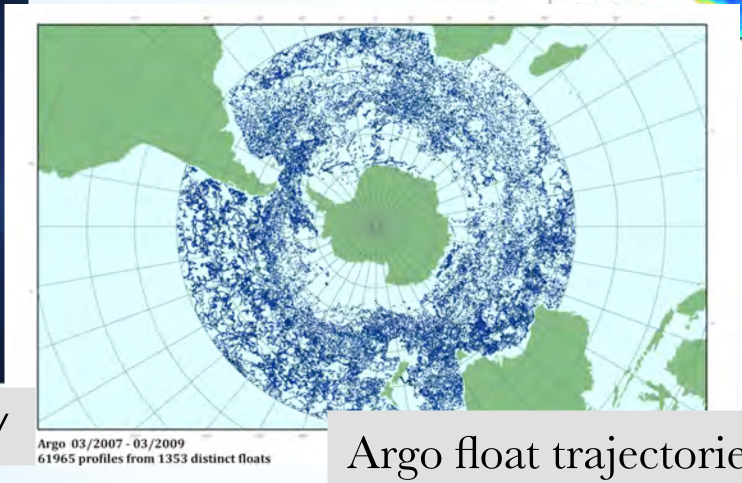
1) New Southern Ocean Observations
2) Southern Ocean State Estimate (SOSE)
3) New Earth System Models that include Carbon Cycle
4) Mesoscale-Resolving Climate Models



EKE (from SSHA)



http://sose.ucsd.edu/



Argo float trajectories

Heat and Carbon Uptake by the Southern Ocean:
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Southern Ocean Working Group	
Igor Kamenkovich, co-chair	University of Miami
Joellen Russell, co-chair	University of Arizona
Cecilia Bitz	University of Washington
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Bob Hallberg	NOAA/GFDL
Ken Johnson	Monterey Bay Aquarium Research Institute
Irina Marinov	University of Pennsylvania
Matt Mazloff	University of California, San Diego/SIO
Jorge Sarmiento	Princeton University
Kevin Speer	Florida State University
Lynne Talley	University of California, San Diego/SIO
Rik Wanninkhof	NOAA/AOML

Goals:

- Improve understanding of how the Southern Ocean stratification, circulation and heat and carbon uptake will respond to a changing climate.
- Improve understanding of the role of mesoscale eddies in the heat and carbon uptake by the Southern Ocean.

SOWG Outcomes and Deliverables

- Observationally-based data/model metrics that will:
  - provide critical observational targets that can be used to detect changes in the heat and carbon content/uptake of the Southern Ocean and characterize key processes that lead to these changes;
  - reveal important model biases that negatively impact model ability to provide reliable climate projections

These metrics will be available on UA-hosted Southern Ocean Climate Model Atlas website.

- A manuscript for submission to the Journal of Climate that discusses the observational metrics (in progress)

- A Workshop/Conference jointly sponsored with the Oceanic Carbon Uptake Working Group at **Fall AGU 2014**

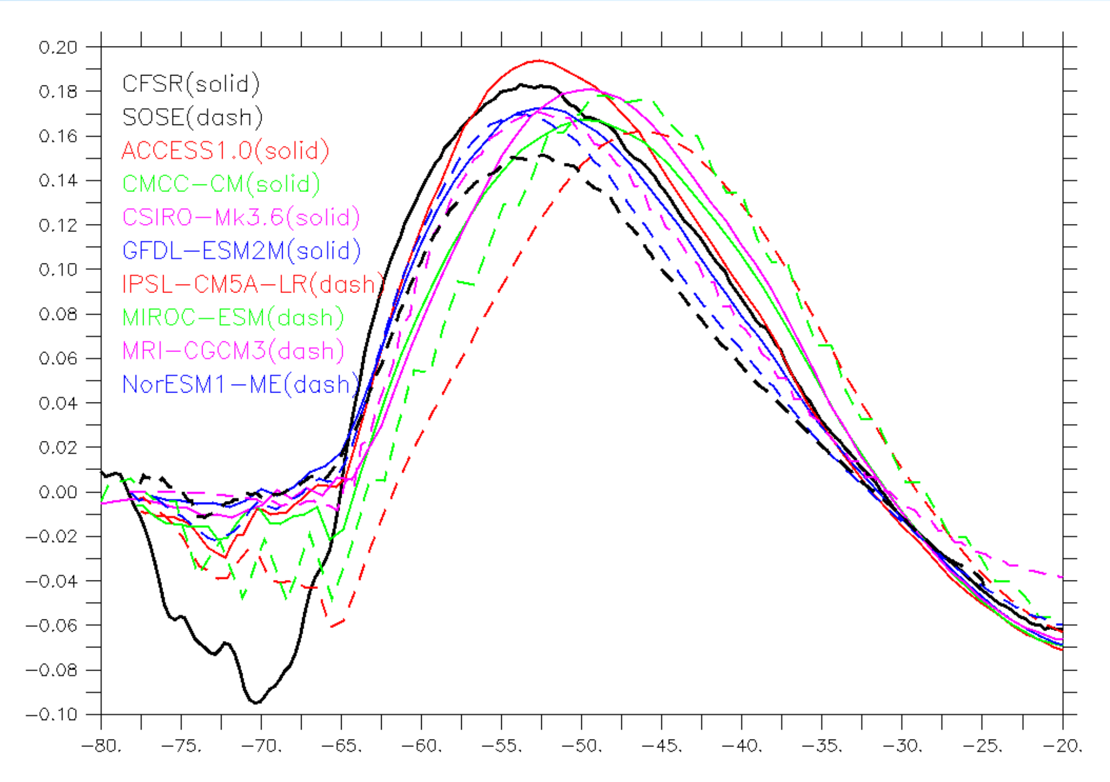
- A summary of WG activities/products for the U.S. CLIVAR and OCB newsletters and websites.

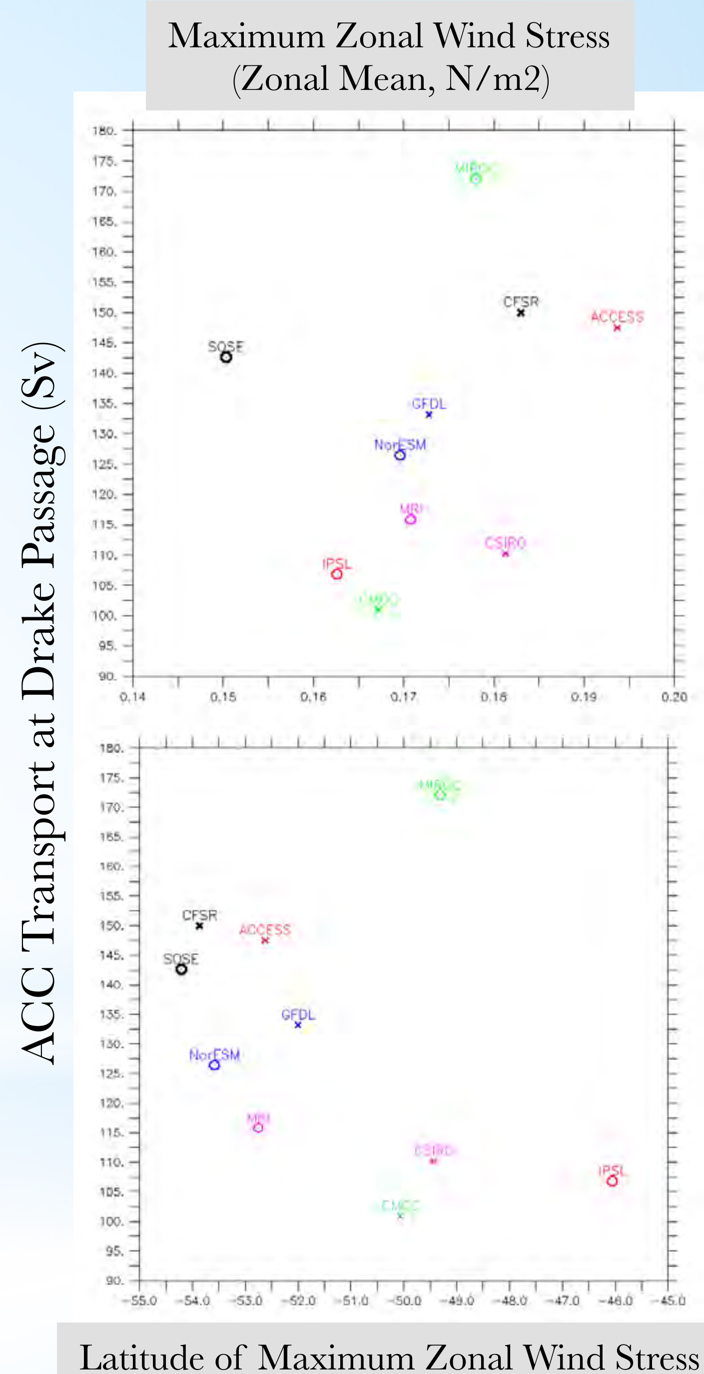
Observation-based Metrics

Air-sea Interactions and Related Variables

- Wind forcing
  –magnitude/position of the maximum wind stress are important (Russell et al. 2006)
  - wind stress controls stratification and impact eddy activity
- Precipitation
  – affect salinity, density and MLD
  - responds to changes in the climate
- Cloud cover
  – represent one of the largest uncertainties in climate simulations
- Mixed-layer depth
  – impacts heat/carbon uptake
  - SAMW/AAIW formation
- Seasonal Sea Ice cover and volume
  – ice cover is observable from space
  - directly affects heat uptake
  - biases indicate errors in heat distribution and mixing, since modern sea-ice models capture the most essential ice physics well

