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

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

OCB Ocean Carbon & Biogeochemistry

U.S. CLIVAR Climate Variability & Predictability

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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
Raffaele Ferrari	Massachusetts Institute of Technology
Sarah Gille	University of California, San Diego/SIO
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 the role of mesoscale eddies in the heat and carbon uptake by the Southern Ocean.
- Improve understanding of how the Southern Ocean stratification, circulation and heat and carbon uptake will respond to a changing climate.

SOWG Outcomes and Deliverables

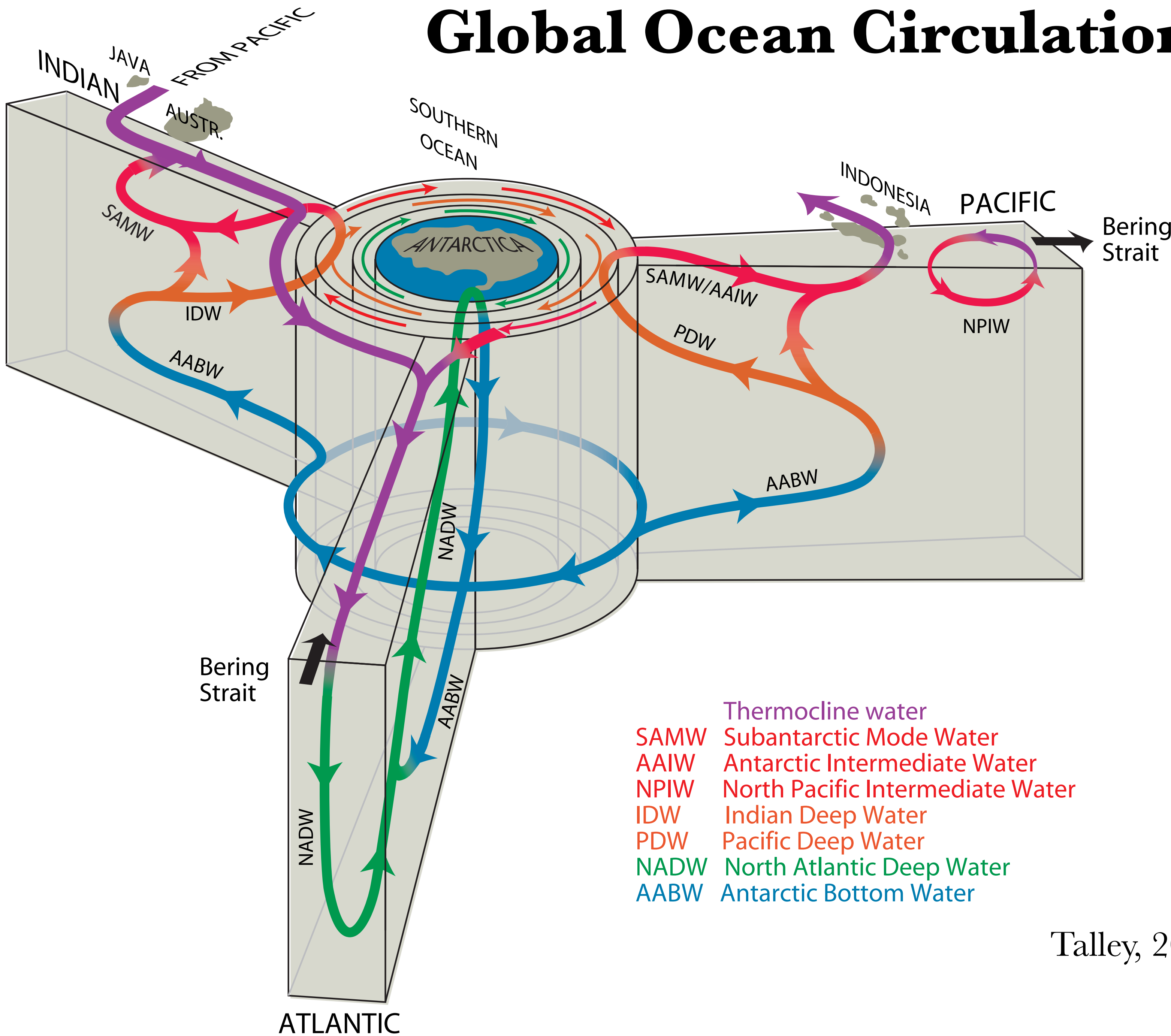
- Observationally-based data/model metrics for the consistent evaluation of modeling efforts by Southern Ocean and Antarctic scientists. Will be available on UA-hosted Southern Ocean Climate Model Atlas website.

- A Manuscript for submission to the Journal of Climate that:
  (i) assesses the state of our understanding of the role of eddies in the Southern Ocean in both the data and the models;
  (ii) identifies the most critical observational targets needed to fill in gaps in our understanding of the role of the Southern Ocean in present and future climate.

- A Workshop/Conference jointly sponsored with the Oceanic Carbon Uptake Working Group at **Fall AGU 2014**, with the goal of:
  (i) sharing the developed metrics for model evaluations;
  (ii) identifying important biases in the AR5/CMIP5-type model simulations of present and future climate, stemming from the lack of mesoscale eddies;
  (iii) providing guidance for estimating and reducing uncertainty in climate projections.

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

Global Ocean Circulation

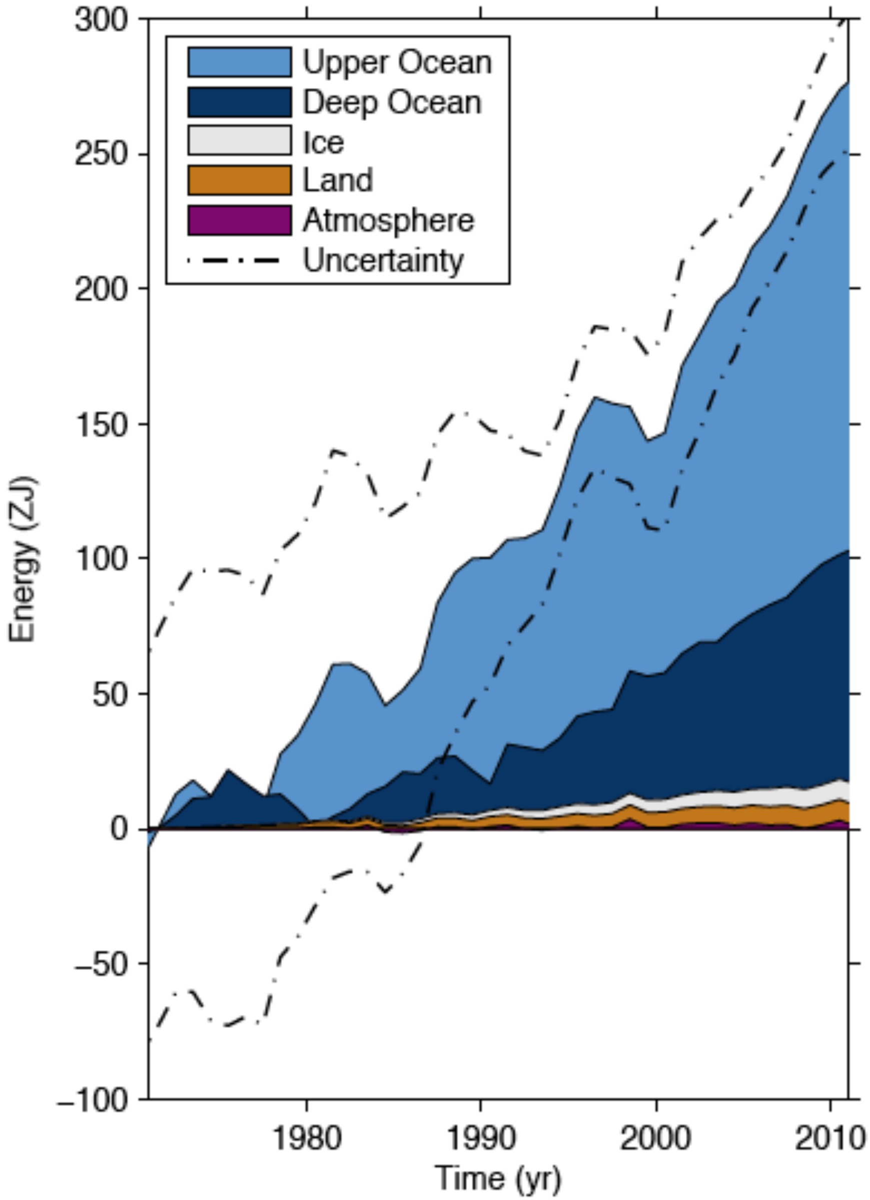


Talley, 2013

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

1. It may account for up to half of the annual oceanic uptake of anthropogenic carbon dioxide from the atmosphere (cf., Gruber et al., 2009)
2. Vertical exchange in the Southern Ocean 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. It may account for up to 70 ± 30% of the excess heat that is transferred from the atmosphere into the ocean each year (see analysis of IPCC AR4 models)
4. Southern Ocean winds and buoyancy fluxes are the principal source of energy for driving the large scale deep meridional overturning circulation throughout the ocean (e.g., Toggweiler and Samuels, 1998; Marshall and Speer, 2012)

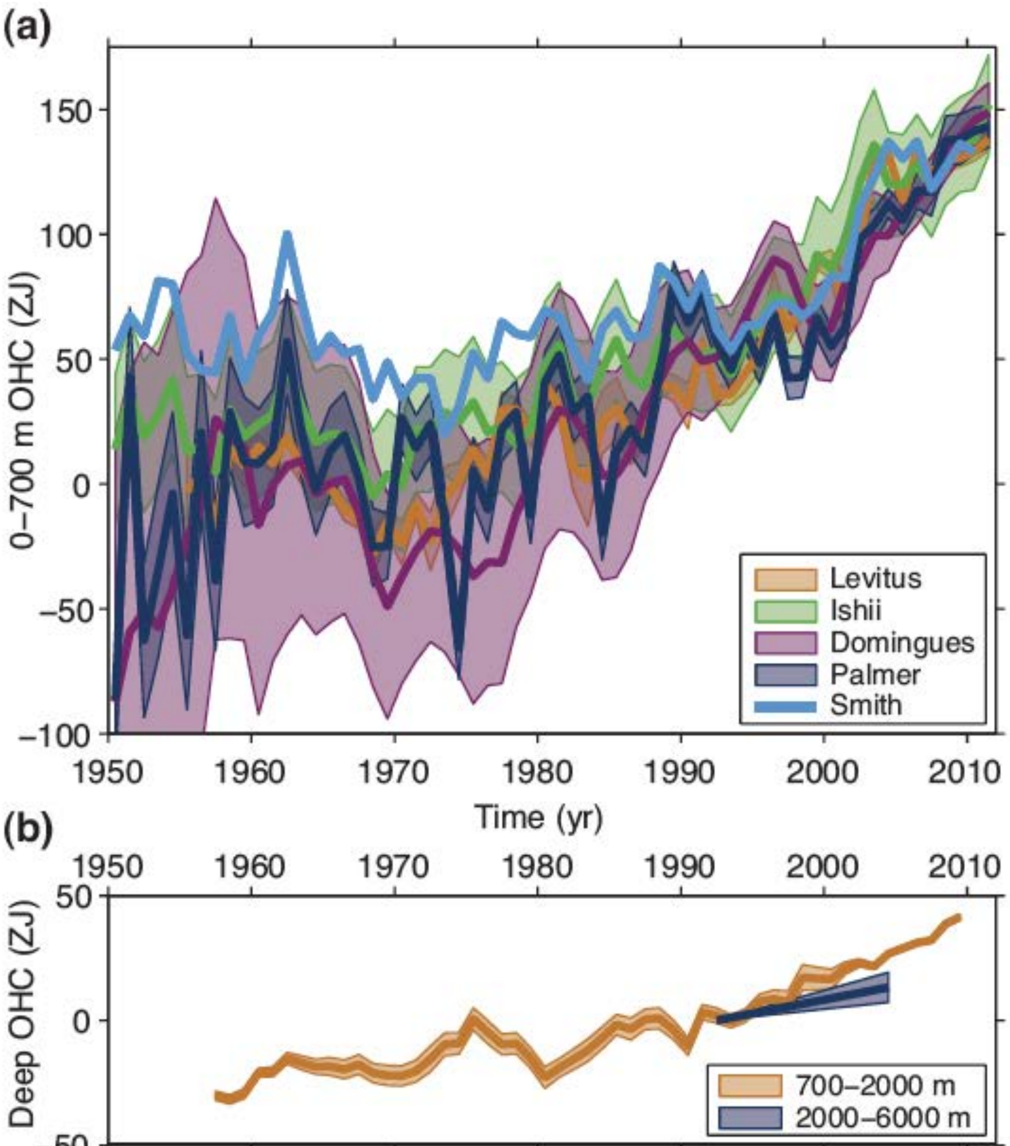
The global energy imbalance goes into the ocean



Box 3.1, Figure 1: Plot of energy accumulation within distinct components of Earth's climate system relative to 1971.

AR5

Ocean heat content is rising at all depths



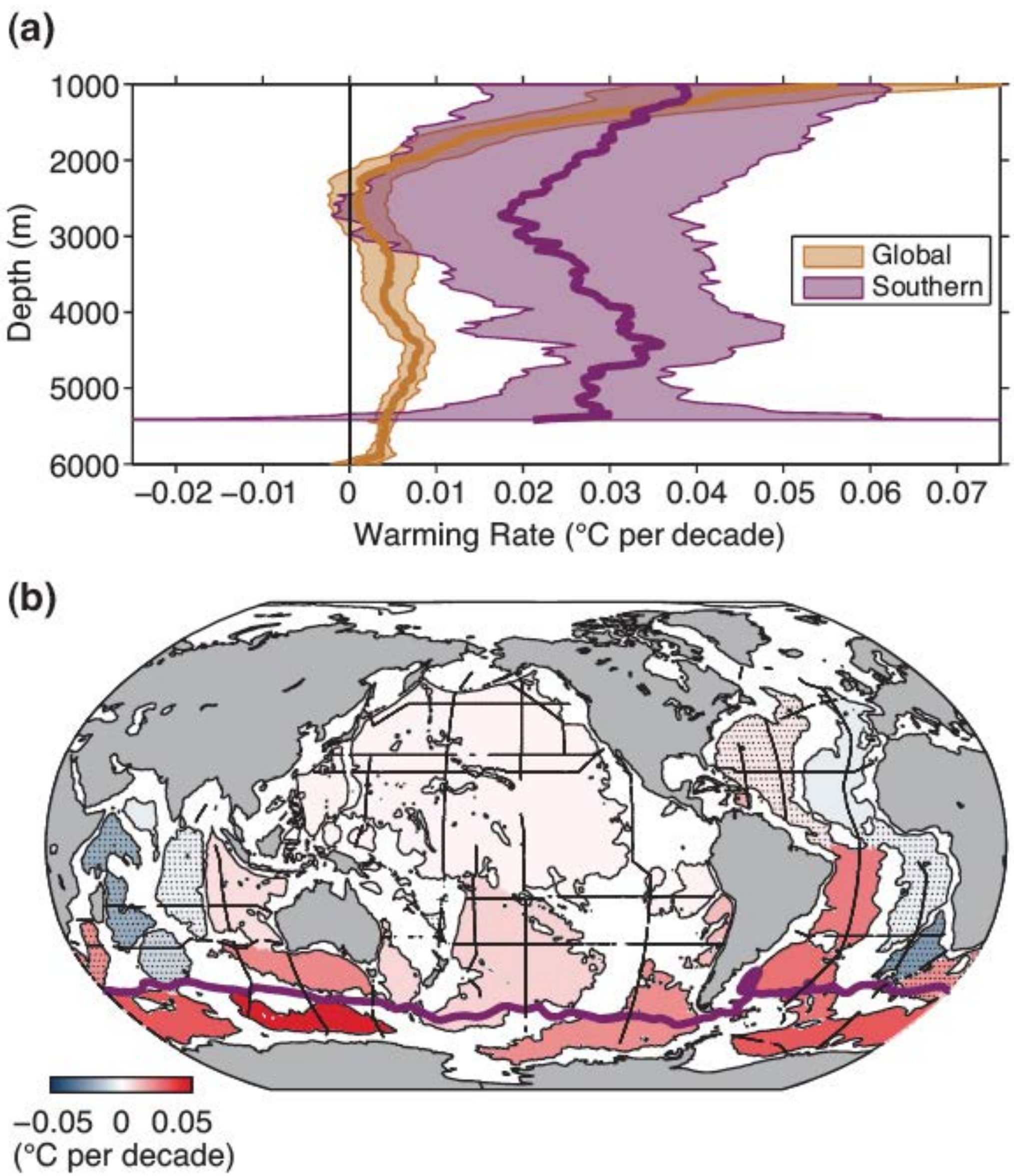
Upper Ocean (0-700m)

Figure 3.2: a) Observation-based estimates of annual global mean upper (0–700 m) ocean heat content. **b)** Observation-based estimates of annual five-year running mean global mean mid-depth (700–2000 m) ocean heat content in and the deep (2000 - 6000 m) global ocean heat content trend from 1992–2005.

