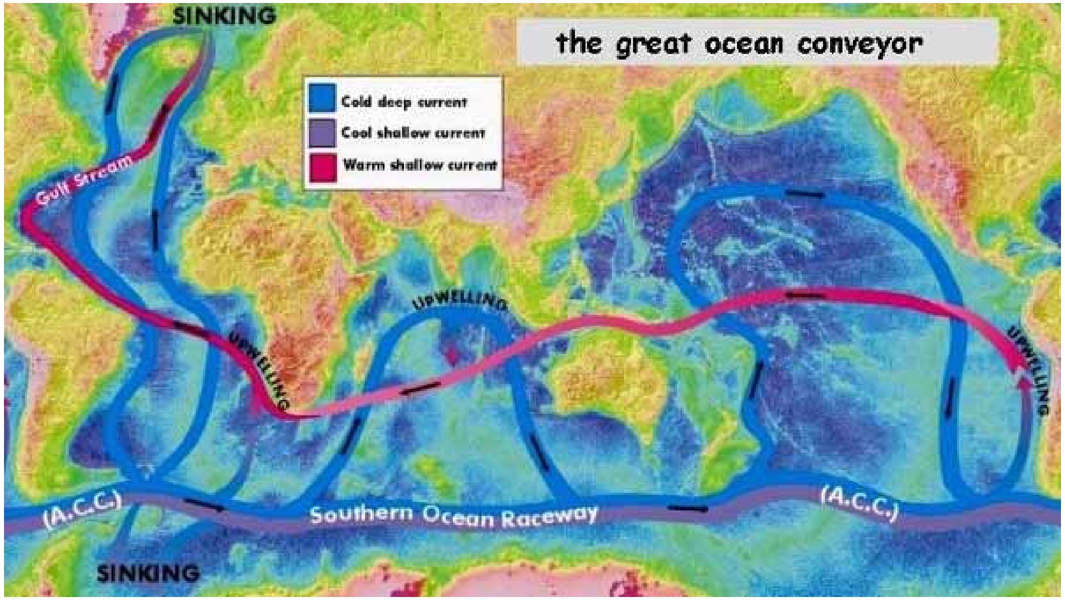
Role of Oceans in Climate
A Modeler's Perspective



http://www.andrill.org/iceberg/blogs/julian/images/greatoceanconveyor.jpg

Ronald J Stouffer
Geophysical Fluid Dynamics Laboratory
NOAA

The views described here are solely those of the presenter and not of GFDL/NOAA/DOC or any other agency or institution.

IPCC AR4 2007
Conclusions

- The planet is warming.
- Greenhouse gases are increasing due to human activity
- Human activity very likely cause of most of the warming in last 50 years or so.
- Future climate changes are likely to be much larger than what we have experienced so far.

Oceans role in Climate

- Wet Surface
- Heat and tracer storage and transport
  - Seasonal
  - Longer time scales
- Natural variability
- Abrupt climate change

Ocean's role
Wet Surface

- Supply water to atmosphere
  - Manabe and Wetherald Swamp Model
  - Manabe, S., and R. T. Wetherald, 1975: **The effects of doubling CO2 concentration on the climate of a general circulation model.** *Journal of the Atmospheric Sciences,* **32(1)**, 3-15.
  - No heat capacity, wet surface only

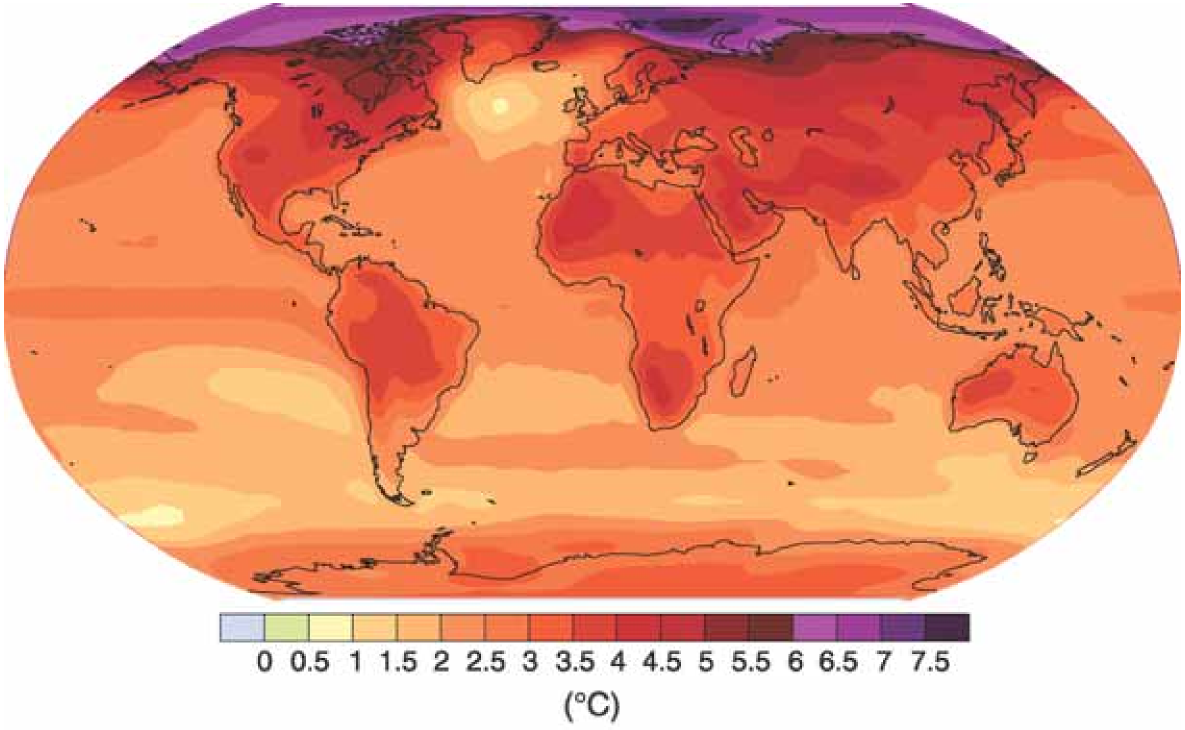
Ocean’s Role
Seasonal Heat Storage

- Atmosphere Mixed Layer Ocean (Slab) Models
  - Manabe and Stouffer 1979
  - 50m deep bucket, no horizontal or vertical heat transport
  - Heat flux adjustments or QFLUXES
  - Assumes no changes in heat transports as climate changes
  - Still being used to estimate climate sensitivity and other types of studies

Ocean’s Role
Longer time scales

- Storage
  - Heat
  - Carbon
  - Other tracers
- Transport

Surface Air Temperature Response to Increasing GHG



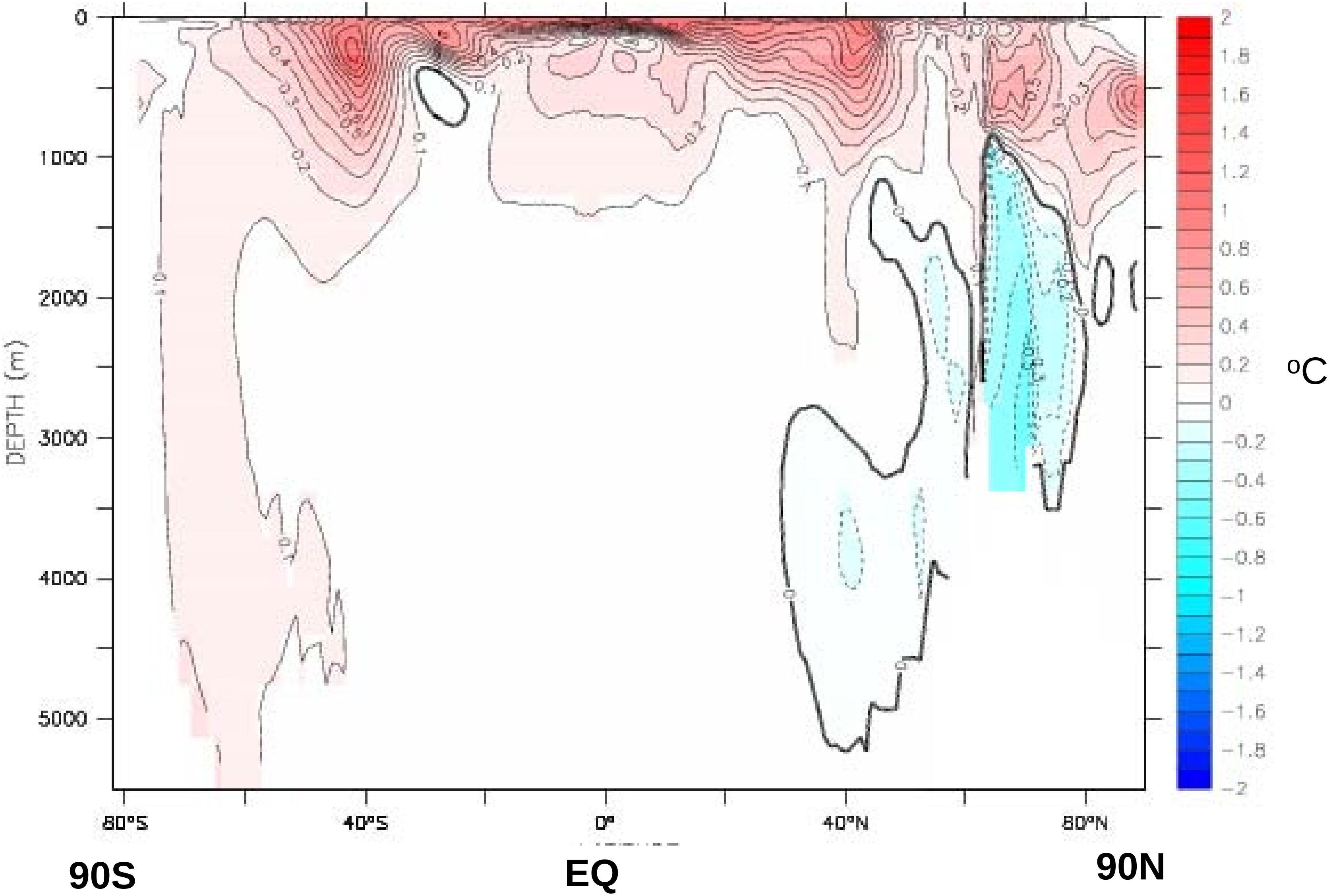
Surface Warming Pattern
A1B, 2090-2099
relative to 1980-1999

- Cooling spots in N Atlantic and SO due to ocean processes.

IPCC WGI SPM

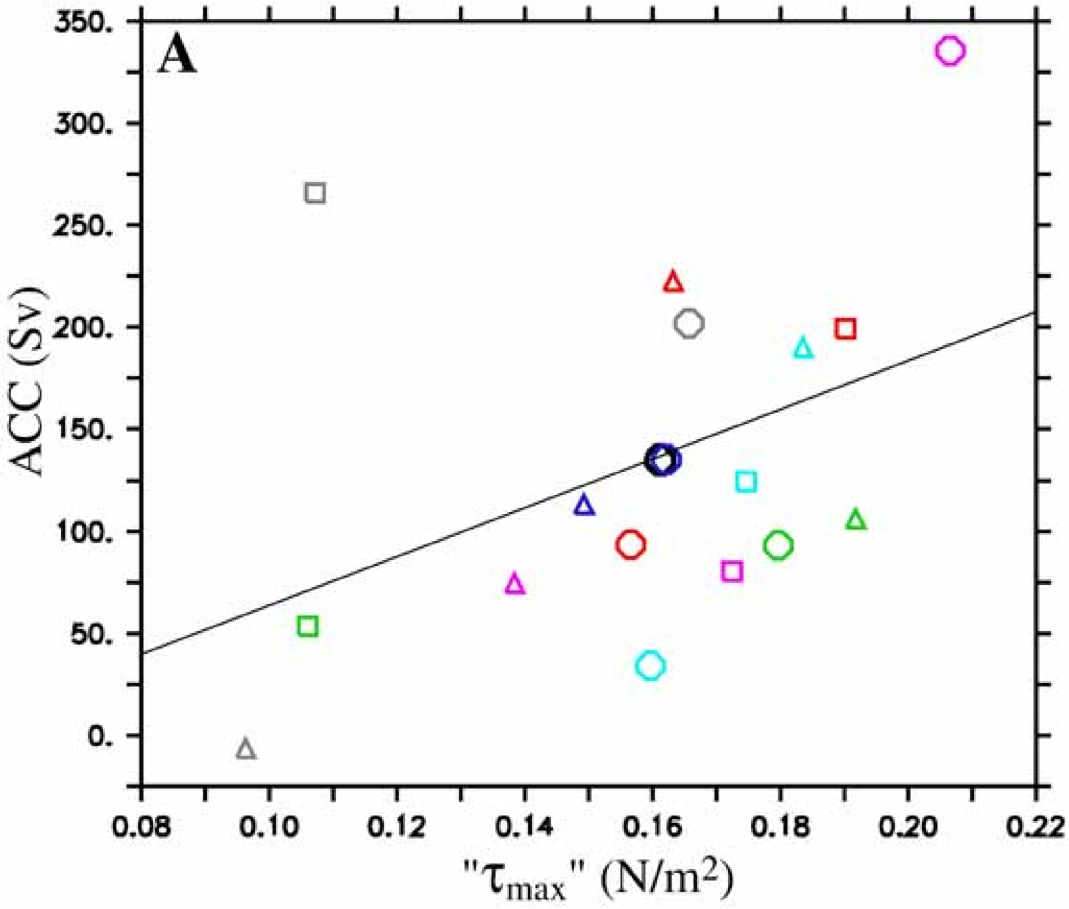
Where is heat stored?

Latitude-Depth, zonal mean difference – 1% run



The Southern Ocean
in the
AR4 Climate Models

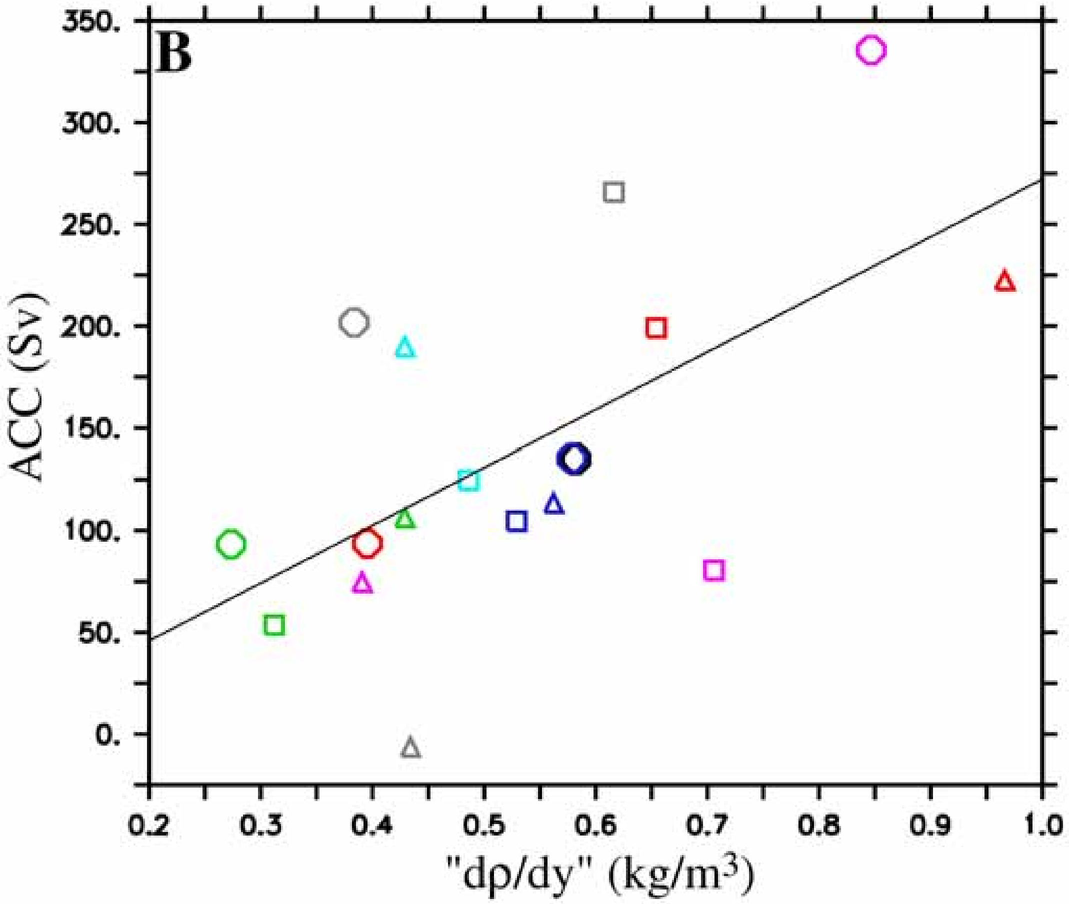
Comparison of AR4 Coupled Climate Models



Russell et al., *2006*

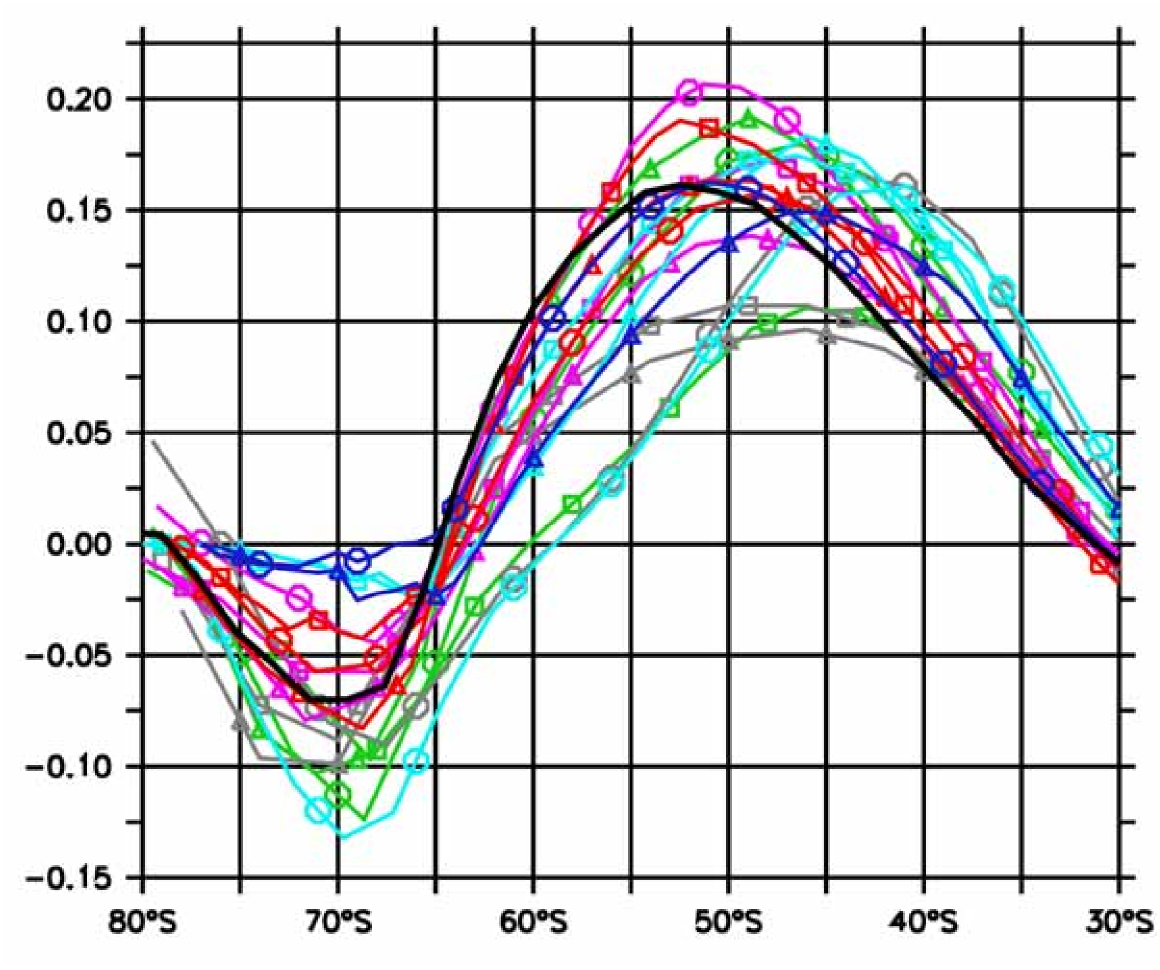
Maximum westerly wind stress vs ACC strength

Comparison of AR4 Coupled Climate Models



Russell et al., *2006*

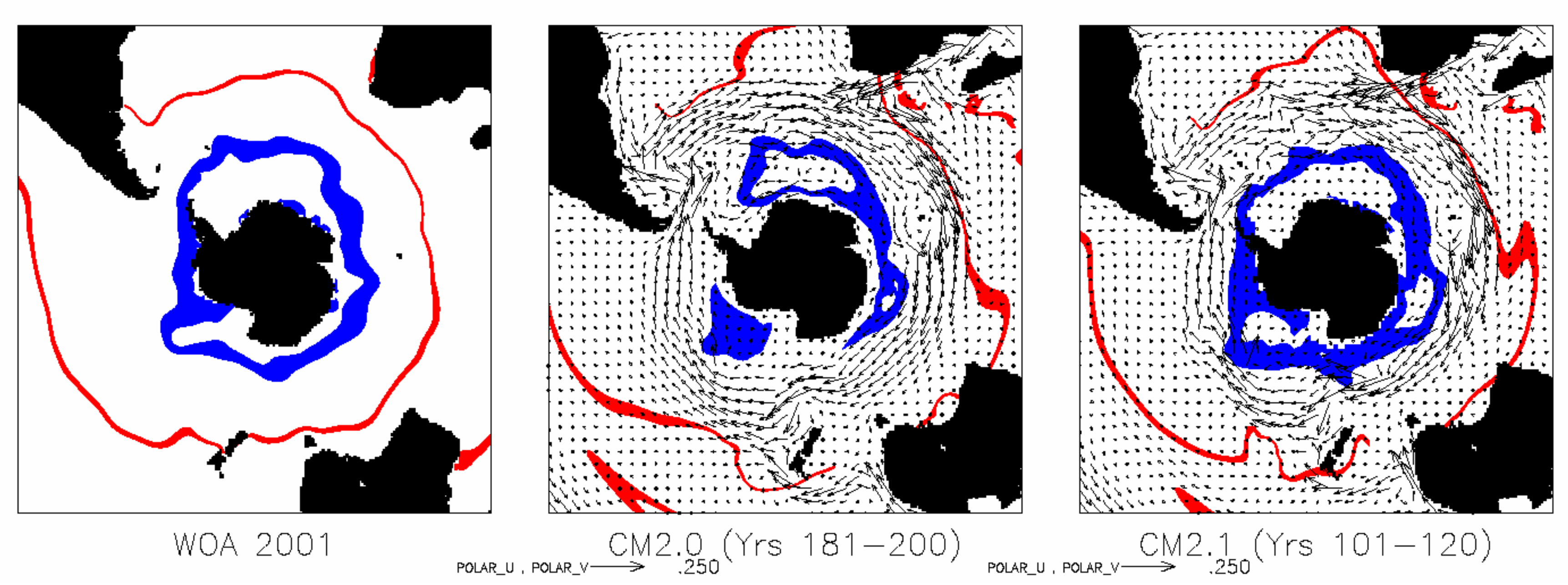
ACC transport vs. difference in density between 65° S and 45° S



Zonally-averaged wind stress (N/m^2).