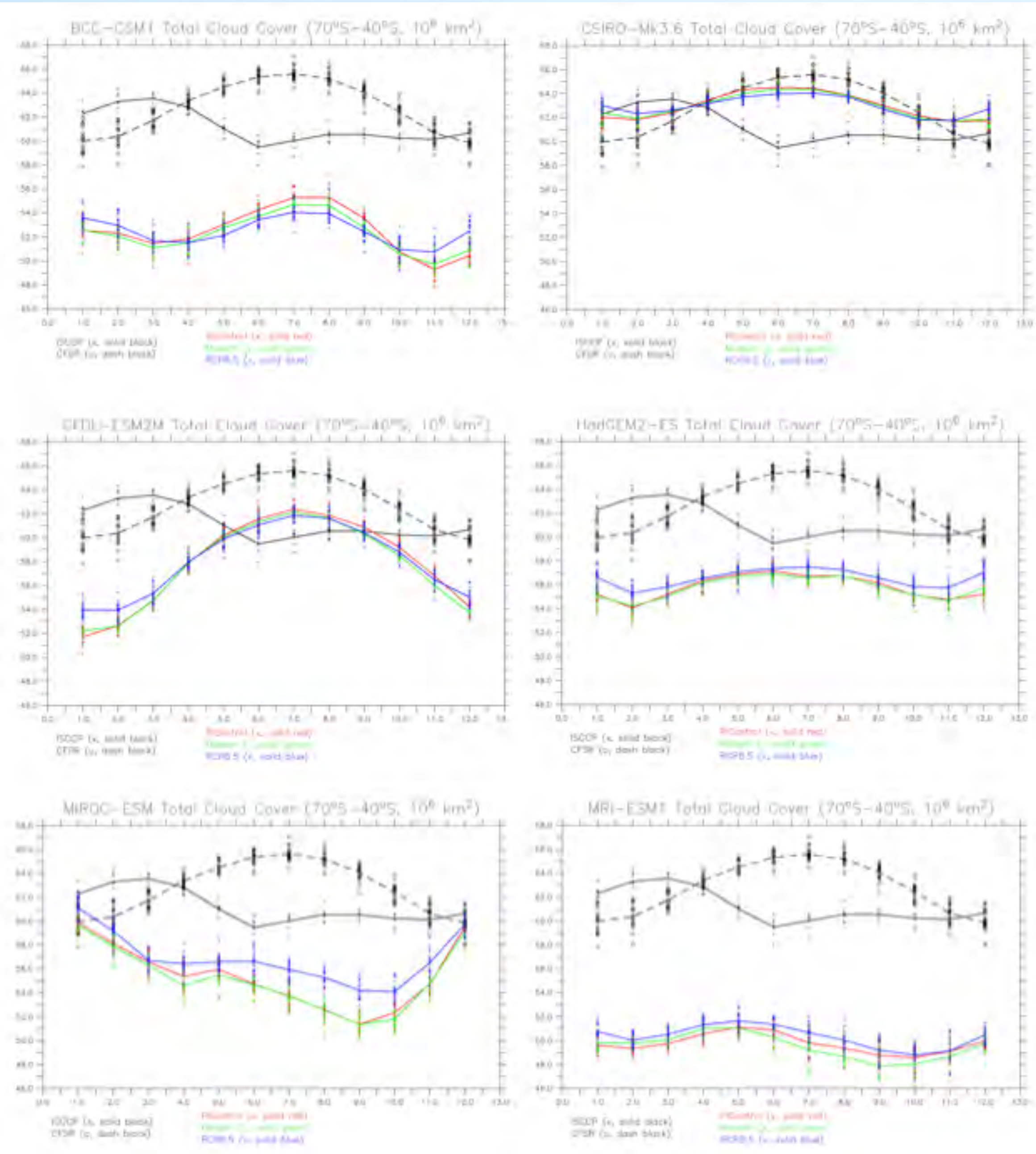
Surface Zonal Wind: CMIP5





- Both the position and magnitude of the maximum wind stress
- To get the ACC transport right, coarse-resolution models need a high bias in the wind stress, high-resolution – low bias

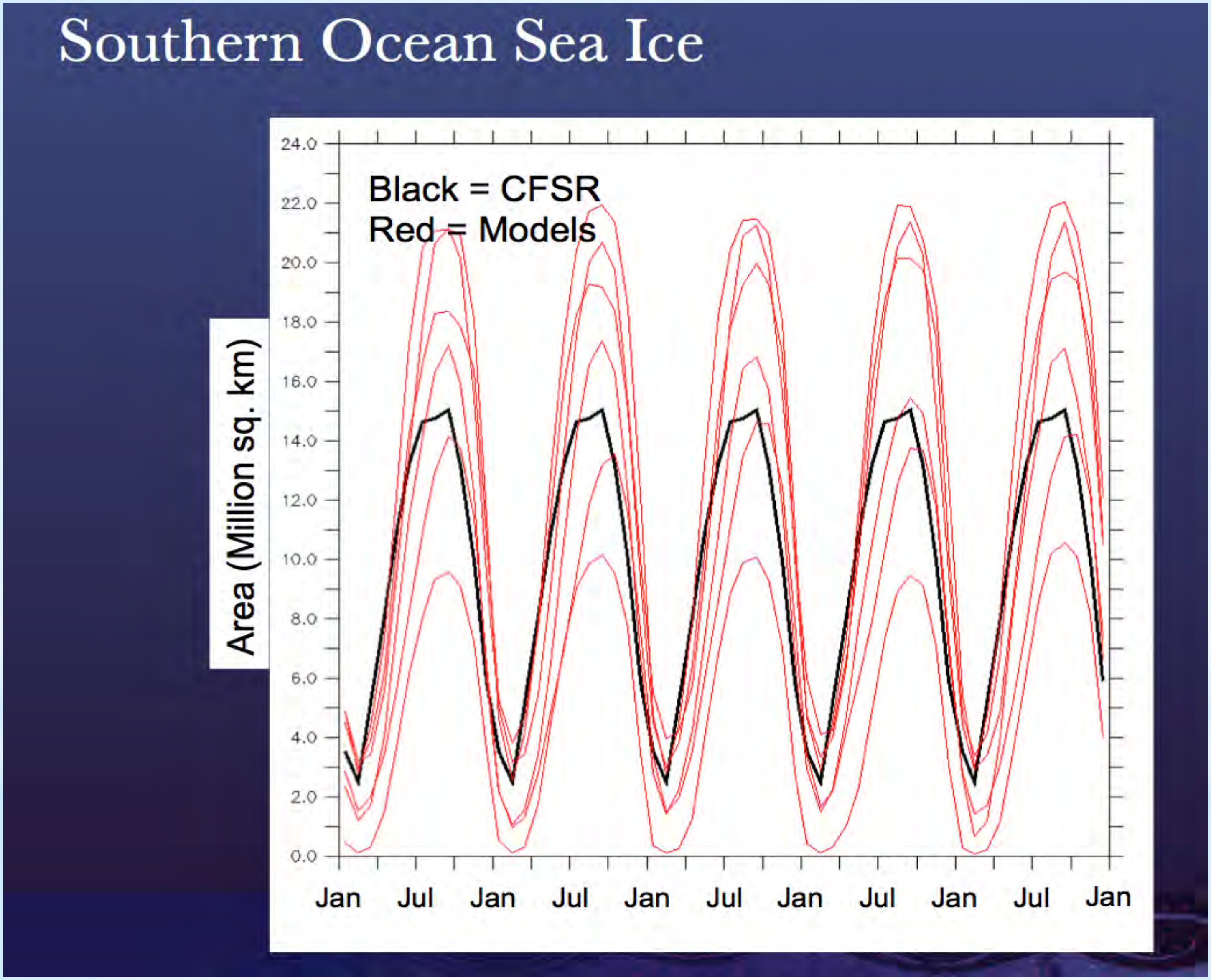
Cloud Cover (70°S-40°S integrated)



The low bias in total cloud cover seen in CMIP3 persists in CMIP5

black curves -- total could cover integrated over the Southern Ocean for each month from **ISCCP (solid) and CFSR (dashed)**.
red curve -- 20-year average from the Pre-Industrial Control simulation
green curve -- from the Historical simulation (~1986-2005)
blue curve -- from the RCP8.5 simulation (~2081-2100).

Climatological Seasonal Cycle in the Sea Ice Cover

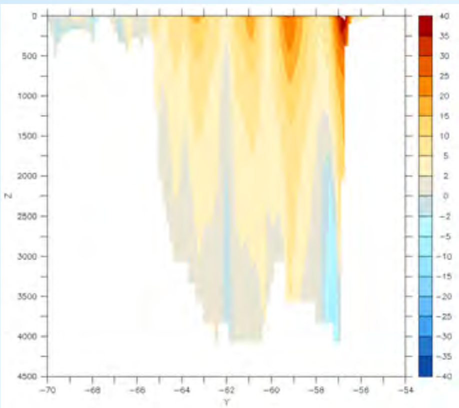


Subsurface Properties: Physics

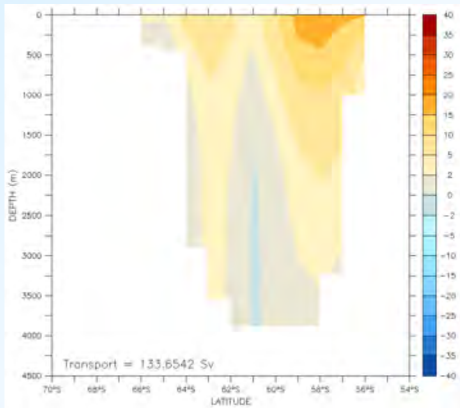
- Mean stratification
  - controlled by the surface forcing and eddy transports of buoyancy
  - SAMW/AAIW are critical for heat/carbon uptake
  - isopycnal orientation is important for the global thermohaline circulation
- Drake Passage heat and volume transport
  - controlled by winds, eddy buoyancy fluxes and dissipation
- Stratification and volume/heat exchanges at the northern flank of ACC
  - these exchange impact the heat/carbon storage in the Southern Ocean
  - impact global stratification
- Heat Content in the upper 2000m and deep ocean
  - climatology and trends/variability are both important
  - together with lateral heat exchanges, changes in heat content help to diagnose heat uptake
  - heat uptake in the deep ocean is an important indicator