Mid-depth (700-2000m)
Deep Ocean (>2000m)

AR5

The Southern Ocean and the deep ocean are warming

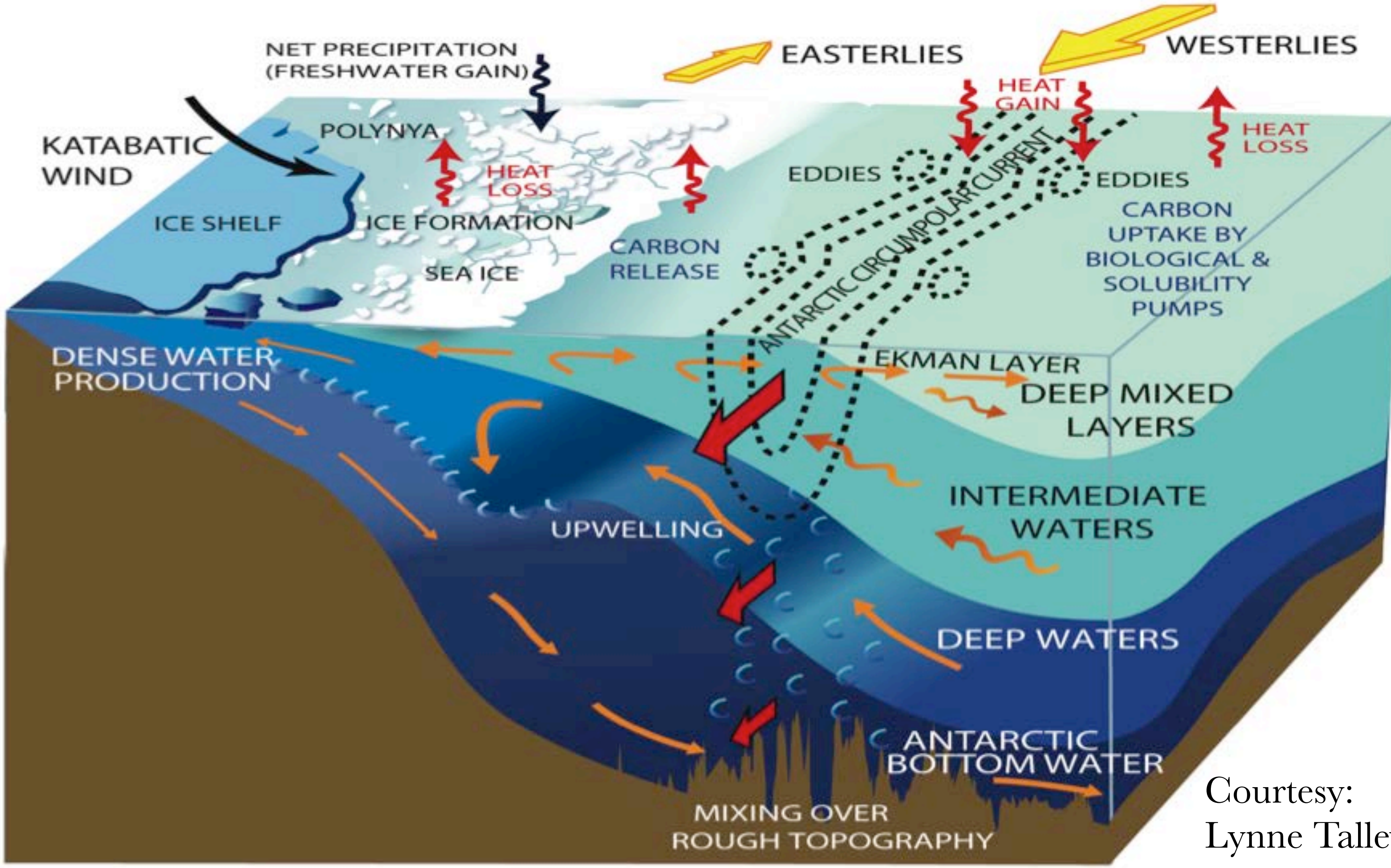


Warming Rate of Southern Ocean (purple) and global ocean (orange)

Figure 3.3: a) Areal mean warming rates (°C per decade) versus depth (thick lines) with 5 to 95% confidence limits (shading), both global (orange) and south of the Sub-Antarctic Front (purple), centred on 1992–2005. **b)** Mean warming rates (°C per decade) below 4000 m estimated for deep ocean basins (thin black outlines), centered on 1992–
2005.

Warming Rate of deep ocean (>4000m)

The Antarctic Circumpolar Current System

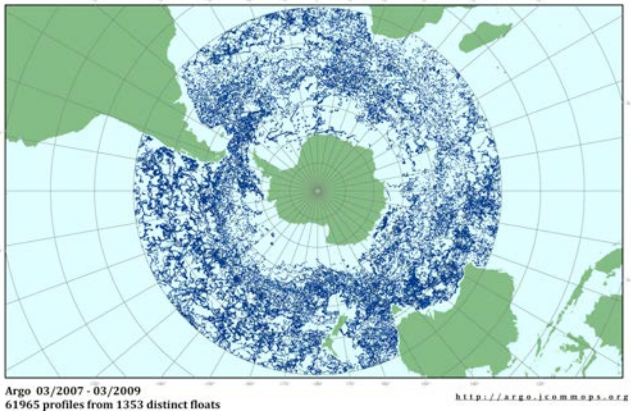


Courtesy:
Lynne Talley

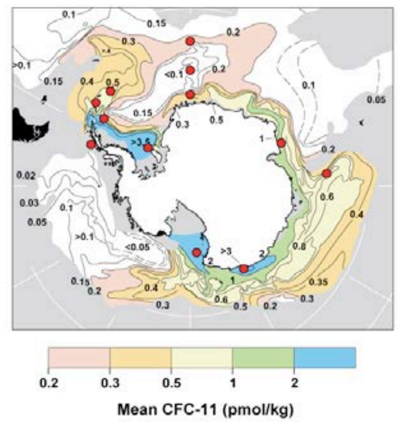
New Tools:

1) New Southern Ocean Observations
2) New Southern Ocean State Estimate
3) New Earth System Models: Carbon!
4) Mesoscale-Resolving Climate Models

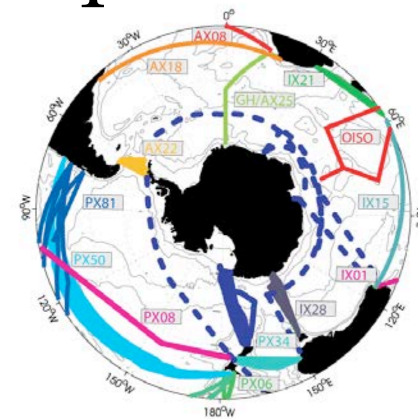
SOOS Observing System Components



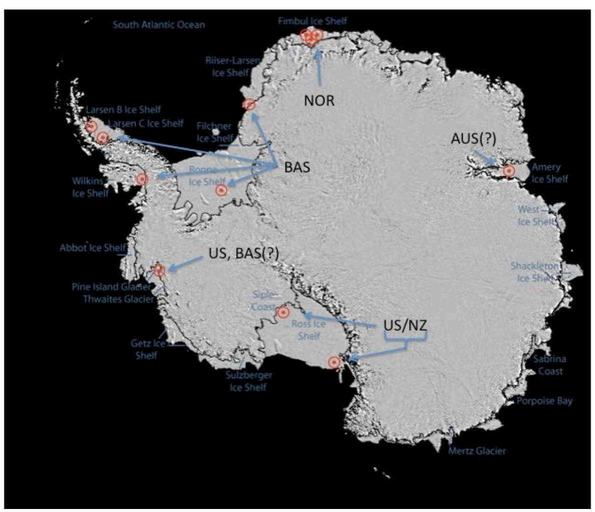
The locations of more than 60,000 Argo profiles of temperature and salinity collected during the 24 months of the IPY. Courtesy of Mathieu Balbeoch, JCOMMOPS



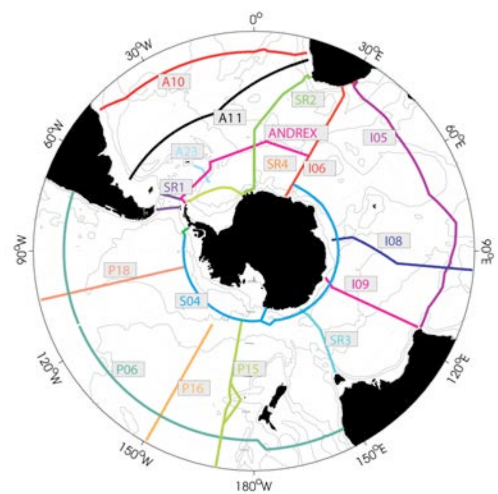
Map of proposed moored arrays (red circles) to sample the primary Antarctic Bottom Water formation and export sites



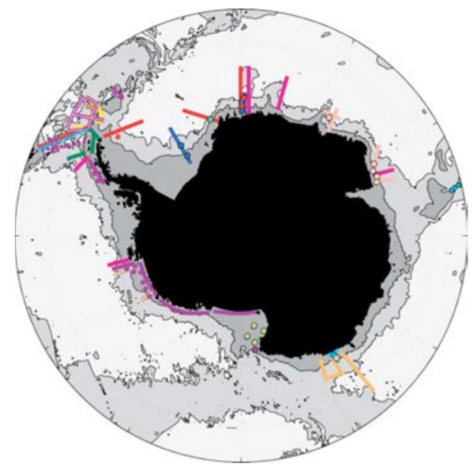
The ship-of-opportunity lines in the Southern Ocean that contribute to SOOS.



White circles indicate location of current or planned drill holes through ice shelves, allowing sampling of underlying ocean waters. .



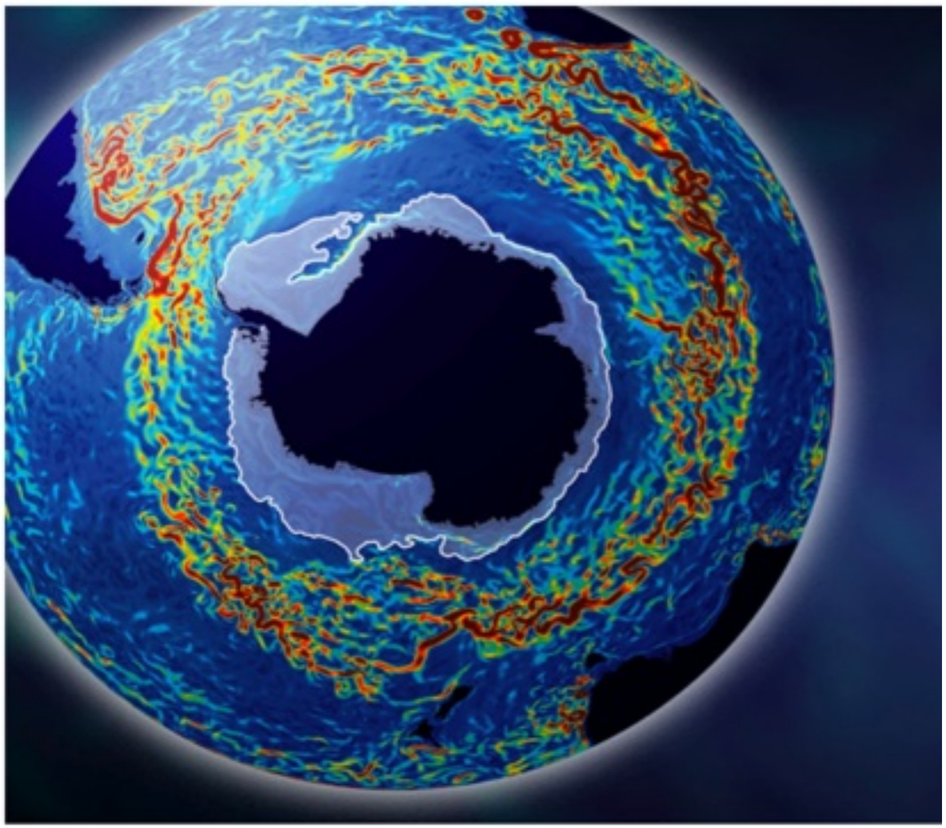
Repeat hydrographic sections to be occupied by SOOS. Symbols indicate the WOCE/CLIVAR designations for each line



Hydrographic sections (lines) and moorings (circles) occupied as contributions to the IPY SASSI program.

The Southern Ocean State Estimate (SOSE)

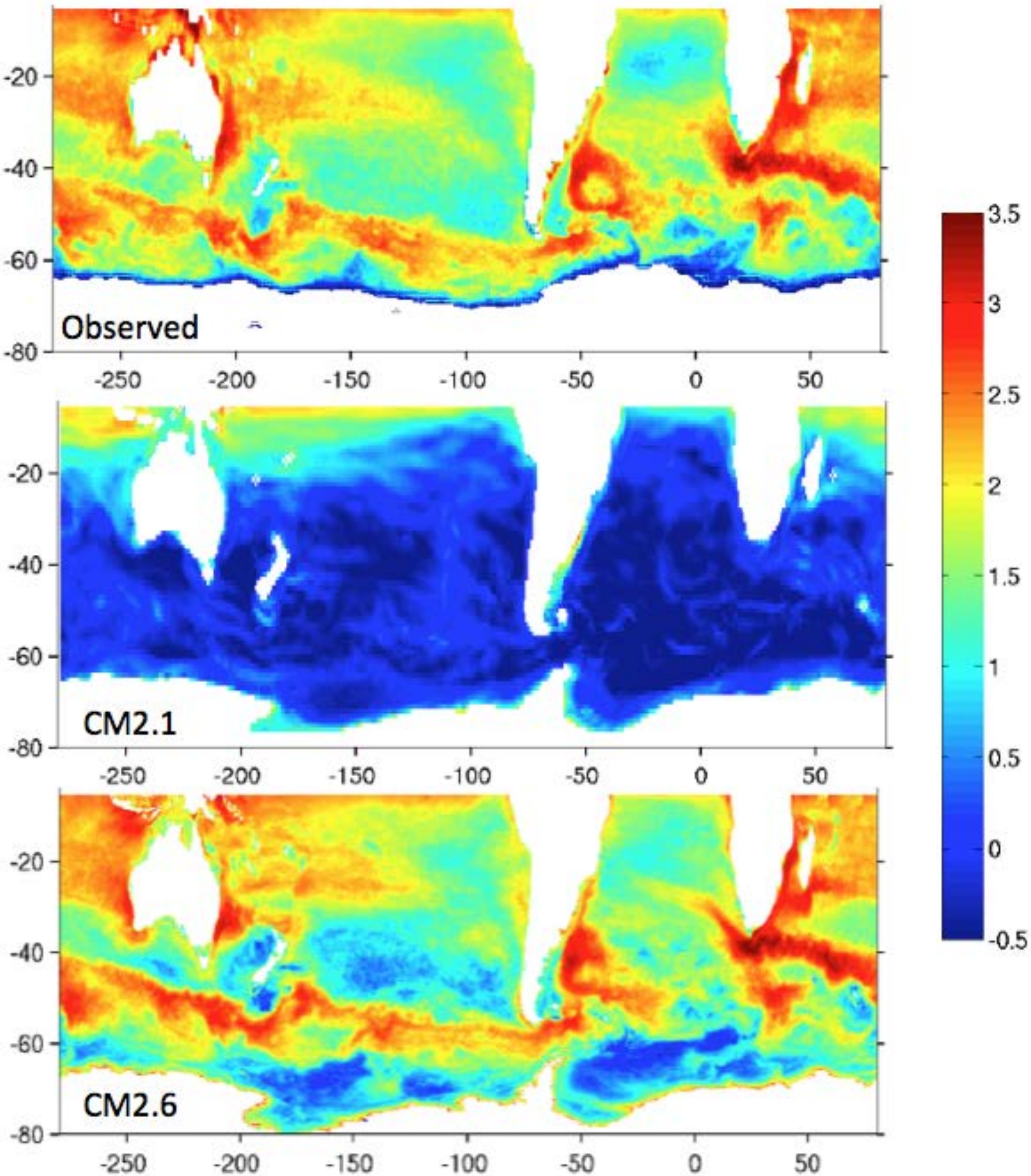
(Nominal Resolution is 1/6°)



http://sose.ucsd.edu/

M. Mazloff, P. Heimbach, and C. Wunsch, 2010: "An Eddy-Permitting Southern Ocean State Estimate." *J. Phys. Oceanogr.*, **40**, 880–899. doi: 10.1175/2009JPO4236.1

Southern Ocean State Estimation
A modern general circulation model, the MITgcm, is least squares fit to all available ocean observations. This is accomplished iteratively through the adjoint method. The result is a physically realistic estimate of the ocean state. SOSE is being produced by Matthew Mazloff as part of the ECCO consortium and funded by the National Science Foundation. Computational resources are provided in part by the NSF TeraGrid.

