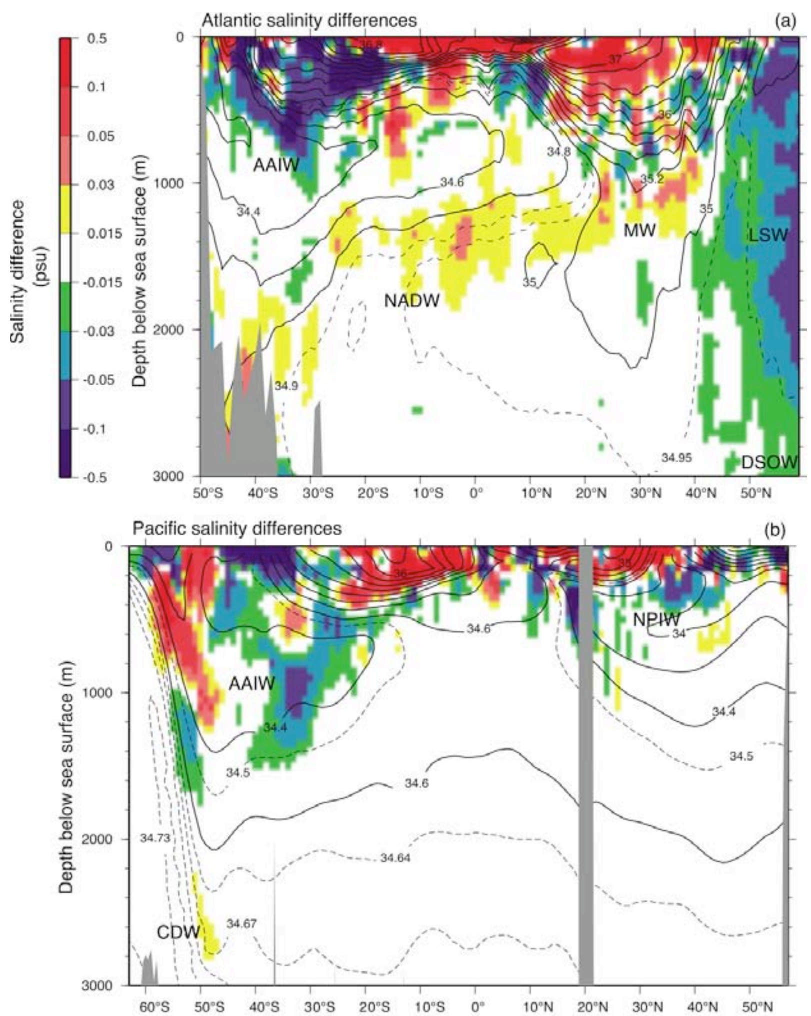
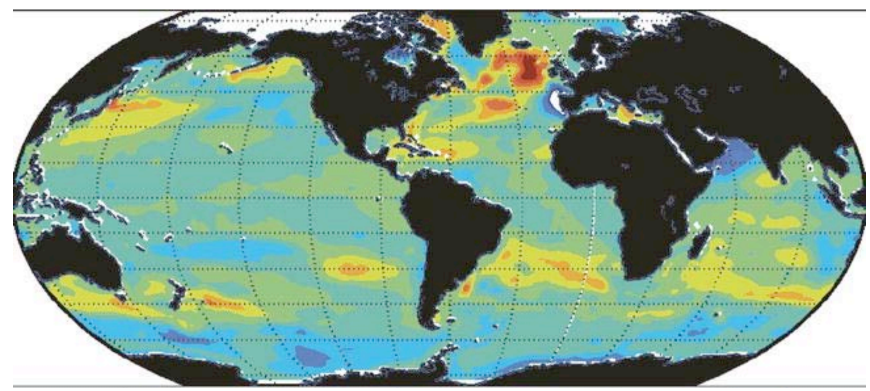
# Observed ocean climate changes: a review based on the IPCC AR4 and subsequent works



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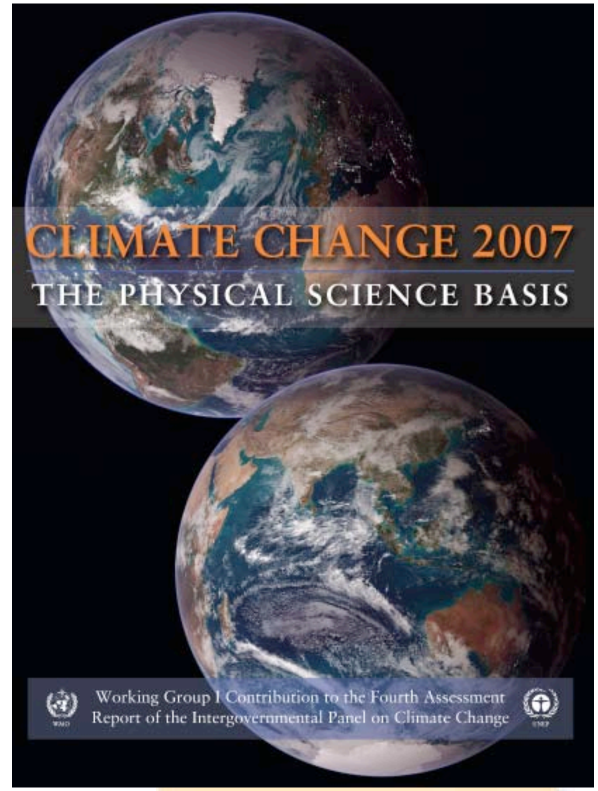
Scripps Institution of Oceanography,
University of California San Diego, USA

Effects of Climate Change on the World's Oceans
Gijon, May 2008

# Outline

- Climate change in general
- IPCC WG1 conclusions
- Observed climate change in the ocean: IPCC AR4 and more recent publications
  - Temperature, heat content, (sea level)
  - Salinity
  - Oxygen
  - Circulation, transports
  - (Changes in carbon and biosphere to be discussed in other sessions and plenary talks)
- Challenges and opportunities for ocean observations




# Building scientifically rigorous consensus on climate change

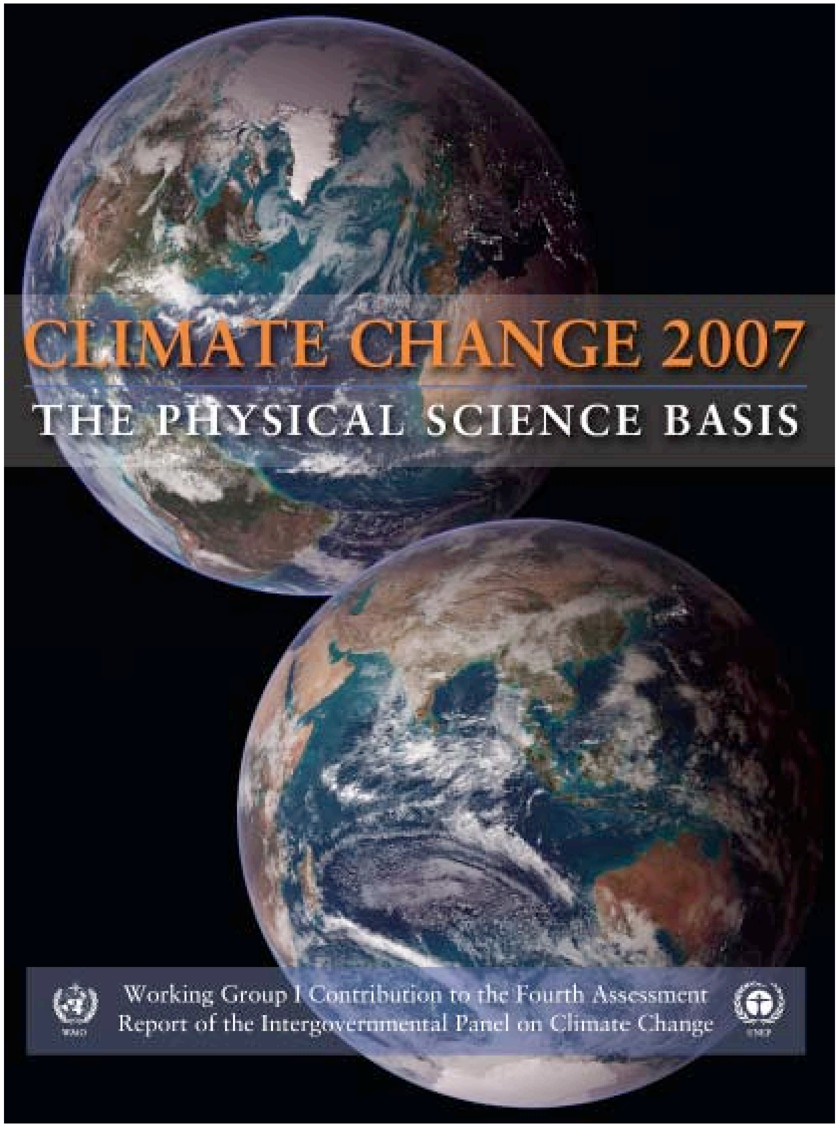
## Intergovernmental Panel on Climate Change
## http://www.ipcc.ch

Leaders of the IPCC accepting the Nobel Peace Prize

- United Nations (UNEP) and World Meteorological Organization
- UN Framework Convention on Climate Change (1994)
  - International agreements such as Kyoto protocol
- Intergovernmental Panel on Climate Change (1988)

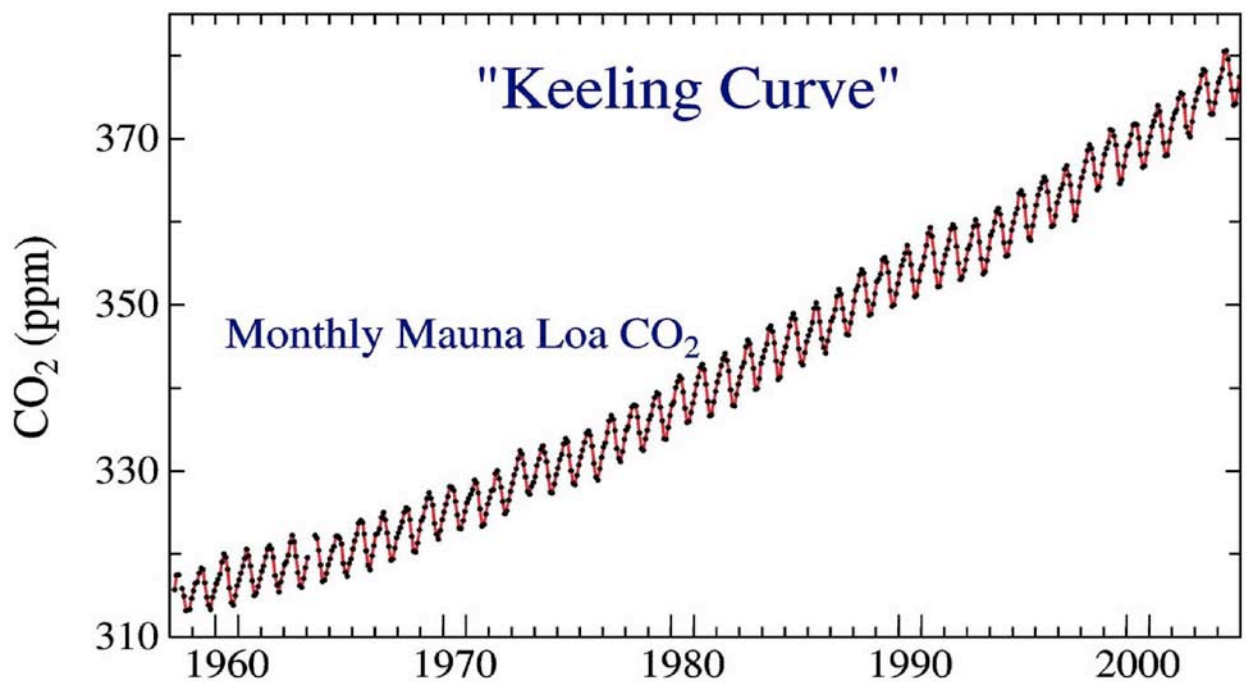
- Working Group 1: Scientific basis
- Working Group 2: Impacts, adaptation and vulnerability
- Working Group 3: Mitigation of climate change

# Physical science basis of climate change:
## IPCC Working Group 1




- "Warming of the climate system is unequivocal, as is now evident from observations of increases in global averages of air and ocean temperatures, widespread melting of snow and ice, and rising global sea level."

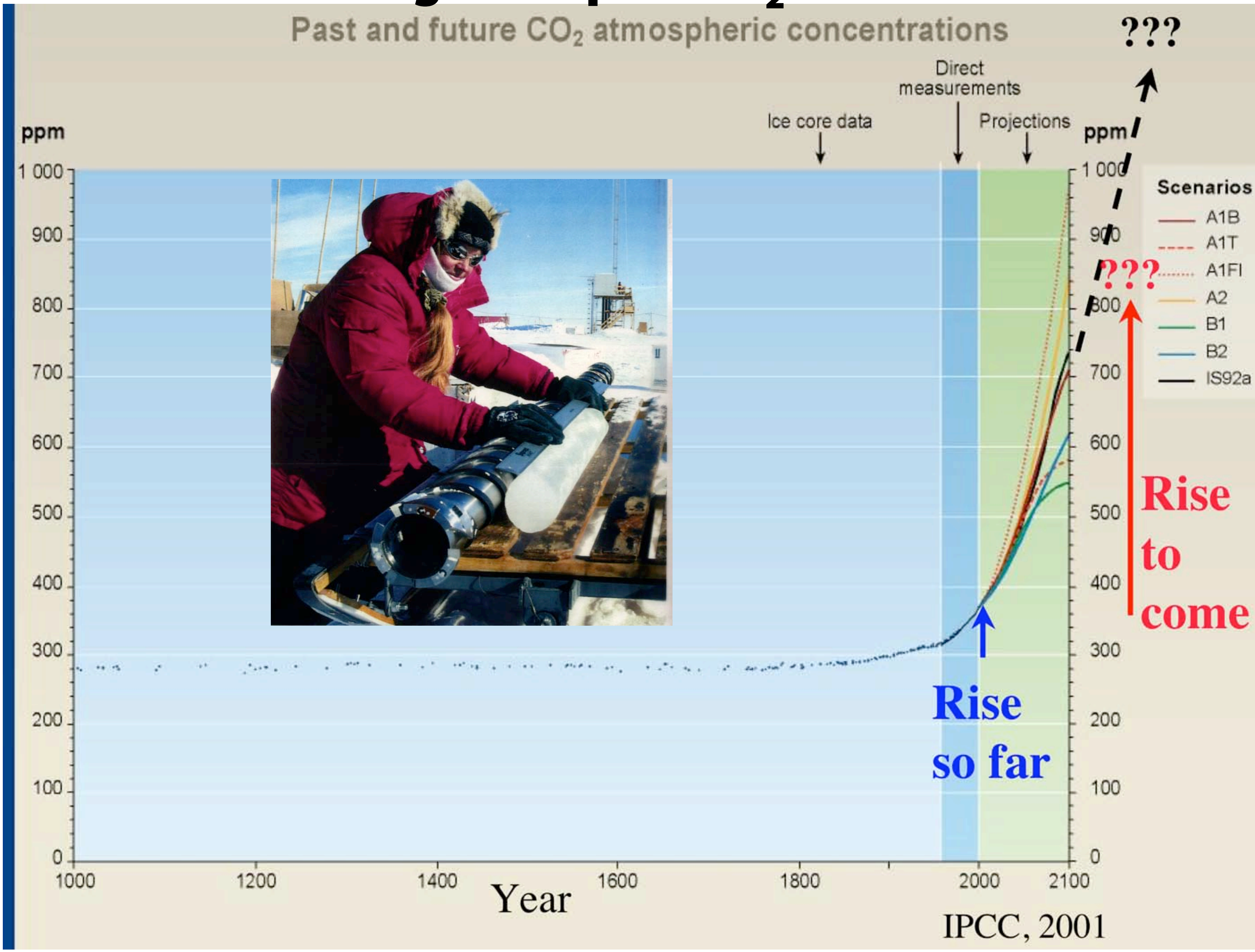
# $CO_2$ rise in the atmosphere

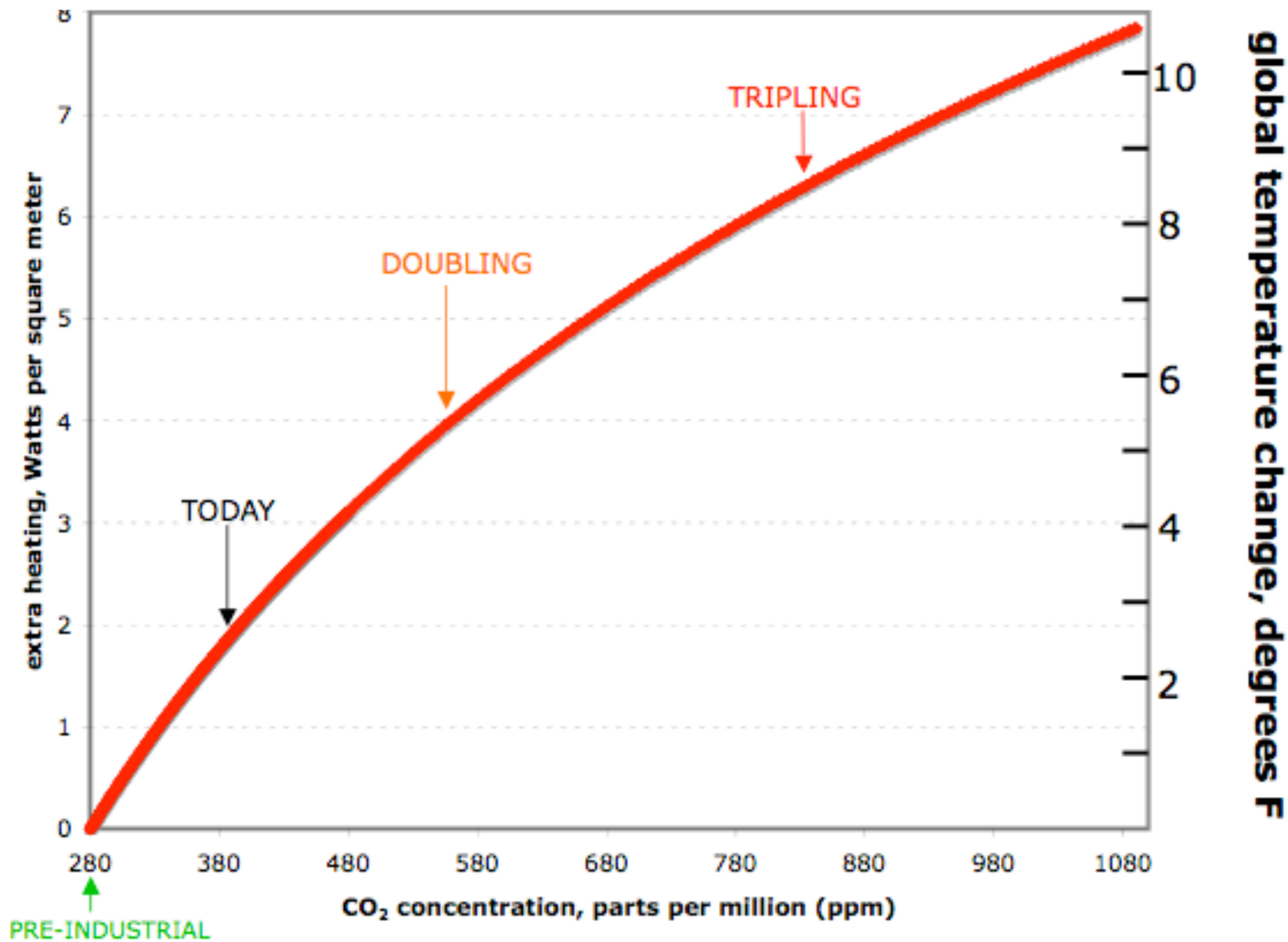

Atmospheric $CO_2$ measured at Mauna Loa, Hawaii.

*Source: NOAA Climate Monitoring and Diagnostic Laboratory*

# Ice cores give us past $CO_2$ concentrations



# How much warming (average for whole Earth) for a given rise in $CO_2$? (courtesy J. Severinghaus)

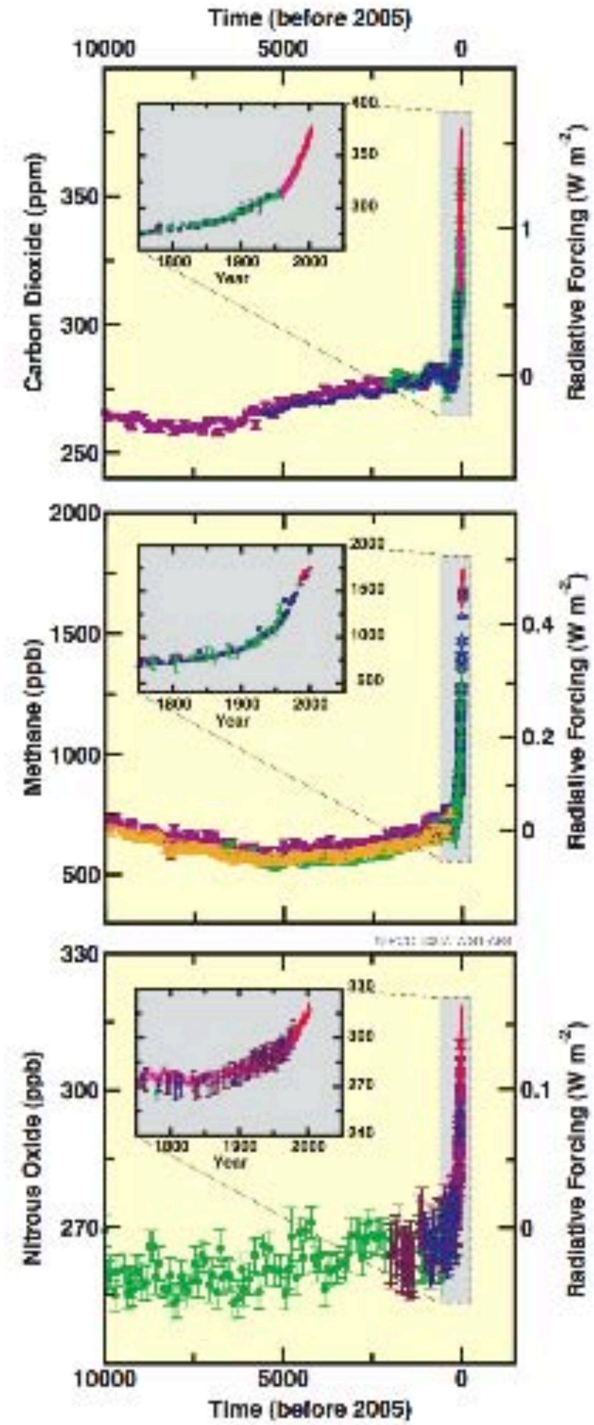


# Observed greenhouse gas changes: IPCC

- “Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values….”