Drake Passage transport: Zonal Velocity at 69°W

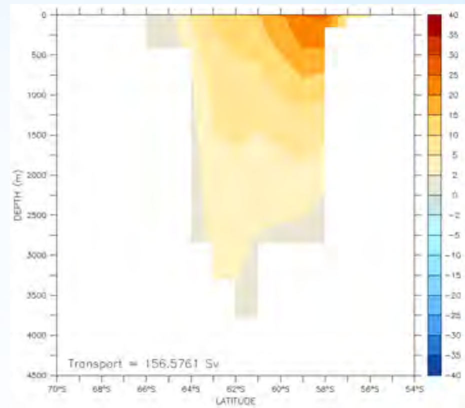
SOSE (2008)
148.1 Sv



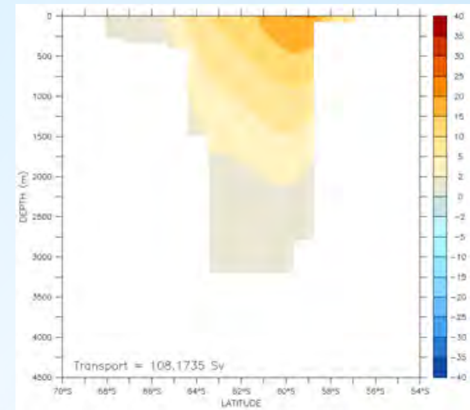
GFDL-ESM2M
133.7 Sv

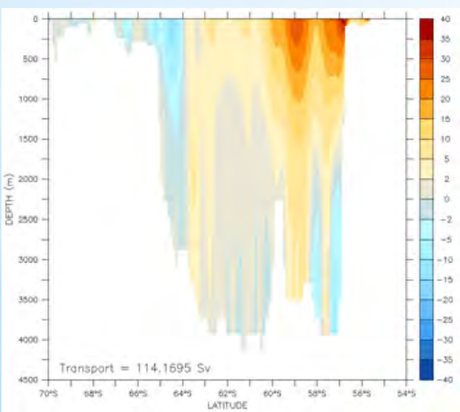


BCC-CSM2
156.6 Sv

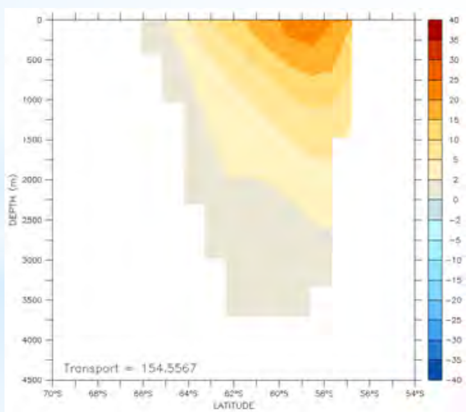


CSIRO-Mk3.6
108.2 Sv

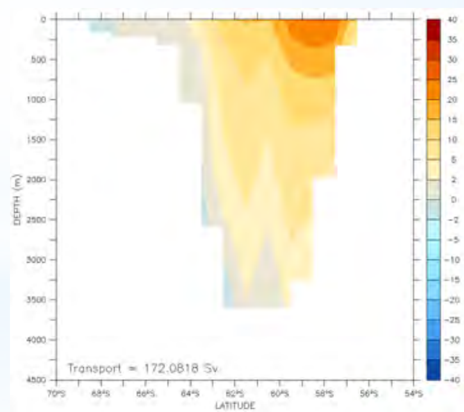




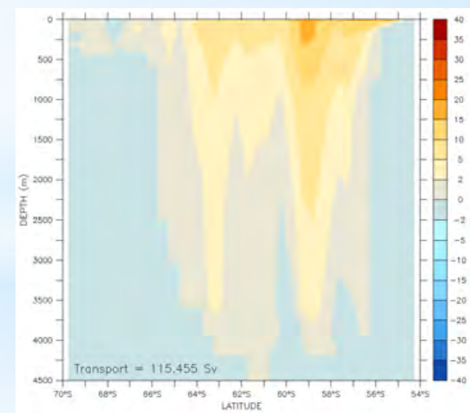
GFDL-CM2.5
114.2 Sv



CanESM2
154.6 Sv



HadGEM2-ES
172.1 Sv



MRI
115.5 Sv

Annual mean (2001-2005) zonal velocity and net transport

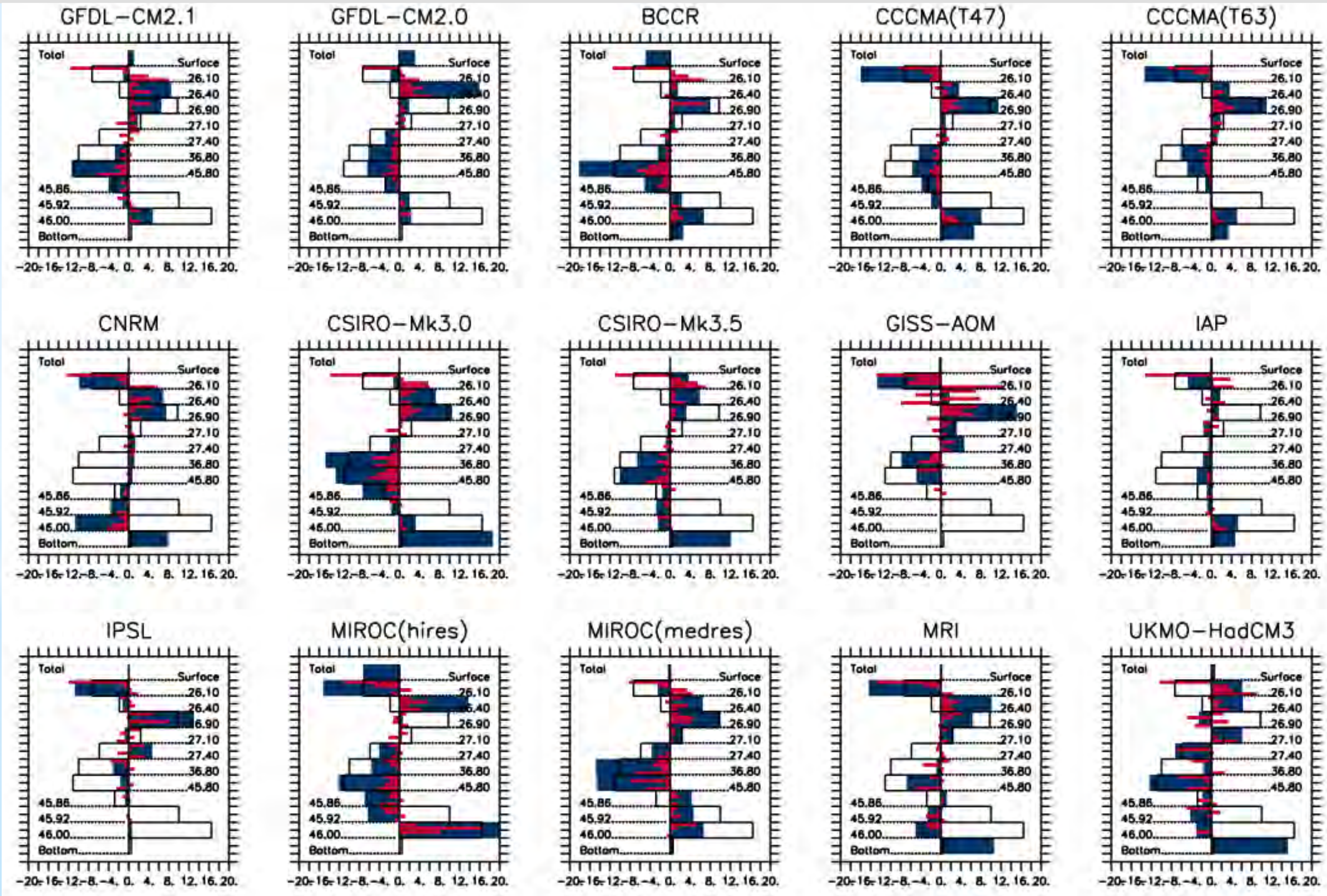
Volume exchanges (Sv) across 30°S (Global)

(IPCC-AR4 Historical Simulations; 1981-2000 Annual Mean)

