Climate Variability and Sensitivity: Ocean and Ice Perspectives

Presented by

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Frontiers in Climate and Earth System Modeling: Advancing the Science

Geophysical Fluid Dynamics Laboratory

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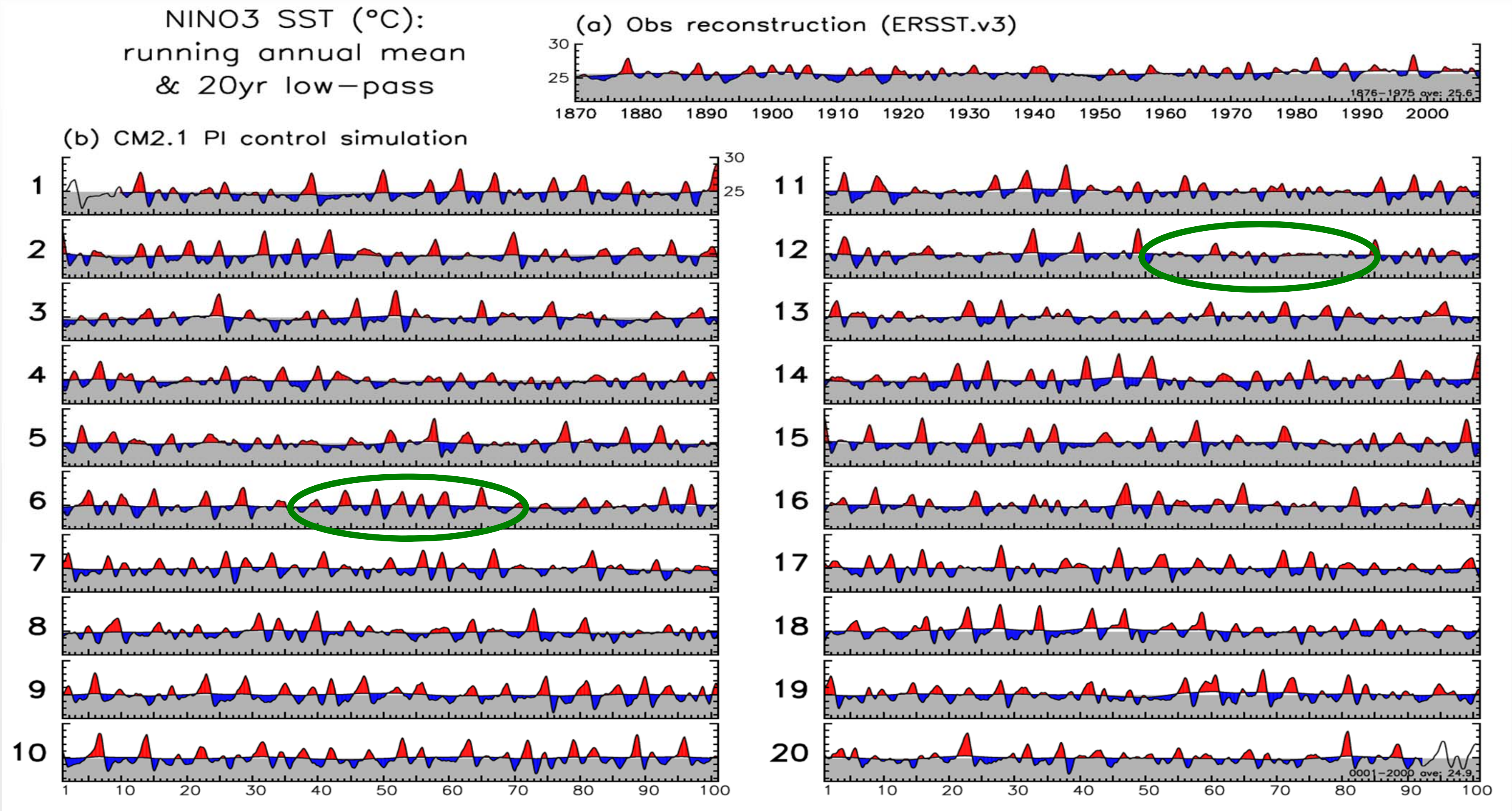
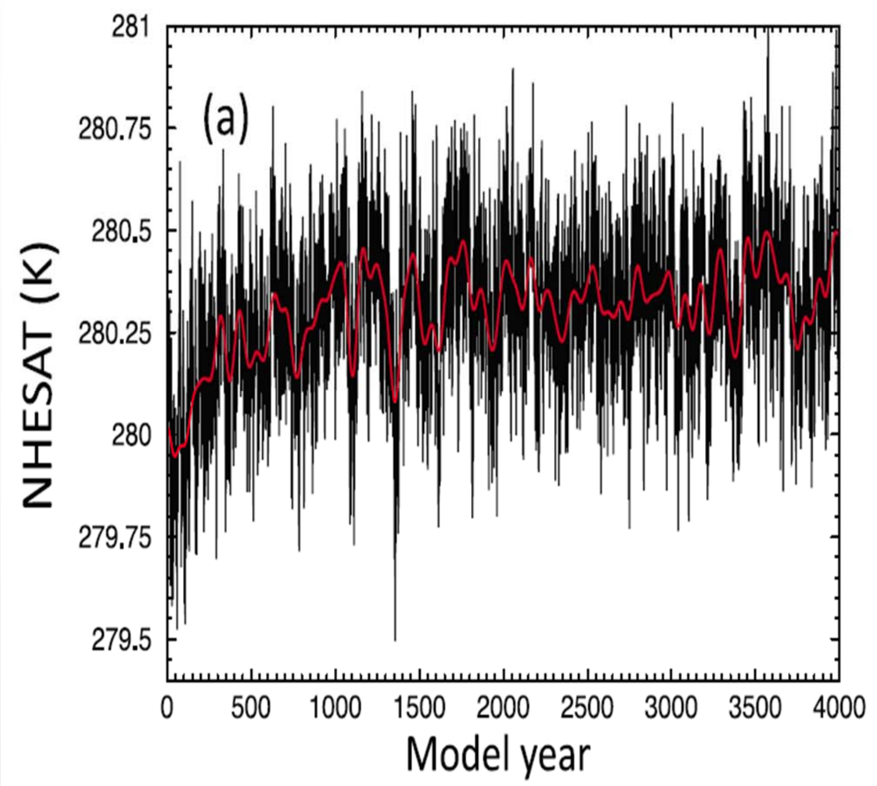
Introduction of Climate Variability

Inter-annual ENSO Variability : 2000-year of simulated NINO3 SSTs in GFDL CM2.1 (Wittenberg, 2009)

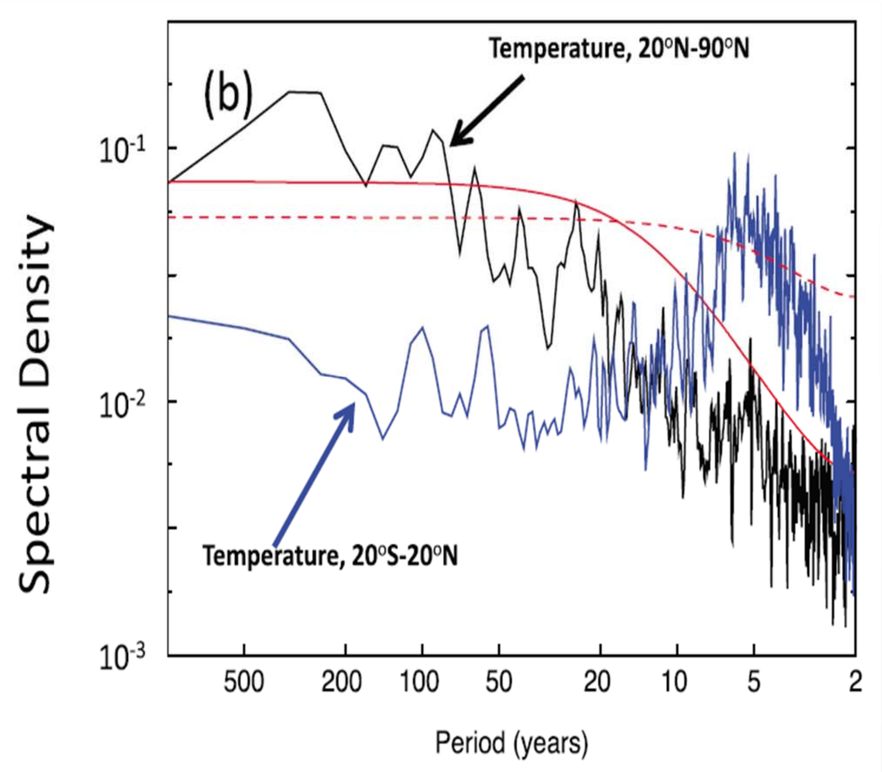


Multi-Centennial Climate Variability

Time series of Northern Hemisphere extratropical surface air temperature



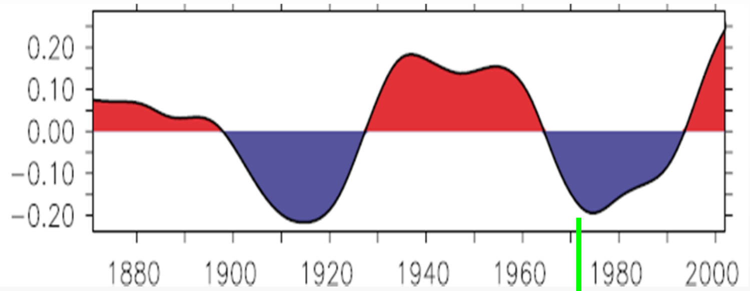
Spectra of Surface air temperature

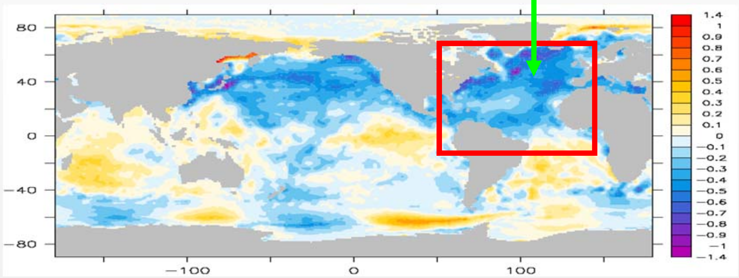


Multi-centennial variability in Northern Hemisphere extra-tropical surface air temperature induced by AMOC variability are found in the 4000-year control simulation of GFDL CM2.1(Delworth and Zeng, 2012).