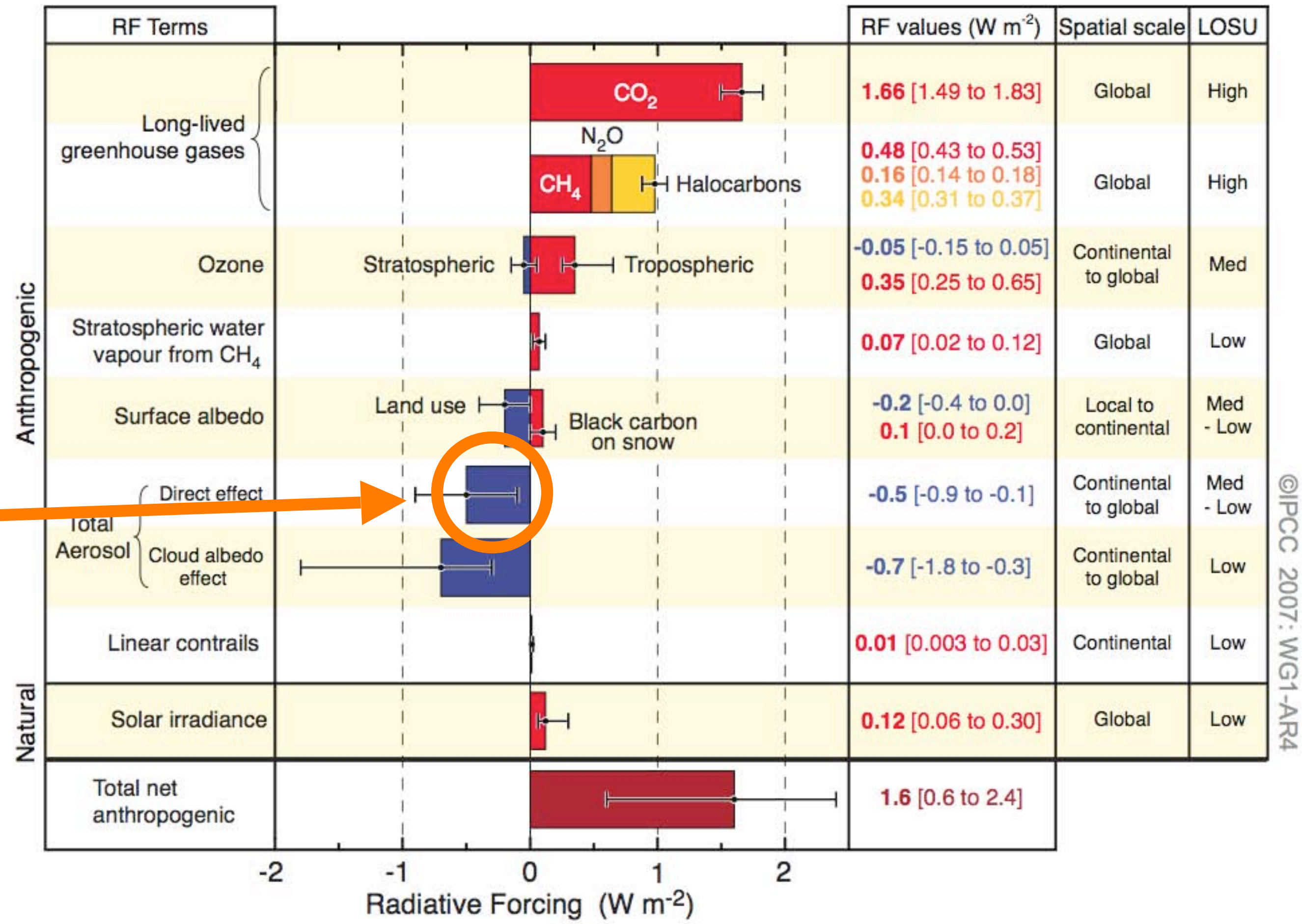
10,000 year records of:

carbon dioxide
methane and
nitrous oxide



# Observed changes in climate forcing (IPCC, 2007)

Effect of soot: presumed mainly to be negative radiative forcing. But new findings (K. Prather, UCSD) indicate that soot combines much more efficiently with sulfate than expected and becomes a positive forcing, which would increase the net radiative forcing value in this figure.



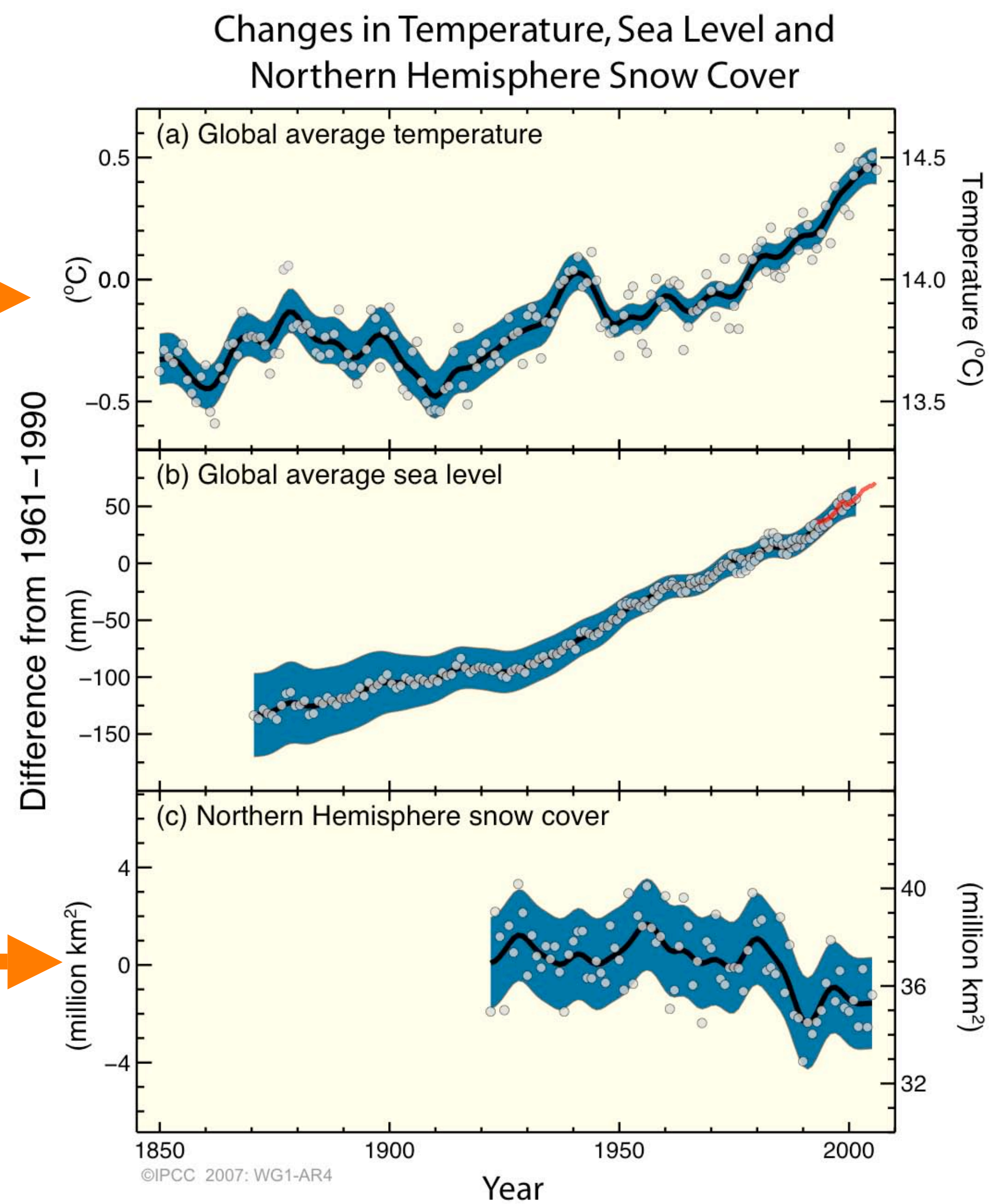

- "The understanding of anthropogenic warming and cooling influences on climate has improved since the TAR, leading to *very high confidence* that the globally averaged net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W $m^{-2}$."

# Observed climate change since 1850: IPCC

Global temperature increase of 1°C

Global sea level rise of ~20 cm (8 inches)

Decrease in snow cover

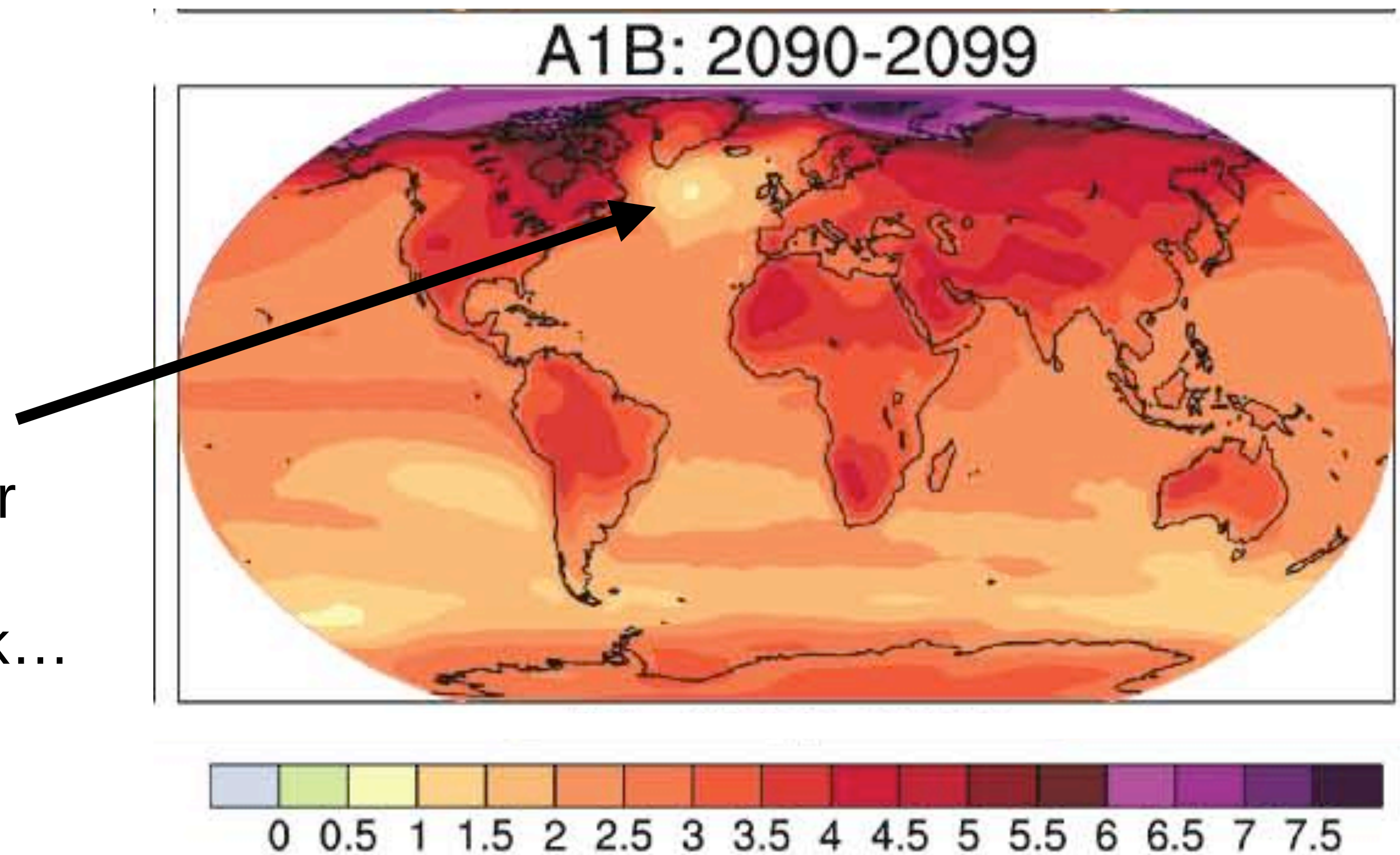


# Climate change projections: IPCC

Temperature projections for 100 years from now:

“Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean.”

(IPCC AR4)




Degrees Centigrade (˚C)

Remember this dot for later in talk…

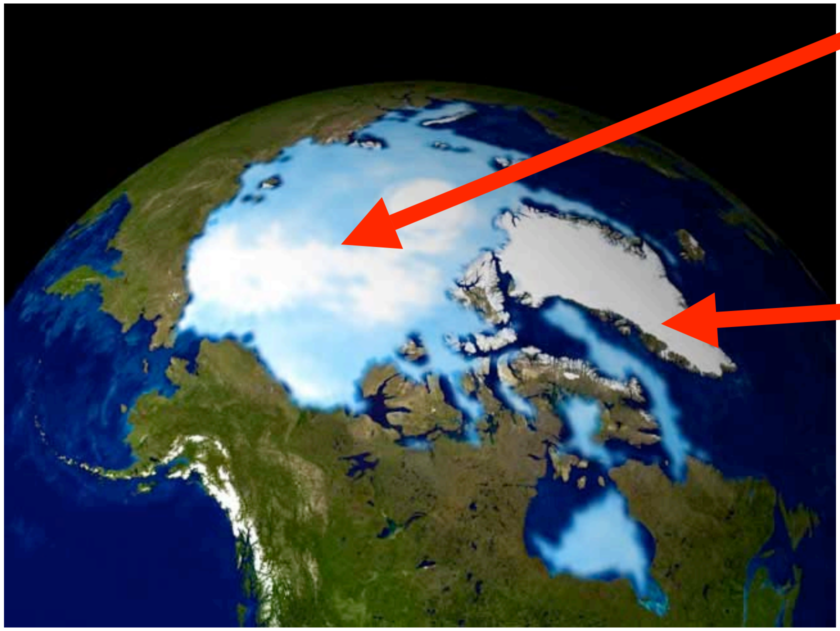
## Wind forcing (IPCC Summary for Policy Makers): these have implications for the T,*S*, $O_2$ changes to be shown below

"Mid-latitude westerly winds have strengthened in both hemispheres since the 1960s."

"Extra-tropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation, and temperature patterns, continuing the broad pattern of observed trends over the last half-century."

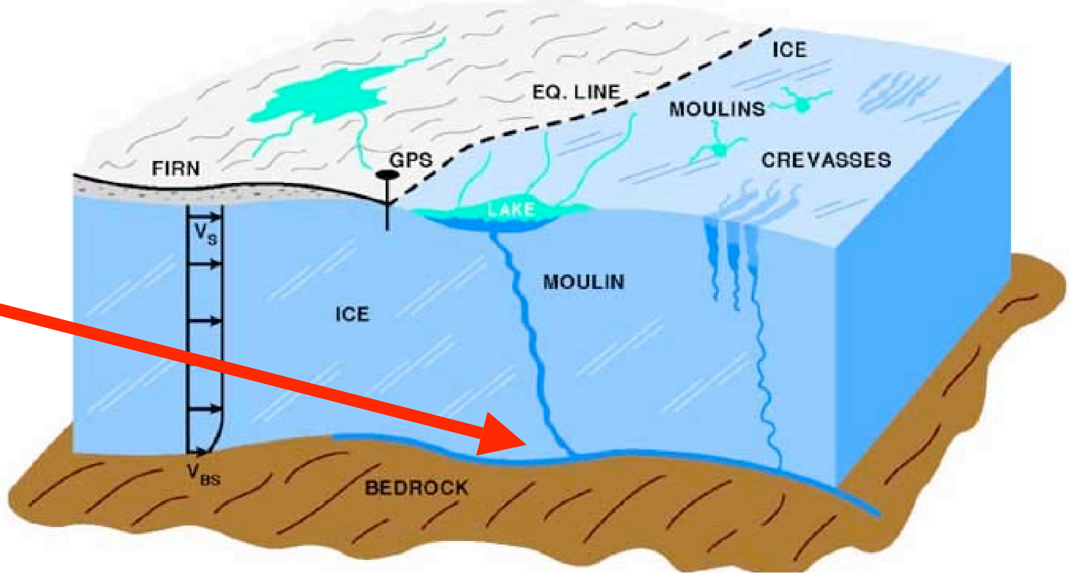
# Sea level rise and ice melt

This melting (of sea ice) "only" causes ocean salinity to change



THIS melting (of land ice) will cause sea level to rise, a maximum of 7 meters if all of Greenland goes (IPCC).

More recent findings: ice sheets slide into ocean more quickly than assumed, since meltwater can fall to bottom and lubricate ice sheet



# Post-IPCC climate research with major consequences: ice sheet dynamics

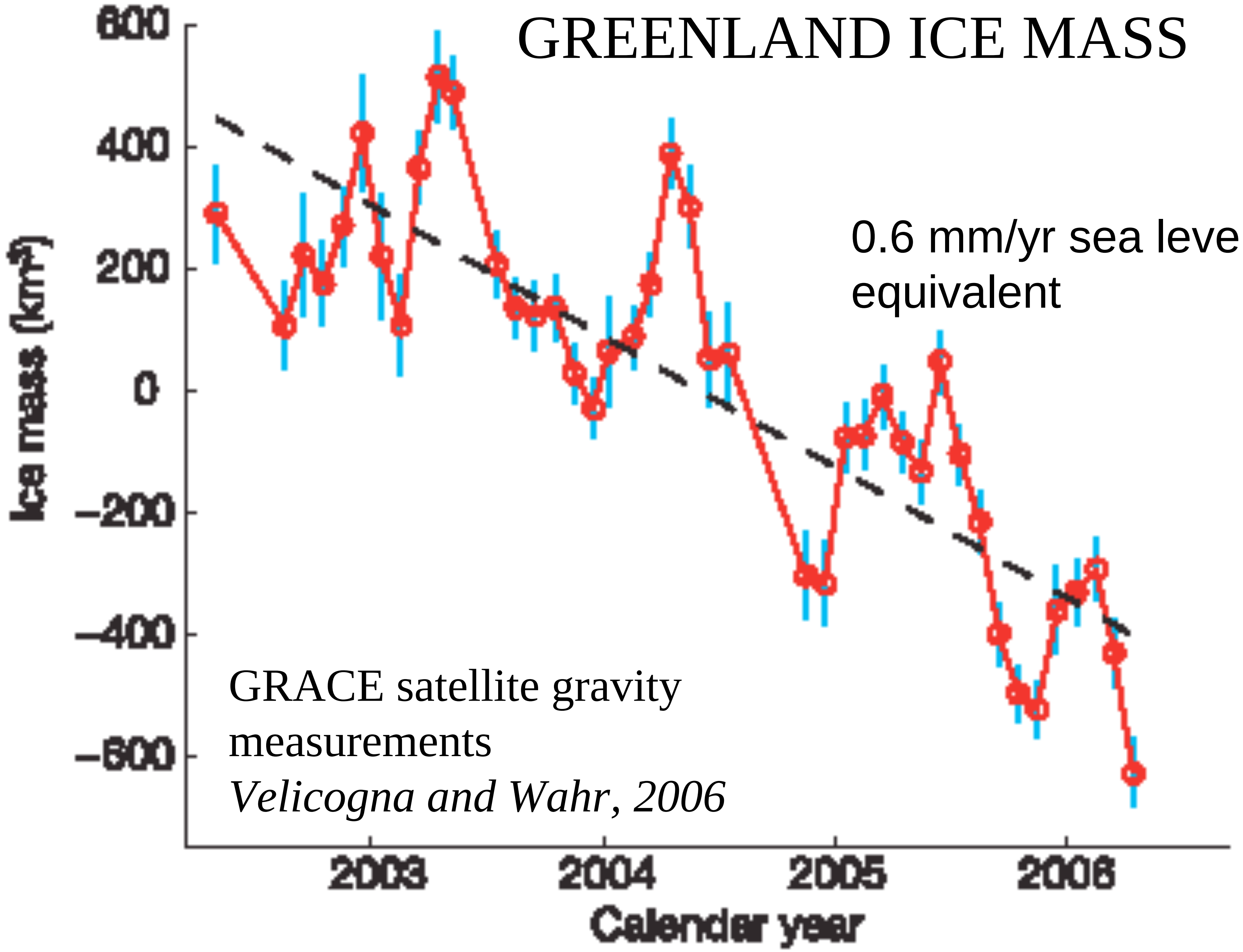
Jakobshavn Ice Stream in Greenland

Discharge from ice streams is increasing markedly. Greenland and Antarctic ice sheets are changing much more quickly than presumed (years to decades rather than the 1000s of years summarized by IPCC)

(Dynamics of ice sheets not well understood, hence not modeled in IPCC scenarios)

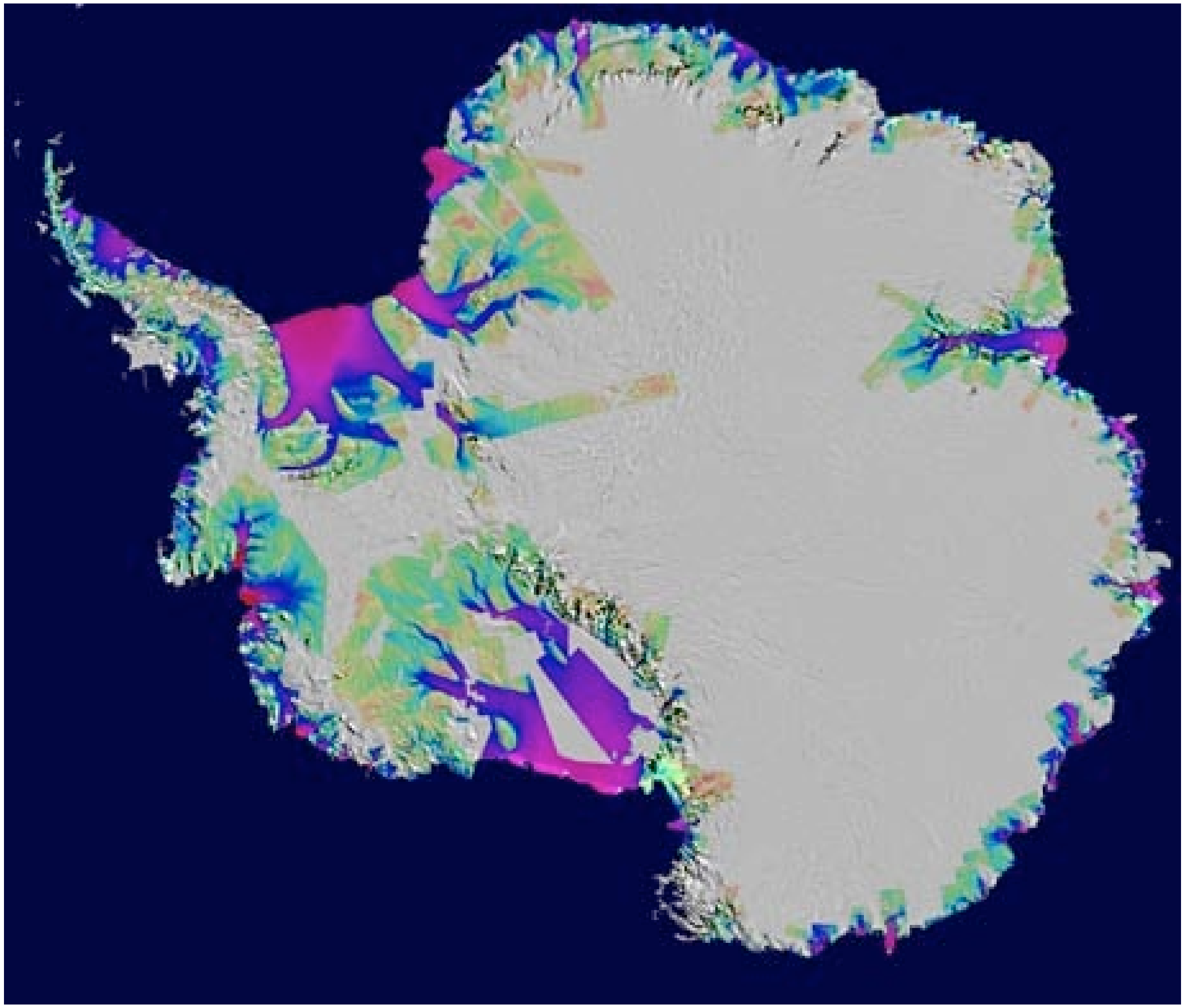
(e.g. Bamber, Alley and Joughin, EPSL, 2007)