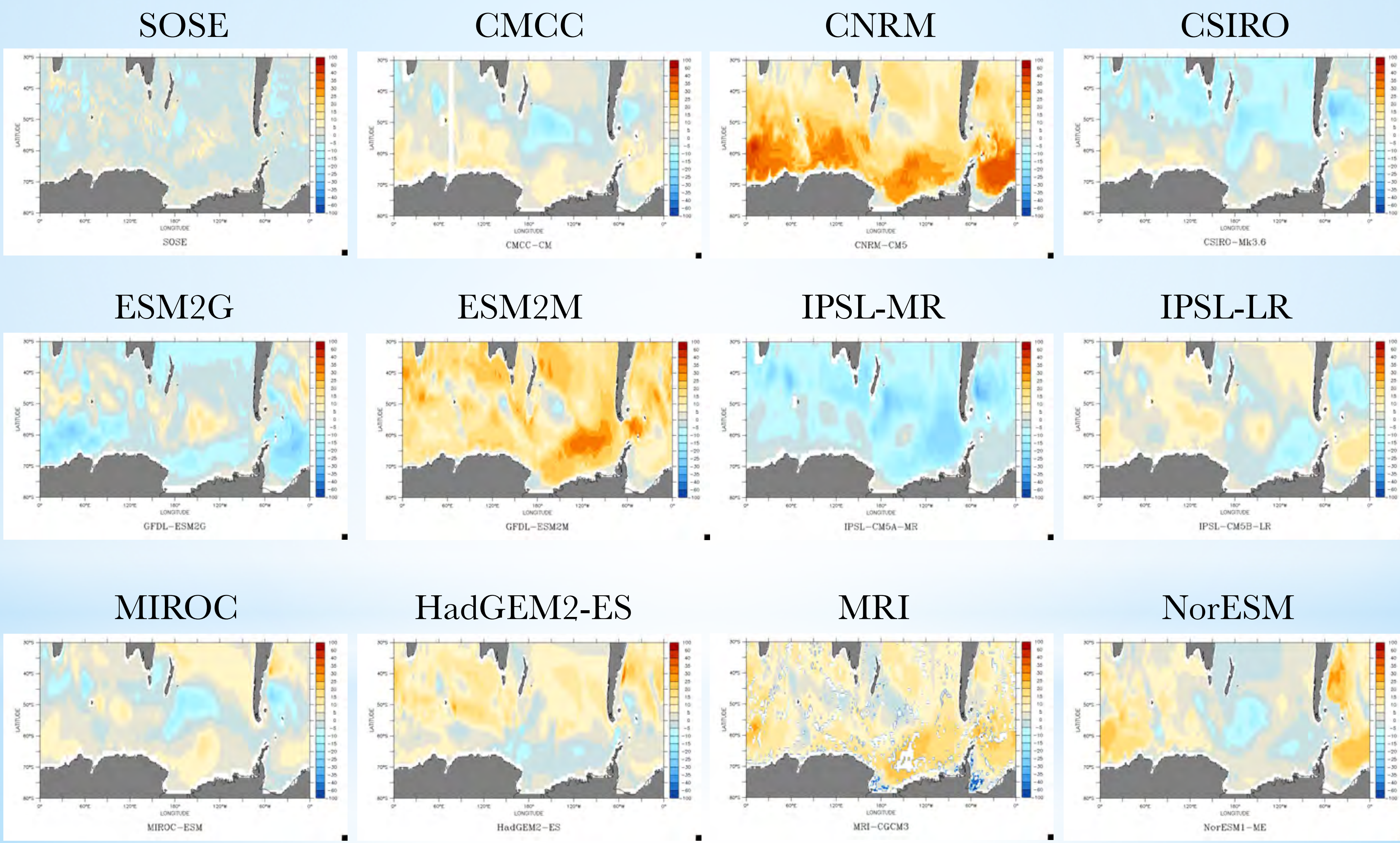
Thin black bars are density-based layer estimates from Talley (2008)

Thick blue bars are modeled layer transports (northward is positive)

Thin red bars are subdivided layer transports (4 equal subdivisions per blue bar)

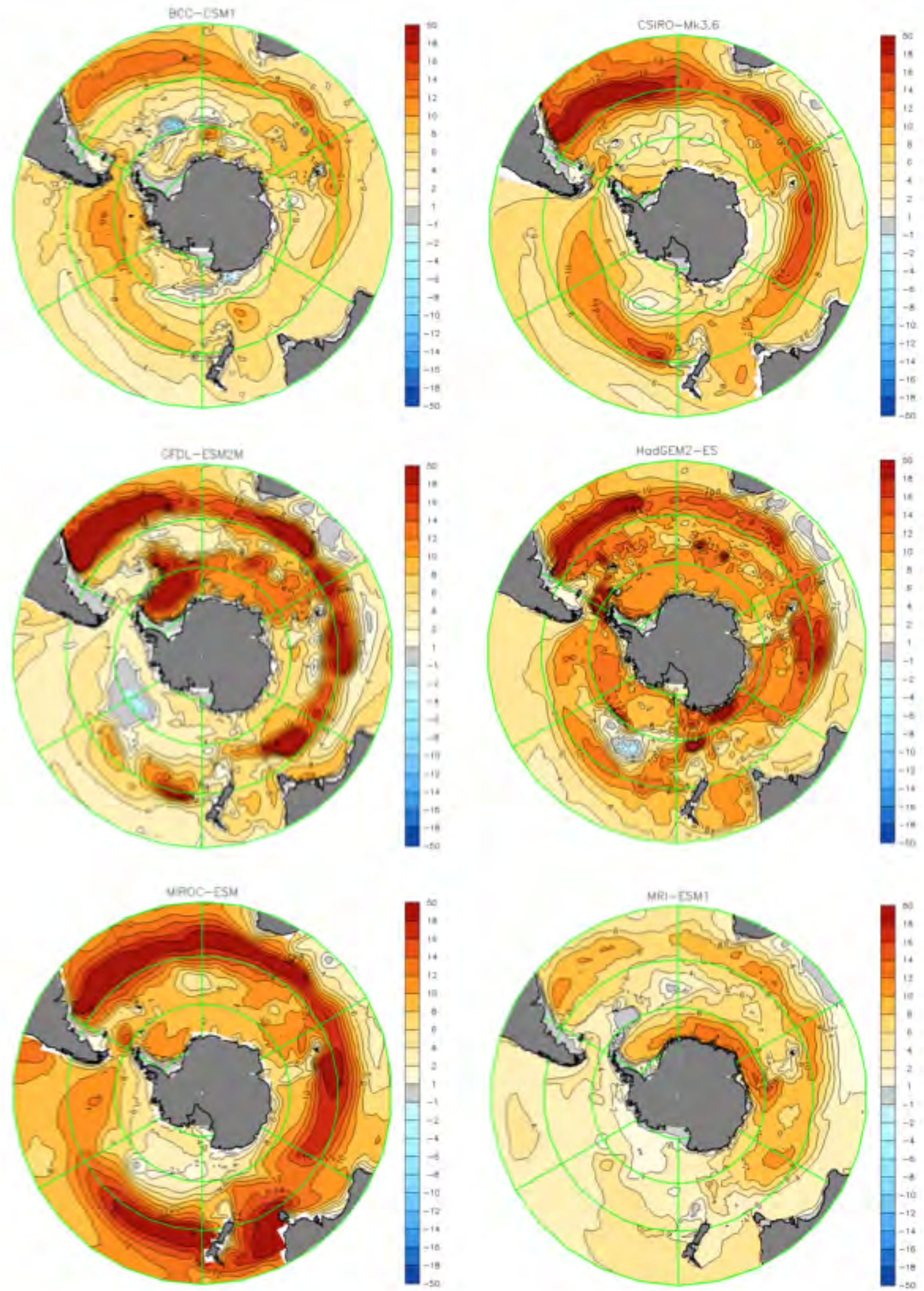


Ocean Heat Content bias (10^9 J/m^2, difference with WOA2009)



All averages are for model years 1986-2005, SOSE is annual average for 2008

Change in the Ocean Heat Content

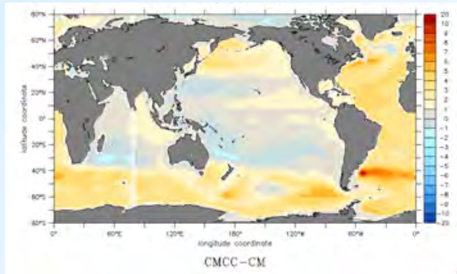


The change in Southern Ocean Heat Content (in 10^9 J/m^2) as simulated by the models from (1986-2005) to (~2081-2100).

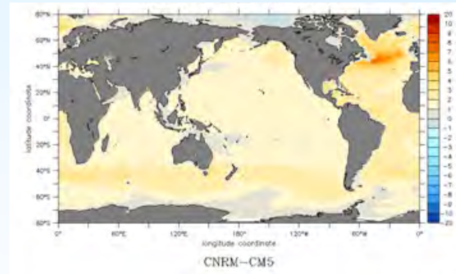
The entire Southern Ocean warms.

Change in the Heat Uptake (W/m^2, 2081-2100 minus 1986-2005)

