# *Meridional Overturning Circulation, Ocean Heat Transport and Climate Change*

1) MOC dynamics and mechanisms
2) Ocean Heat Transport

# Abyssal circulation dynamics

Thermohaline = temperature and salinity processes

Thermohaline processes that most strongly impact deep waters:

1.  deep convection:  1000 to 1500 dbar (or more) overturn due to buoyancy loss (mostly cooling that causes densification)

2.  brine rejection: salt rejected from sea ice during formation, most effective when mixed into a shallow layer, say, on a continental shelf.  B.R. in some special sites makes the densest ocean waters.

3.  diffusion:  mixing of heat and salt.  Diapycnal diffusion is essential for deep waters to warm and upwell diapycnally (balances the other two densification processes)
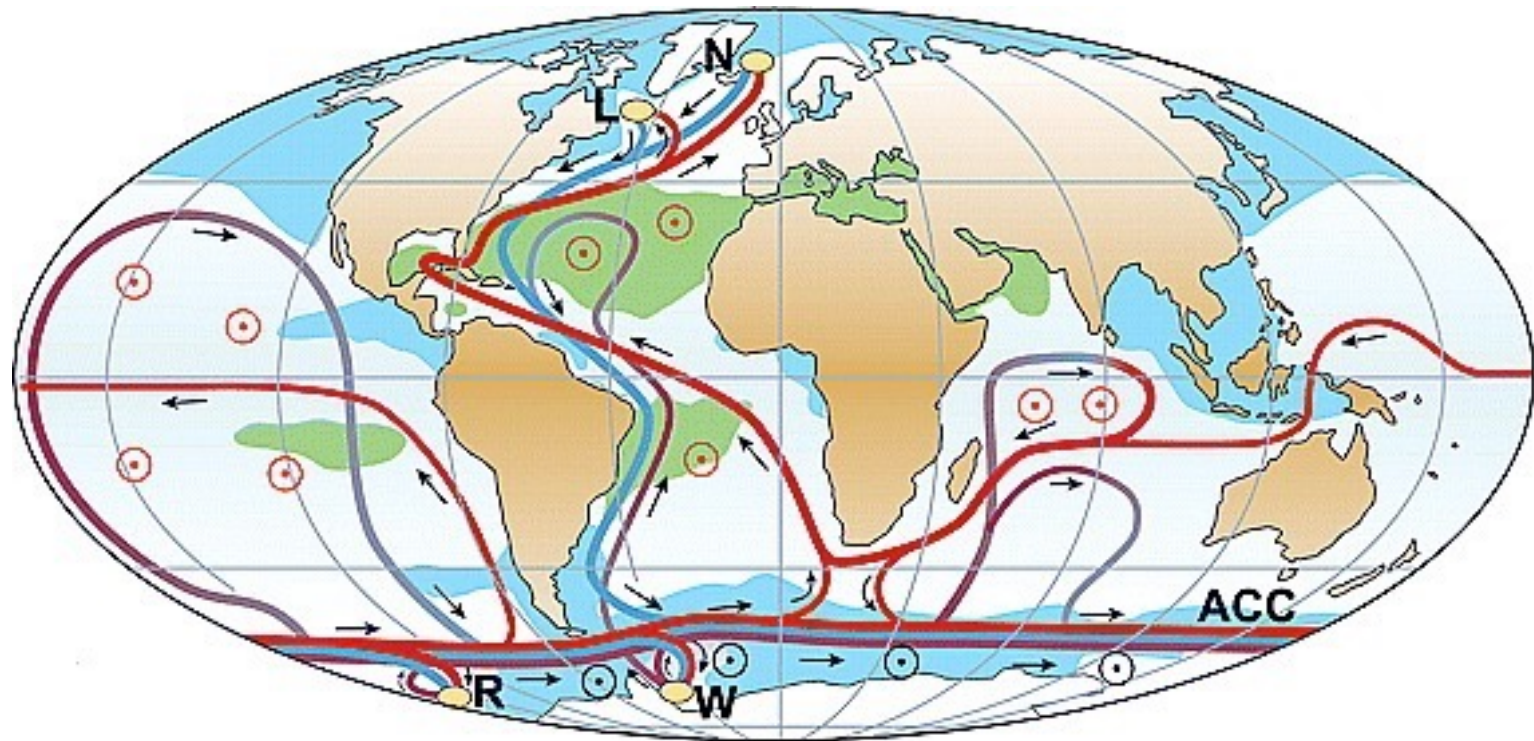
# Abyssal circulation dynamics

Controversy on names:

"Thermohaline circulation": widely used to describe this very large-scale overturn. Involves sources of dense water and Deep Western Boundary Currents and return warm flow to feed the isolated dense sources.

In physical oceanography, we also refer to "abyssal circulation" when discussing the theory of deep circulation (*See Stommel-Aaron's Model*)

"Meridional overturning circulation": essentially the same as THC, but acknowledging that diffusion is a very important factor in controlling the flow, that diffusion itself does not result from thermohaline forcing (but from turbulence due to the **wind** and **tides**), and that wind also upwells deep waters.
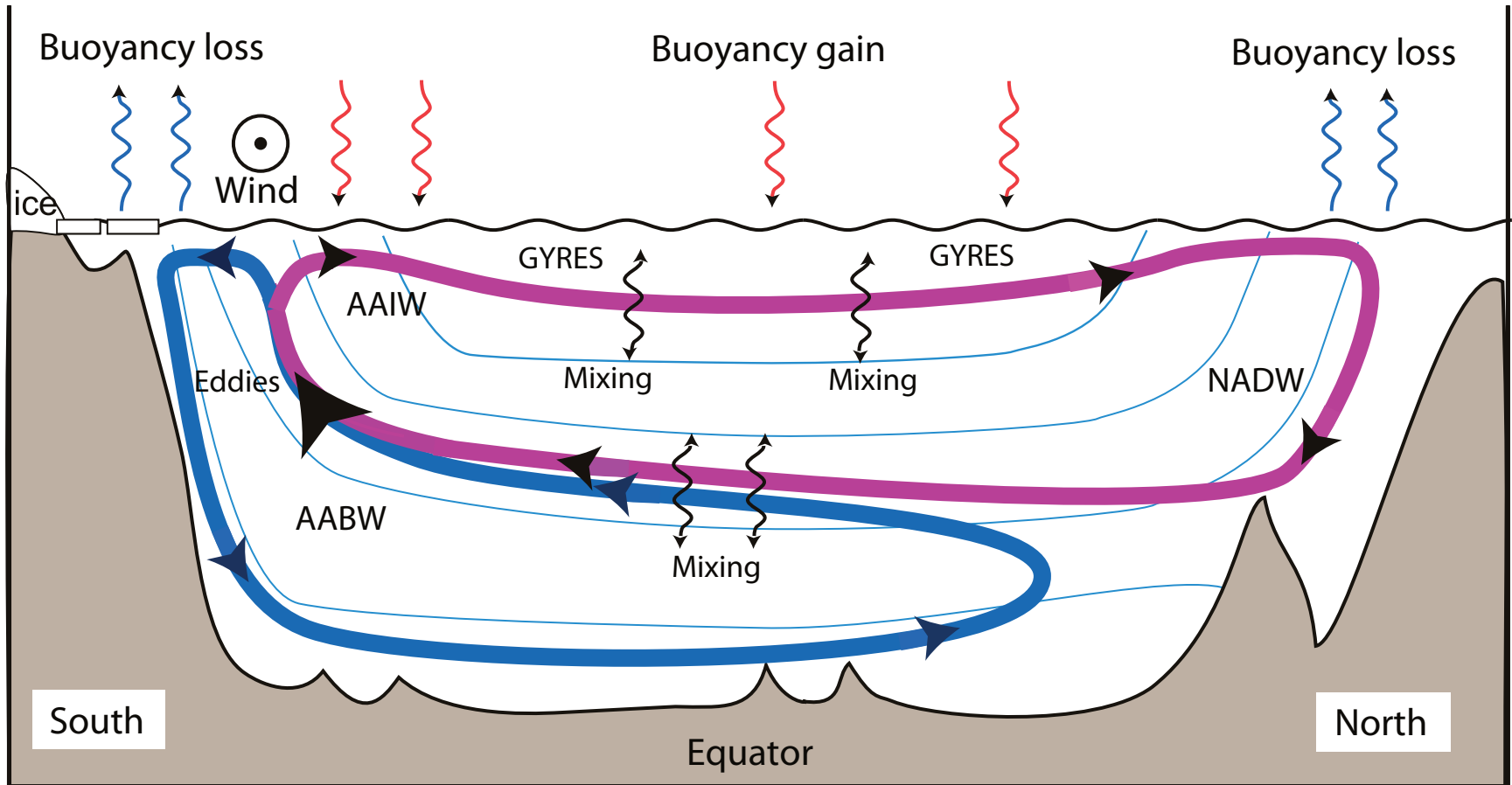
# Meridional Overturning Circulation



| | | |
|---|---|---|
| ── Surface flow | ⊙ Wind-driven upwelling | L Labrador Sea |
| ── Deep flow | ⊙ Mixing-driven upwelling | N Nordic Seas |
| ── Bottom flow | Salinity > 36 ‰ | W Weddell Sea |
| ⌀ Deep Water Formation | Salinity < 34 ‰ | R Ross Sea |

# Buoyancy and Wind-driven MOC

# What is thermo-haline circulation (THC) ?

THC is that part of the ocean circulation which is driven by fluxes of heat and freshwater across the sea surface and subsequent interior mixing of heat and salt.
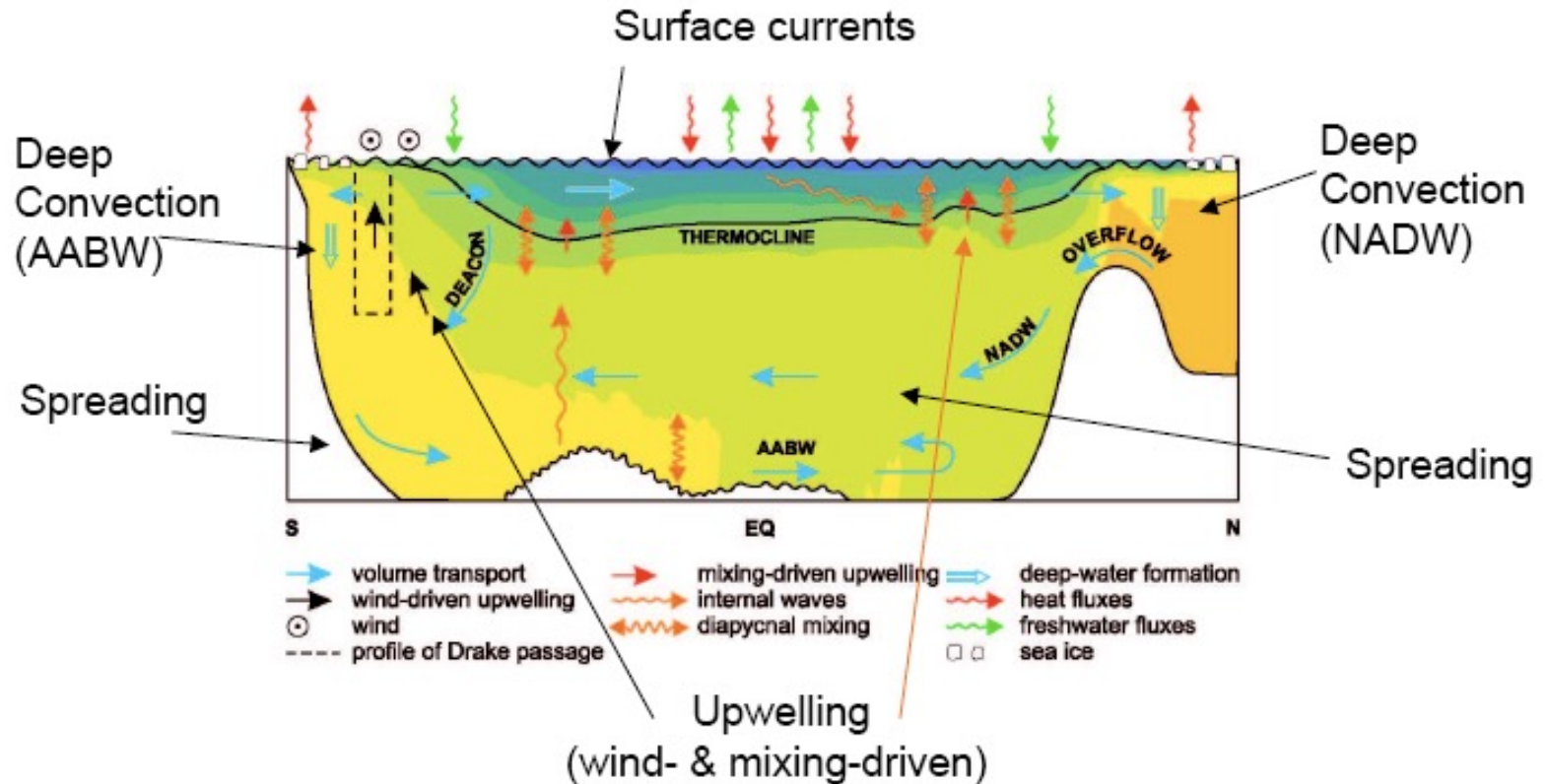


Its drivers are: (a) turbulent diapycnal mixing, (b) wind-driven upwelling in the Southern Ocean

# Mixing & Winds

## Case 1

$\rho 2$

Mixing

$\rho 1$

## Case 2

Wind

$\rho 2$

$\rho 1$

◯ dense to light water conversion

Sketch of the two extreme cases: "only diapycnal mixing" (case 1) and "only wind-driven upwelling" (case 2).

