SIO 210: Climate and the ocean

- Climate equilibria, forcing, feedbacks, hysteresis
- (ENSO - previous lecture)
- Pacific Decadal Oscillation - ENSO modulation
- North Atlantic Oscillation, Arctic Oscillation & Northern Annular Mode
- Southern Annular Mode
- North Atlantic meridional overturning and climate change
- Impacts of anthropogenic forcing

Reading: skim DPO Chapter 15 (supplementary)

Climate variability vs. climate change

- Now common usage

- "Climate variability" = natural variability
  - Natural "modes" of variability
- "Climate change" = anthropogenic forcing
  - (due to man-made changes in greenhouse gases, land surfaces, species distributions, etc.)

Elements of the climate system

Sun

Atmosphere

Ocean

Cryosphere (ice, snow)

Land surface

Biological and chemical cycles

(Moon, in its effect on tidal cycles and hence mixing)

Climate forcing

External forcing for earth's climate includes

earth orbit parameters (solar distance factors)

solar luminosity

moon orbit

volcanoes and other geothermal sources

tectonics (plate motion)

greenhouse gases (to the extent that they are not part of the climate system itself)

land surface (likewise with respect to the climate system)

Internal forcing: looking at each element of the climate system and how it is forced by another element

(e.g. winds forcing ocean, change in ice extent forcing atmosphere or ocean, etc)

Interactions/couplings: sometimes include feedbacks

Natural climate modes with interannual to millenial time scales

Interannual time scale (> 1 year, < 10 years)

ENSO

Decadal time scale (10 to multiple decades)

Pacific Decadal Oscillation (or Pacific-North America Pattern)

North Atlantic Oscillation (or Arctic Oscillation or NAM)

Southern Annular Mode

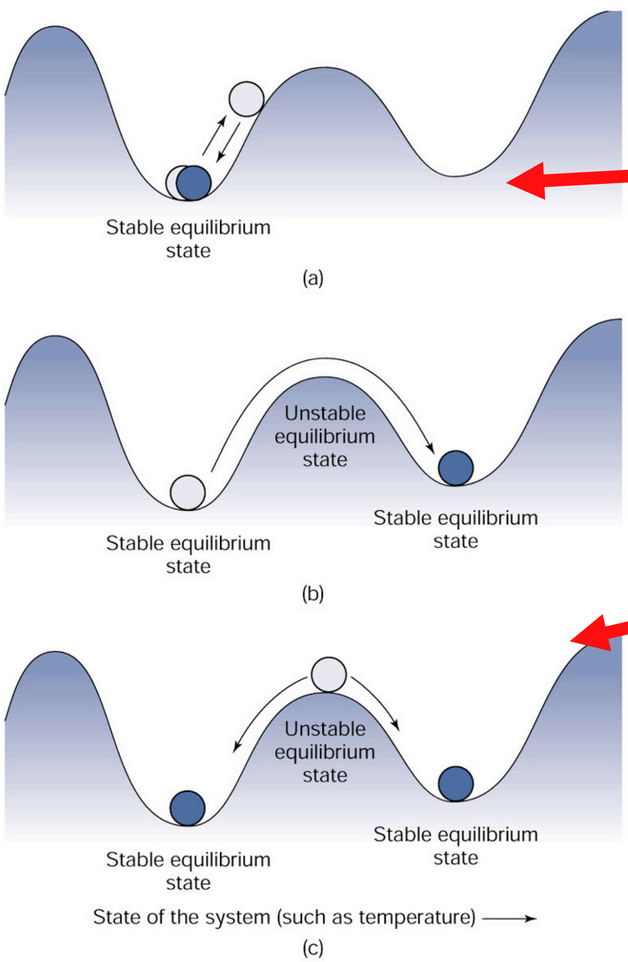
Centennial time scale

Atlantic Overturning mode

What sets the time scales?

decadal to centennial suggests longer processes than just atmosphere - for instance ocean circulation, ocean's planetary wave propagation, or changes in land surface

Stability and equilibria



Kump, Kasting and Crane (2003)

Asymptotically stable: force system away from initial condition and the system returns to initial state

Stable or Neutral: force away and system stays where it was pushed to (not illustrated here).

Unstable: force away and system moves to a different state. This usually implies multiple possible stable equilibria, with forcing that is strong enough to push into a different equilibrium state.

Forcing (coupling) with no feedback

- Cause and effect: example of negative coupling (increase in one parameter causes a decrease in the other)
    - Volcano causes aerosols
    - Causes cooling and decrease in temperature

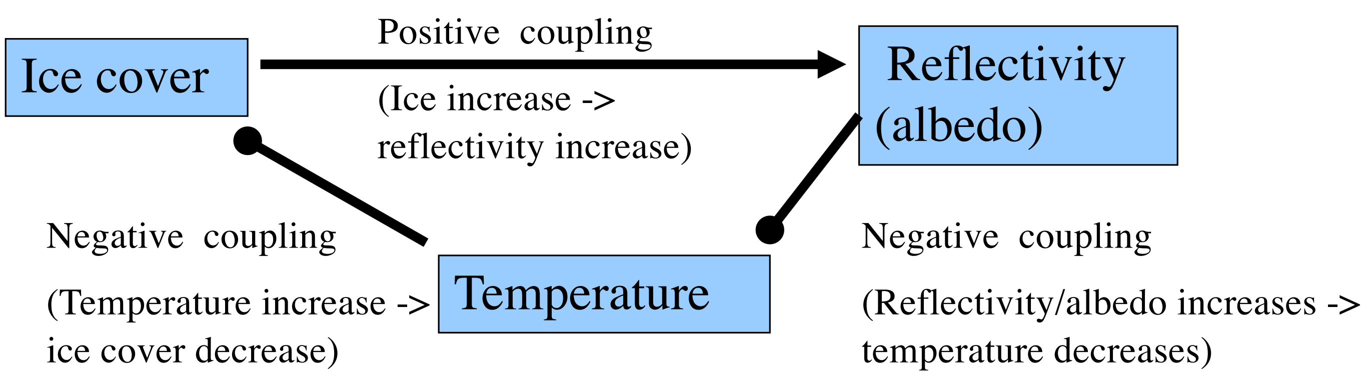
Volcano eruption —— Negative coupling / Reduction in sunlight ——● Temperature

Feedback? None since air temperature does not change incidence of volcanoes

Positive feedbacks

Albedo = reflectivity, scale of 0-1 with 0 = no reflection, 1 = all reflected

- Example: ice-albedo feedback
  - Increased ice and snow cover increases albedo
    - (Positive coupling, denoted by arrow)
  - Increased albedo decreases temperature of atmos.
    - (negative coupling, denoted by circle)
  - Decreased temperature of atmos. Causes ice increase
    - (negative coupling, denoted by circle)
  - Two negatives cancel to make positive; net is positive feedback (“runaway”, unstable)



Modes of natural climate variability:

Large-scale patterns of temperature, wind, currents, fluxes, etc

All have couplings between climate system components

Spatial structure is like a ‘normal mode’, say sine, cosine, Bessel function, etc.: these are the natural modes of the climate system

ENSO

PDO (PNA, IPO)

NAO

SAM

AMO

And many others

Indices are based on observed quantities or on amplitude of an empirical orthogonal function or principal component.

Modes of natural climate variability: role of ocean

Note that advection time scales are similar to these climate modes:

tropical ocean – years

ocean gyres - decades

ocean basins - centuries

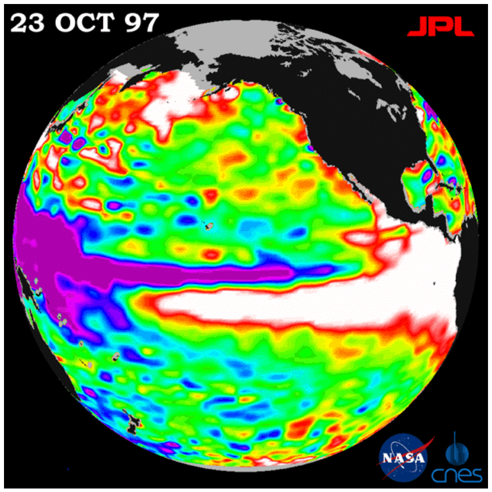
global ocean - ~1000 years

(1) Advection of heat and salinity anomalies: from surface forcing regions, subducted, and then returning to surface where they change the forcing for the atmosphere, or change the ice extent.

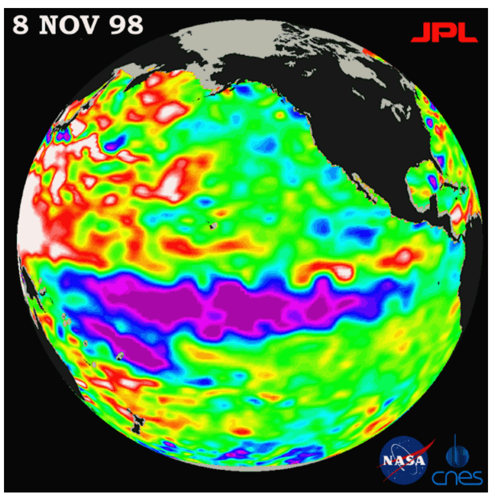
(2) Or similar advection that changes the upper ocean stratification, hence changing the mixed layer depths heated and cooled by the same air-sea fluxes, thus changing surface temperature

(3) Or propagation of anomalies via Rossby or Kelvin waves, which then reset the temperature in remote locations.

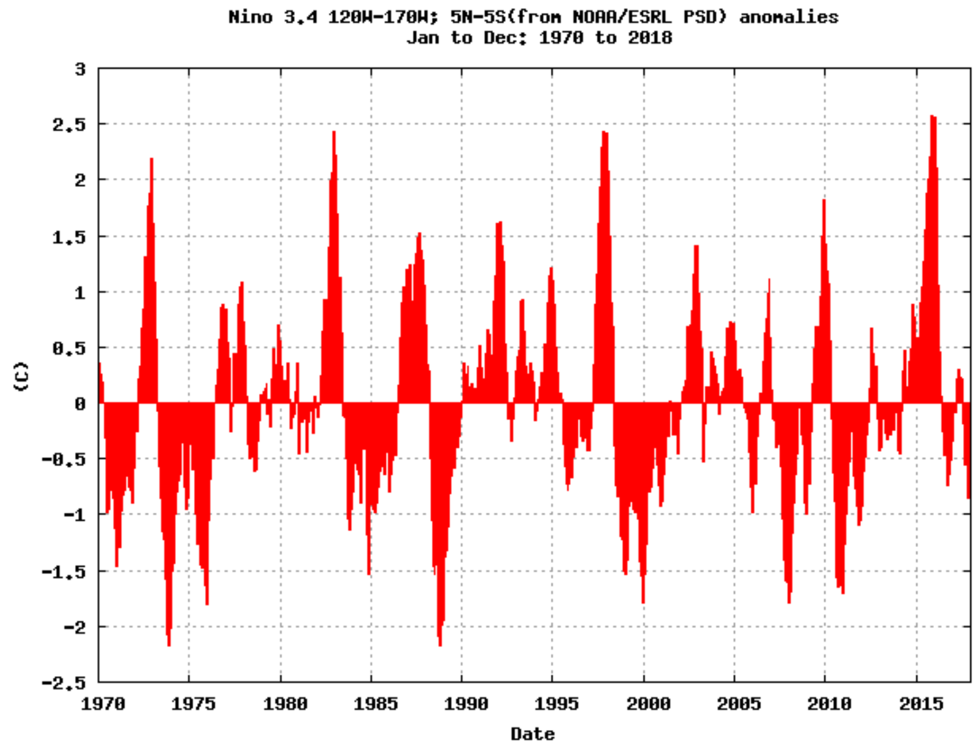
ENSO: interannual (5 to 7 years) http://topex-www.jpl.nasa.gov/elnino/index.html



El Niño



La Niña



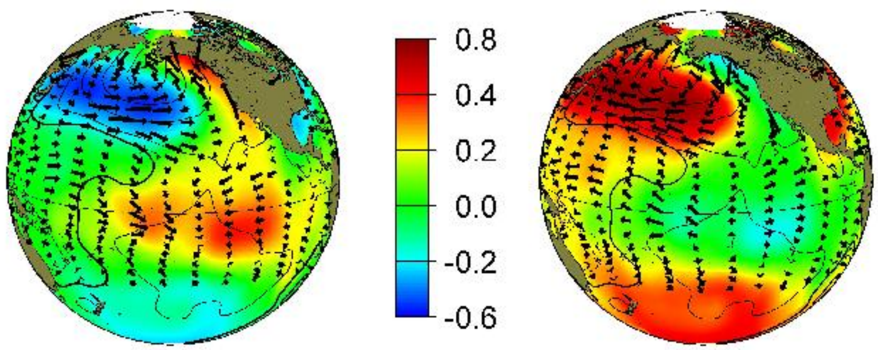
Nino 3.4 index for ENSO: surface temperature in central equatorial Pacific

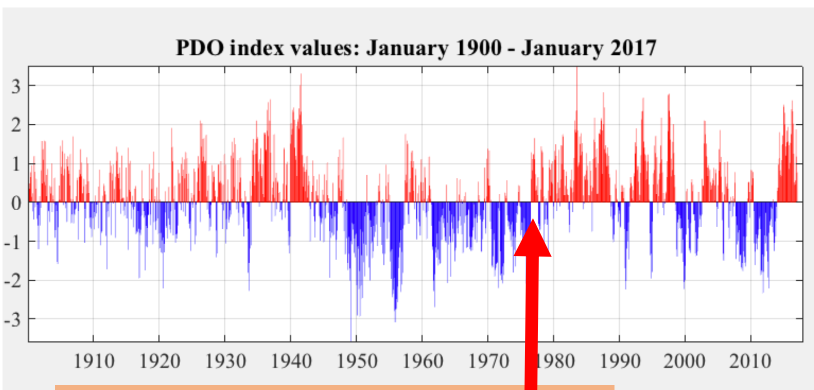
Positive: El Nino

Negative: La Nina

Pacific Decadal Oscillation (PDO)

Warm phase (SST) Cool phase (SST)





1976 "regime shift" to warm phase PDO, strong Aleutian Low

PDO pattern is similar to ENSO, but broader (whole Pacific)