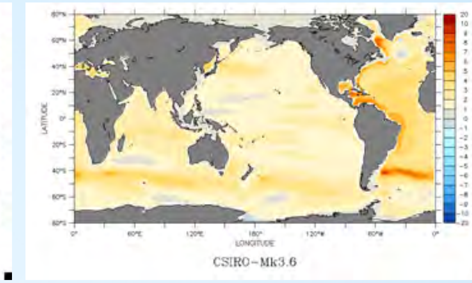
CMCC



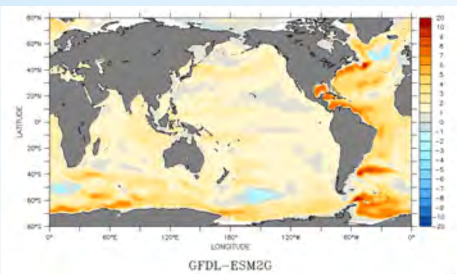
CNRM



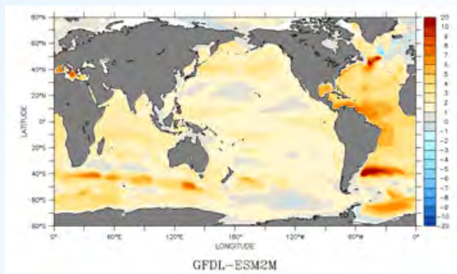
CSIRO



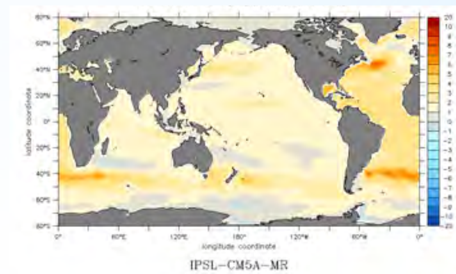
ESM2G



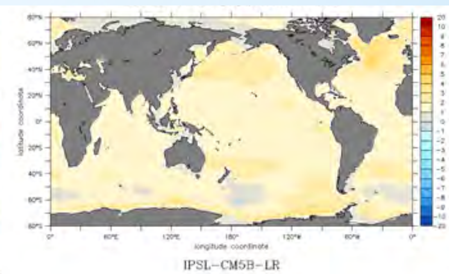
ESM2M



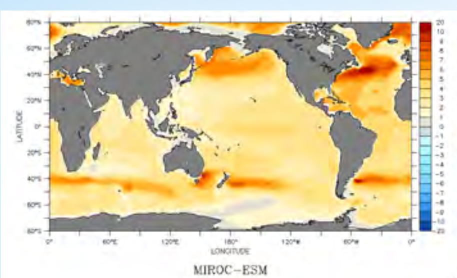
IPSL-MR



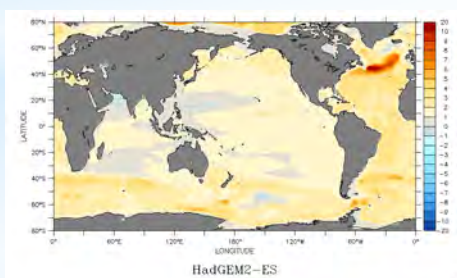
IPSL-LR



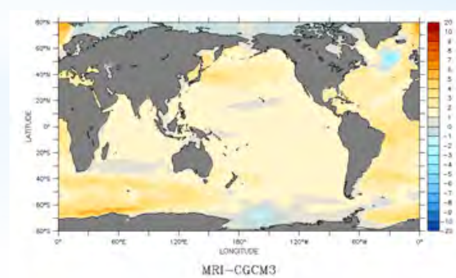
MIROC



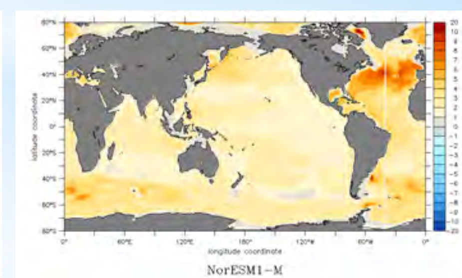
HadGEM2-ES



MRI

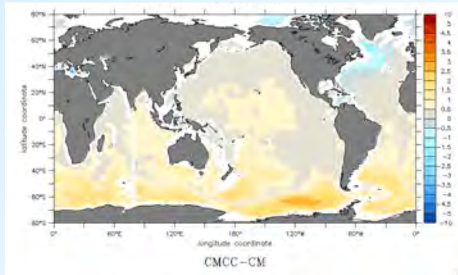


NorESM

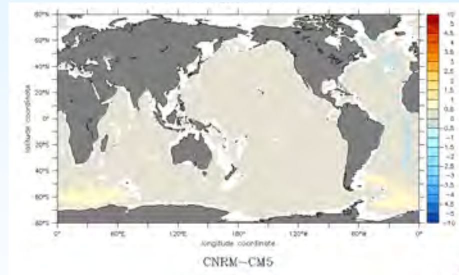


Change in the Heat Uptake by the Deep Ocean (below 2000m, W/m^2, 2081-2100 minus 1986-2005)

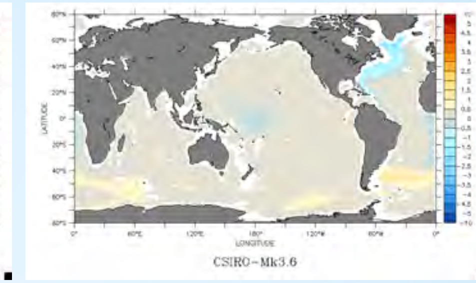
CMCC



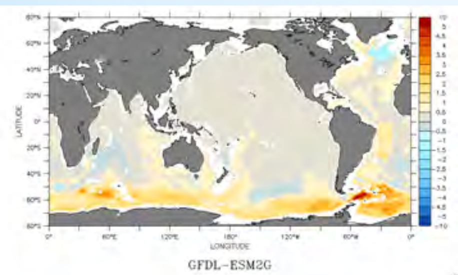
CNRM



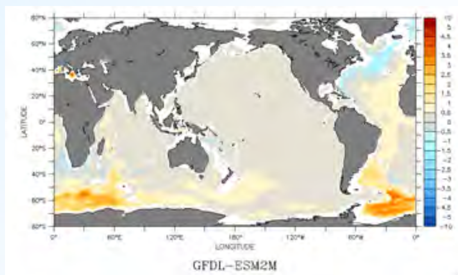
CSIRO



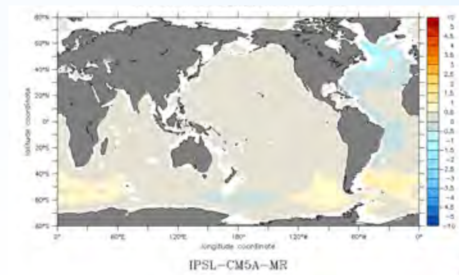
ESM2G



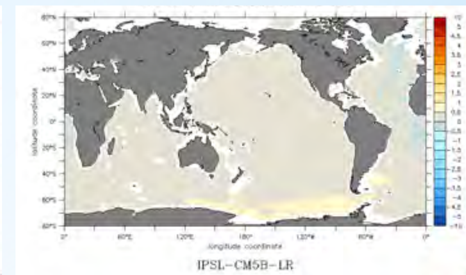
ESM2M



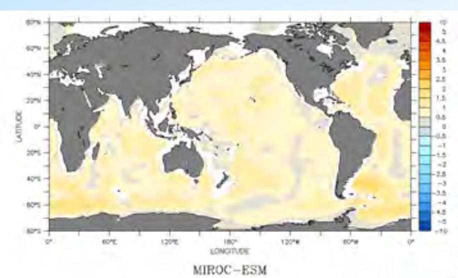
IPSL-MR



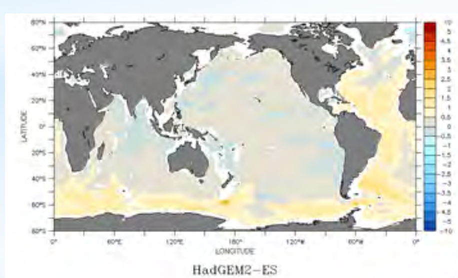
IPSL-LR



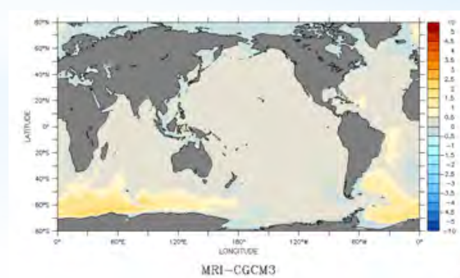
MIROC



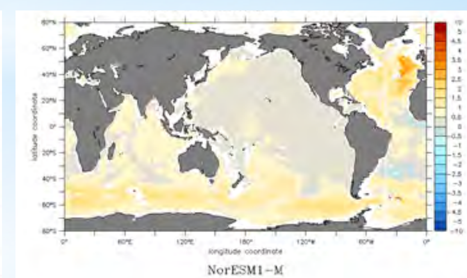
HadGEM2-ES



MRI



NorESM



Biogeochemical (BGC) properties

- Surface pCO2 variance
- Aragonite saturation depth
- Alkalinity sections (P16, A16, Indian Ocean)

- Nutrients (oxygen, phosphorous, nitrogen)
  - distributions within SO (P16, A16, Indian Ocean)
  - exchanges across 30S