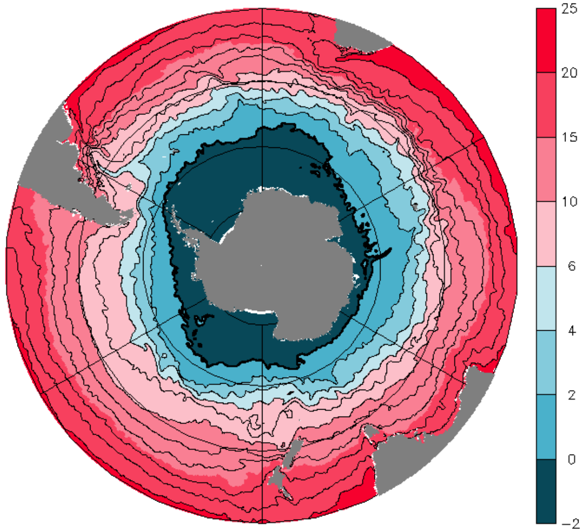


Eddy Resolving Coupled Climate Models:

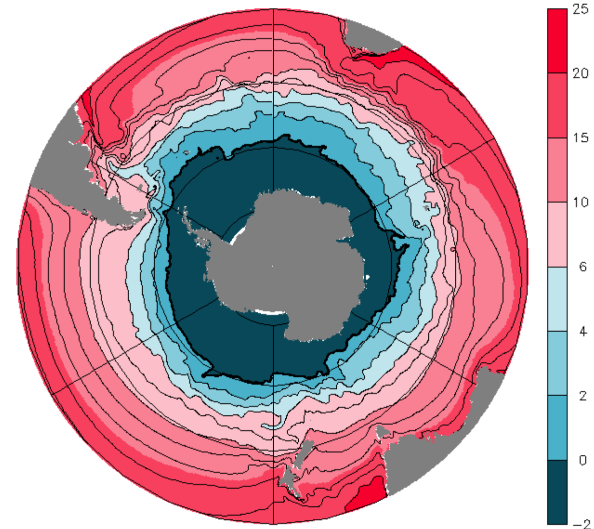
Southern Ocean Eddy Kinetic Energy

(Delworth et al., 2012)

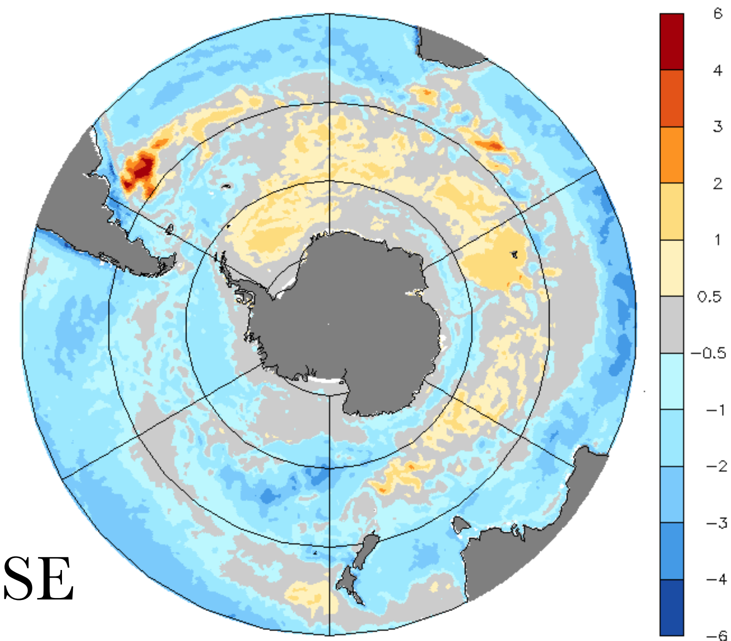
SOSE



CM2p5



SST



CM2p5 - SOSE

New Metrics

Person	Affiliation	Area of Interest	Metric(s)
Cecilia Bitz	U. Washington	Role of Sea Ice in Climate	Sea Ice Extent/Volume/Seasonality
Raffaele Ferrari	MIT	Ocean Turbulence	Eddy Kinetic Energy; Eddy-induced diffusivities and heat transport/uptake
Sarah Gille	UCSD/SIO	Air/Sea Exchange	Mixed-layer depth; Heat Content (400m) Non-solubility pCO_2 variance
Robert Hallberg	NOAA/GFDL	Ocean Dynamics	Water mass properties (upper 2000m and abyssal); Age tracer distribution; Drake Passage transport
Ken Johnson	MBARI	Chemical Sensors/ Biogeochemical Cycles	Seasonal cycle of nitrate
Igor Kamenkovich	U. Miami	Mesoscale Eddies/ Role of SO in global MOC	Stratification at the northern flank of the SO; Eddy-induced diffusivities
Irina Marinov	U. Pennsylvania	Carbon Cycle/Ecology	Oxygen, Temperature, Salinity Precipitation; Background nutrients
Matt Mazloff	UCSD/SIO	State Estimates	Mean dynamic topography; Temperature transport through the Drake Passage
Joellen Russell	U. Arizona	Role of Ocean in Climate	Strength and position of SO Westerly Winds Area of deep-water outcrop; Depth of AAIW isopycnal
Jorge Sarmiento	Princeton U.	Biogeochemical Cycles	Fractional uptake of heat and carbon by the SO
Kevin Speer	Florida State U.	Large-Scale Circulation	Stratification north and south of ACC (esp. SAMW) Mean flow/shear in SE Pacific; tracer spreading rates
Lynne Talley	UCSD/SIO	Physical Oceanography	Repeat hydrography inventories
Rik Wanninkhof	NOAA/AOML	Inorganic Carbon Cycle	Aragonite saturation state

PCMDI Data Availability
(by model and variable)

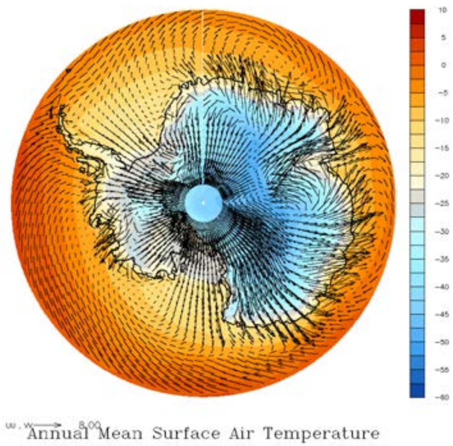
Historical Run (~1861-2005)

Carbon system variables are in green (DIC, pH, nitrate, phosphate, total alkalinity, global atmospheric CO_2, surface ocean pCO_2)

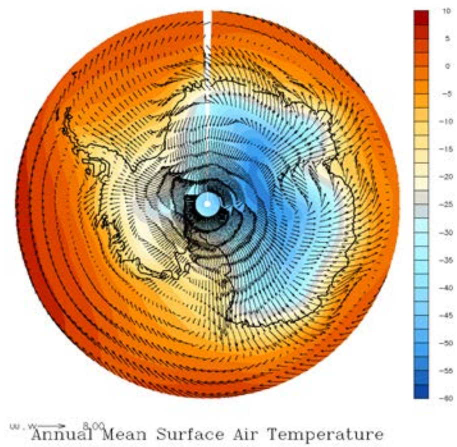
	DISSIC	pH	no3	po4	talk	cfc11	agessc	hfds	fgco2	tauuo	tauvo	thetao	so	uo	vo	tas	uas	vas	spco2
ACCESS1.0							x	x		x	x	x	x	x	x	x	x	x	
ACCESS1.3							x	x		x	x	x	x	x	x	x	x	x	
BCC-CSM1.1								x	x			x	x	x	x	x	x	x	x
BCC-CSM1.1(m)								x	x			x	x	x	x	x	x	x	x
BNU-ESM	x	x		x	x			x	x			x	x	x	x	x	x	x	x
CanCM4												x				x	x	x	
CanESM2	x	x	x		x				x	x	x	x	x	x	x	x	x	x	x
CCSM4						x	x			x	x	x	x	x	x	x			
CESM1(BGC)	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x			
CESM1(CAM5.1,FV2)						x	x			x	x	x	x	x	x				
CESM1(CAM5)						x	x			x	x	x	x	x	x	x			
CESM1(FASTCHEM)						x	x			x	x	x	x	x	x	x			
CESM1(WACCM)						x	x			x	x	x	x	x	x	x			
CMCC-CESM	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	
CMCC-CM								x		x	x	x	x	x	x	x	x	x	
CMCC-CMS								x		x	x	x	x	x	x	x	x	x	
CNRM-CM5	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	
CNRM-CM5-2								x		x	x	x	x	x	x	x	x	x	
CSIRO-Mk3.6.0								x		x	x	x	x	x	x	x	x	x	
CSIRO-Mk3L-1-2								x		x	x	x	x	x	x	x			
EC-Earth								x		x	x	x	x	x	x	x	x	x	
FGOALS-g2								x				x	x	x	x	x			
FIO-ESM												x	x	x	x	x			
GFDL-CM2.1										x	x	x	x	x	x	x	x	x	
GFDL-CM3						x				x	x	x	x	x	x	x	x	x	
GFDL-ESM2G	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
GFDL-ESM2M	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	
GISS-E2-H												x	x	x	x	x	x	x	
GISS-E2-H-CC	x		x						x			x	x	x	x	x	x	x	
GISS-E2-R								x				x	x	x	x	x	x	x	
GISS-E2-R-CC	x		x					x	x			x	x	x	x	x	x	x	
HadCM3												x	x	x	x	x	x	x	
HadGEM2-AO										x	x	x	x	x	x	x	x	x	
HadGEM2-CC	x	x	x		x				x			x	x	x	x	x	x	x	
HadGEM2-ES	x	x	x		x				x			x	x	x	x	x	x	x	x
INM-CM4	x							x	x	x	x	x	x	x	x	x	x	x	x
IPSL-CM5A-LR	x	x	x	x	x				x	x	x	x	x	x	x	x	x	x	
IPSL-CM5A-MR	x	x	x	x	x				x	x	x	x	x	x	x	x	x	x	
IPSL-CM5B-LR	x	x	x	x	x				x	x	x	x	x	x	x	x	x	x	
MIROC-ESM	x	x	x		x			x	x	x	x	x	x	x	x	x	x	x	x
MIROC-ESM-CHEM	x	x	x		x			x	x	x	x	x	x	x	x	x	x	x	x
MIROC4h								x				x	x	x	x	x	x	x	
MIROC5								x		x	x	x	x	x	x	x	x	x	
MPI-ESM-LR	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	
MPI-ESM-MR	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	
MPI-ESM-P								x		x	x	x	x	x	x	x	x	x	
MRI-CGCM3								x		x	x	x	x	x	x	x	x	x	
MRI-ESM1	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x
NorESM1-M							x	x		x	x	x	x	x	x	x	x	x	
NorESM1-ME	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	

Antarctic Surface Winds & Air Temperature

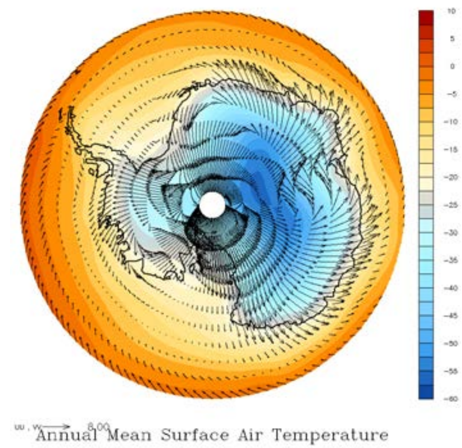
Observed (Modern)



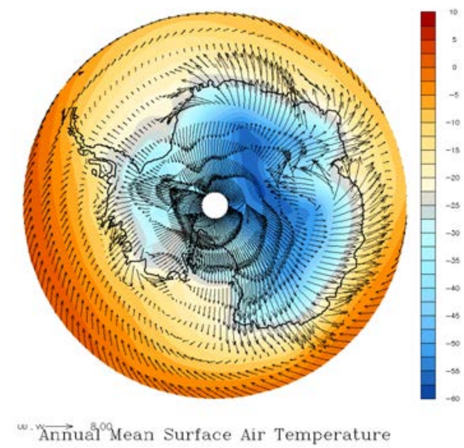
GFDL-ESM2M

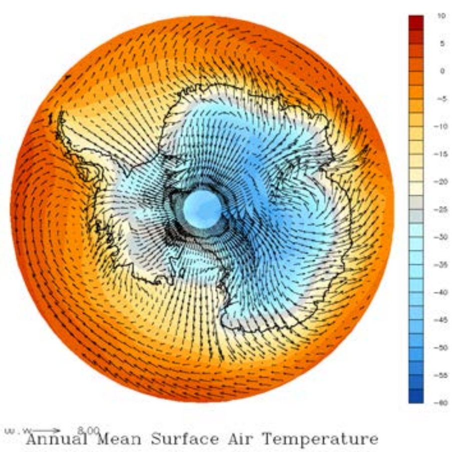


BCC-CSM

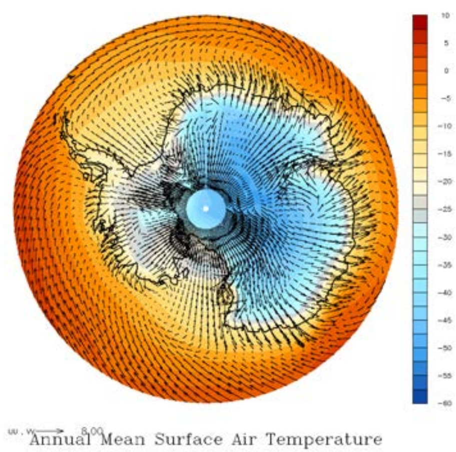


Can-ESM

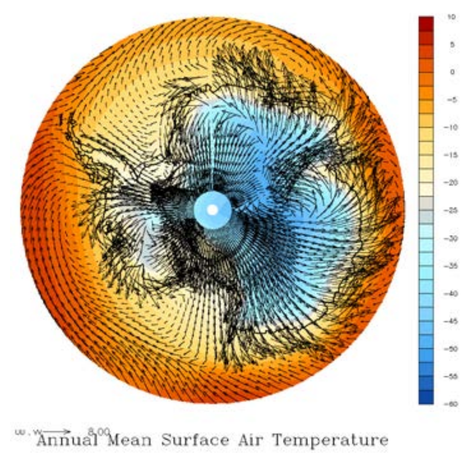




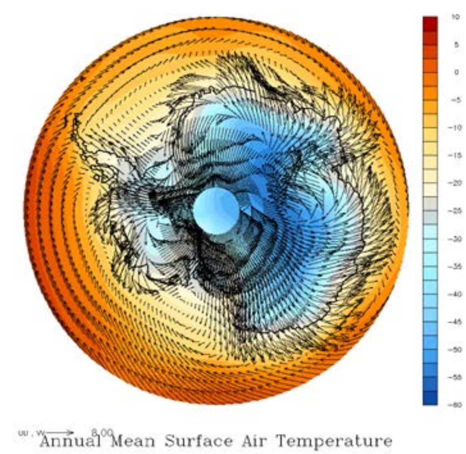
HadGEM-ES



MIROC4h

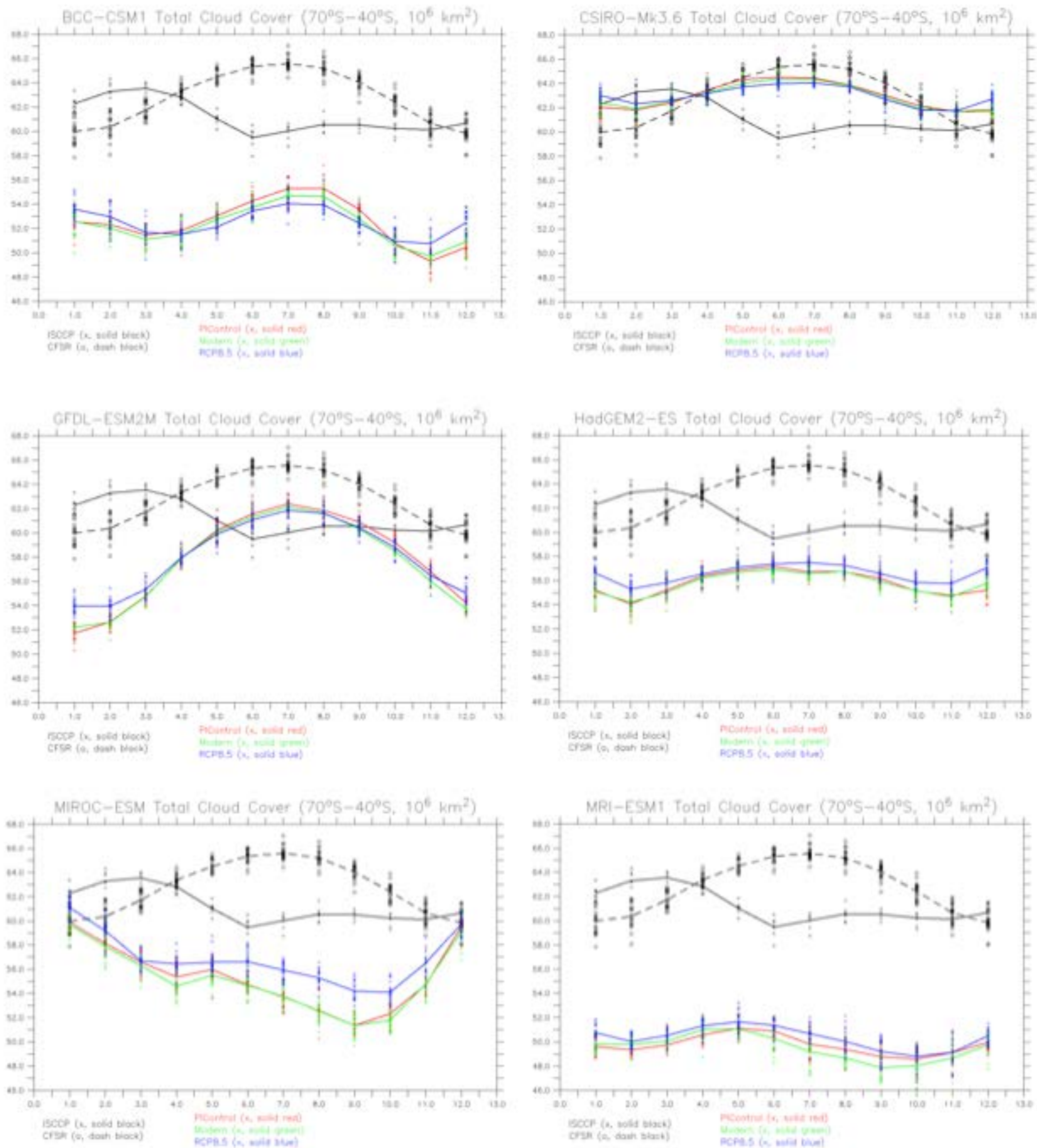


MRI



NorESM

Variability in Cloud Cover (70°S-40°S integrated)