Observed (black), GFDL-CM2.1 (blue, circle), GFDL-CM2.0 (blue, triangle)

Position of Subtropical Front and Southern Boundary of the Antarctic Circumpolar Current


WOA 2001

CM2.0 (Yrs 181–200)

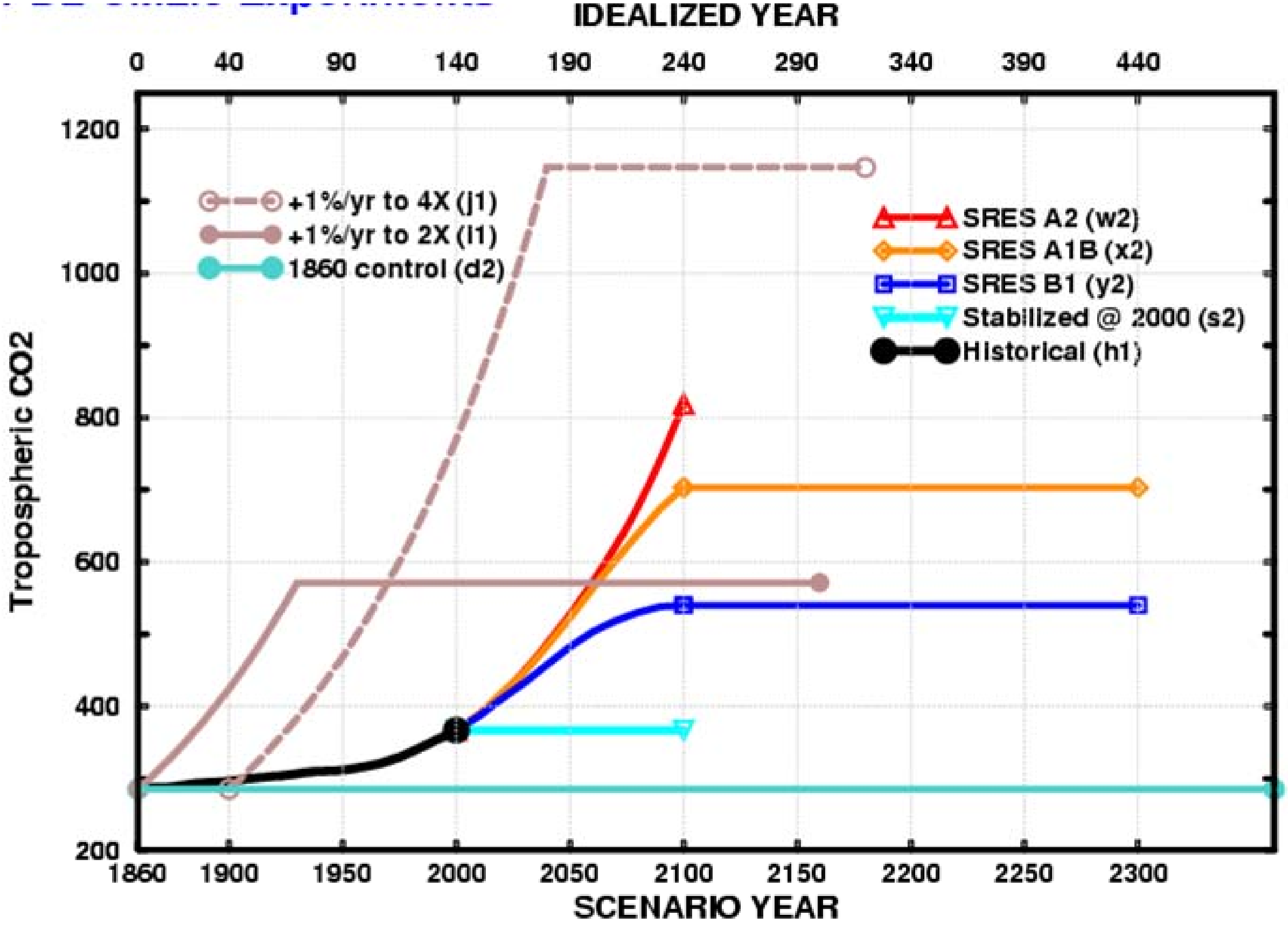
CM2.1 (Yrs 101–120)

The Subtropical Front is defined as a Salinity of 34.9-35.0 at 100m
The southern boundary of the ACC is defined as σ_0 of 1027.6 at 200m
(After Orsi, 1999)

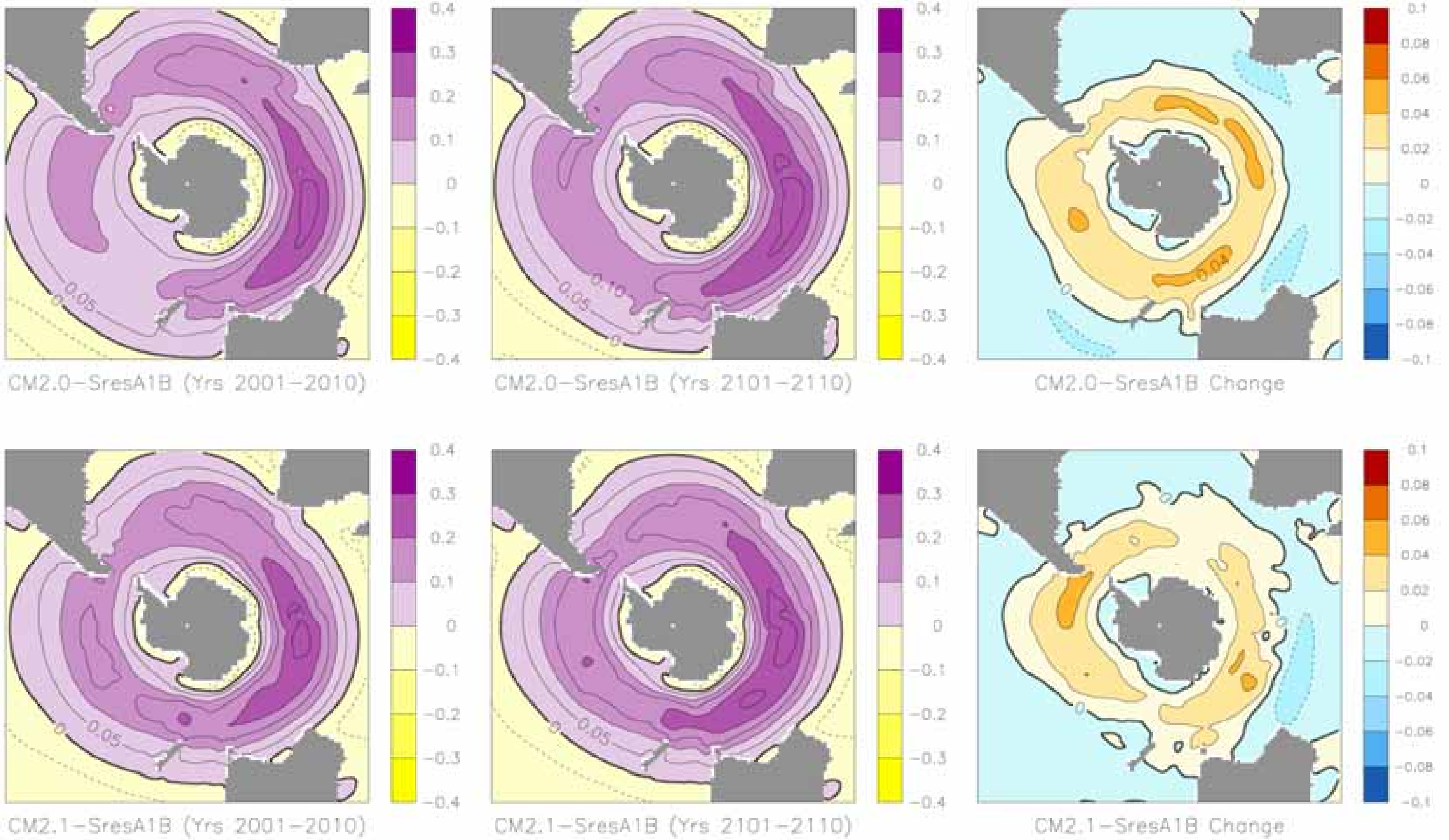
The Southern Ocean
in a
Warming World

How will the AR4 model errors impact the simulation of climate change?

Use CM2.1 and CM2.0 as examples – “good” and “bad” SO simulation


IDEALIZED YEAR
0
40
90
140
190
240
290
340
390
440
Tropospheric CO2
1200
1000
800
600
400
200
+1%/yr to 4X (j1)
+1%/yr to 2X (i1)
1860 control (d2)
SRES A2 (w2)
SRES A1B (x2)
SRES B1 (y2)
Stabilized @ 2000 (s2)
Historical (h1)
1860
1900
1950
2000
2050
2100
2150
2200
2250
2300
SCENARIO YEAR

Surface Westerly Wind Change



CM2.0–SresA1B (Yrs 2001–2010)

CM2.0–SresA1B (Yrs 2101–2110)

CM2.0–SresA1B Change

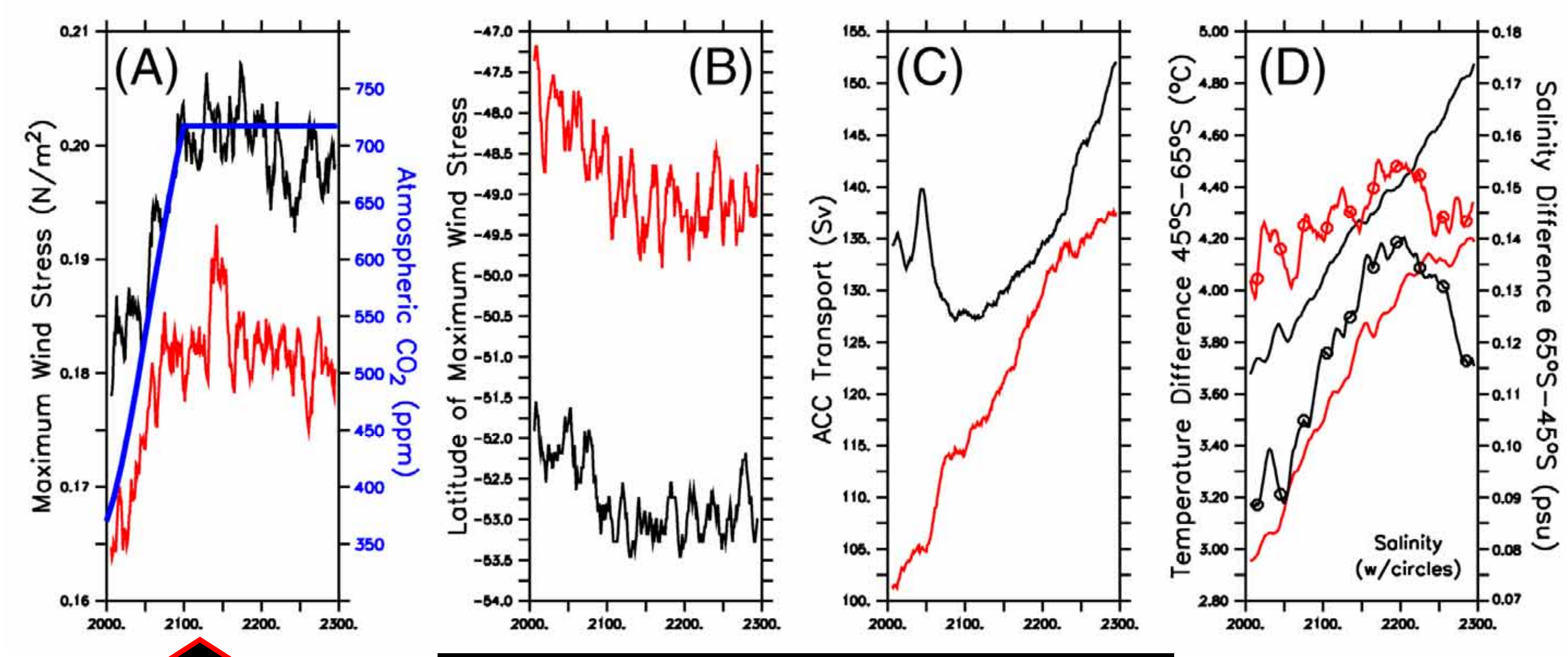
CM2.1–SresA1B (Yrs 2001–2010)

CM2.1–SresA1B (Yrs 2101–2110)

CM2.1–SresA1B Change

Model Response to SRESA1B Scenario

(CO_2 increases to 700+ppm @ year 2100, steady to 2300)



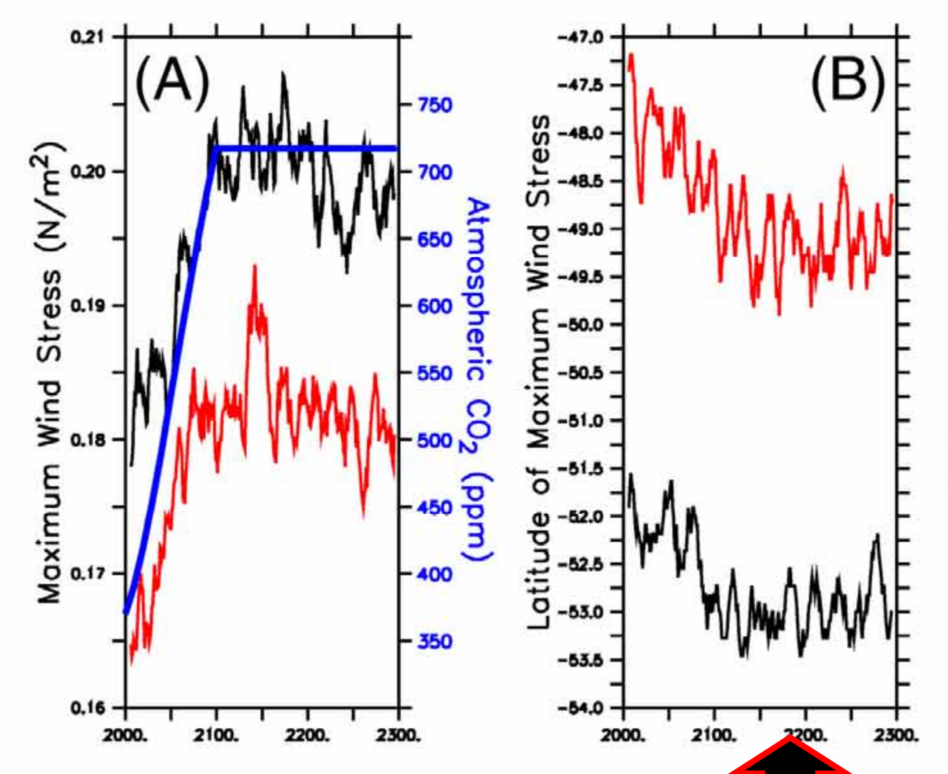
Red=CM2.0, Black=CM2.1

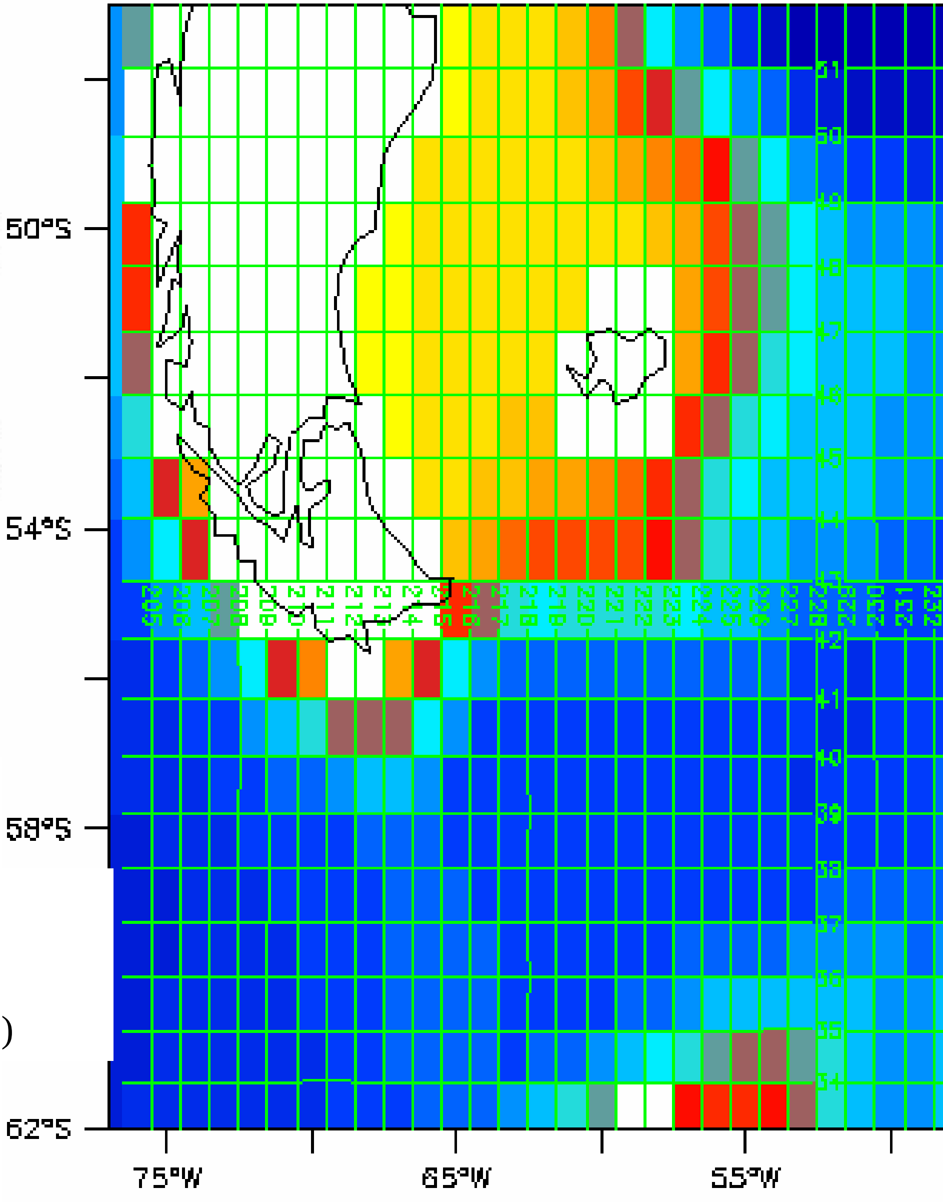
…as CO_2 increases (~doubles), the S. Hemisphere's westerly winds strengthen (max zonal wind stress + ~10%)

Russell et al., *In press*.