Flow into a moulin (NASA website, 2002)



GREENLAND ICE MASS
0.6 mm/yr sea level equivalent
GRACE satellite gravity measurements
Velicogna and Wahr, 2006
600
400
200
0
−200
−400
−600
Ice mass (km³)
2003
2004
2005
2006
Calendar year

# Antarctic ice loss speeding up 1996-2006, now nearly matching Greenland



- Jan. 2008 NASA JPL release, Grace satellite mission
- Rignot et al. (Nature Geoscience, 2008)

# Changes in precipitation and evaporation

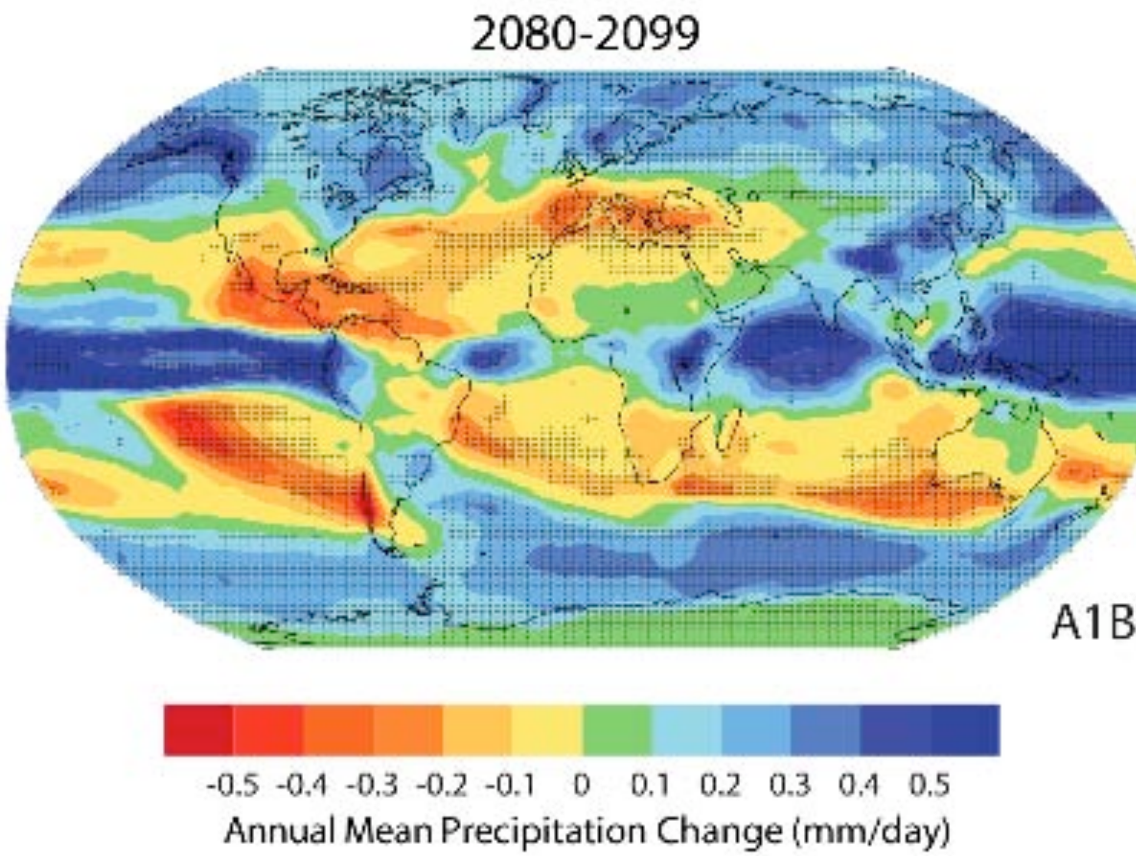
A warmer world pumps more water vapor into the atmosphere (with the ocean an enormous holding tank for the water): increased hydrological cycle

Impacts are recorded in ocean salinity, potential for (indirect) feedbacks on climate through changed ocean stratification

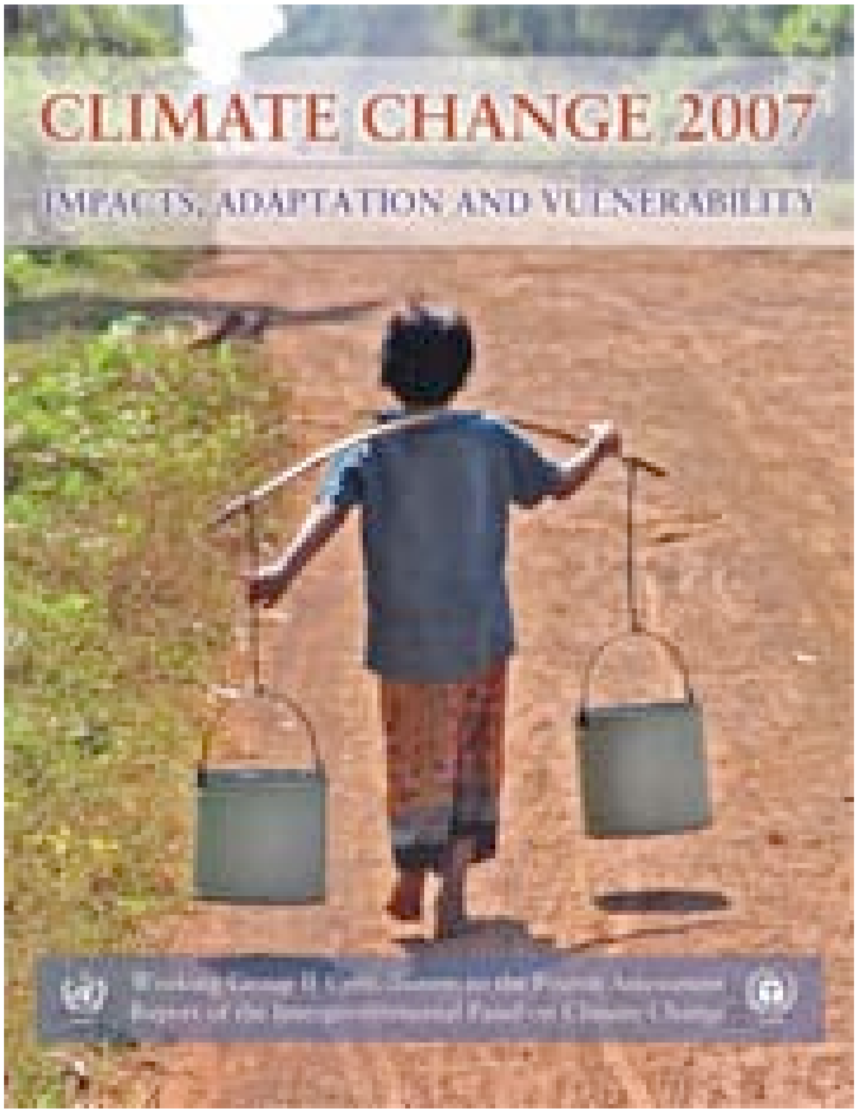
Dry areas become drier

Wet areas become wetter

Predicted precipitation change



# Impacts of climate change: IPCC Working Group 2




- "There is high confidence that recent regional changes in temperature had discernible impacts on many physical and biological systems."
- For developed regions (N. America, Europe, etc)
  - High adaptive capacity
  - Increased pressure on water resources
  - Coastal impacts
  - Agricultural impacts
- For developing regions (e.g. Africa)
  - Low adaptive capacity
  - "One of most vulnerable continents … because of multiple stresses and low adaptive capacity"
  - 75-250 million people exposed to increased water stress by 2020
  - Agricultural production severely compromised
  - Rise in malnutrition

# IPCC WG I Ocean Observations chapter in Norway, summer 2006

**Total of 11 such chapters in IPCC Vol. 1, 20 in Vol. 2, 13 in Vol. 3, so about 700 (?) scientists involved in writing this particular report, plus about the same reviewing it**

2 coordinating lead authors

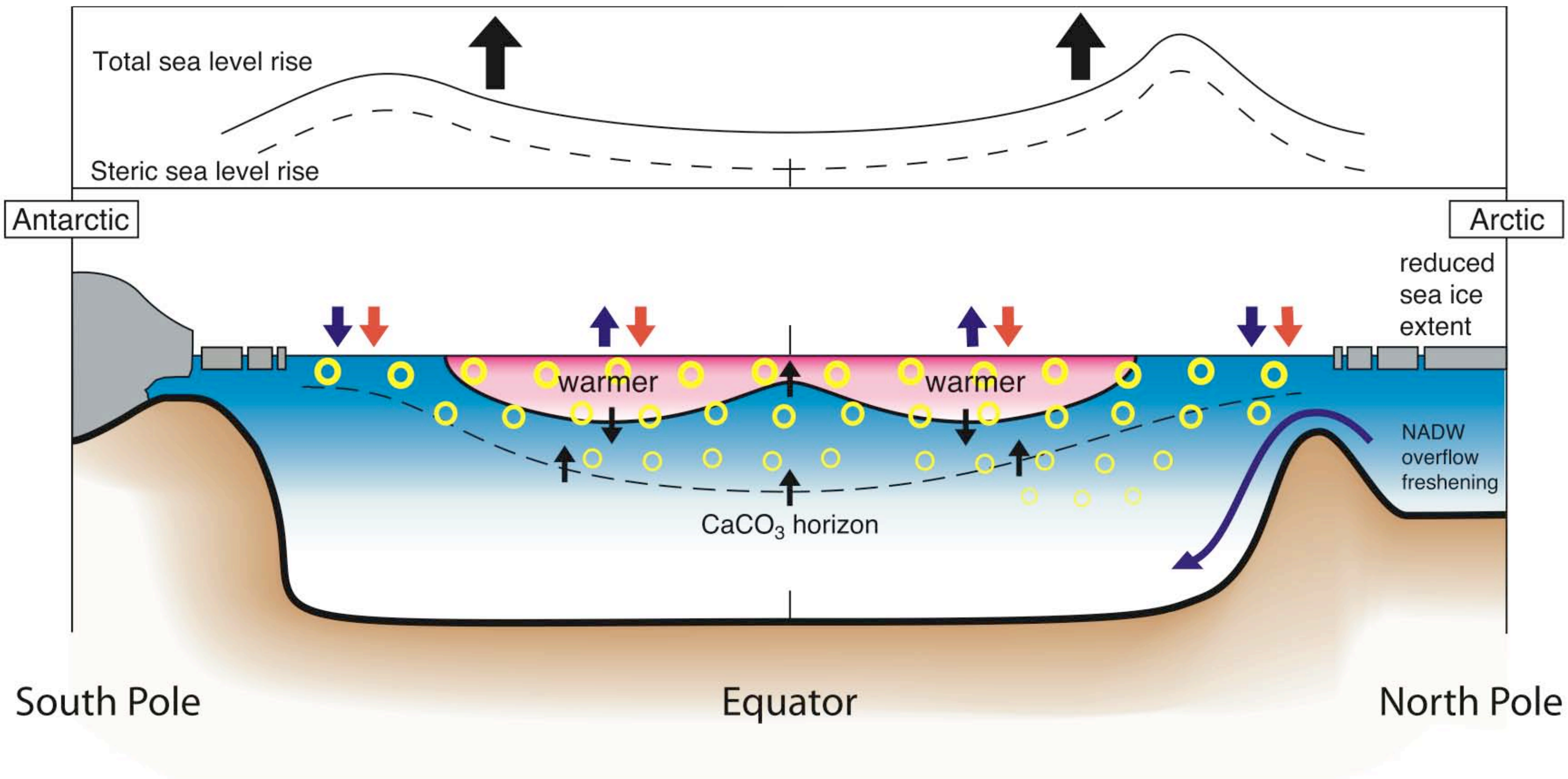
9 other lead authors

2 review editors

53 contributing authors

Many Reviewers (MANY THANKS)

# Schematic of observed ocean changes (IPCC Fig. 5.23)




Heat and $CO_2$ increased / decreased into ocean

Freshwater (Precipitation - Evaporation) increased / decreased

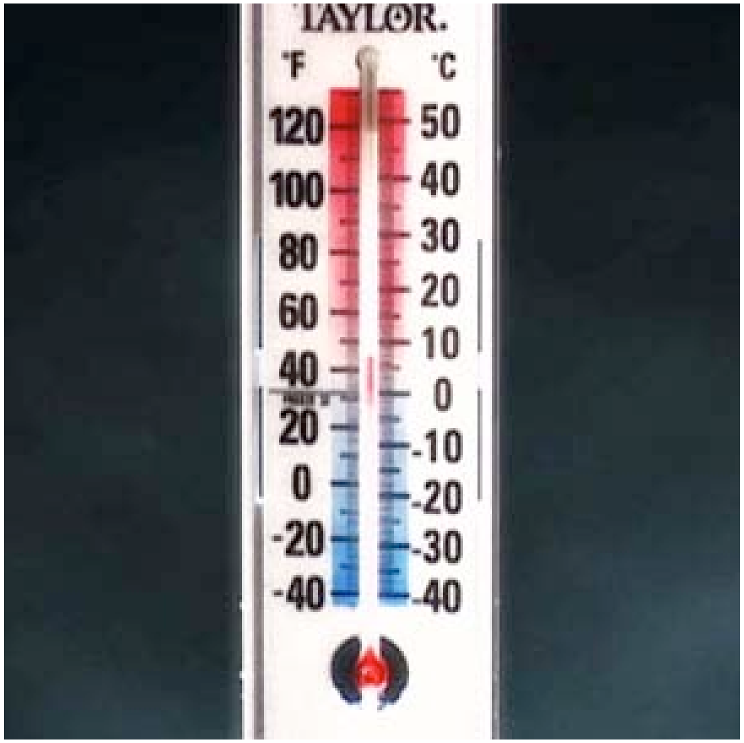
Freshening

Salinification

Deepening / shallowing of isotherms, isopycnals and $CaCO_3$ horizon

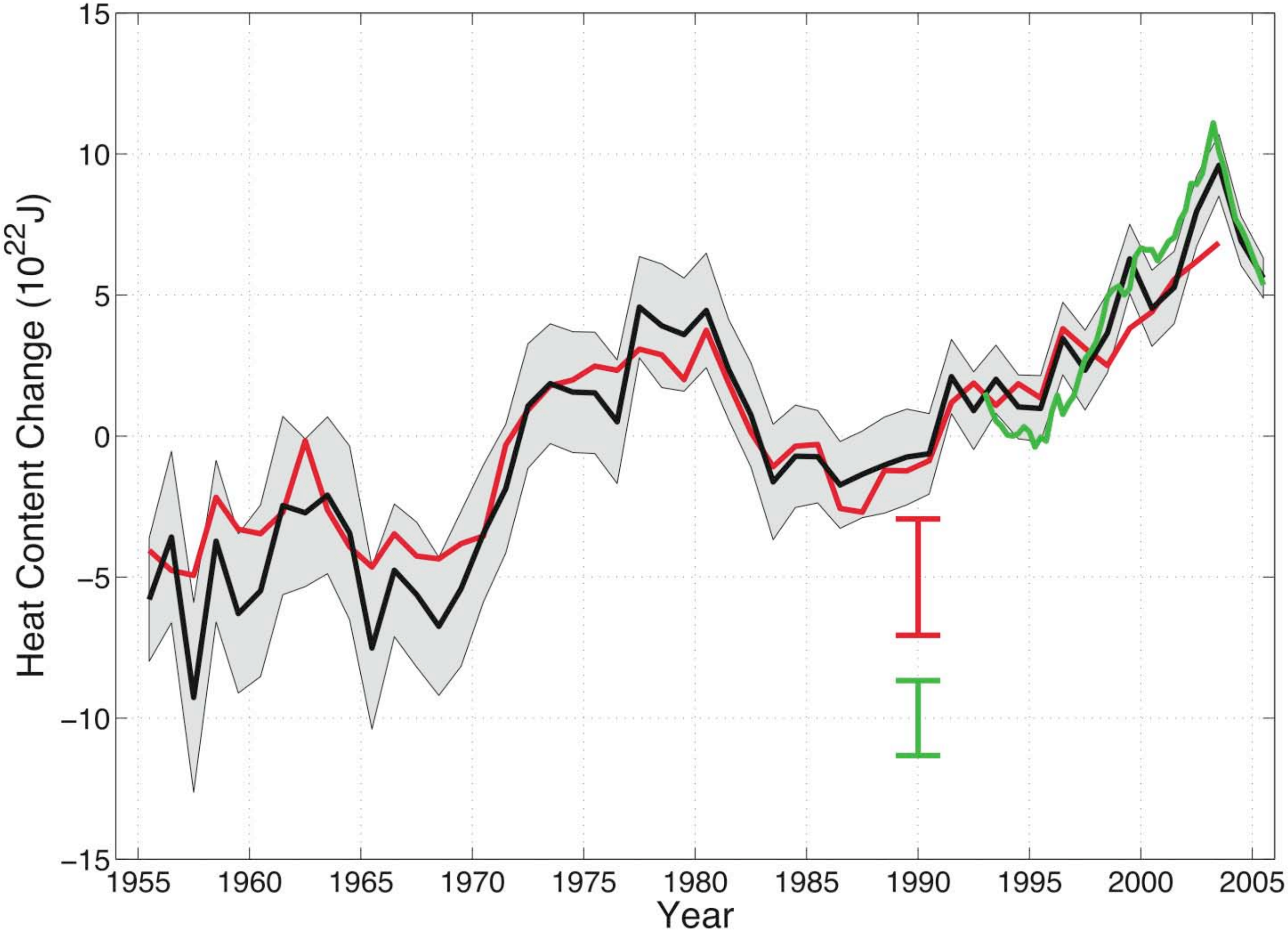
Decreased pH

# Temperature and heat content changes



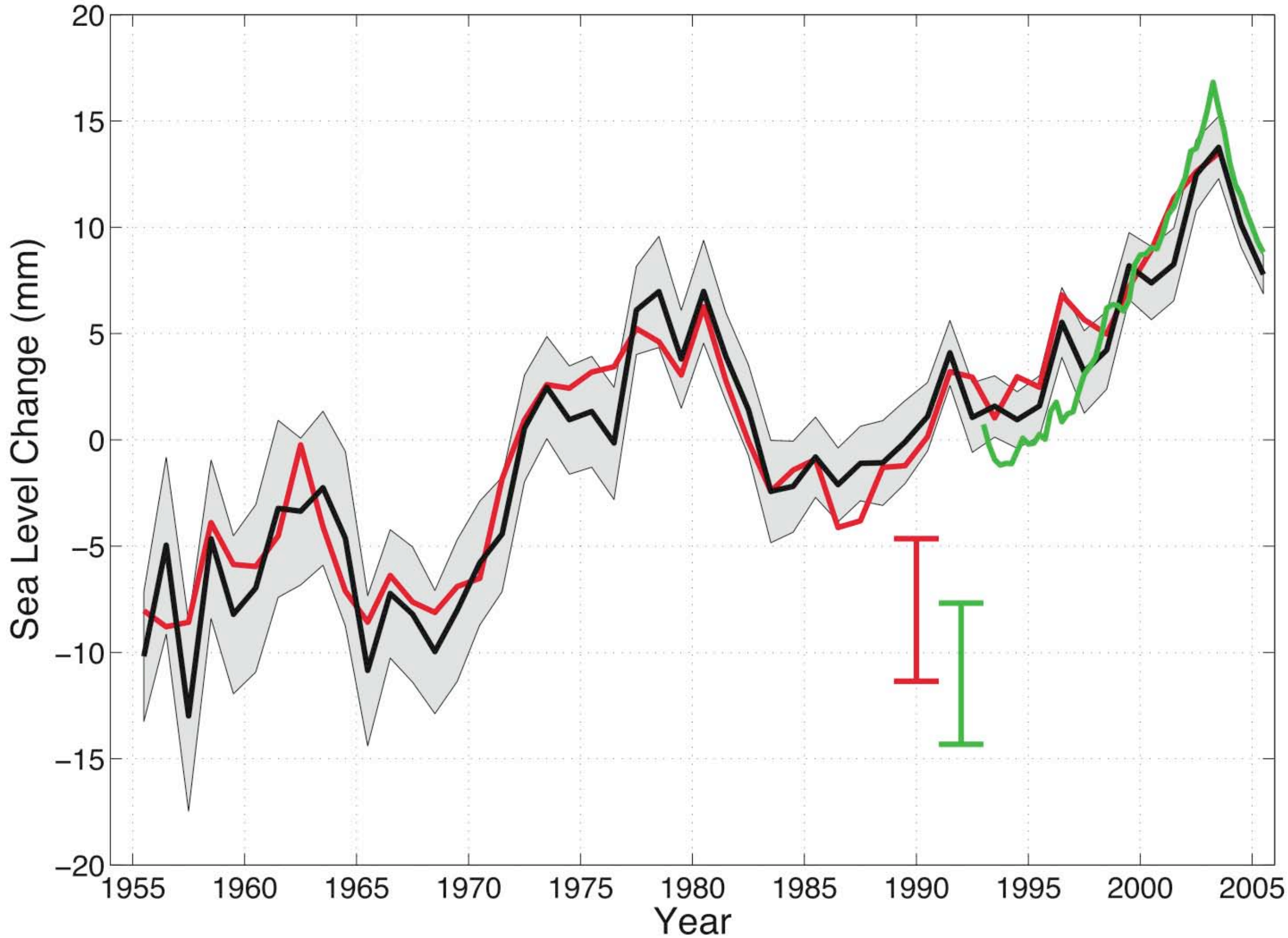

"..the average temperature of the global ocean has increased to depths of at least 3000 m and the ocean has absorbed more than 80% of the heat added to the climate system. Such warming causes seawater to expand, contributing to sea level rise."