PDO timescale is 'decadal', i.e. 20 to 30 years

Strong impact on NE Pacific ecosystem

Mechanism is unknown

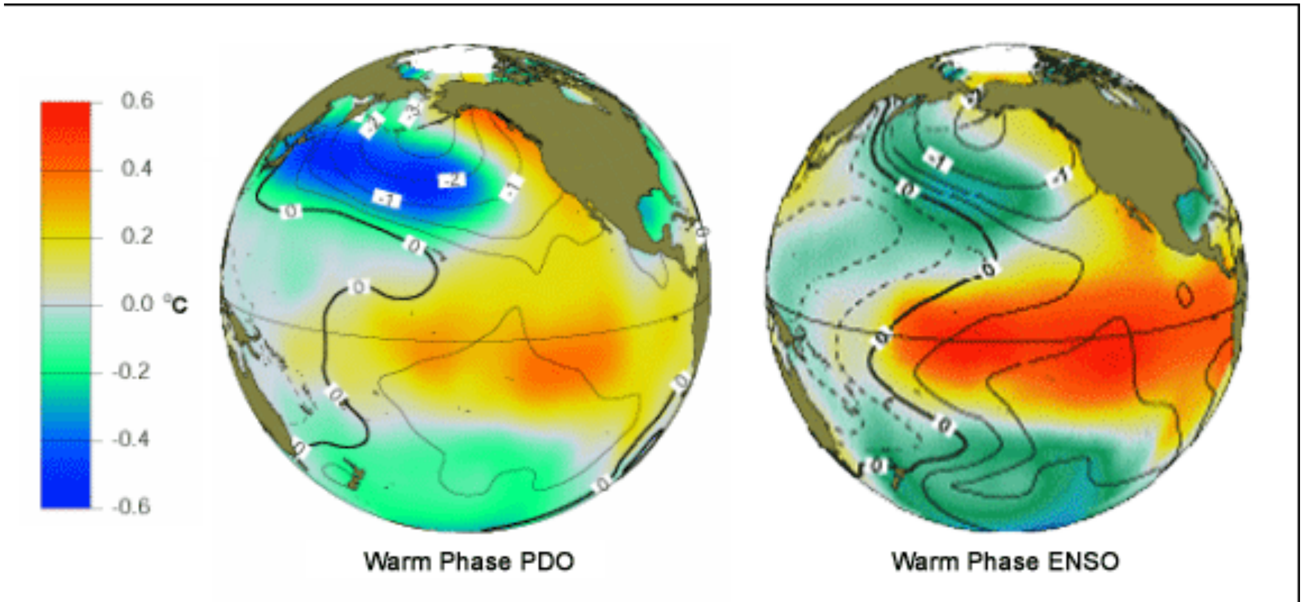
Orthogonal mode: Eastern Gyral Oscillation (EGO), in N. Pacific, important in CA Current

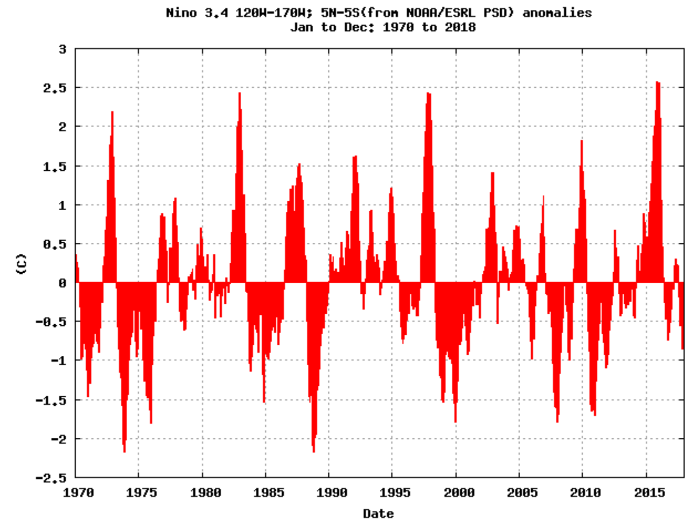
Related modes: PNA, IPO, PSA

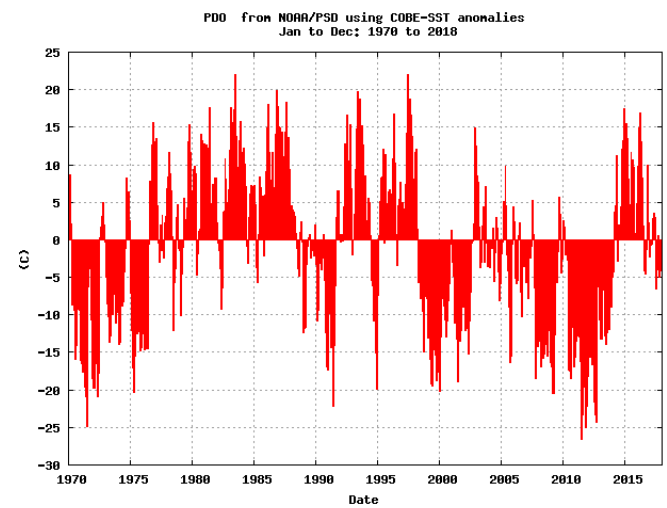
Great website

http://research.jisao.washington.edu/pdo/

PDO versus ENSO







PDO pattern (sort of EOF)

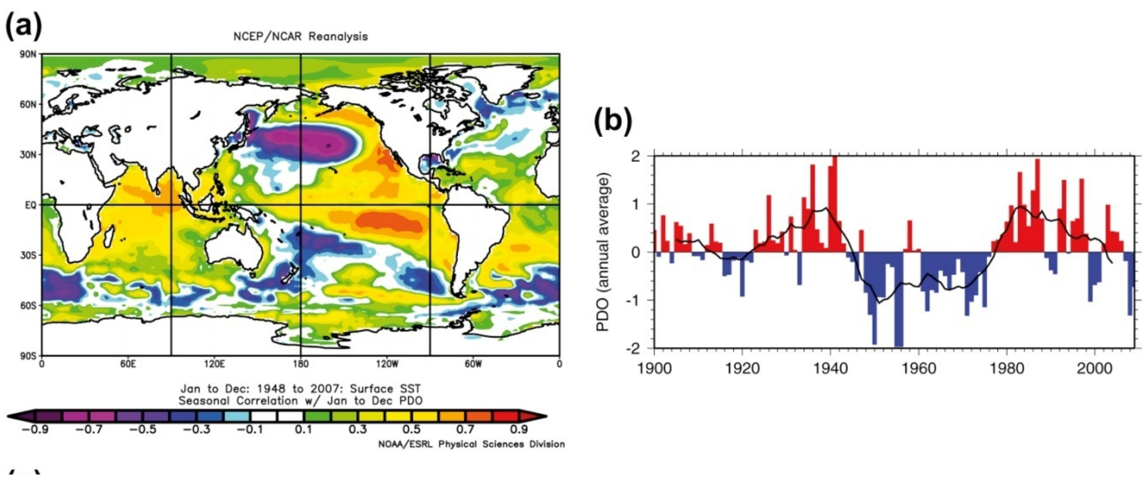
20-30 year time scale

ENSO pattern (sort of an EOF)

3-7 year time scale

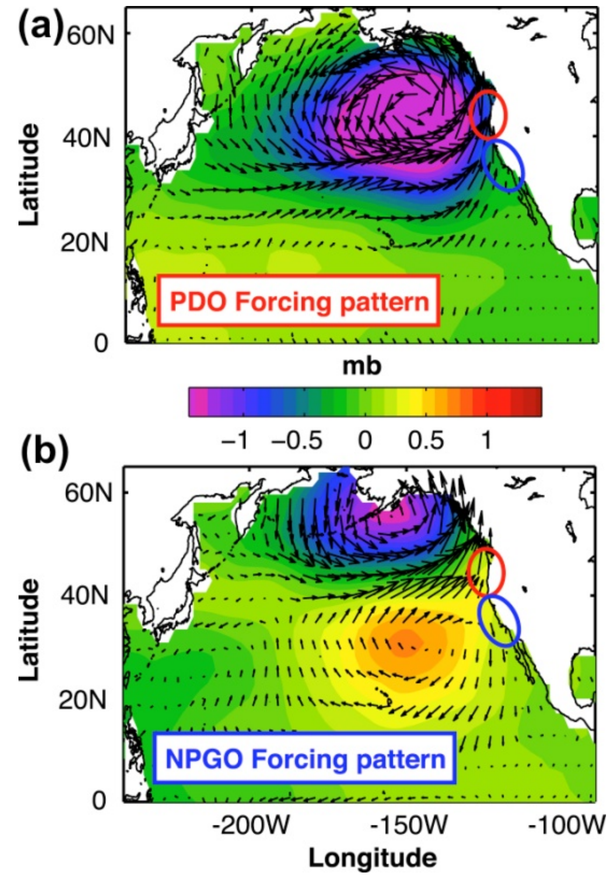
Similar patterns, but ENSO is very peaked in the tropics, and PDO is spread out to higher latitudes, particularly N. Pacific.

PDO and EPGO (NPGO)



Pacific Decadal Oscillation (PDO)

FIGURE S15.5

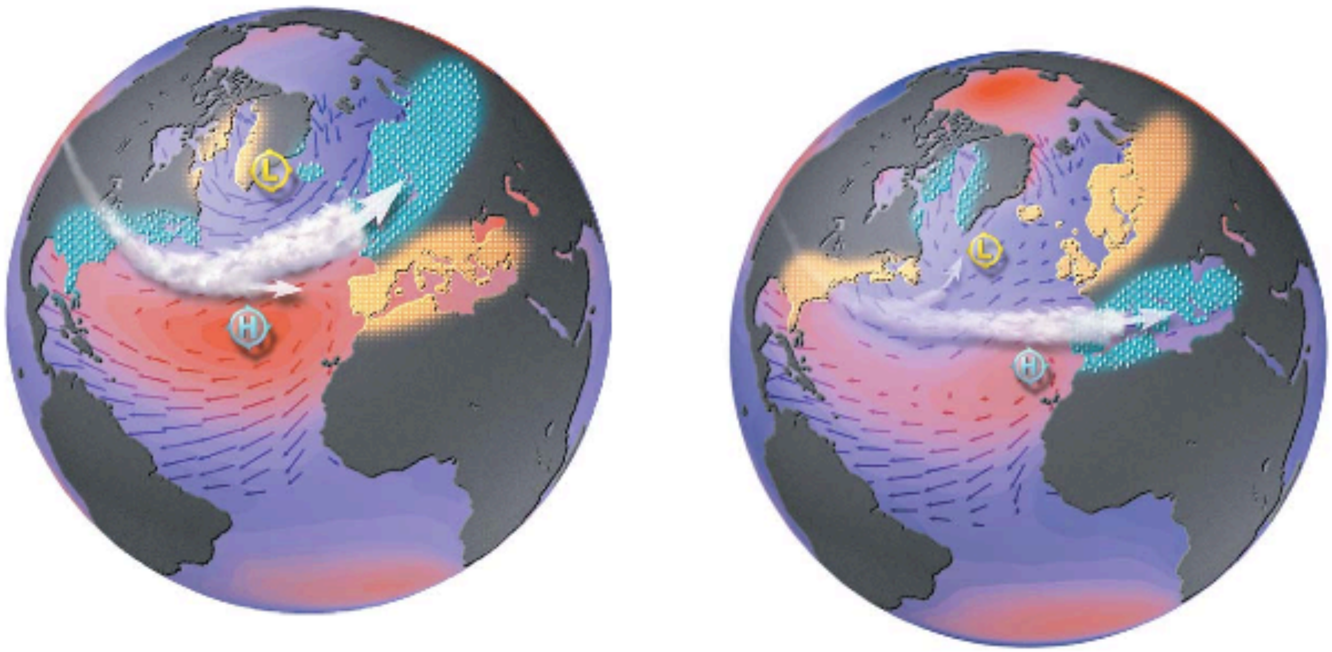


Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (EPGO)

FIGURE S15.6

North Atlantic Oscillation (NAO) (decadal)

NAO$^+$: Positive Phase of the NAO **NAO$^-$: Negative Phase of the NAO**



The two extreme phases of the North Atlantic Oscillation (NAO) and some climatic impacts. Courtesy of Lamont Doherty Earth Lab./NOAA).

"High" and "Low" refer to the anomaly of atmospheric pressure difference between the Azores and Iceland

NAO sea surface temperature and pressure patterns

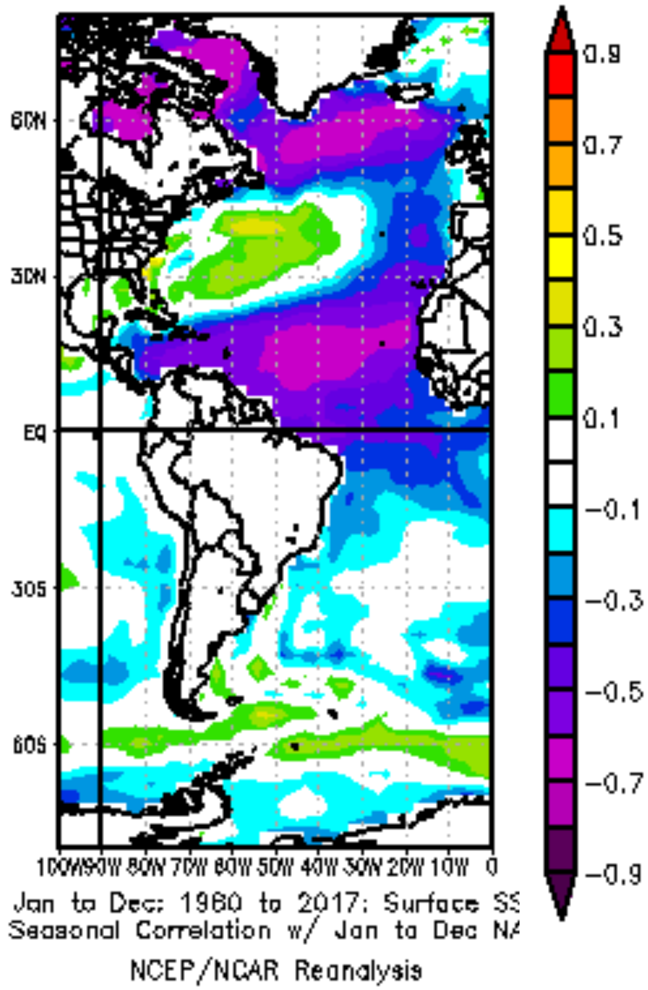
High NAO:

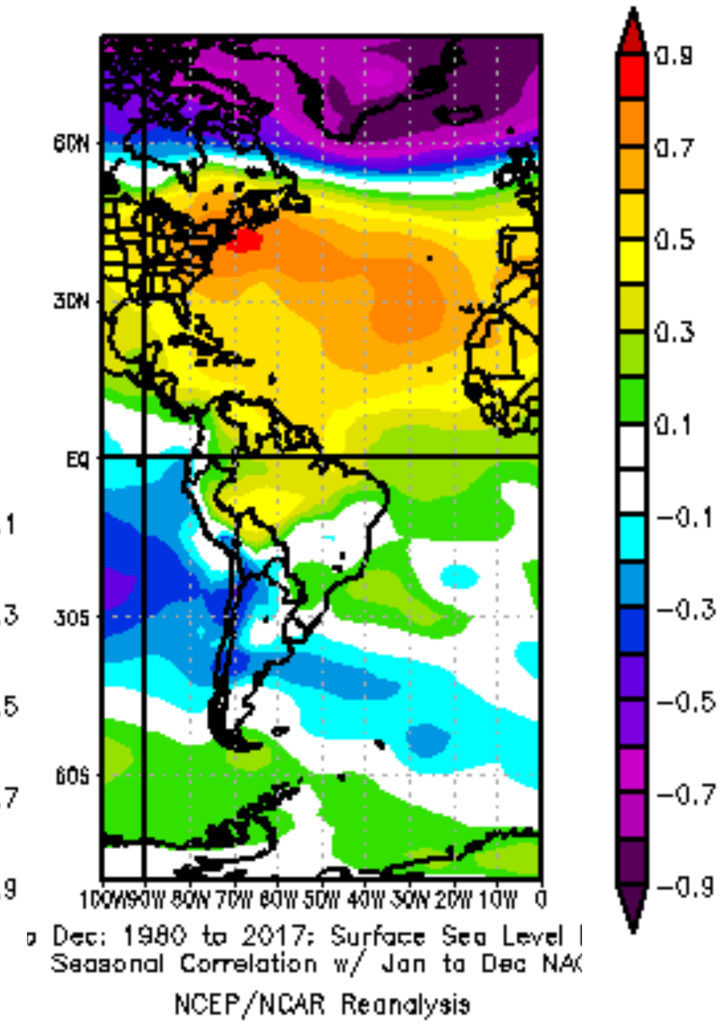
Nordic Seas: cool, low pressure

Subpolar N. Atlantic: Cool SST and Low surface pressure

Subtropical N. Atlantic: Warm SST and High surface pressure

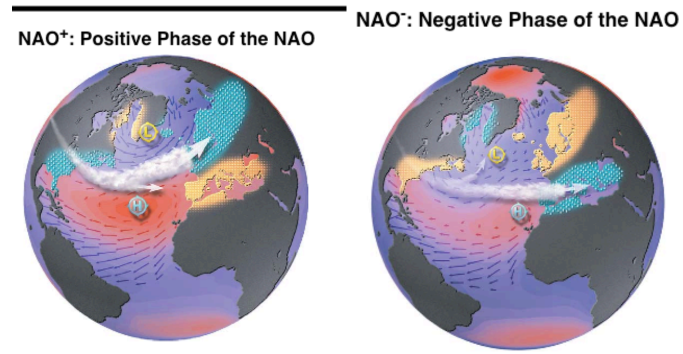
Cool tropical N. Atlantic

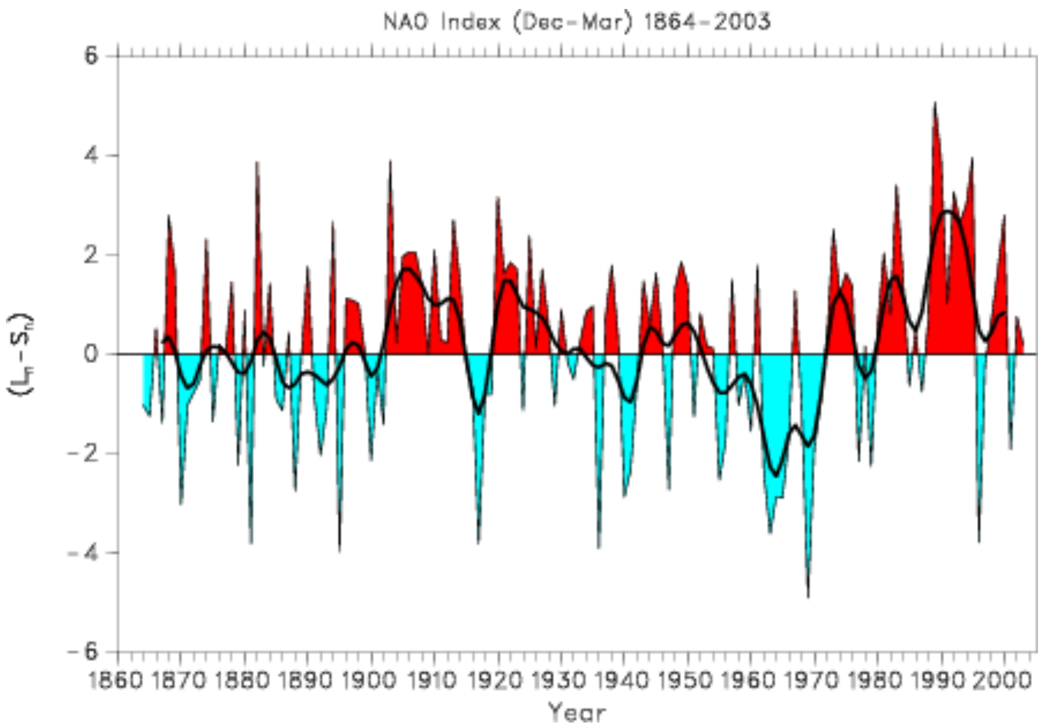


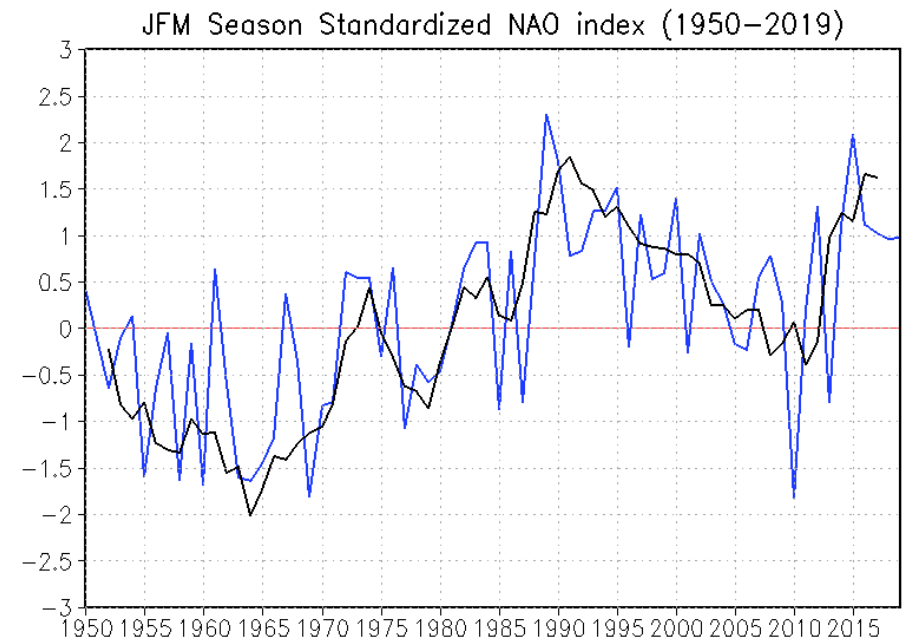


NAO index: Azores to Iceland atmospheric pressure difference

High: exceptionally cold Labrador Sea Water, warm/non-existent Eighteen Degree Water







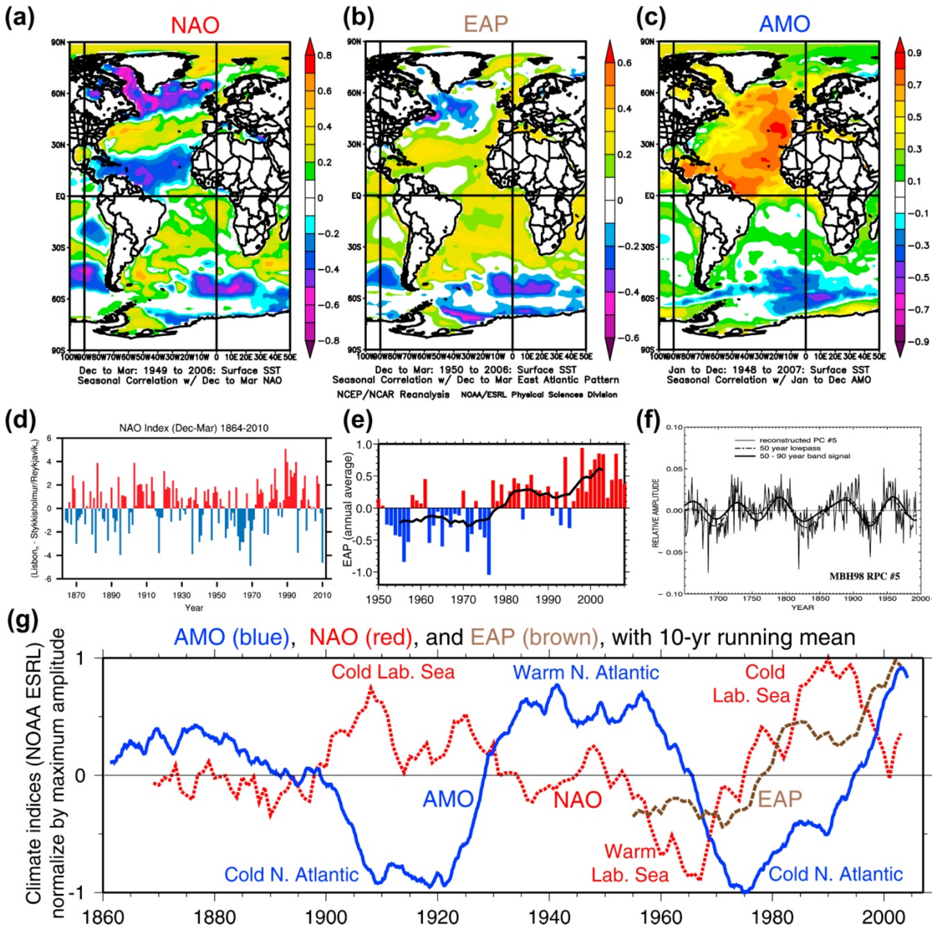


FIGURE S15.2

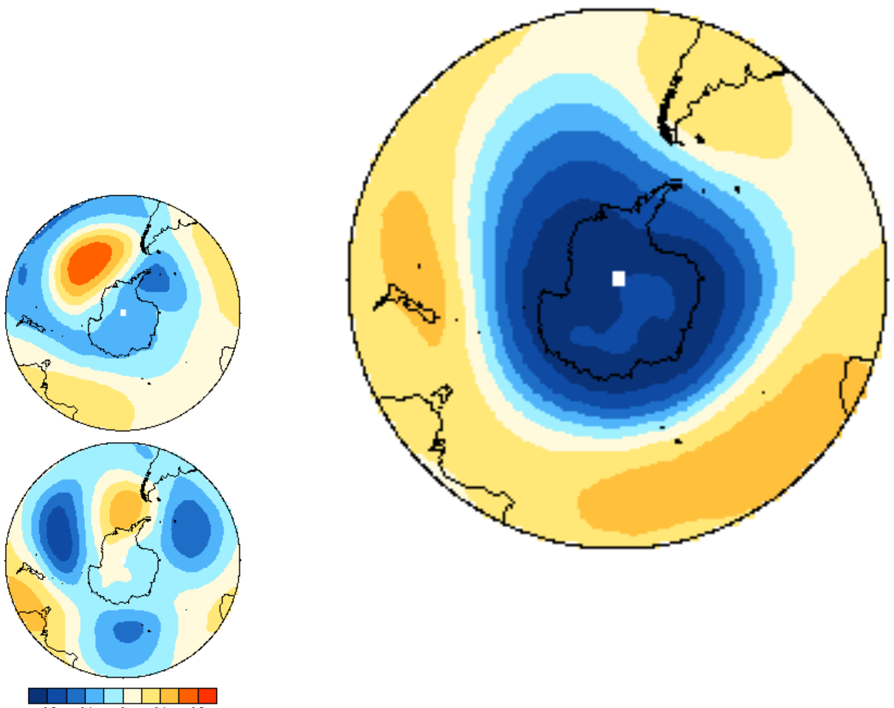
Atlantic decadal to multidecadal climate modes. (a) North Atlantic Oscillation (NAO), (b) East Atlantic Pattern (EAP), and (c) Atlantic Multidecadal Oscillation (AMO). Maps of SST correlation with each index: positive is warm and negative is cold. (Data and graphical interface from NOAA ESRL, 2009b.) (d) NAO index (Hurrell, 1995, 2009): difference of sea level pressure between Lisbon, Portugal and Stykkisholmur, Iceland. *Source: Updated by Hurrell (personal communication, 2011)*. (e) EAP index: amplitude of second EOF. *Source: From NOAA ESRL (2009b).* (f) AMO: amplitude of the principal component of proxy temperature records. *Source: From Delworth and Mann (2000).*
(g) Time series, each with a 10-year running mean and "normalized" by its maximum amplitude. NAO and EAP as above. The AMO is the Enfield et al. (2001) SST-based index.

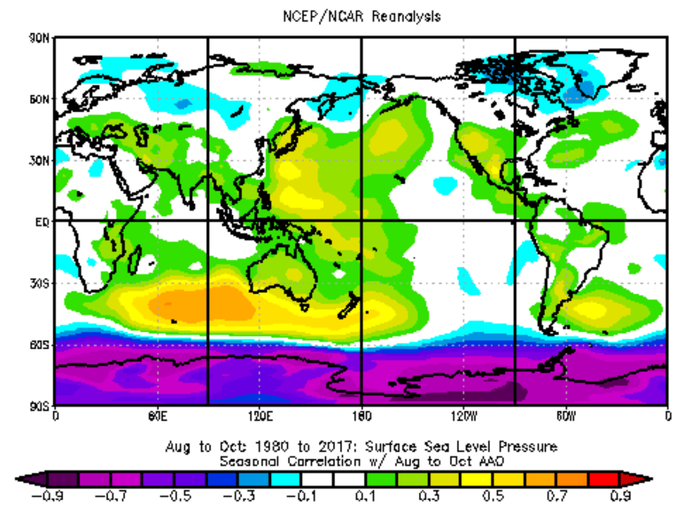
TALLEY

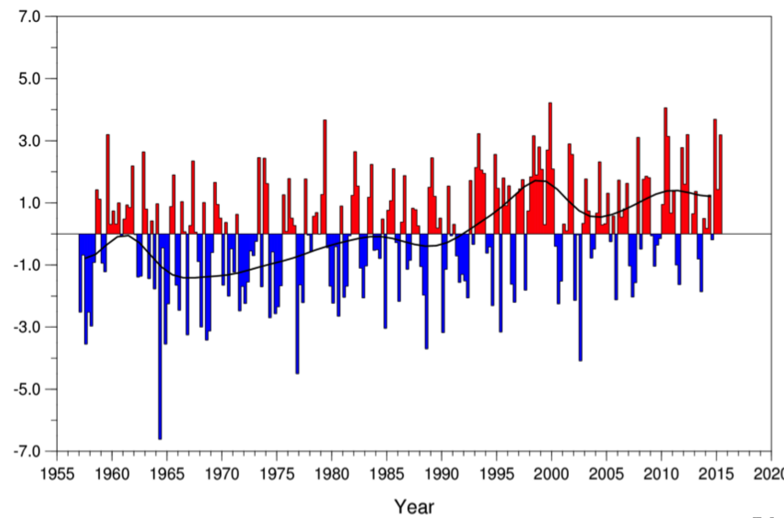
Southern Annular Mode (SAM) (decadal)