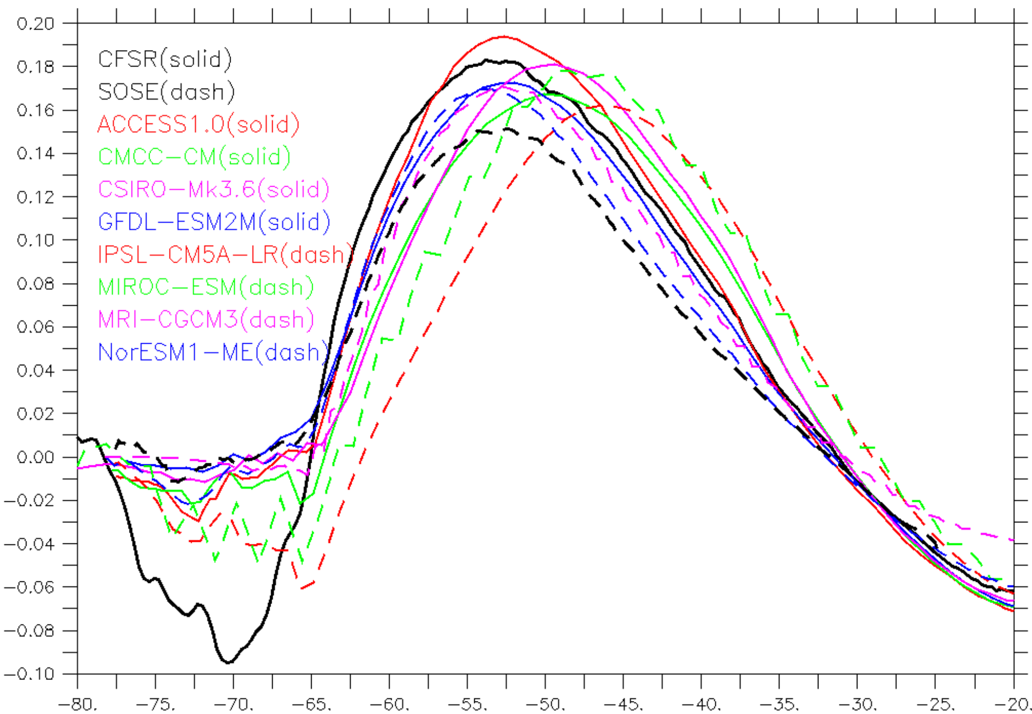


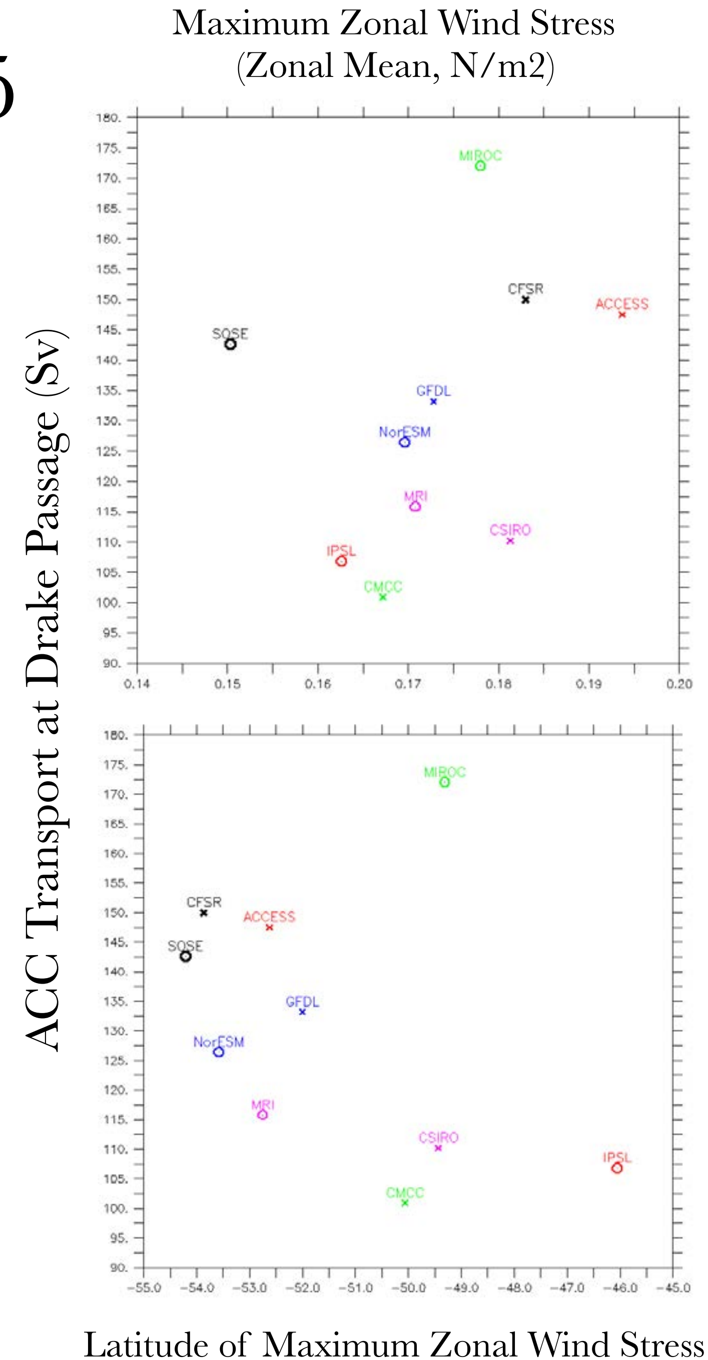
The negative bias in total cloud cover seen in CMIP3 persists in CMIP5

These figures show the annual cycle and interannual variability as simulated by several of the CMIP5 Earth System and Coupled Climate Models.

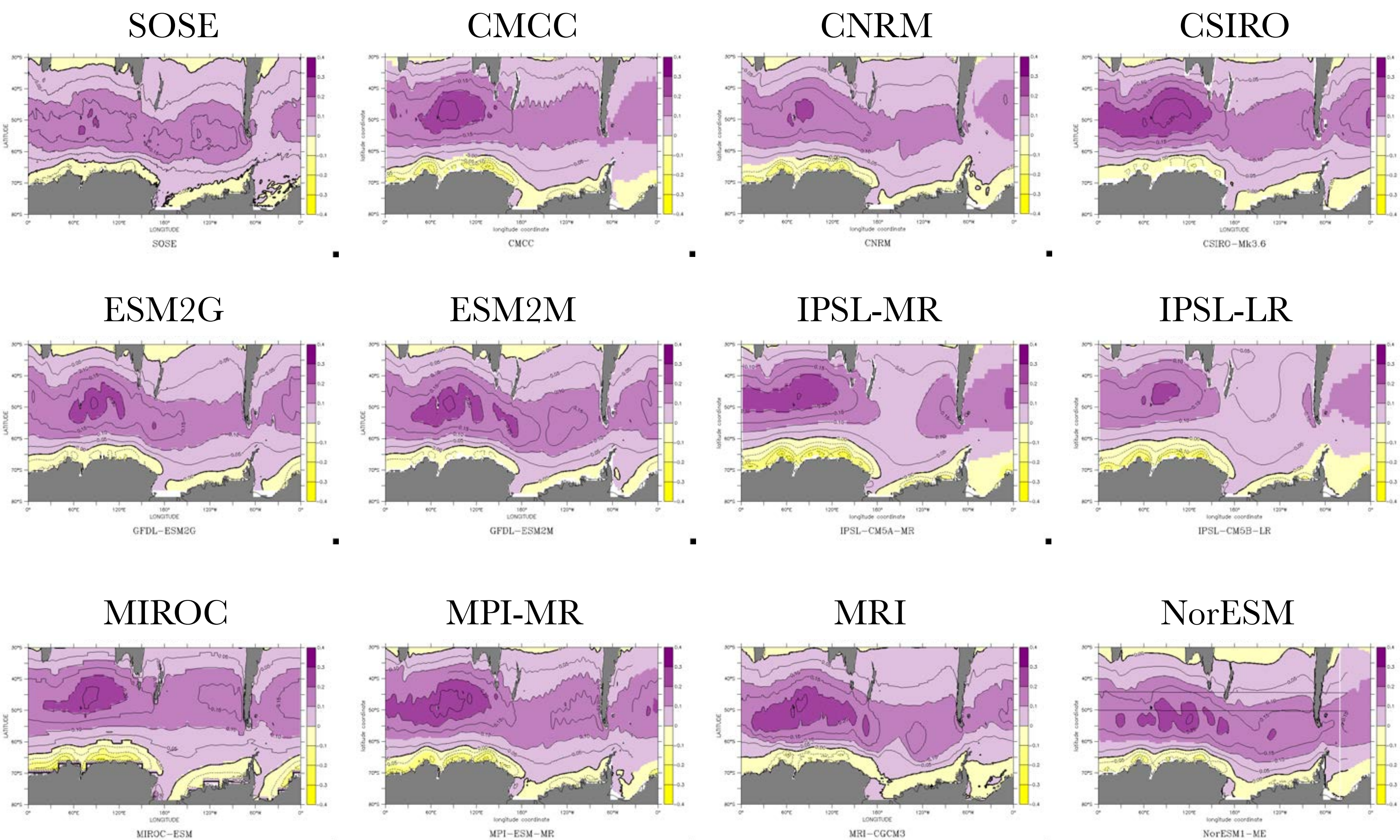
In each panel, the **black** curves are the total could cover integrated over the Southern Ocean for each month from **ISCCP (solid) and CFSR (dashed)**. The red curve is a 20-year average from the Pre-Industrial Control simulation, the green curve is from the Historical simulation (~1986-2005), and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

Surface Zonal Wind: CMIP5





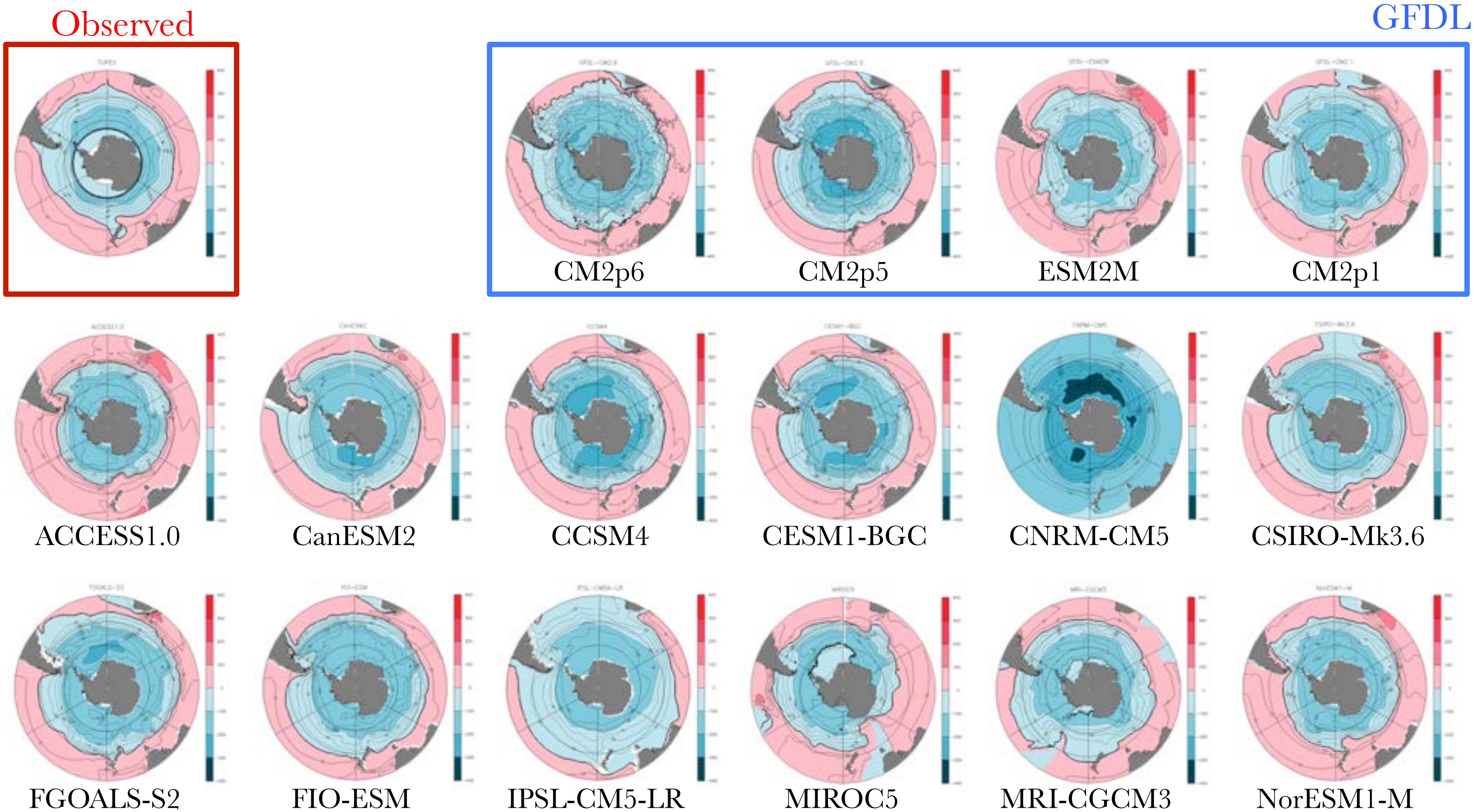
Surface Zonal Wind Stress (N/m^2, Annual Mean)



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

Simulated Sea Surface Height (cm)

Annual mean, 2001-2005

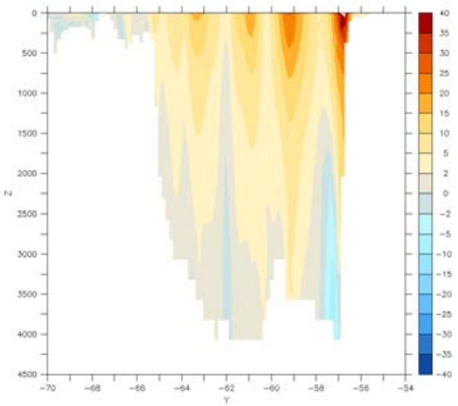


This is a different subset of CMIP5 models

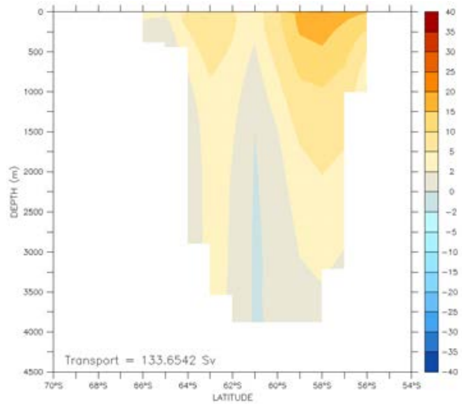
Drake Passage Transport: Zonal Velocity at 69°W