# Ocean heat content 0-700 m (IPCC Fig. 5.1)



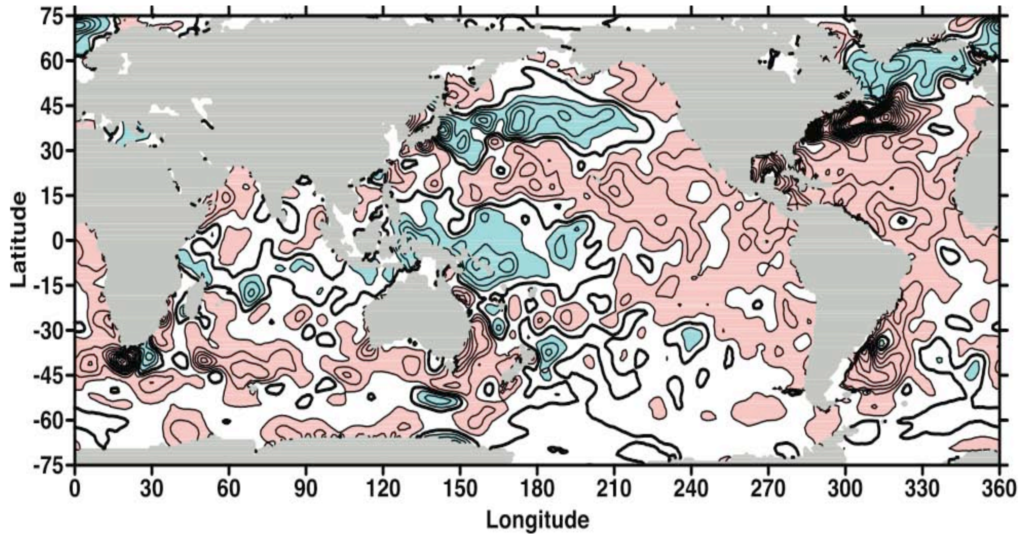

Based on Levitus et al. (2005), Ishii et al. (2006), Willis et al. (2004)

# Ocean heat content 0-700 m (IPCC AR4, 2007) and sea level change due to thermal expansion (IPCC Fig. 5.19)




Based on Levitus et al. (2005), Ishii et al. (2006), Willis et al. (2004)

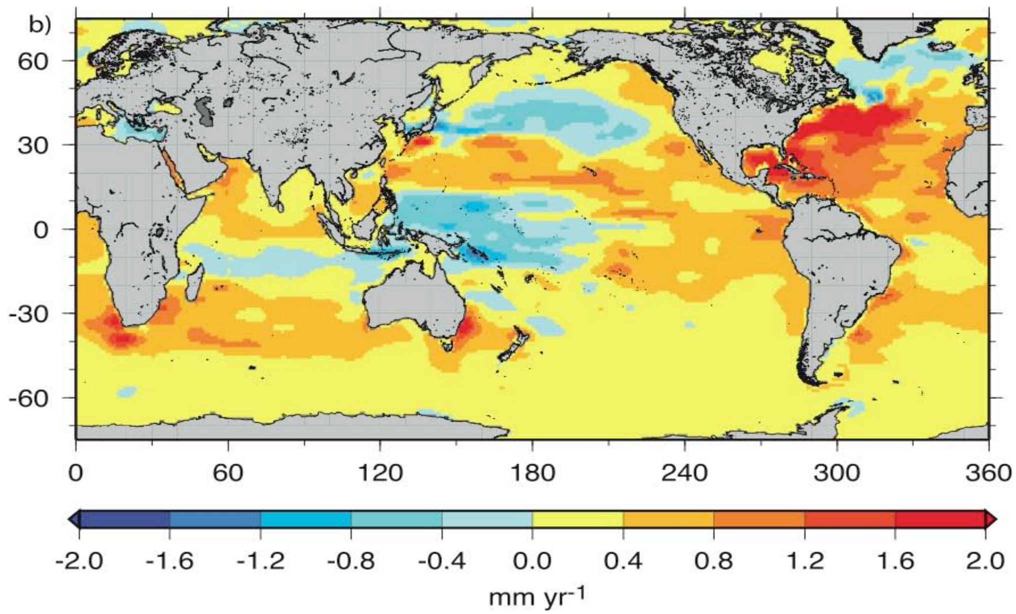
# Ocean heat content and thermal expansion change: linear trend 0-700 m for 1955-2003 (IPCC Figs. 5.2 and 5.16)




Heat content

Contour interval: 0.25 W/m$^2$

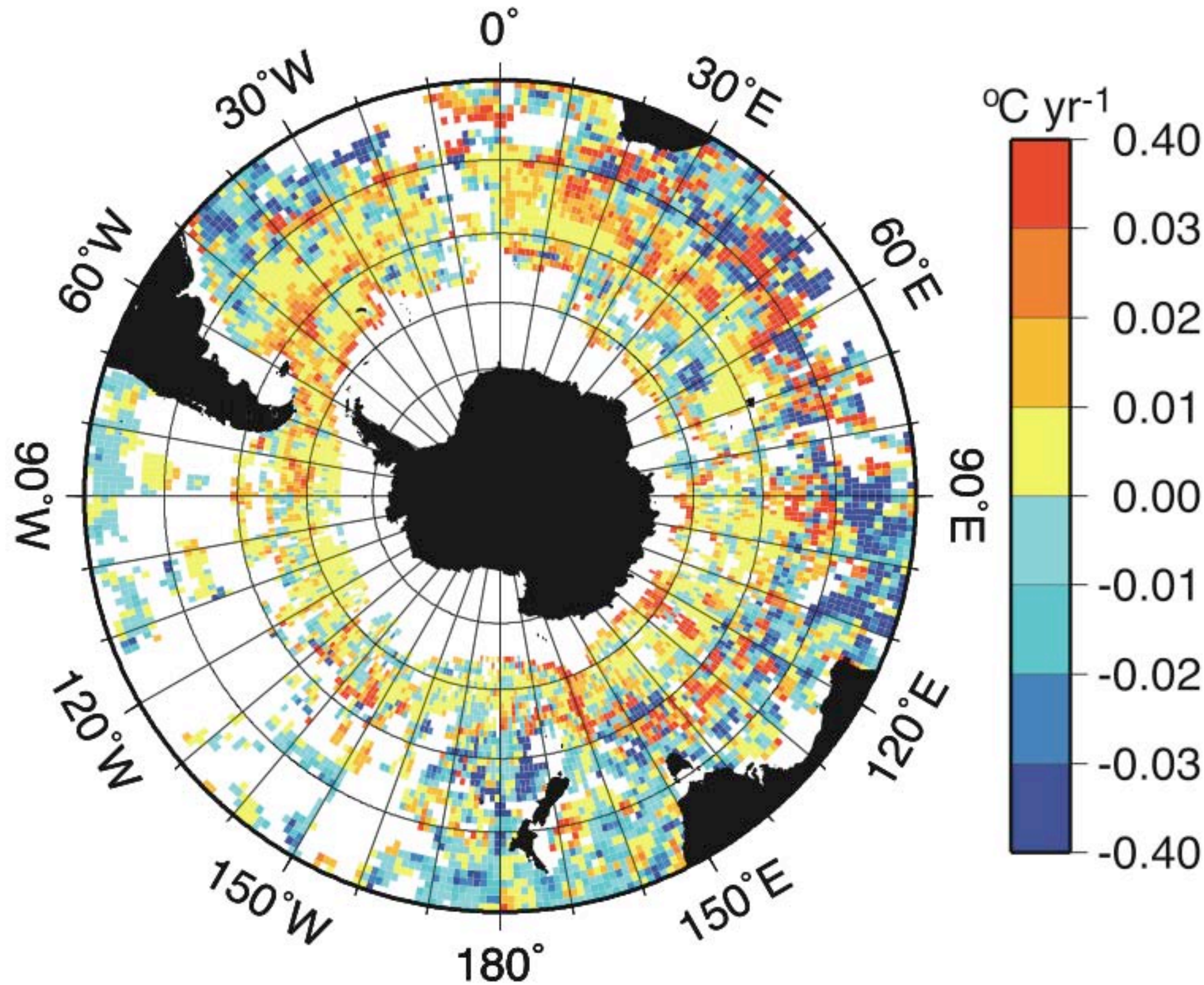
Based on Levitus et al. (2005)




Thermal expansion (sea level)

Ishii et al. (2006)

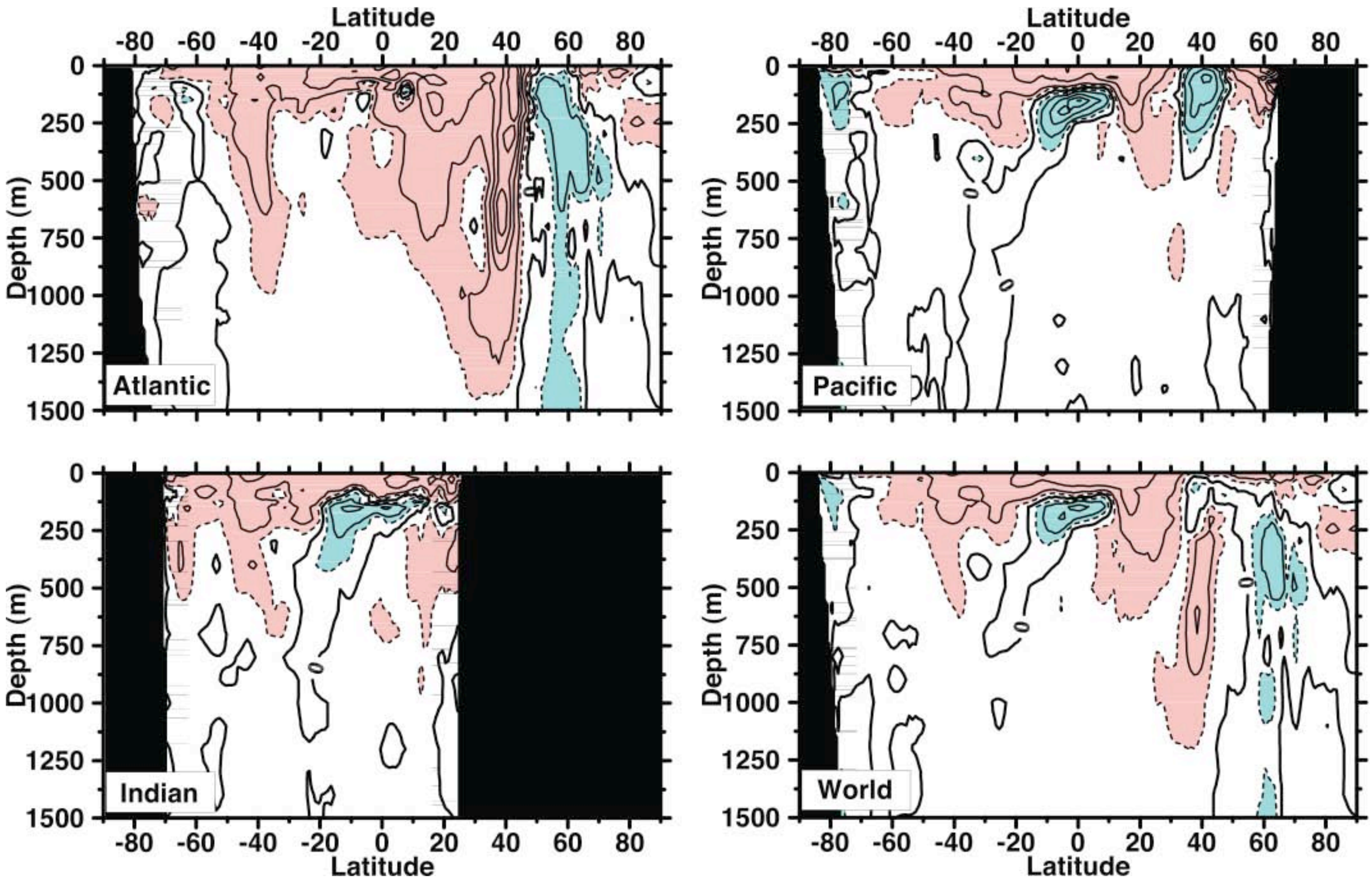
# Southern Ocean temperature trend at 900 m 1930s-2000 (IPCC Fig. 5.8)




From Gille (Science, 2002)

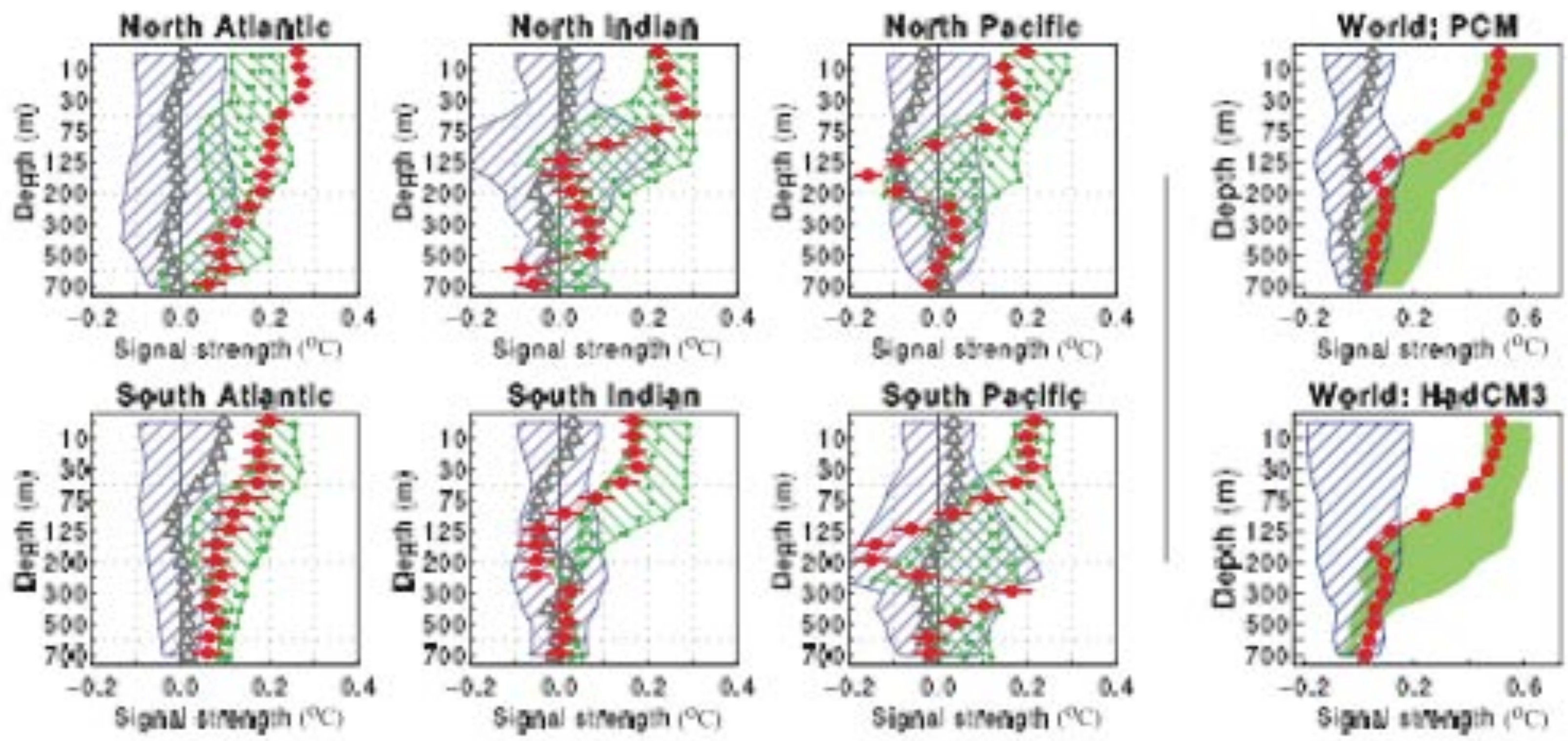
# Temperature trends (zonally-averaged) 1955-2003

**(IPCC Fig. 5.3)**




From Levitus et al. (2005)

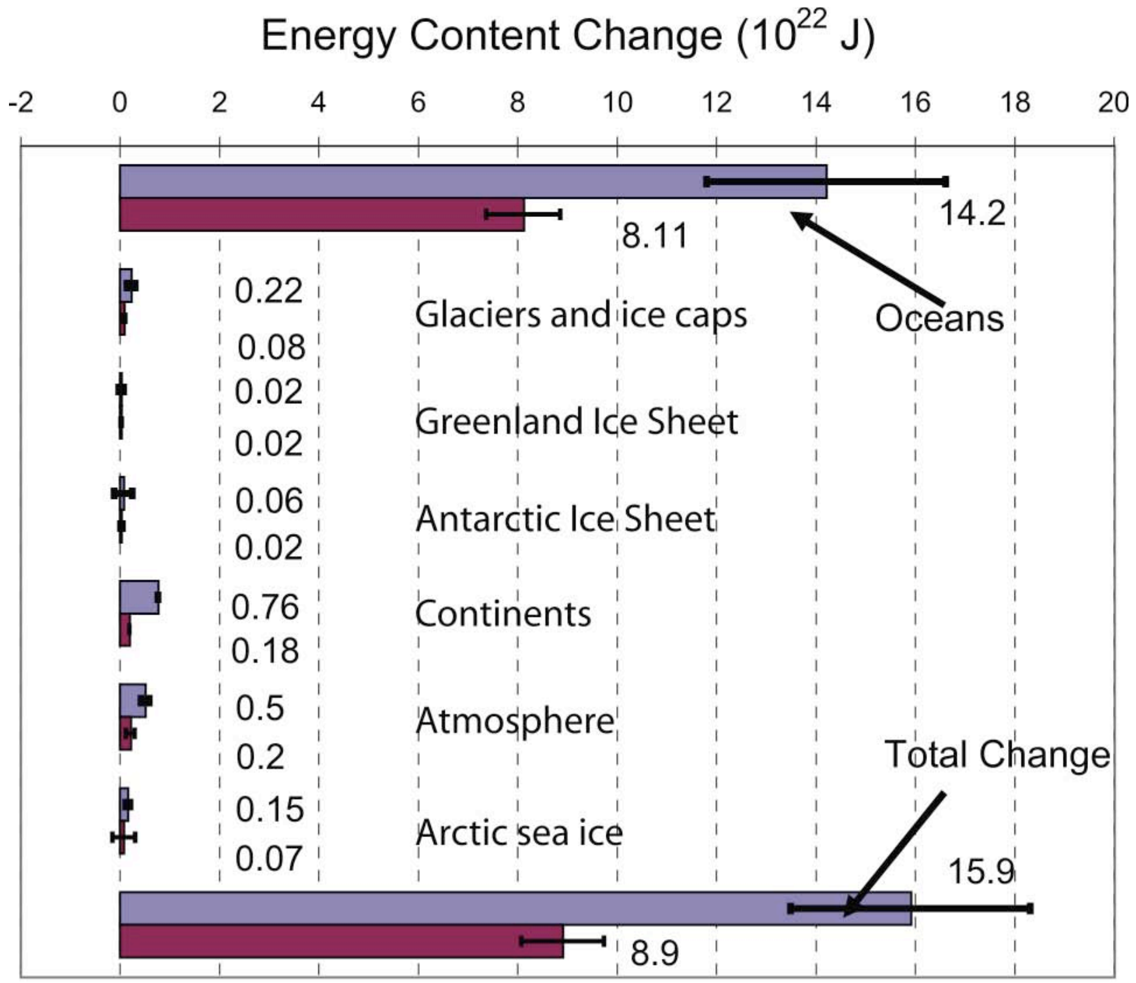
# Attribution of ocean warming (IPCC, Fig. 9.15, Ch. 9)




From Barnett et al. (2005)

- Ocean T observations projected on two ocean models. Models were run with and without anthropogenic forcing. Warming in upper ocean is outside the range predicted by natural variability,including solar/volcanic forcing and is therefore attributed to anthropogenic forcing

# Global energy content change (IPCC, Fig. 5.4)

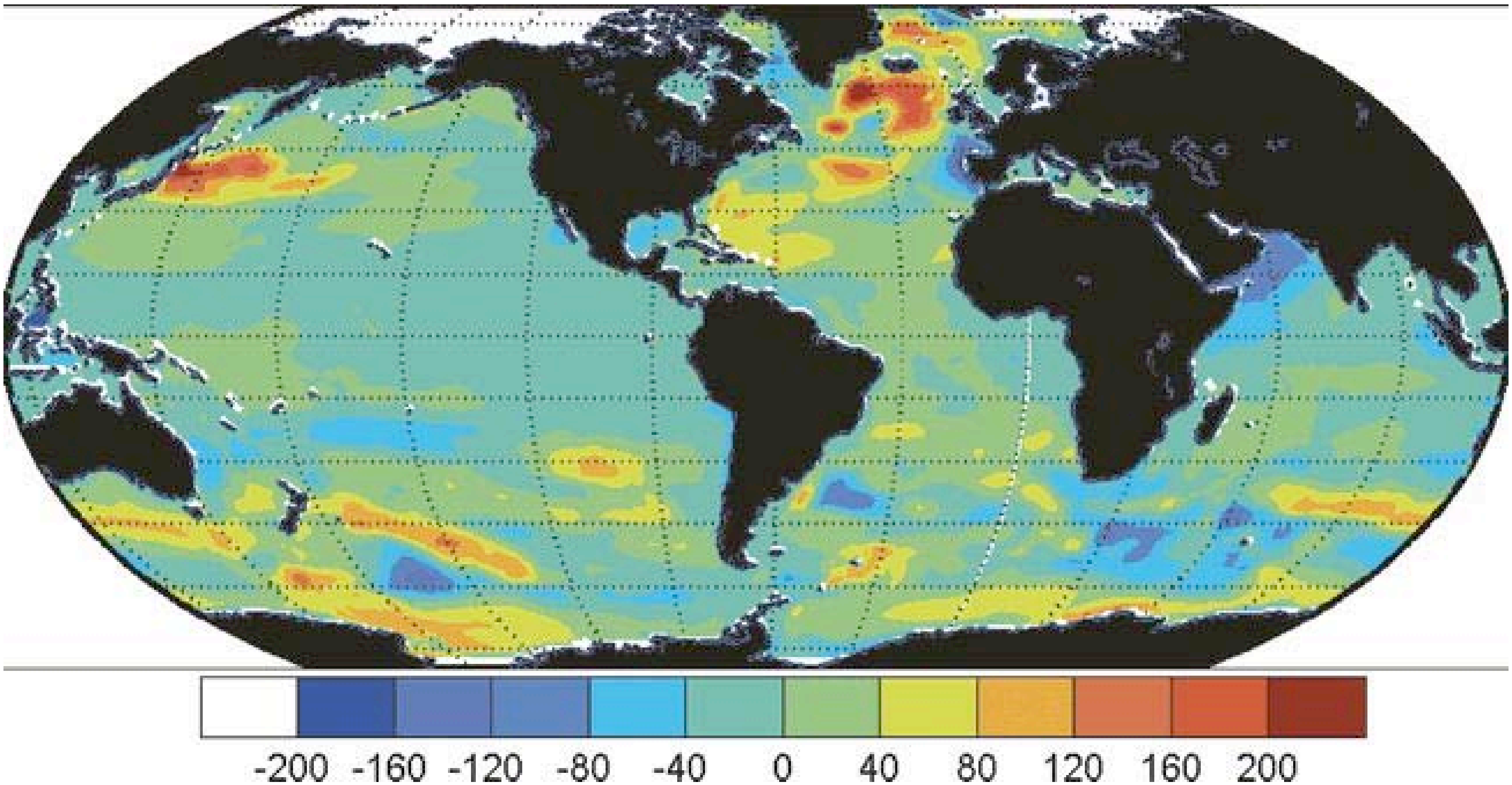



90% of the heat gained by the earth system is in the ocean.

The ocean has warmed by about 0.1°C.

If all were in the atmosphere, the air would be 100°C warmer.