Model Response to SRESA1B Scenario

(CO$_2$ increases to 700+ppm @ year 2100, steady to 2300)



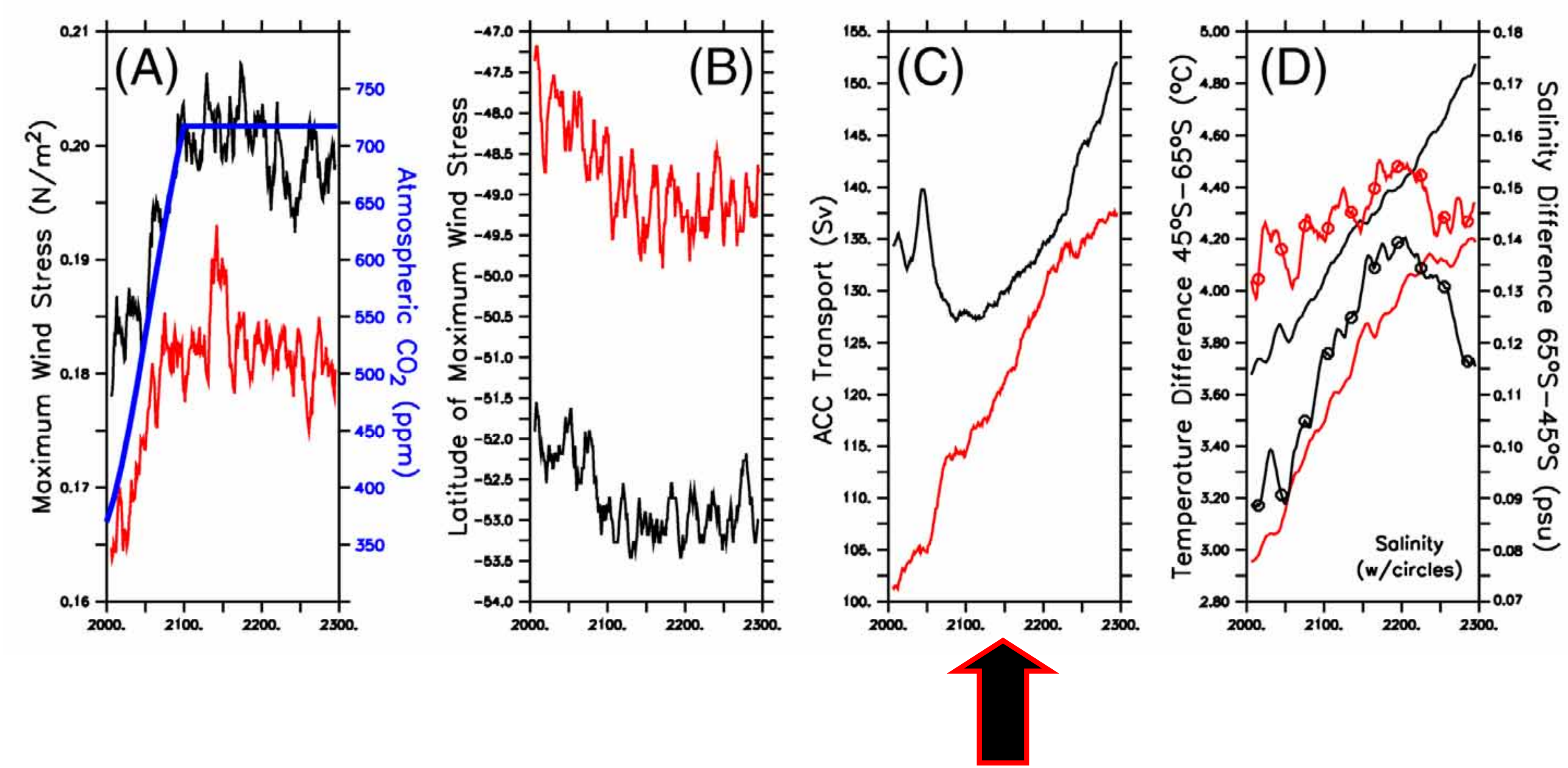


…as CO2 increases, the latitude of the maximum westerlies moves south

(~1½ ° (CM2.1) to 2° (CM2.0) closer to Drake Passage)

Model Response to SRESA1B Scenario

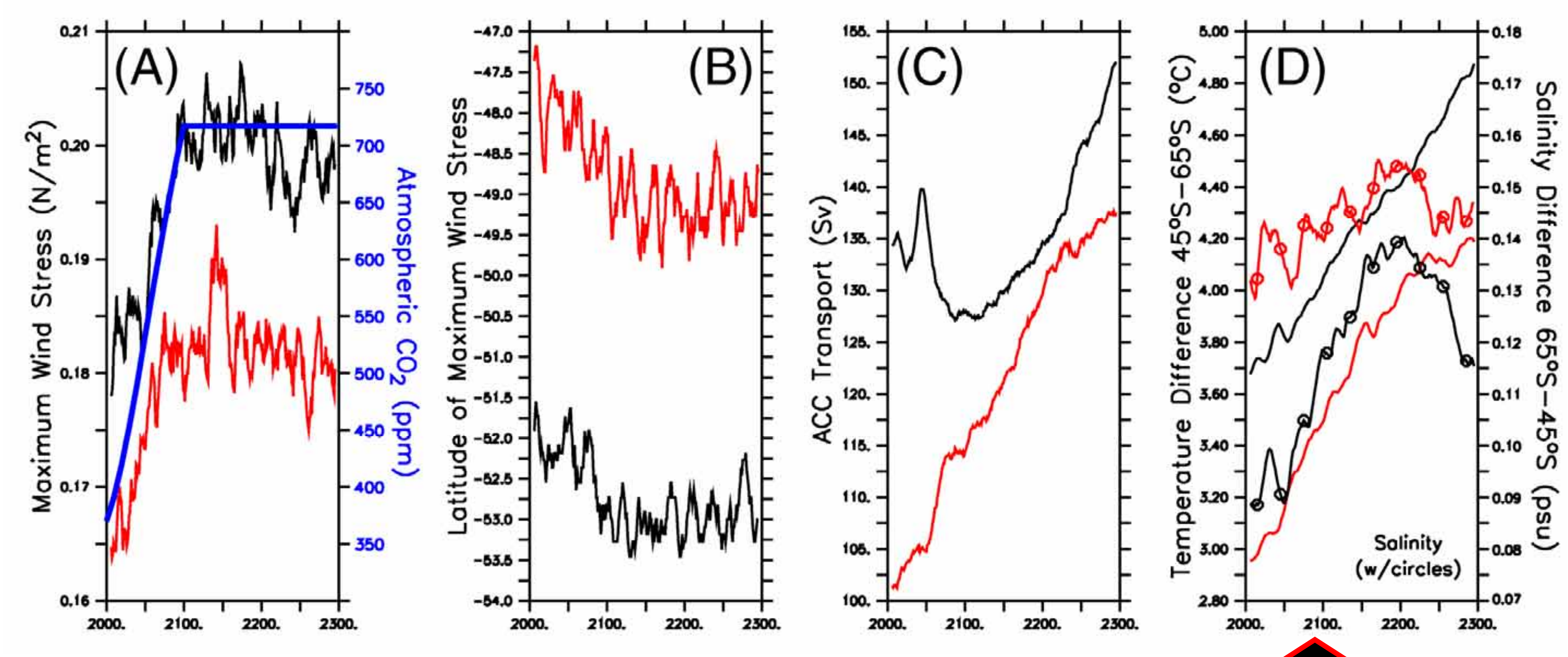
(CO$_2$ increases to 700+ppm @ year 2100, steady to 2300)



…and the ACC strengthens over time, even after CO2 stabilization
(from year 2000 to 2300, CM2.0 ~100 to 137Sv, CM2.1 ~135 to 152Sv)

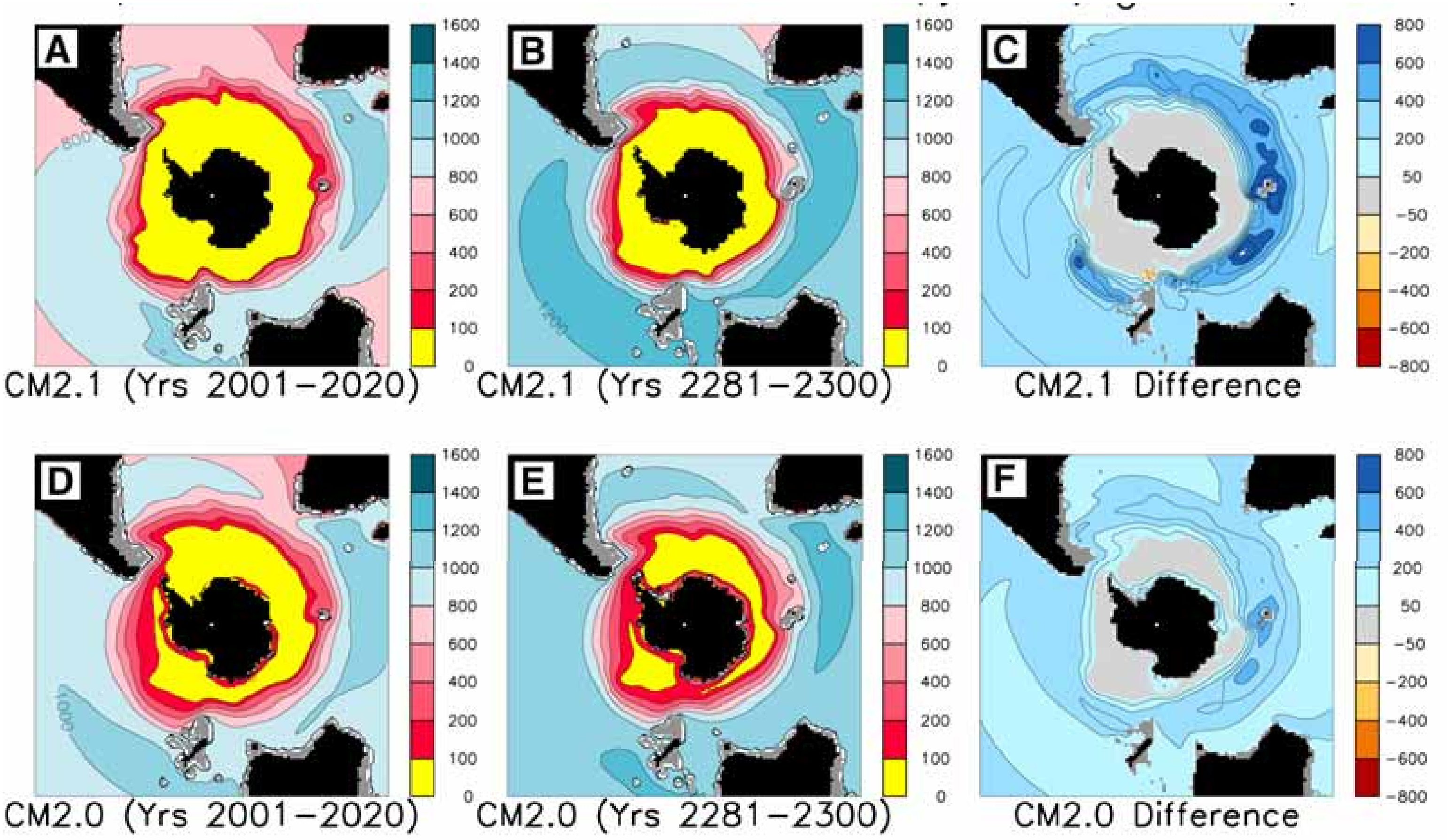
Model Response to SRESA1B Scenario

(CO_2 increases to 700+ppm @ year 2100, steady to 2300)



…N-S temperature and salinity gradients strengthen,
leading to a stronger density gradient across the ACC (0-2500m)

Depth of Antarctic Intermediate Water ($\sigma_\theta = 27.1$)

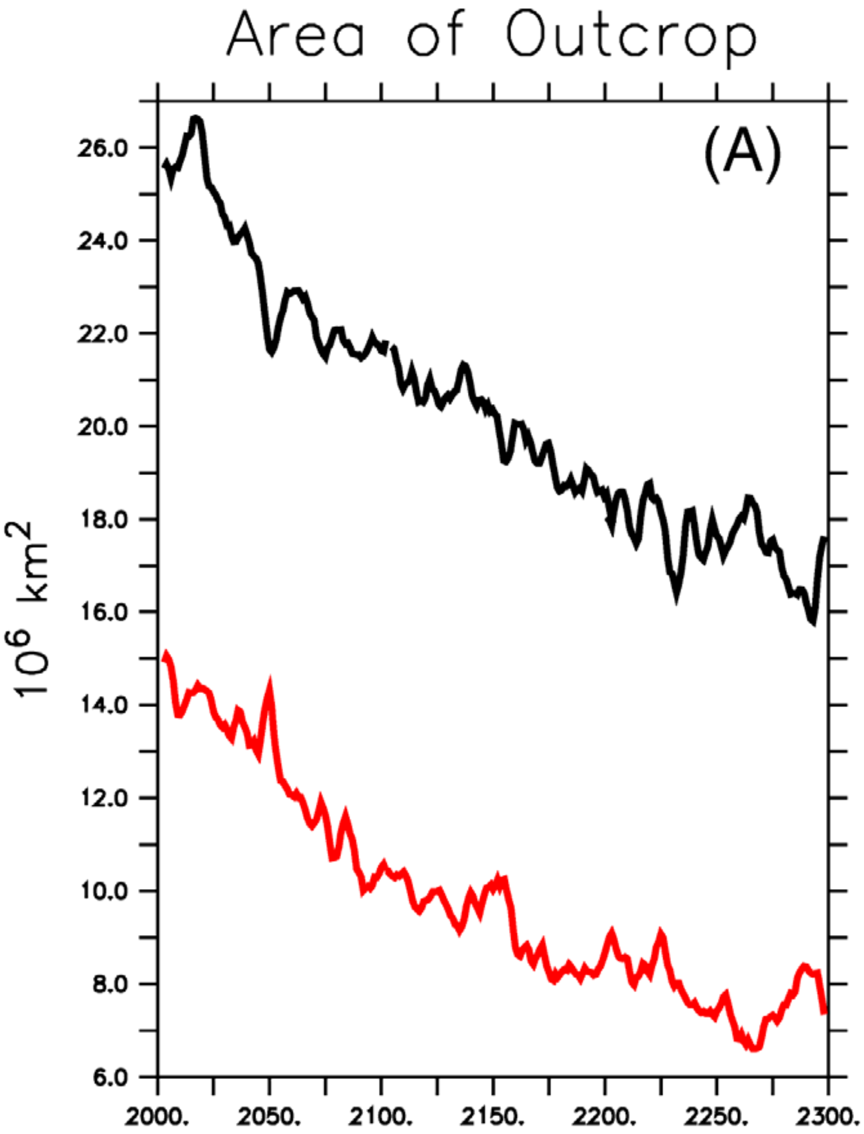


CM2.1 (Yrs 2001–2020)
CM2.1 (Yrs 2281–2300)
CM2.1 Difference
CM2.0 (Yrs 2001–2020)
CM2.0 (Yrs 2281–2300)
CM2.0 Difference

As one might expect in a warming world, the area over which potential densities exceed 27.1 (σ_θ) at 100m depth (shown in yellow) is reduced as surface waters warm, and the depths at which the σ_θ 27.1 surface lie become deeper.

Area of Outcrop for AAIW

($\sigma_\theta = 27.1$)



Red=CM2.0 Black=CM2.1

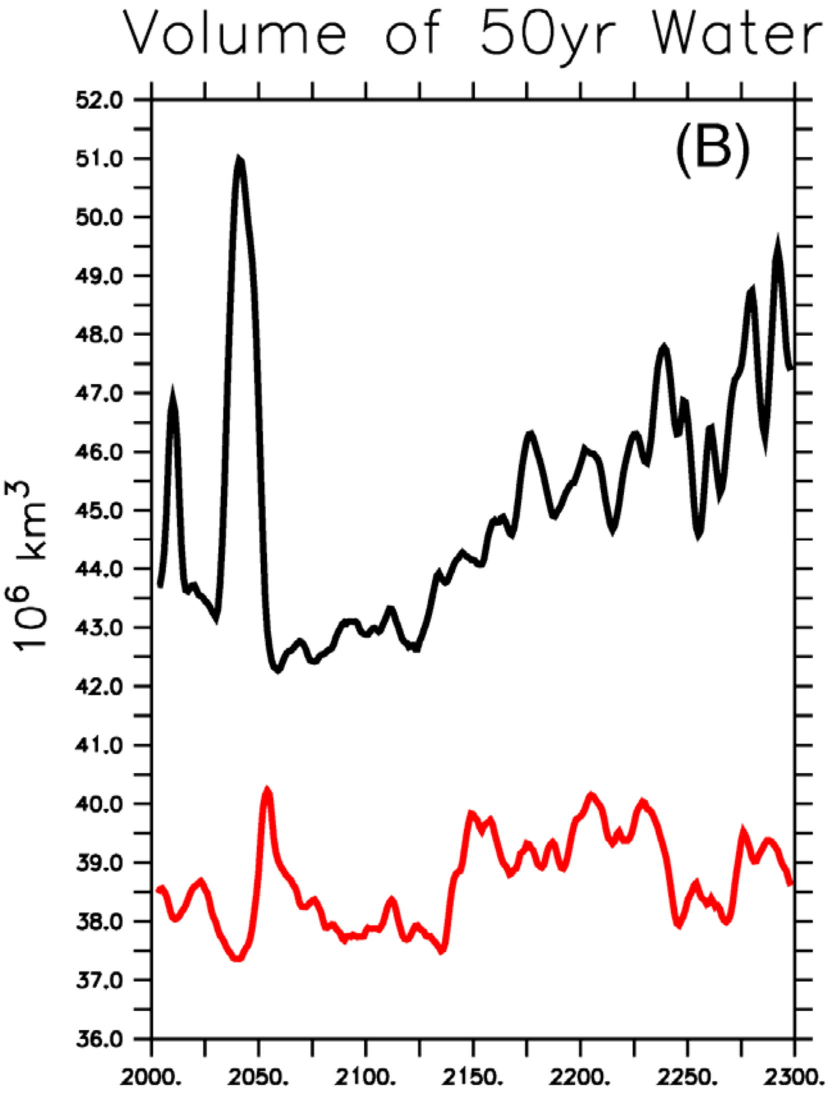
The outcrop area decreases as the surface waters warm.

…decreases by ~8x10^6 km^2 (~33%) in CM2.1

… decreases by ~7x10^6 km^2 (~50%) in CM2.0

Volume of
water
ventilated
within
50 years

(from model’s
idealized age tracer

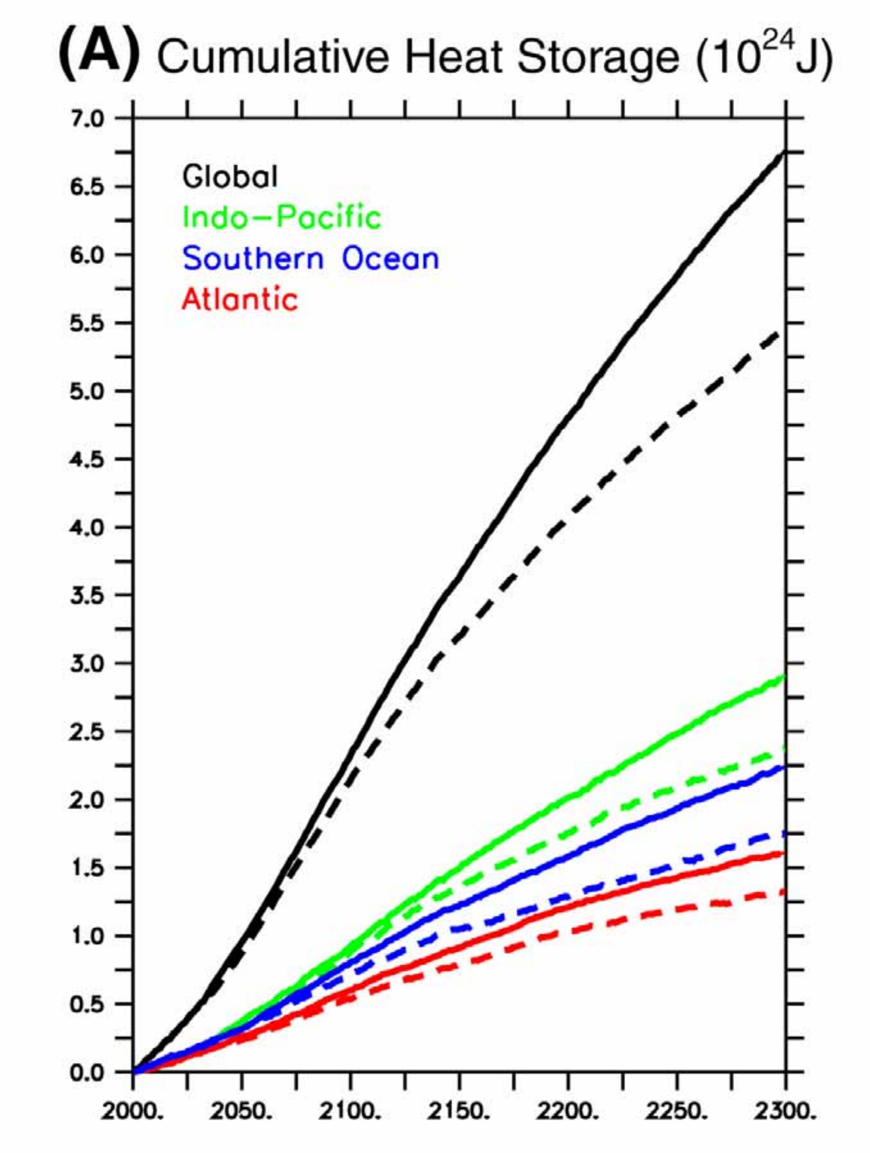


Red=CM2.0 Black=CM2.1

Yet the amount of water that has been in contact with the surface less than 50 years prior grows because of more Southern Ocean ventilation.
(due to more surface divergence)