The curved line indicates the thermocline that separates denser from lighter waters.
The open circles indicate regions of dense-to-light conversion of water masses (Water Mass Transformation)
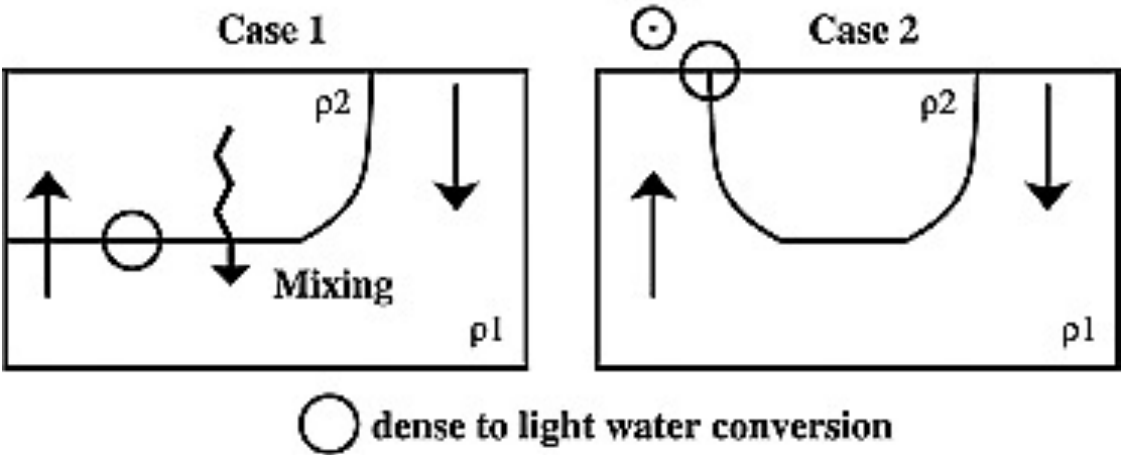
A more 'realistic' AMOC.
The two cells are driven by both diapycnal mixing and wind-driven upwelling.
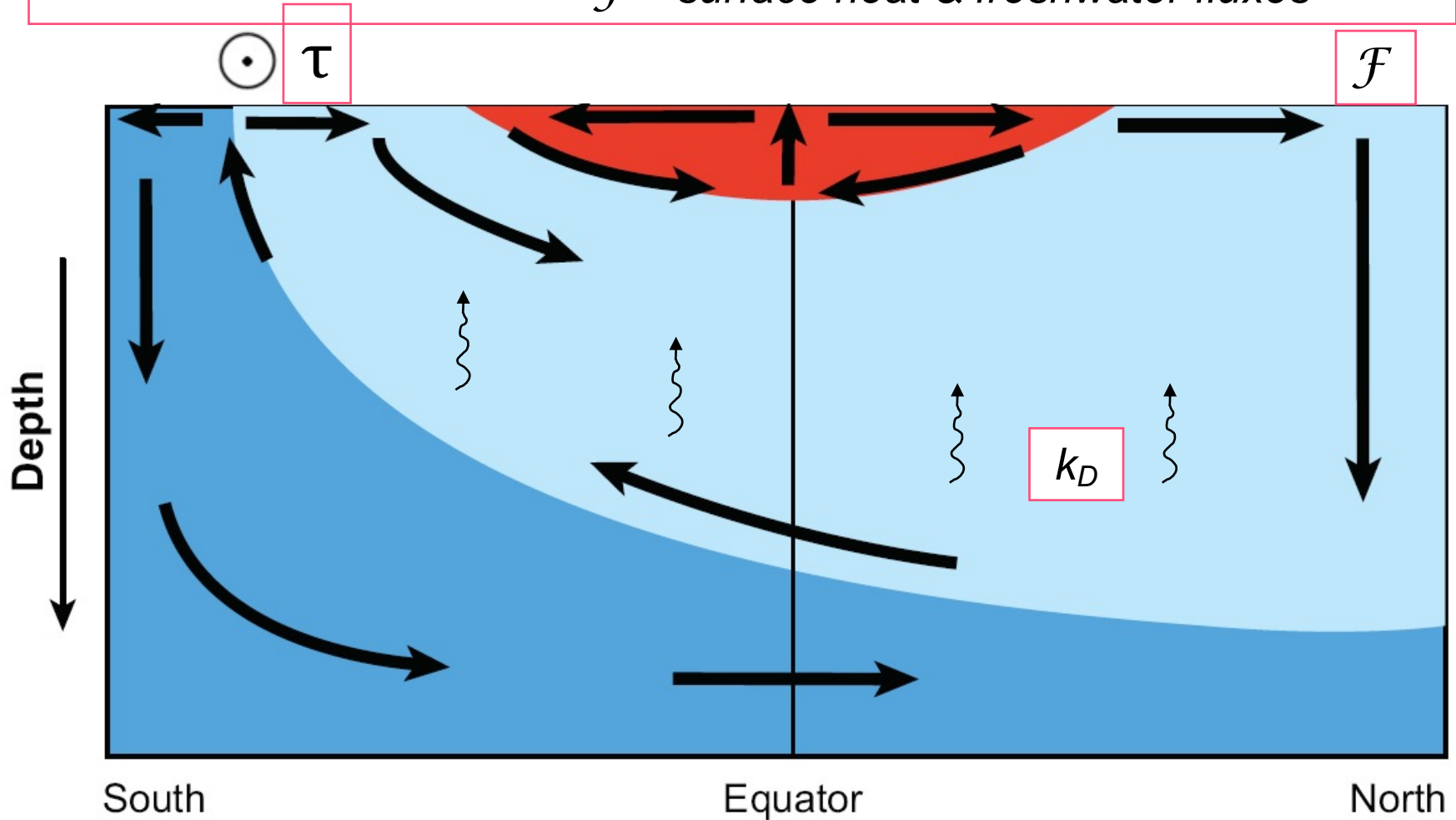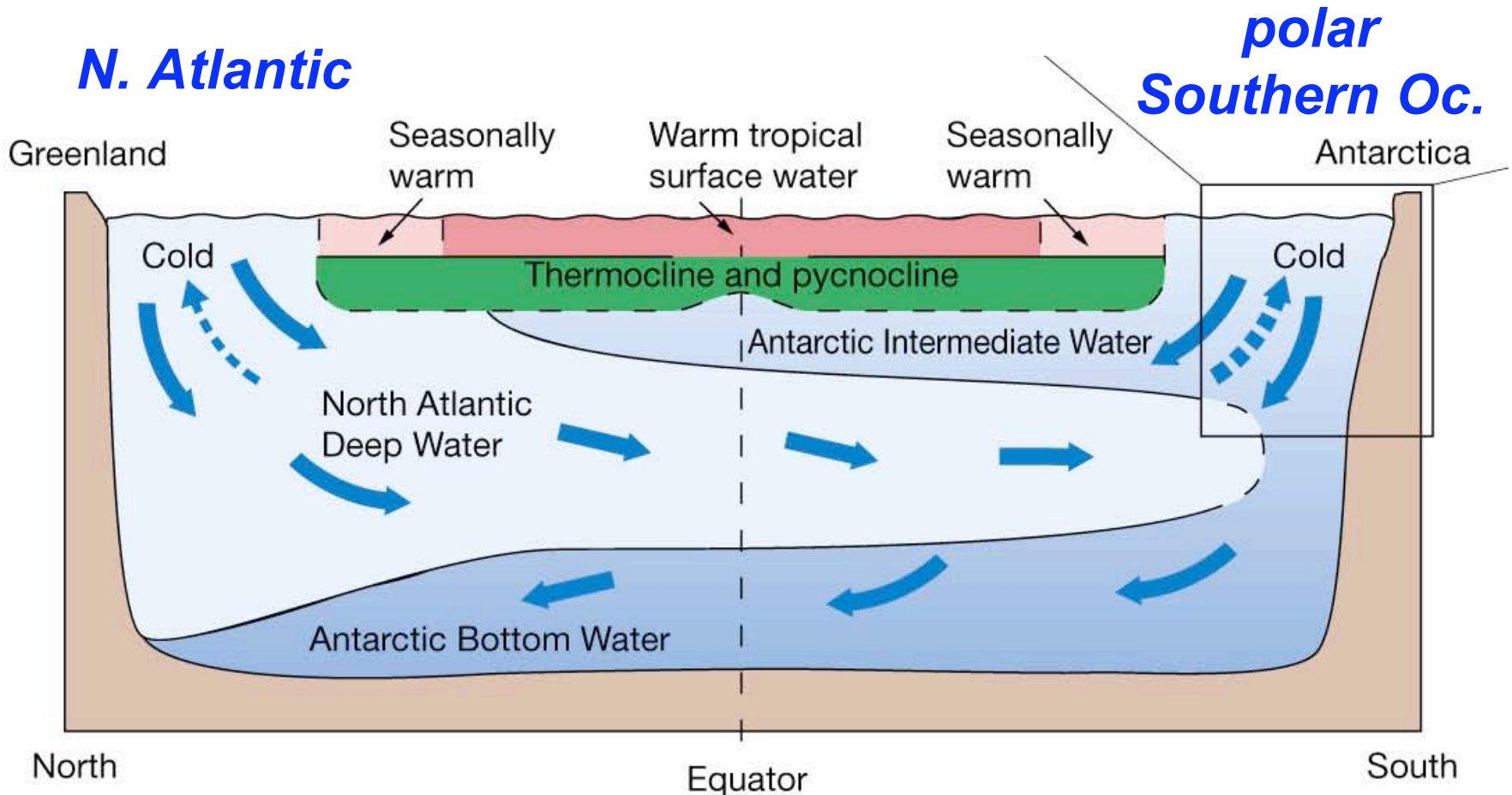
IW

27.4

NADW

27.8

AABW

28.2

S          EQ          N
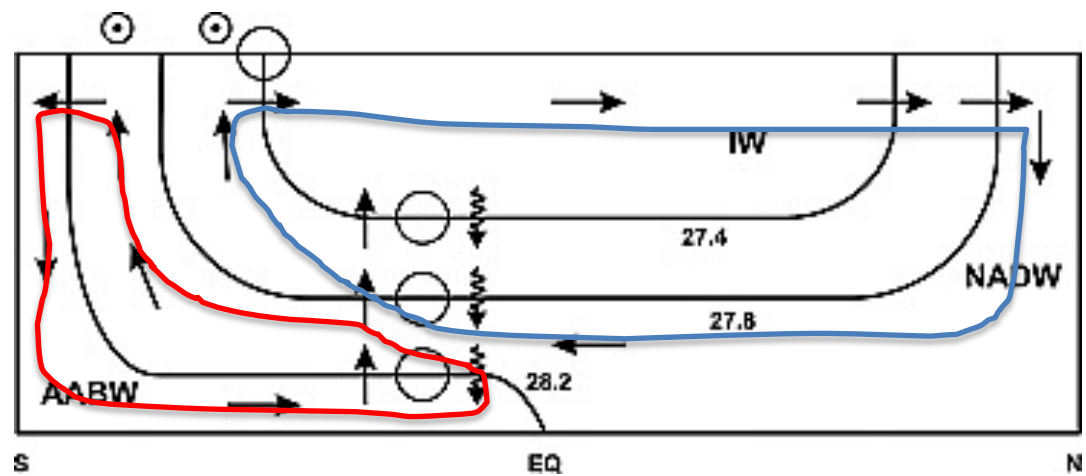
*Important parameters:*     $\tau$ – *wind stress in the Southern ocean*
    $k_D$ – *diapycnal diffusivity*
    $\mathcal{F}$ – *surface heat & freshwater fluxes*