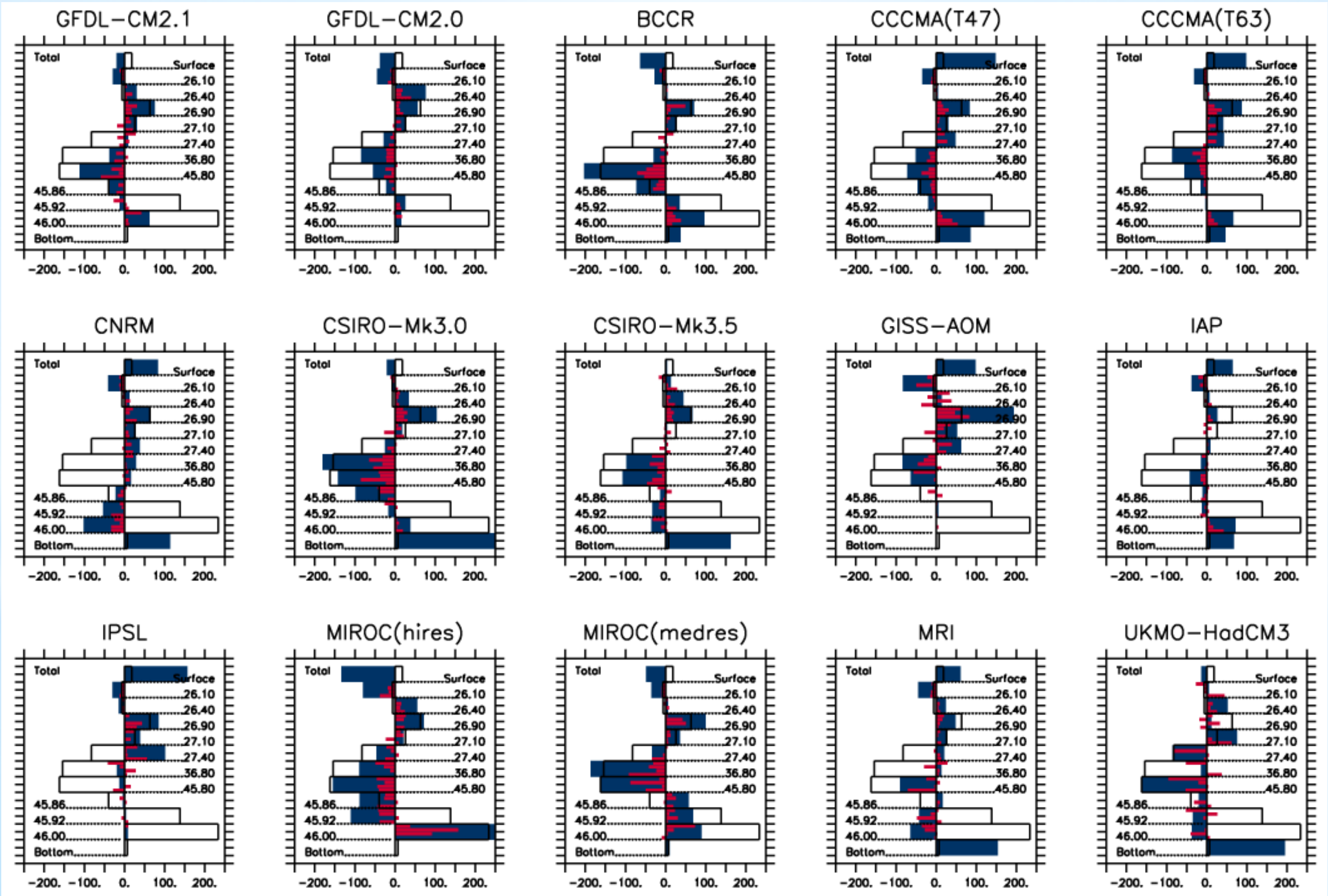
- pH distributions
- DIC inventories

- Uptake of total carbon

IPCC-AR4 Historical Simulations (1981-2000 Annual Mean)
Nitrate transport (TgN/yr) across 30°S (Global)

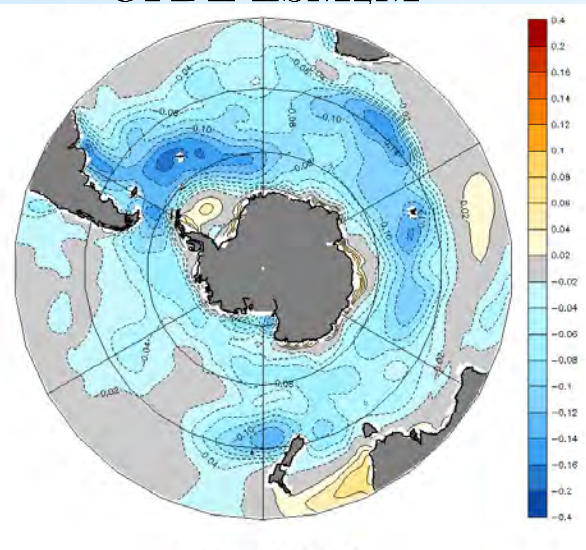
Black bars: volume transport (from Talley, 2008) multiplied by the WOA01 nitrate

Blue bars: volume transport multiplied by the WOA01 nitrate

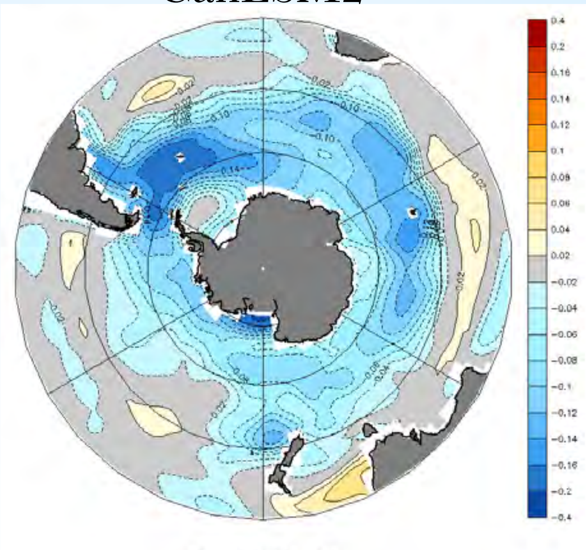


Surface pH biases (annual-mean (2001-2005), from GLODAP/WOA2001)

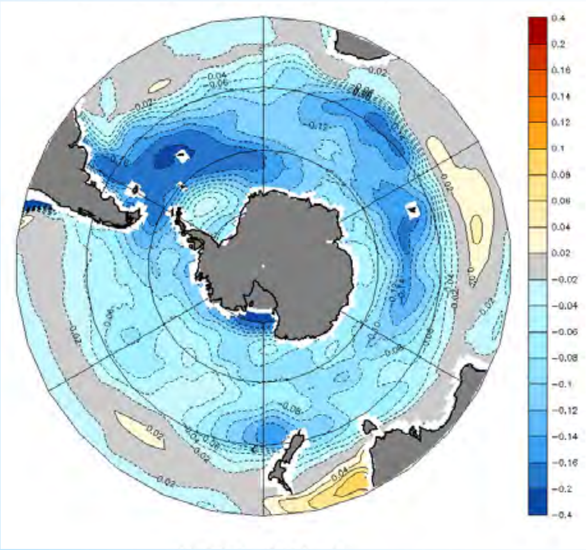
GFDL-ESM2M



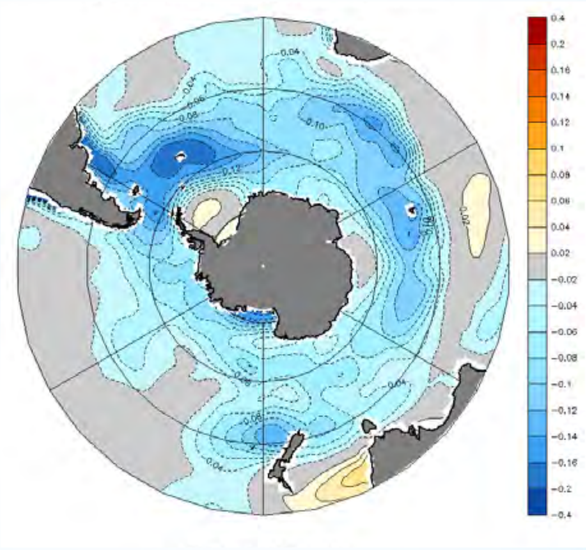
CanESM2



MIROC-ESM



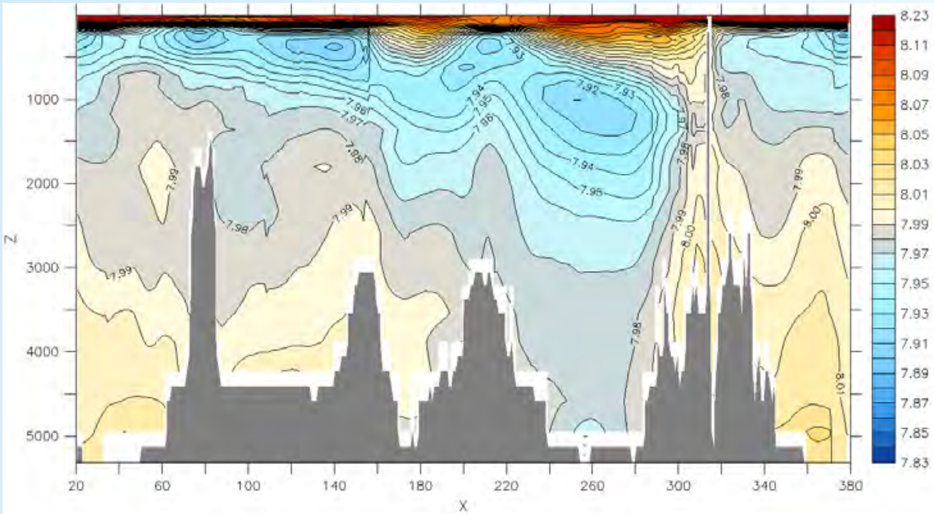
MRI-ESM1



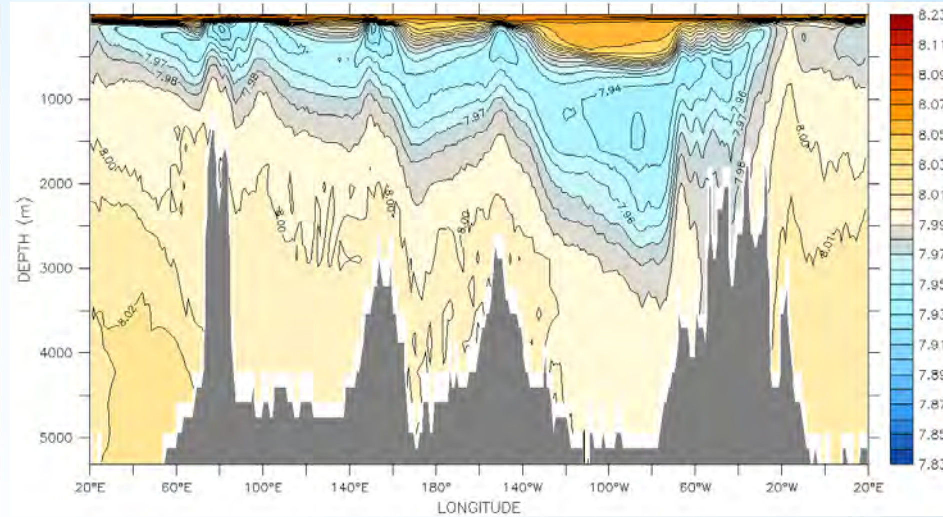
Observed pH was calculated from the GLODAP TCO_2 and alkalinity and the World Ocean Atlas (2001) temperature and salinity, using the formulas from Dickson (2007)