Atlantic Multidecadal Variability (AMV)

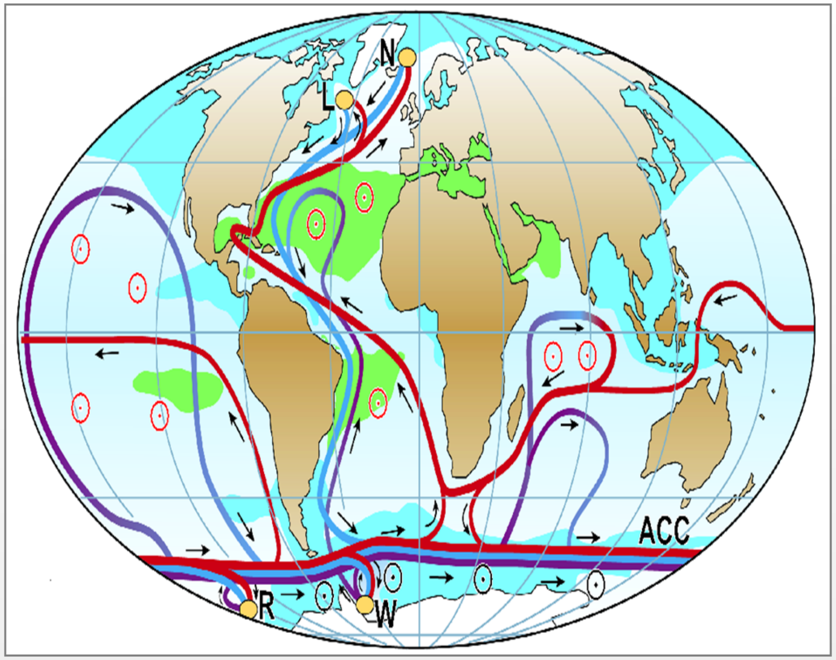
Observed AMV Index (Sutton and Hodson, 2005)





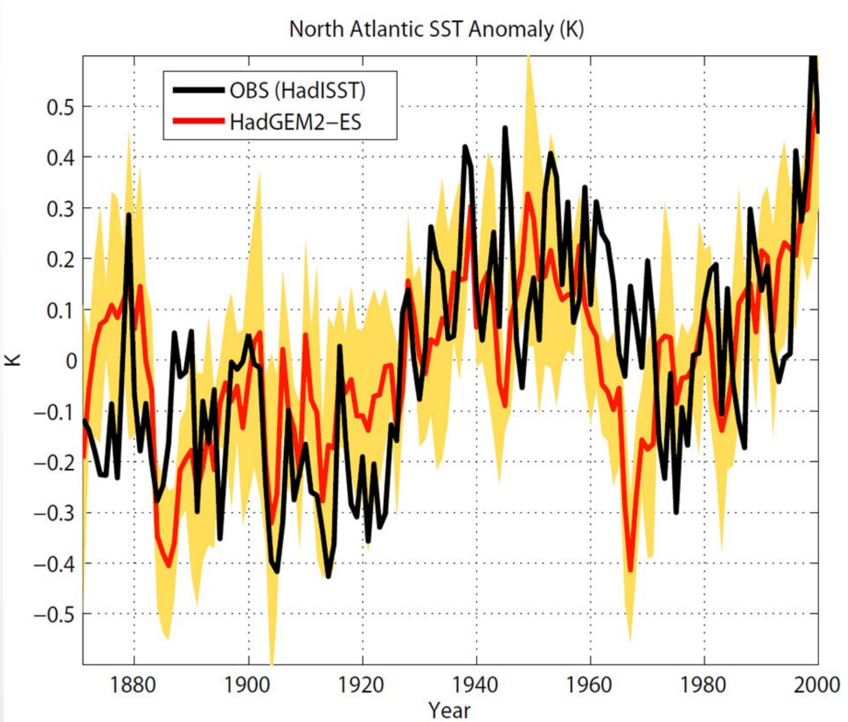
Observed Multidecadal SST Difference (1971-1990) – (1941-1960) (HadISST, detrended)

Atlantic Meridional Overturning Circulation (AMOC)



The AMV is often thought to be linked to AMOC variations. The AMOC includes a northward flow of warm water in the upper Atlantic, and a southward flow of cold water in the deep Atlantic, and carries huge amount of heat northward. The observed large-scale AMV pattern is similar to numerical simulated SST anomaly induced by the weakening of the AMOC (Zhang and Delworth, 2005).

Mechanisms and Climate Impacts of Atlantic Multidecadal Variability (AMV)

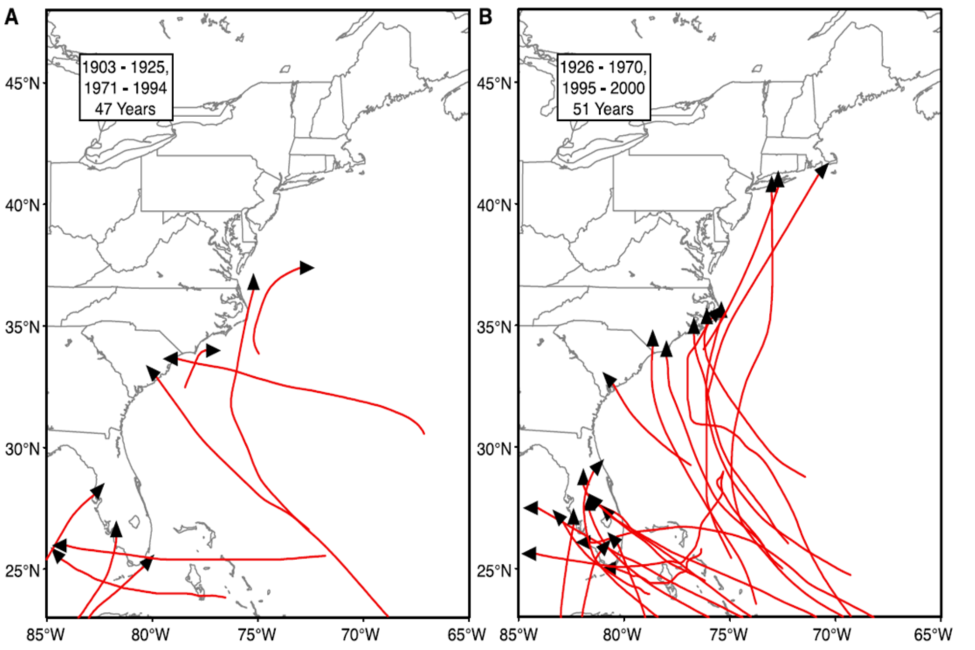


Negative AMV Phases

Cold North Atlantic

Positive AMV Phases

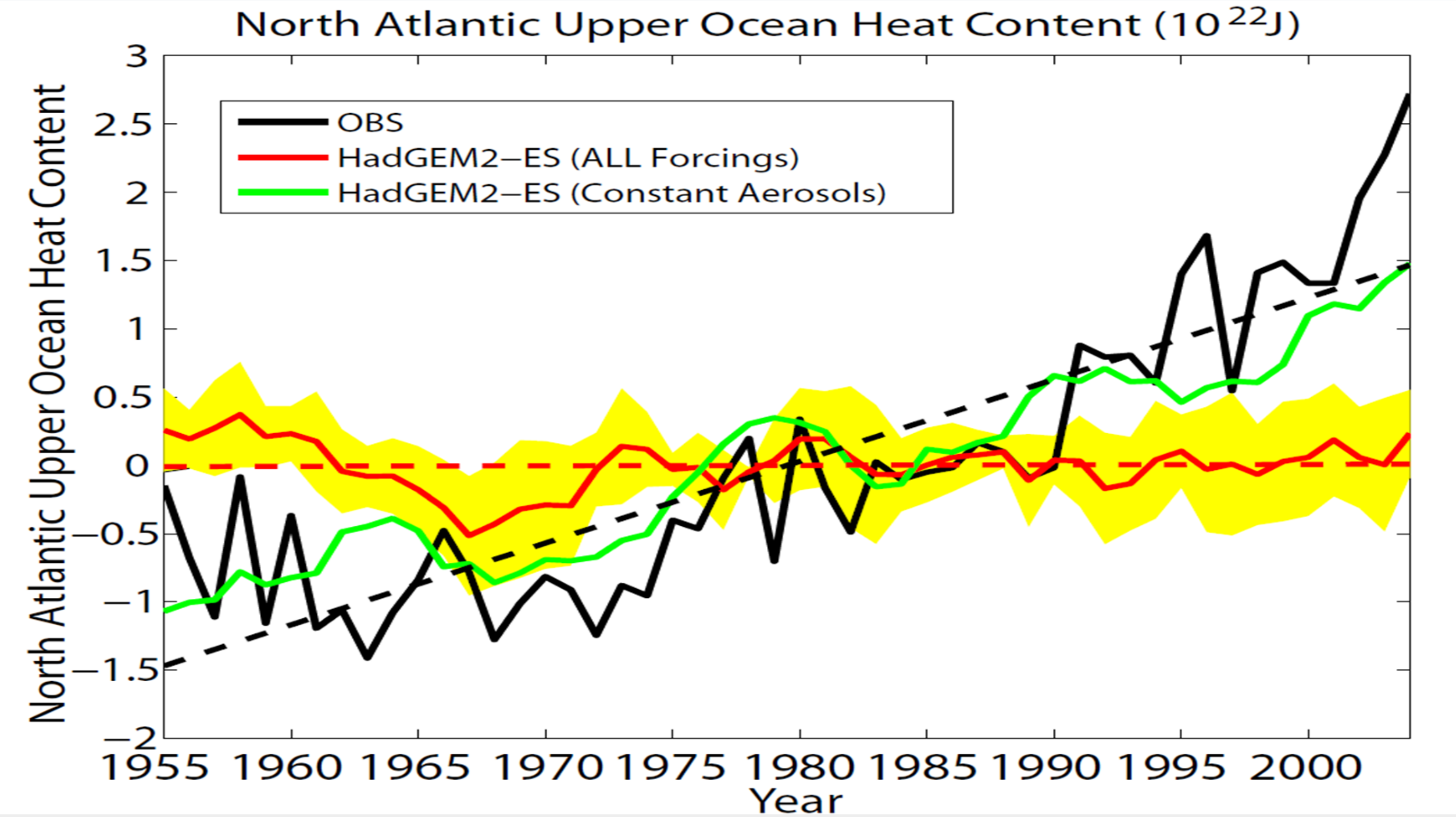
Warm North Atlantic



A recent study using the latest Met Office Hadley Centre Earth System Model (HadGEM2-ES) closely reproduces the observed multidecadal variations of area-averaged NASST, through simulated aerosol indirect effects that modify net surface shortwave radiation. Hence the study claimed aerosols as a prime driver of observed AMV (Booth et al., 2012).