$\tau$

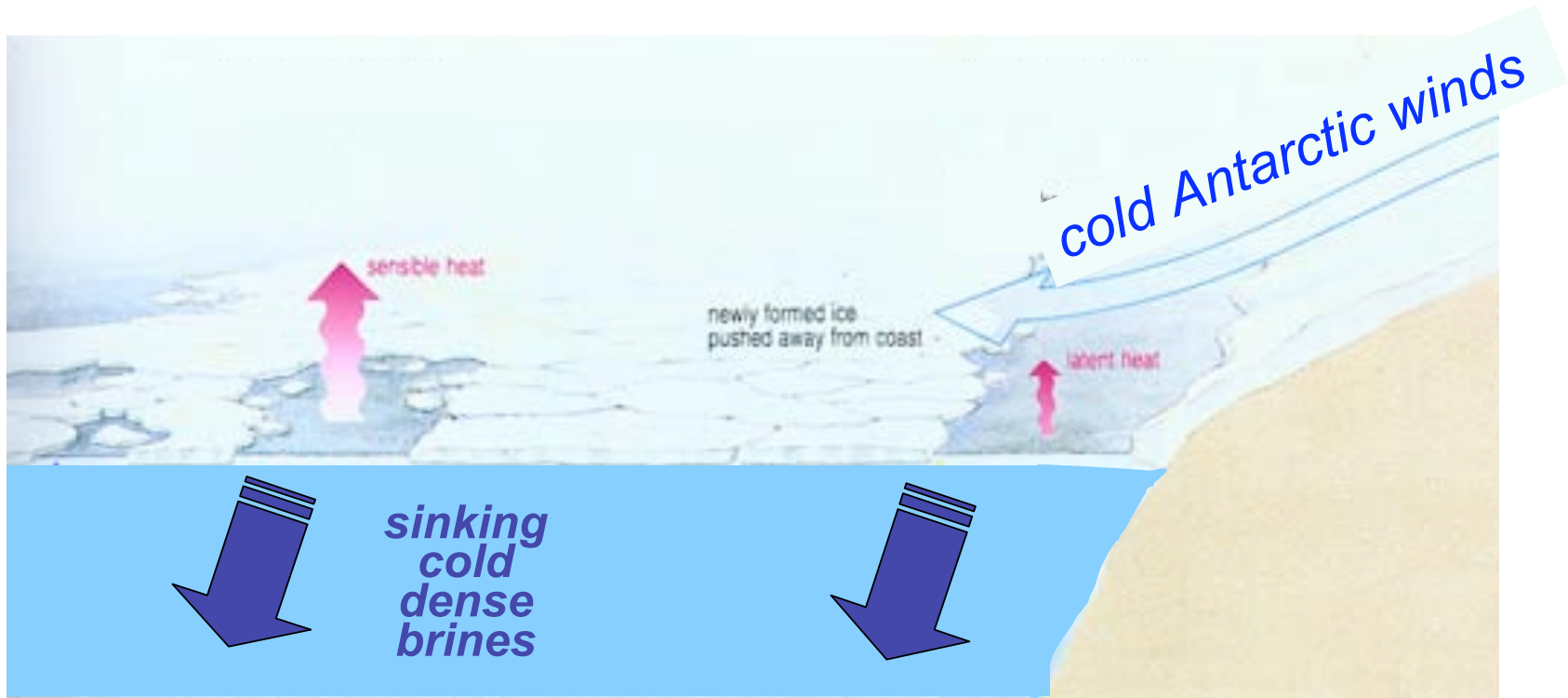$\mathcal{F}$

Depth

$k_D$

South

Equator

North

# polar sources of deep water



*waters cooled at high latitudes fill the ocean interior with cold, dense water*

# the Antarctic sea-ice factory



cold winds blow sea-ice out to sea as it formed, allowing continual formation of new sea ice… as sea ice is formed from sea water, salt is rejected, enriching salt content below

*the extra salt promotes deep water formation (i.e. "Antarctic Bottom Water")*

# Deep convection and brine rejection sites

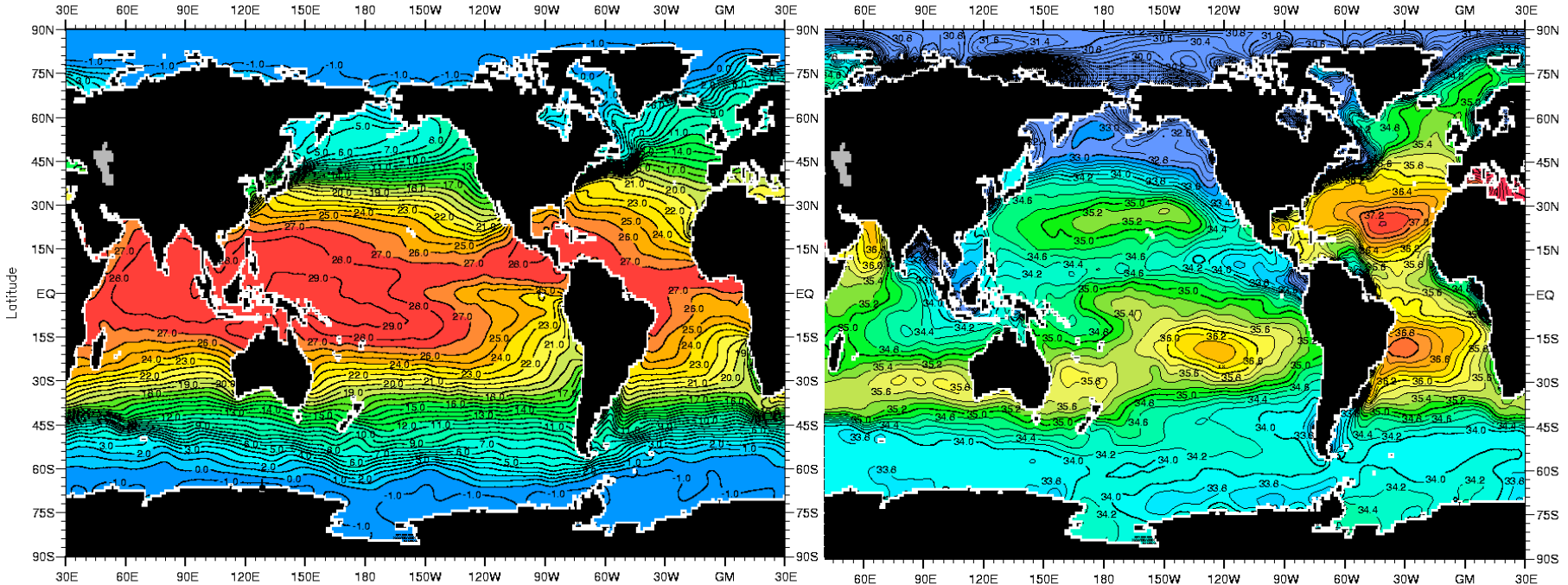Labrador Sea    Greenland Sea    Mediterranean Sea

**Brine rejection in all sea ice areas**



Ross Sea    Weddell Sea
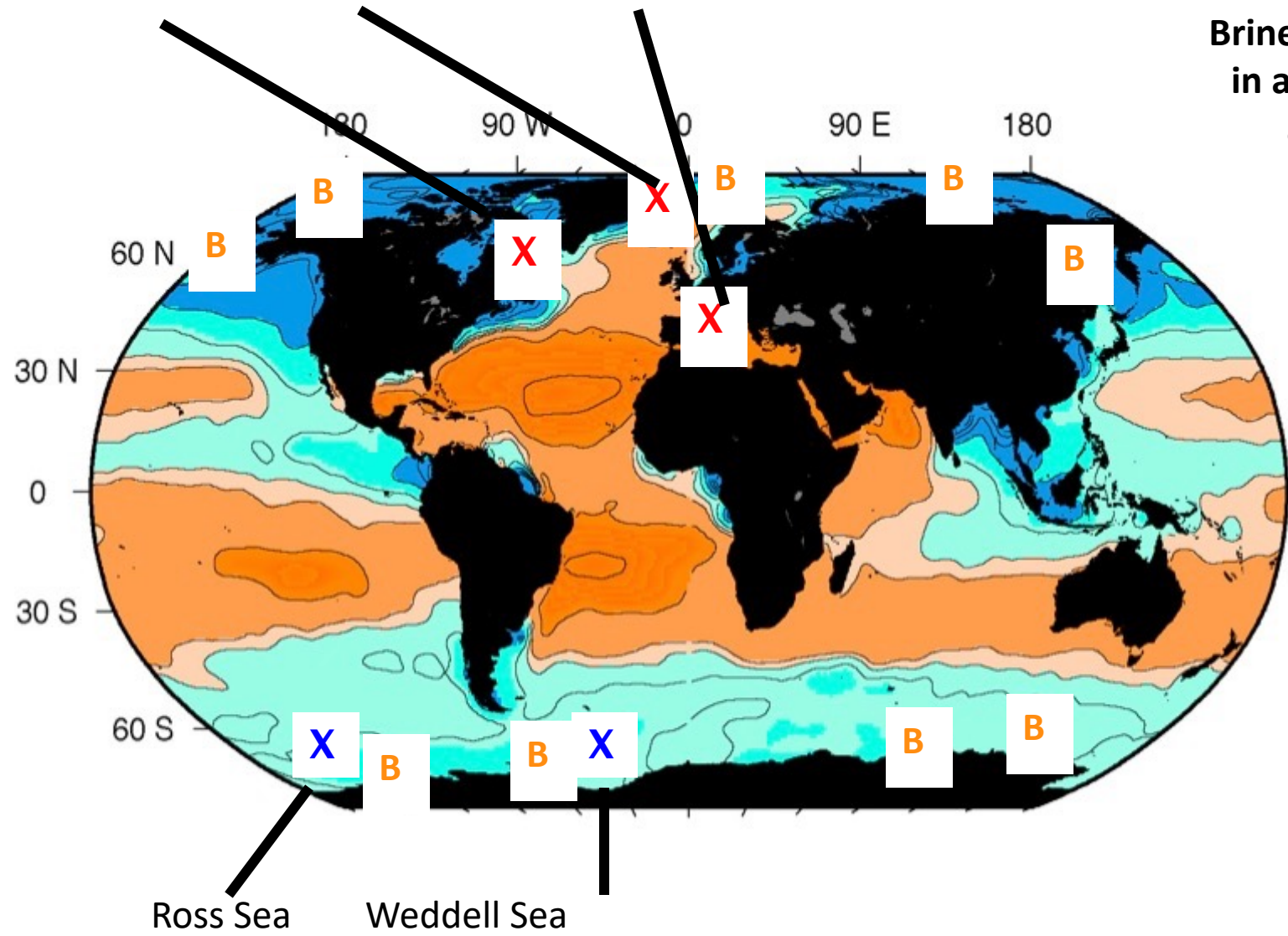
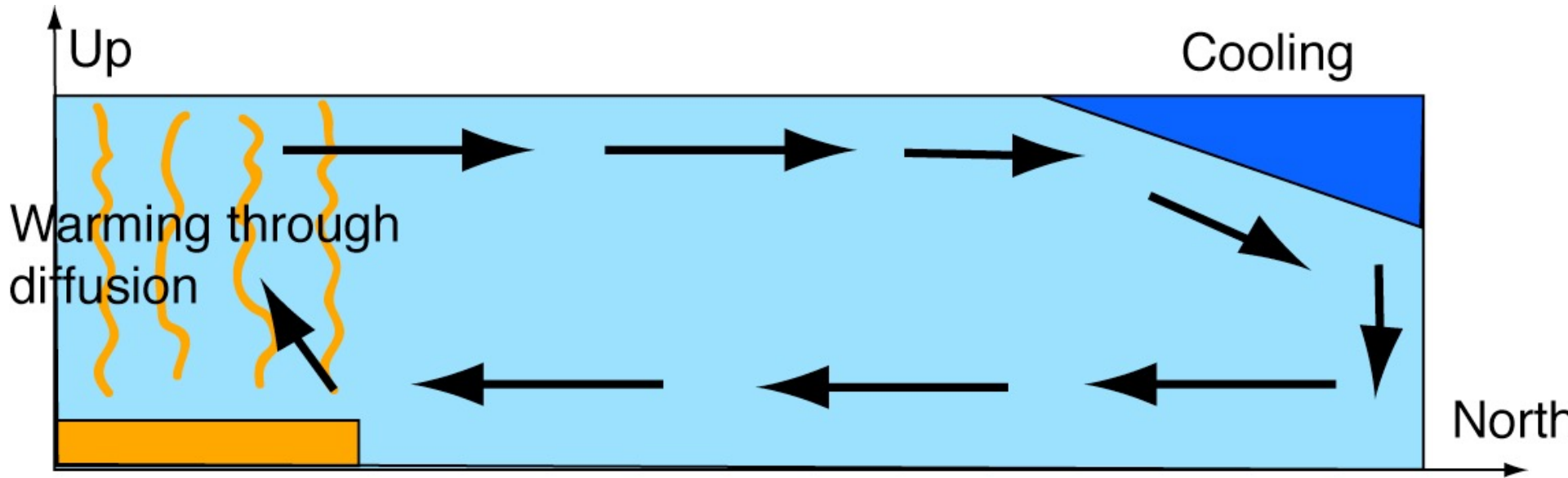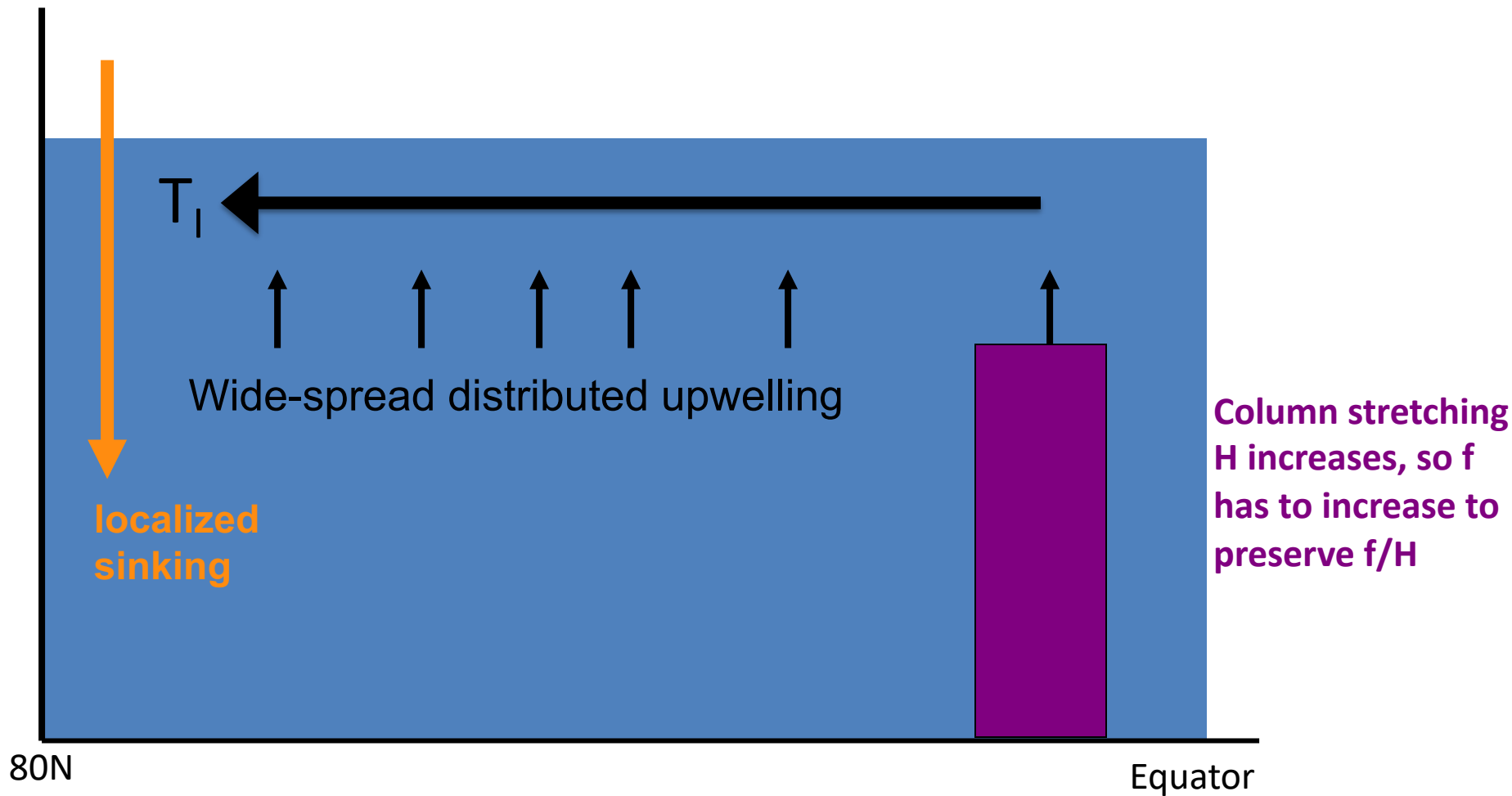# clicker question:

temperature

salinity



**surface waters are cold throughout the high latitudes, so why might deep water formation occur in the N. Atlantic but not in the N. Pacific?**

**a) not *really* cold in N. Pac, b) not windy enough, c) Coriolis wrong direction, d) <u>not salty enough</u>, e) too sunny**
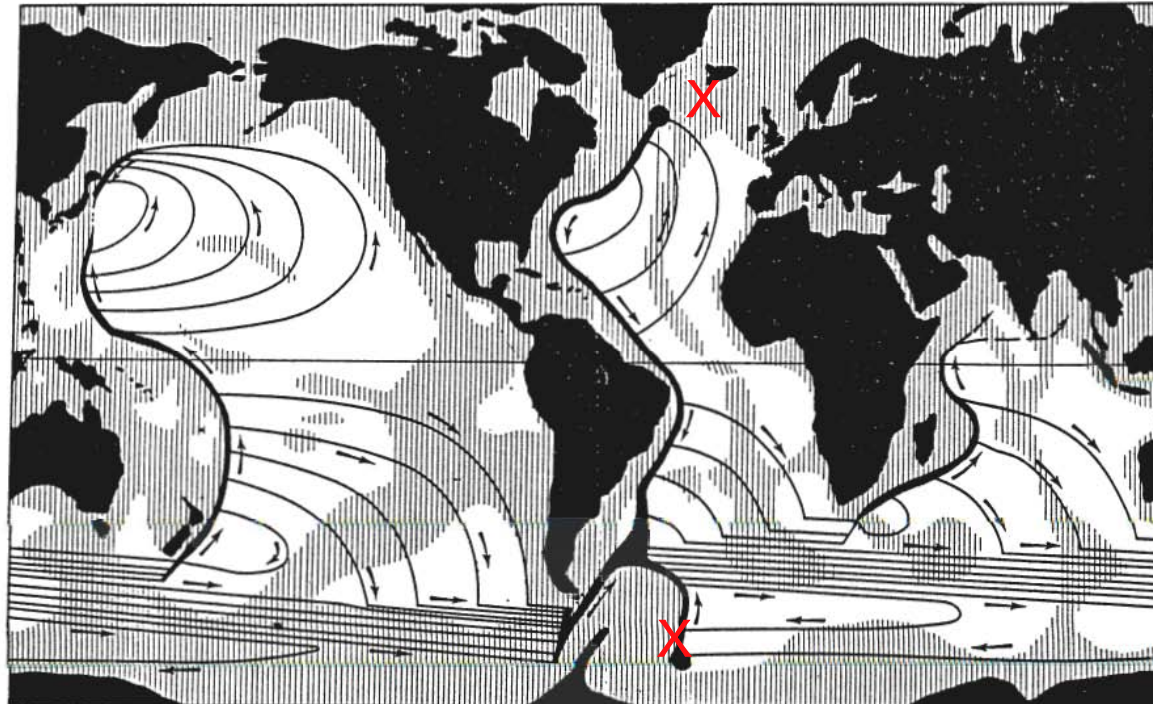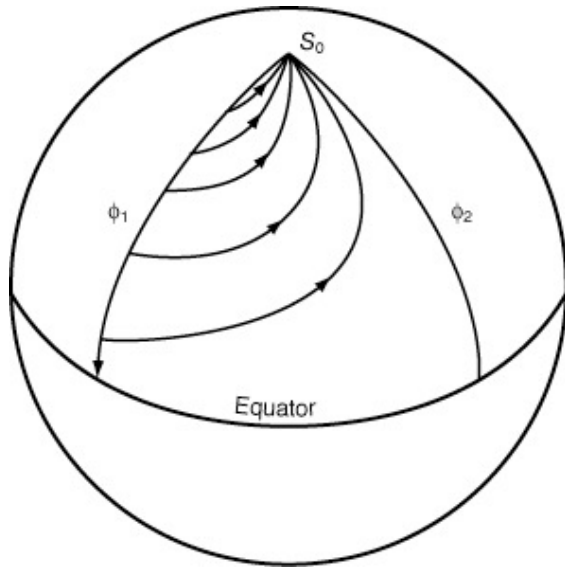
# Abyssal circulation dynamics

Diffusion (diapycnal, i.e. across isopycnals) is required to return convected/cooled waters back upwards to surface

$T_l$

Wide-spread distributed upwelling

localized sinking

Column stretching H increases, so f has to increase to preserve f/H

80N

Equator

**Remember the conservation of PV, and the STommel-Arons model**

# Abyssal circulation: Stommel-Arons model



1/ Local deep water sources $S_0$

2/ General upwelling U

3/ Yields poleward interior flow ($T_i$), connected with Deep Western Boundary Currents ($T_w$)
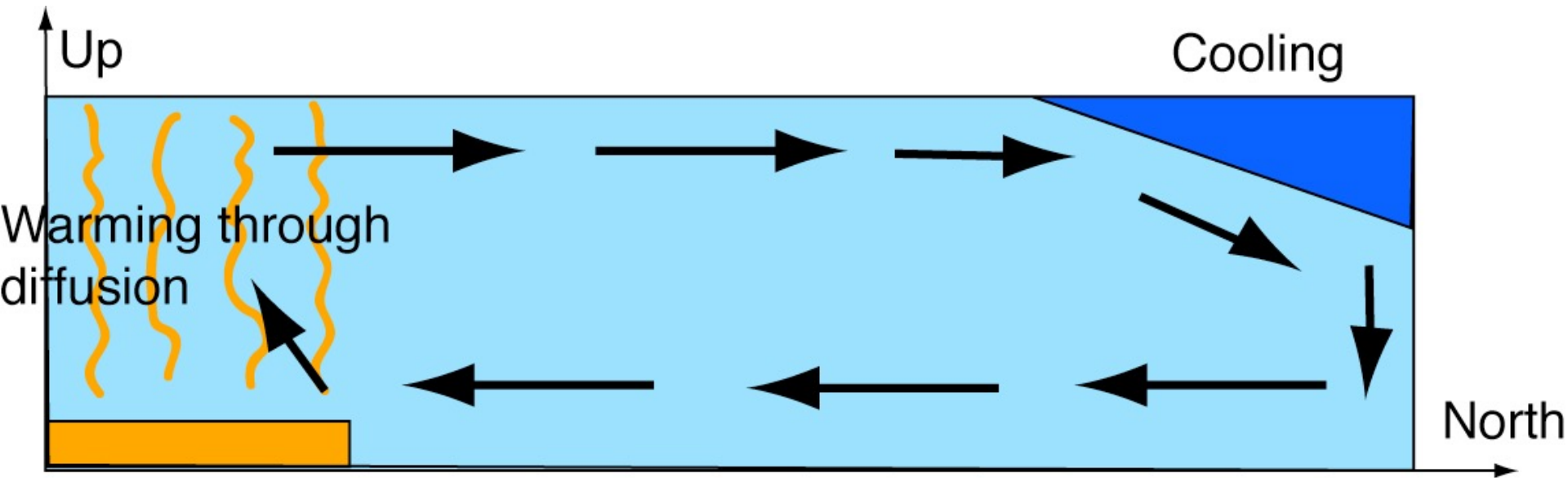
# Very idealized model of global DWBCs (Stommel, 1958)
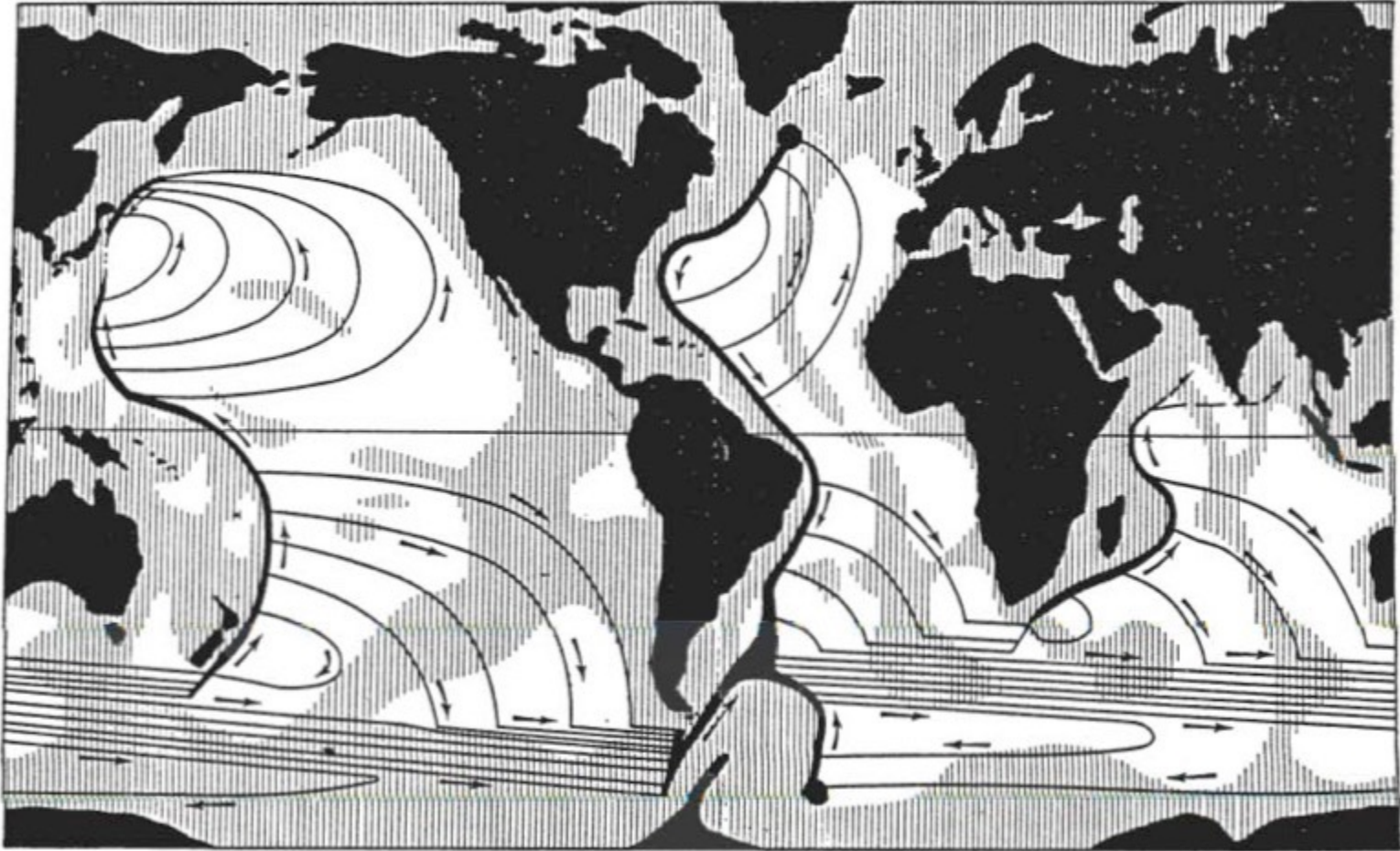


**No topography**

**2 sources:NADW and AABW (very idealized versions!!!)**

**Poleward (weak) interior flow, strong DWBCs to connect flows**

# What about the upwelling part of the meridional overturning?



Diffusion (diapycnal, i.e. across isopycnals) is required to return convected/cooled waters back upwards to surface

It can be argued that the diapycnal diffusivity governs the overall strength of the overturn, rather than the convection rates (which are small).