Southern Ocean pH at 60°S (annual mean 2001-2005)

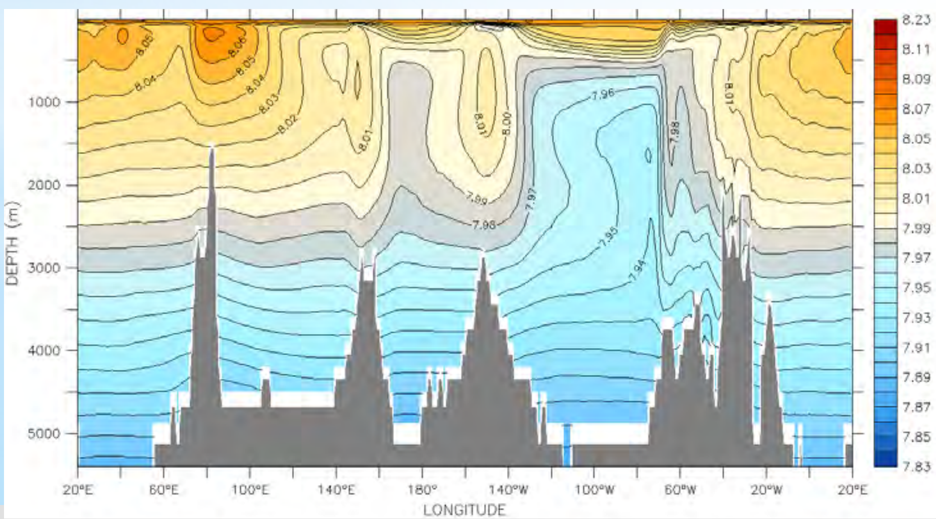
Observed



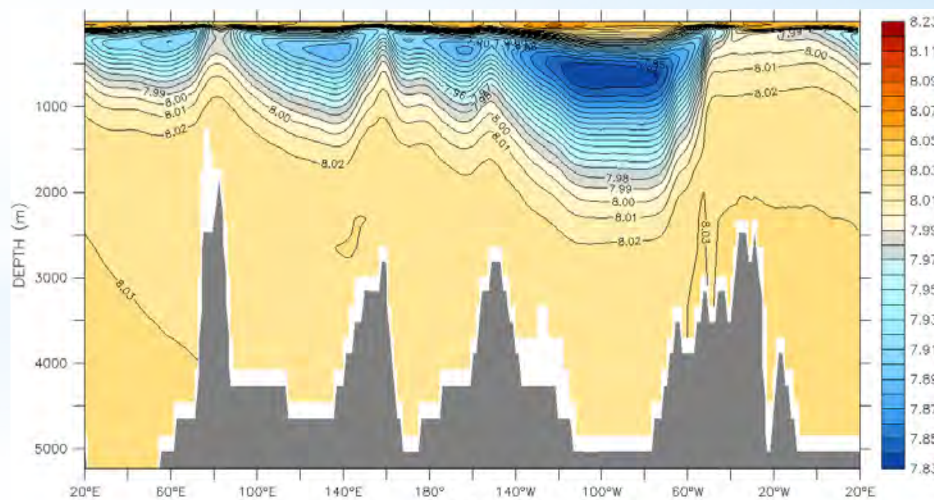
GFDL-ESM2M



MRI-ESM1

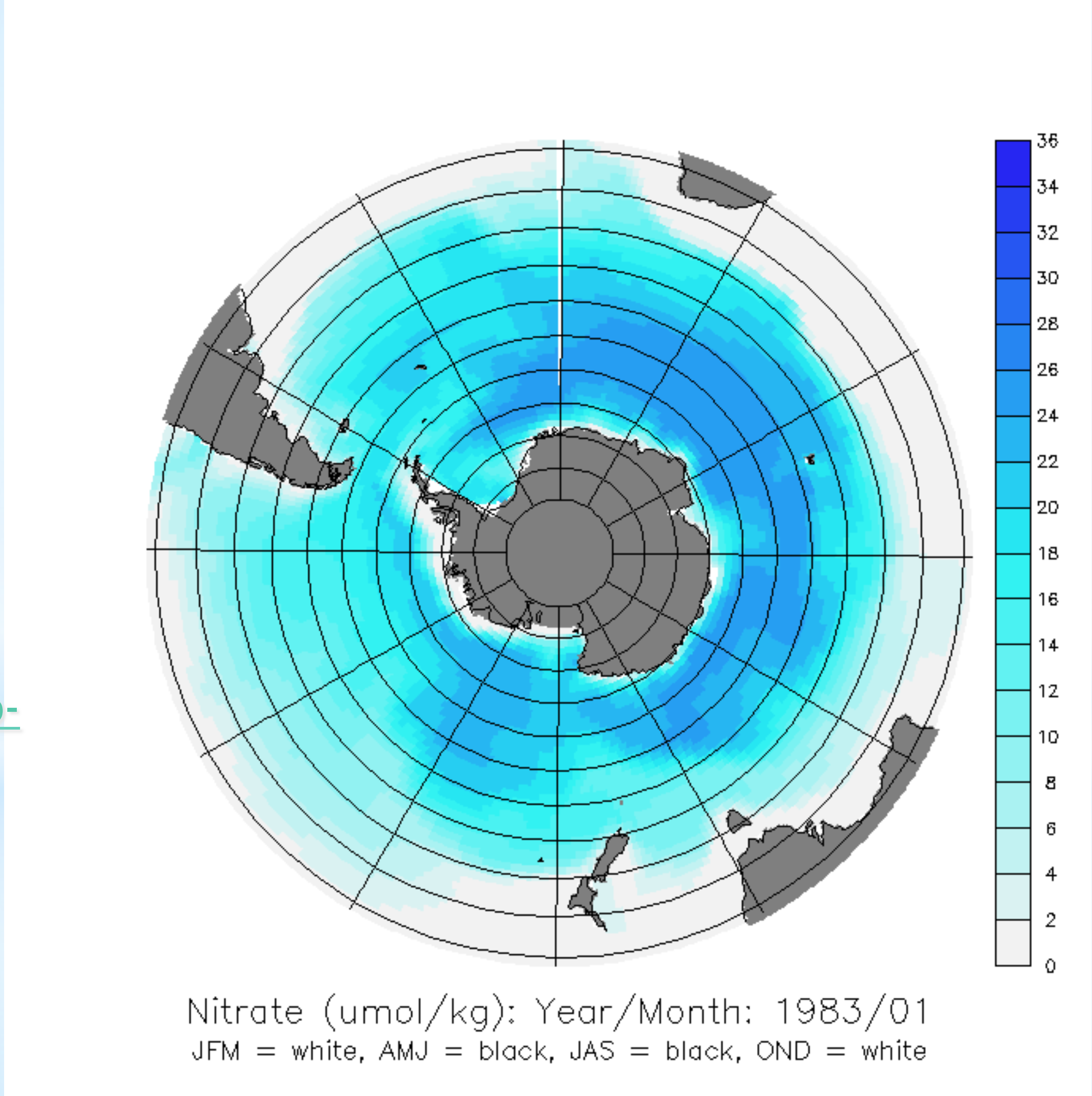


CanESM2



(Observed pH was calculated from the GLODAP TCO_2 and alkalinity and the World Ocean Atlas (2001) temperature and salinity, using the formulas from Dickson (2007)

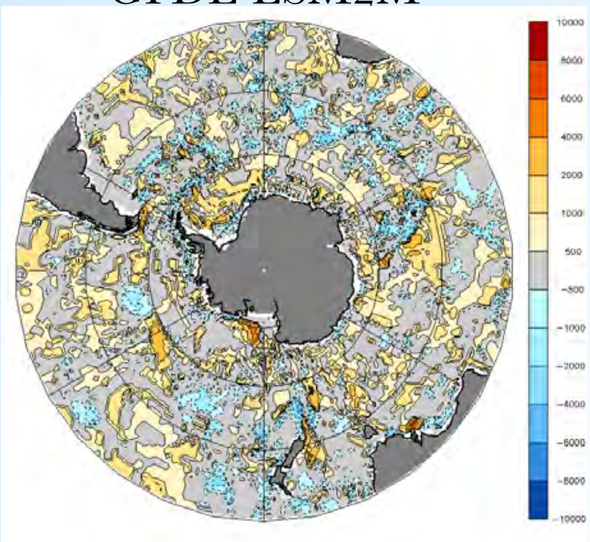
Animation of Southern Ocean Nitrate: Modeled and Observed CM2.6 Nitrate as background with observations overlaid



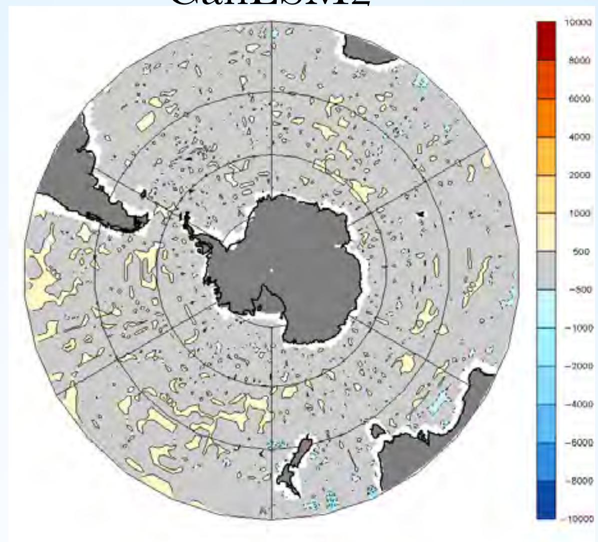
Potential projected Bio-Argo through SOCCOM

Column Inventory DIC Difference (annual-mean (2001-2005) in mol/ m^2; difference with GLODAP)