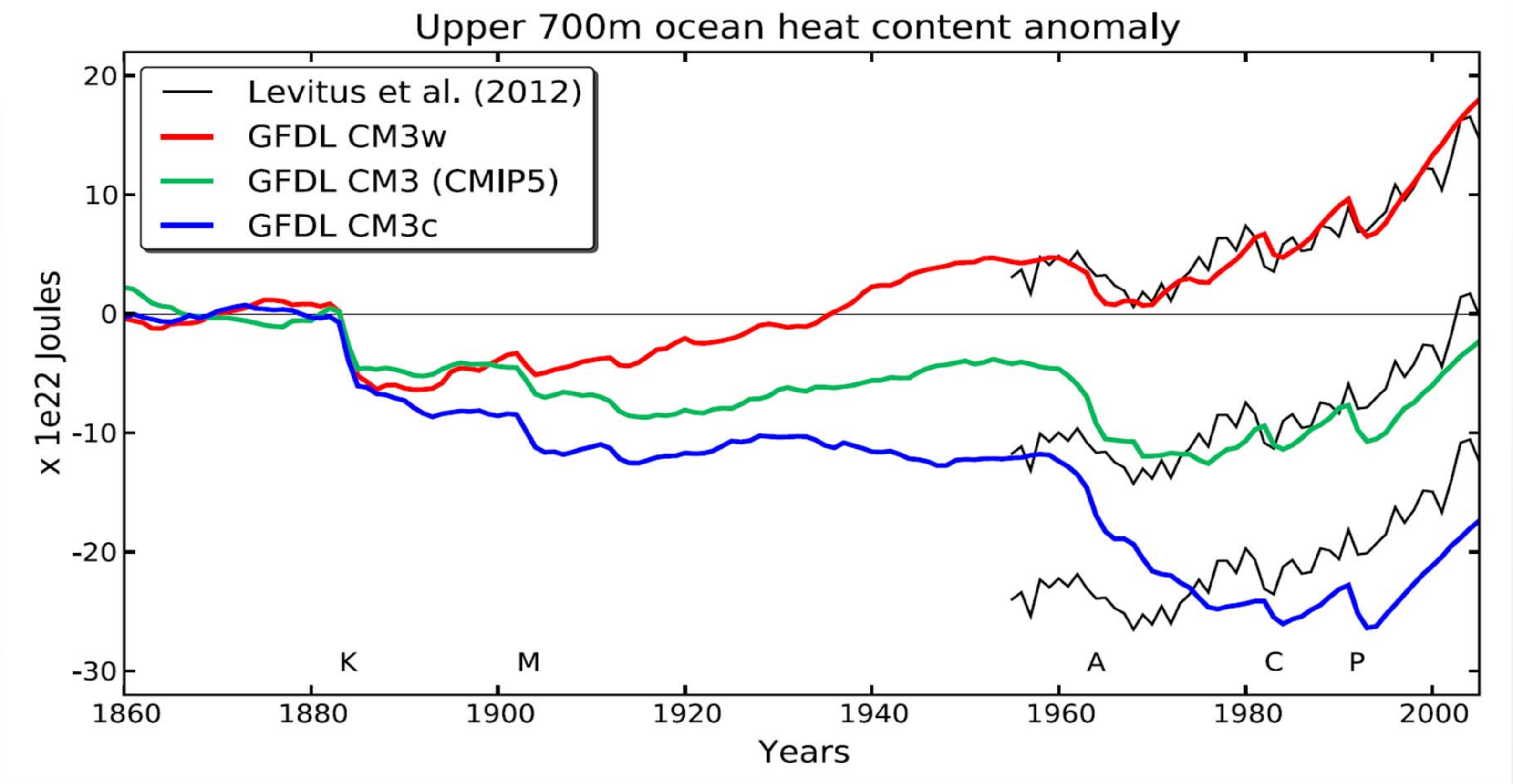
Observational and modeling studies suggested that the multidecadal Atlantic Hurricane activity is strongly associated with the AMV (Goldenberg et al. 2001; Zhang and Delworth 2006; Knight et al. 2006)

Aerosol Effects and North Atlantic Upper Ocean Heat Content



Observations show substantial warming trend in the North Atlantic upper ocean heat content, in contrast, the All-forcing simulations in HadGEM2-ES show no warming trend. The discrepancy is mainly due to anthropogenic aerosols and suggests that aerosol effects are strongly overestimated (Zhang et al. 2013).

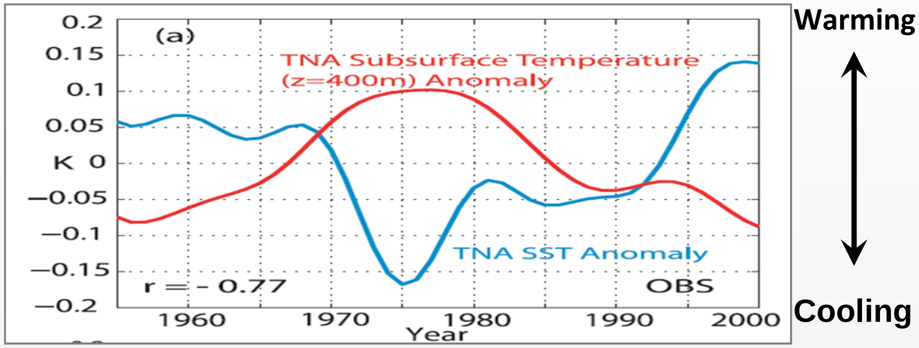
Sensitivity of Upper Ocean Heat Content to Aerosol Forcing in GFDL CM3

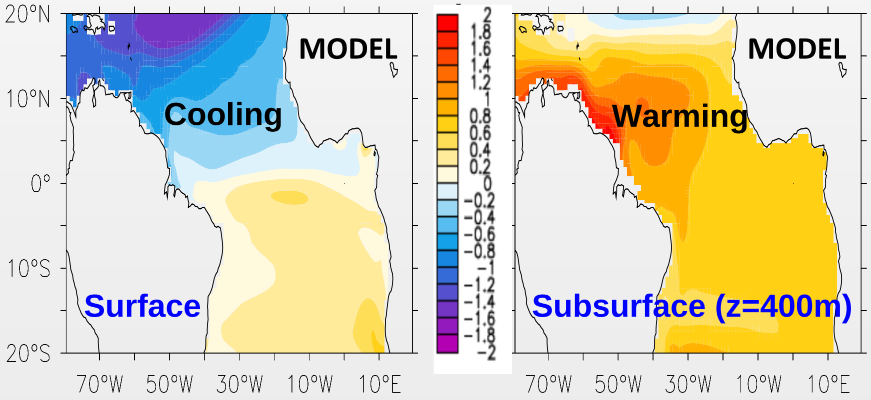


The magnitude of aerosol indirect effects is sensitive to cloud parametrization, uncertainties in cloud processes can result in significant different aerosol indirect effects and very different global upper ocean heat content evolution over the 20th century (Golaz et al., 2013).

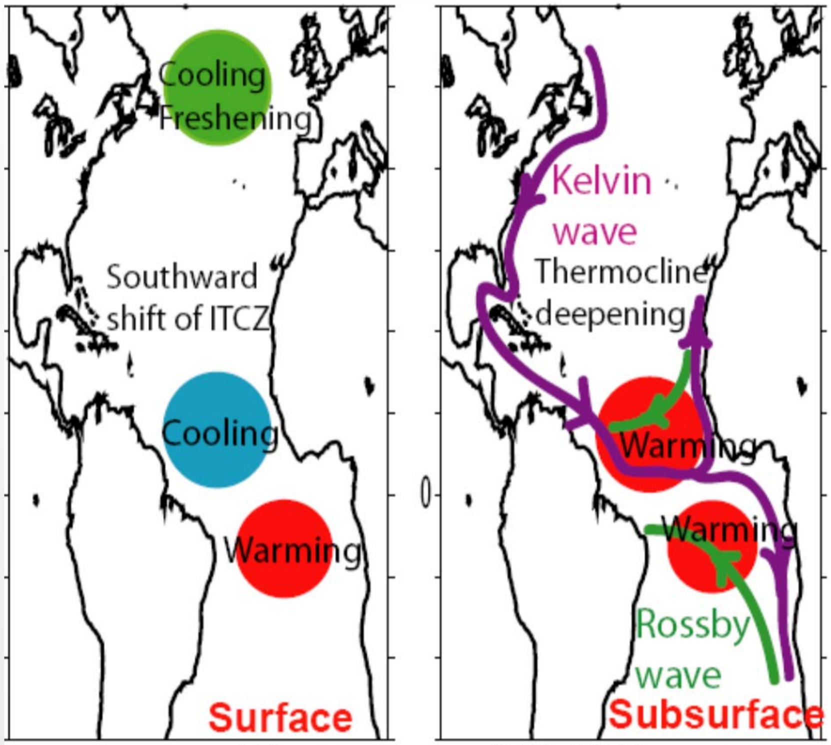
Tropical Fingerprint of AMOC variations

Observed Tropical North Atlantic (TNA) SST is anticorrelated with TNA subsurface ocean temperature. The anticorrelation is a fingerprint of AMOC variations in GFDL CM2.1 simulations, indicating observed TNA SST fluctuations may be AMOC-related (Zhang 2007).