This is true in coarse-resolution numerical ocean models! ...

# What causes the diapycnal diffusivity?

It is both tides (surface tides creating internal tides, creating internal waves that break in the deep ocean and cause turbulence)

And wind

(creating internal waves that break in the deep ocean, or eddies)

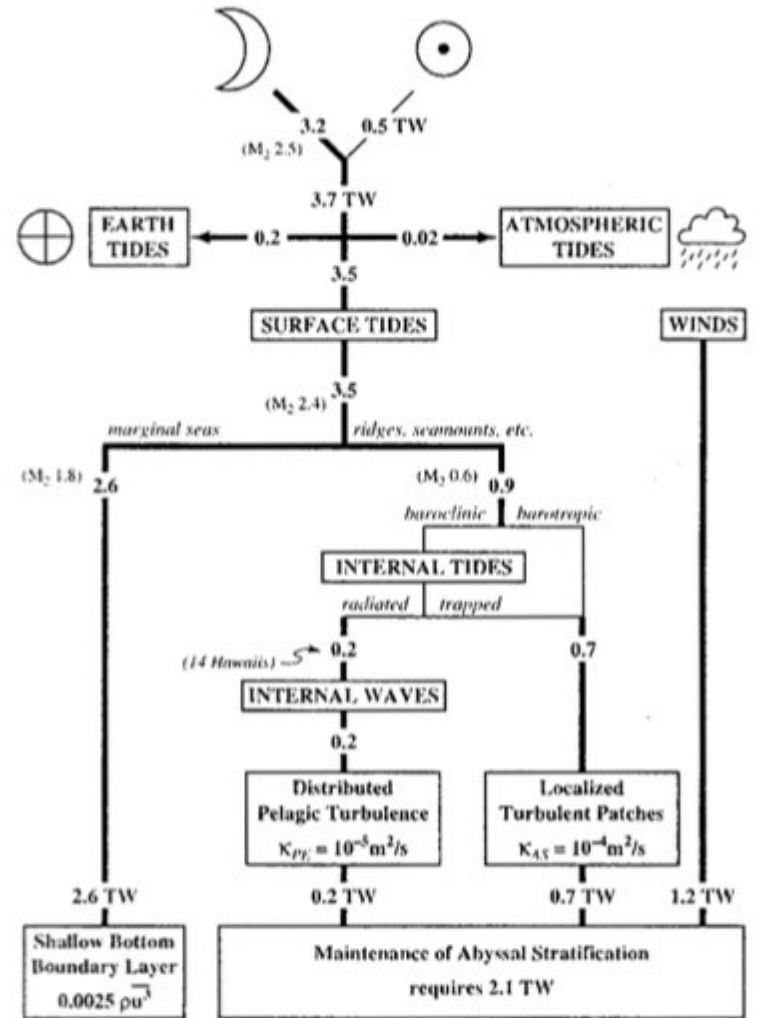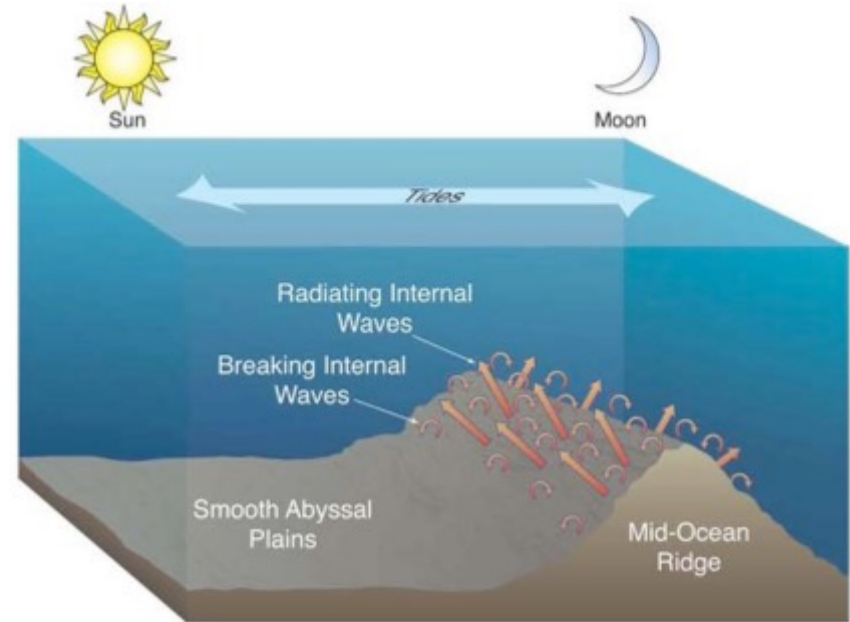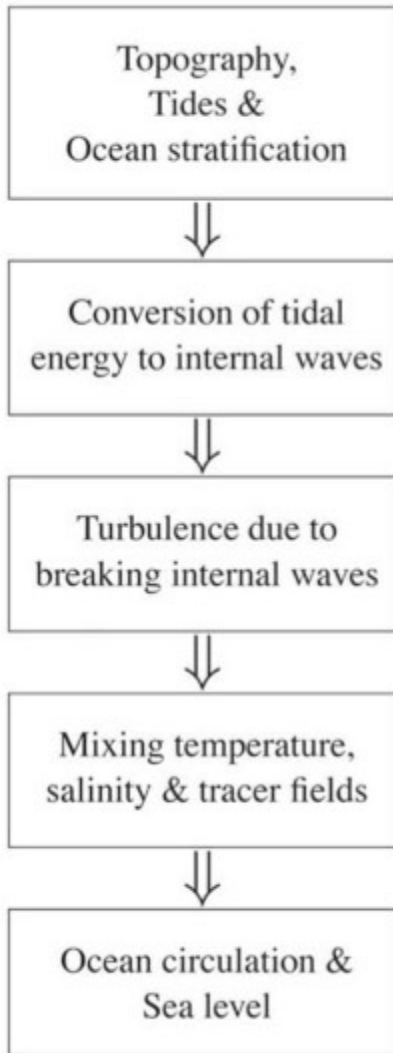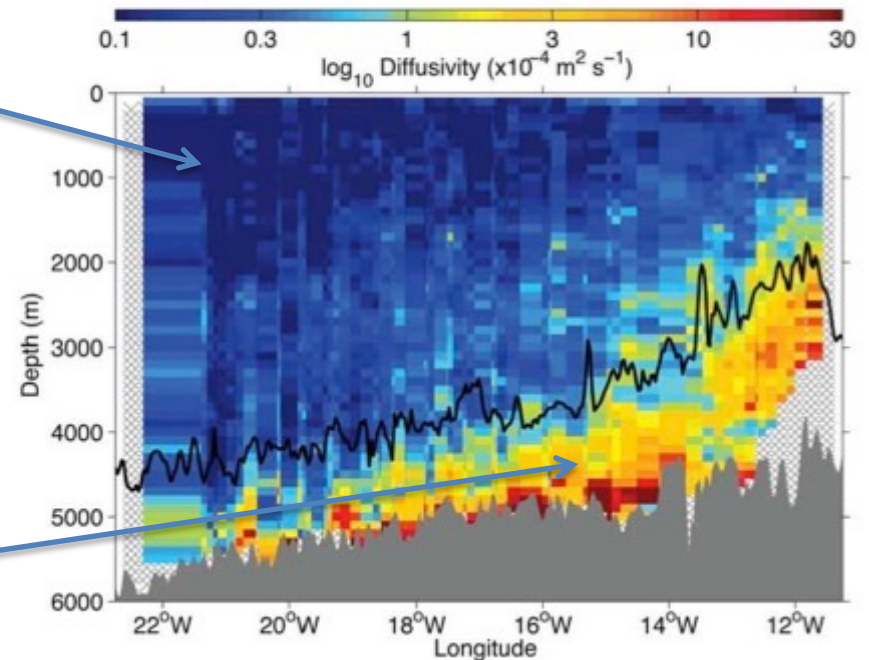Seminal paper by Munk and Wunsch (1998)



Fig. 4. An impressionistic budget of tidal energy flux. The traditional sink is in the bottom boundary laye (BBL) of marginal seas. Preliminary results from Egbert (1997) based on TOPEX/-POSEIDON altimetry suggest that 0.9 TW (including 0.6 TW of $M_2$ energy) are scattered at open ocean ridges and seamounts Light lines represent speculation with no observational support. "14 Hawaiis" refers to an attempted globa extrapolation of surface to internal tide scattering measured at Hawaii, resulting in 0.2 TW available for internal wave generation. The wind energy input is estimated from Wunsch (1998), to which we hav added 0.2 TW to balance the energy budget. This extra energy is identified as wind-generated interna waves — radiating into the abyss and contributing to mixing processes.

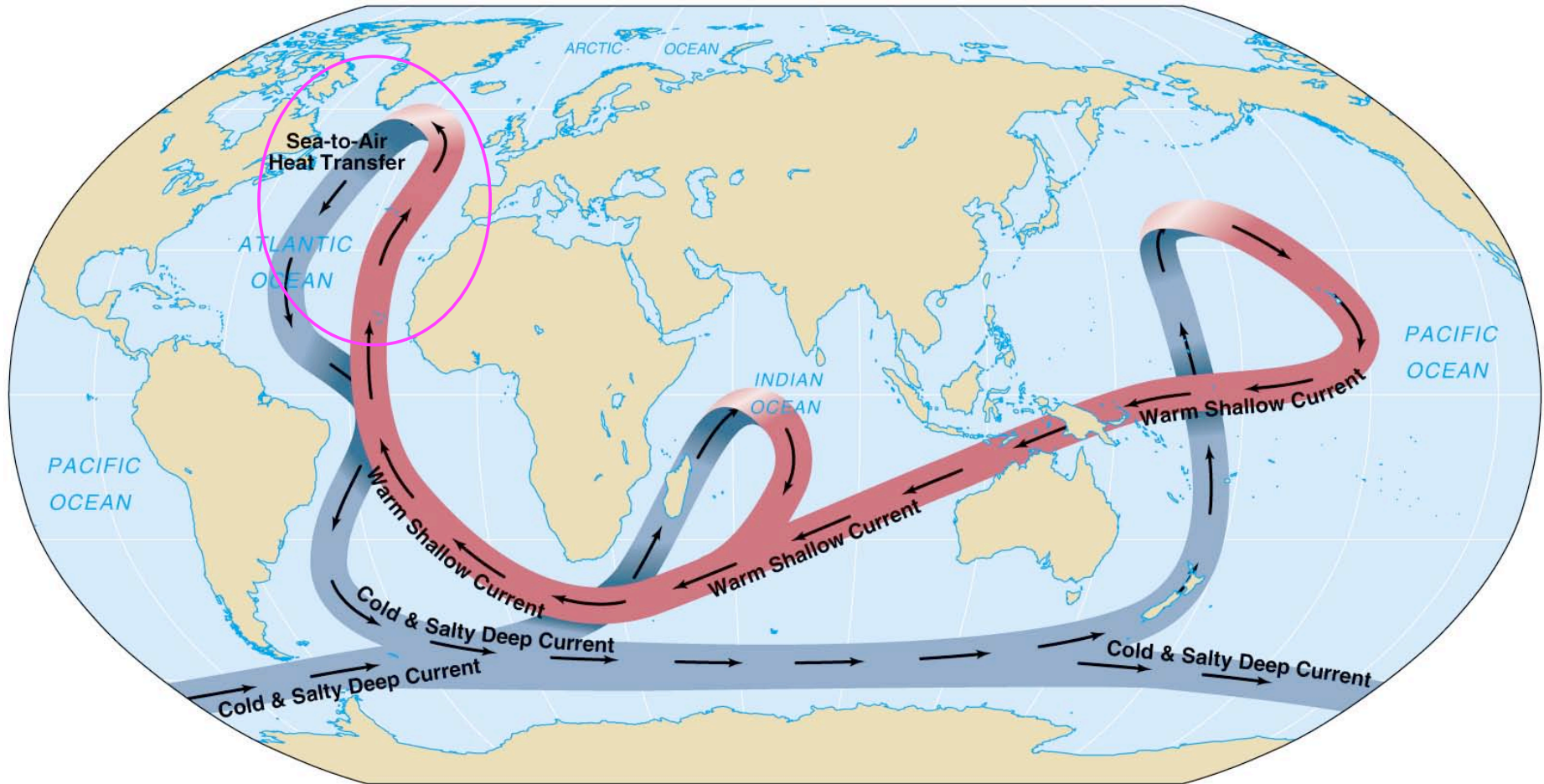# Relation of tides and wind to diapycnal diffusivity