Annual mean, 2001-2005
Zonal Velocity
Values are net transport
through Drake Passage

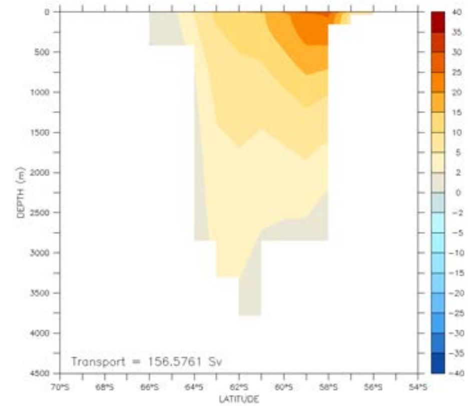
SOSE (2008)
148.1 Sv



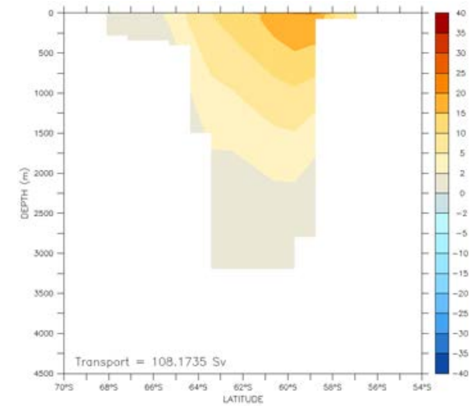
GFDL-ESM2M
133.7 Sv

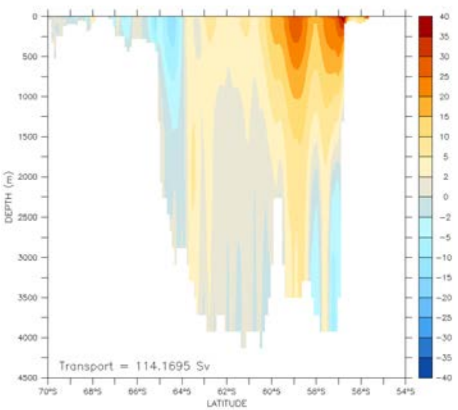


BCC-CSM2
156.6 Sv

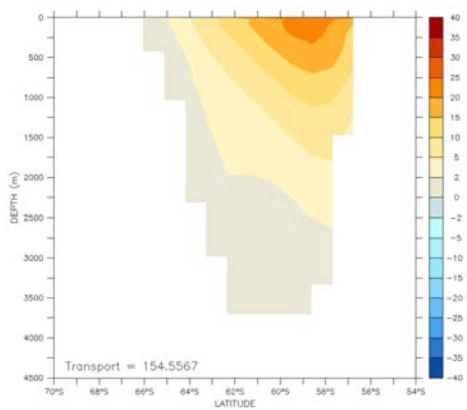


CSIRO-Mk3.6
108.2 Sv

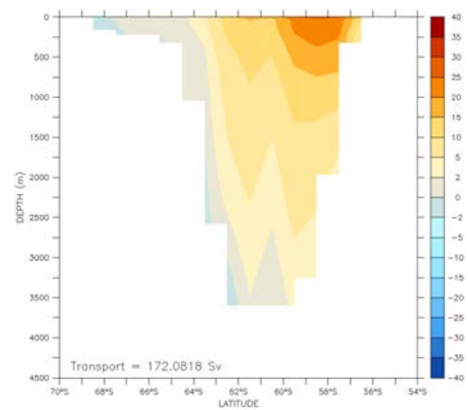




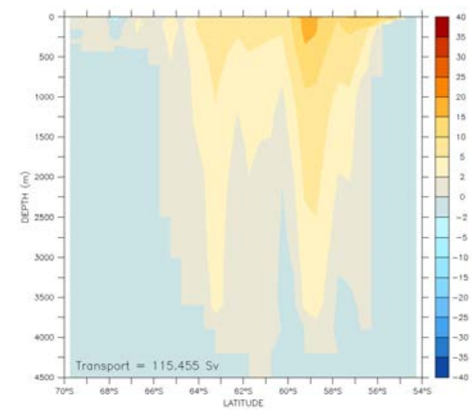
GFDL-CM2.5
114.2 Sv



CanESM2
154.6 Sv



HadGEM2-ES
172.1 Sv



MRI
115.5 Sv

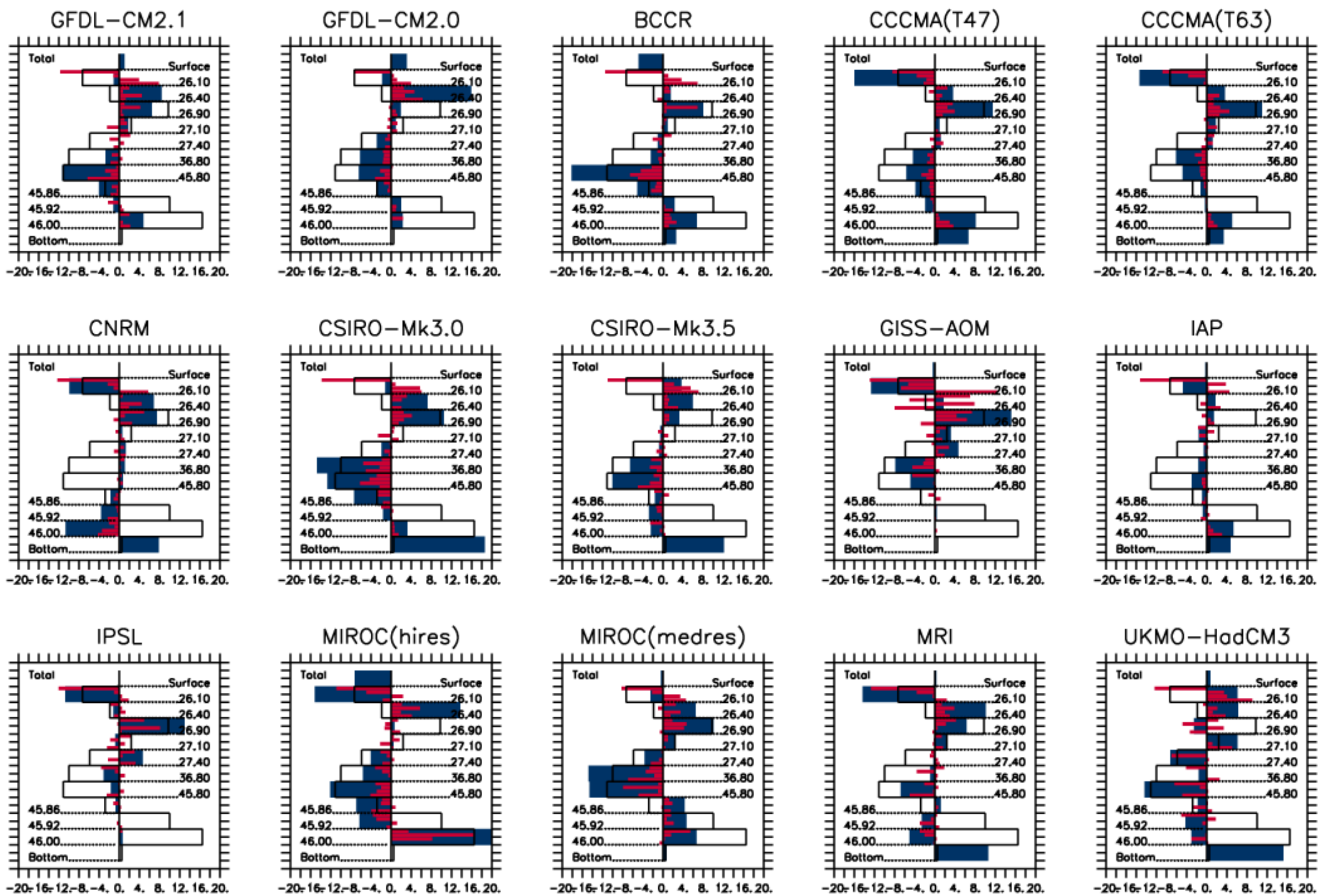
Frontal structure is not captured by lower resolution models

IPCC-AR4 Historical Simulations (1981-2000 Annual Mean)
Volume transport (Sv) across 30°S (Global)

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

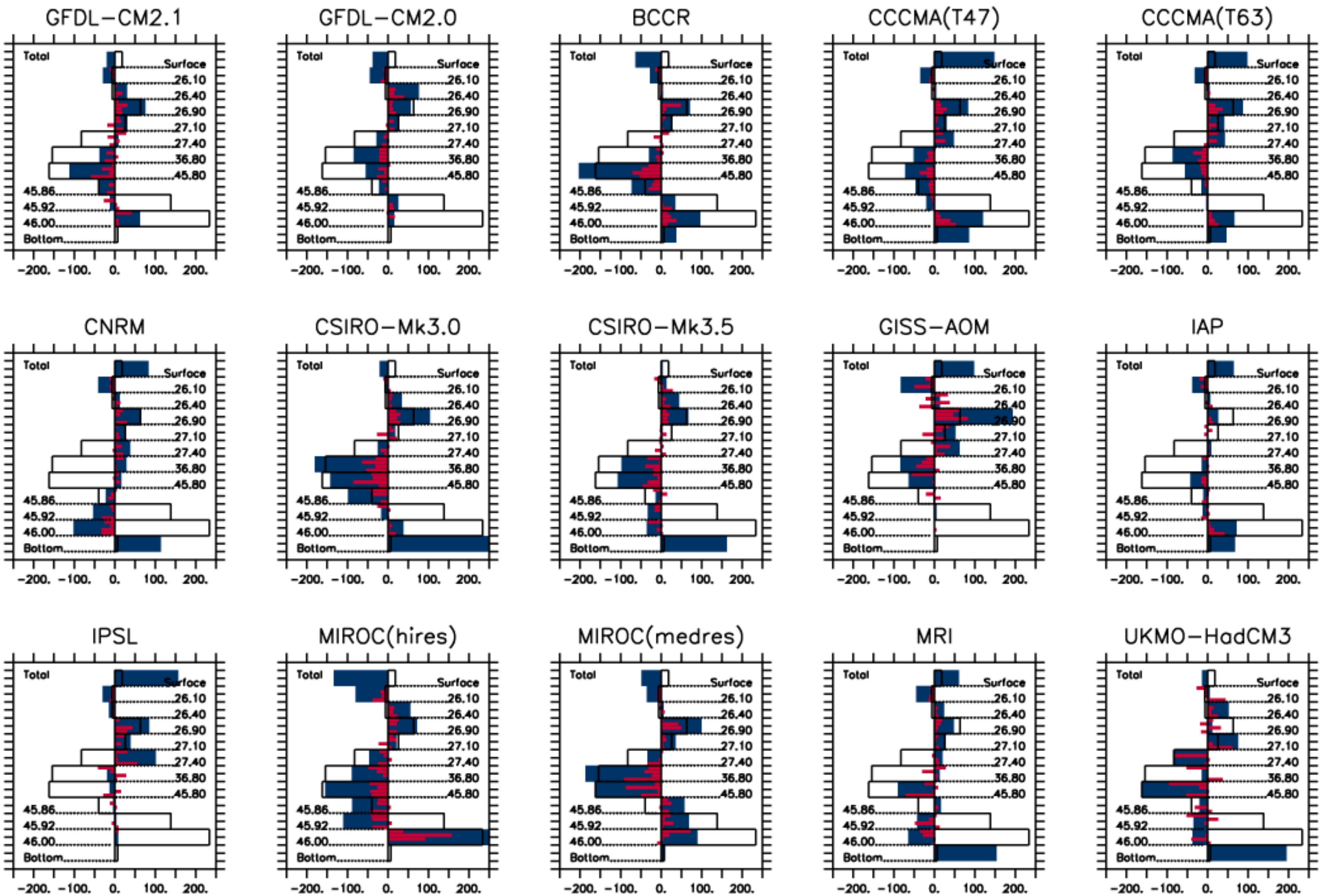
Thick blue bars are modeled layer transports (northward is positive)

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



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

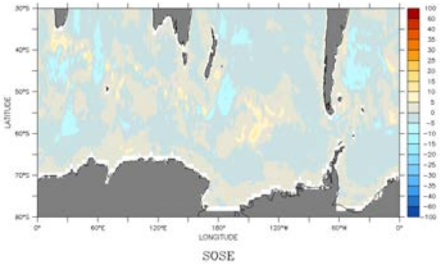
Thin black bars are "observed estimates" where the net transport in each layer (from Talley, 2008) is multiplied by the observed mean nitrate in that layer from the World Ocean Atlas (2001)
Thick blue bars are integrated modeled velocity multiplied by WOA01 nitrate at the same depth



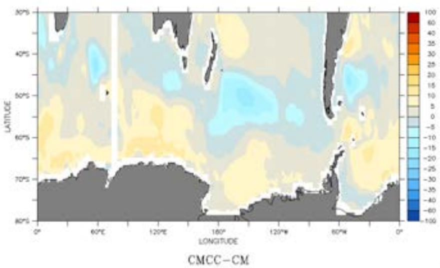
Ocean Heat Content "Error" (Modern)

(10^9 J/m^2, difference from WOA2009)

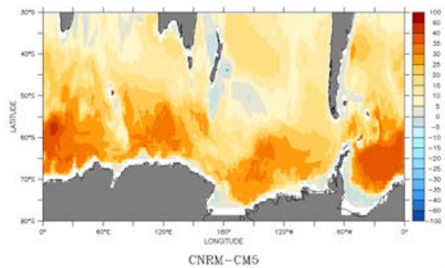
SOSE



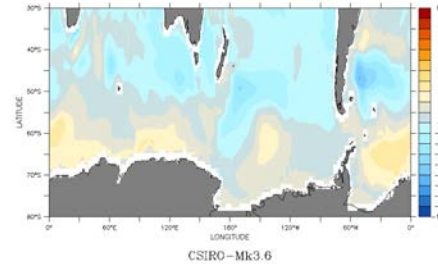
CMCC



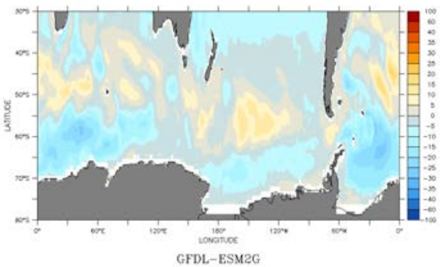
CNRM



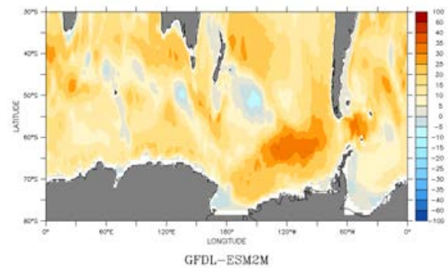
CSIRO



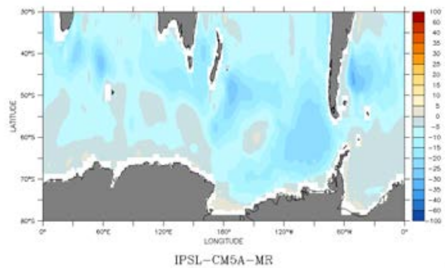
ESM2G



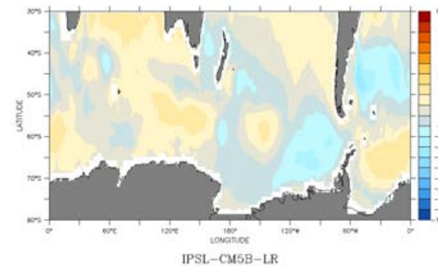
ESM2M



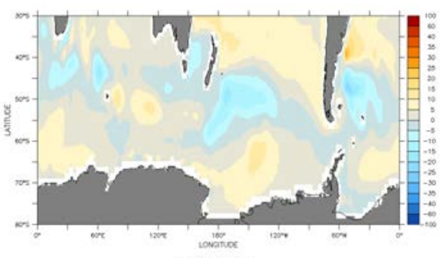
IPSL-MR



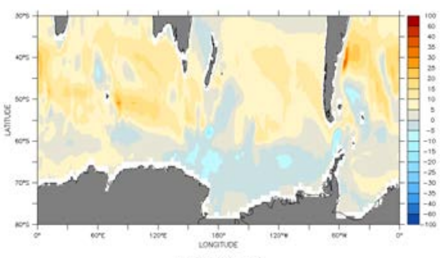
IPSL-LR



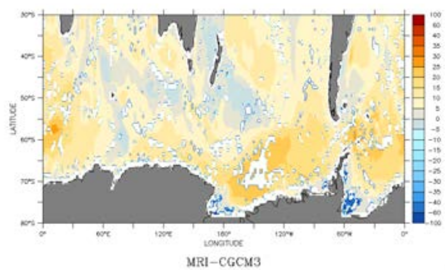
MIROC



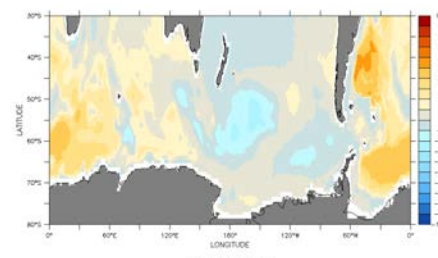
HadGEM2-ES



MRI



NorESM



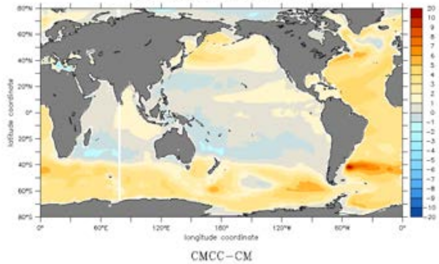
All averages are for model years 1986-2005, SOSE is annual average for 2008