Circumpolar mode; variation in surface pressure and hence in westerly wind strength

EOFs 1-3 of SH extratropical 850 hPa Z (plotted as correlations)

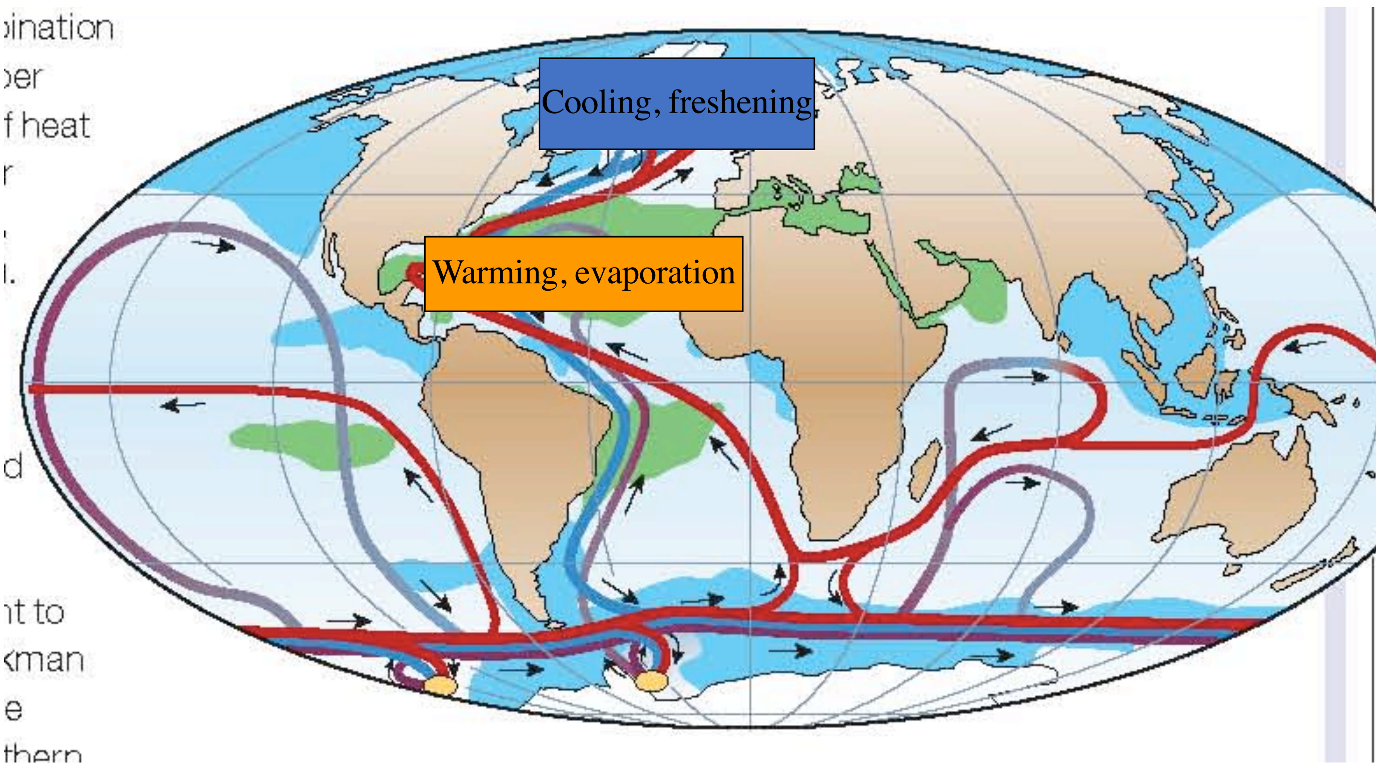






Talley SIO210 (2019)

Atlantic Meridional Overturning Circulation: can it strengthen and weaken?



Rahmstorf, Nature, 2002

North Atlantic thermohaline circulation variations - Millenial time scales and abrupt climate change

(1) If, say, fresh water is dumped on the northern North Atlantic through excessive melting or runoff, how will the N. Atlantic overturning circulation change? Will it:

Absorb the freshwater and return to nearly the initial condition (asymptotically stable)? (stay in the initial equilibrium state)

Shift to a slightly different state and remain there? (neutrally stable) (stay in essentially the same equilibrium state)

Jump into a completely different state of overturn (unstable)? (new equilibrium state)

(2) If the freshwater forcing is continuously changing (increasing and decreasing), what is the response? ("hysteresis" predicted – see next slide)

North Atlantic thermohaline circulation variations - millenial time scales and abrupt climate change

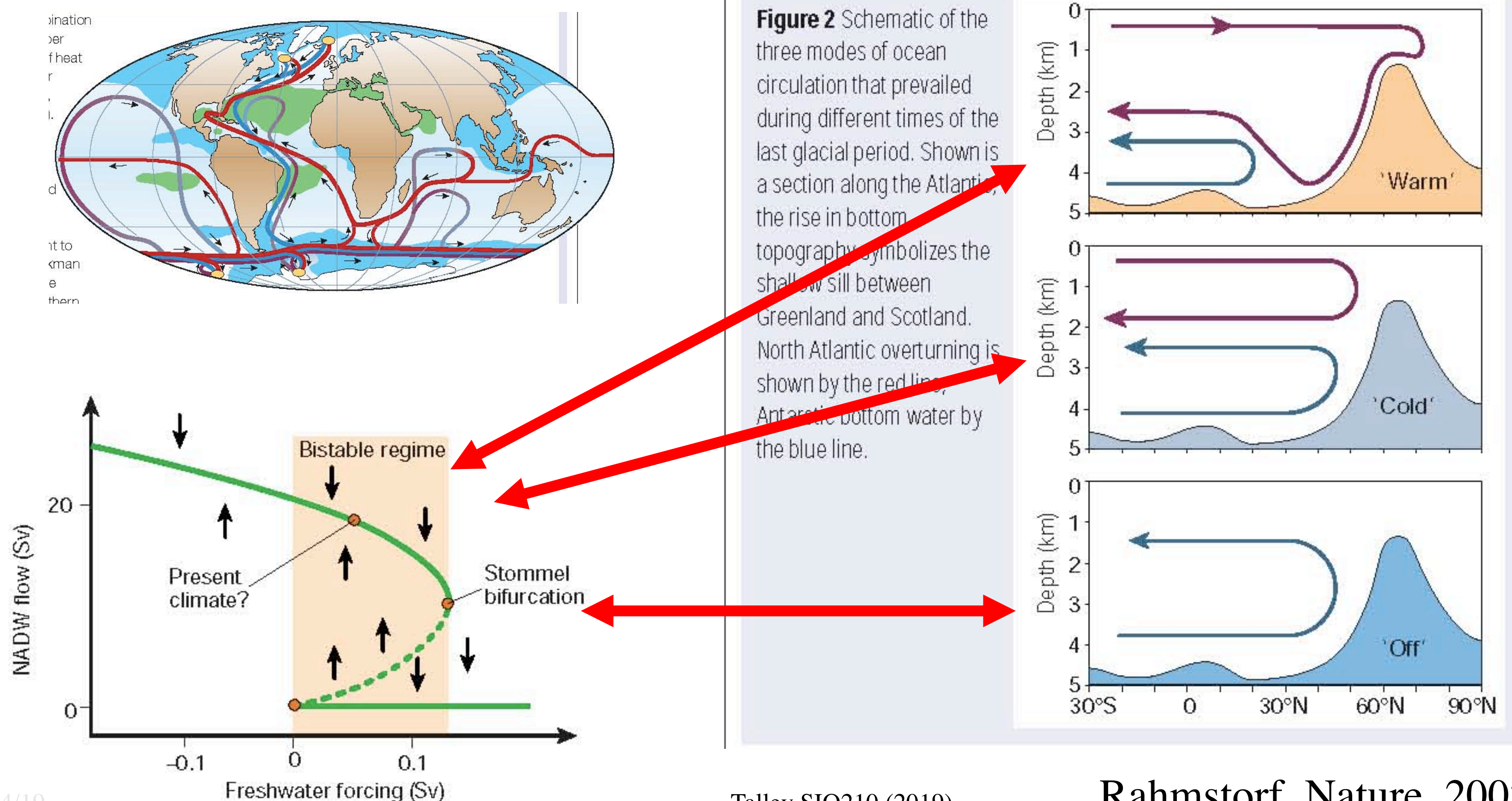
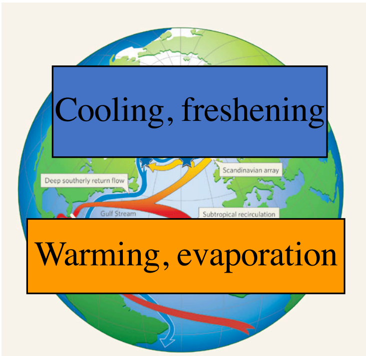
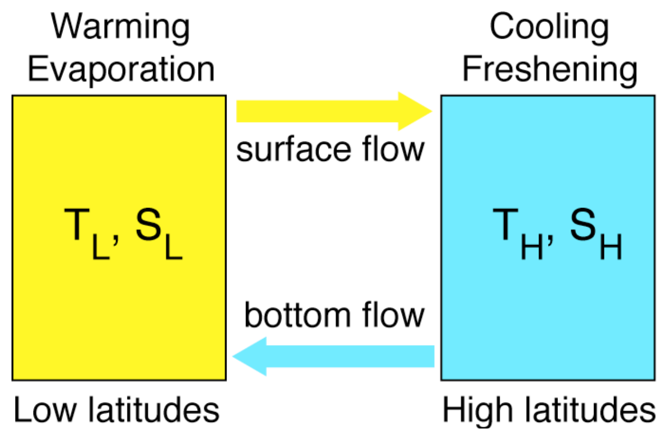


Figure 2 Schematic of the three modes of ocean circulation that prevailed during different times of the last glacial period. Shown is a section along the Atlantic; the rise in bottom topography symbolizes the shallow sill between Greenland and Scotland. North Atlantic overturning is shown by the red line, Antarctic bottom water by the blue line.

Rahmstorf, Nature, 2002



Salt oscillator (Stommel 1961): example of hysteresis



Model:

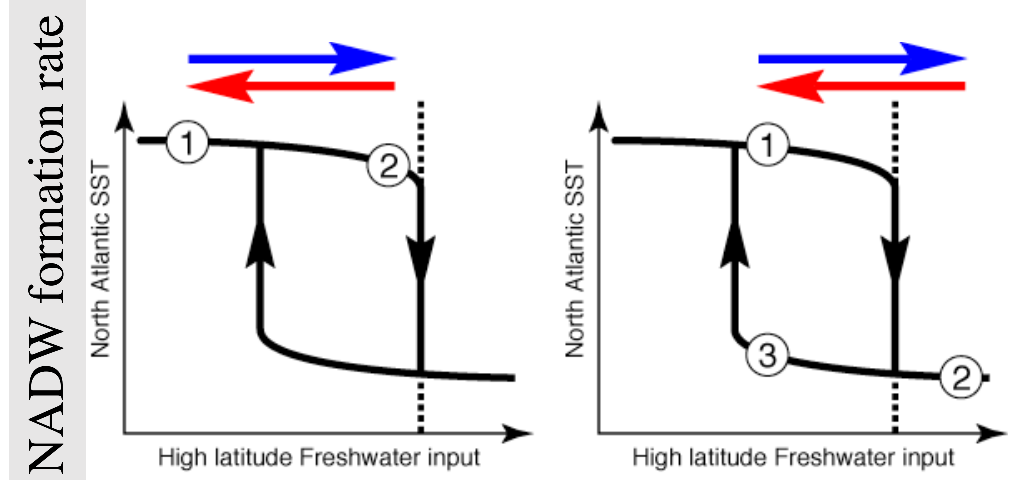
(1) increase freshwater at high latitudes.

Starts to reduce overturn and reduce high latitude SST slightly.

Then overturn shuts off, SST drops abruptly.

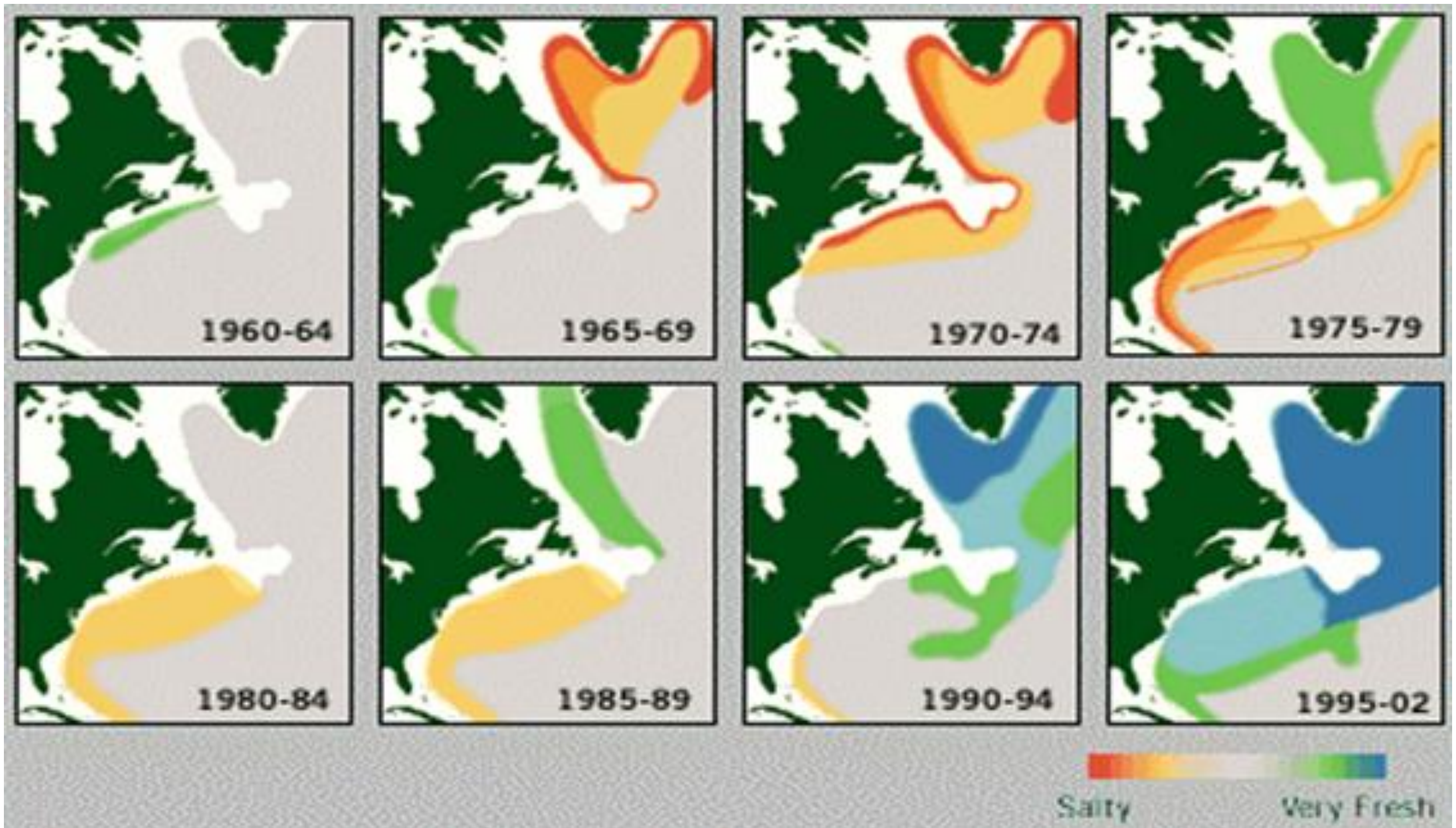
(2) Reduce freshwater at high latitudes. Takes a long time to restore overturn (through circulation of high salinity into high latitude box - overshoot (hysteresis)