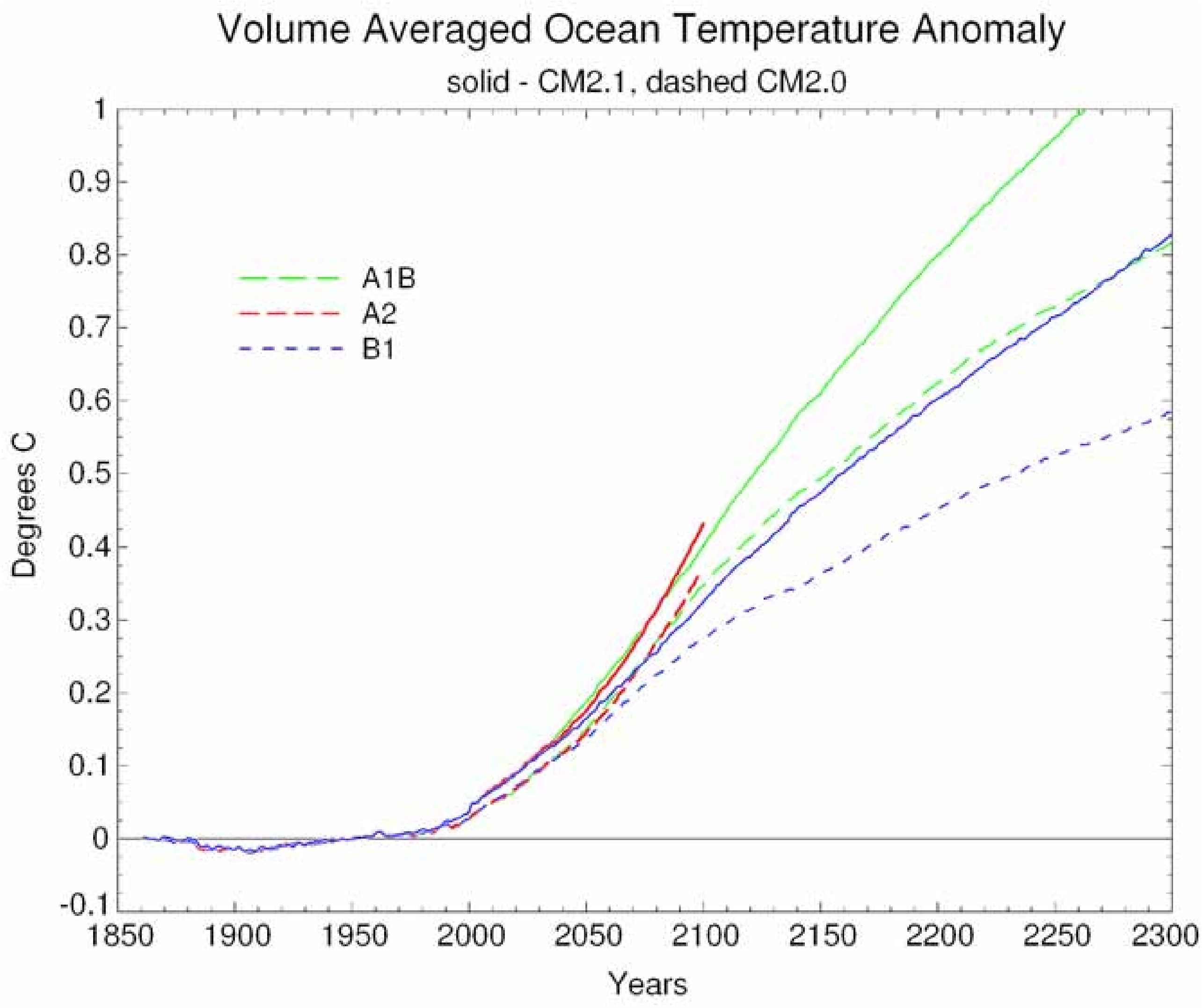
…increases by ~6% in CM2.1…

…less so in CM2.0



The Ocean's Heat Inventory Grows Over Time

More so in CM2.1 (solid) than CM2.0 (dash) as time goes on & effects of deep ventilation differences become more apparent. The largest differences are in the Southern Ocean uptake and subsequent storage in the Indian and Pacific Oceans



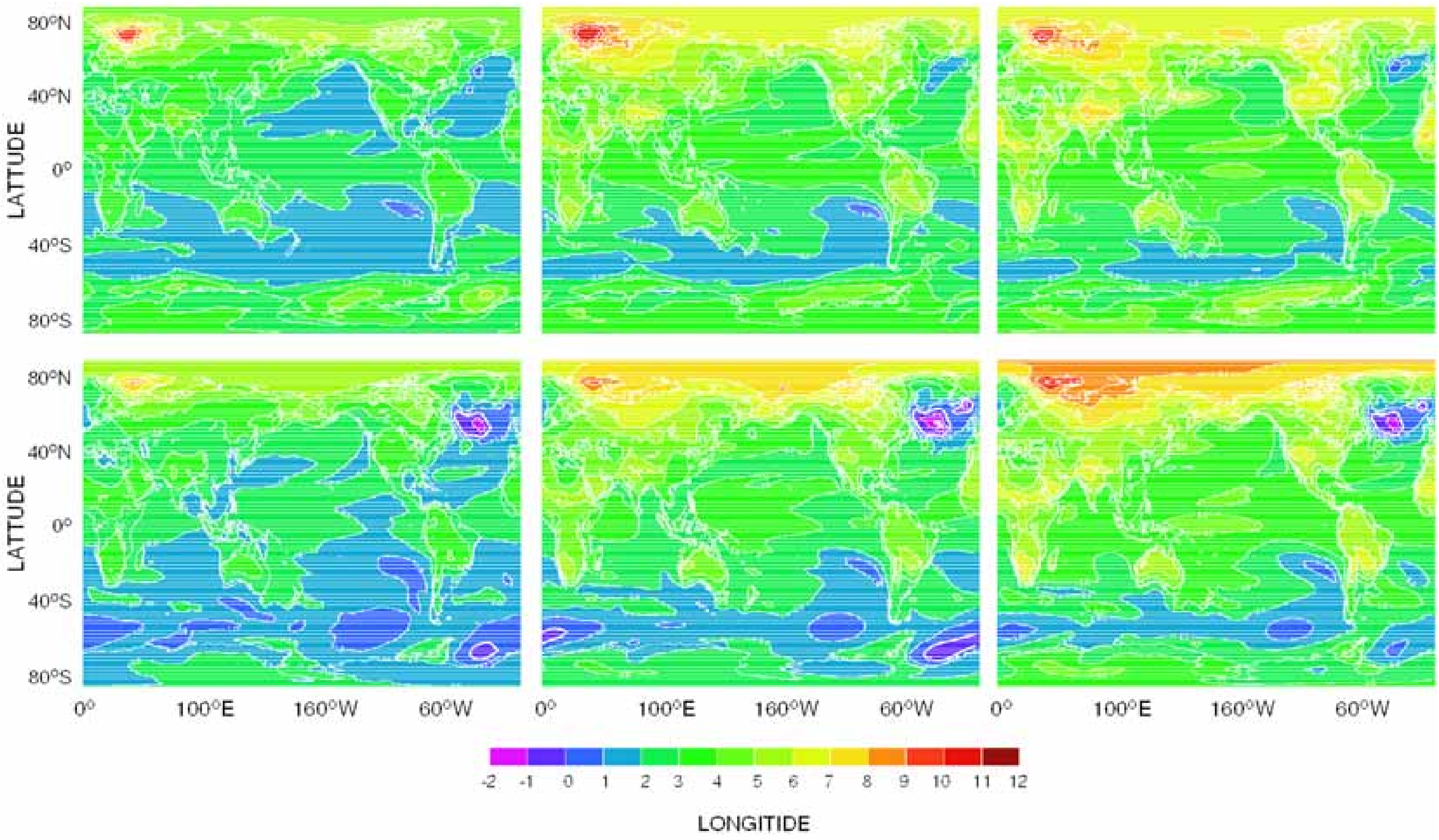
Time series of volume averaged ocean temperature difference (^{o}K), the various integrations minus the control.

From Stouffer, Russell & Spelman, 2006

SRES B1 SRES A1B SRES A2

CM2.0

CM2.1



Surface air temperature difference, perturbation integration minus the 1860 control integration (ºK).

So how might the Southern Ocean change in a warming world?

Changes that could lead to **less** oceanic CO_2 uptake…

- Warmer, fresher, more stably stratified Southern Ocean surface waters would decrease ocean ventilation rates.
- CO_2 solubility decreases as SSTs warm.

Changes contributing toward **more** oceanic CO_2 uptake…

- S.H. westerlies strengthen and move poleward, thereby increasing divergence, exposing more water to the atmosphere.
- pCO_2 difference between majority of upwelled water and atmosphere increases as tropospheric CO_2 increases, driving more CO_2 uptake by the ocean.

Note: we're not including biological mechanisms and feedbacks here!

Method for inferring future solubility-related “carbon” uptake

- We estimate the inferred anthropogenic CO_2 concentration due to changes in solubility by:

$$C_{anth} = C_{sat} - C_{eq\text{-}modern}$$

where C_{sat} is the saturation value of DIC calculated from the modeled temperature, salinity and atmospheric pCO_2 and where C_{eq} is the WOCE distribution of DIC from GLODAP.

- We assume 100 percent saturation with respect to the atmospheric pCO_2 over a 5 year period, an unchanging biological pump (C_{bio}) and pH distribution (ignoring the effect of buffering).

Caveats!

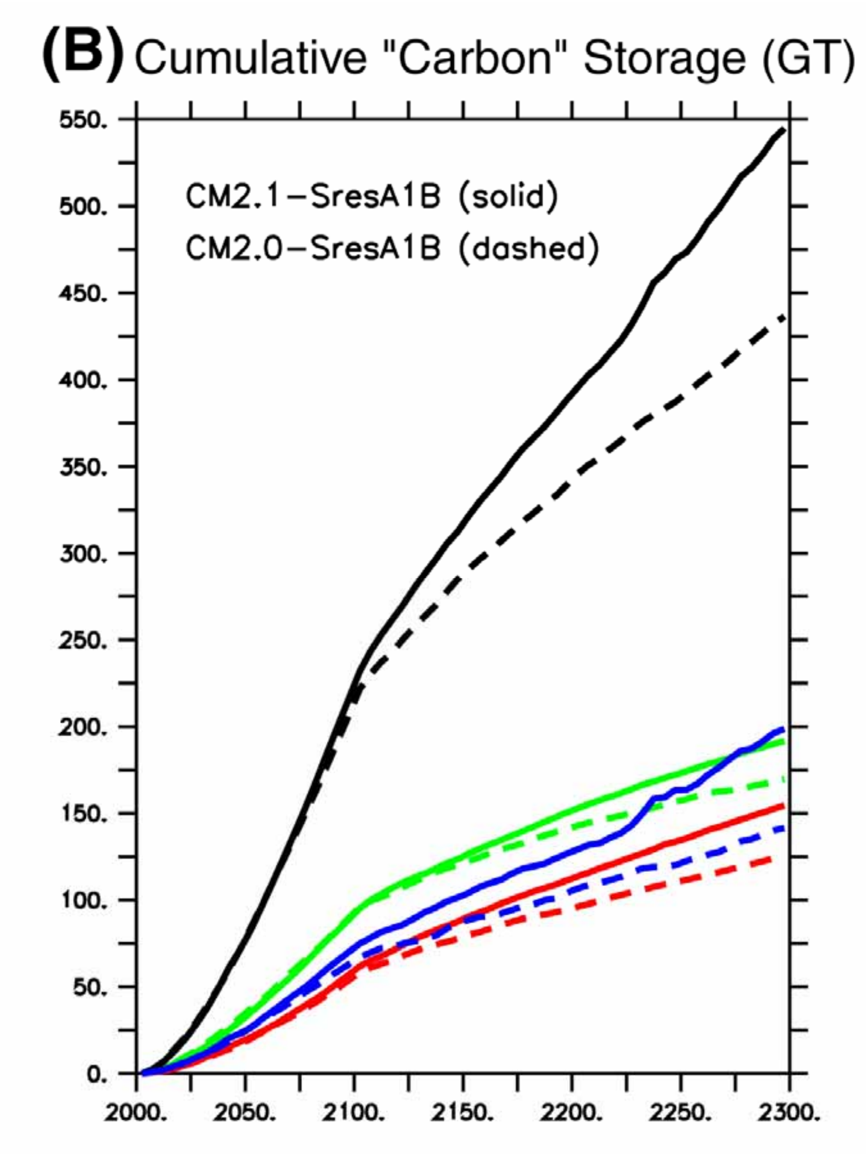
- We assume a constant pH distribution, ignoring the effect of buffering.

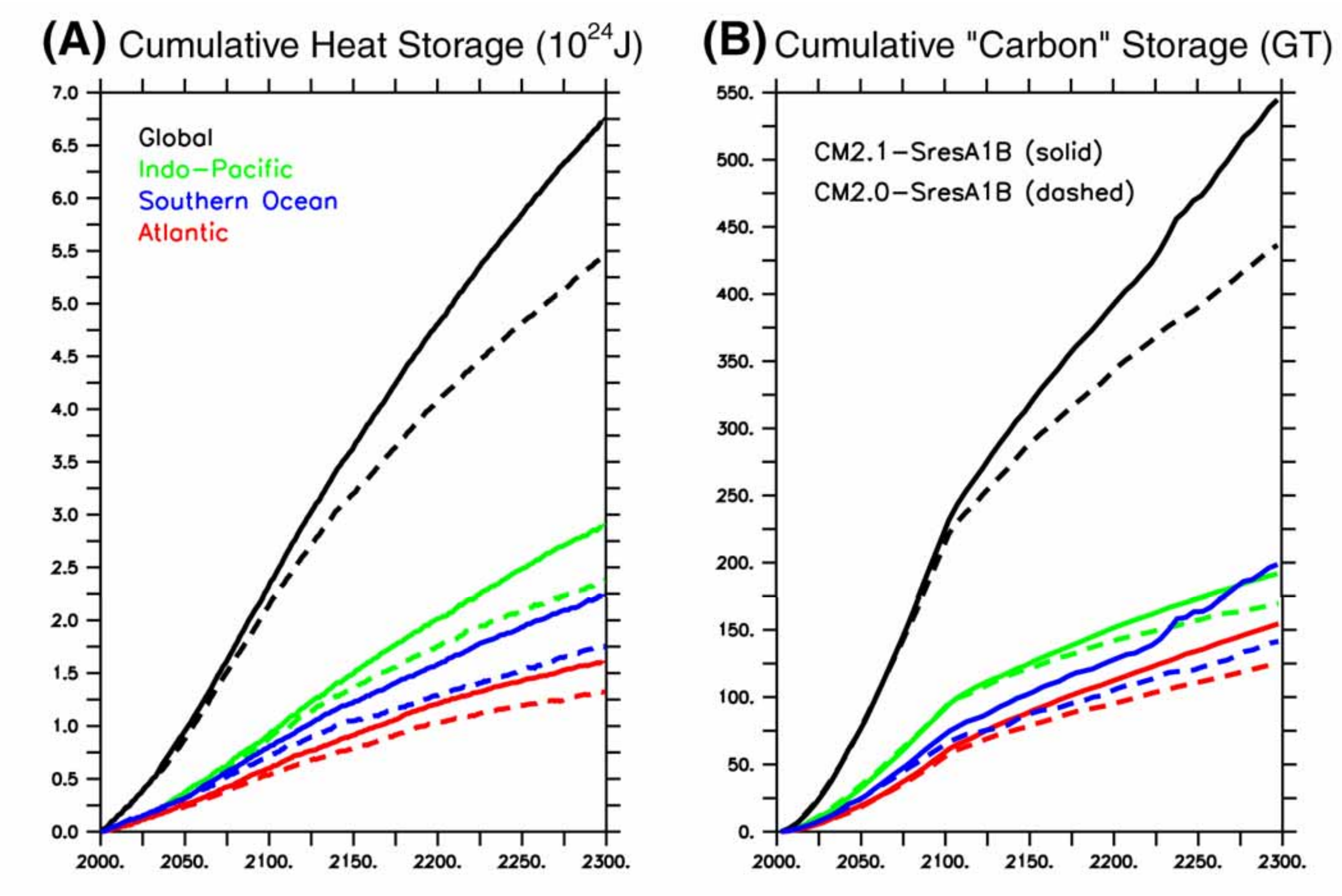
- We assume a constant biological pump, i.e. no change in surface to deep DIC distribution

  - These are clearly important effects that need to be addressed - but the appropriate tracers weren’t included in the AR4 models.

The Ocean’s Solubility-related Carbon Inventory Grows Over Time

Over the first 50 years, the dominant effect is the increasing carbon dioxide in the atmosphere driving an increase in surface ocean solubility. After 50 years, deep ocean ventilation diverges due to the poleward intensification of the Southern Hemisphere Westerly Winds.



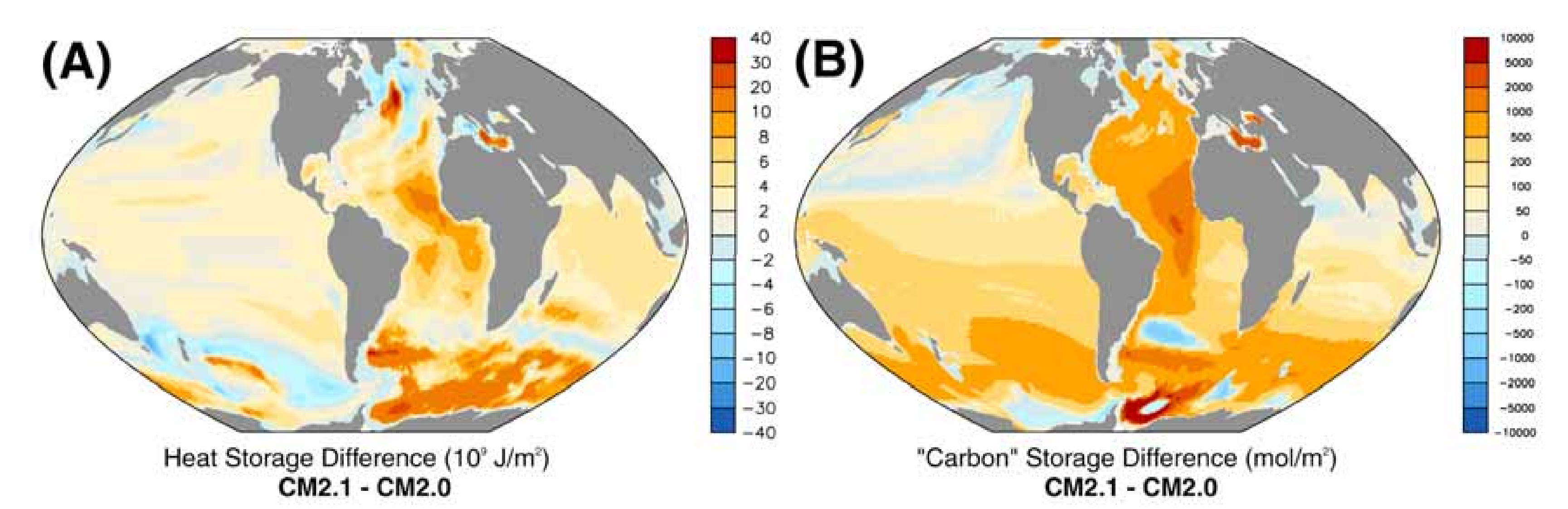


Heat and solubility-related carbon inventory grows over time

More so in CM2.1 (solid) than CM2.0 (dash) as time goes on & effects of deep ventilation differences become more apparent.

Heat and “Carbon” Storage Difference in 2300

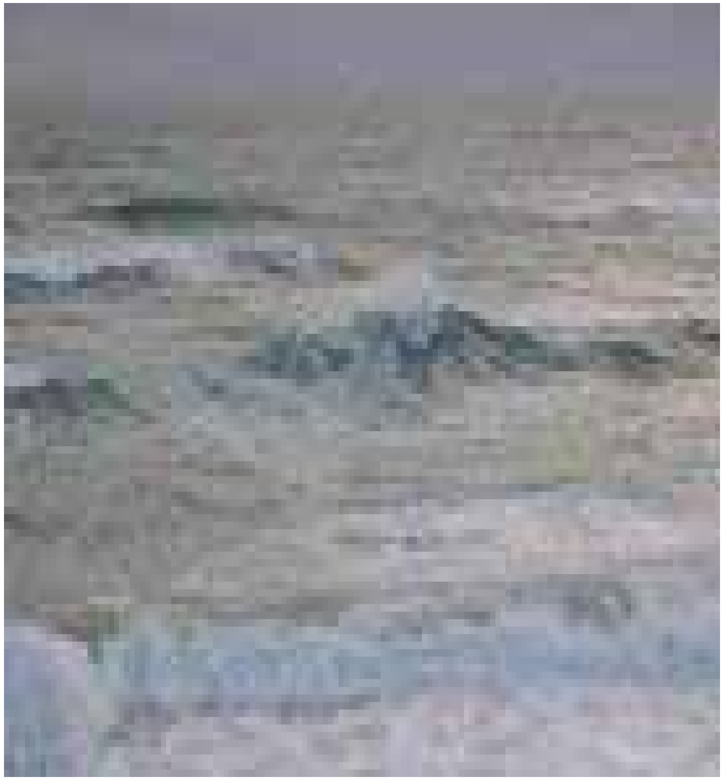
CM2.1 - CM2.0 (2300-2000)



Heat Storage Difference (10^9 J/m^2)

Carbon Storage Difference (mol/m^2)

Response time scales
Role of Oceans



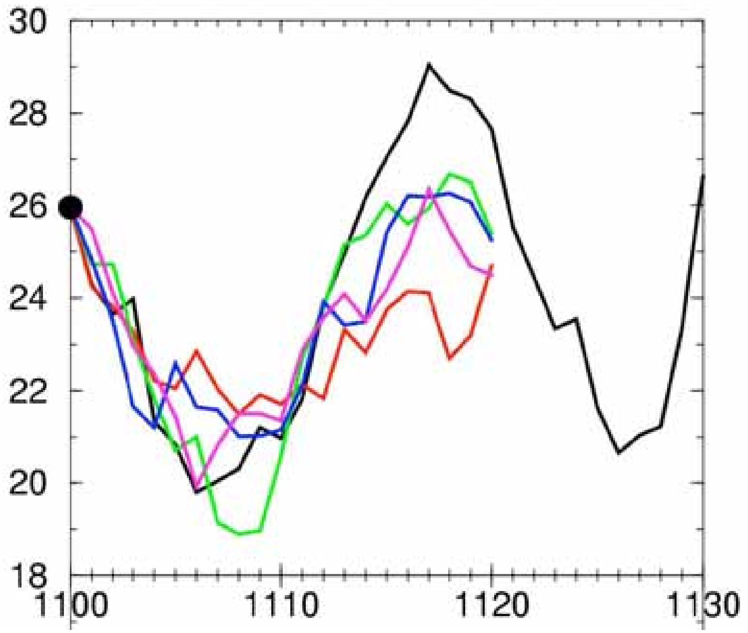
IPCC WGI SPM

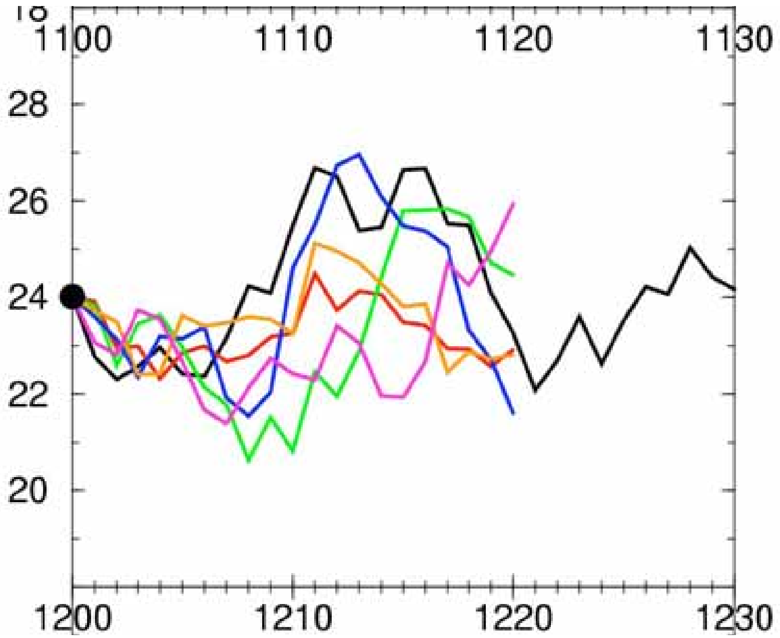
Anthropogenic warming and sea level rise would continue for centuries, even if GHG concentrations were to be stabilized at or above today’s levels.