# Ocean temperature trends: post-IPCC results 1993-2004 using ocean state estimation

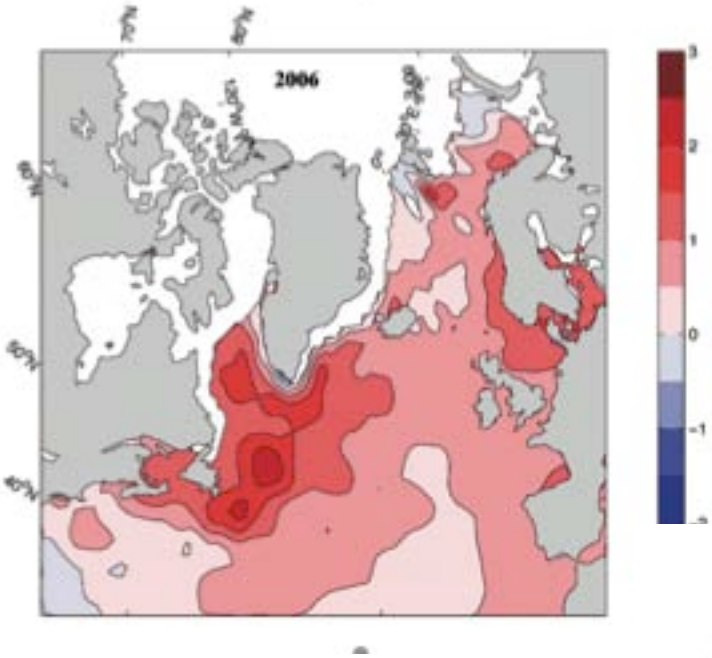



Vertically integrated trend in temperature in °C m yr–1. Wunsch et al. (J. Clim., 2007)

Some major differences from Levitus et al., but possibly mainly because of different time period

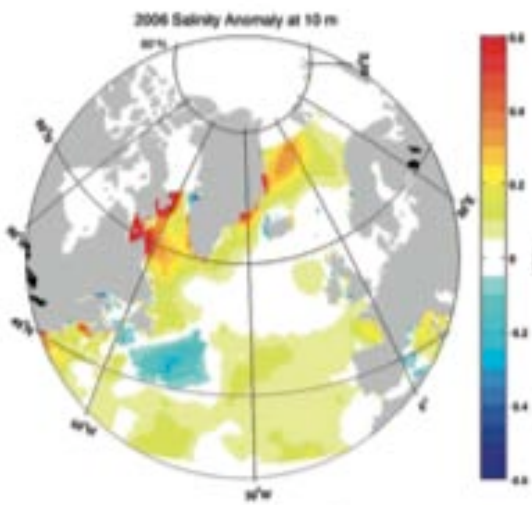
# Northern N. Atlantic results, post IPCC

## Argo observations and continuing time series to document each year

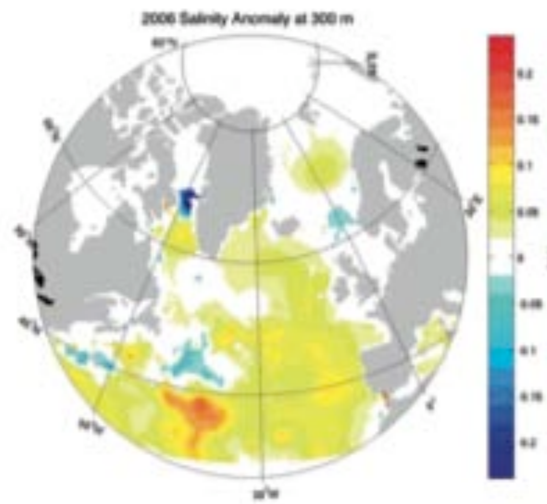



In 2006, “the upper layers of the North Atlantic and Nordic Seas were warmer and more saline than the long-term average”.

Sal. Anomaly at 10 m




Sal. Anomaly at 300 m




- Annual ICES Report on Ocean Climate: a good source of updated anomaly maps (Hughes and Holliday (eds.), 2007) http://www.ices.dk/marineworld/oceanclimate.asp

# Relation of temperature and heat content changes to climate change

Global nature of warming, enhancement in the upper several hundred meters, and some of the spatial patterns of warming/cooling*

Indicate absorption of excess energy by the oceans, consistent with climate change.

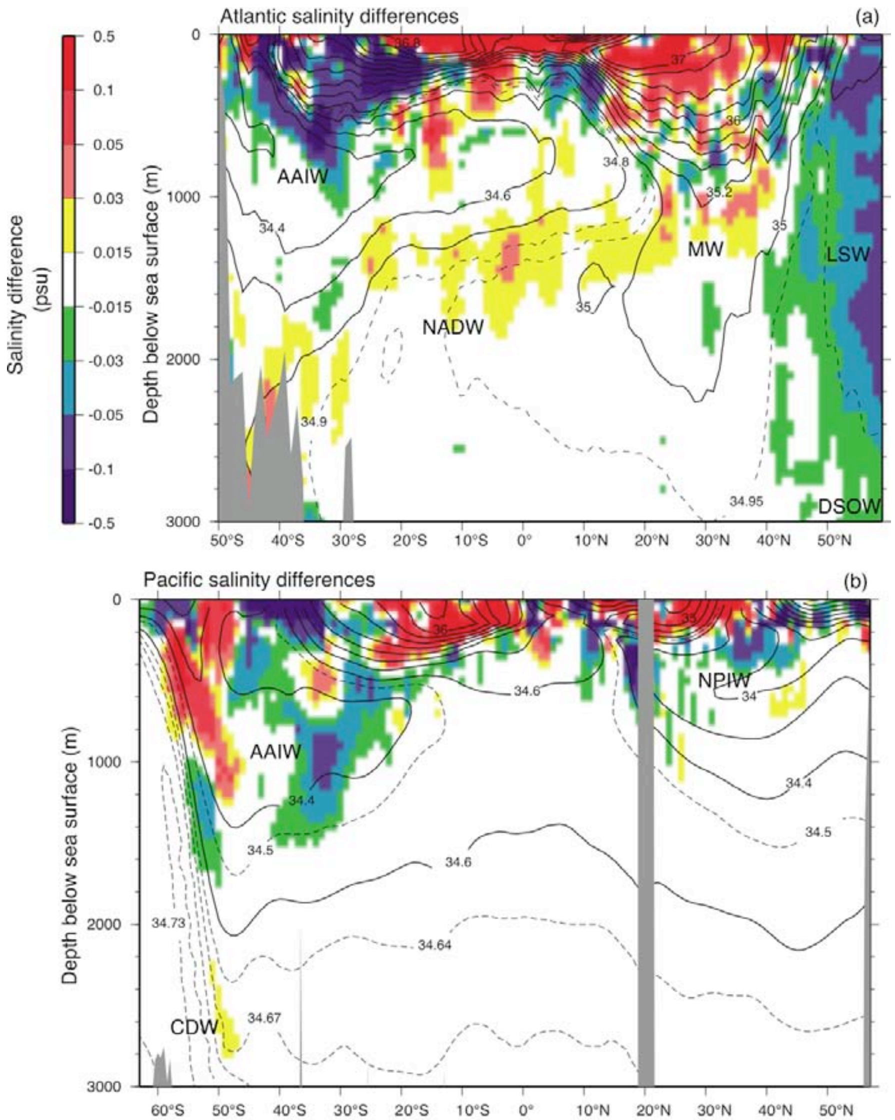
(rather too obvious)

*Tropical Pacific pattern suggests extended/enhanced El Nino state, which is a prediction for climate change.

# Salinity changes

“Changes in precipitation and evaporation over the oceans are suggested by freshening of mid and high latitude waters together with increased salinity in low latitude waters.” (IPCC Summary for Policy Makers)

# Salinity changes in Atlantic and Pacific (IPCC Fig. 5.6)




Atlantic

1985-1999 minus 1955-1969

Based on Curry et al.(2003)

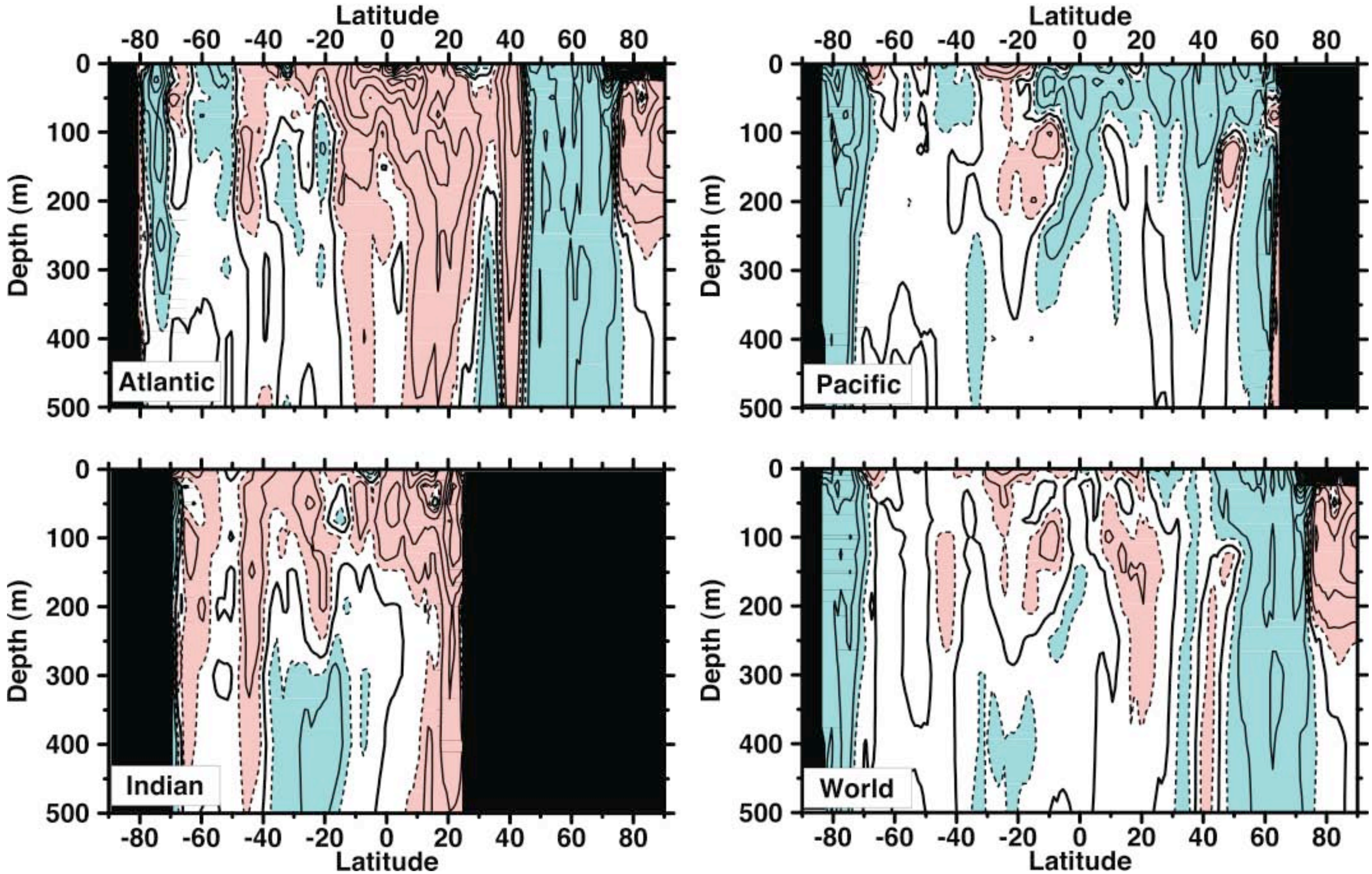
Pacific

1991-1992 minus ~1968

Based on Wong et al.(2003)

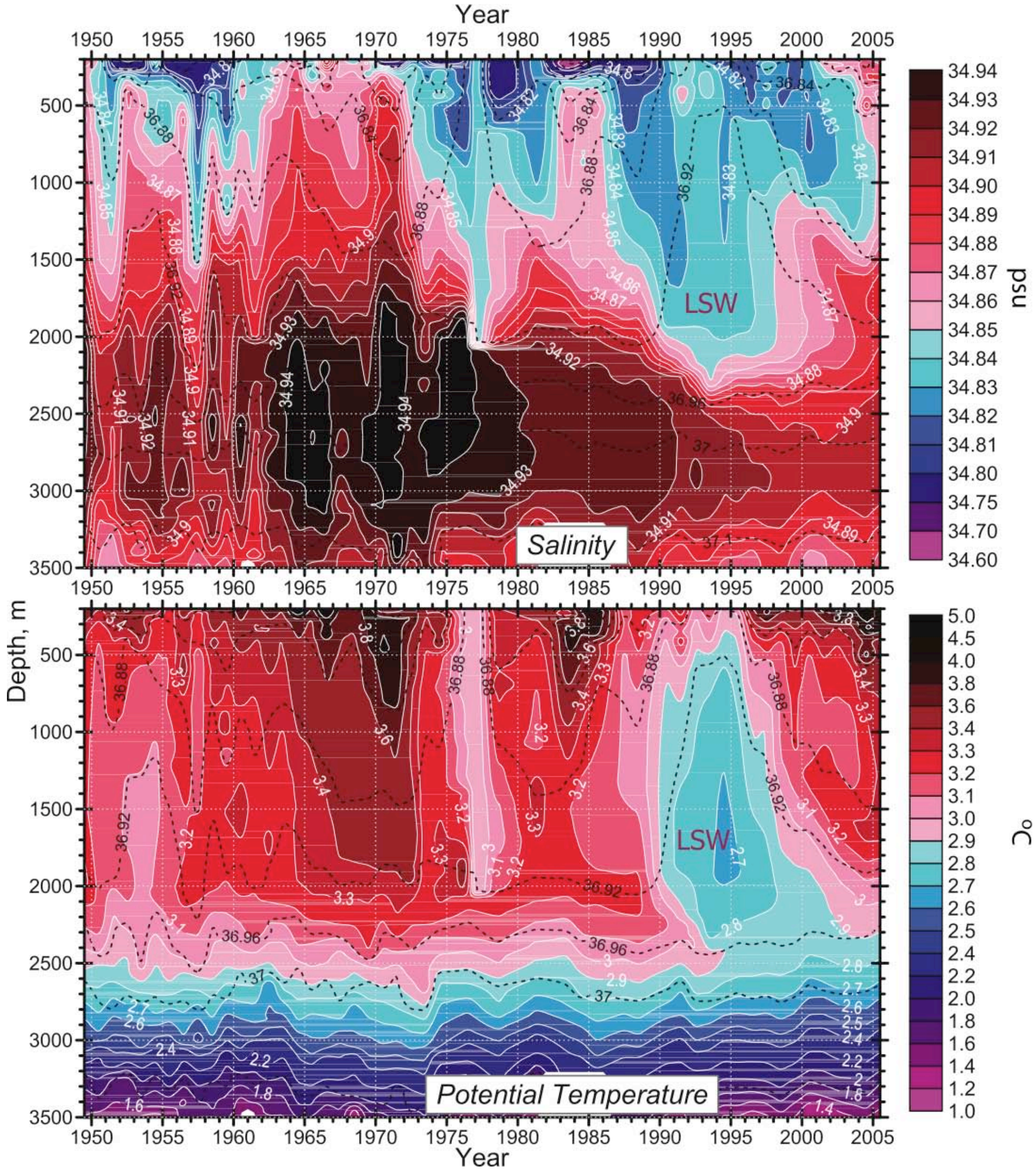
Higher salinity in surface subtropics (where salty), lower salinity at higher latitudes (where fresh), more or less.

# Salinity changes by ocean (IPCC Fig. 5.5)




Linear trend 1955-1998, zonally-averaged salinity.
Based on Boyer et al. (2005)

# Salinity change in the Labrador Sea (IPCC Fig. 5.7)




Updated from Yashayaev et al. (2003)

Decadal time scale is clear

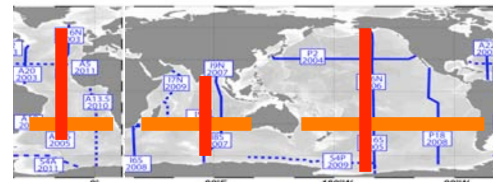
Longer term trend towards freshening (but this has reversed now).

Temperature change: showing the penetration of surface conditions through the Labrador Sea Water, 0-2000 m depth.

Closer study shows impact of salinity stratification on temperature structure

# Salinity change at 30°: results from repeat hydrography minus WOCE (post-IPCC product)

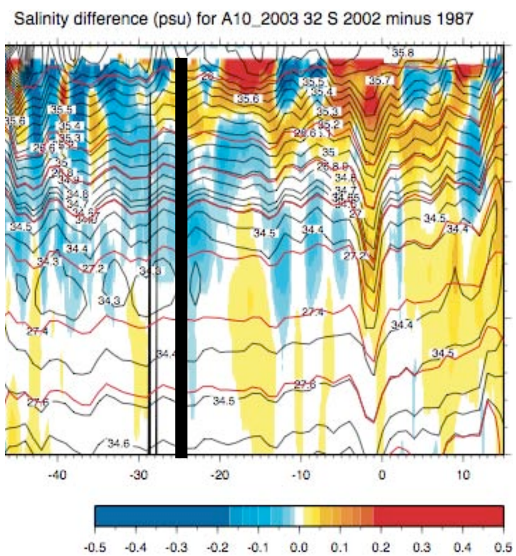
Freshening Pacific and salinifying Indian and eastern Atlantic

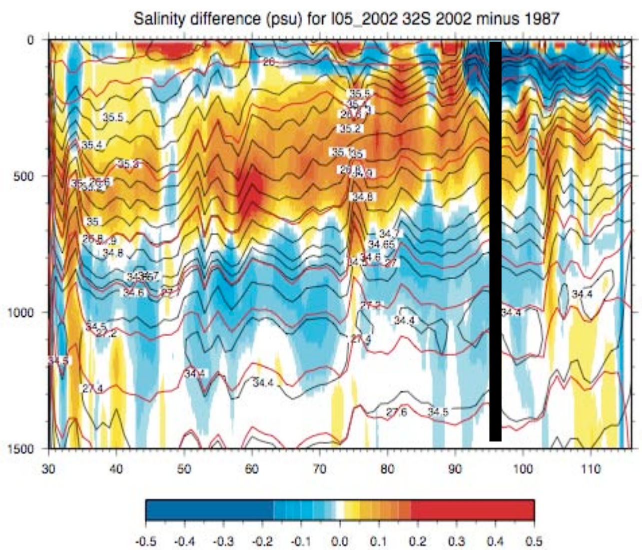


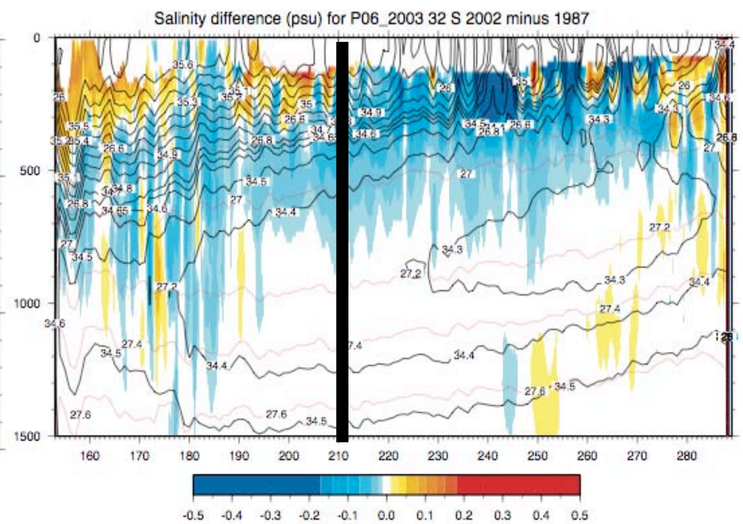
Atlantic 2003 minus 1992

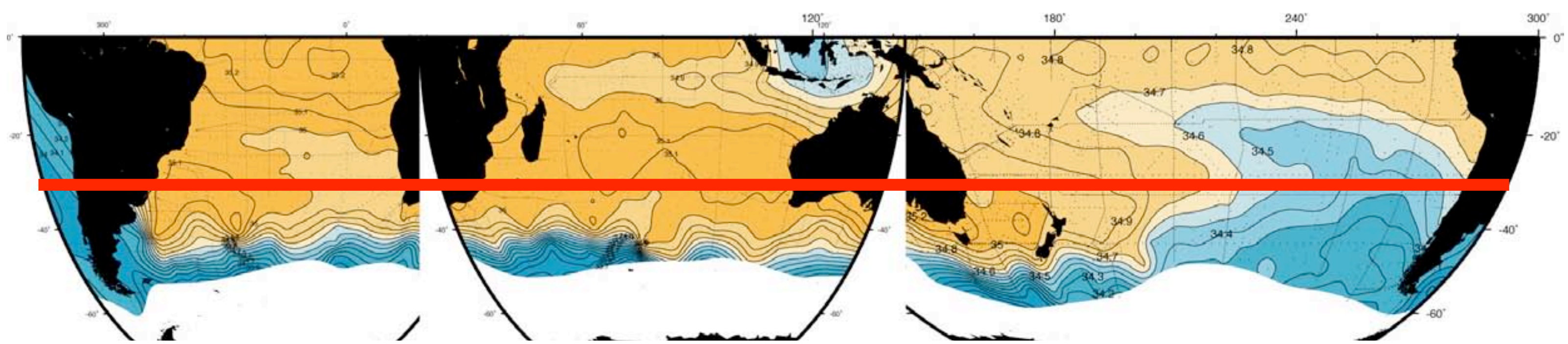
Indian: 2002 minus 1987

Pacific: 2003 minus 1991



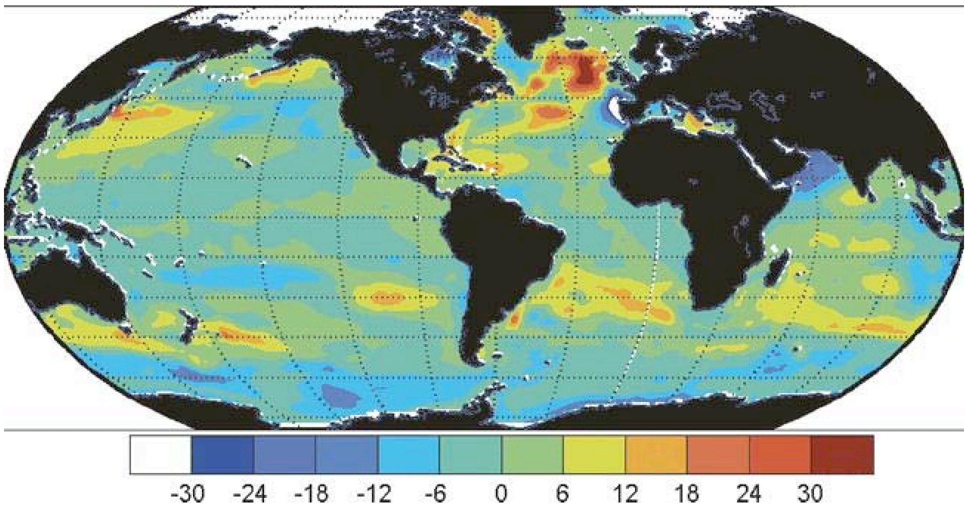



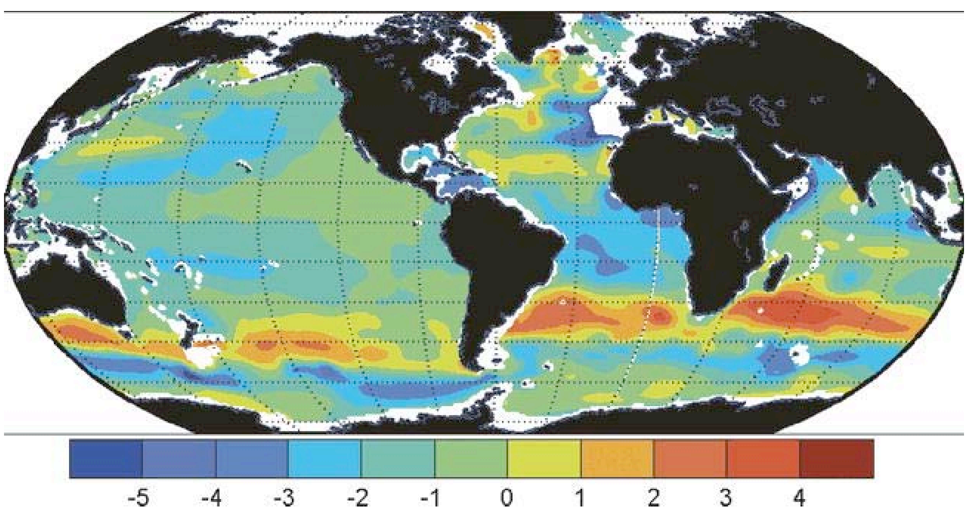
# Salinity changes by state estimation (post-IPCC)

Wunsch et al. (2007)




Trends in vertically integrated salinities (m yr─1)

Years 1993-2004 both plots




Trends in salinity at 985-1750 m depth.