DPO section 7.10.4

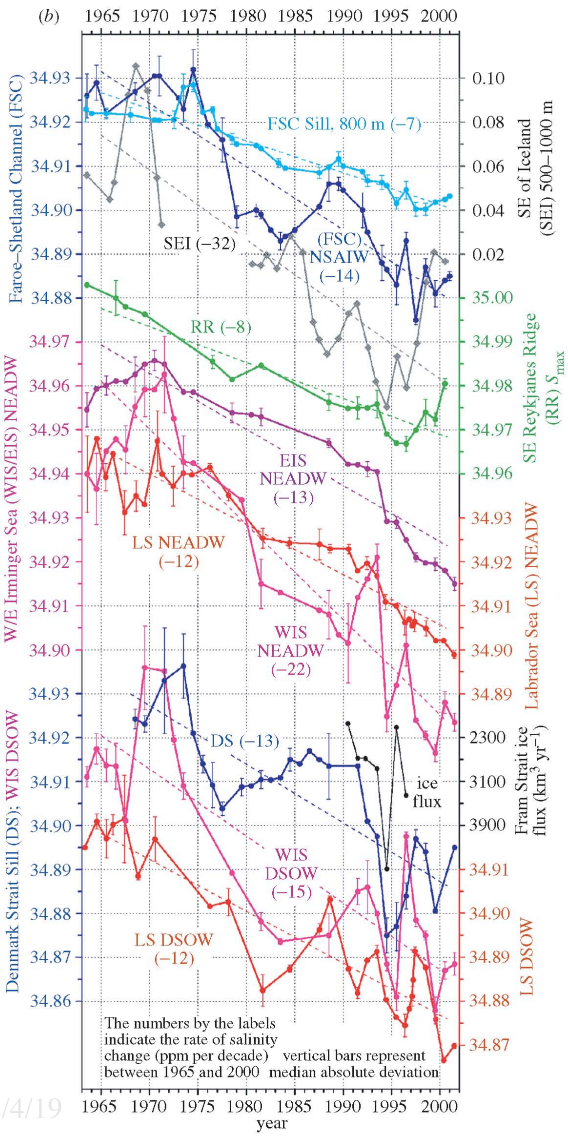


North Atlantic salinity variations

Can these changes in surface salinity create changes in circulation?

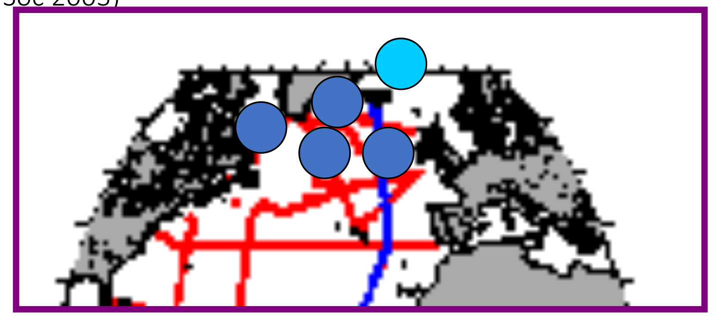


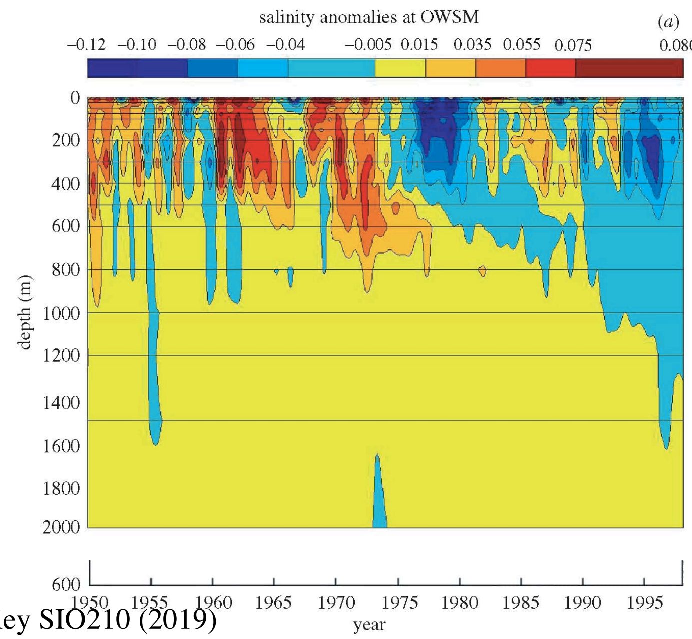
Curry (WHOI)



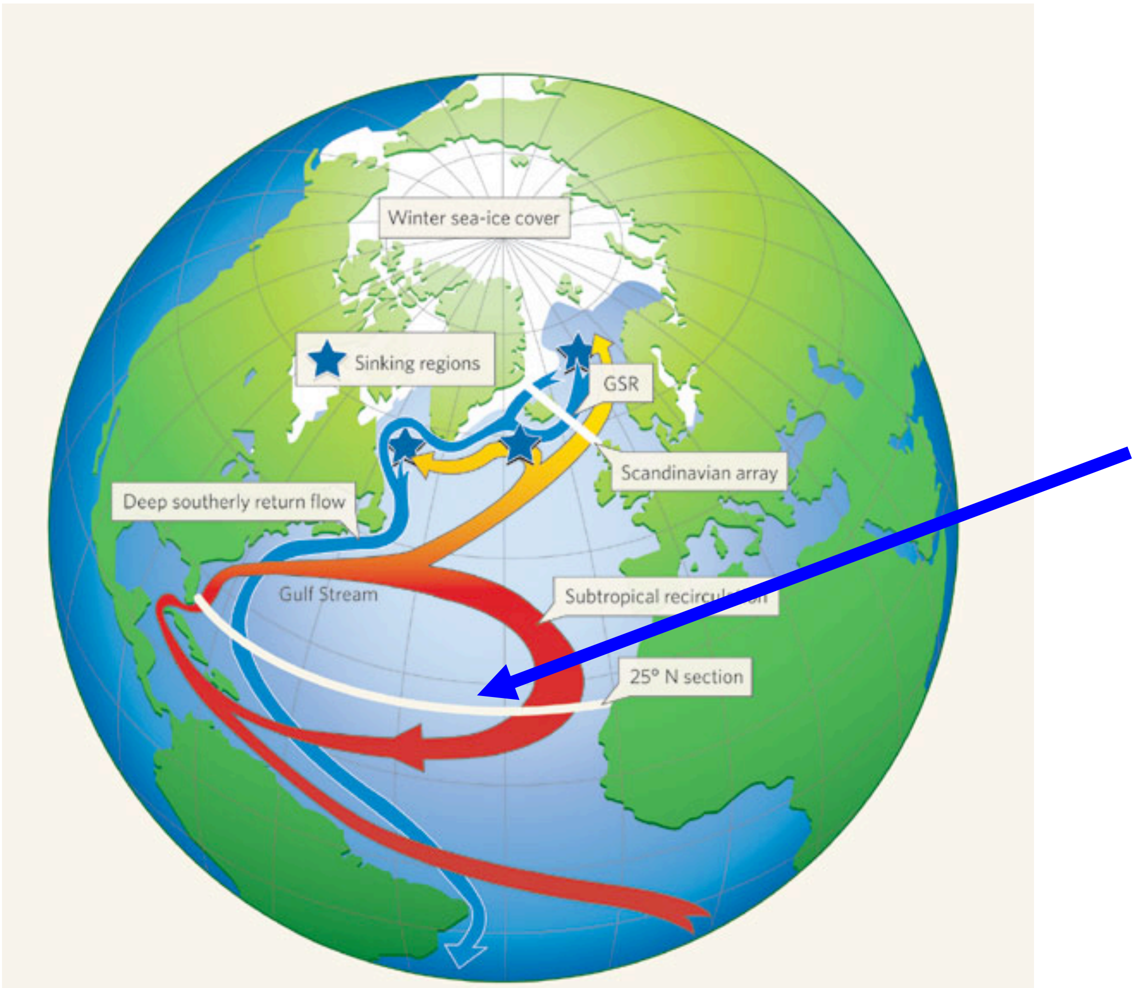
Observed changes:
Freshening of the Atlantic and Nordic Seas

(Dickson et al, Phil Trans Roy Soc 2003)





Is the Atlantic “AMOC” changing, possibly in response?



AMOC changes are largely due to NAO variability.

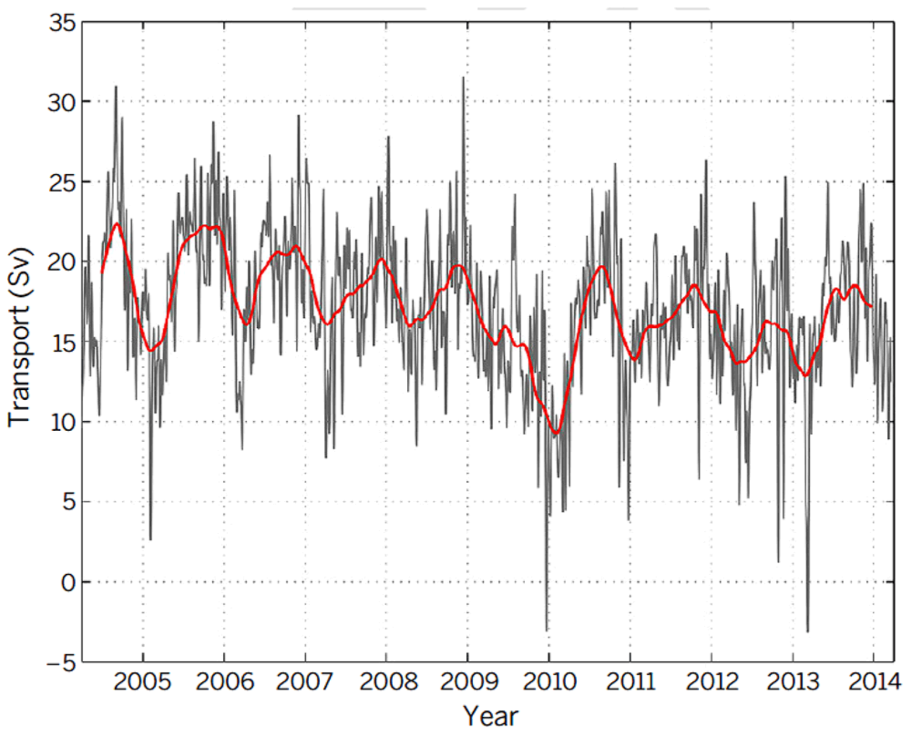
BUT, recent evidence of slowdown at 25° N

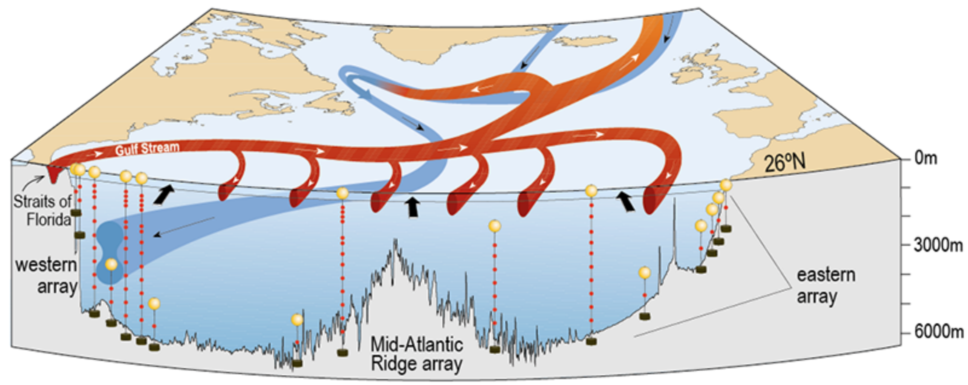
Controversial because early: Bryden et al. (Nature, 2005)

More recent papers begin to confirm a slowdown.

Cartoon of “conveyor” and measurement arrays from Quadfasel (Nature, 2005)

Is the Atlantic "AMOC" changing, possibly in response?





Consequence of AMOC slowdown:

Large heat uptake in northern North Atlantic

Paradoxically, SST cooling in the subpolar N. Atlantic (due to less Gulf Stream water)

http://www.rapid.ac.uk/research/tenyearsofrapid.php

10-year time series of the AMOC measured at 26.5°N from April 2004 to March 2014. The gray line represents the 10-day filtered measurements, and the red line is the 180-day filtered time series. The seasonal cycle, the low AMOC event in 2009-2010 and the overall decrease in strength over the 10 years are all clearly visible.

Anthropogenic climate change

The ocean is an excellent integrator of change since its heat capacity is large, and it is an enormous reservoir for freshwater (compared with the atmosphere).