Ocean temperature anomaly due to the weakening of AMOC from GFDL CM2.1 water hosing experiment

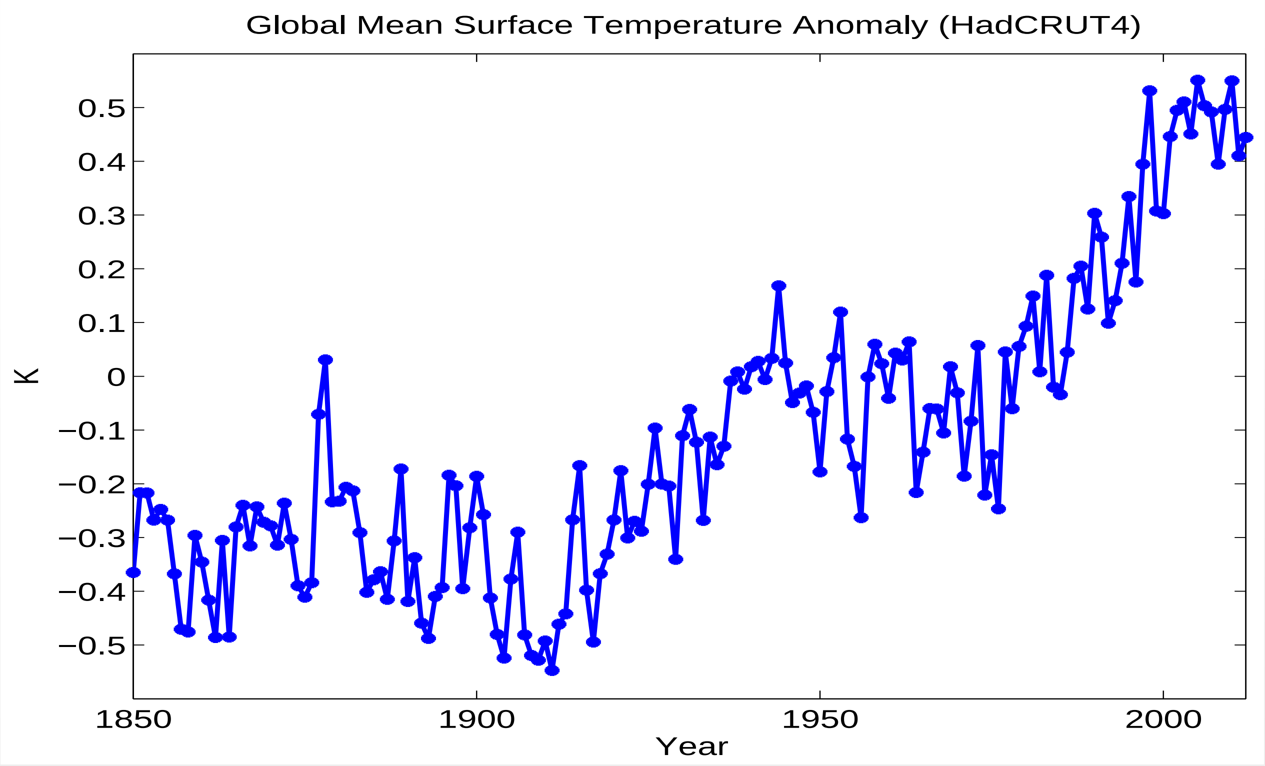


Weakening of AMOC

The weakening of the AMOC leads to a southward shift of the Atlantic ITCZ, TNA surface cooling, and thermocline deepening and subsurface warming in the TNA.

Summary on the Debate of Mechanisms for AMV

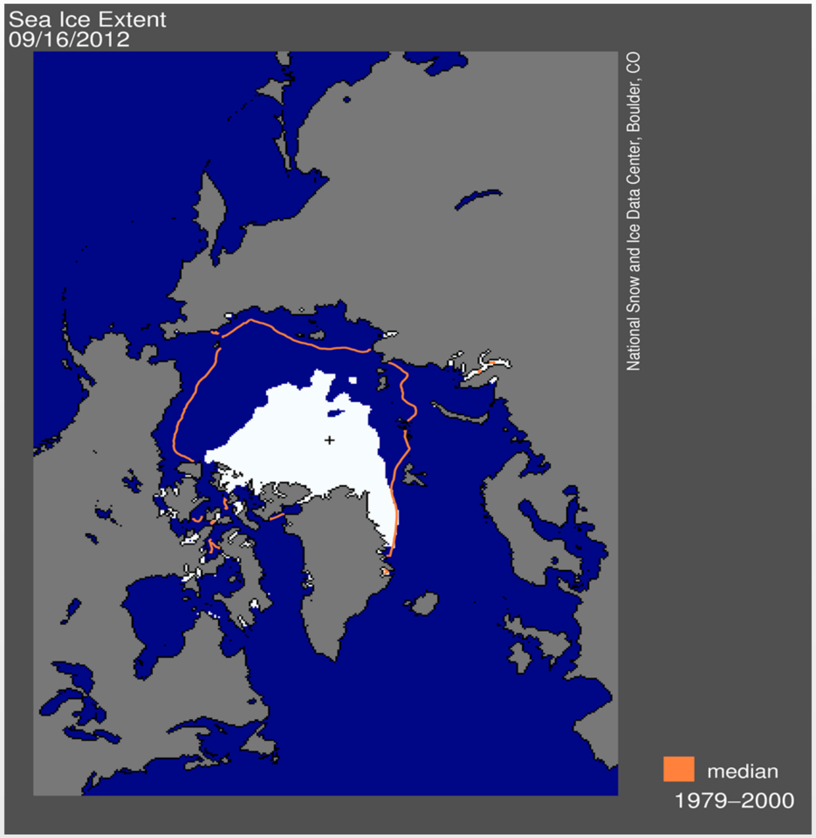
- Identifying the main drivers of the observed AMV is crucial for predicting future climate change.



- Anthropogenic and natural aerosols have likely played some role in forcing the observed AMV. Quantifying the relative importance of AMOC variability vs. aerosol forcing on the Atlantic Multidecadal Variability remains a key challenge.

Rapid Decline in Arctic Sea Ice Extent in the Early 21st Century

Satellite observations reveal a record-breaking low September Arctic sea ice extent in 2012, a 49% declined compared to the 1979-2000 climatology. The extreme low in 2012 continued the rapid downward trend seen in the early 21st century.

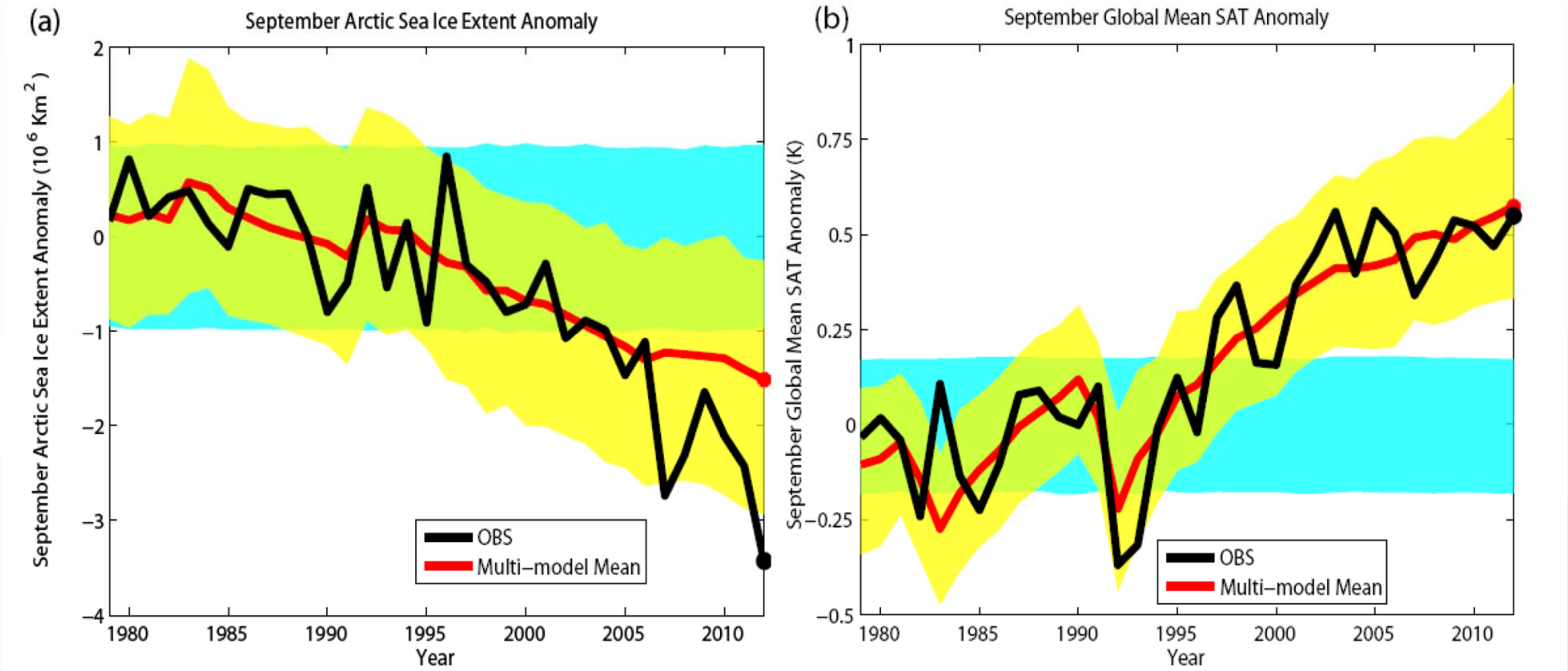


The observed decline in Arctic sea ice extent has been attributed in large part to greenhouse gas forcing (Hegerl et al. 2007), and some climate models project that the Arctic Ocean will be ice-free in summer within a few decades (Stroeve et al. 2012; Massonnet et al. 2012).

A crucial question is the relative role of radiative forcing vs. internal variability in the recent rapid decline of Arctic sea ice extent.