Rate of Uptake of Heat by the Ocean (Future-Modern)

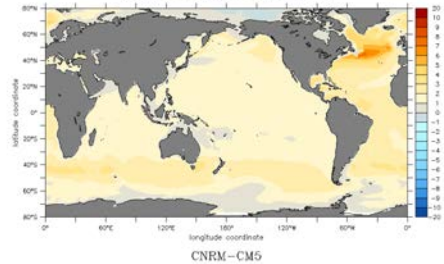
(W/m^2, over the next century [2081-2100 minus 1986-2005])

SOSE

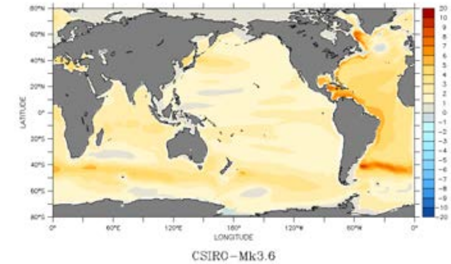
CMCC



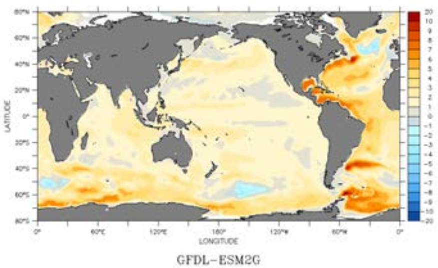
CNRM



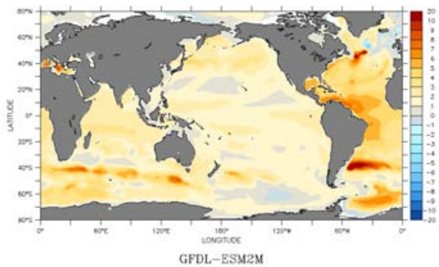
CSIRO



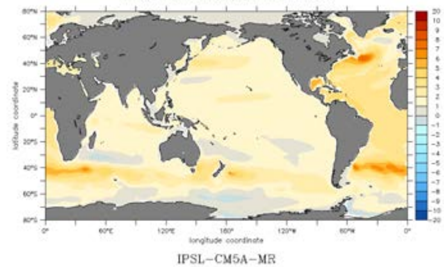
ESM2G



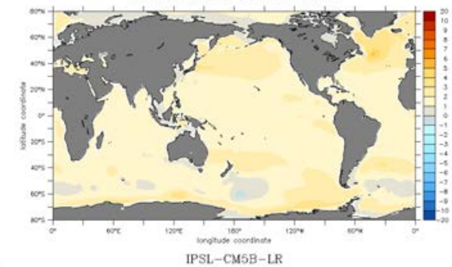
ESM2M



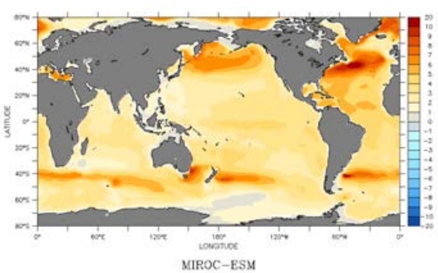
IPSL-MR



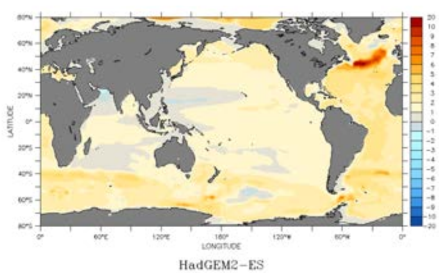
IPSL-LR



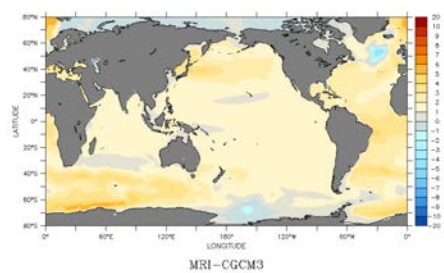
MIROC



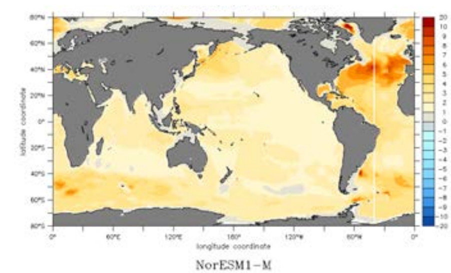
HadGEM2-ES



MRI



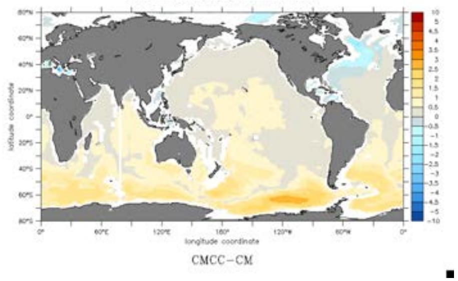
NorESM



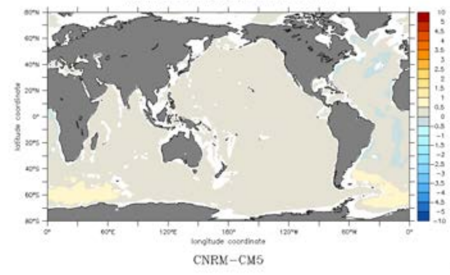
Rate of Uptake of Heat by the Lower Ocean (below 2000m)

(W/m^2, over the next century [2081-2100 minus 1986-2005])

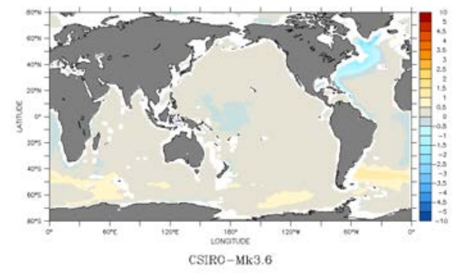
CMCC



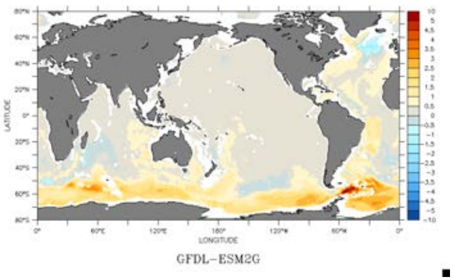
CNRM



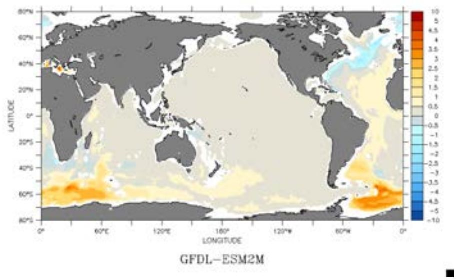
CSIRO



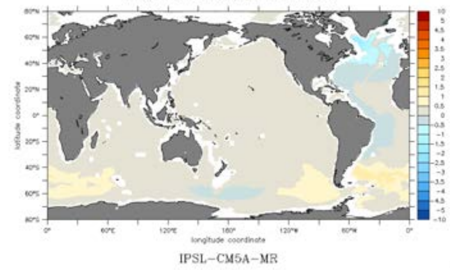
ESM2G



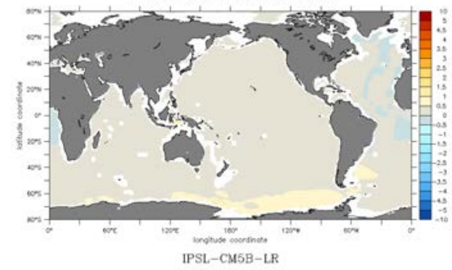
ESM2M



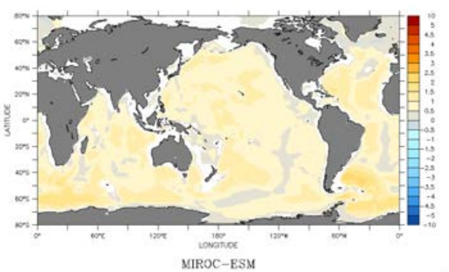
IPSL-MR



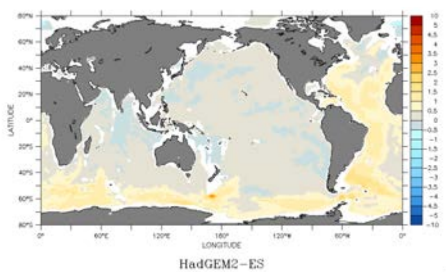
IPSL-LR



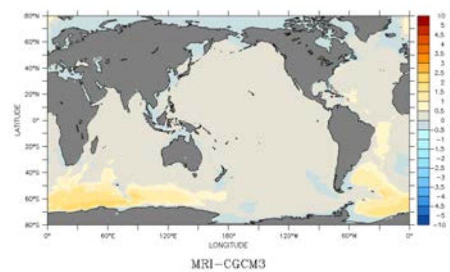
MIROC



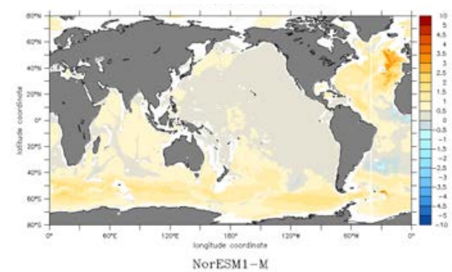
HadGEM2-ES



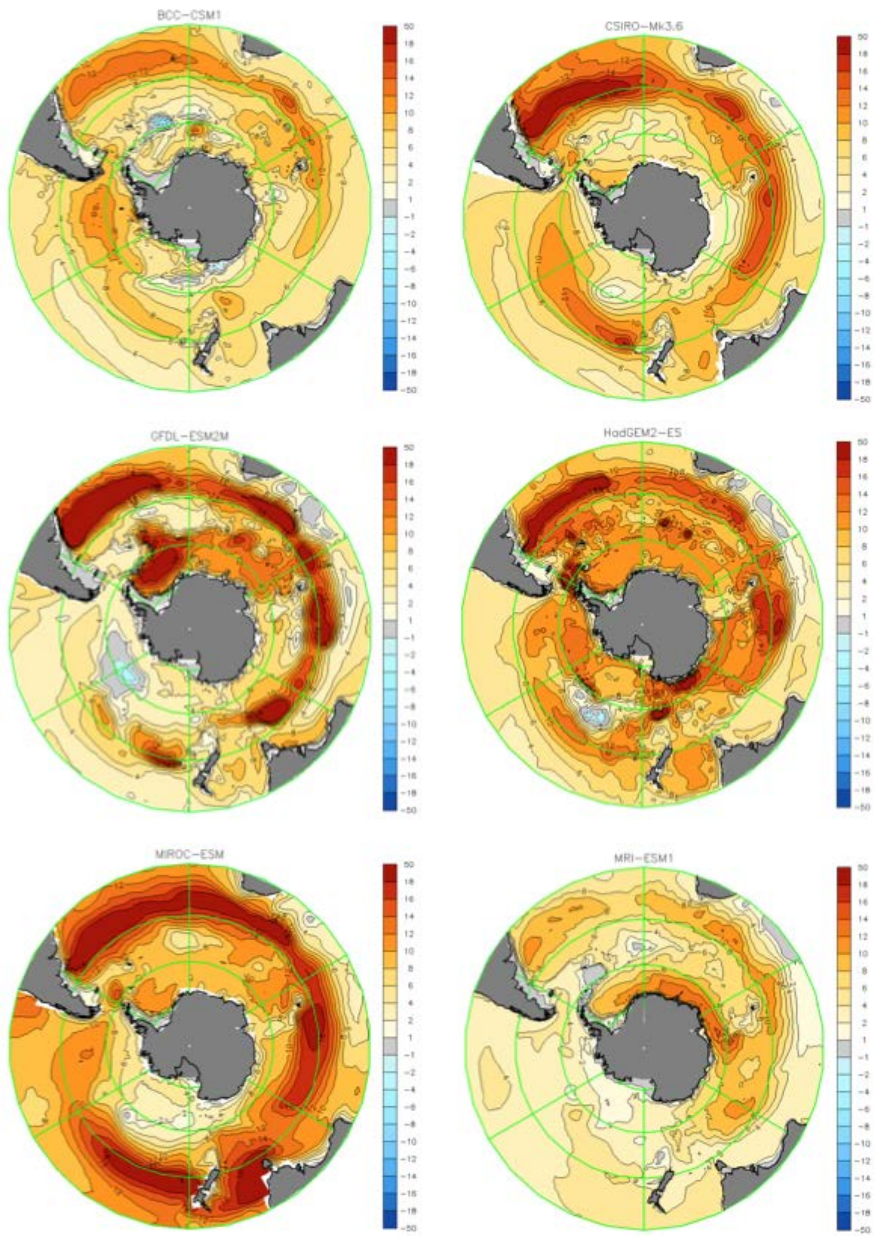
MRI



NorESM



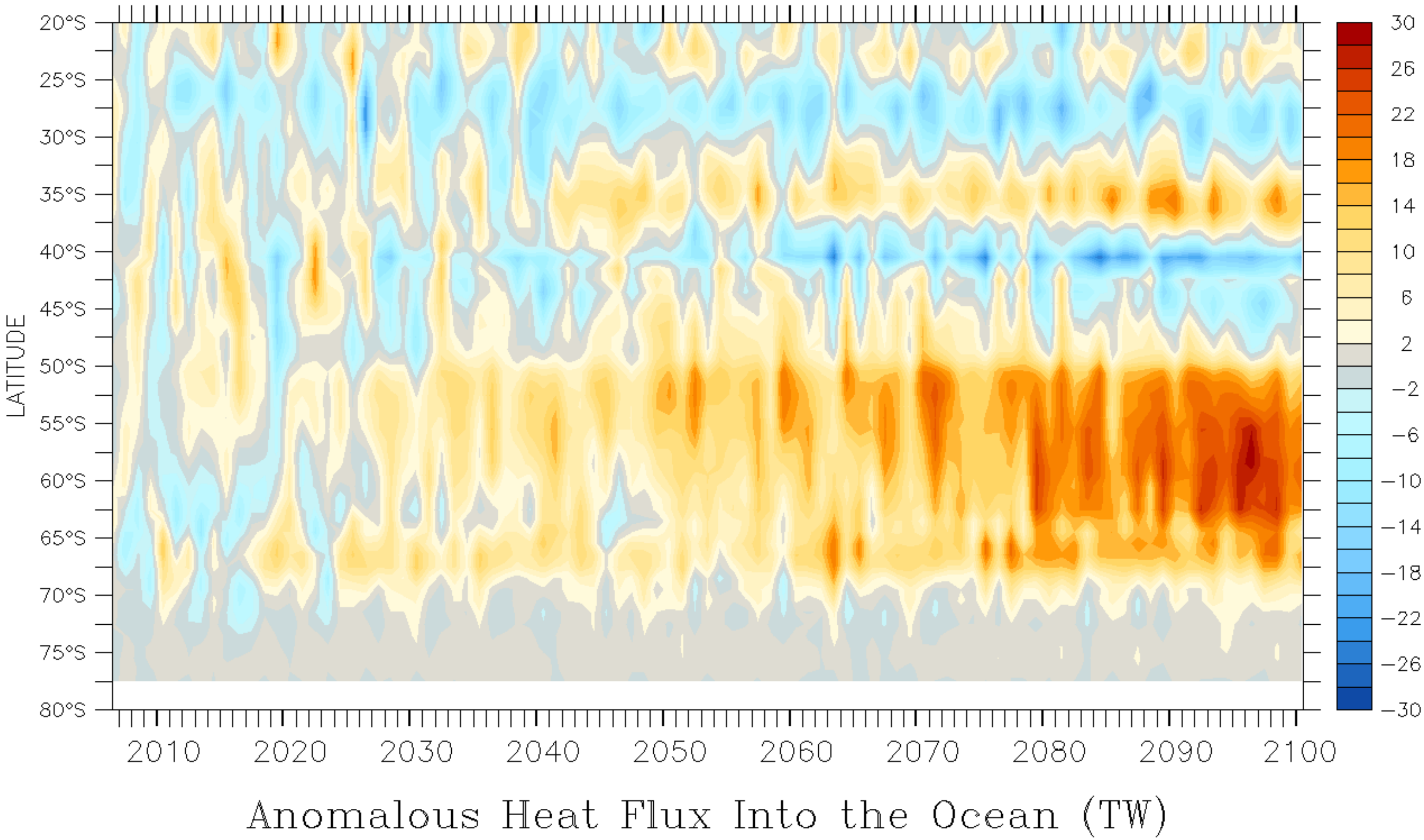
Change in Integrated Ocean Heat Content



The change in Southern Ocean Heat Content (OHC, in 10^9 J/m^2) as simulated by the models from the modern period (~1986-2005) to the end of the 21st Century (~2081-2100). OHC is calculated by integrating the temperature with depth and the multiplying by the density and the specific heat. The entire Southern Ocean warms.