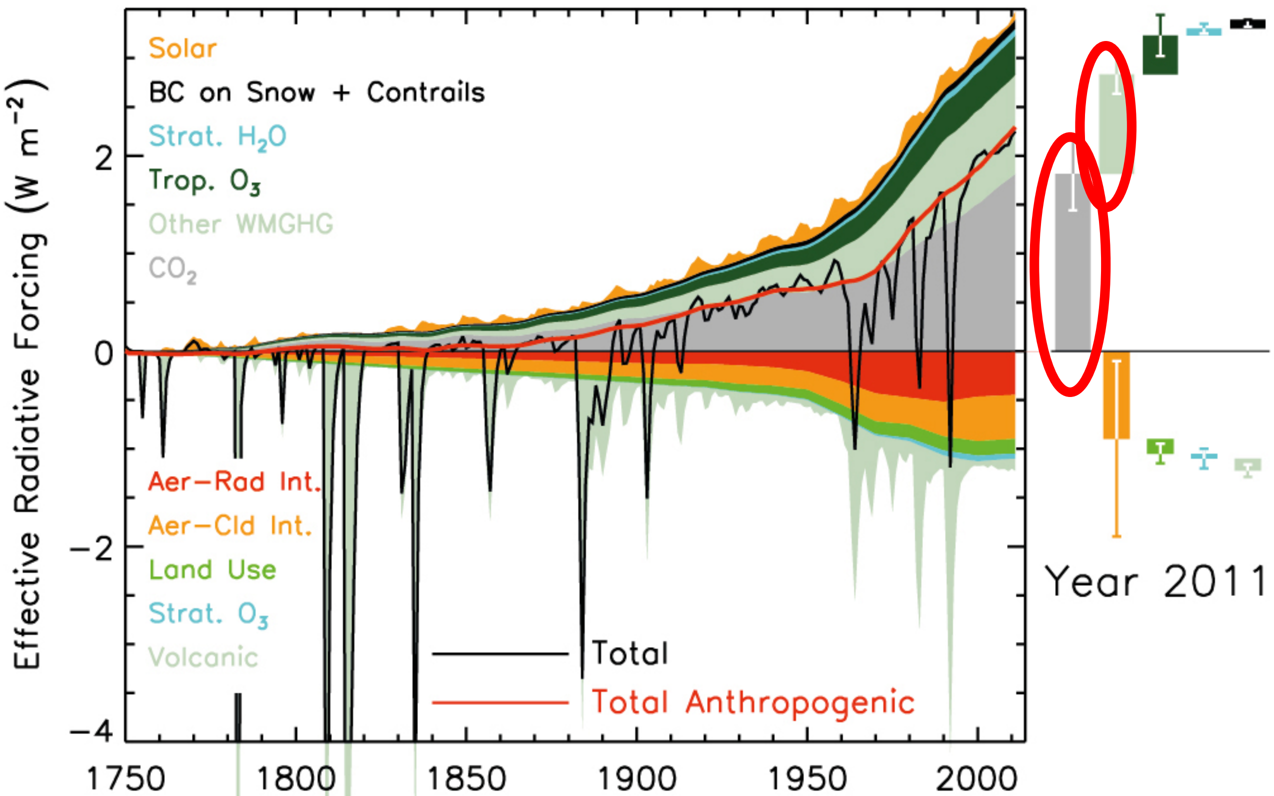
Long-term trends in heat content, salinity and oxygen are observed.

Necessary to integrate over large areas to see this signal separate from the decadal natural modes.

Patterns of A.C.C. might well resemble the natural climate modes since these are, after all, the natural modes that would be forced into a particular state.

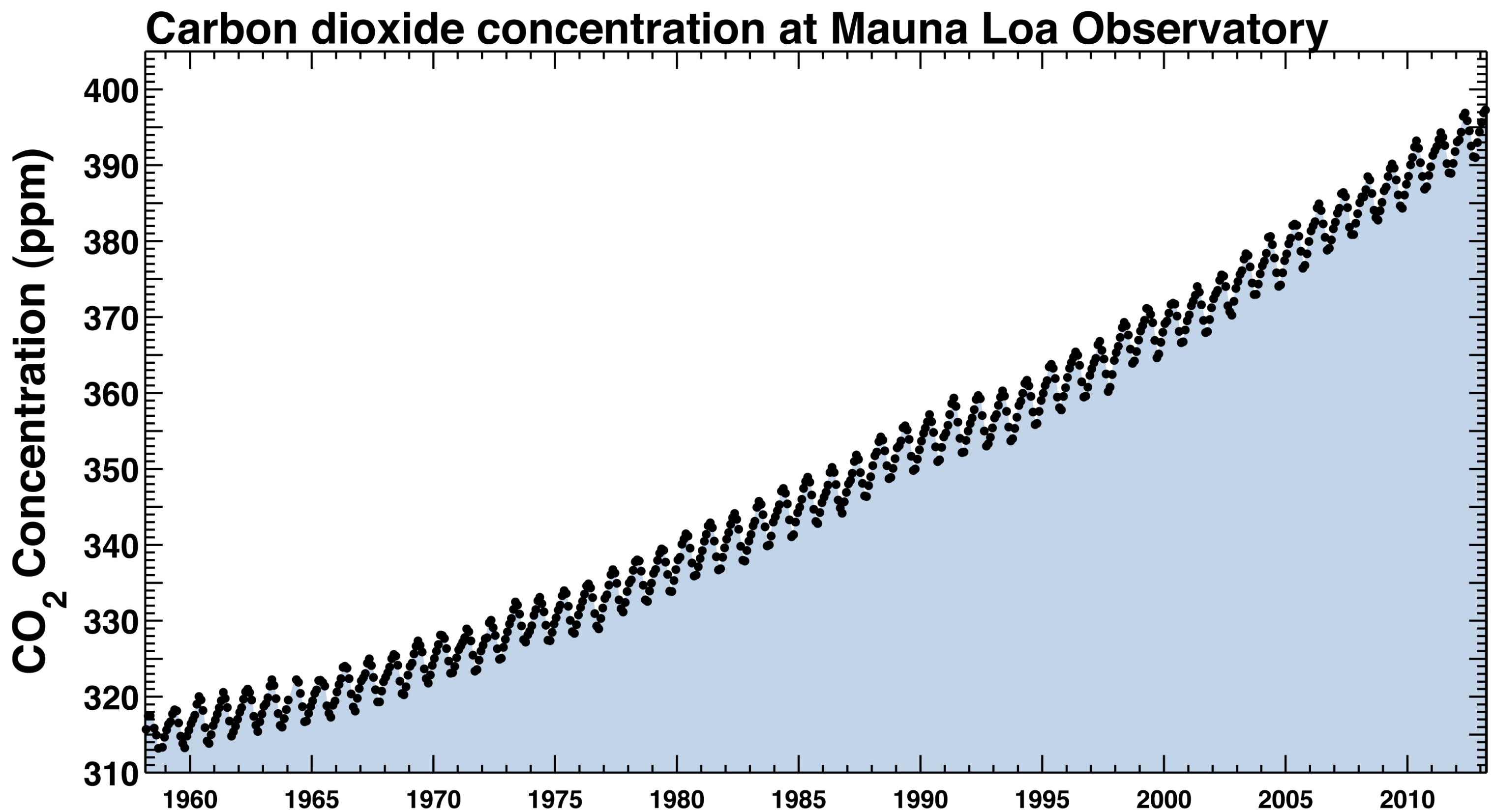
Relation to anthropogenic climate change is made through relation to atmosphere trends that are footprints of A.C.C. (night vs. day temperature, troposphere vs. stratosphere heating/cooling, low vs. high latitude warming)

Long-term atmospheric measurements: drivers of climate change

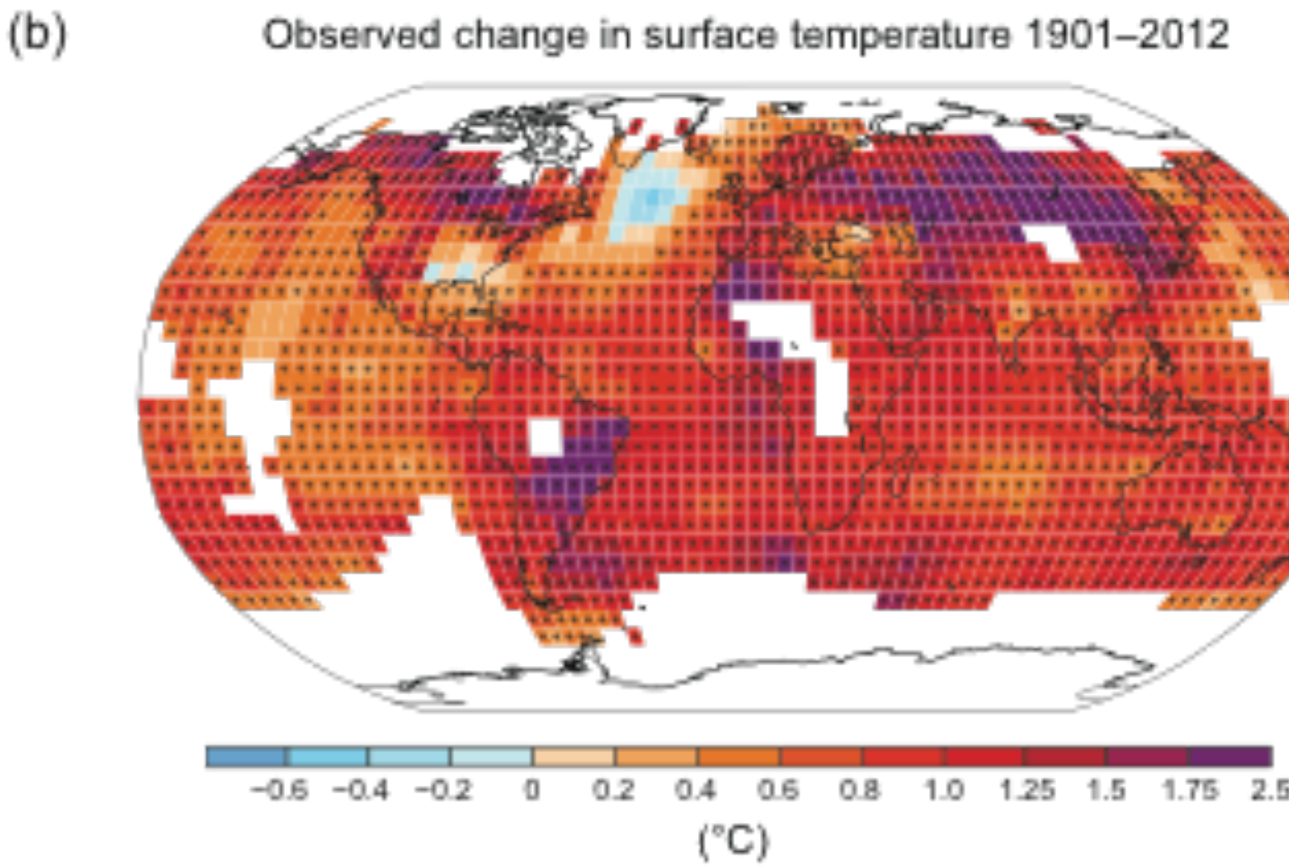


Attribution of changes in radiative forcing since 1750 (IPCC AR5 WG1, 2013)

Long-term atmospheric measurements: drivers of climate change

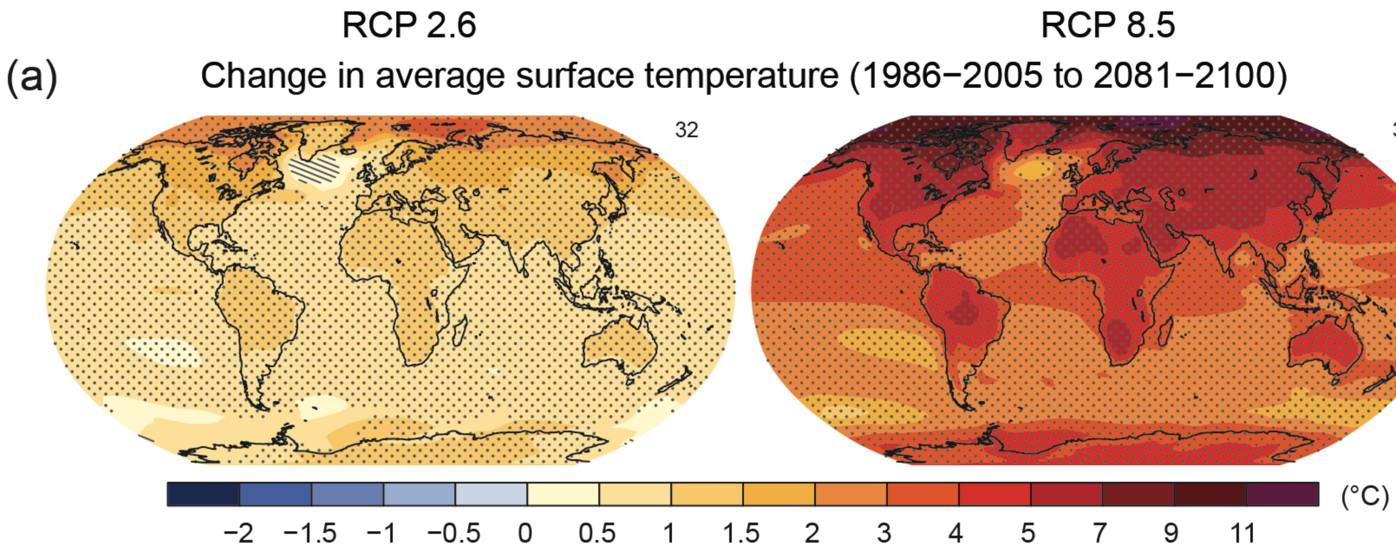


Is the Earth warming? Yes



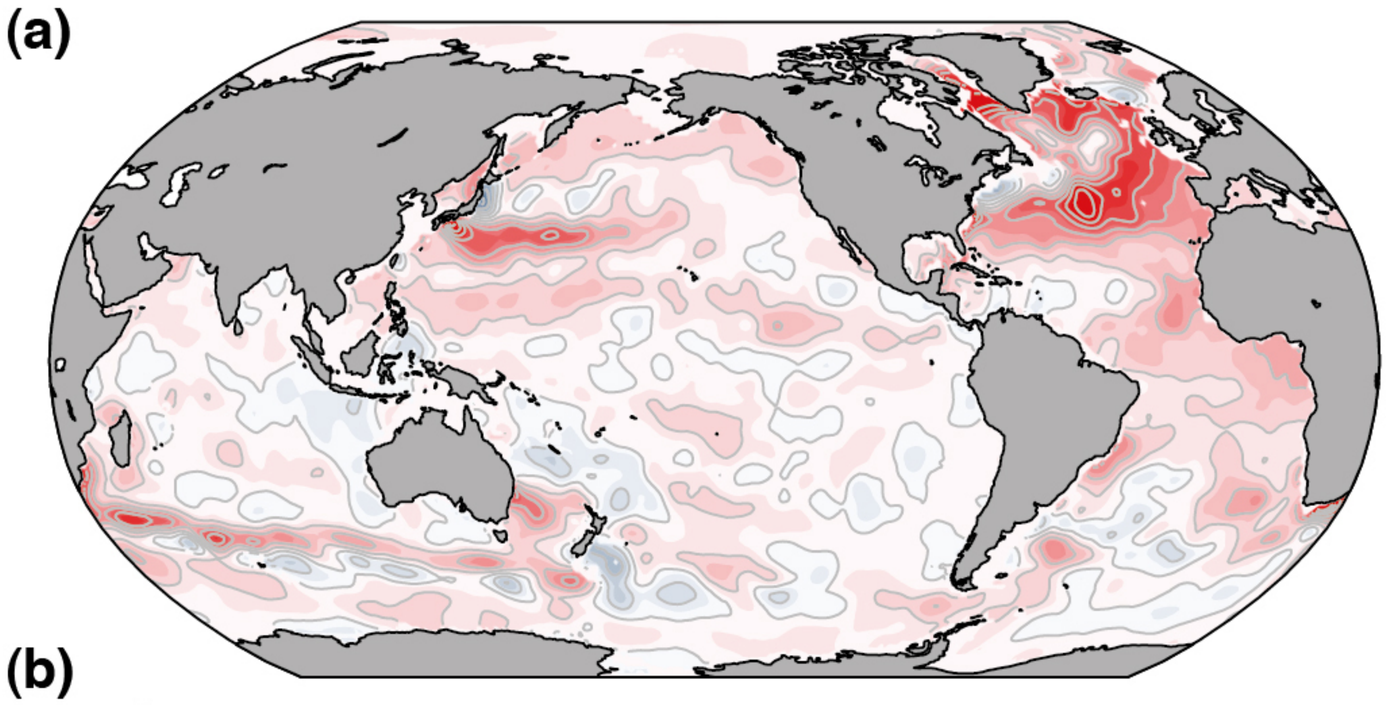
IPCC AR5 (2013) WGI
Summary for Policymakers