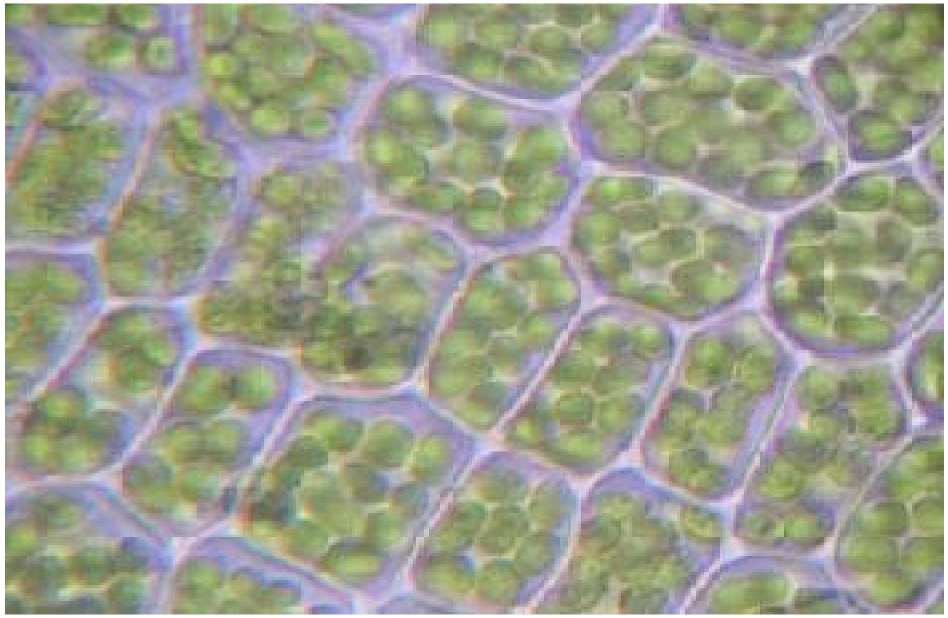
# Relation of salinity changes to climate change

Simplistically, at the largest scales, fresh regions becoming fresher and salty regions becoming saltier. (Caveat - N. Atlantic now becoming saltier.)

This suggests enhanced precipitation and evaporation but with spatial patterns that are not too different from the mean. (Necessary to really look carefully at how the salinity changes project on E-P though.)

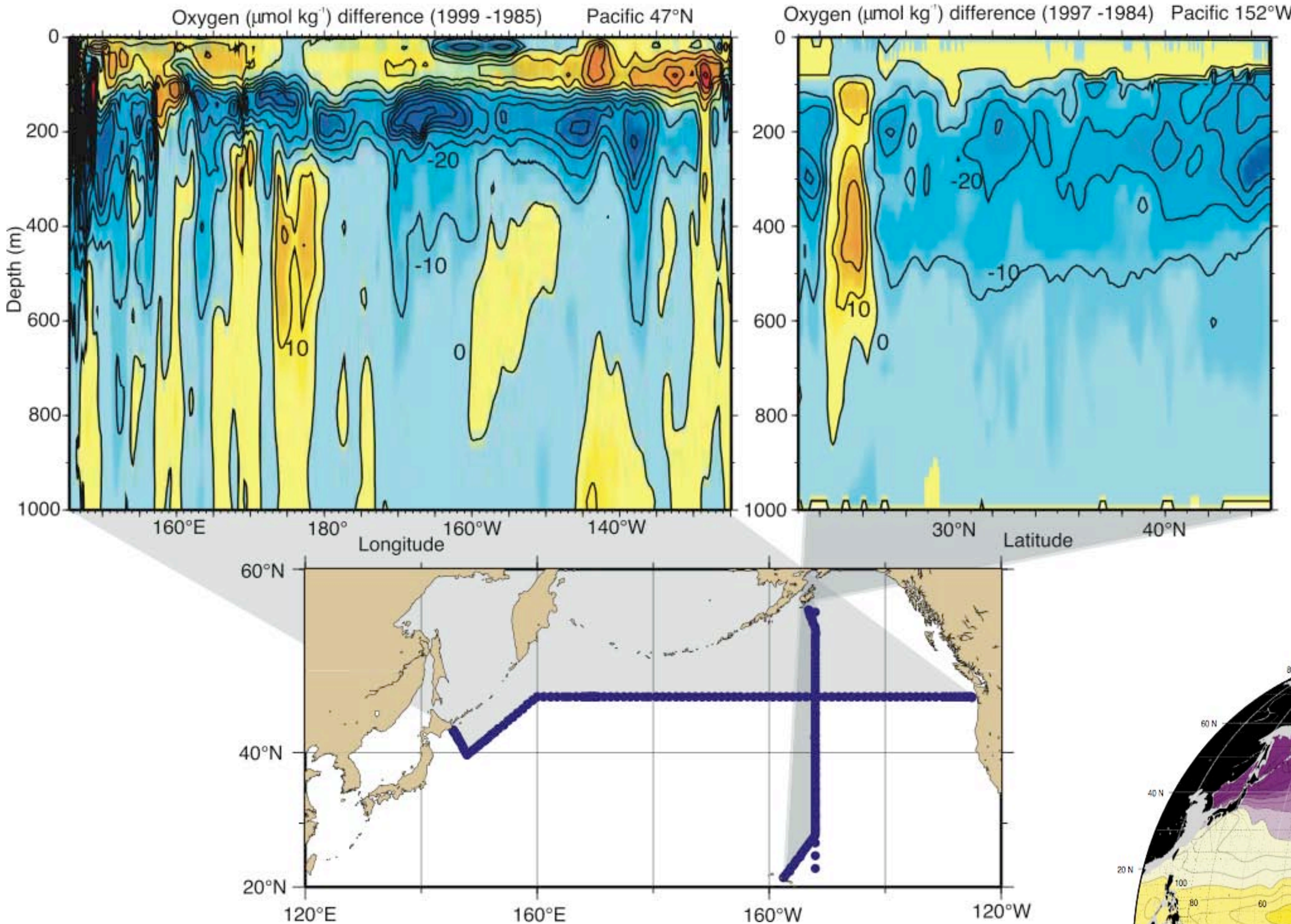
This suggests an enhanced hydrological cycle in the atmosphere which is consistent with a warmer atmosphere, hence with climate change.

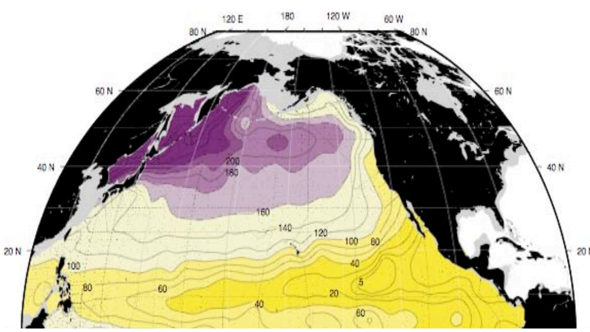
# Oxygen changes



"There is evidence for decreased oxygen concentrations, likely driven by reduced rates of water renewal, in the thermocline in most ocean basins from the early 1970s to the late 1990s." (IPCC Ch. 5 executive summary)

# Oxygen decrease in N. Pacific pycnocline (thermocline) (IPCC Fig. 5.12)

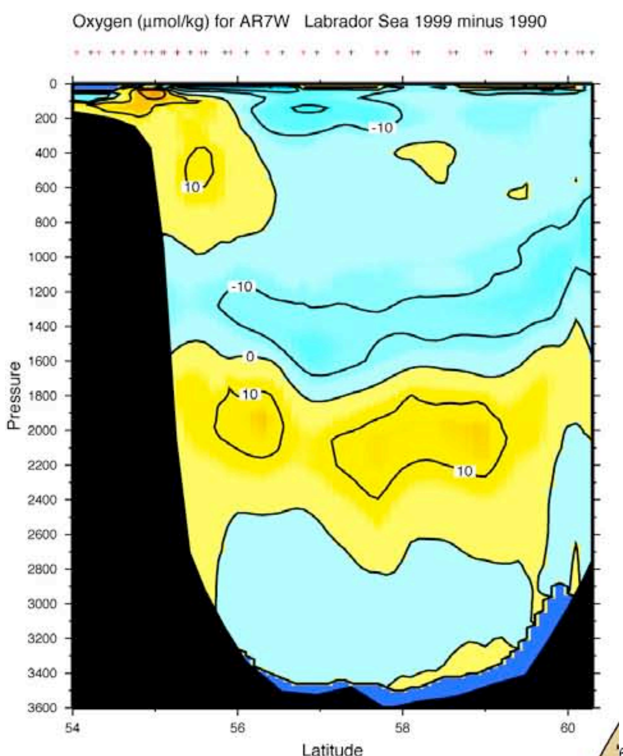


Attributed mainly to physical factors (circulation, stratification), not biological. Based on Deutsch et al. (2005)

# Oxgyen decrease in N. Atlantic upper layers and Labrador Sea Water, increase in NADW (IPCC and other data)

1999 minus 1990

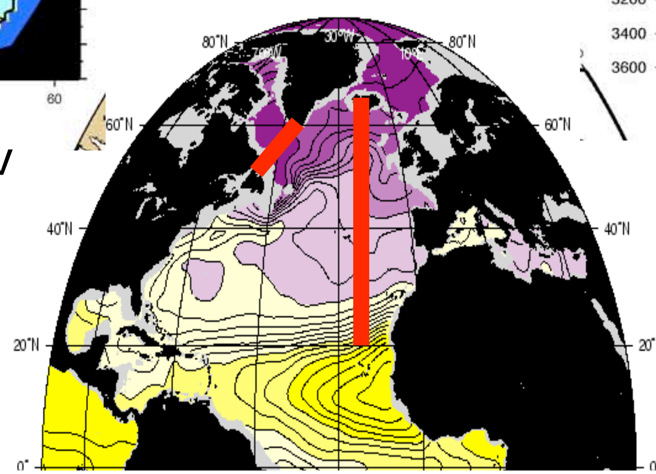



Data from I. Yashayaev

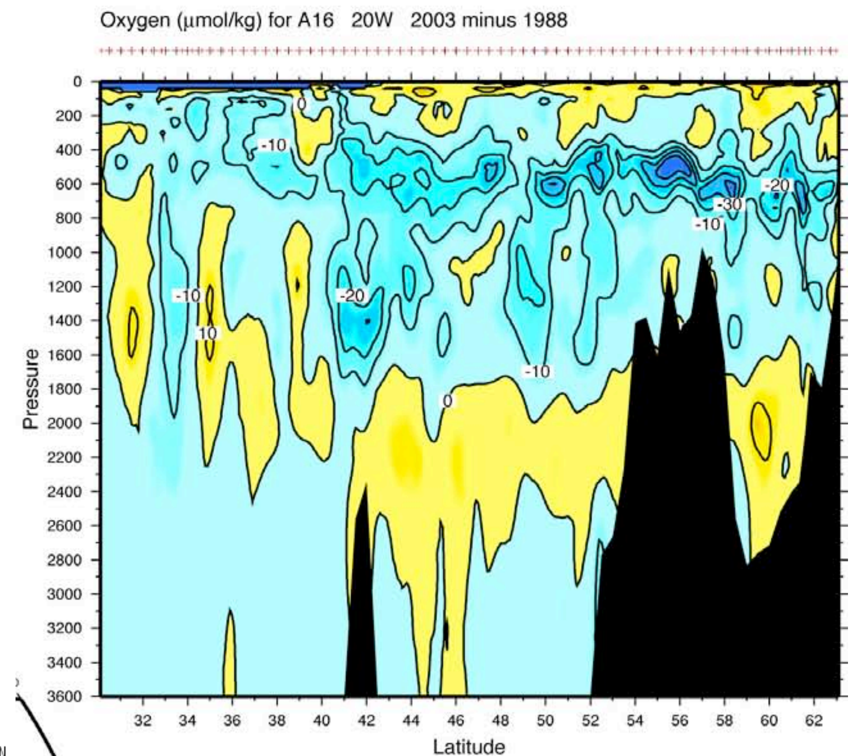
SPMW layer

LSW/NADW

NADW



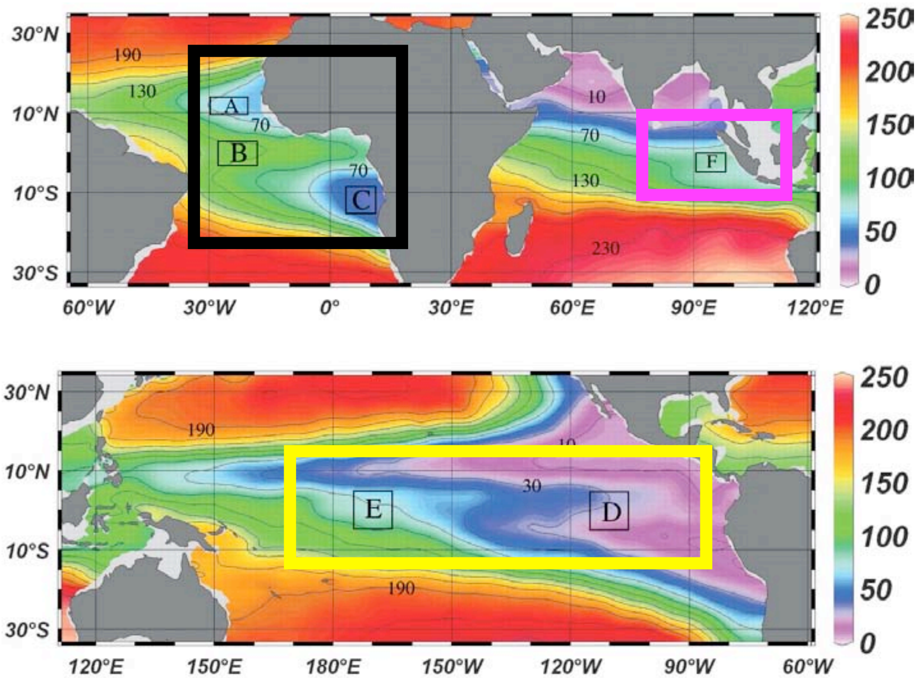

2003 minus 1988



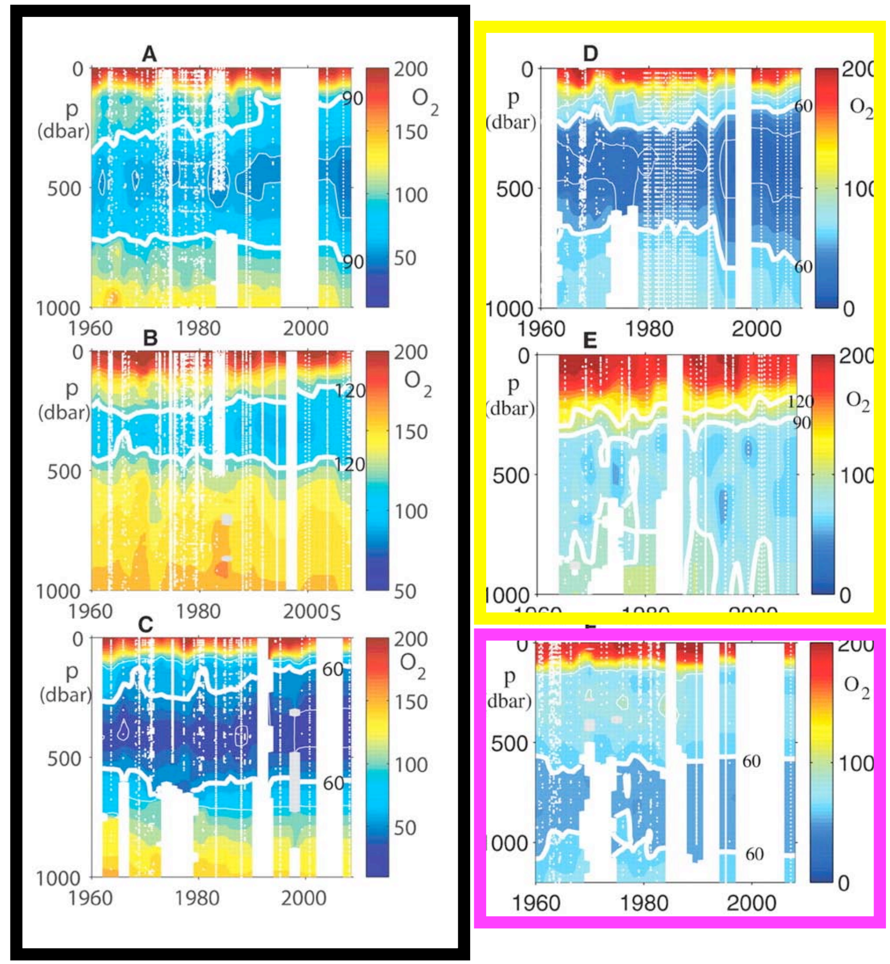

Attributed mainly to physical factors, not biological

Johnson and Gruber, 2005

# Oxgyen decrease in tropical oxygen minimum zones: post IPCC (Stramma et al., 2008)




Time series 1960-present




Oxygen minimum zones expanding, oxygen content decreasing if possible.

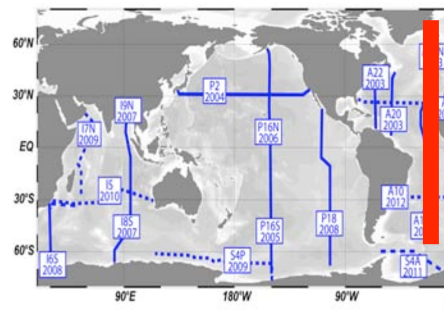
Consistent with climate change response (Bopp et al., 2002).

# Oxygen differences from repeat hydrography

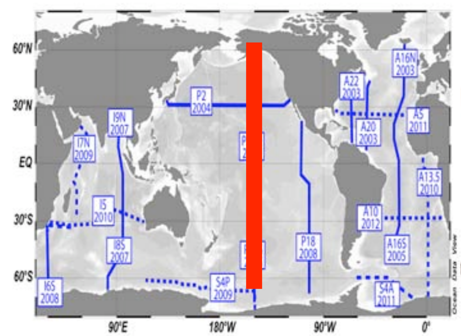
All previously-noted features in purple.

Increase in southern hemisphere subtropics

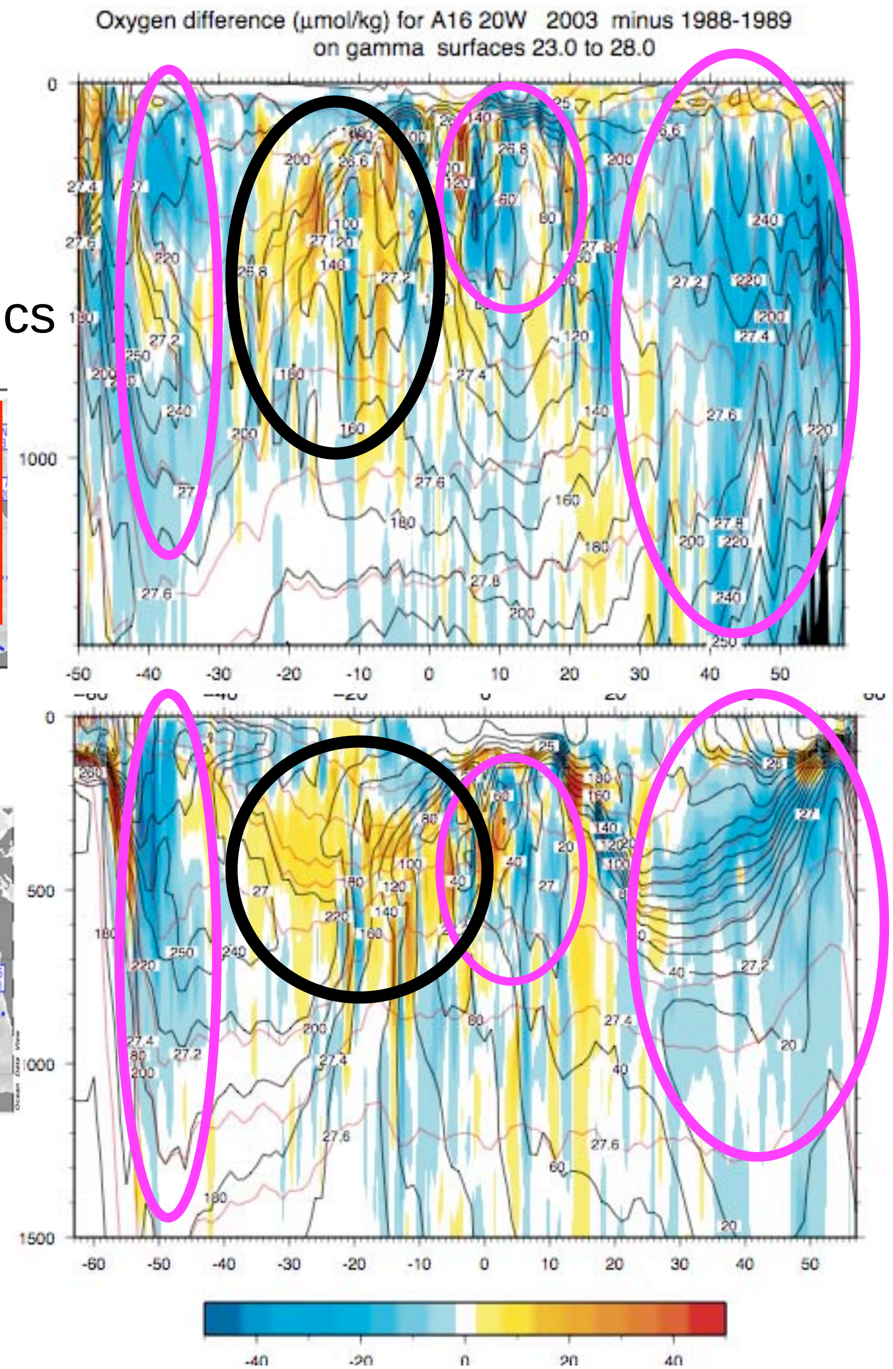
**Atlantic 20°W**
**2004 minus 1991**



**Pacific 150°W**
**2006 minus 1991**



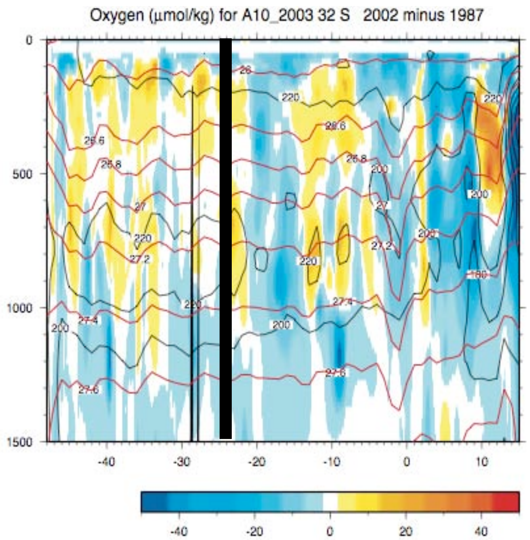
**Indian 90°E 2007 minus 1995 - similar result (McDonagh et al., 2005)**