Comparing Observations with CMIP5 Simulation
(Zhang and Knutson, 2013)

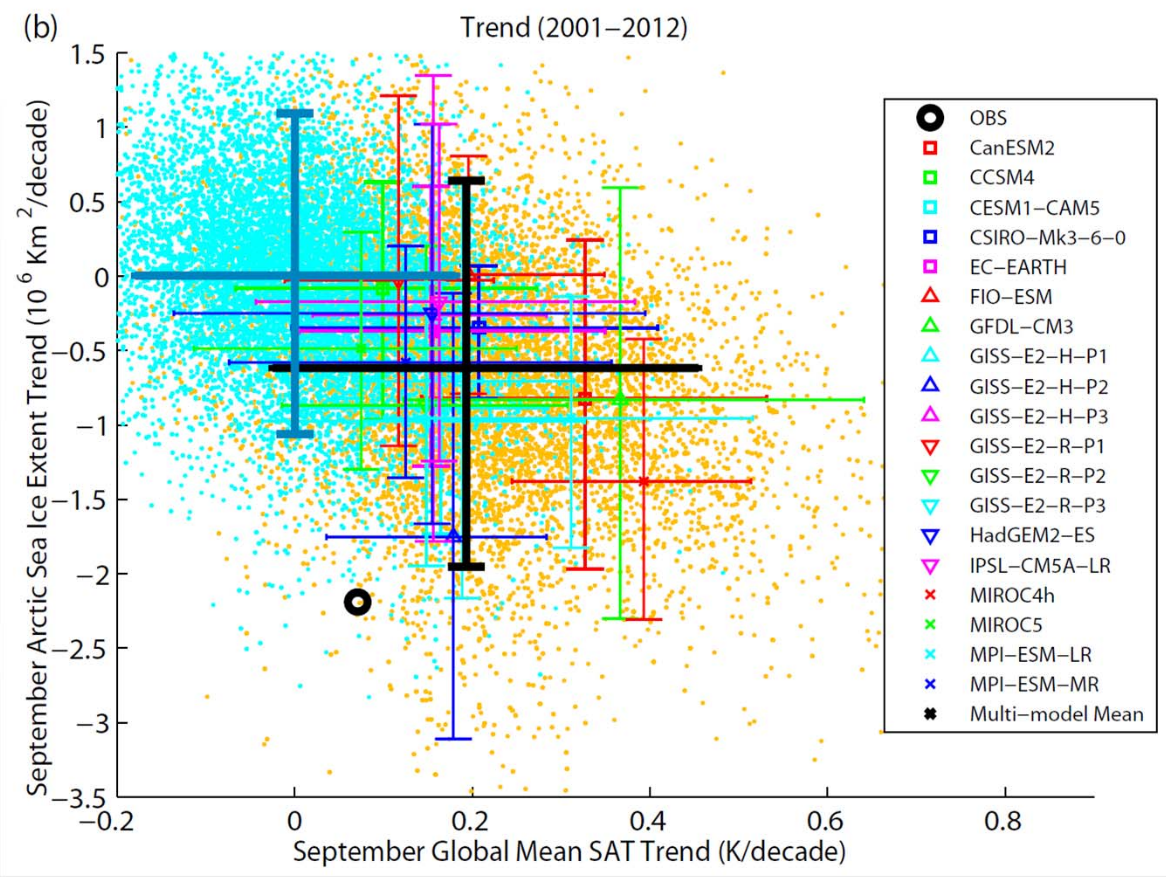
We use 19 CMIP5 (Historical + RCP4.5) All-forcing simulations (total 88 ensemble members) to explore whether the observed summer 2012 Arctic sea ice extent anomaly and the 2001-2012 trend can be explained as a response to anthropogenic and natural forcing, and how it relates to the observed increase in global mean surface air temperature.



The observed Arctic sea ice extent anomaly (relative to 1979-2000 climatology) is detectable and significantly stronger than the ensemble All-Forcing response. The observed SAT anomaly in 2012 is detectable and consistent with the models' All-Forcing response.

Trends for the Early 21st Century (2001-2012)

(Zhang and Knutson, 2013)



The observed September Arctic sea ice extent decline trend for 2001-2012 is so rapid that it lies outside the 5th to 95th percentile range of multi-model All-Forcing runs, but the observed September global mean SAT warming trend for the same period is so small that it is not detectable.

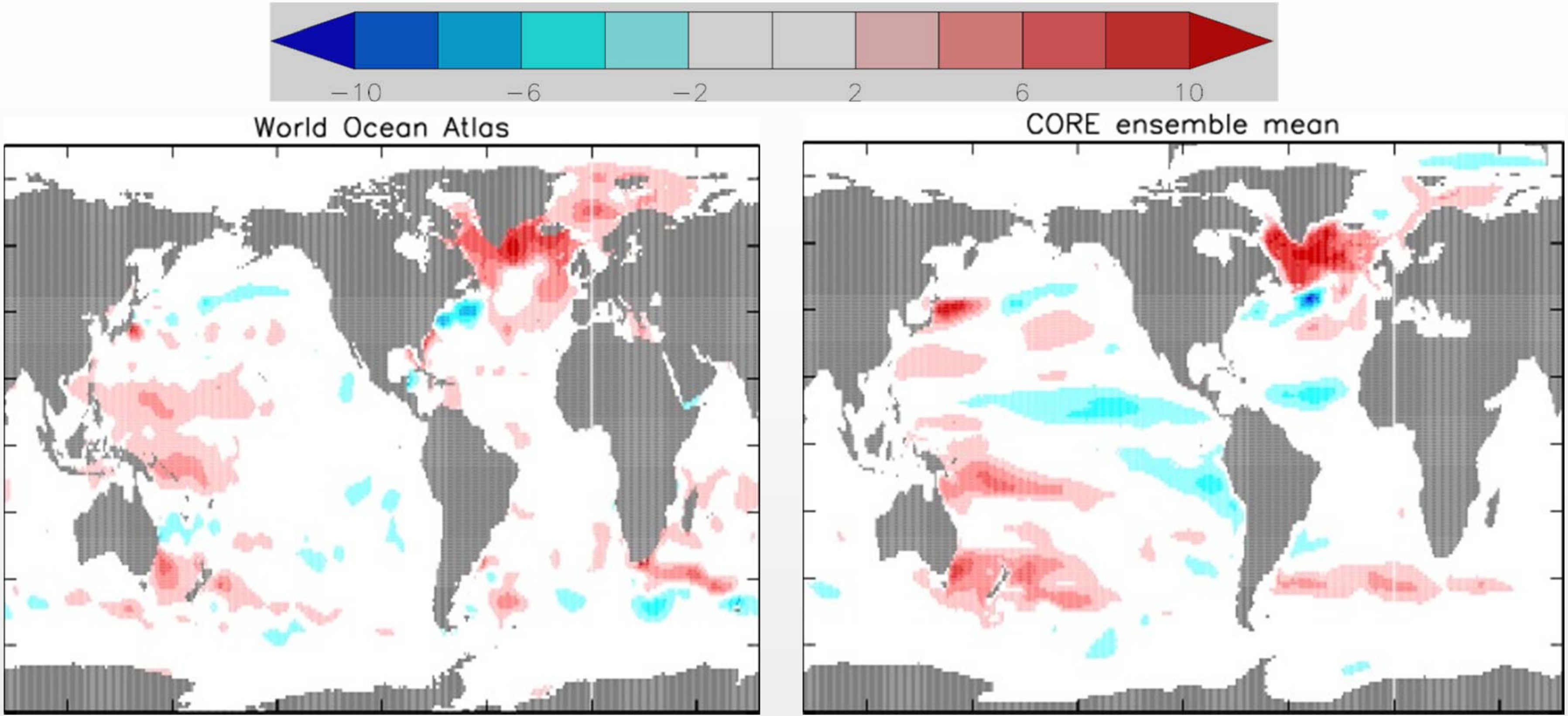
The observed summer Arctic sea ice extent trend in the early 21st century can be explained as an extreme rare scenario in either the “pure internal variability” case (cyan dots) or the “forced plus internal variability” case (orange dots) .

Discussion on the discrepancy between observations and CMIP5 simulations

Our findings raise the question why such a rapid decline in the summer Arctic sea ice extent occurred at the same time as the relatively “flat” trend in the global mean SAT. The discrepancy between observations and CMIP5 simulations suggest several possibilities:

- **Most CMIP5 models may underestimate the polar amplification of temperature change or the decrease of summer Arctic Sea Ice Extent in the response to a given forcing**
- **Internal variability of summer Arctic Sea Ice Extent may be underestimated by the models**
- **There may be important errors/omissions in forcings used in the models that can directly or indirectly affect summer Arctic Sea Ice Extent**
- **The observations represent a plausible but rare scenario, i.e. outside the 5th to 95th percentile ranges.**

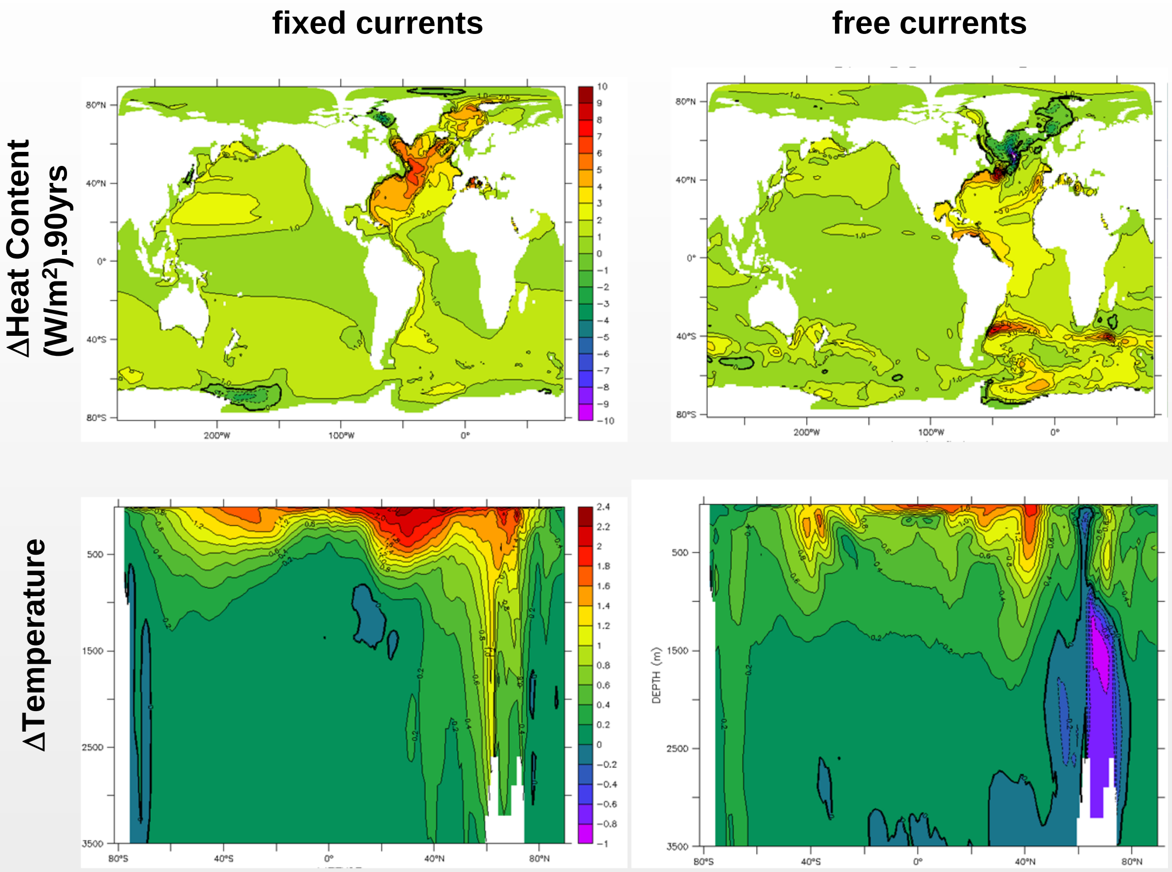
Ocean heat storage: Obs and COREII



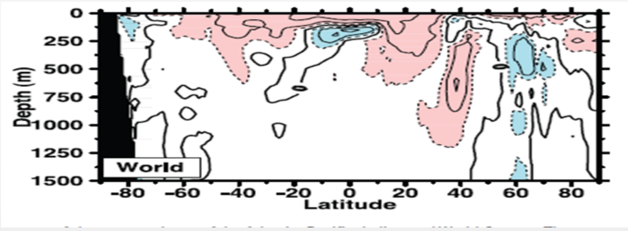
Griffies et al, in prep.