AR4 estimates 0.2 to 0.6m sea level rise per ^{o}C at equilibrium due only to thermal expansion of sea water.

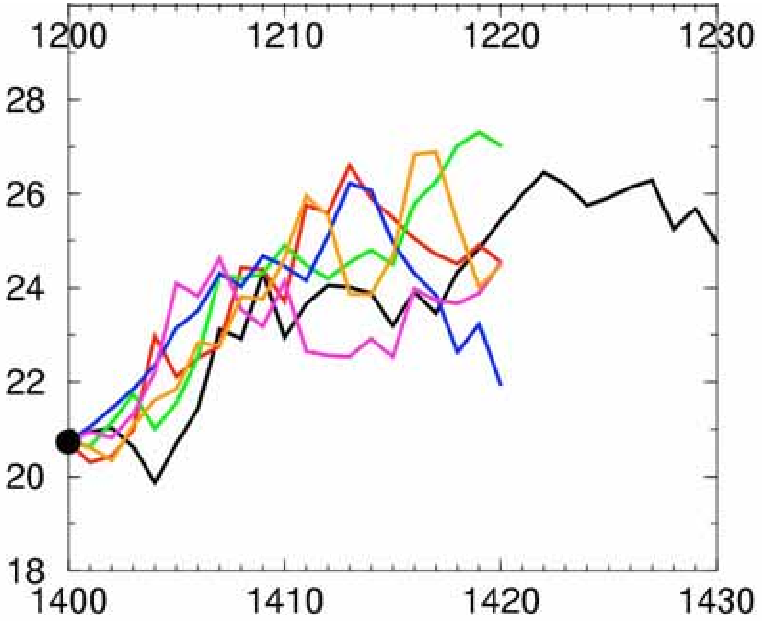
Oceans:
Role in Natural Variability

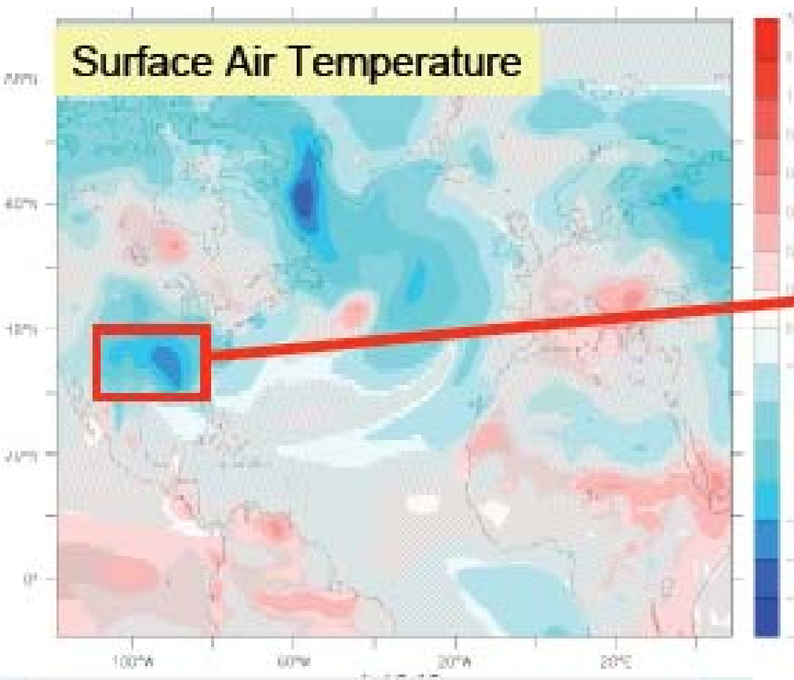
- ENSO
  - What sets time scale?
    - Atmosphere/Ocean/both?
  - What impacts ENSO?
    - Atmosphere convection scheme, ocean color, ocean mixing
- NAO/AO/AMO/MOC
  - Multi-decadal variability
    - Predictable?
  - Hurricanes
- Century or longer oscillations in SO
  - In some models, in real world?
- Eddies – feedback on larger scale surface climate?

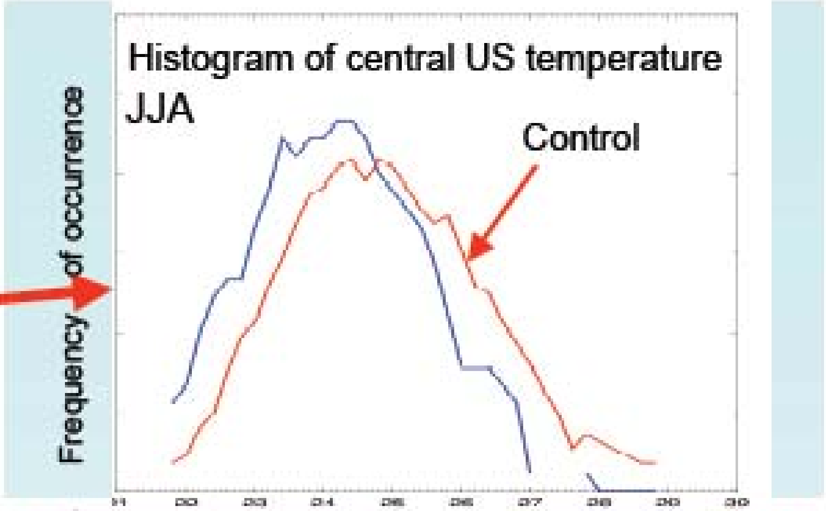


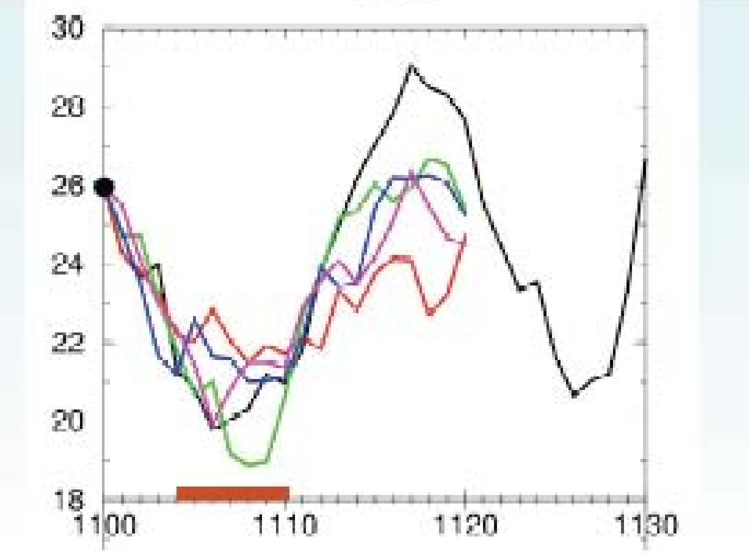


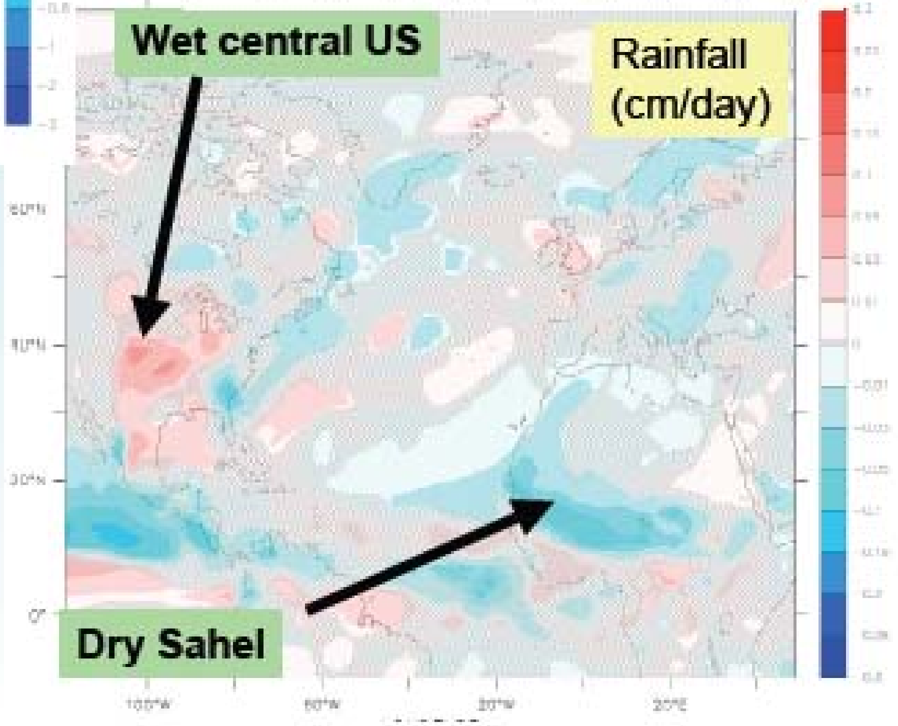
Predictability of Atlantic Meridional Overturning Circulation (AMOC) in GFDL CM2.1 Climate Model




Surface Air Temperature
100°W
60°W
20°W
20°E


Histogram of central US temperature
JJA
Frequency of occurrence
Control

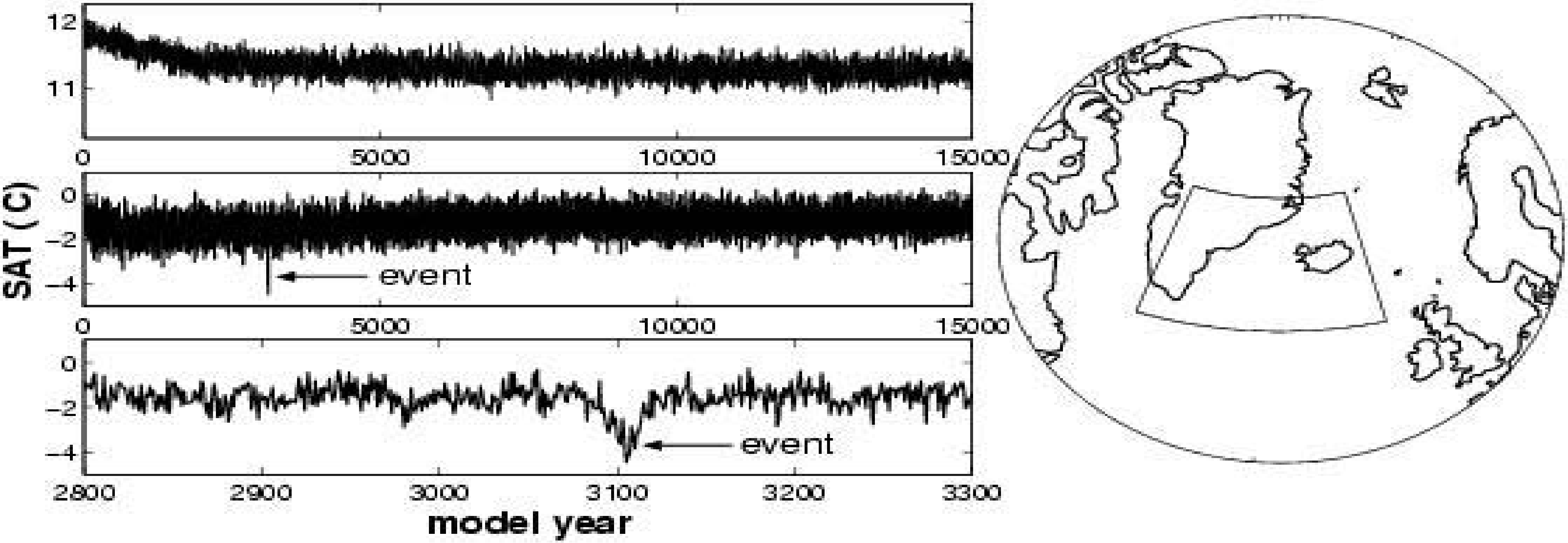

30
28
26
24
22
20
18
1100
1110
1120
1130


Wet central US
Rainfall
(cm/day)
Dry Sahel
100°W
60°W
20°W
20°E

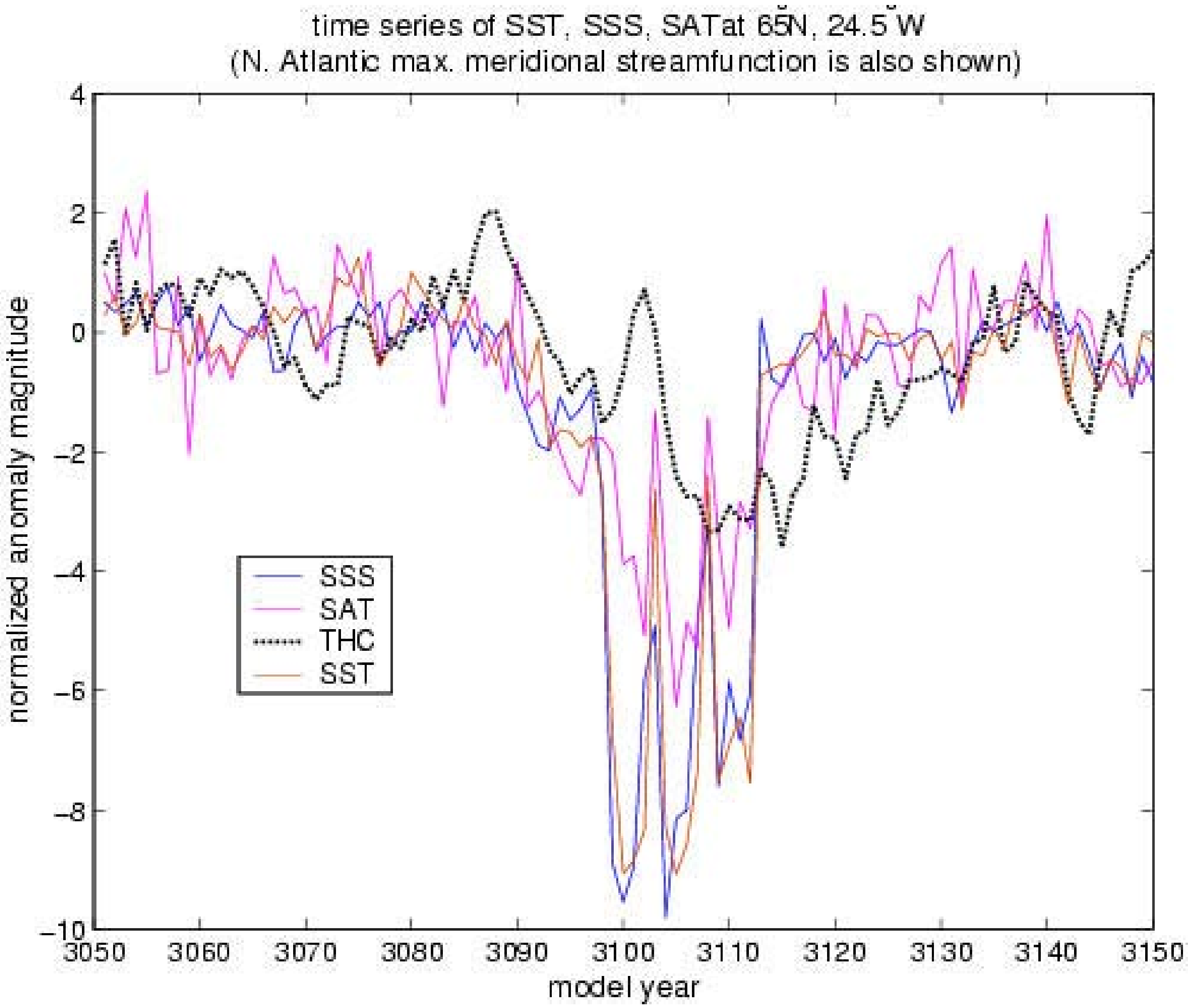
Oceans:
Role in Abrupt Climate Change

- MOC
  - Unforced
  - Forced
    - Idealized (Hosing)
    - GHG increase
- Other processes?

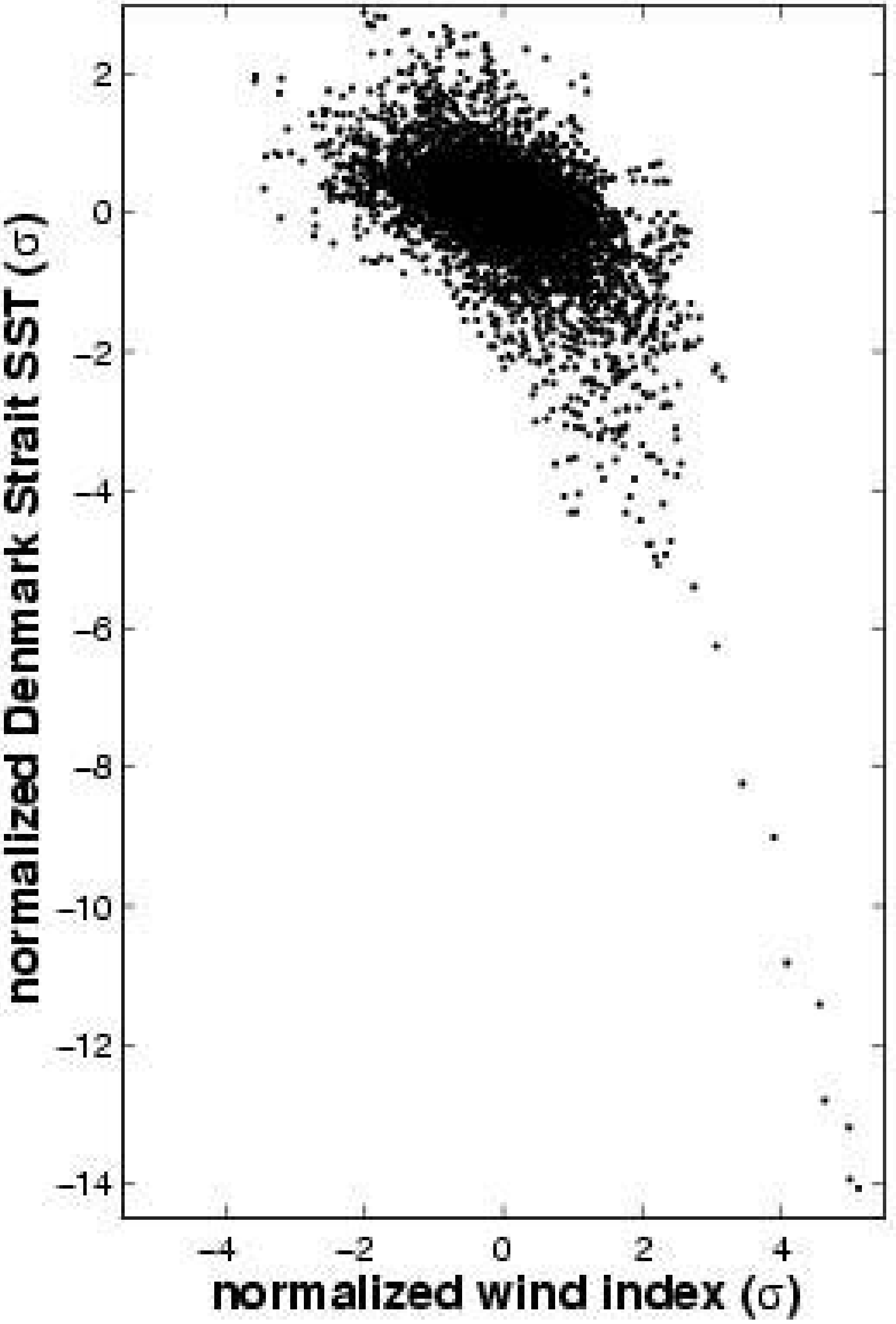
Transient
An Anomalous Event (Unforced)