Heat Uptake by the Southern Ocean

(GFDL-ESM2M, RCP8.5, TW/yr – anomalies relative to annual mean 2006-2010)

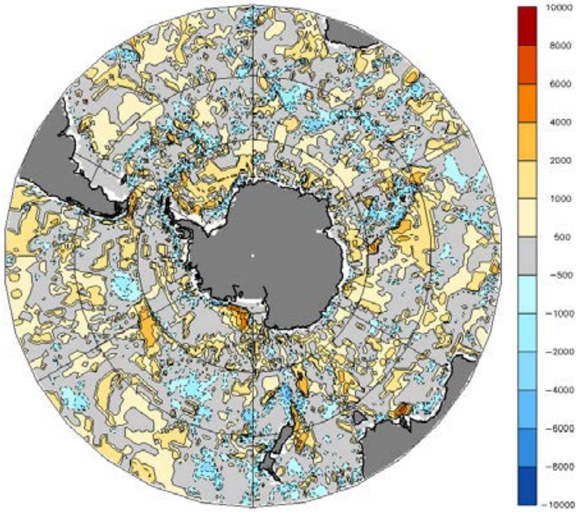


Column Inventory DIC Difference

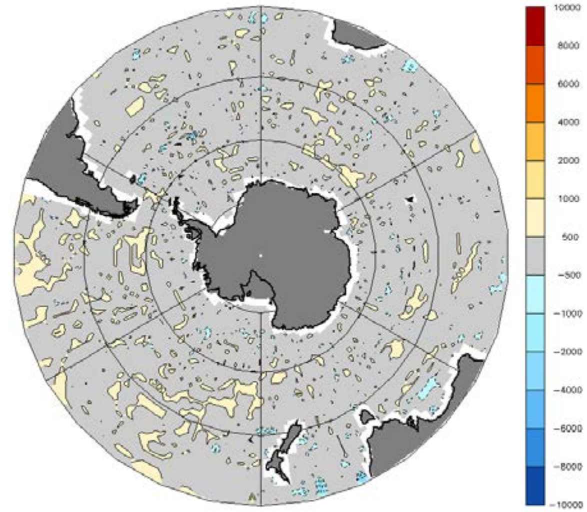
(mol/m^2; Difference From GLODAP)

Annual mean (2001-2005)

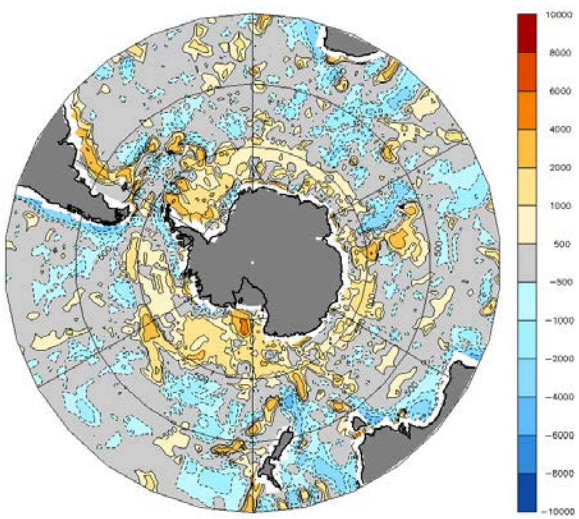
GFDL-ESM2M



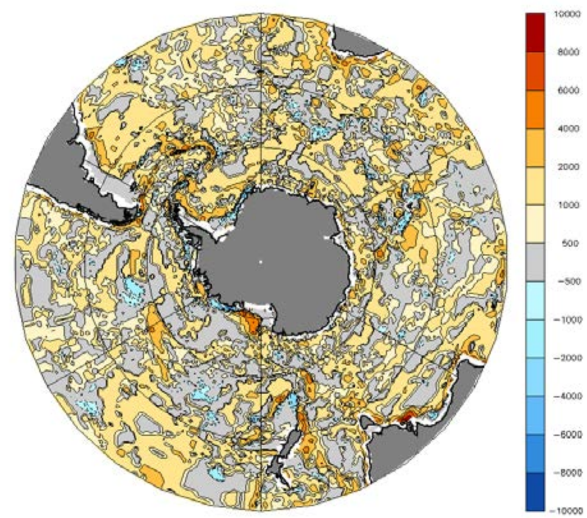
CanESM2



MIROC-ESM



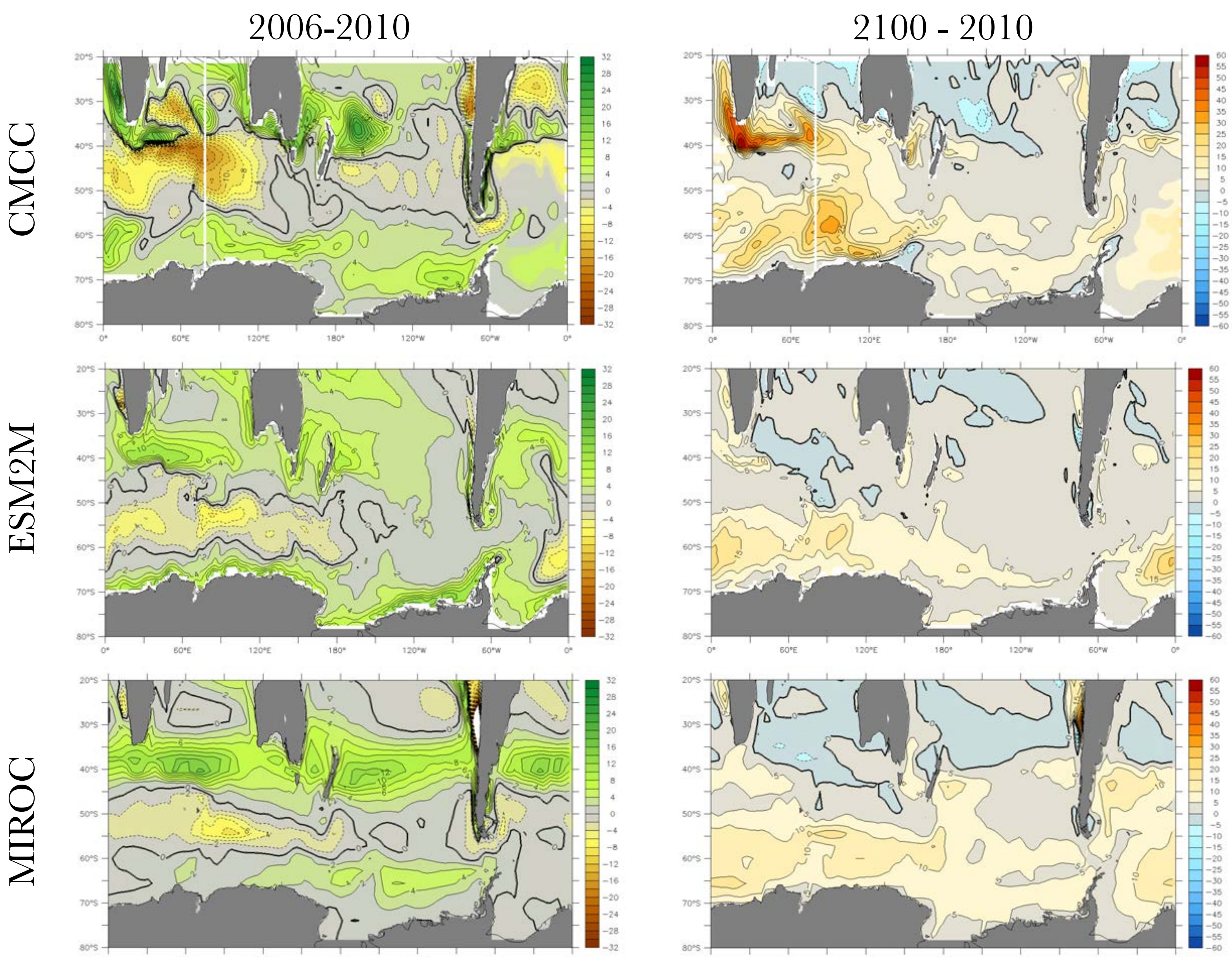
MRI-ESM1



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

Change in Southern Ocean Carbon Uptake (Future-Modern)

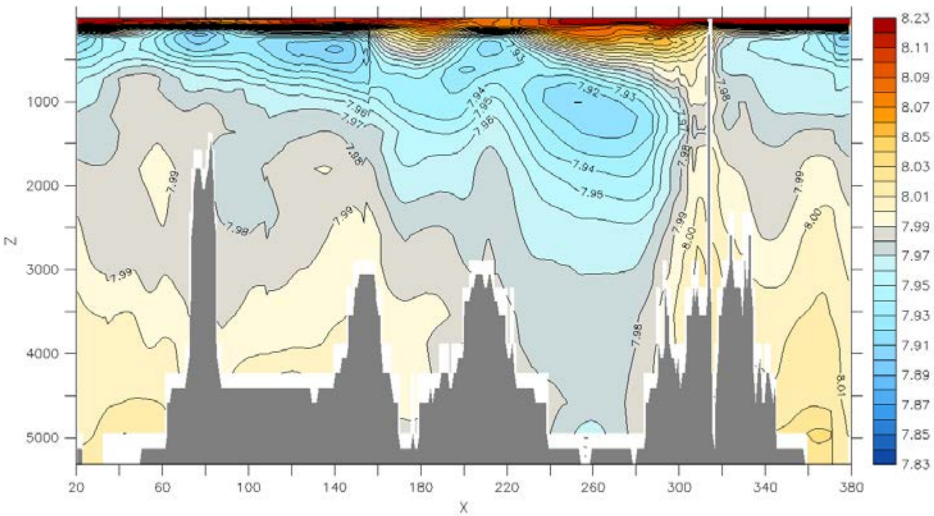
(mol/m^2/yr, 80°S-45°S, RCP8.5, POSITIVE values are INTO the ocean and increased UPTAKE by the ocean)



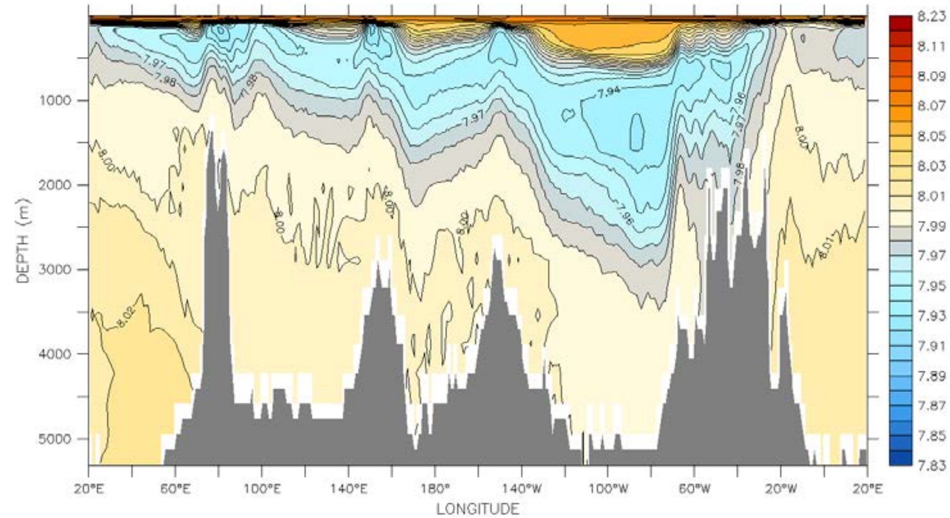
Southern Ocean pH at 60°S

Annual mean (2001-2005)