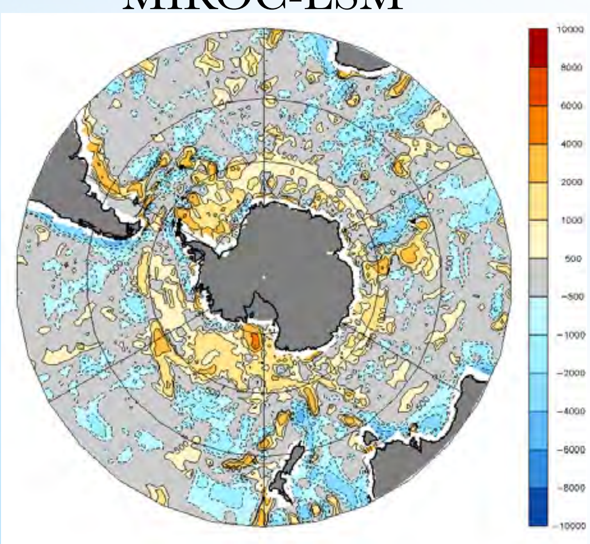
GFDL-ESM2M



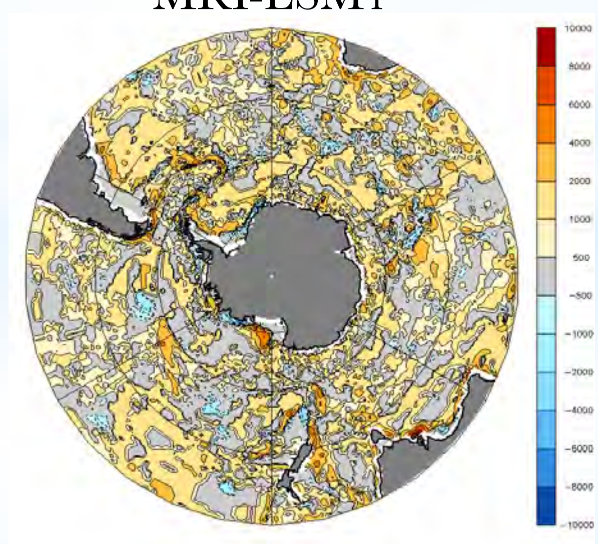
CanESM2



MIROC-ESM

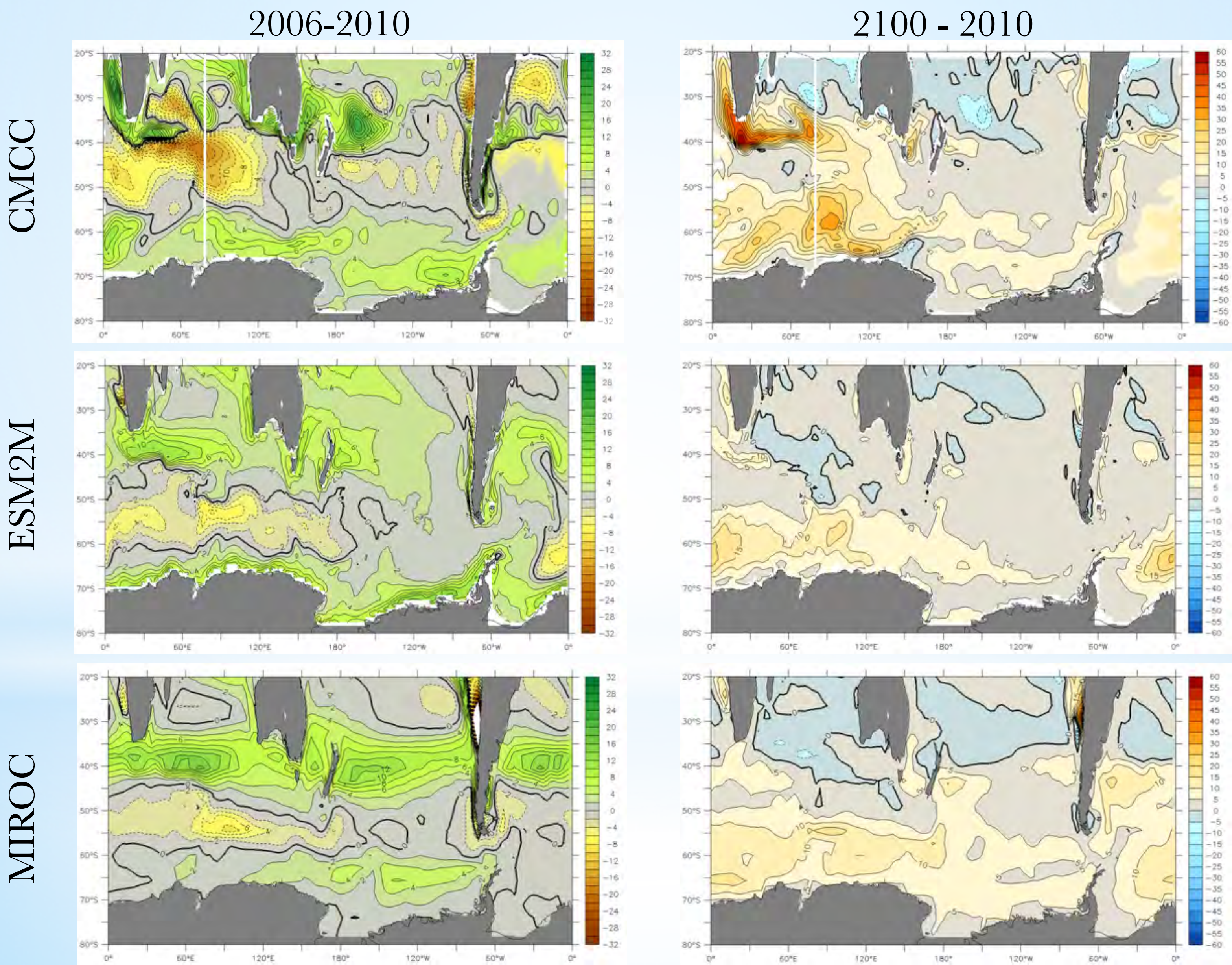


MRI-ESM1



Some of the column inventory difference may reflect differences in the model bathymetry from observed

Change in the Southern Ocean Carbon Uptake(mol/m²/yr, RCP8.5)



Mesoscale eddies and eddy-induced fluxes

Mesoscale Eddies:

- play a key role in setting the stratification in the SO;
- regulate surface heat/carbon uptake and exchanges at the base of the mixed layer;
- result in the meridional along-isopycnal transport that play a key role in ventilation of the mid-depth and deep SO

Issues:

- CMIP-class models parameterize these transports; these transports are not always available
- observations are not available, except in the DIMES region

Metrics: "Eddy diffusivity"

Along-isopycnal gradients of
Eddy-permitting models can be used to estimate "eddy diffusivities".
They can be compared to parameterizations used in coarse-resolution models

- Significance of the differences is not clear
- These estimates reveal complexity of eddy properties: dependence on the mean flow ("steering levels"), transport barriers, anisotorpy

Southern Ocean Working Group Model Metrics

Ocean Carbon & Biogeochemistry

U.S. CLIVAR Climate Variability & Predictability

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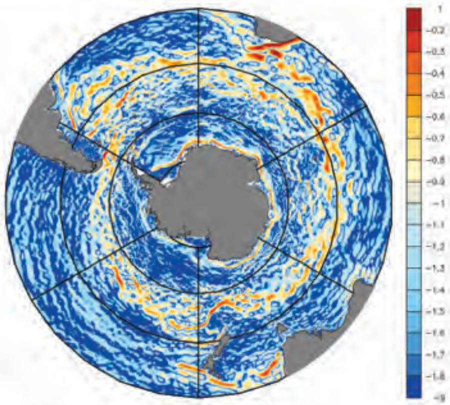
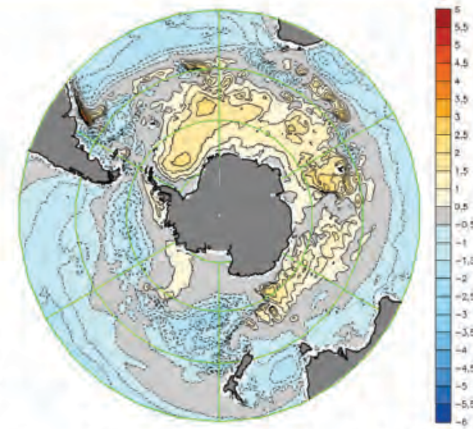


Log of Surface current speed (GFDL-CM2.6)

The use of observationally-based ***metrics*** for the evaluation and assessment of climate model simulations is essential for the reduction of uncertainty in climate model projections of the future. The Southern Ocean Working Group (SOWG) has compiled a series of metrics that efficiently quantify the representativeness of simulations relative to a wide range of variables.

This Atlas allows users to view standard metrics applied to a wide range of cimate model simulations and to download the scripts necessary to analyze new simulations or to base the various metrics on new observations.



Sea surface temperature error (GFDL-CM2.5)

METRICS	SCRIPTS	MAPS	MODELING CENTERS	LINKS
Carbon (DIC)	Excel	Latitude/Longitude	BCC	**Observations:**
Heat Flux	FERRET	Longitude/Depth	CCCma	CDIAC
Heat Transport	Fortran	Latitude/Depth	CMCC	ESRL
Nutrients	GrADS	Polar	CNRM	NODC
Overturning	MATLAB		CSIRO	
Salt	NCL	Profiles (Depth)	GFDL	**Model Simulations:**
Temperature		Zonal Averages	GISS	PCMDI
Velocity			INM	
Water Masses		Inverse Estimates	IPSL	**Model Code:**
Wind Stress			MPI	GFDL
			NCAR	NCAR
see more...	see more...	see more...	see more...	see more...

Email: sowg_metrics@usclivar.org