Surface variables/THC



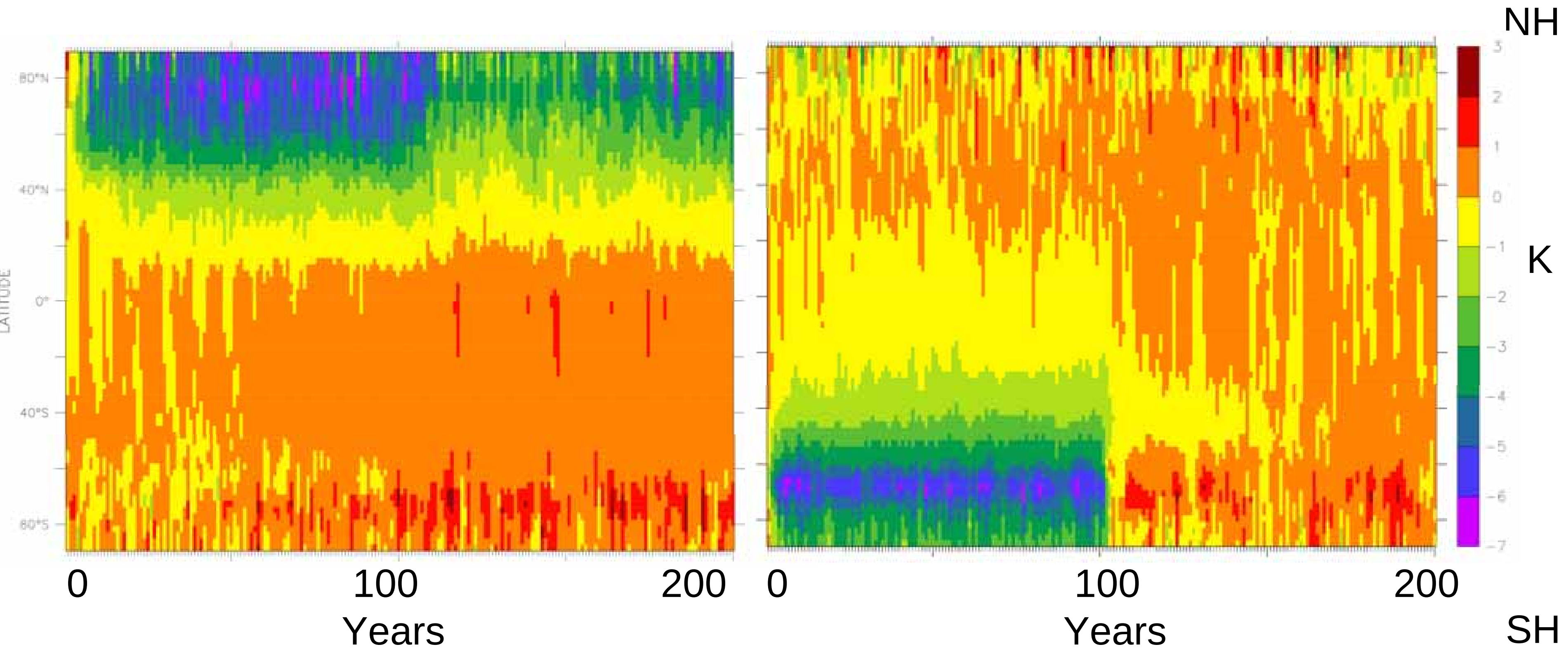
Summary of Physical Mechanism



Idealized Forced THC Response

- Additional 1SV for 100 years
  - Hosing in N Atlantic
  - Hosing around Antarctica
- After 100 years, additional flux set to 0SV

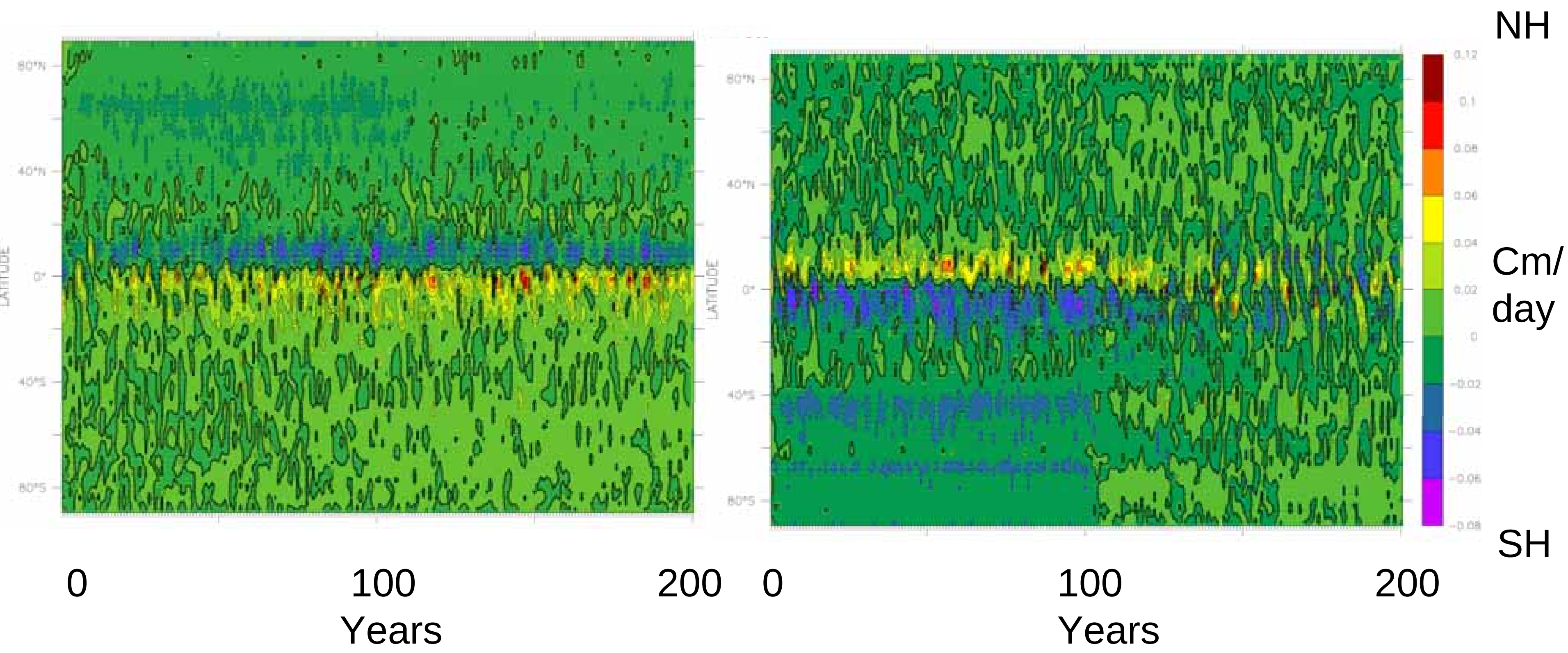
Surface Air Temperature Response



Response remarkably symmetrical (first 100 yrs)

Magnitude very similar

Precipitation Response



Response very symmetric

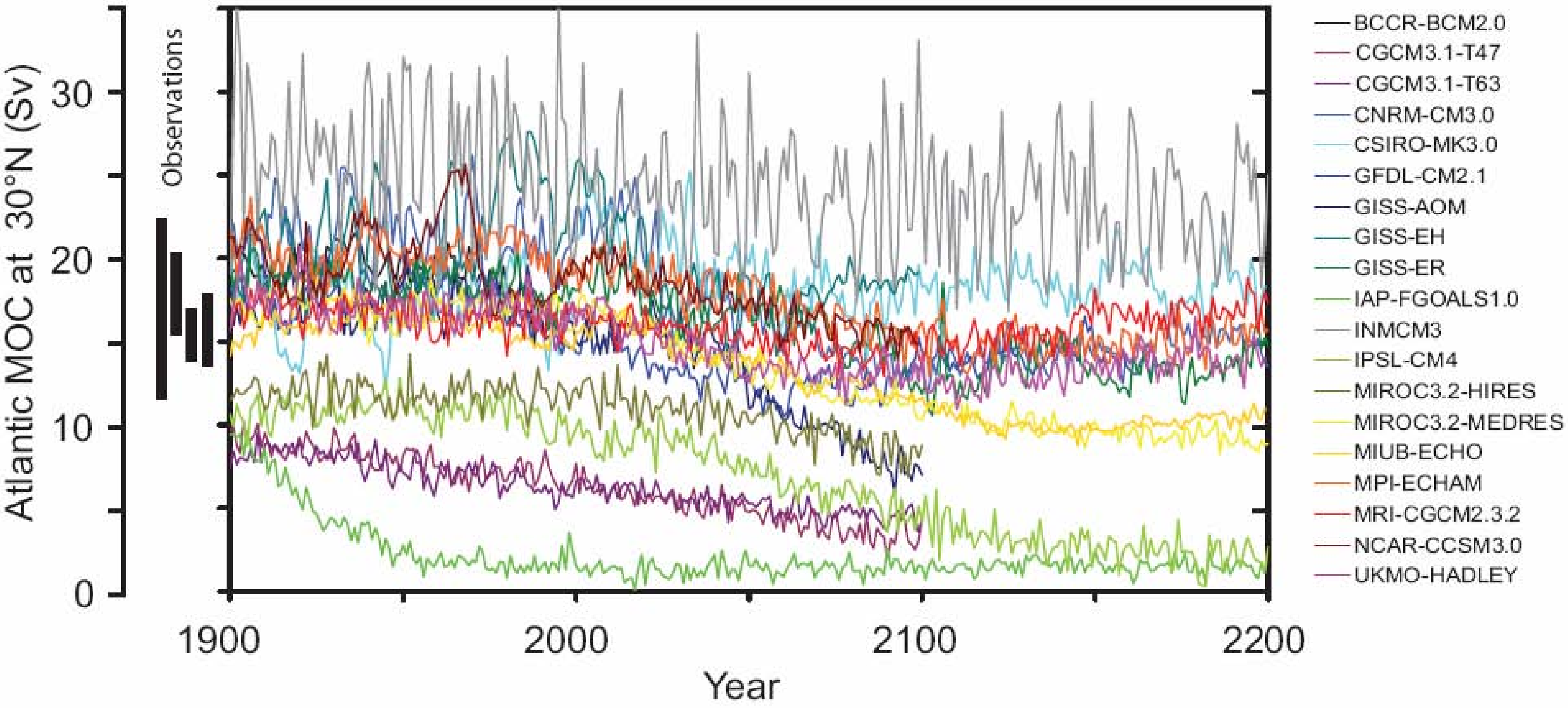
Magnitude very similar

ITCZ shifts toward warmer hemisphere

Hosing Experiment Summary

- Symmetrical Atmospheric Response
- Much less symmetry in ocean
- Why?
  - Strong Circum-Antarctica winds
  - Northward flowing surface waters
  - Freshwater “escapes” into other basins
    - Far a field impacts
    - Less local impacts

MOC and Forced Climate Change

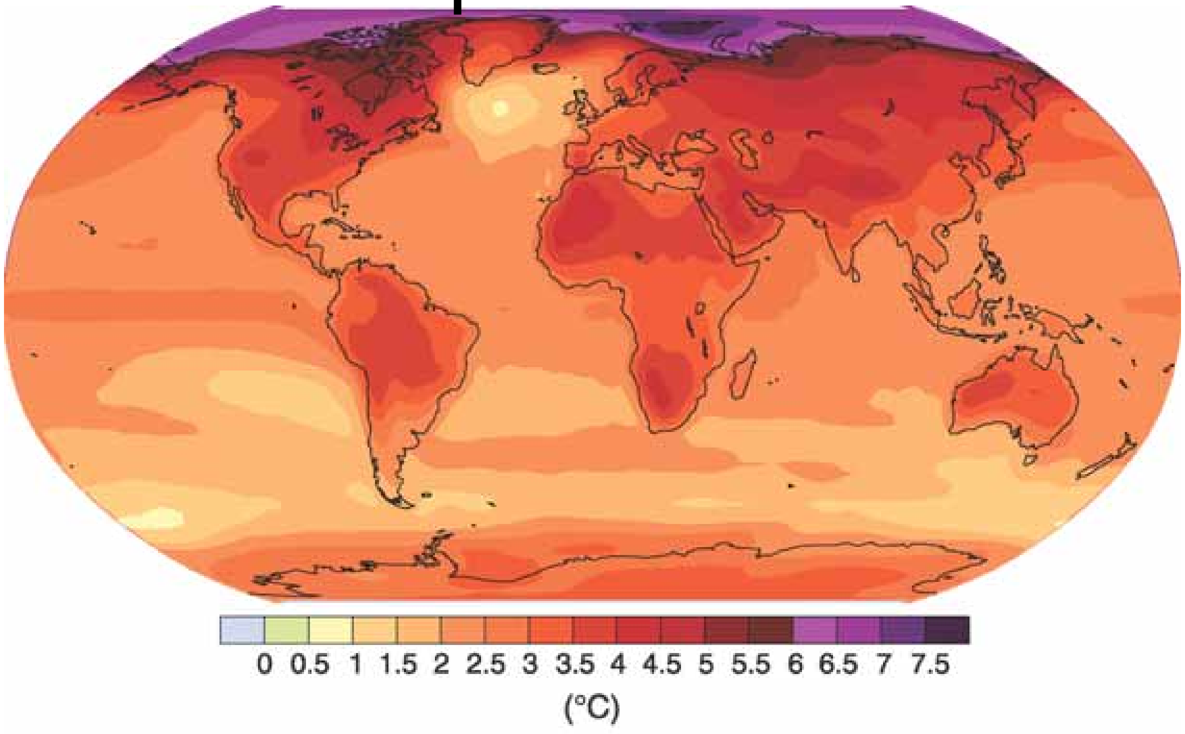


AR4 WG1 Assessment:

❑ MOC *very likely* to weaken

❑ MOC shutdown *very unlikely*

Warming greatest over land and at most high northern latitudes and least over Southern Ocean and parts of the North Atlantic Ocean



Surface Warming Pattern
A1B, 2090-2099
relative to 1980-1999

- Weakening of MOC contributes to minimum in cooling in N Atlantic => smaller climate change => a positive impact?

IPCC WGI SPM

Summary
Ocean’s Role in Climate

- Wet surface
- Heat and tracer storage
  - Climate change
  - Variability
- Heat, water, tracer transport
- Abrupt climate change

Questions

- Is weakening of MOC a positive or negative impact?
- What is impact of MOC shutdown?
  - How large are changes?
- What is role of oceanic eddies in climate change?
- Do we have enough measurements to evaluate heat and other tracer storage terms and transports as climate changes?
  - XBTs – good enough?
  - ARGO
  - Initialization of decadal prediction experiments

Thank you

AR4 ensemble mean error
Temperature

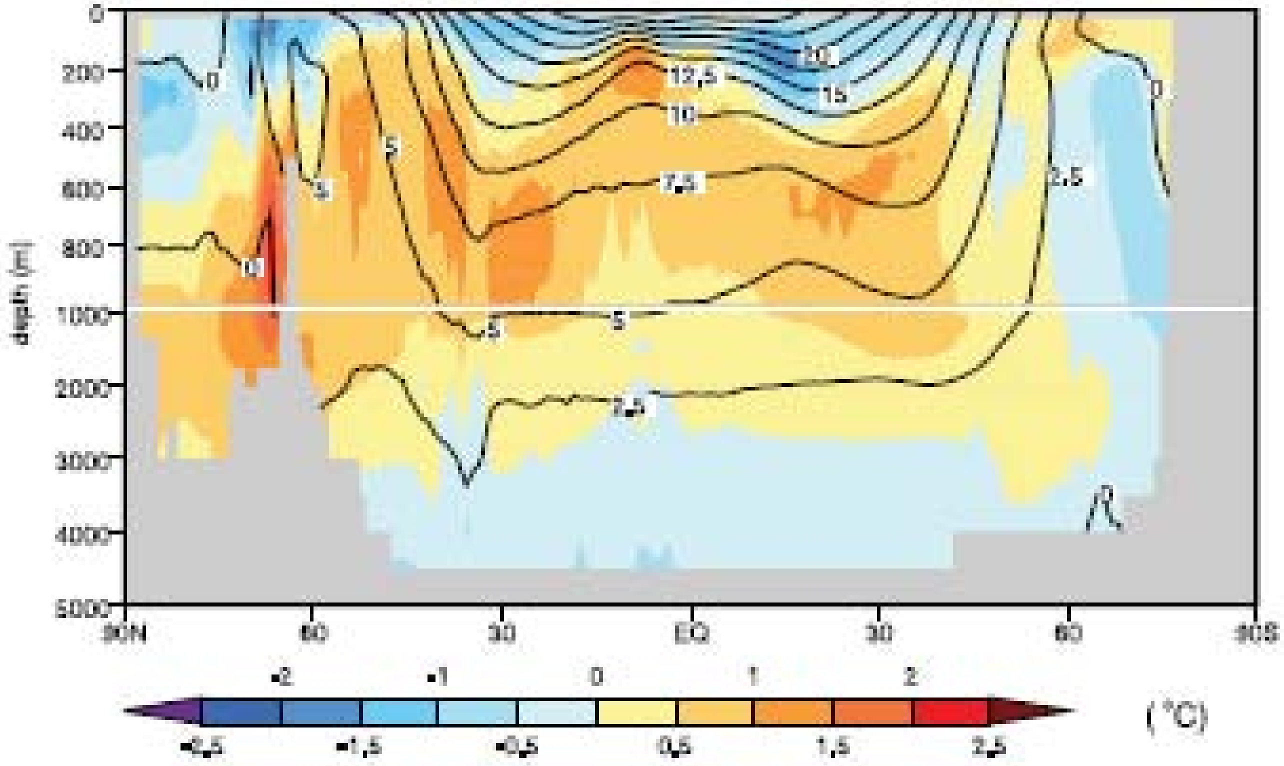
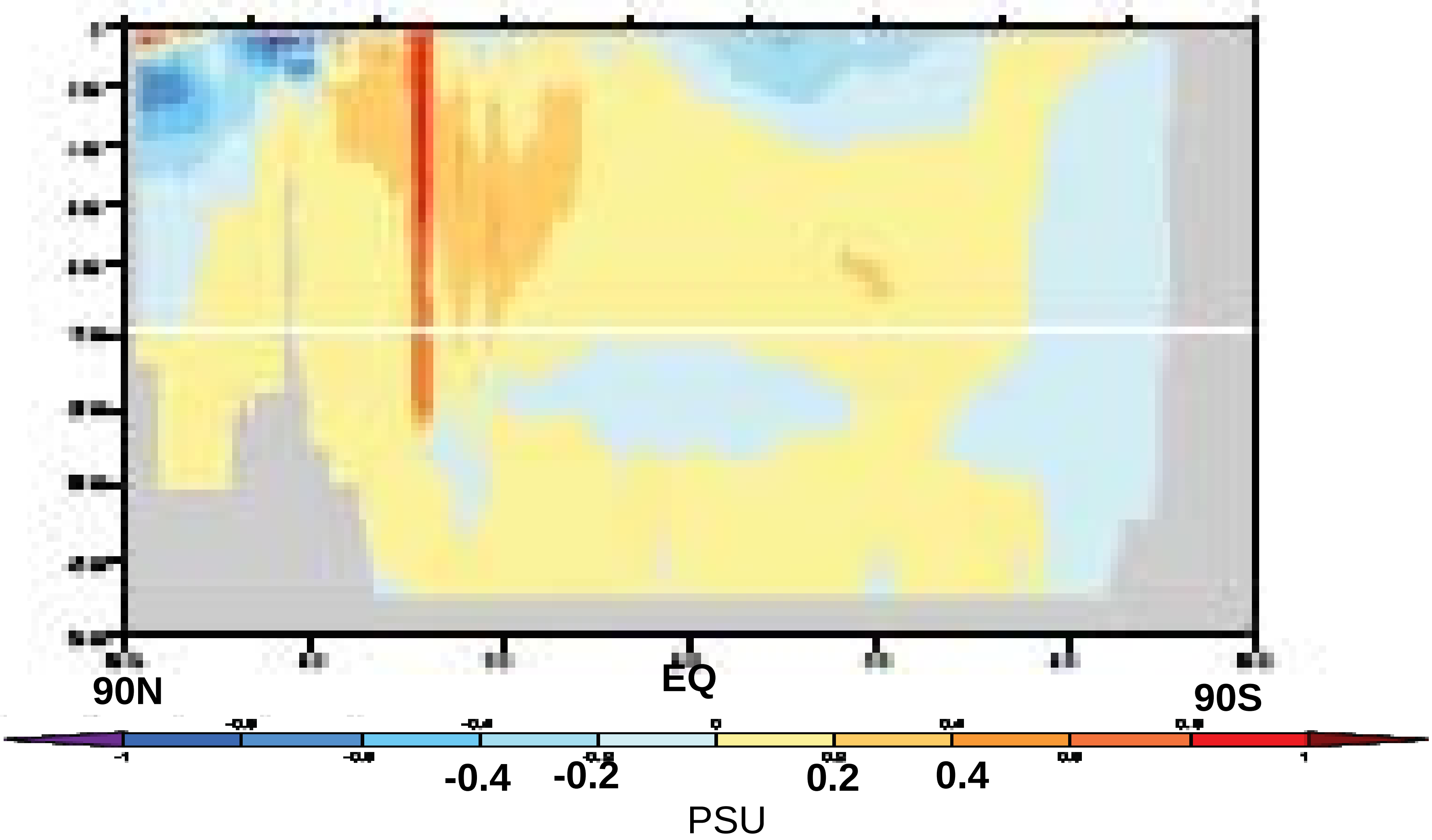


Figure 8.9. *Time-mean observed potential temperature (°C), zonally averaged over all ocean basins (labelled contours) and multi-model mean error in this field, simulated minus observed (colour-filled contours). The observations are from the 2004 World Ocean Atlas compiled by Levitus et al. (2005) for the period 1957 to 1990, and the model results are for the same period in the 20th-century simulations in the MMD at PCMDI. Results for individual models can be seen in the Supplementary Material, Figure S8.12.*