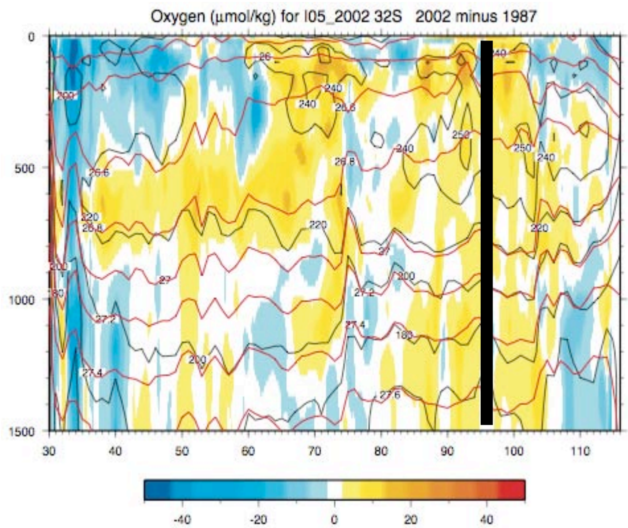
# Oxygen increase across subtropics at 30°S

Indian Ocean increase attributed to strengthened wind forcing -> strengthened circulation -> strengthened ventilation (McDonagh et al., 2005)

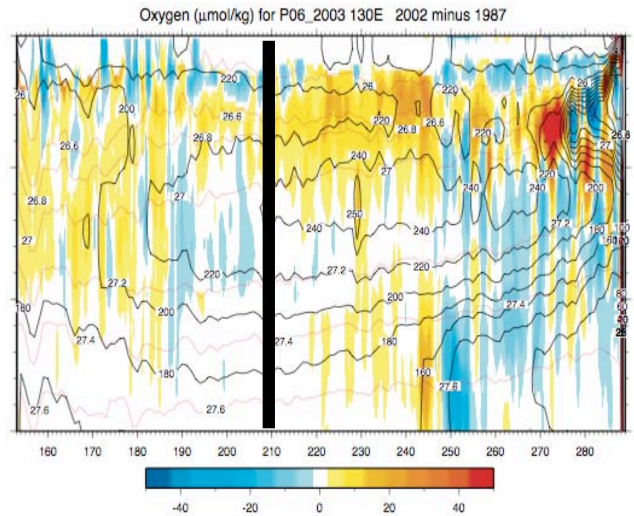
Atlantic 2003 minus 1992

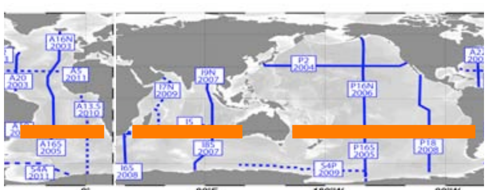


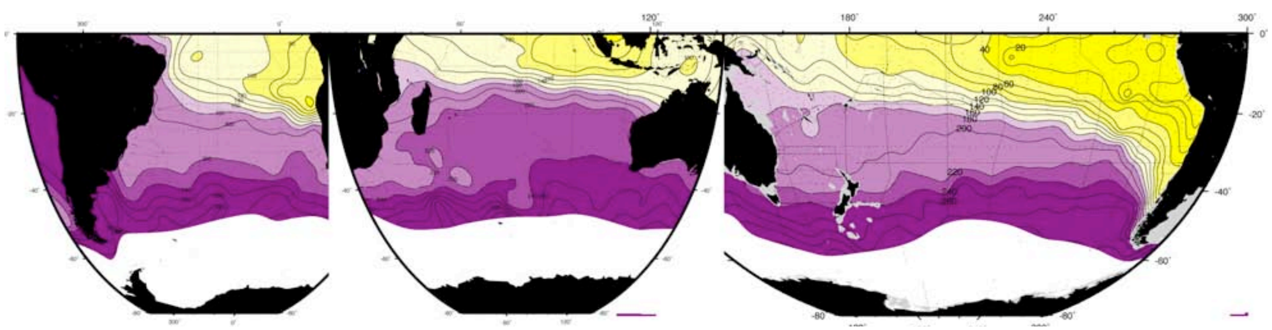

Indian: 2002 minus 1987




Pacific: 2003 minus 1991





# Relation of oxygen changes to climate change

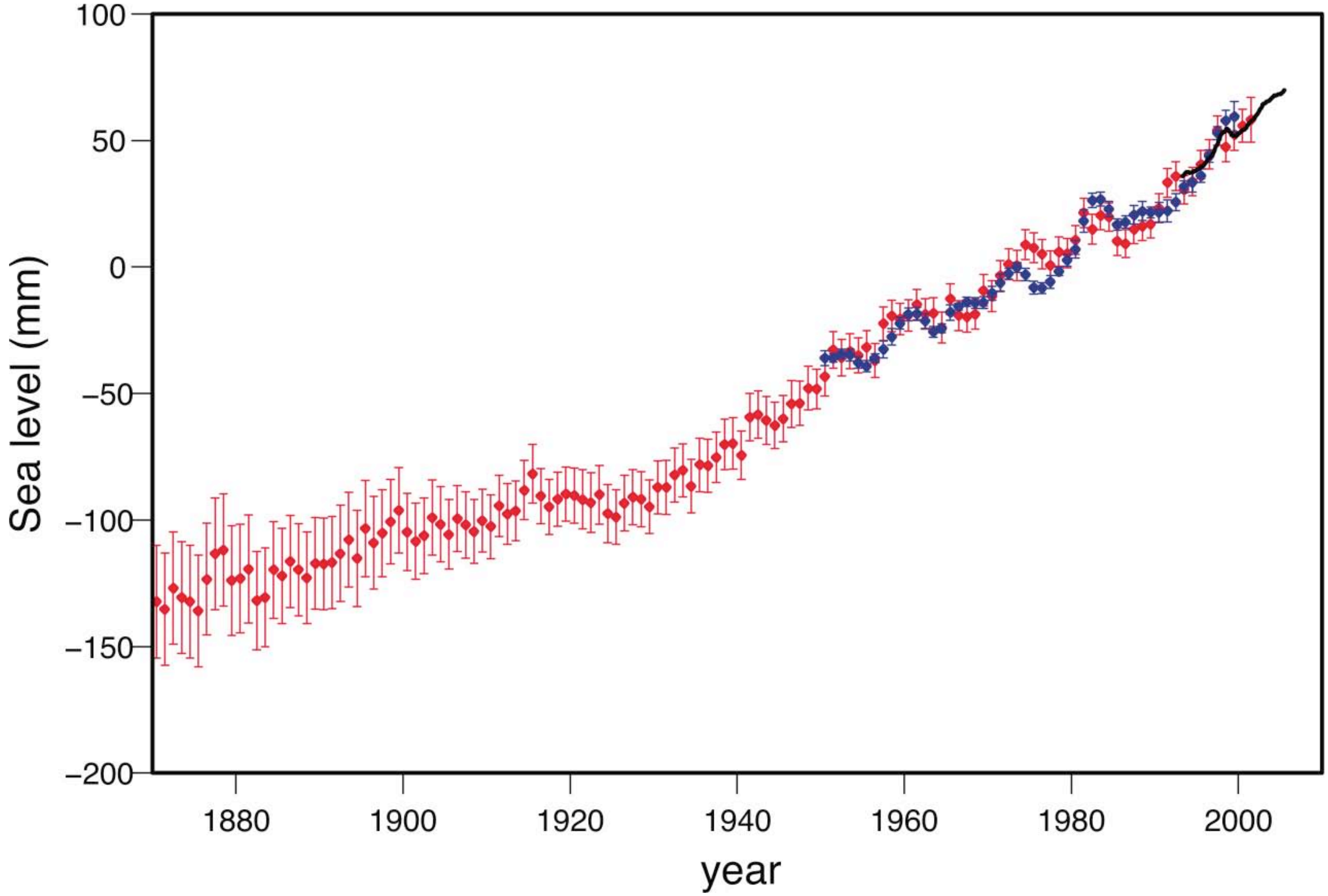
Changes in ventilation caused by changes in both stratification and wind forcing are creating changes in the oxygen content and distribution.

These changes in stratification (warming, salinity stratification changes) and winds (shifts in location and strength of westerlies) may be related to climate change.

# Sea level changes

“Global average sea level rose at an average rate of 1.8 (1.3 to 2.3) mm per year over 1961 to 2003. The rate was faster over 1993 to 2003…Whether the faster rate … reflects decadal variability or an increases in the longer-term trend is unclear.” (IPCC SPM)

# Global mean sea level (mm) (IPCC Fig. 5.13)



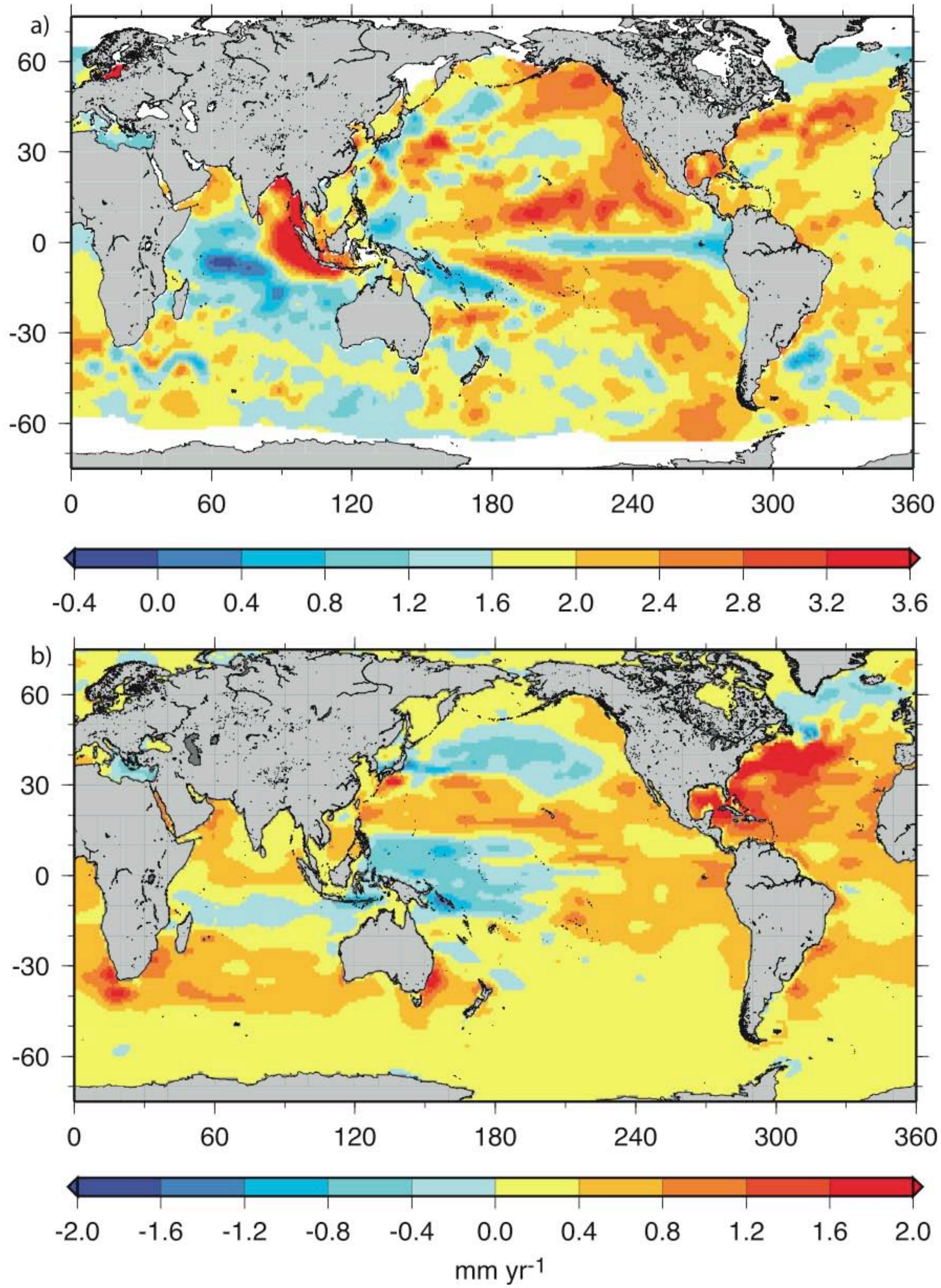

Based on Church and White (2006) (red), Holgate and Woodworth (2004) (blue), Leuliette et al. (2004) (black)

# Mean sea level: linear trend 1955-2003

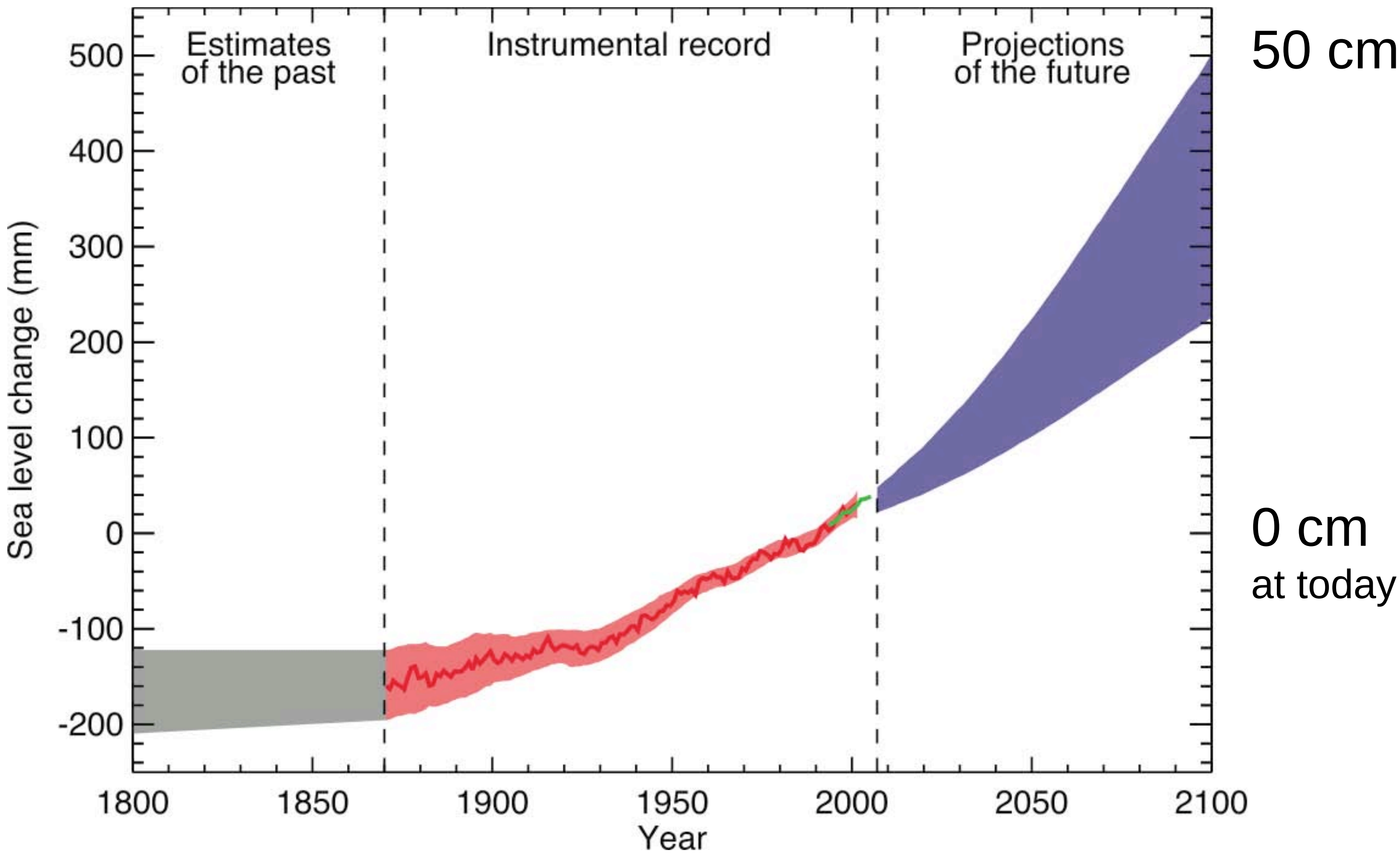
**(IPCC Fig. 5.16)**

Overall, based on tide gauges and altimetry (Church et al., 2004)

Portion due to thermal expansion (Ishii et al., 2006)



# Sea level change: a frequently asked question - how fast and how high? (IPCC FAQ 5.1, Fig. 1)




Post-IPCC concern: faster-melting ice caps not figured in

# Relation of sea level change to climate change

Monotonic long-term rise in sea level

Relation of a good portion of the sea level rise to heat content increase

Relation of another portion of sea level rise to land ice melt

Heat content increase and land ice melt are linked to climate change.

# Circulation changes


“There is insufficient evidence to determine whether trends exist in the meridional overturning circulation of the global ocean….”

“… very likely that the meridional overturning circulation of the Atlantic Ocean will slow down during the 21st century. … Temperatures in the Atlantic region are projected to increase despite such changes due to the much larger warming associated with projected increases of greenhouse gases. It is very unlikely that the MOC will undergo a large abrupt transition during the 21st century. Longer-term changes in the MOC cannot be assessed with confidence.” (IPCC Summary for Policy Makers)

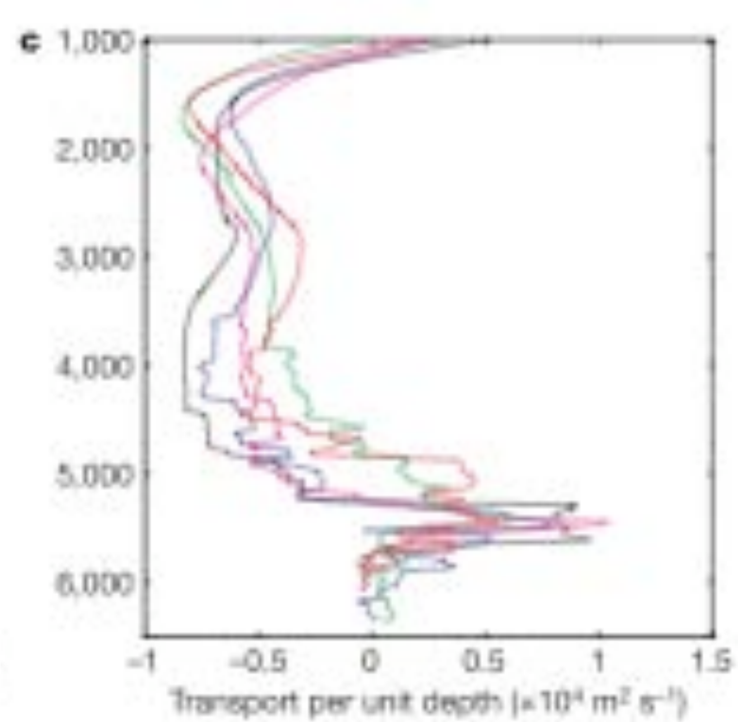
# North Atlantic meridional overturning changes

Great interest because of potential impact on surface temperature anomalies in the North Atlantic which can affect winds/air temperature, especially in Europe


Quadfasel, 2005

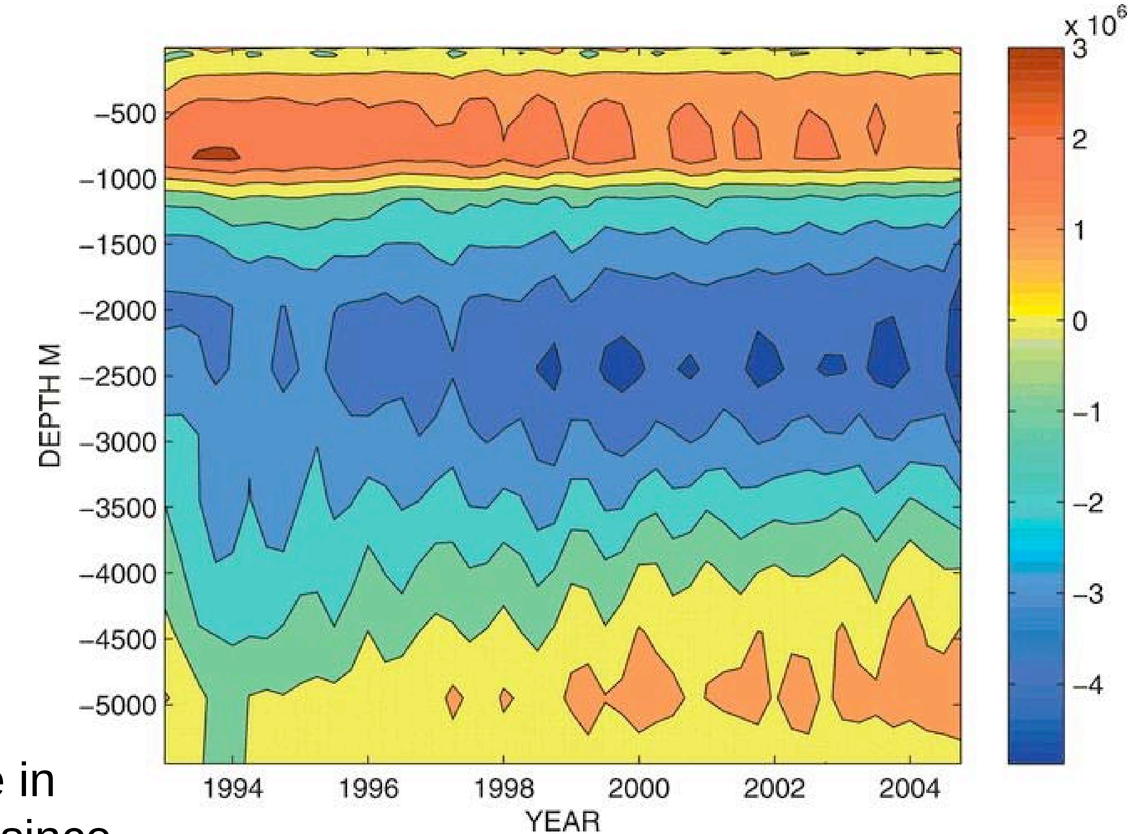
- IPCC AR4 Ch. 5 reviewed a large number of papers on observed changes in the Atlantic MOC.
- Changes are observed, documented and published, but the natural (mainly decadal) variability is large and sampling is aliased so attributing changes in the MOC strength to anthropogenic forcing is problematic.