Surface temperature projection for 90 years from now



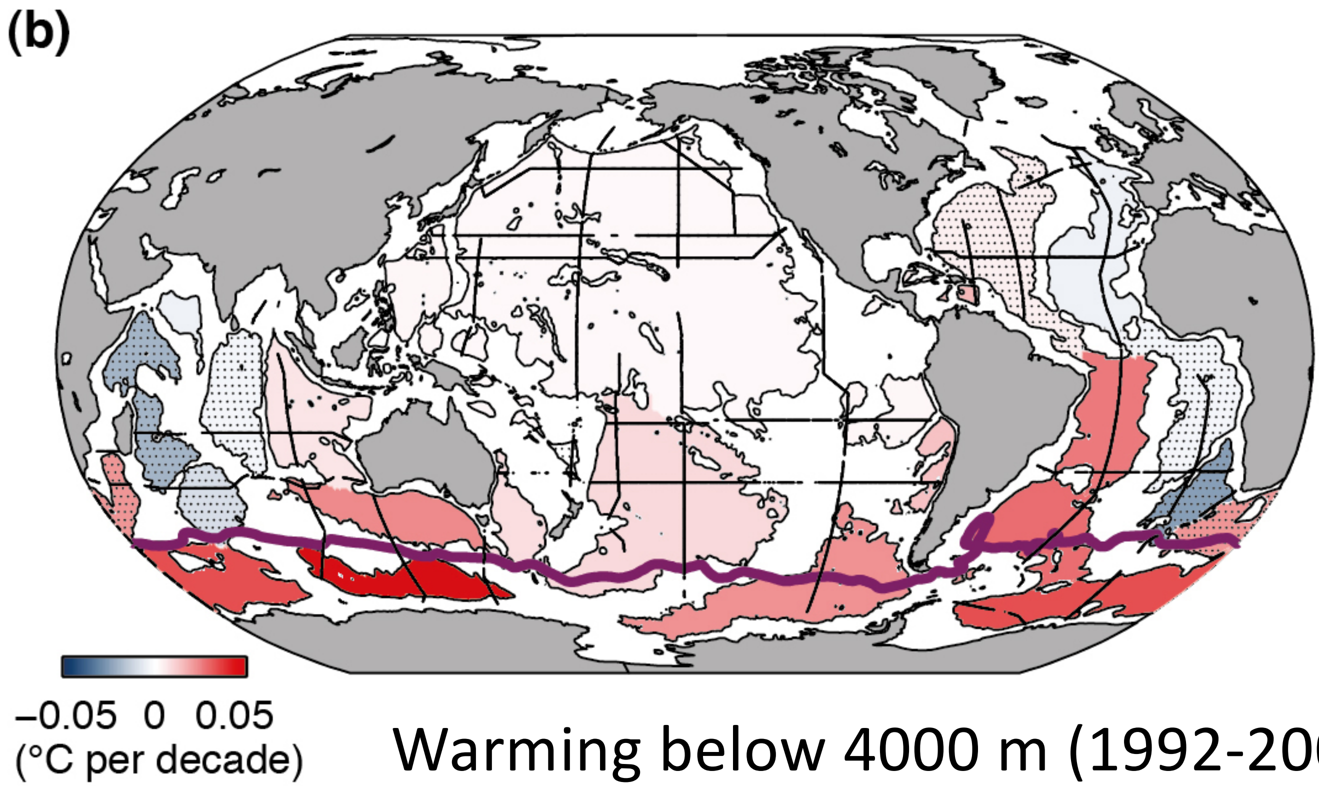
Greatest projected warming in the Arctic and over land

Is ocean temperature changing? Yes



0.3°C in the upper 700 m since 1950

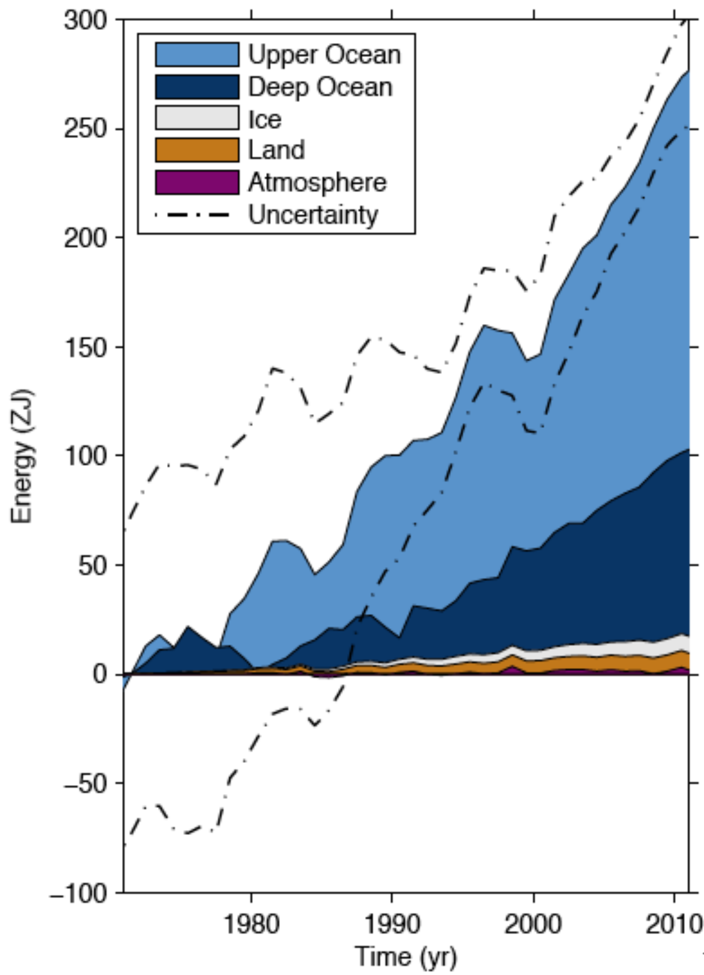
Is the deep ocean temperature changing? Yes – mostly warming



Warming below 4000 m (1992-2005)

Mostly in the Antarctic!

Global warming is ocean warming: 93% of excess heat is in the ocean

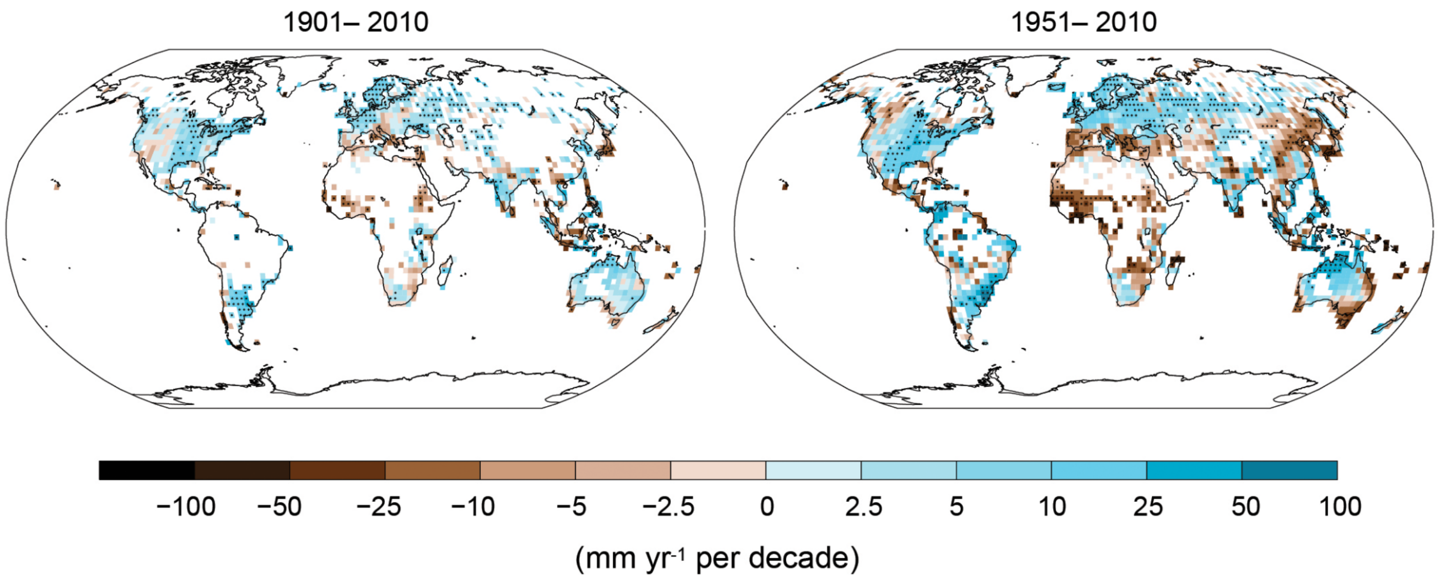


The global energy excess is mostly in the ocean

Atmosphere

IPCC AR5 (2013) WGI Chapter 3 (ocean observations)

Has precipitation changed? Yes

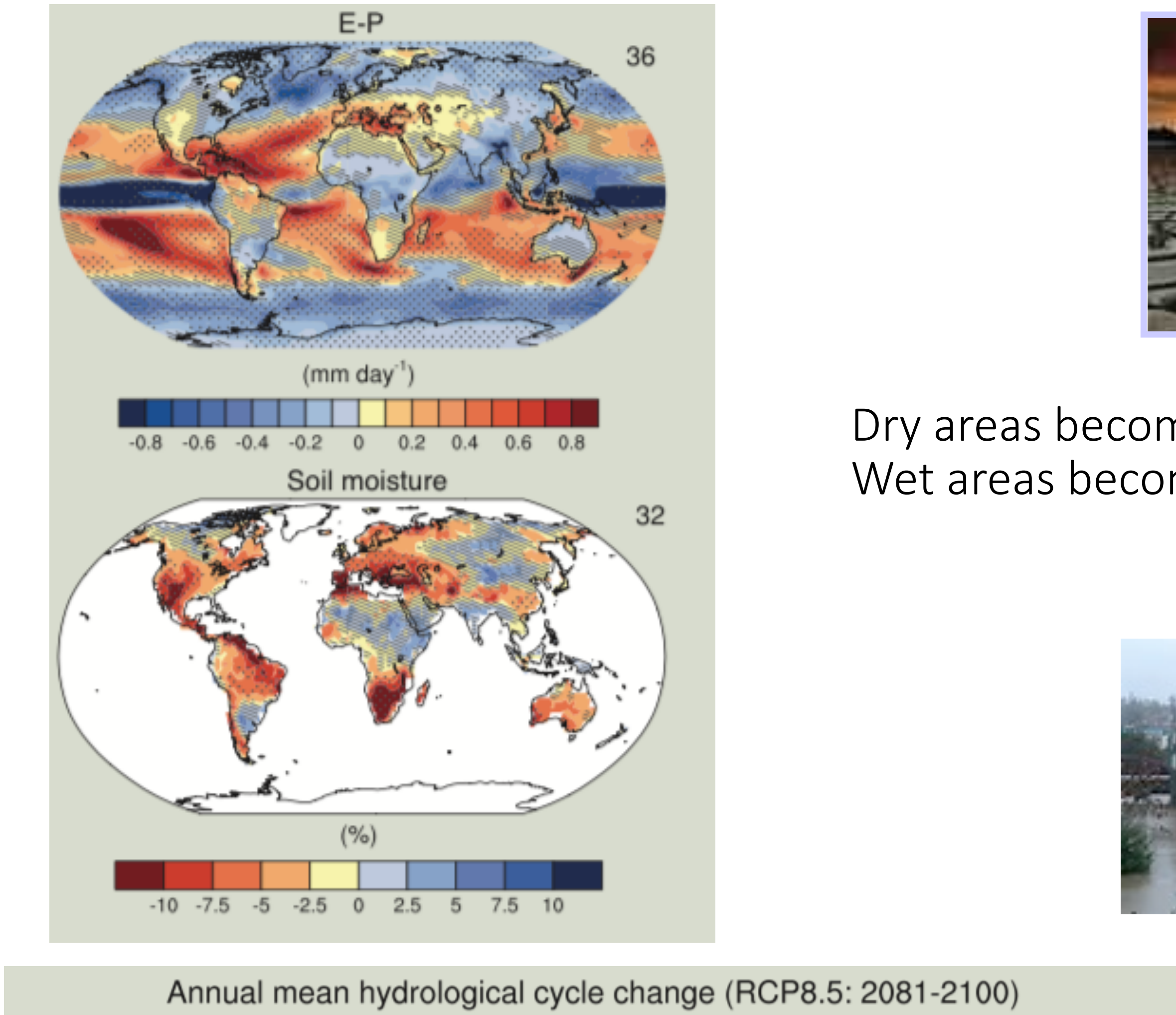


Dry areas ~ becoming drier
Wet areas ~ becoming wetter

Notice that we can only measure long-term changes OVER LAND.
Salinity is the global rain gauge.