Linear trend in annual mean ocean heat content vertically integrated over the upper 700 m (units: W m^{-2}) for the years 1993-2007

Ocean circulation change and heat uptake



1% year CO2 increase experiments with **fixed** and **free** ocean circulation

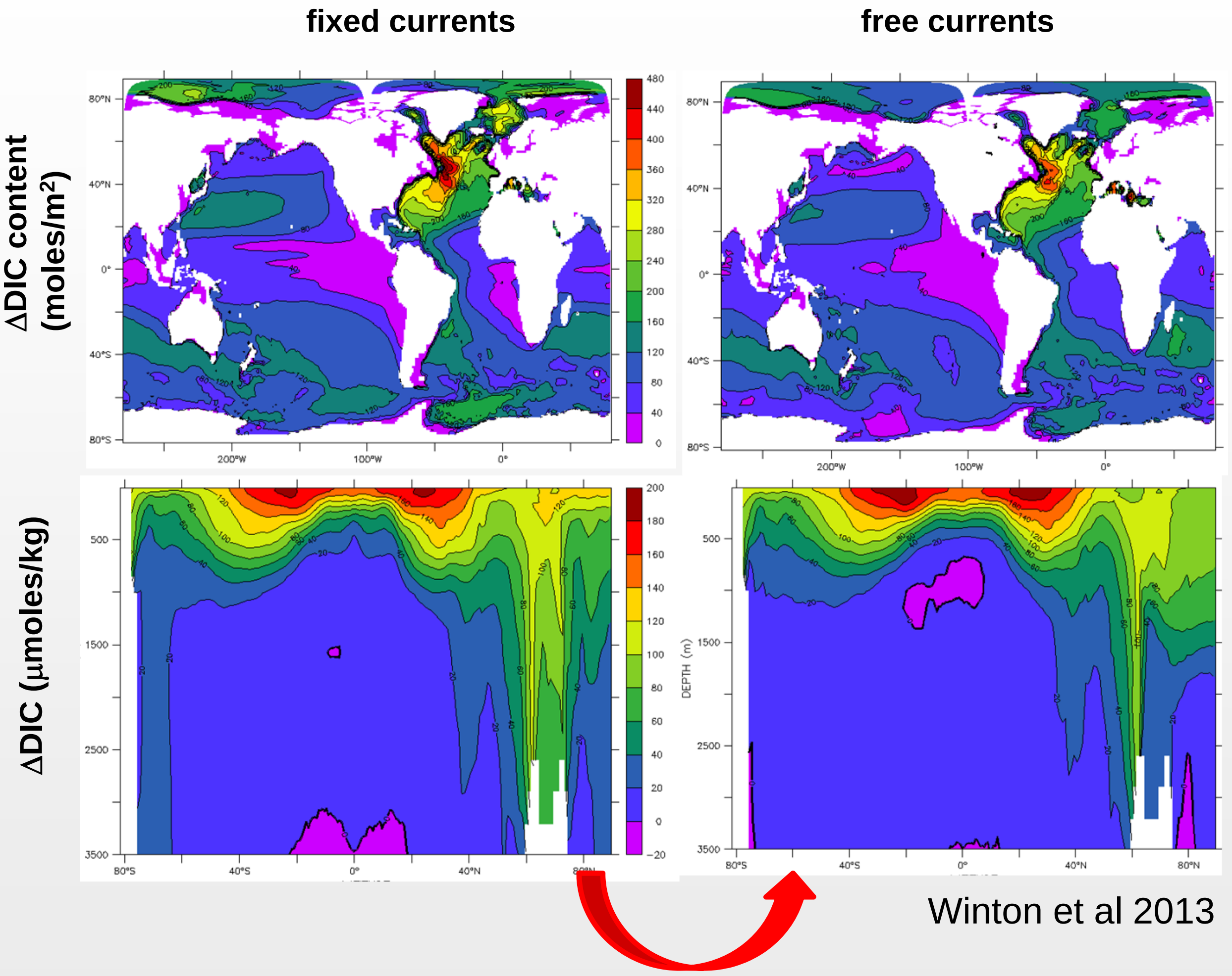


50-year zonal mean temp. trends (IPCC AR4)

Winton et al 2013

Impact of circulation response on perturbation heat storage

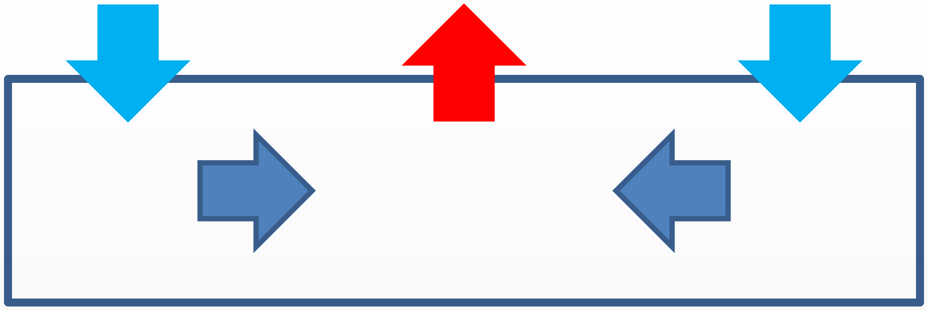
Carbon less affected by circulation change