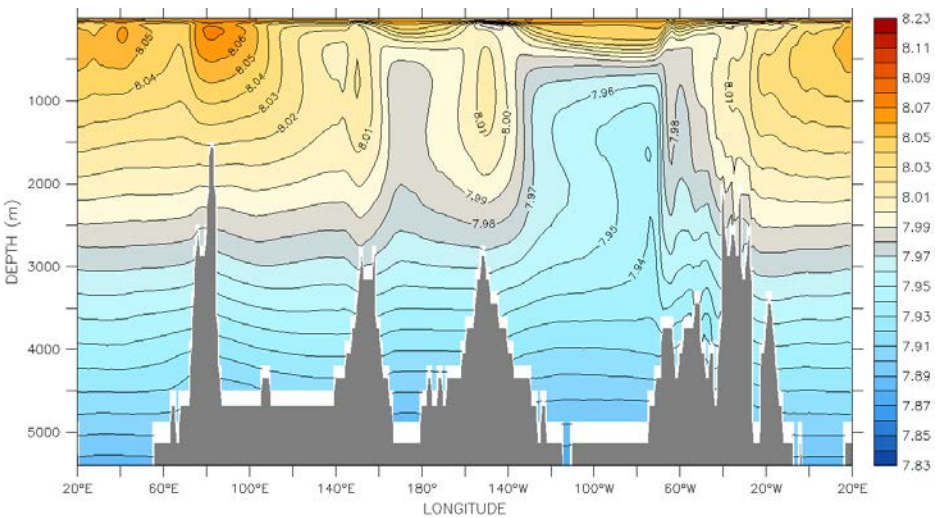
Observed



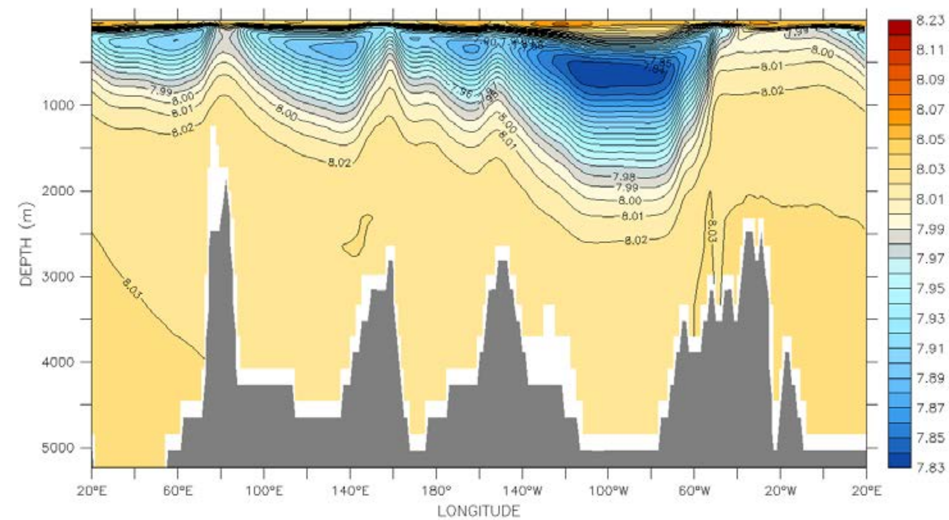
GFDL-ESM2M



MRI-ESM1



CanESM2

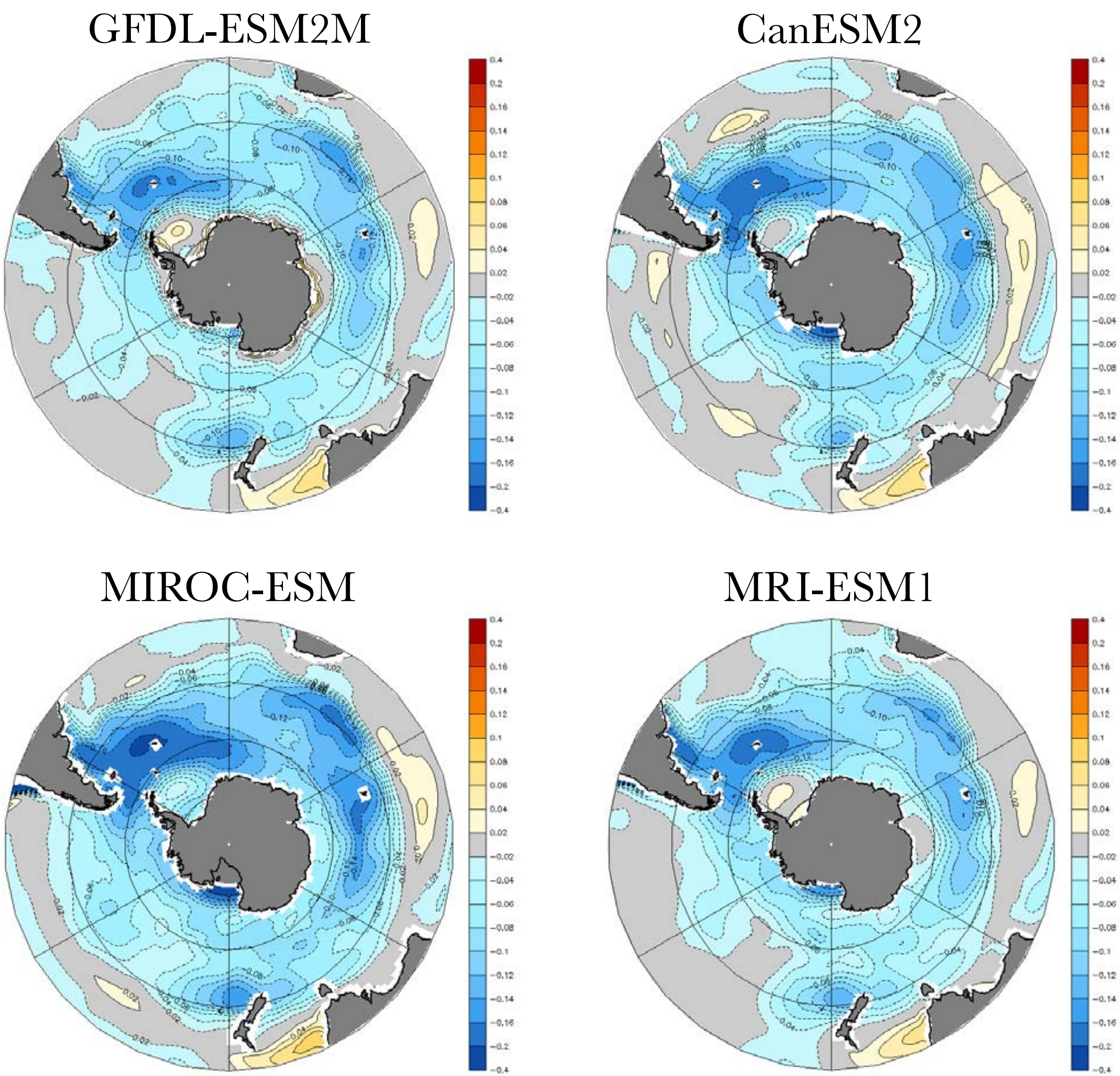


Observed pH was calculated from the GLODAP TCO_2 and Alkalinity and the World Ocean Atlas (2001) Temperature and Salinity using the formulas from Dickson (2007)

Surface Water pH Difference

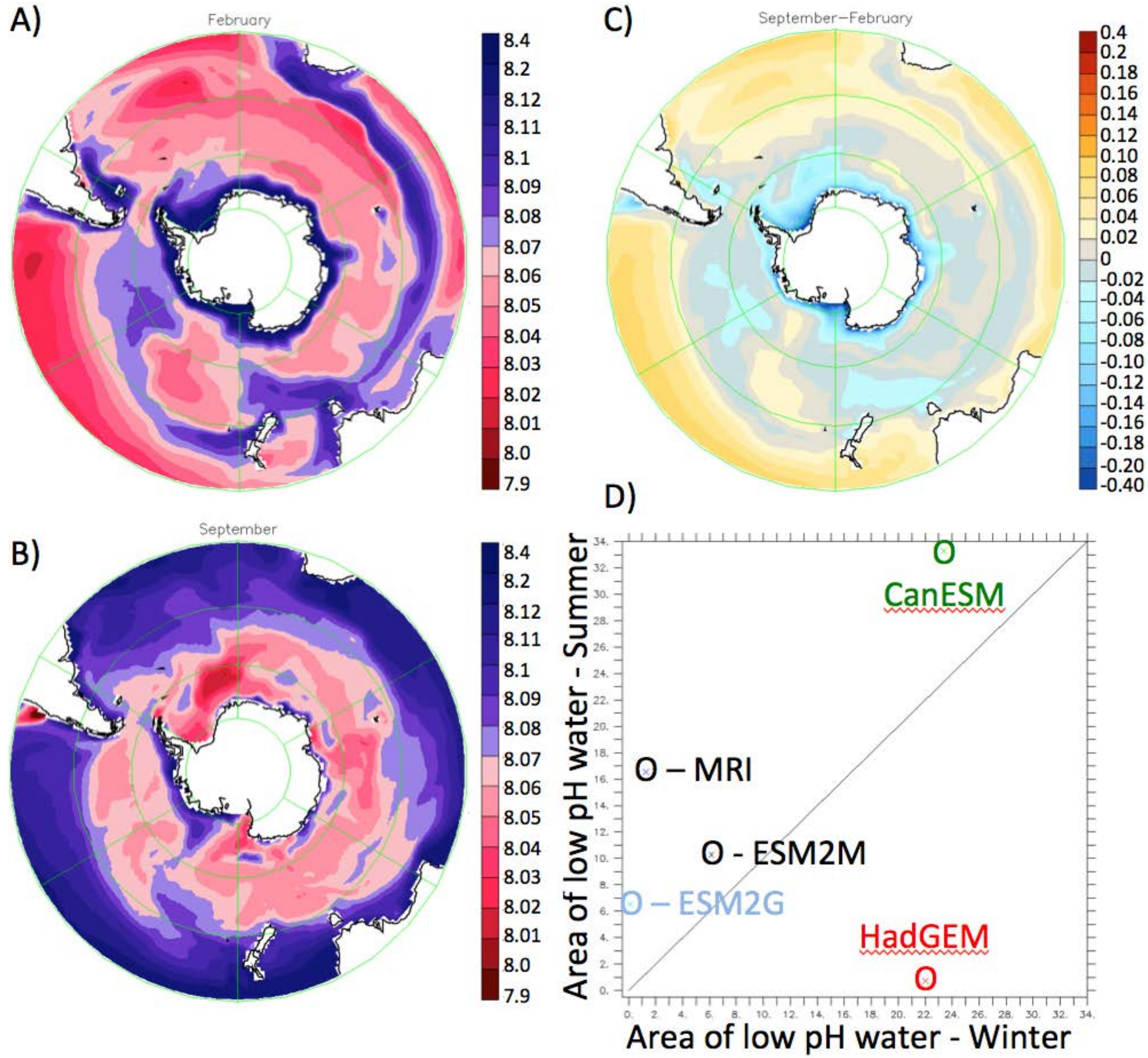
(From GLODAP/WOA2001)

Annual mean (2001-2005)



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)

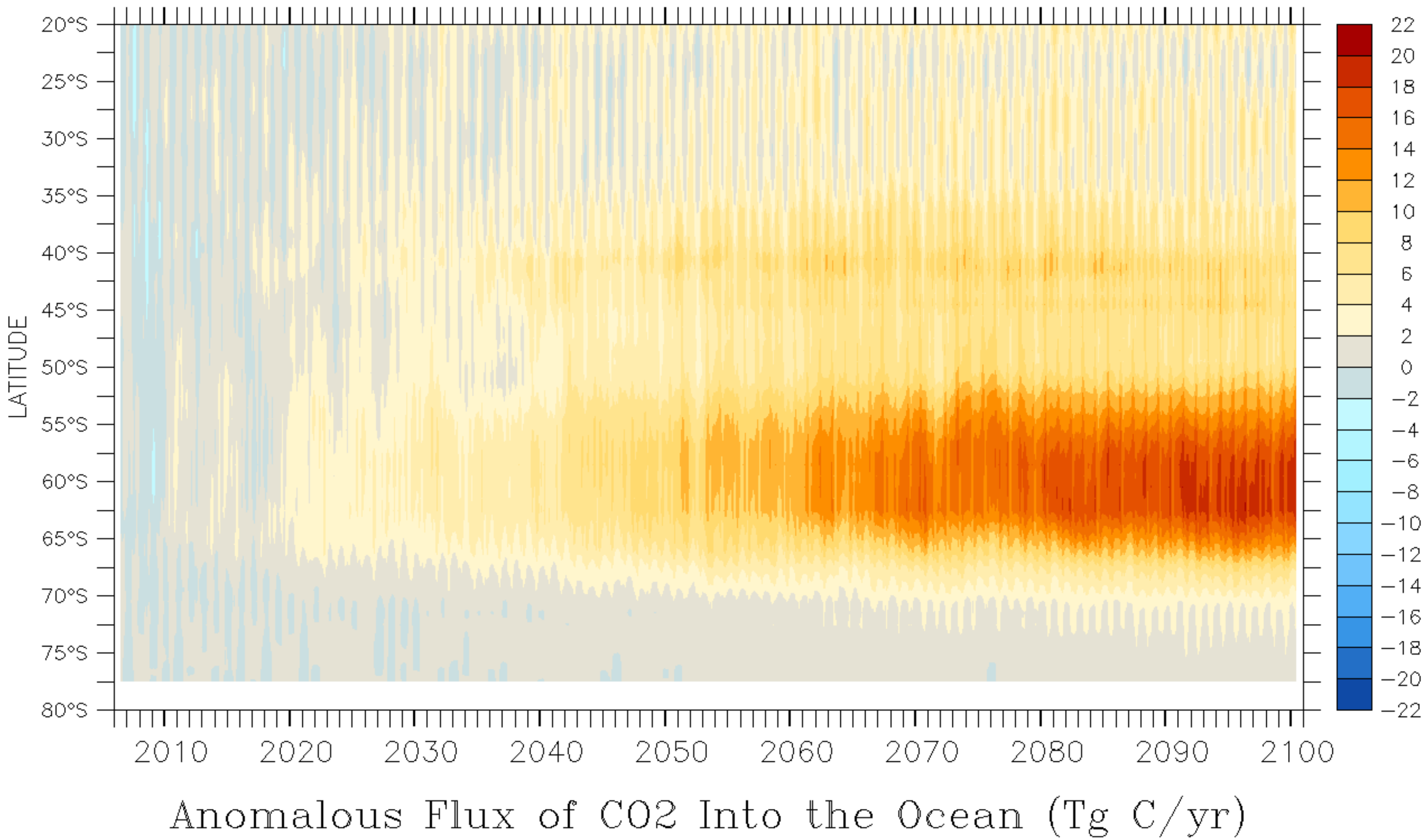
Surface pH Summer/Winter/Difference



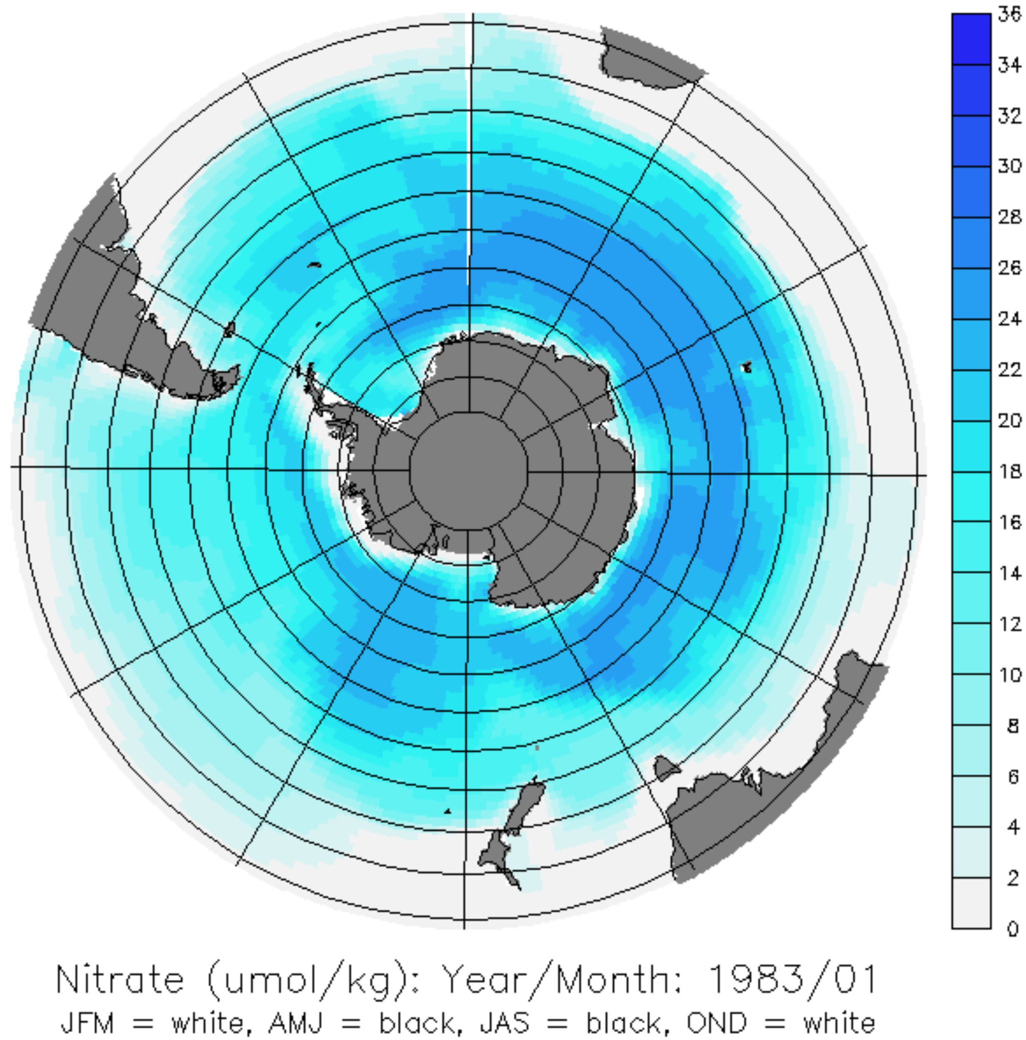
Simulated surface pH from the GFDL-ESM2M Earth System Model for A) Summer (February); B) Winter (September); C) Winter minus Summer. Panel D) shows the area of surface water below 8.05 pH units (south of 40°S, in 10^6 km^2) in the Summer vs the Winter for 5 of the available ESMs. All Summers and Winters are averaged for model years 2001-2005. This figure is directly comparable to Figure 2 of McNeil and Matear (2008), whose analysis was of the CSIRO coupled climate model.

Flux of CO_2 Into the Southern Ocean (Zonal Integral)

(GFDL-ESM2M, RCP8.5, TgC/yr – anomalies relative to annual mean 2006-2010)



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



[Potential projected Bio-Argo through SOCCOM]

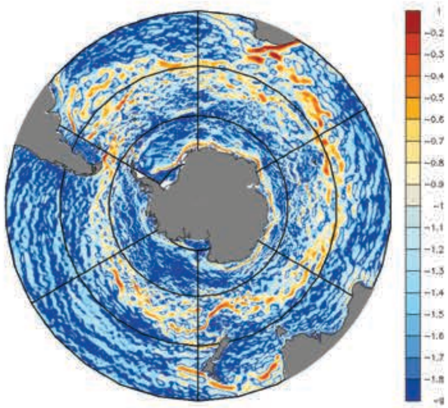
Courtesy of R. Slater

Southern Ocean Working Group Model Metrics

Ocean Carbon & Biogeochemistry

U.S. CLIVAR Climate Variability & Predictability

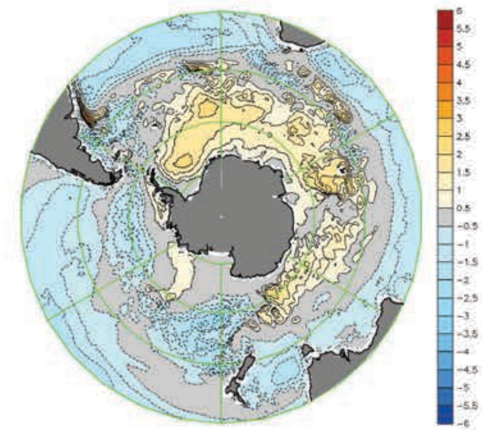
HOME CONTACT



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

Draft Conclusions:

We need to reduce the uncertainty in our projections of the Southern Ocean's role in climate.

1) We need more in situ biogeochemical observations of the Southern Ocean, including floats, ships, moorings, etc.

2) We need more Southern Ocean Climate Process Teams

3) We need more Observationally-based climate model metrics

4) We need a Southern Ocean model intercomparison project