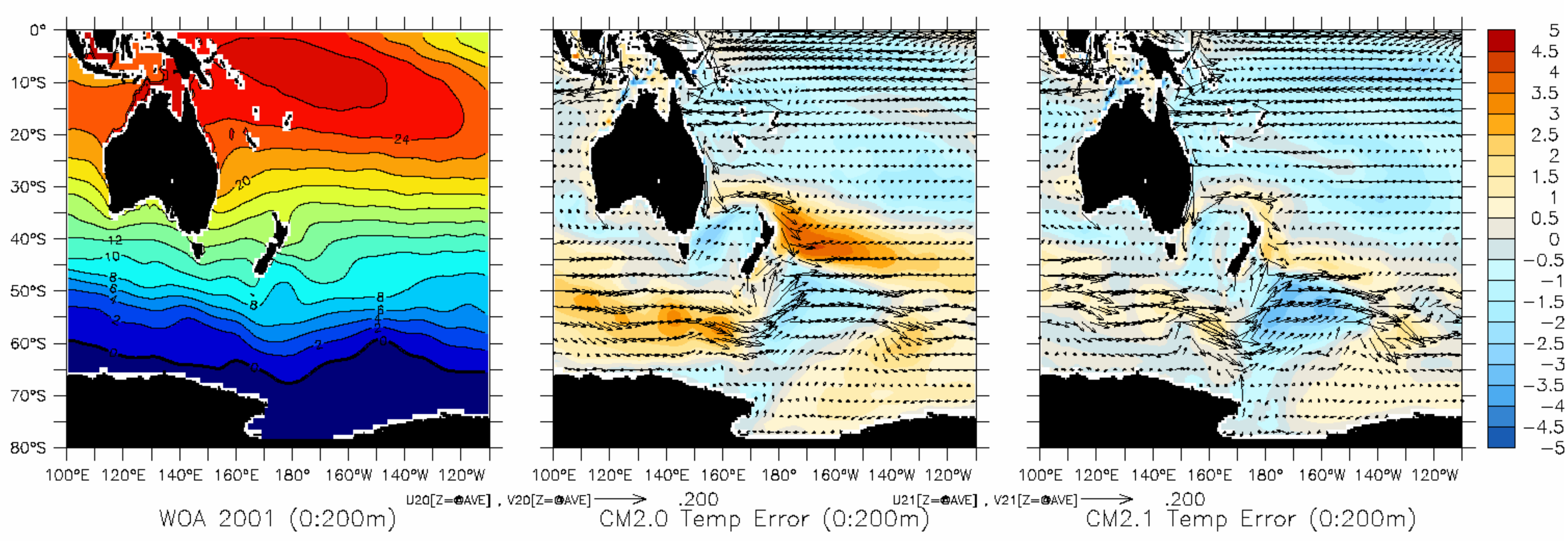
IPCC WGI Chapter 8

AR4 ensemble mean error
Salinity



IPCC WGI Chapter 8 Suppl. Material

Impact of Current Position on Temperature Error (0:200m)



WOA 2001 (0:200m)

CM2.0 Temp Error (0:200m)

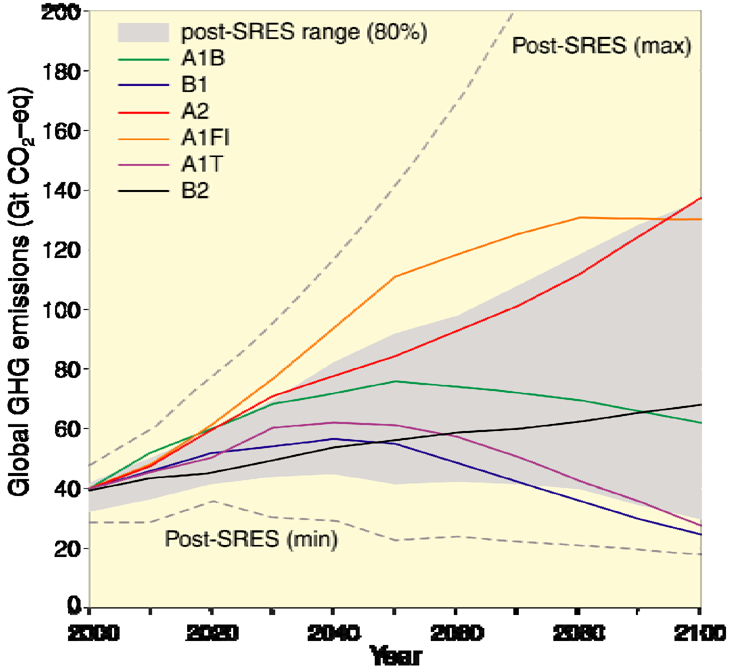
CM2.1 Temp Error (0:200m)

Time scales of Response Implications of Heat Storage

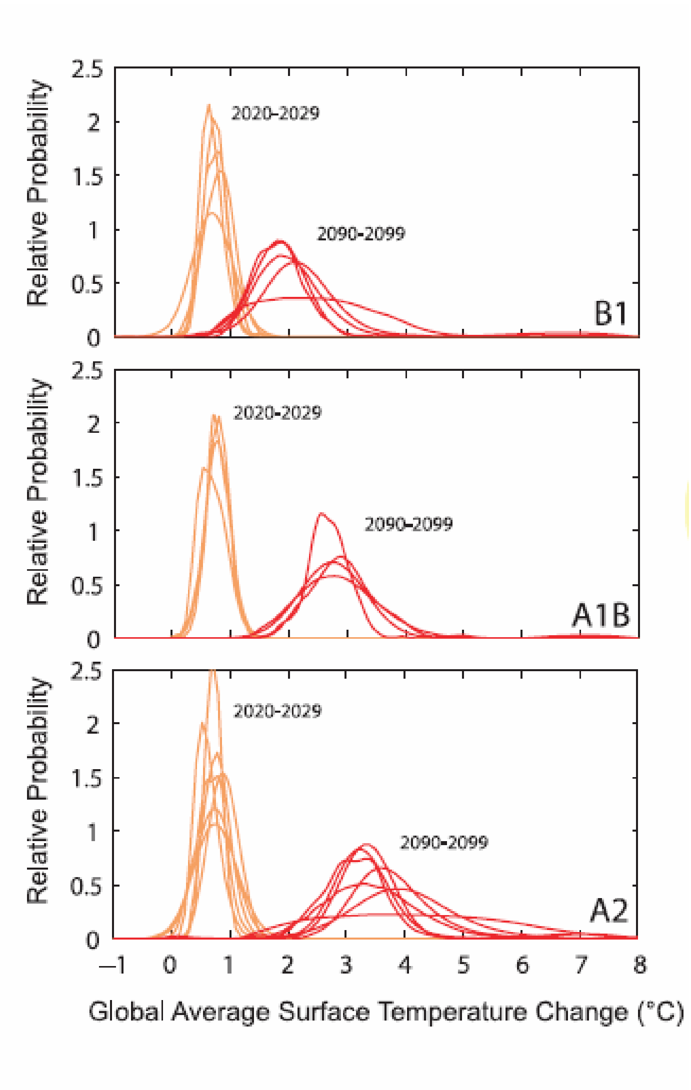
- Human and natural systems
- Physical climate system
  - Greenhouse gas lifetimes in atmosphere
  - **Ocean**
  - Ice sheets

Special Report on Emission Scenarios (SRES, 2000) and Post-SRES scenarios

- SRES emission scenarios used to make projections of 21st century changes.
- There is *high agreement* and *much evidence* that with current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades.

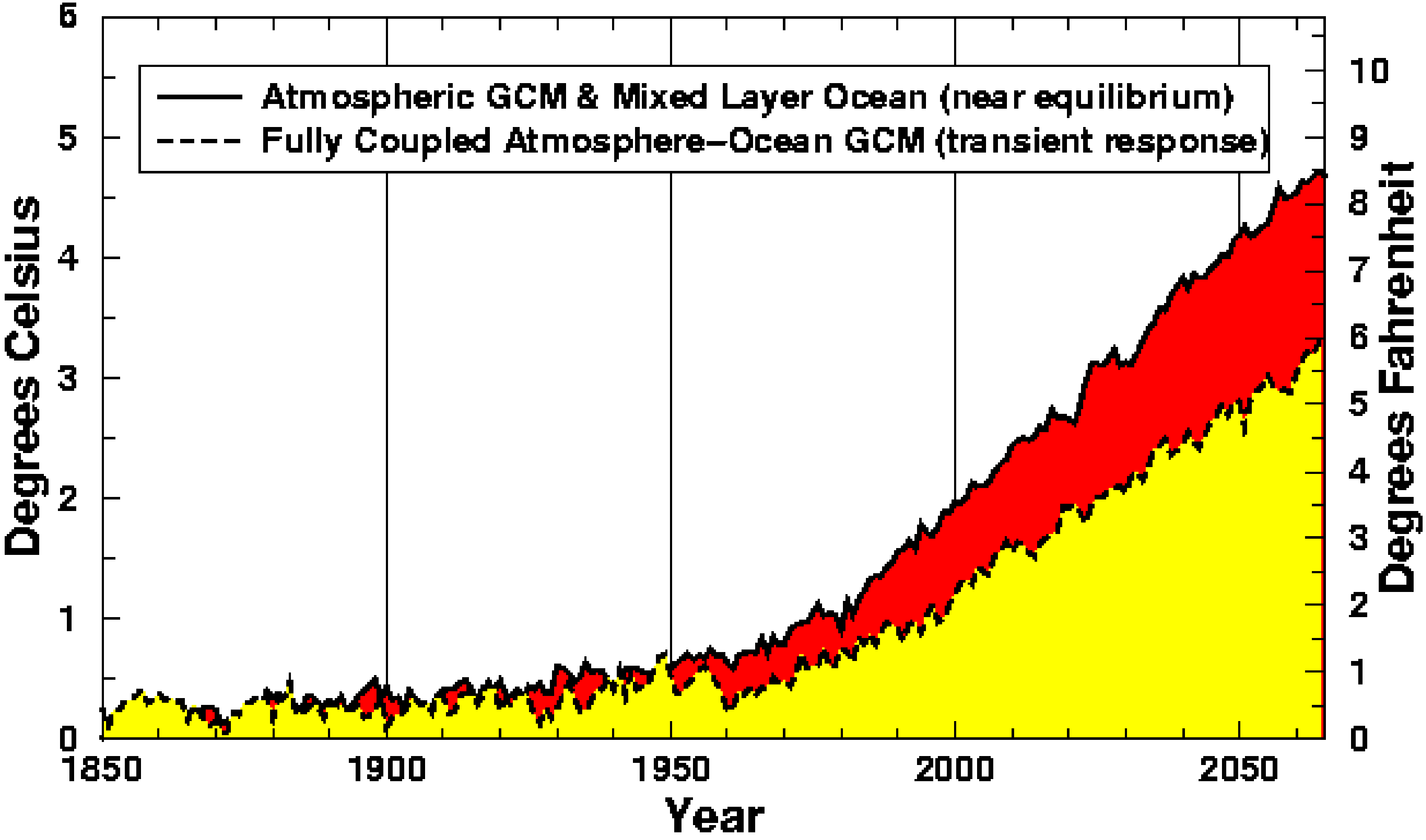


Response time scales



- Note response in 2020’s very similar in spite of very different emissions.
- Note response in 2090’s much more scenario dependent.
- Actions taken today only have large impacts in climate response in the future.

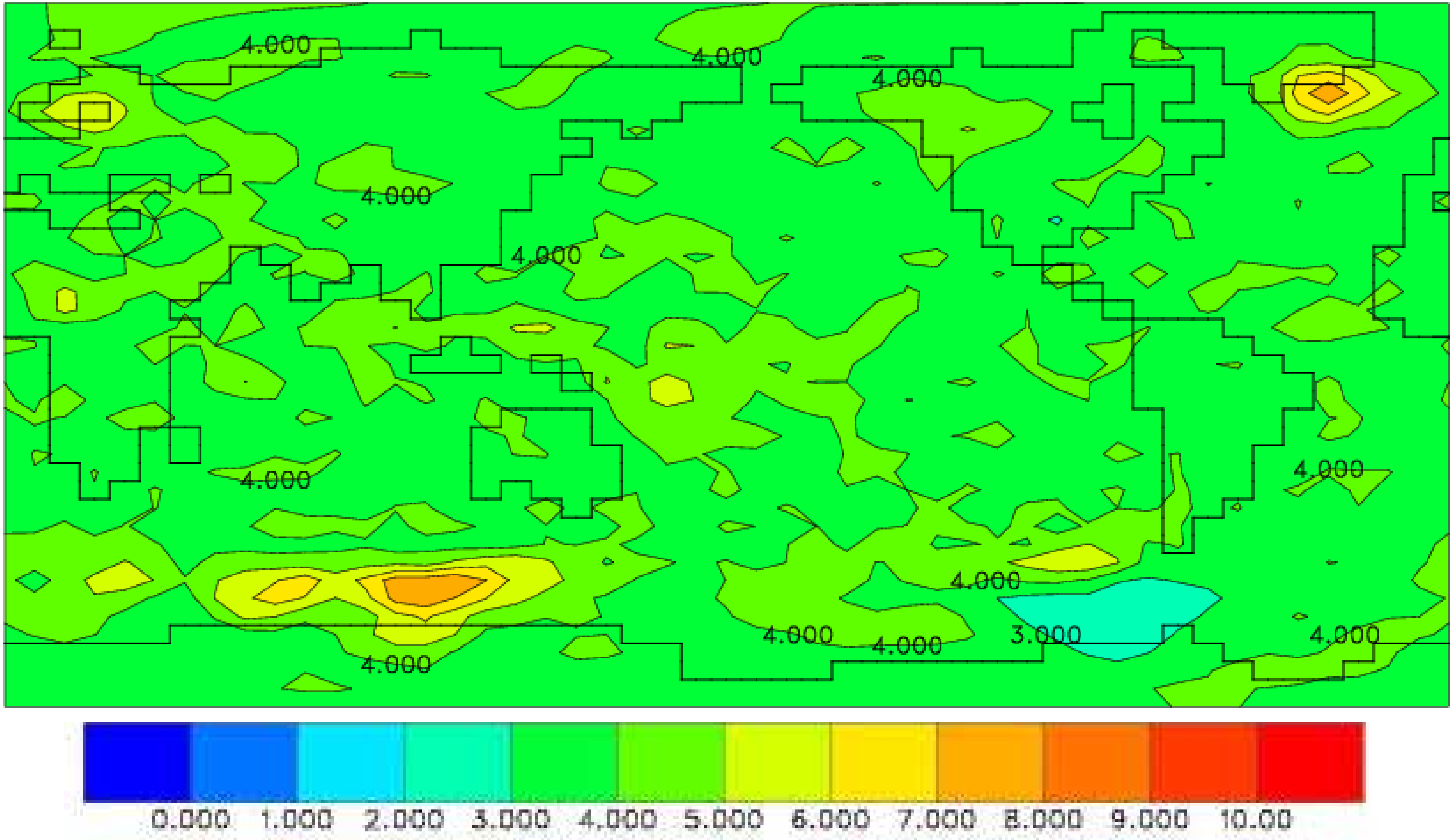
Response time scales
Role of Oceans



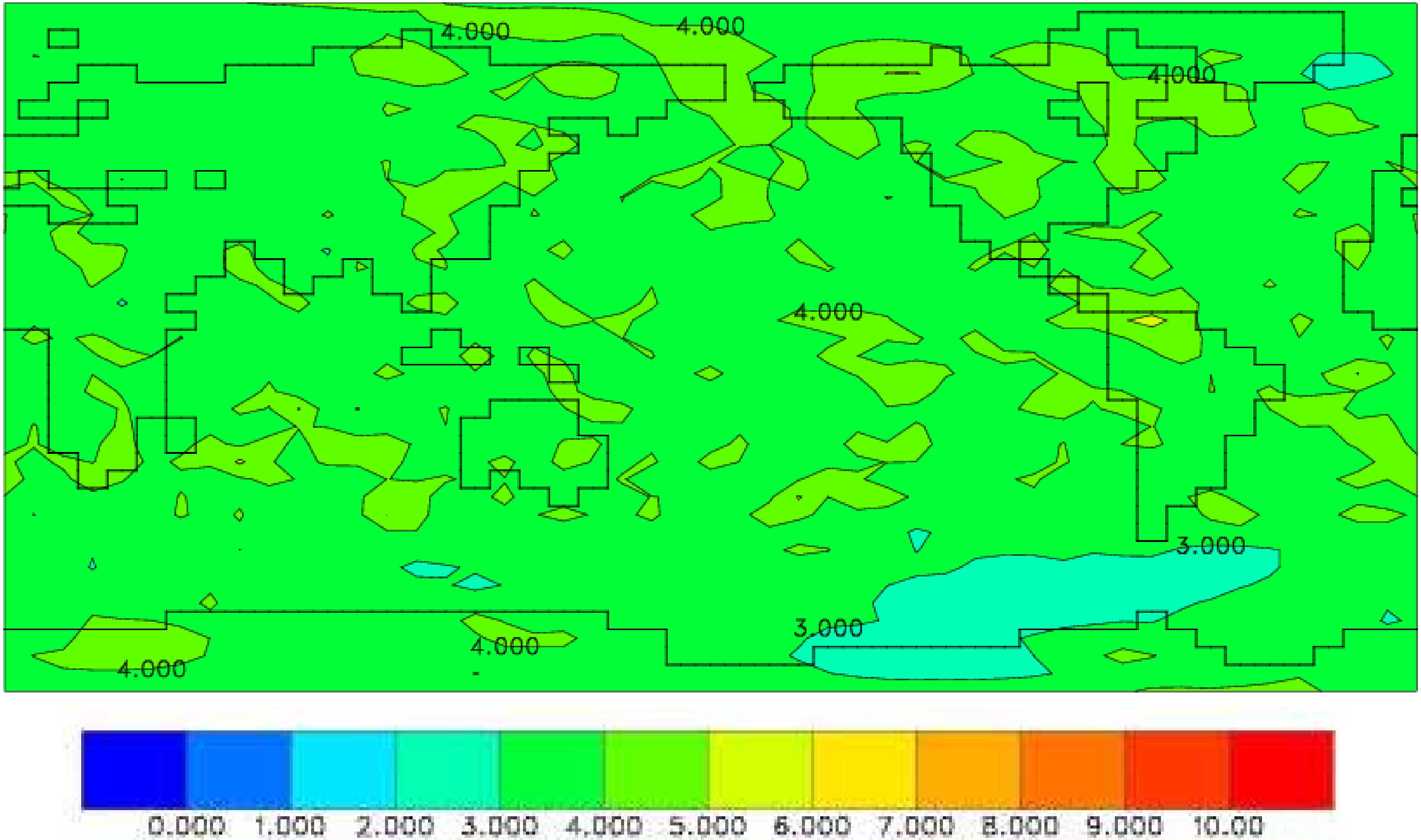
Experimental Design
Manabe Climate Model “MCM”

- R30 AOGCM coupled model
- Idealized Water hosing
  - 1 Sv for 100 years
  - After 100 years, stop hosing - allow recovery
- Case 1: Hosing 50N to 70N in Atlantic
- Case 2: Hosing south of 60S in Southern Ocean
- Compare to long control integration