IPCC AR5, 2013

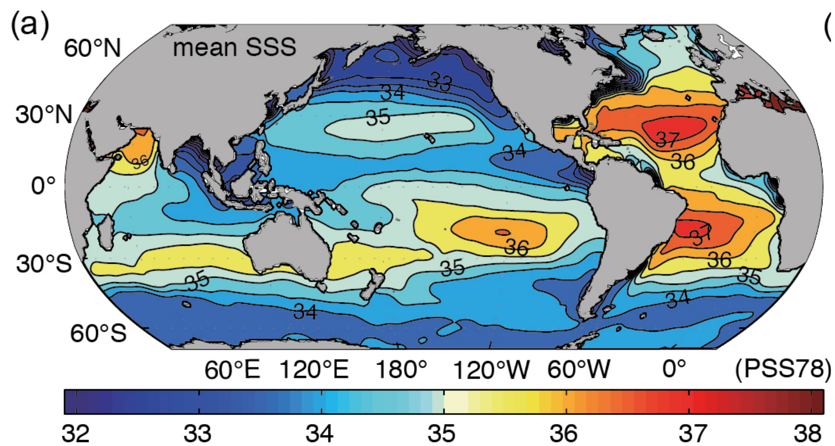
Water cycle projection for 90 years from now



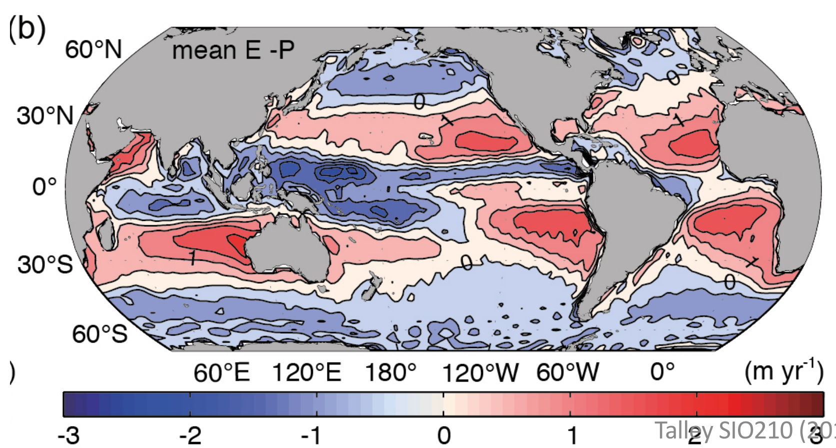
Dry areas become drier
Wet areas become wetter

IPCC AR5, 2013

Ocean surface salinity as rain gauge

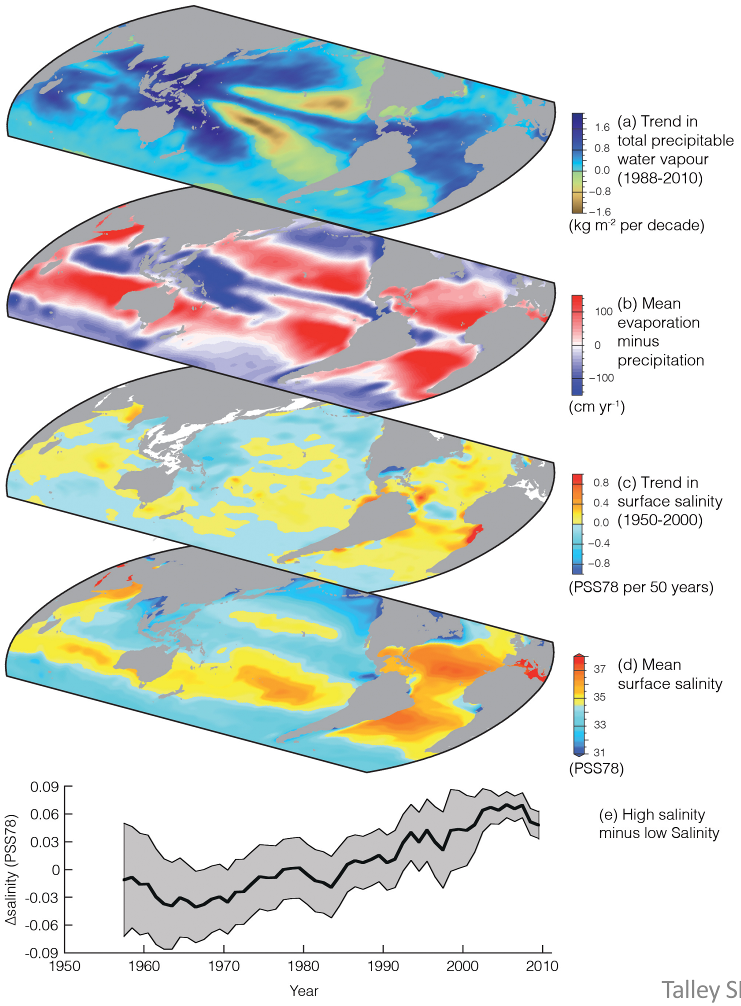


Surface salinity
Orange is salty
Blue is fresh



Evaporation
minus
Precipitation
Red evaporates
Blue rains

Salty areas are getting saltier; fresh areas are getting fresher



Trend in water vapor in atmosphere: mostly wetter (because it's warmer)

Evaporation - precipitation

Trend in surface salinity: Salty getting saltier, fresh getting fresher

Salinity

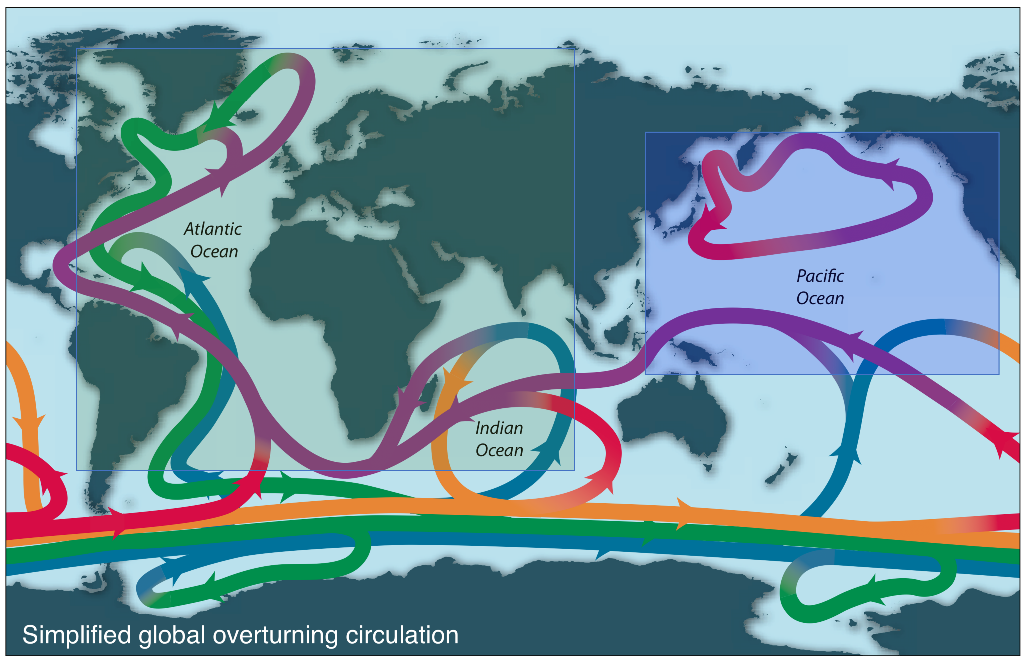
IPCC AR5, 2013

How might these salinity changes affect the ocean's global overturning circulation?

GOC is determined by salinity since there can be very cold water in all high latitude regions.

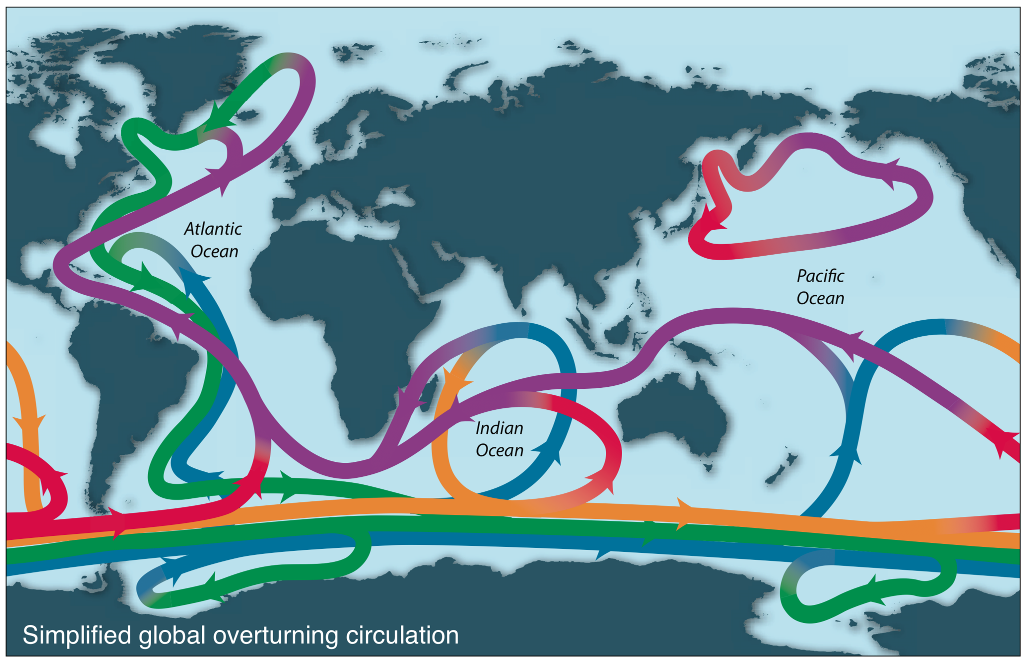
Salty Atlantic/Indian
Deep water sinking
(North Atlantic Deep Water)

Fresher Pacific
NO deep water sinking
(Very old deep water)



How might all of the anthropogenic changes affect the ocean's global overturning circulation (GOC)?

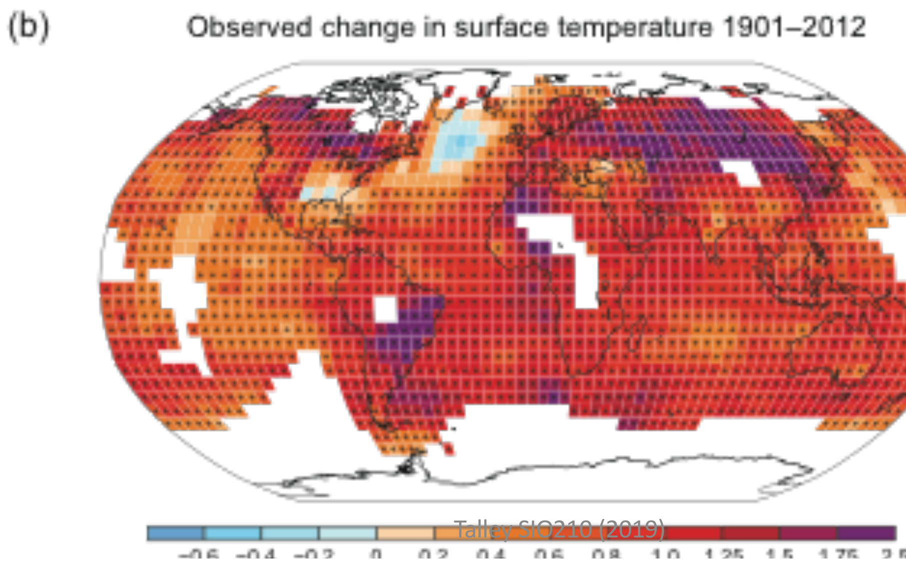
Salinity changes: higher Atlantic salinity, which would strengthen GOC
Warming oceans: more temperature stratified, which would weaken GOC
Wind changes: stronger westerlies, which would increase Antarctic overturning

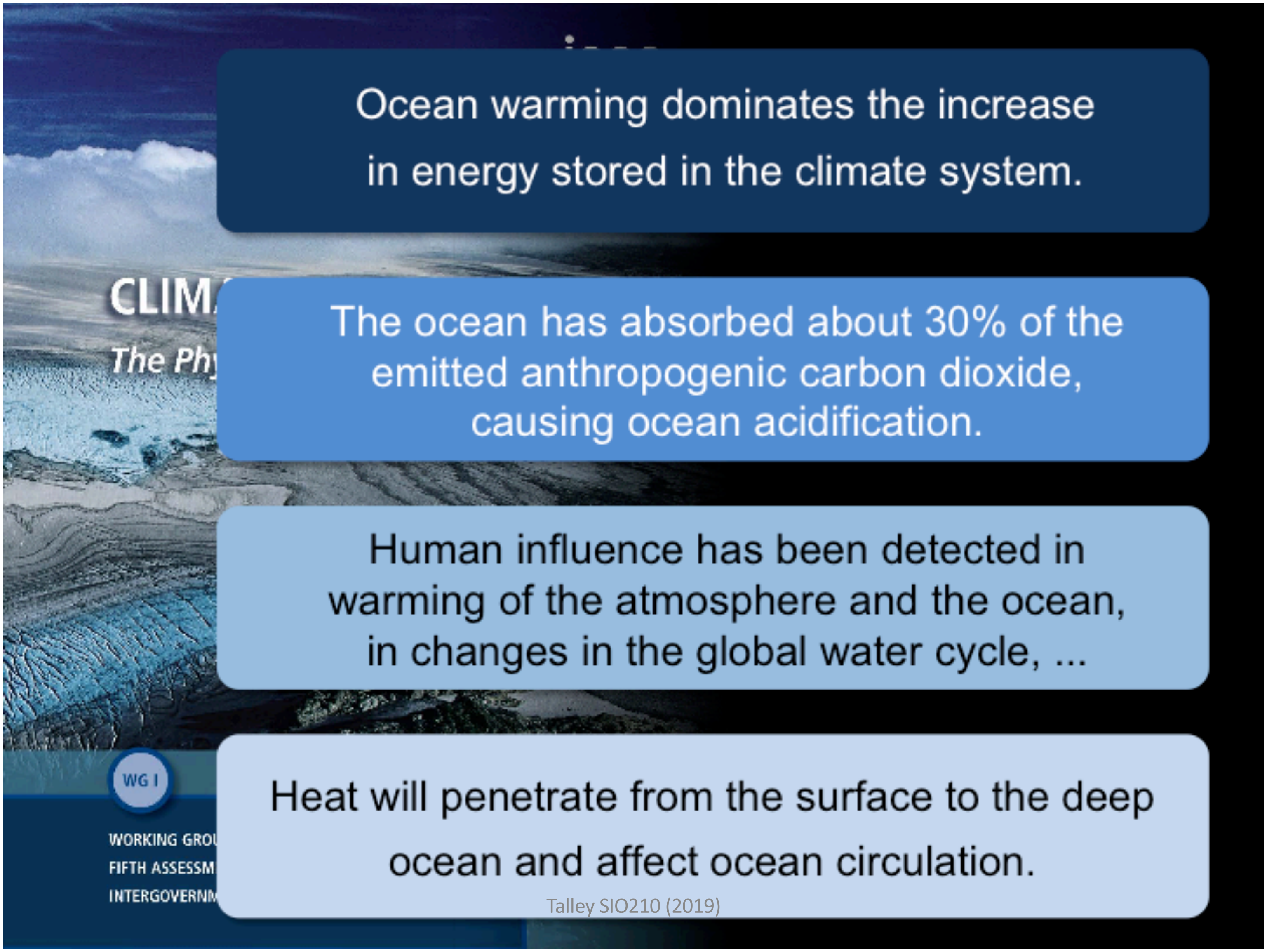


Summary: climate change and oceans

- the Earth is warming now; 93% of heat is in ocean
- the hydrological balance is shifting now
- the oceans are acidifying now
- ice sheets are breaking up
- sea level rise is rising now

All of these are projected to strengthen




Ocean warming dominates the increase in energy stored in the climate system.
The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.
Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, ...
Heat will penetrate from the surface to the deep ocean and affect ocean circulation.
WG I