# N. Atlantic overturning transport anomalies: active pre and post-IPCC discussion focused at 26°N




Bryden et al. (2005): large decrease in upper ocean component of overturn since 1957

Cunningham et al. & Bryden (2007): shorter timescale variability can alias the 2005 result, requiring long, continuous time series

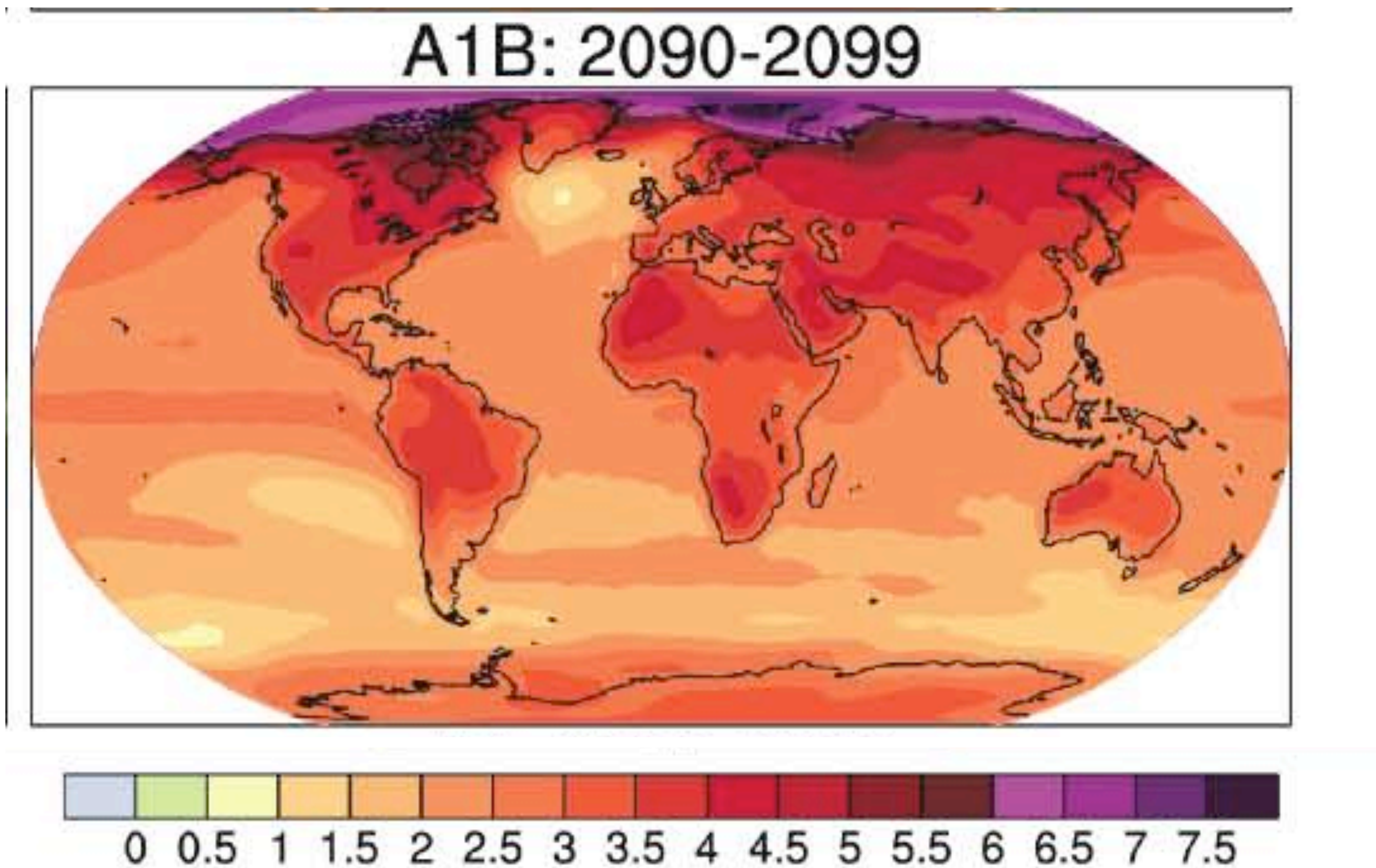



Wunsch and Heimbach (2006) state estimation indicates weak decrease over 15 years in state estimation, with analysis including higher frequencies

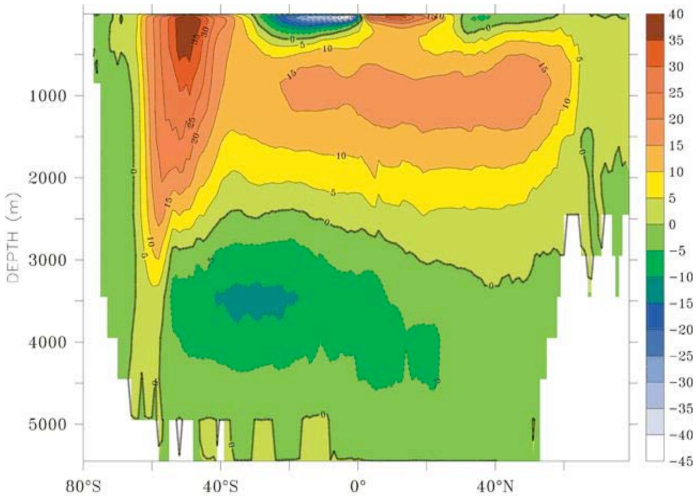
## e.g. look again at IPCC SST projection

"Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean."

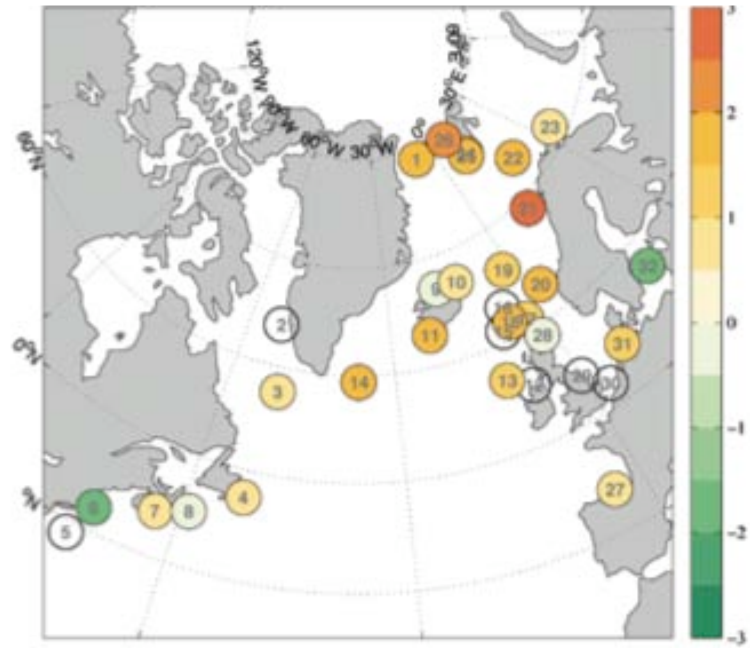
Neutral SST in N. Atlantic is due to weakening of the MOC. No IPCC models predict a shutdown however. (But none include fast Greenland melting…)



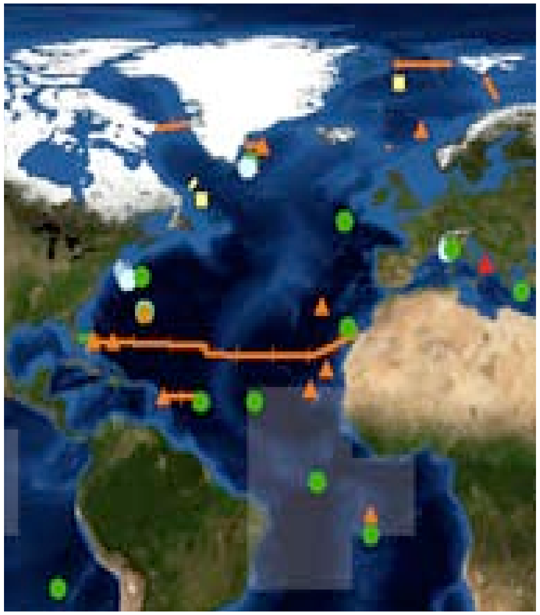
# Post-IPCC activities on monitoring N. Atlantic MOC: far too much to summarize properly here

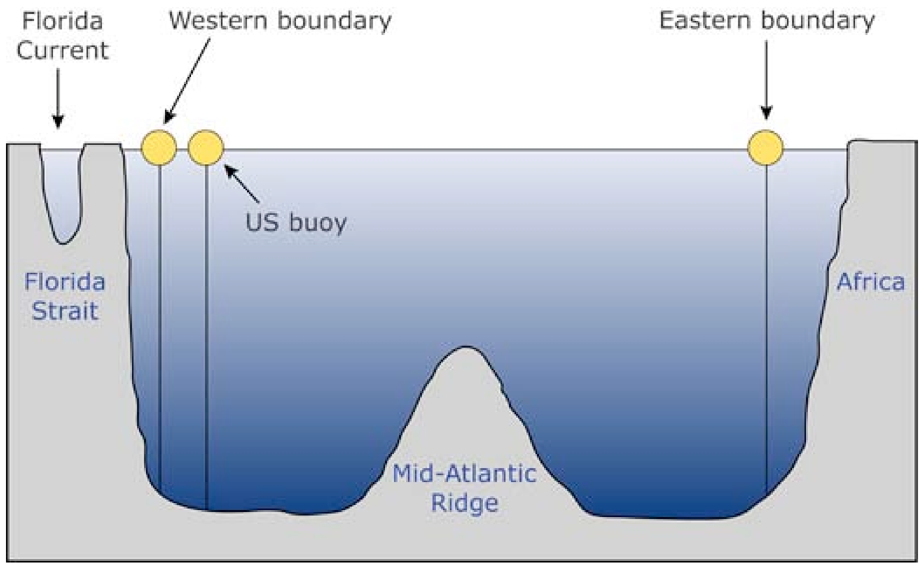



State estimation can begin to reproduce the MOC, e.g. Köhl et al. (2007)



Ongoing time series are crucial - all instruments, satellites, etc



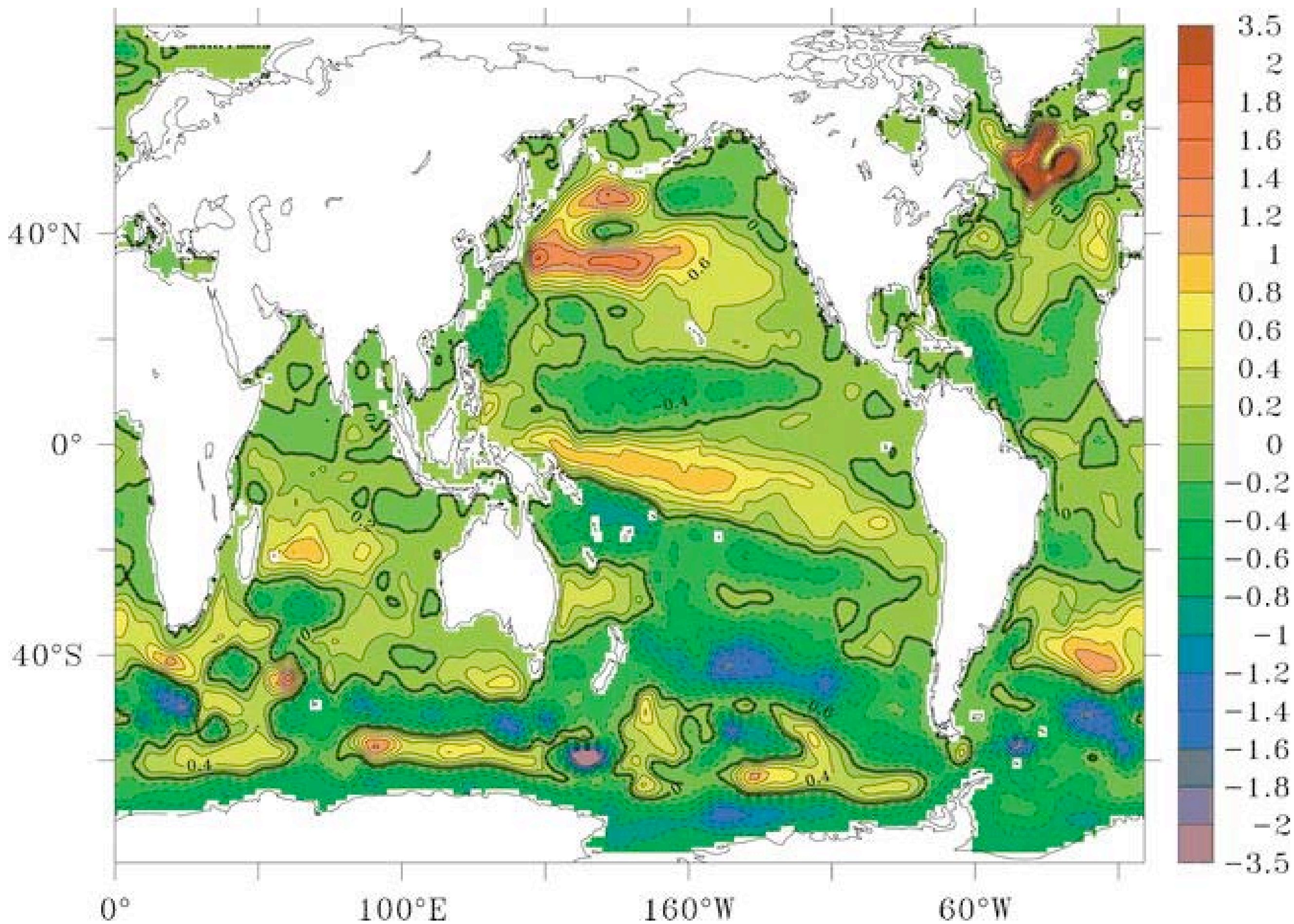



RAPID exp't at 26N

# Changes in circulation: post IPCC analysis

Change in barotropic streamfunction (linear trend) 1992-2003, using state estimation. Changes are associated with changing winds. Attribution not possible because 11 years is not long enough.  Results suggest the promise of much longer estimates. **(Köhl et al., 2007)**

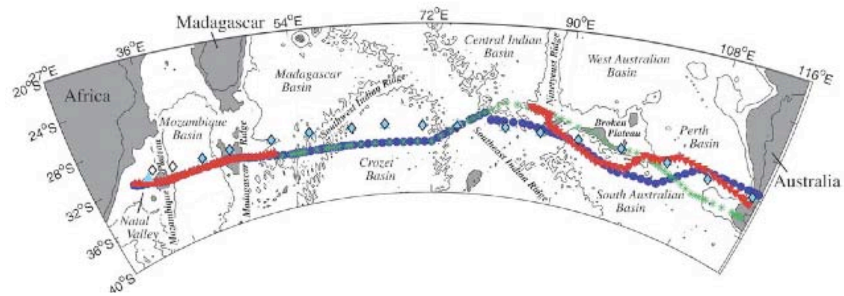
Stronger
ST gyre



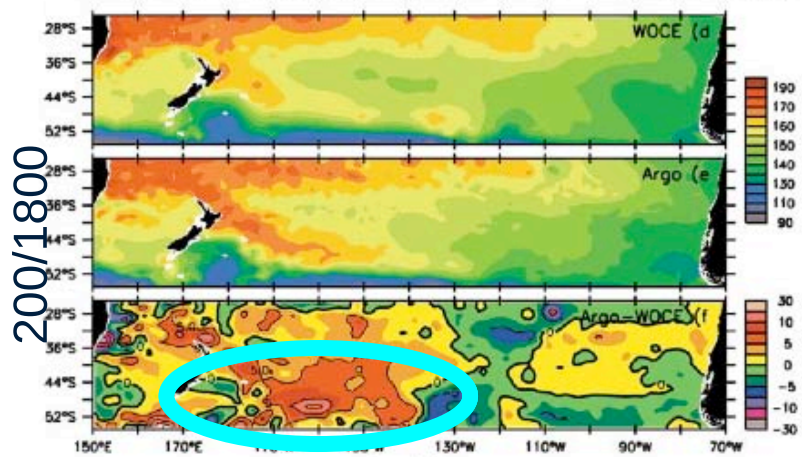

Weaker
SP gyre

# Southern hemisphere circulation changes: pre and post-IPCC

Subtropical Indian Ocean circulation intensified 15-20%, 1987 to 2002, identified through in situ tracers and oxygen increase, I.e. ventilation increase (McDonagh et al., 2005)

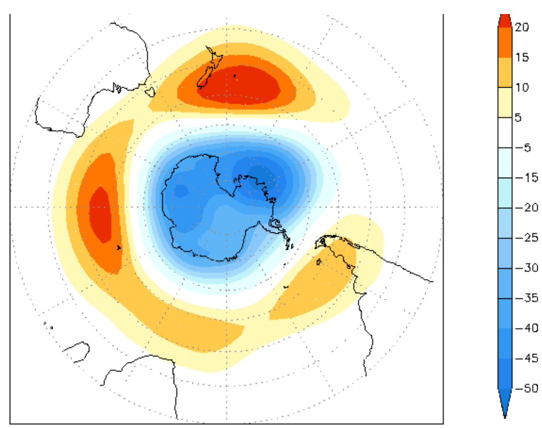


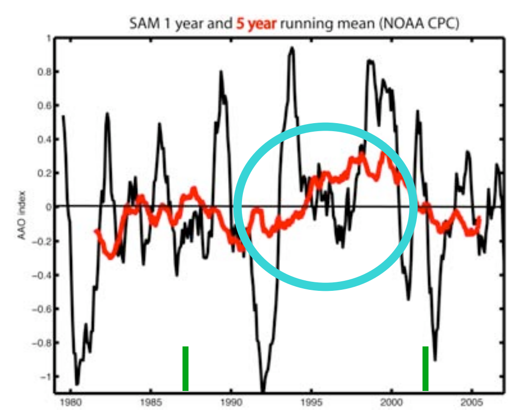

Dyn.ht. changes Argo-WOCE




Subtropical South Pacific circulation intensification 20% in 1990s (Roemmich et al., 2007)

Relation to strengthening of the Southern Annular Mode and thus change in Ekman pumping

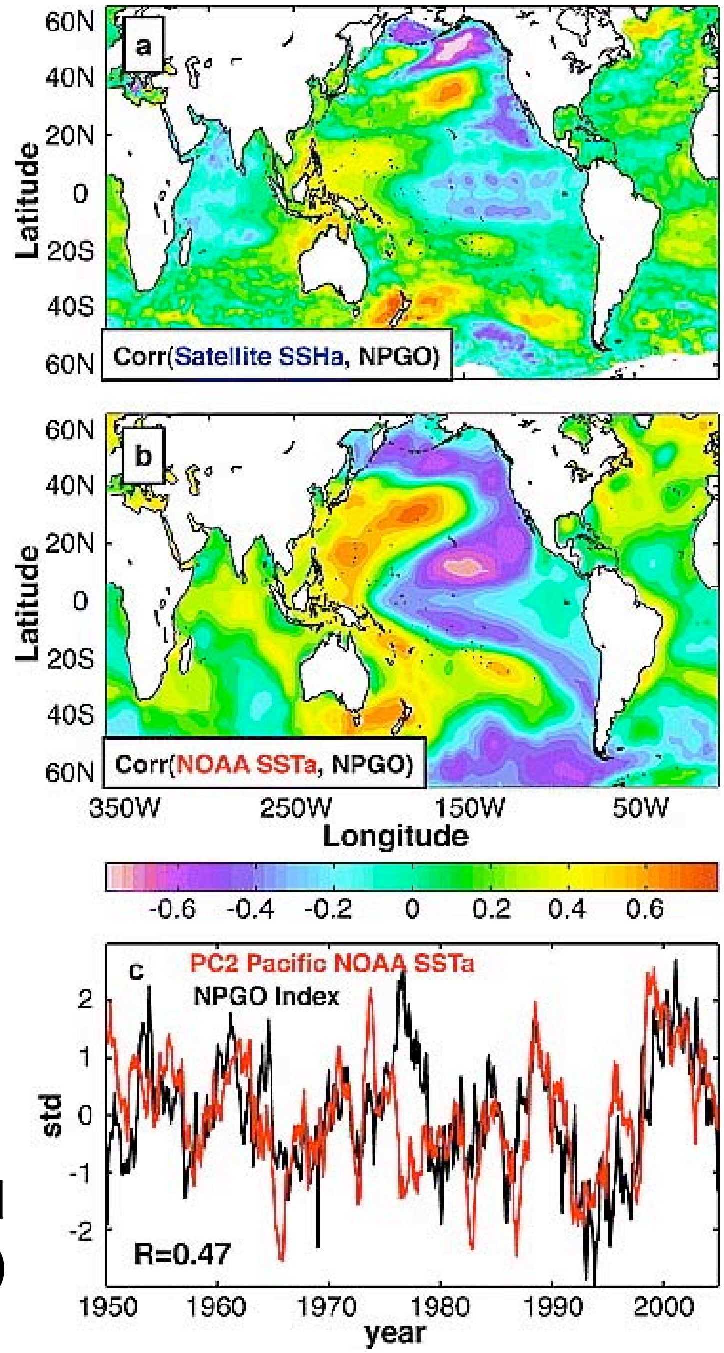




# Natural modes of variability

Natural modes, such as ENSO, SAM, NAM/NAO, AMO, etc. characterize the interannual to centennial modes of variability, and of course there are longer periods as well.

Continued characterization and understanding of these modes, and especially how anthropogenic climate change projects on these modes is important to understand. Many are working on this, but perhaps not enough attention is paid to this, other than to think of the natural mode as 'noise' to be removed.




Relation between 2nd Pacific EOF and the ecosystem: DiLorenzo et al. (2008)

# Relation of observed circulation changes to climate change

Observed circulation changes in the N. Atlantic are consistent with NAO patterns; natural variability may well mask longer-term changes for quite a long time (signal to noise issue). But monitoring/modeling are necessary.

Observed circulation changes in the southern hemisphere could be considered consistent with climate change, but they are also consistent with decadal change in the SAM. Thus again long time series are needed.

# Grand summary: take-home messages for physical climate change in the ocean

- The oceans are changing
- They are warming, albeit unevenly
- Sea level is rising, also unevenly
- Sea ice coverage is decreasing
- Salinity changes indicate a change in raininess/dryness that go along with global change
- Oxygen distribution in the ocean is changing as a result, which might affect ecosystems
- Circulation may be strengthening in the southern hemisphere due to increased winds
- Atlantic MOC changes are large but dominated by natural variability

# A personal list of some community challenges, in no particular order and without conferring with any particular group

- High latitude water column, sea ice, and ice sheet drainage observations
- Improved air-sea fluxes, especially in data-poor regions
- Mainstreaming of state estimation work, along lines of ECMWF/NCEP reanalyses for atmosphere
- Maintaining commitment to continuous time series
- Broader focus on truly “global” change, while maintaining the scientific momentum and institutional support for understanding/monitoring N. Atlantic climate change
- Need for monitoring of all remote regions, need for better understanding of role of stratification changes in all high latitude and subtropical
- Integration of understanding of natural modes and climate change, including tropical climate in all 3 oceans