Topography, Tides & Ocean stratification

⇓

Conversion of tidal energy to internal waves

⇓

Turbulence due to breaking internal waves

⇓

Mixing temperature, salinity & tracer fields

⇓

Ocean circulation & Sea level
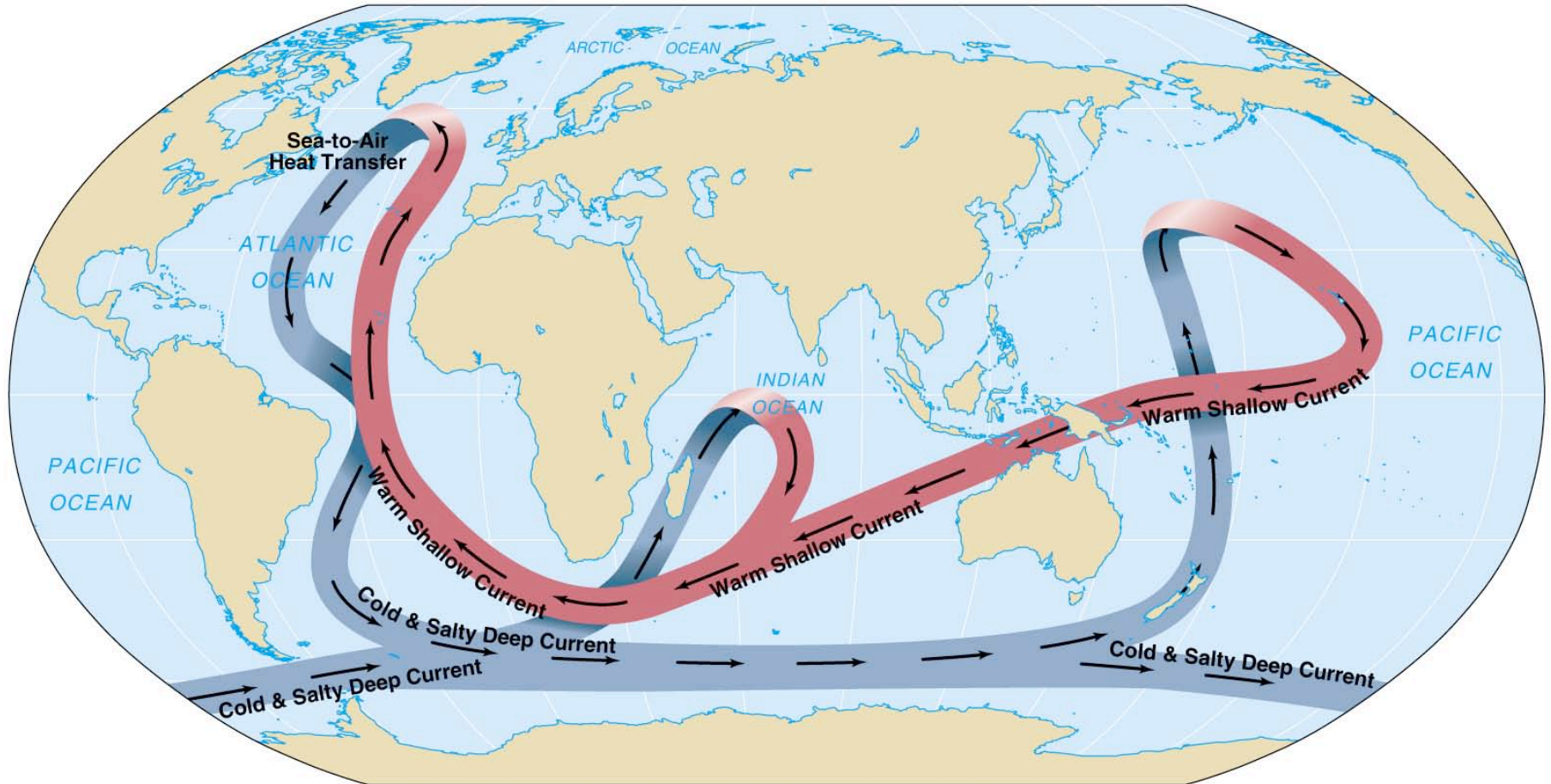
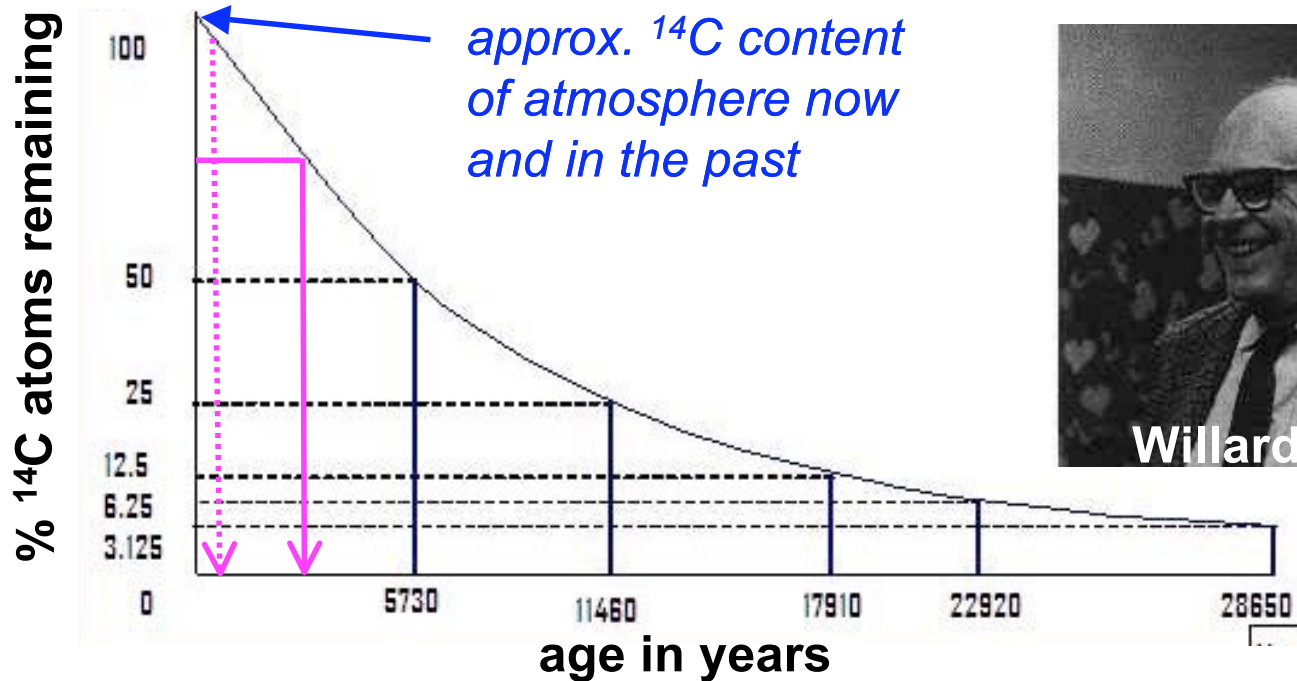$Kv = 10^{-5}$

$Kv = 10^{-3}$

# the ocean "conveyor belt"



**deep circulation dominated by a continuous circuit associated with formation of deep water in the N. Atlantic (i.e. NADW)**
**"what goes around comes around"**

# the ocean "conveyor belt"



*long route implies long time to complete circuit*
*how long?*

# how old is the deep ocean?



approx. $^{14}C$ content of atmosphere now and in the past

Willard Libby

% $^{14}C$ atoms remaining

age in years

- half the $^{14}C$ decays away every 5730 years

- so measuring how much $^{14}C$ tells us how long since water absorbed new carbon (as $CO_2$) at the surface

- more $^{14}C$ means water was at the surface more recently

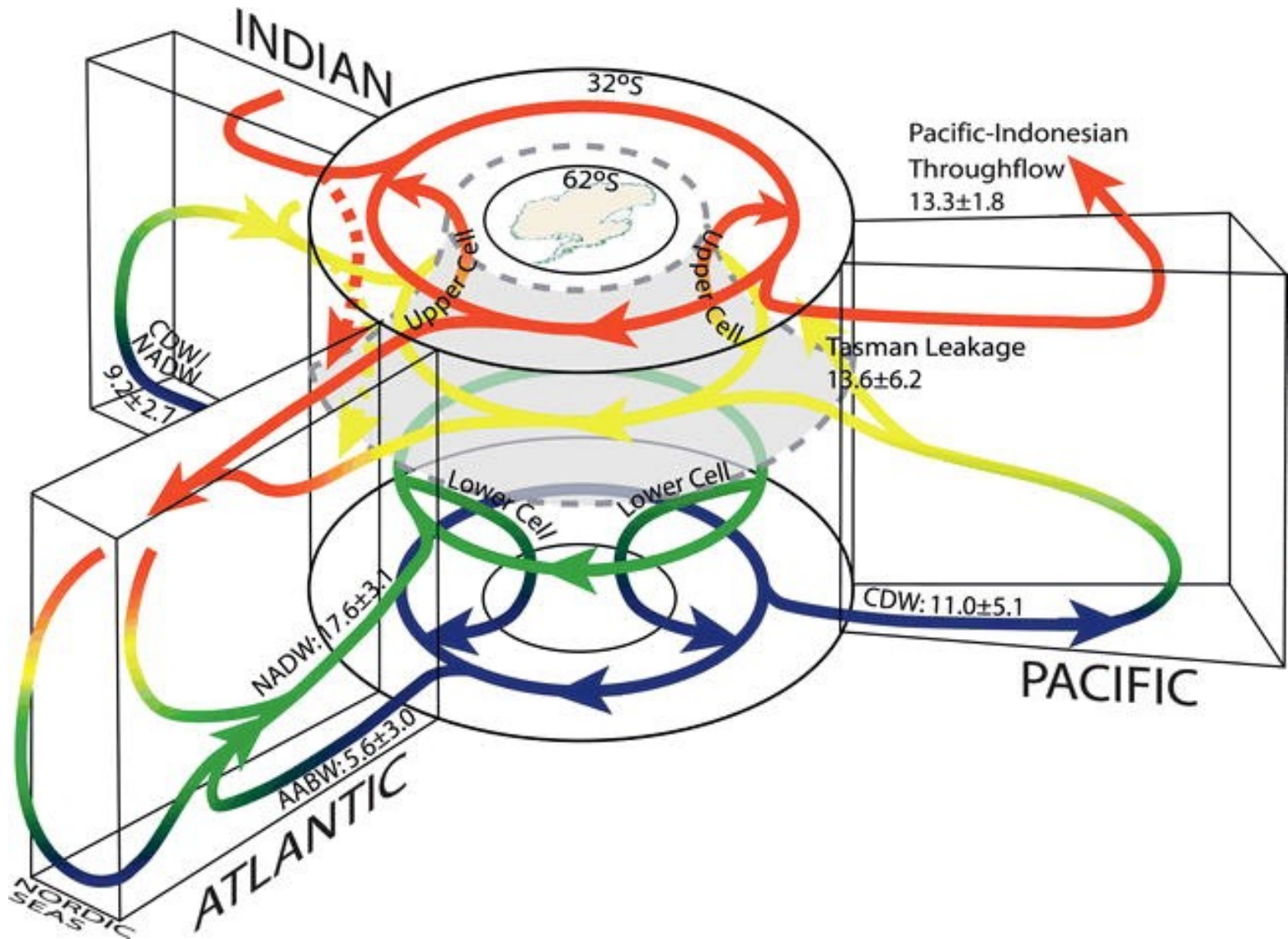- less $^{14}C$ means water was at the surface less recently
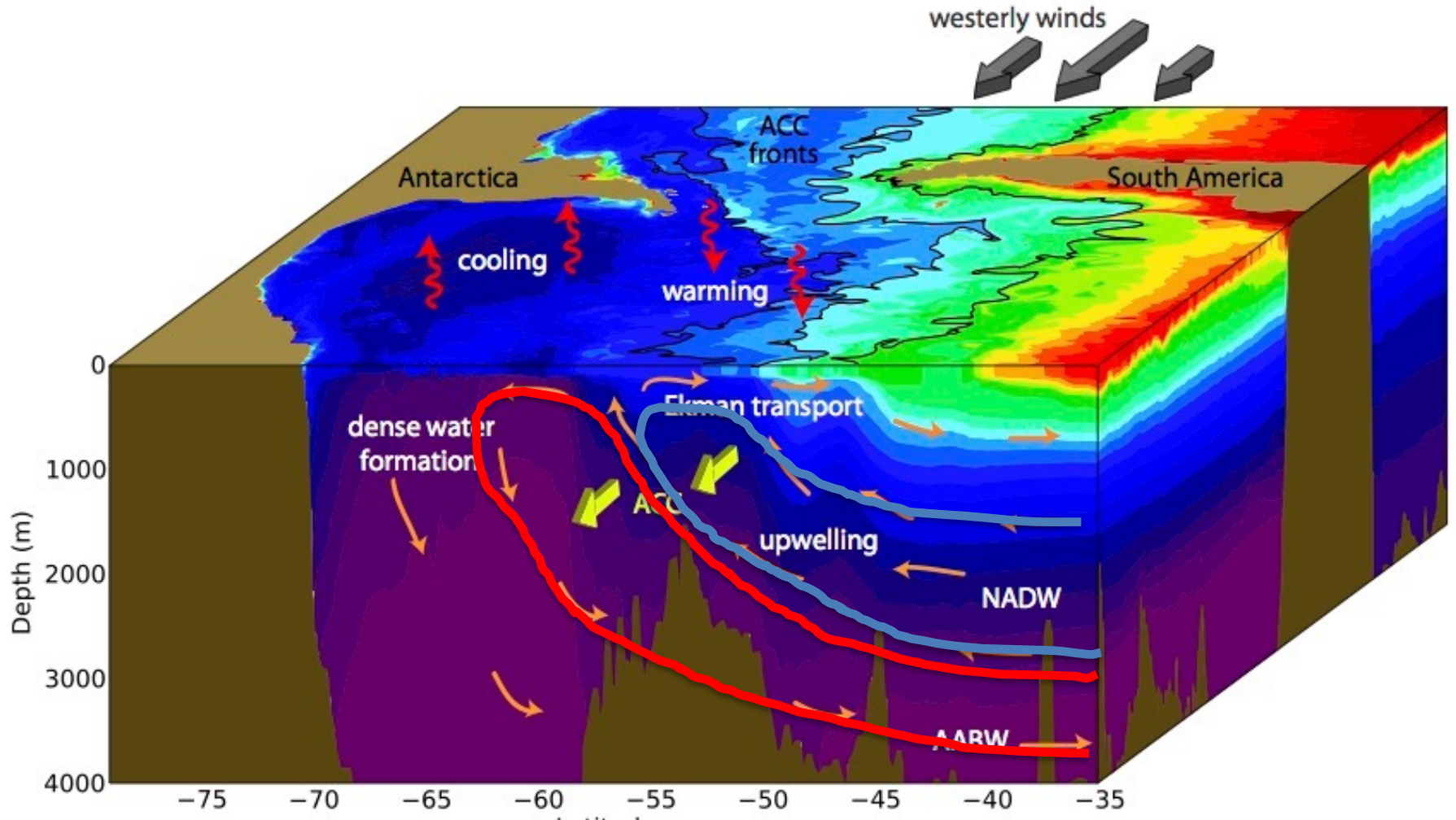
# less ¹⁴C means older water!