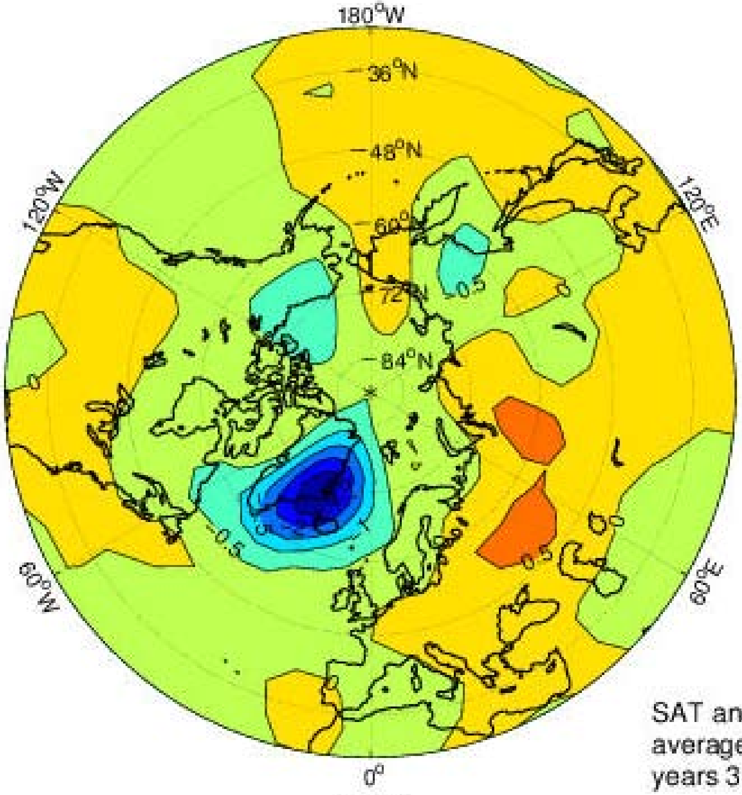
Maximum Negative Anomaly



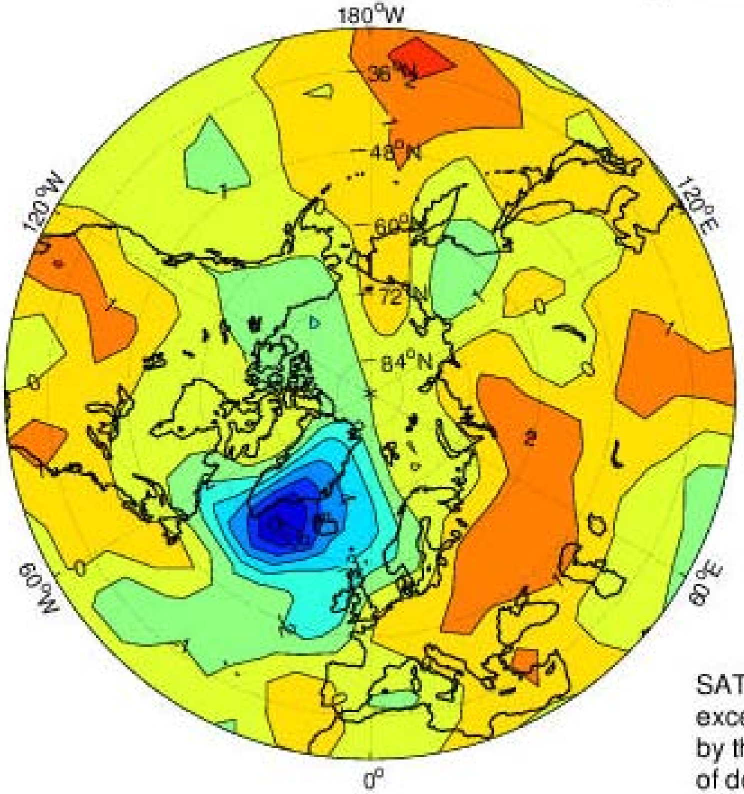
Maximum Positive Anomaly



Surface Air Temperature Decadal Mean Difference

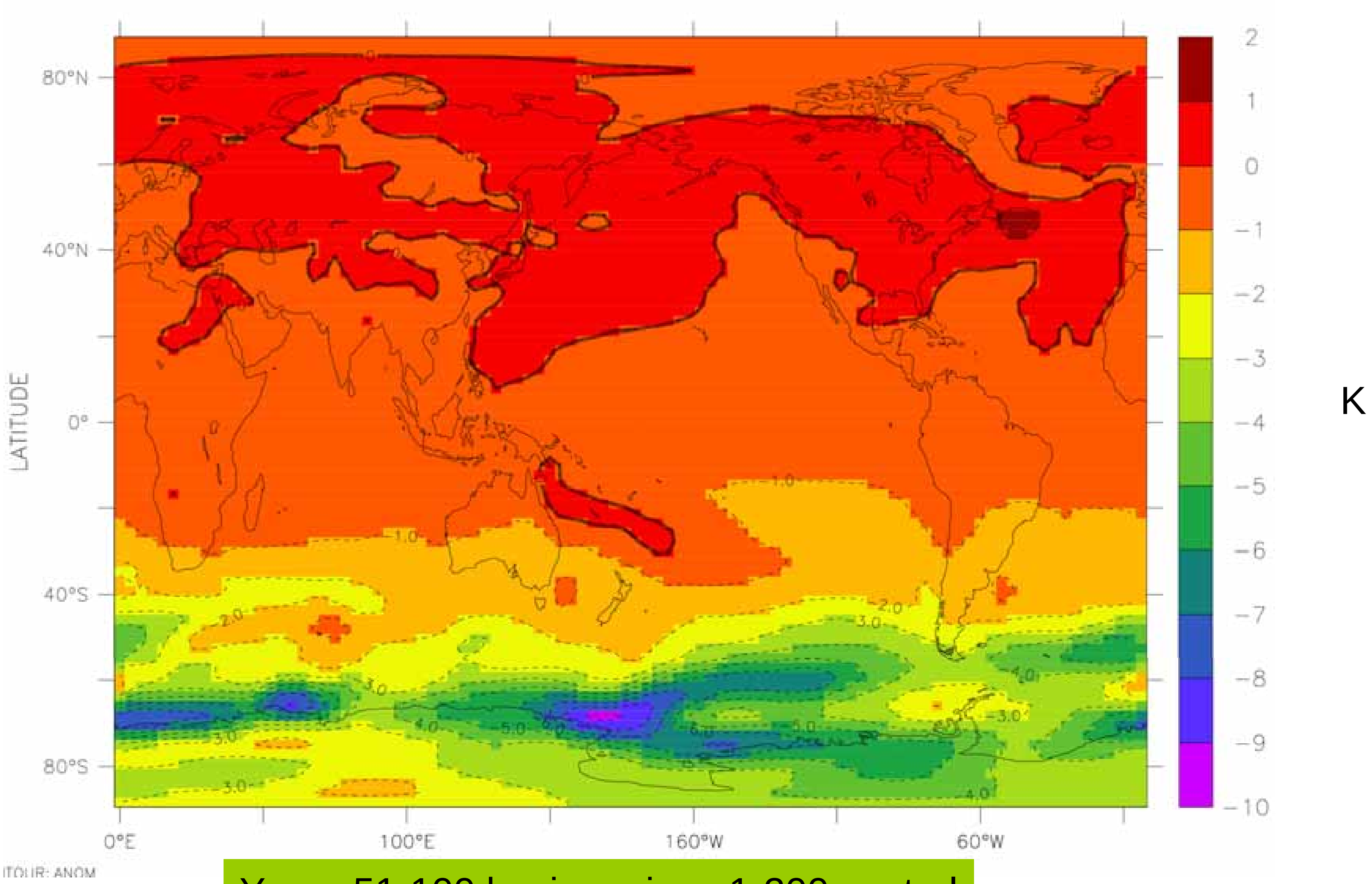


SAT anomaly (°C
averaged over
years 3100–310



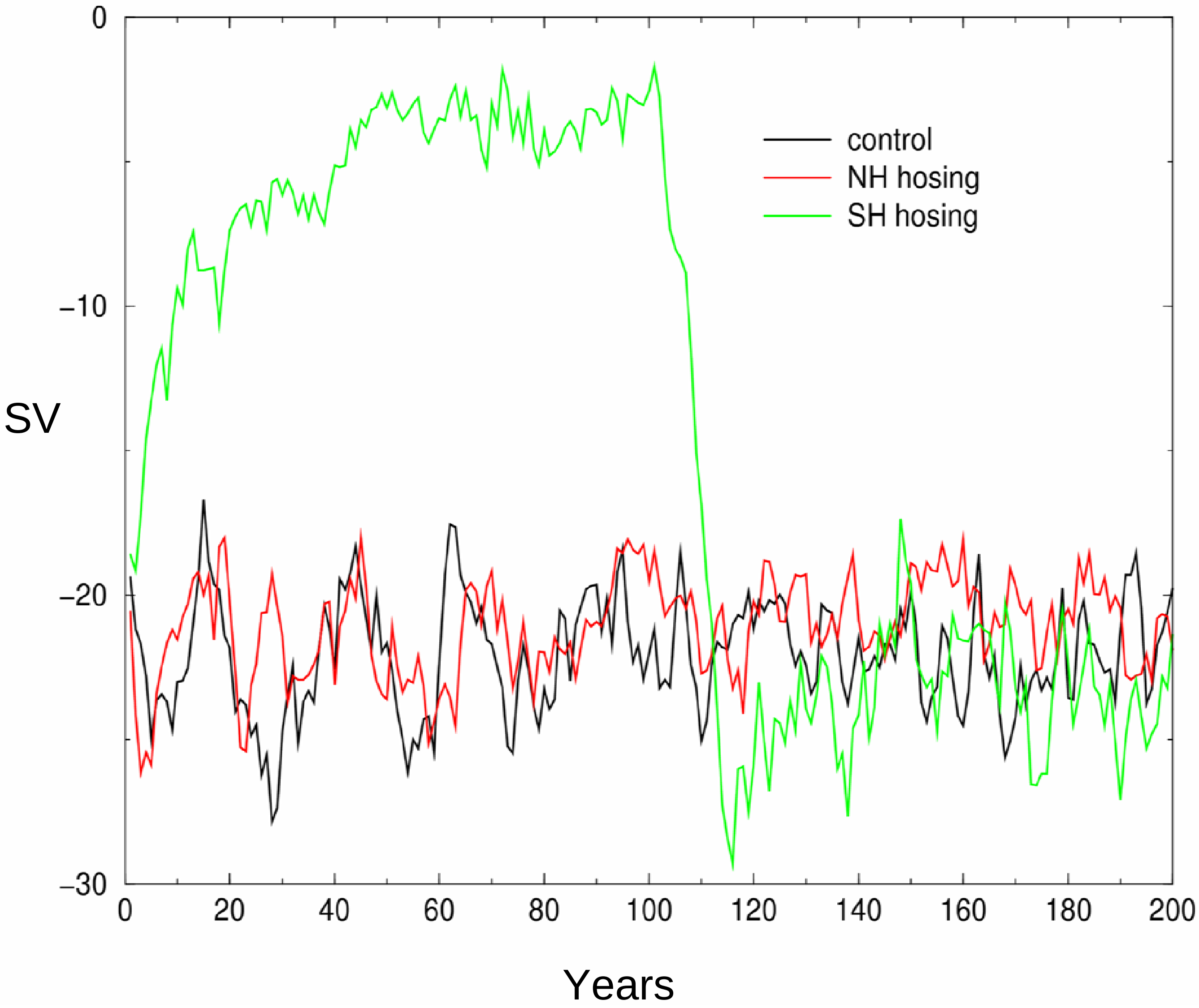
SAT anomaly (above)
except normalized
by the standard deviation
of decadal mean SAT.

SAT Difference map
SH hosing



Years 51-100 hosing minus 1-200 control

SH THC Response

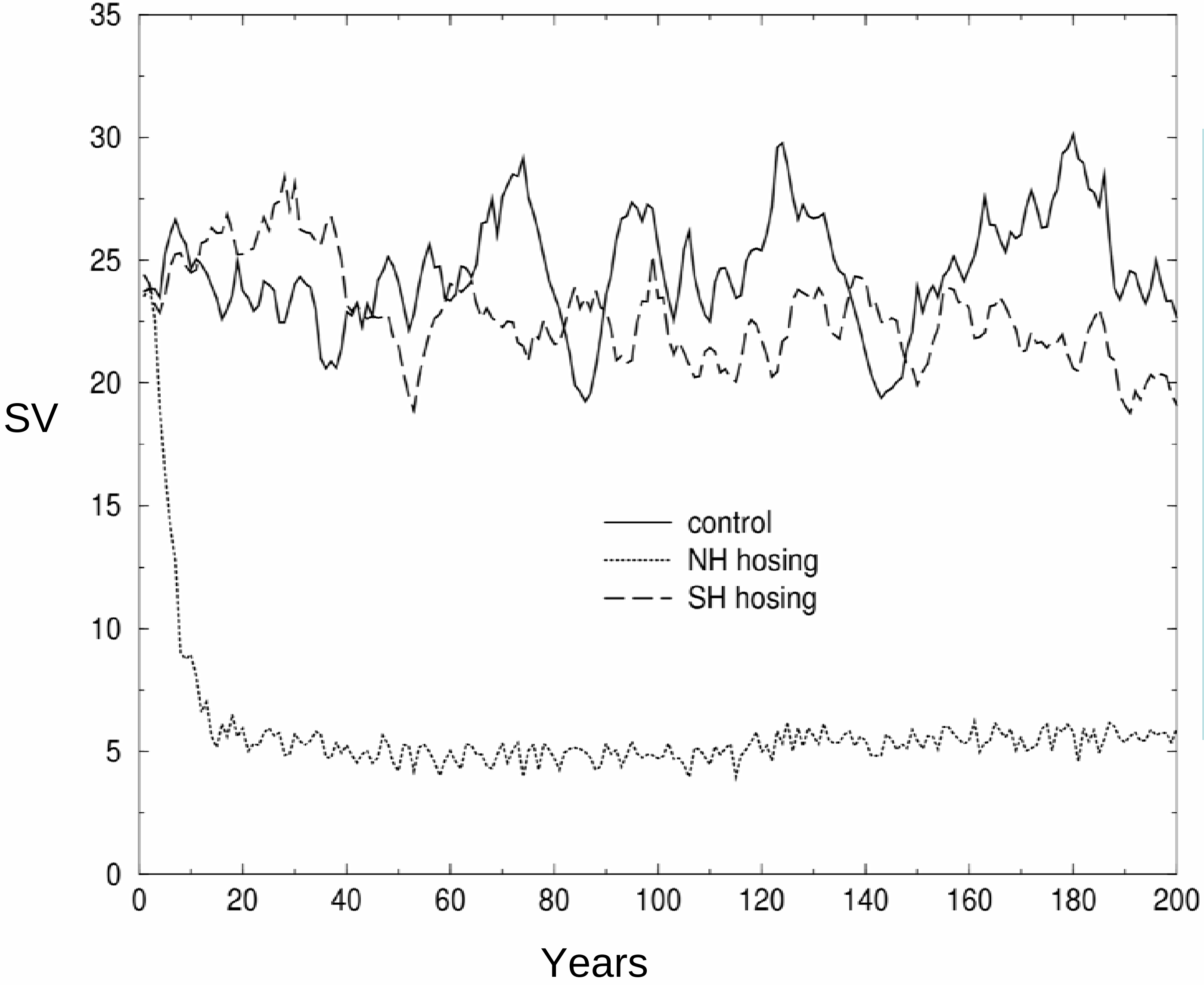


SH Hosing –

SH THC weakens.

SH THC does not shut down

Atlantic THC Response

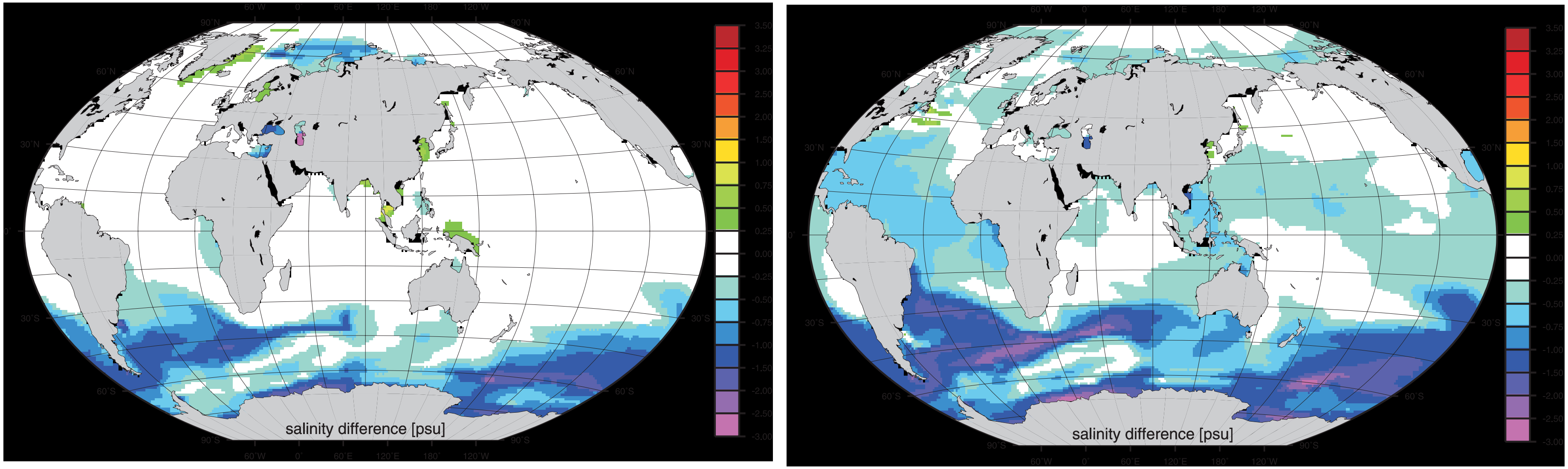


Atlantic THC does not respond in a seesaw-like manner

NH Hosing – NH THC shuts down

Differences in Sea Surface Salinity (PSU)

Southern Freshwater Escape

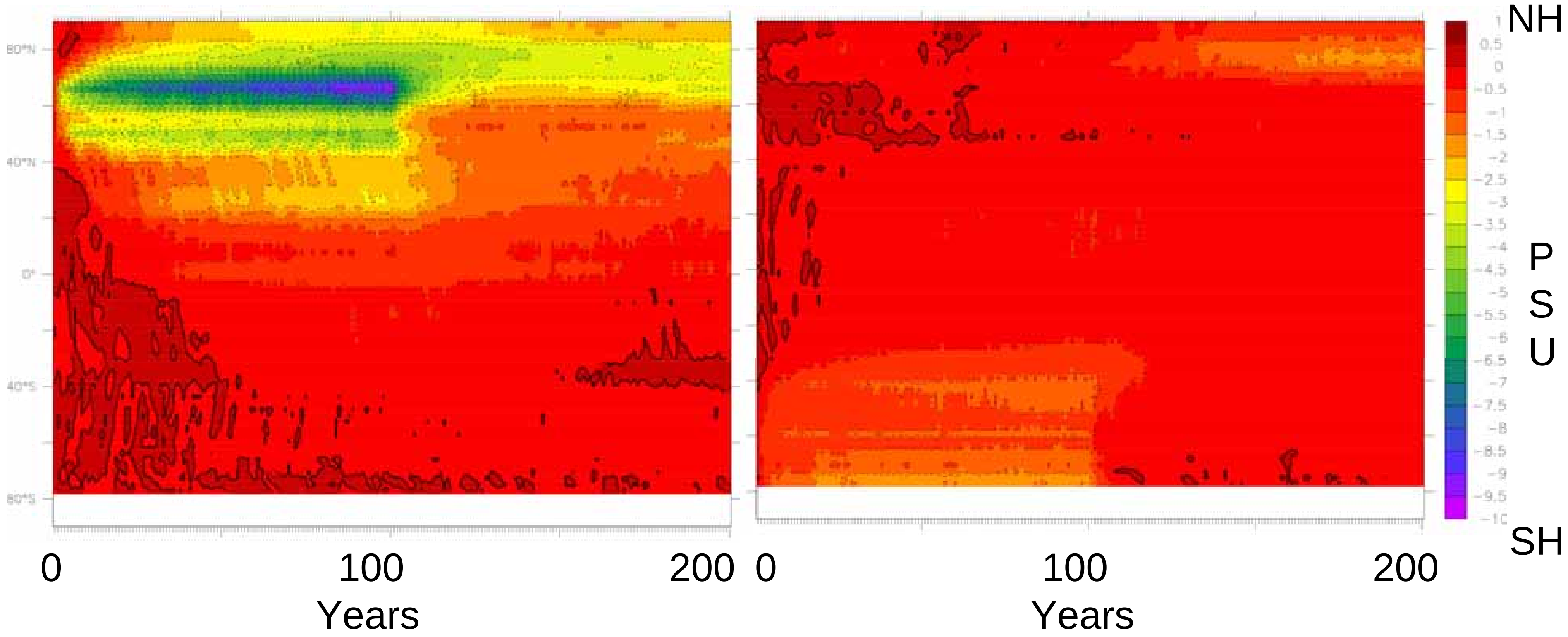


25 years

100 years

Hosing minus Control

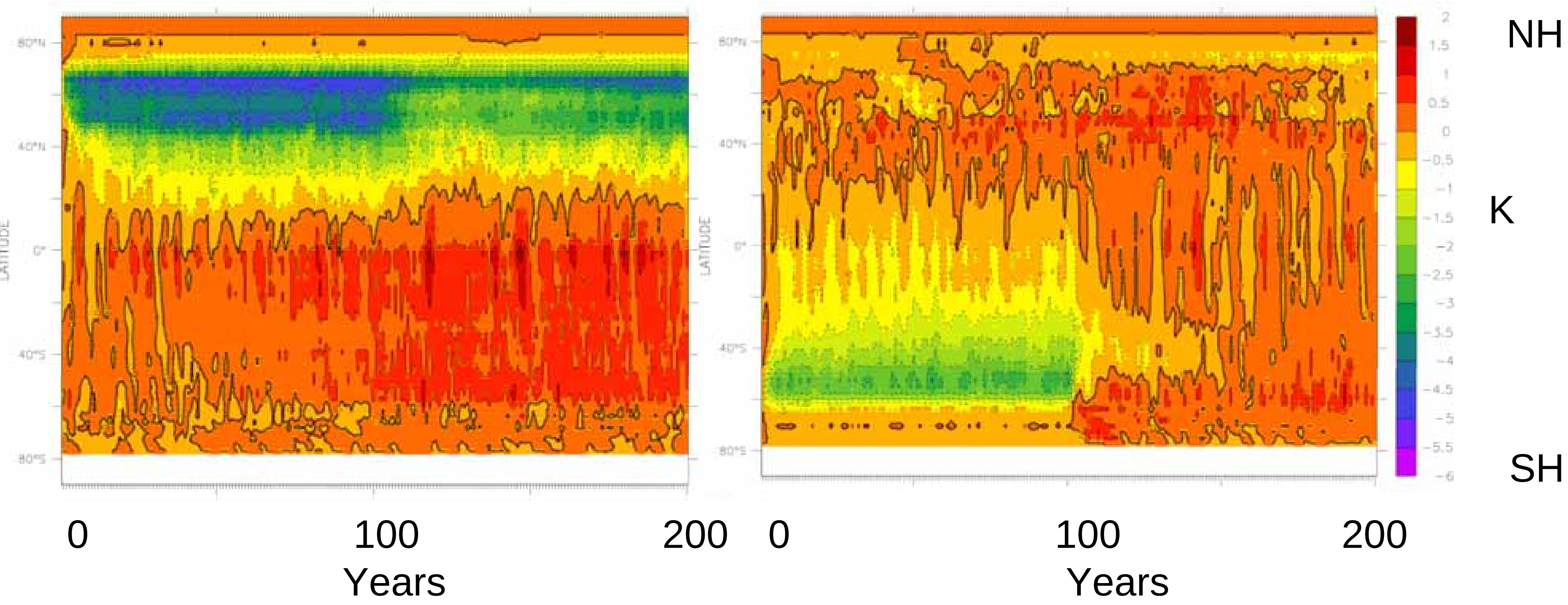
Surface Salinity Response



NH SSS anomaly –
Intense and confined

SH SSS anomaly –
Weaker and spreads

Sea Surface Temperature Response



Response more symmetrical than SSS
Magnitude also becoming more similar