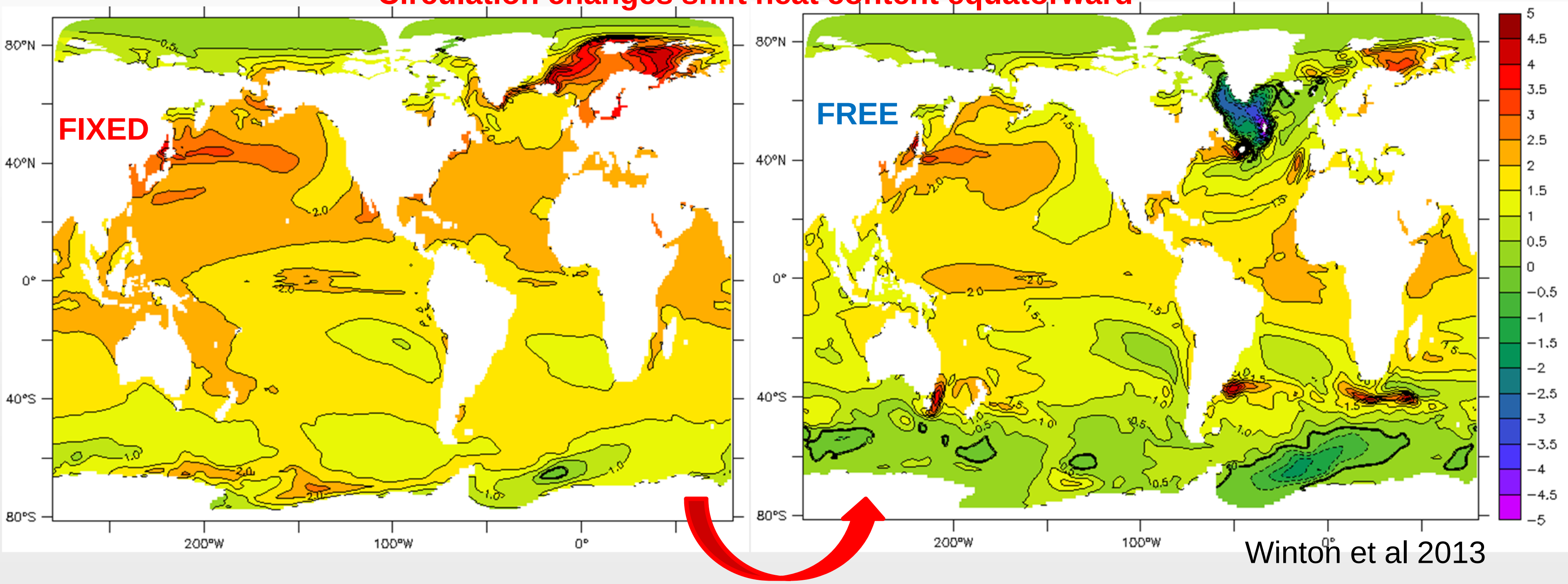
Winton et al 2013

Impact of circulation response on perturbation DIC storage

Circulation changes influence SST response



Circulation changes shift heat content equatorward

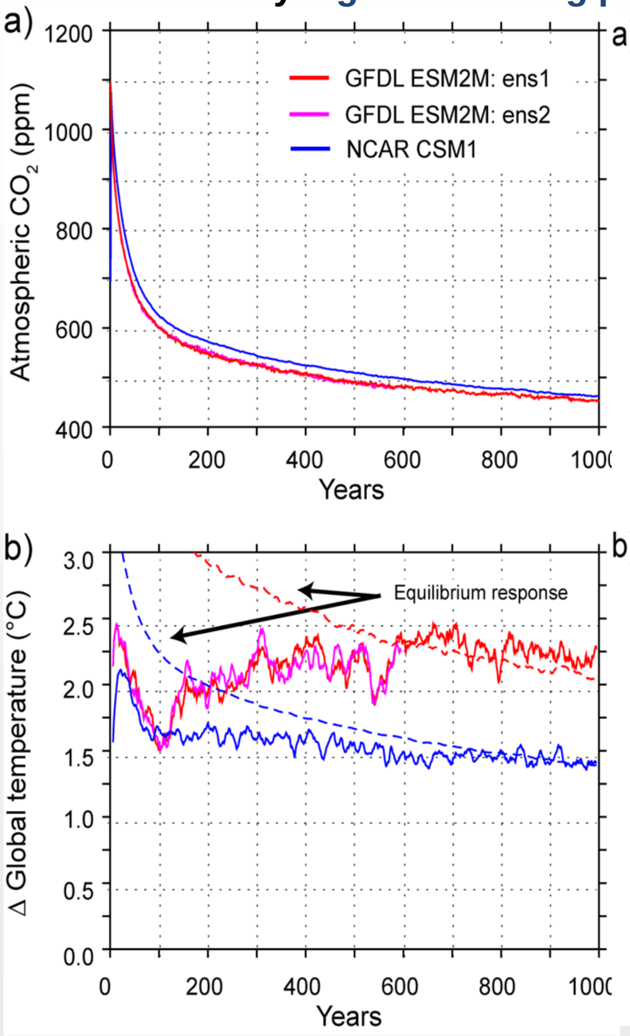


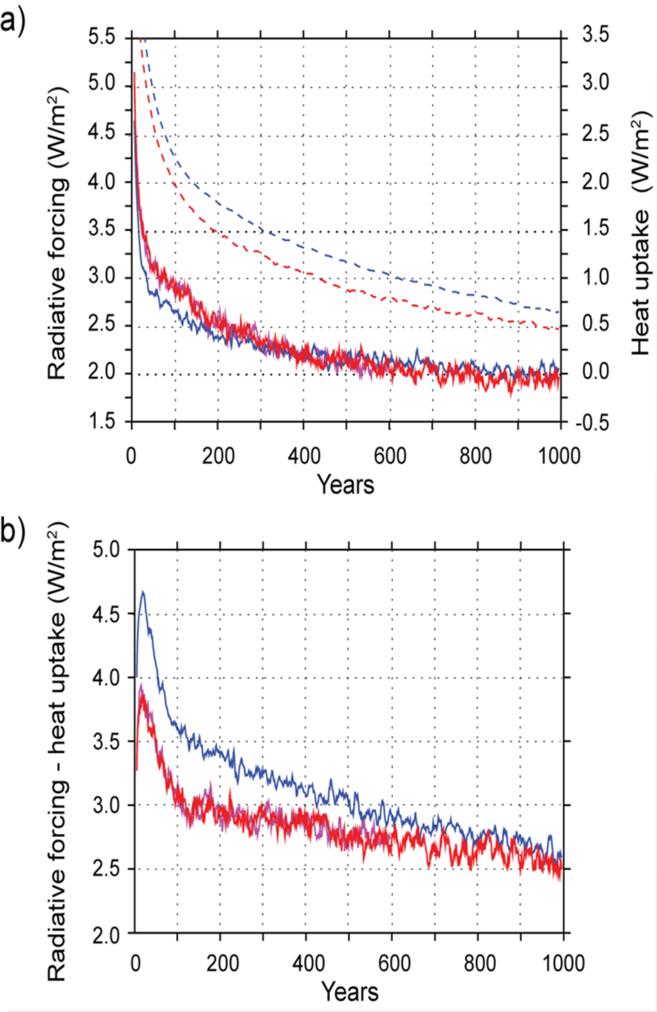
Winton et al 2013

Induced surface flux changes alter SST response

ESM response to instant 4x CO_2

Efficacy = global cooling per W m^{-2} ocean heat uptake / global warming per W m^{-2} CO_2 forcing

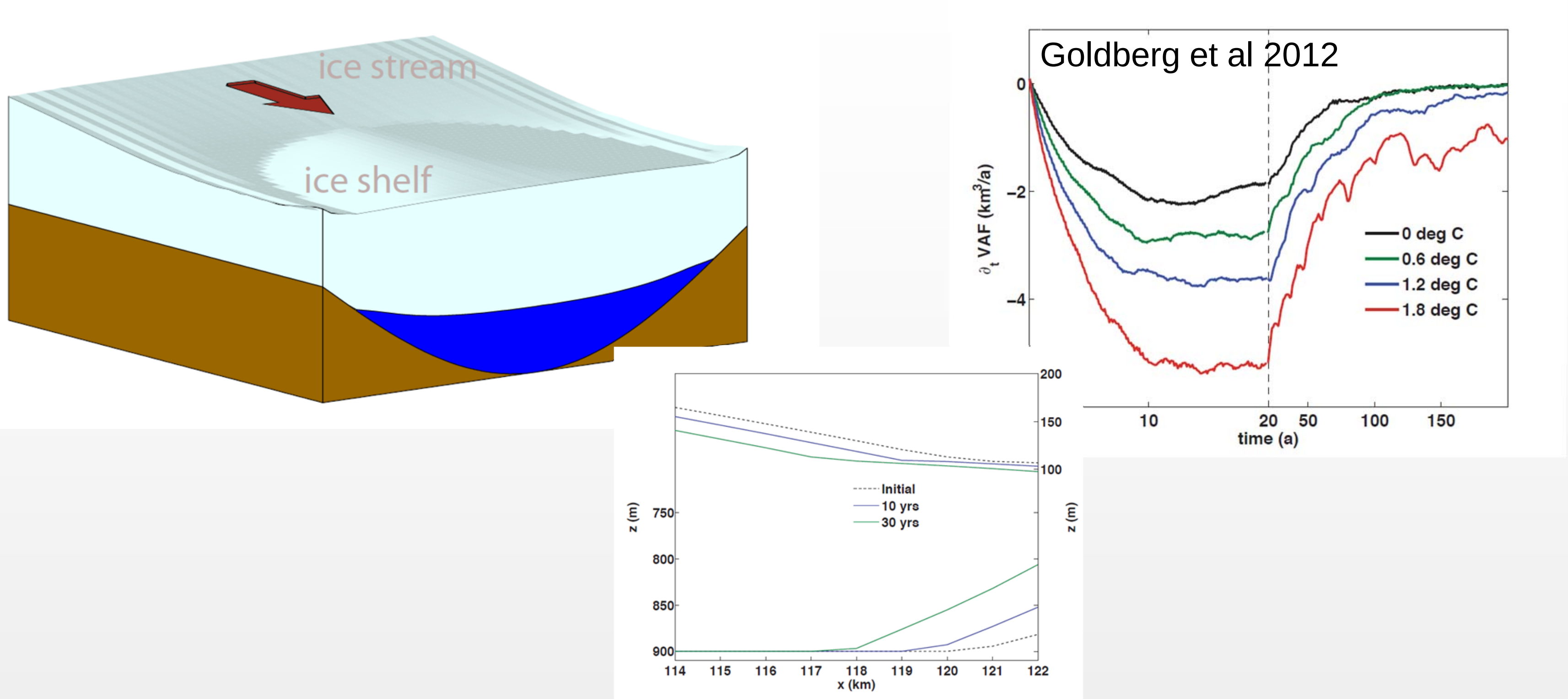




Froelicher et al in prep

Efficacy of about 2 causes global temperature to stabilize or even rise after cessation of CO_2 emissions.

Sea level rise: Ice-sheet/ocean interaction



Goldberg et al 2012

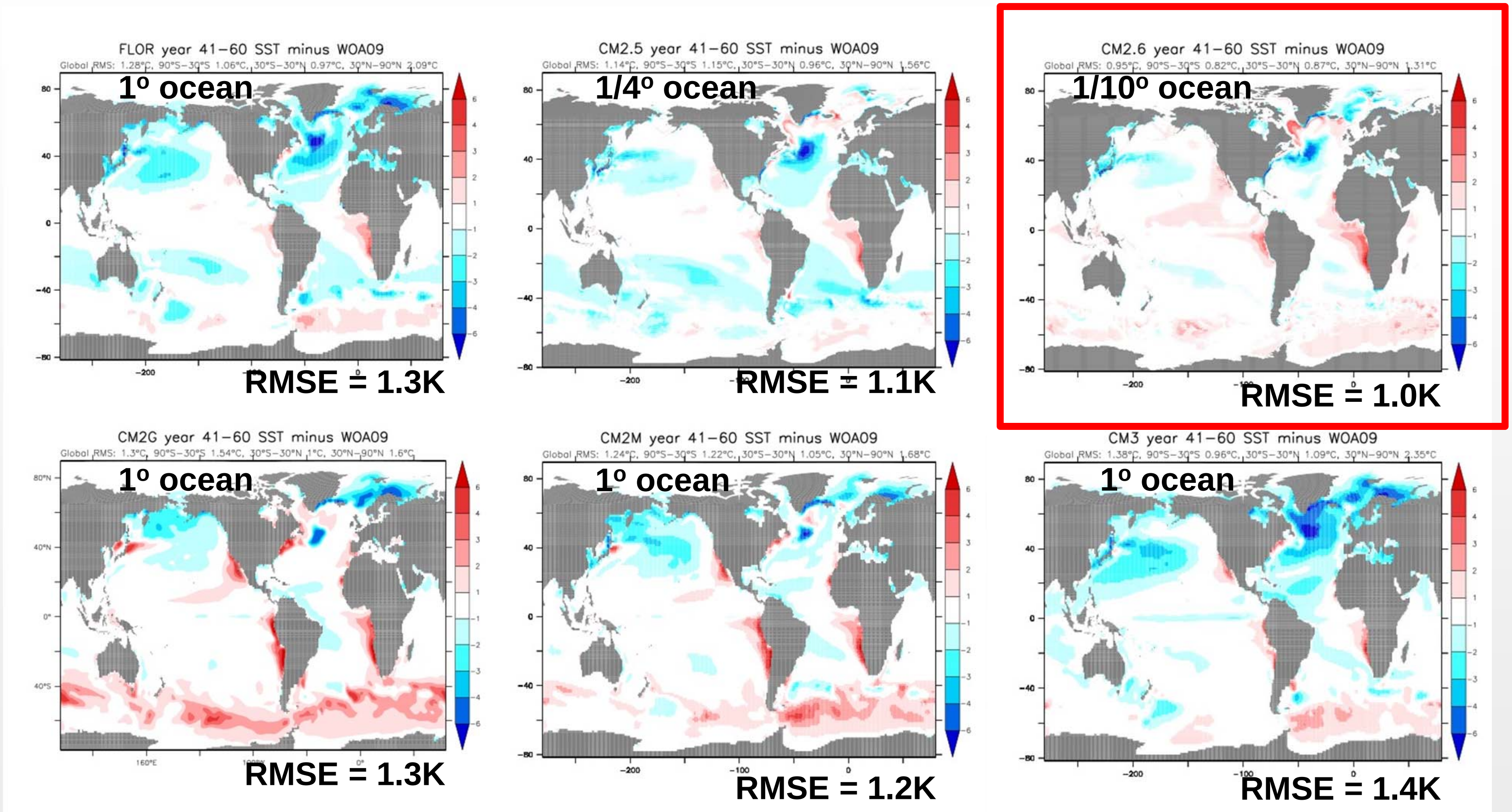
* After initial retreat, grounding line approaches a steady state position over the next 100-120 years in all simulations apart from the one with ocean bottom temperature 1.8C.