new water from sinking

oldest water (must come up)
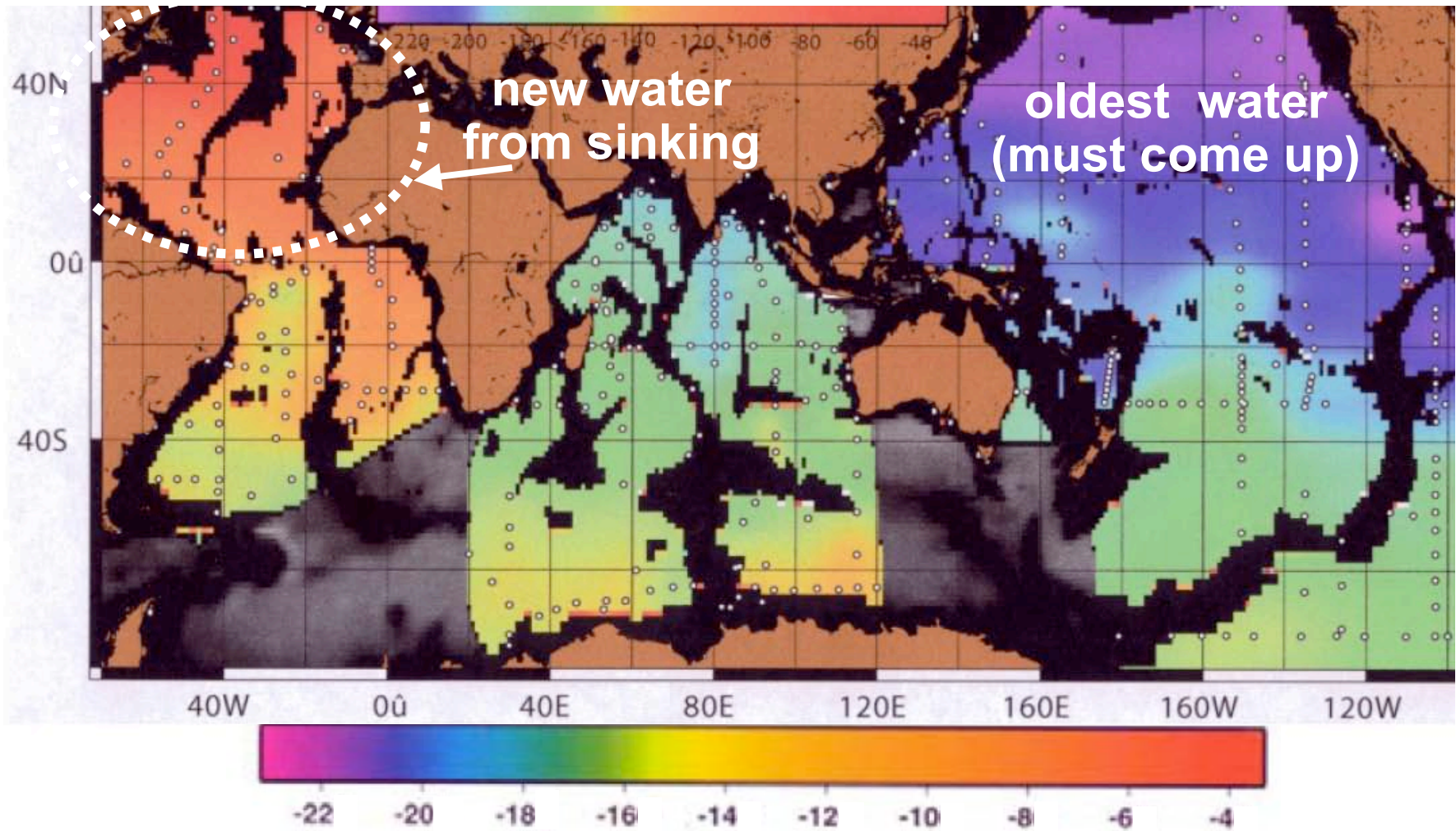
near bottom ¹⁴C (% deviation from modern )

*can estimate avg. timescale of deep circulation is 1000 years!*
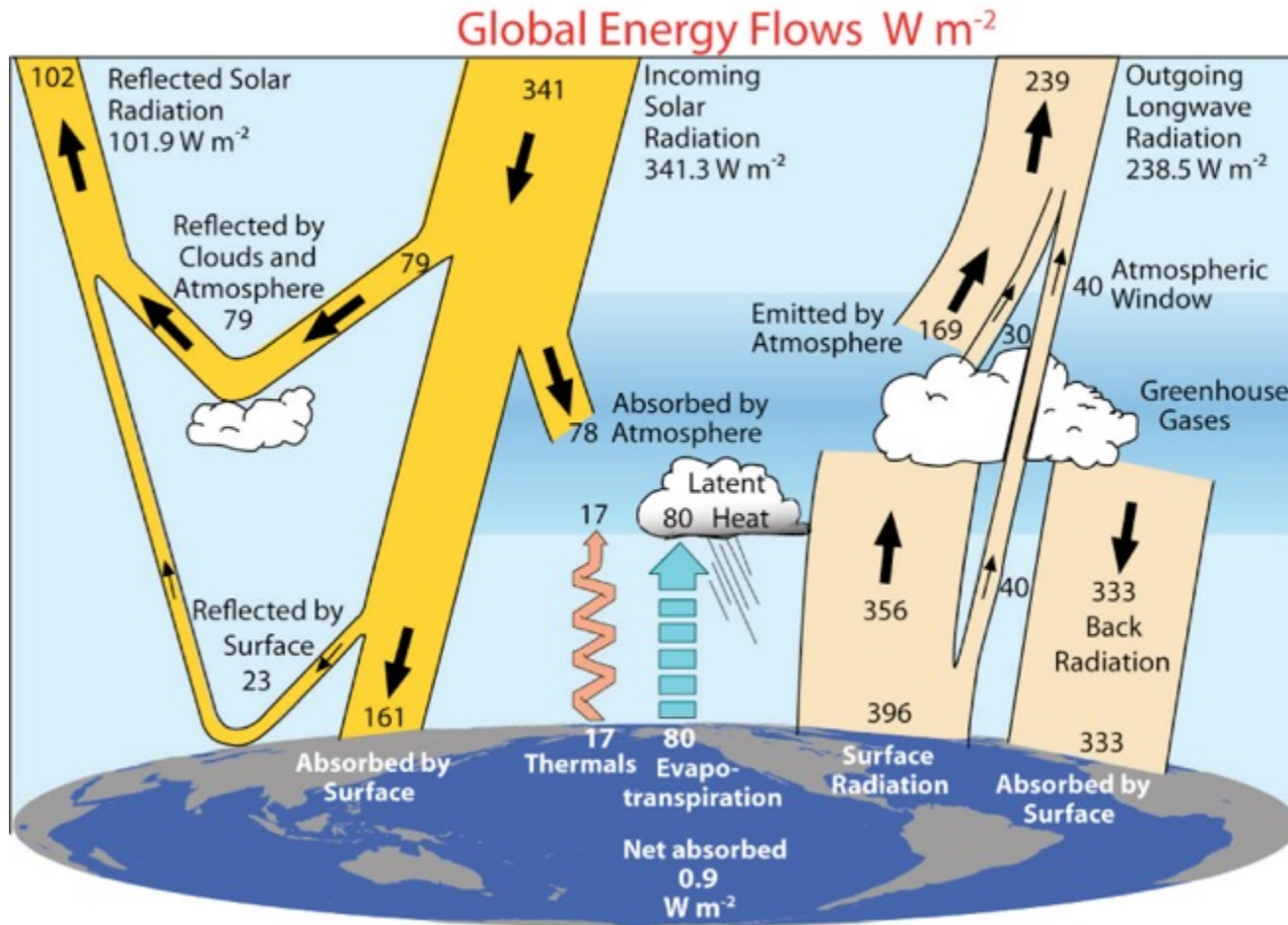
# The Southern Ocean: a pivotal role

# The Southern Ocean

# Ocean Heat Transport

# Earth's Heat Budget



Global Energy Flows W m⁻²

Notice that insolation balances infrared radiation at the top of the atmosphere (341-239-102=0)

At the surface, latent heat flux and net infrared radiation tend to balance insolation, and sensible heat flux is small.

Note that only 20% of insolation reaching Earth is absorbed directly by the atmosphere while 49% is absorbed by the ocean and land

# A few numbers

- The heat capacity of the ocean is about 1000 times larger than the heat capacity of the atmosphere
- The top 3.5 meters of the ocean hold as much energy as all of the air on the planet
- The ocean is by far the largest reservoir of heat in the climate system



Heat capacity of air: 1005 J/kg/K

Global Calculation of all air and ocean mass
Energy content in Joules/Degree Kelvin
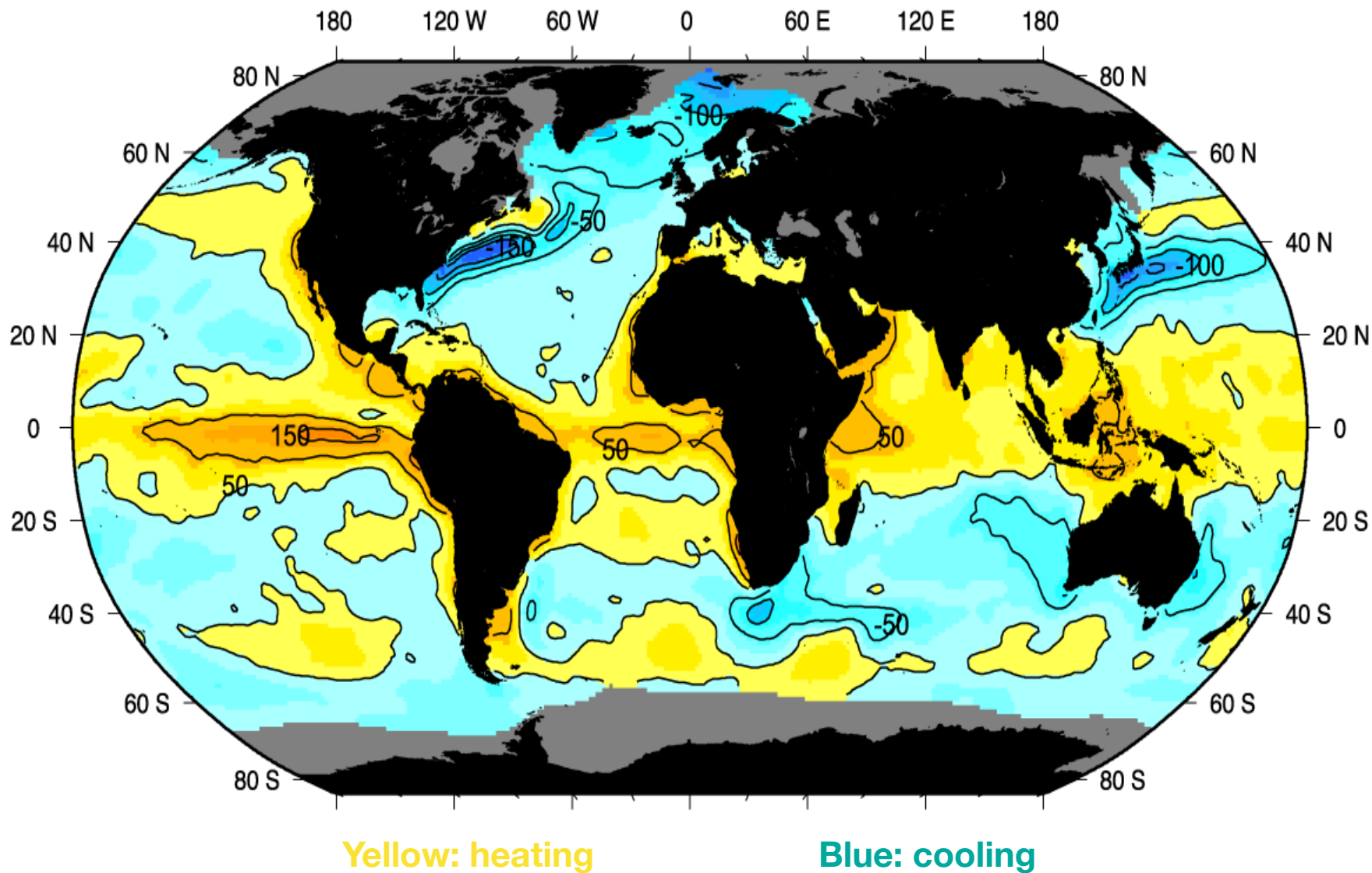
$5.6 \times 10^{24}$

$5 \times 10^{21}$

Air    Ocean

Heat capacity of ocean water: 3993 J/kg/K

Source: http://noconsensus.wordpress.com/2011/04/05/234-5/

To heat 1 m³ of air by 1C it takes about 2,000 Joules. But to warm a cubic metre of ocean one needs about 4,200,000 Joules.