* Warming of the bottom ocean waters can trigger the grounding line migration that leads to accelerated loss of the grounded ice.

High-resolution climate model : CM2.6

- Eddy resolving (1/10^o) ocean coupled to 50 km AM2-based atmosphere
- Contains a simple 3 tracer (C, P, O) ocean biogeochemistry subcomponent
- Too costly to be a workhorse: 2 yrs/day on 1/5 Gaea (need 3 yrs/day on 1/8 Gaea for IPCC)
- Must be used strategically to answer ocean-focused variability and sensitivity questions
- CM2.6 champions: Whit Anderson, Tom Delworth, Tony Rosati, …

CM2.6 has GFDL’s best SST simulation



50 km atmosphere

1^{o} ocean **RMSE = 1.3K**

1/4^{o} ocean **RMSE = 1.1K**

1/10^{o} ocean **RMSE = 1.0K**

200 km atmosphere

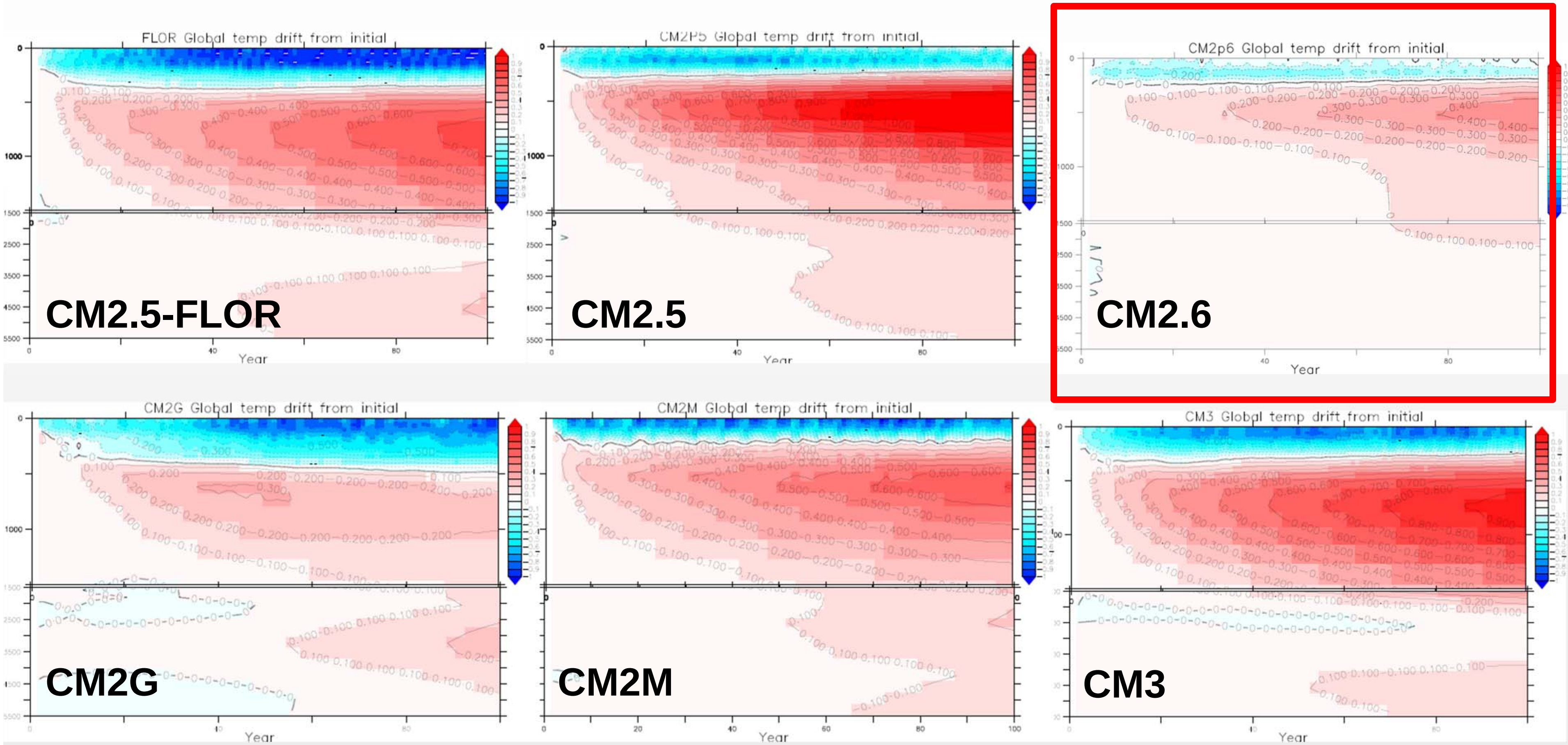
1^{o} ocean **RMSE = 1.3K**

1^{o} ocean **RMSE = 1.2K**

1^{o} ocean **RMSE = 1.4K**

1990 control run (year 41-60 average)

CM2.6 has small interior temperature drift

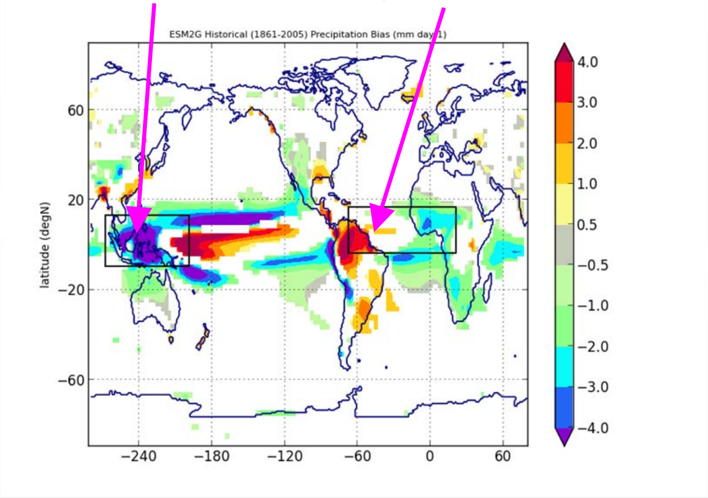


1990 control run (100 years)

North Atlantic Deep Water (NADW) Biases in GFDL ESMs are attributable to a Tropical Precipitation Bias

North Atlantic Deep Water
has a warm (and salty)
bias in ESMs

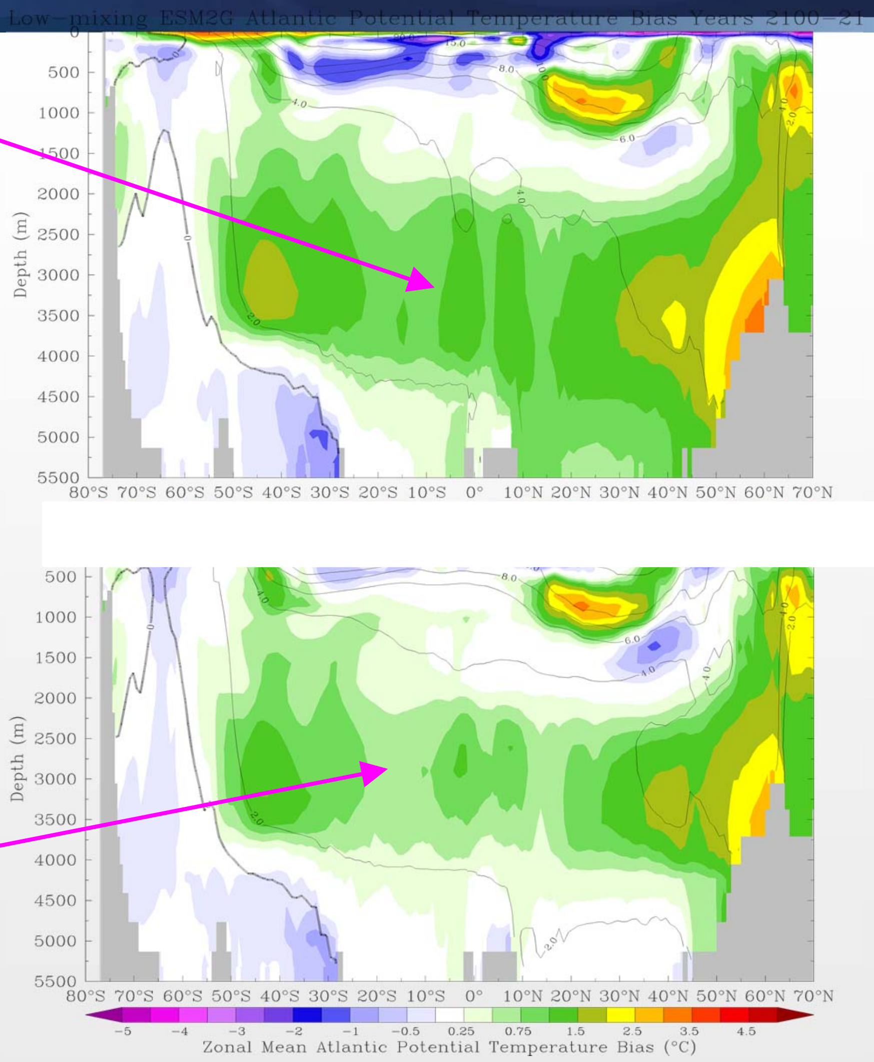
Wet Indonesian Bias **Dry Amazon Bias**



ESM2G Precipitation Bias

Adjusting for the precipitation
bias cools (and freshens) NADW
and reduces this model bias

Results are consistent with Talley (2008)
estimate of Atlantic basin freshwater export.



Harrison, Adcroft and Hallberg, in press Climate Dynamics

CM2.6: ocean realism in a climate model

Animation: Remik Ziemlinski