# Surface heat flux (W/m²) into ocean



**Yellow: heating**    **Blue: cooling**

# Zonal averages of heat transfer to the ocean by insolation $Q_{SW}$, and loss by long wave radiation $Q_{LW}$, sensible heat flux $Q_S$, and latent heat flux $Q_L$
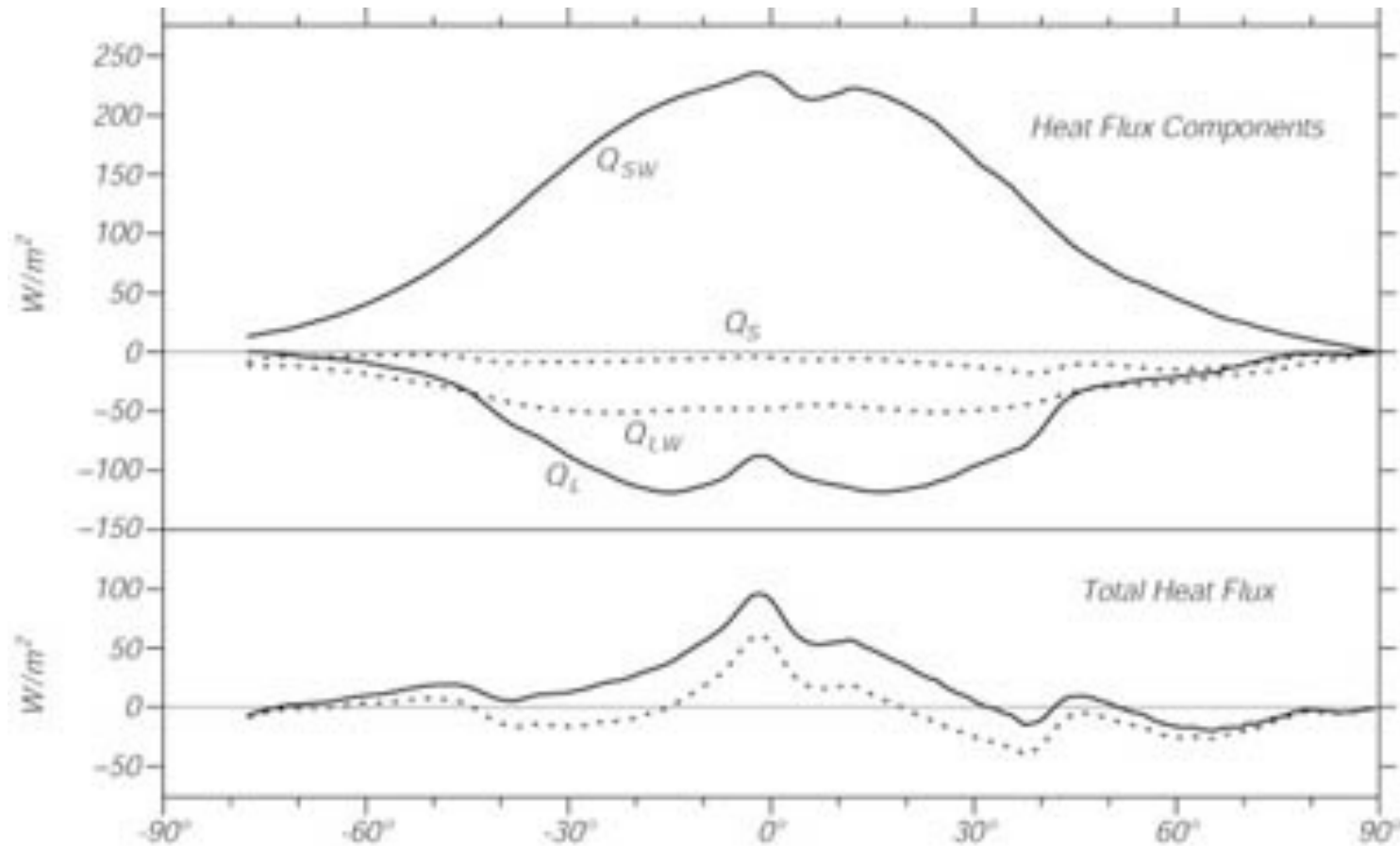


The zonal average of the oceanic heat-budget terms shows that insolation is greatest in the tropics, that evaporation balances insolation, and sensible heat flux is small

# The earth's Radiation Balance

- A balance between incoming solar radiation and outgoing long-wave radiation
- The incoming radiation is "sunlight", shortwave radiation, some of which is reflected back to space.
- The percentage of energy reflected is called the albedo, and the albedo is higher over lighter areas like snow and lower over darker areas like the ocean.
- Most of the incoming radiation occurs in the tropical and equatorial regions, so there is more incoming radiation than outgoing radiation for latitudes less that 35 degree.
- There is more outgoing radiation than incoming radiation in subpolar and polar regions.
- To maintain the heat budget at each latitude, **the ocean + atmosphere must transport heat poleward away from tropical regions toward polar regions**; and the maximum ocean +atmosphere heat transport occurs at a latitude of about 35 degree.
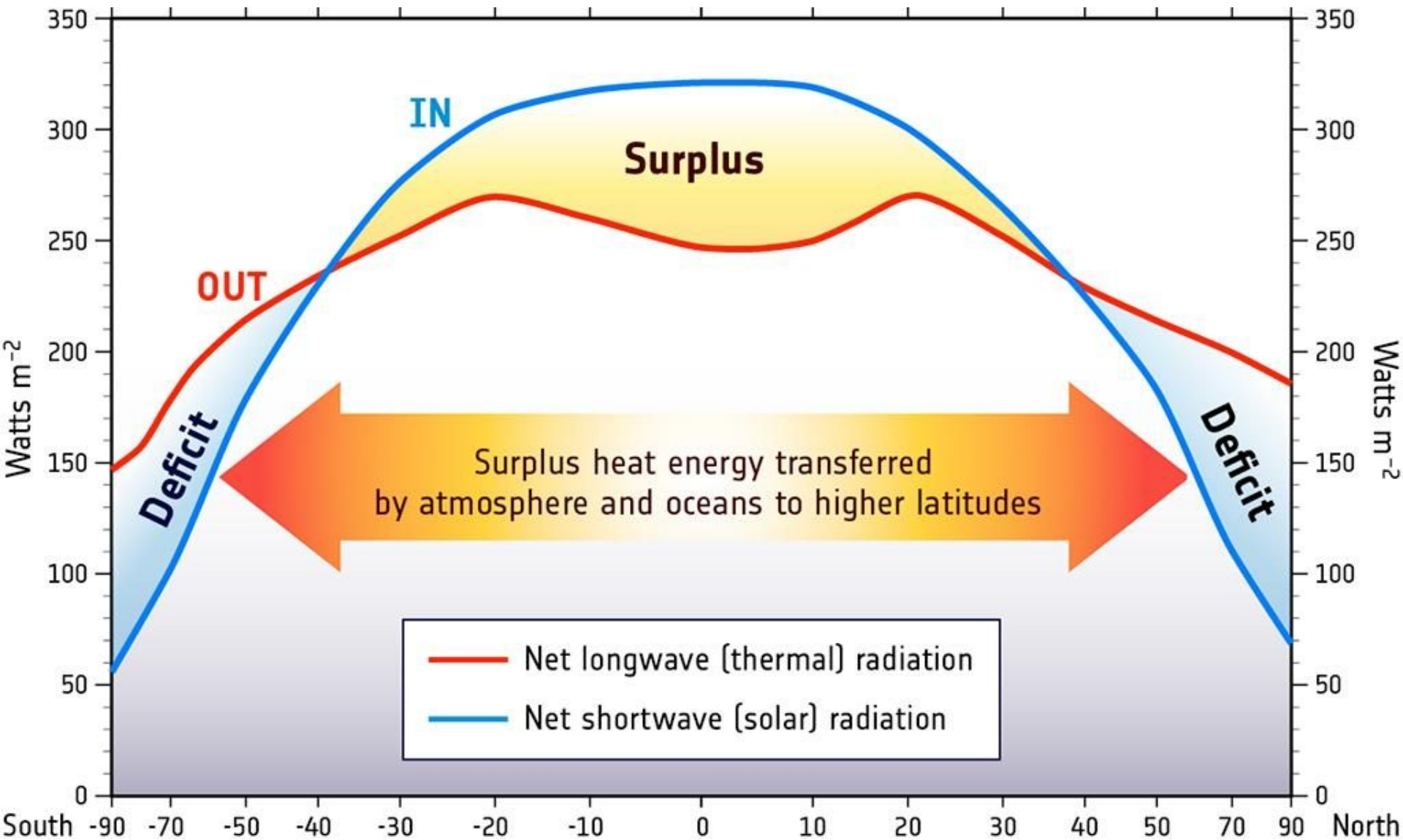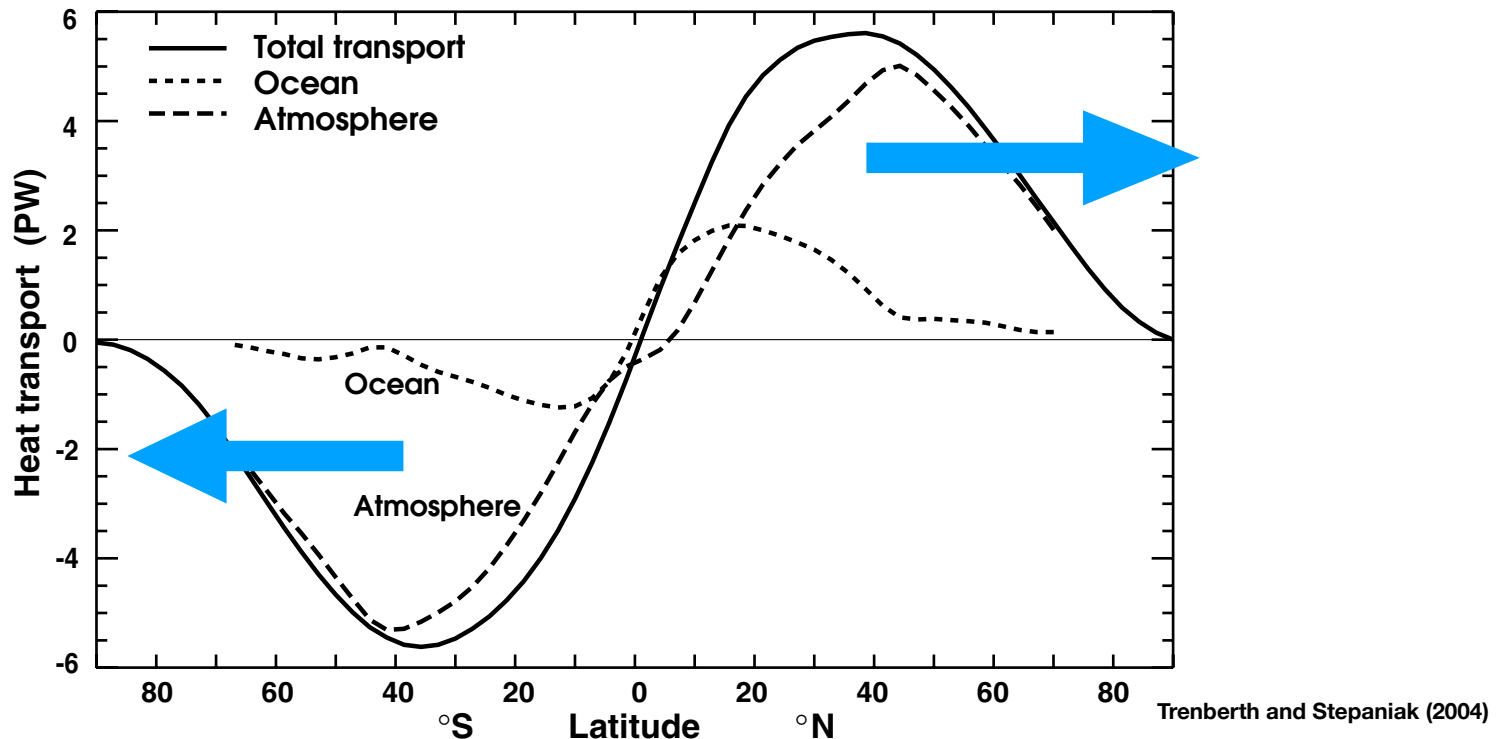
# Heat Transport

Locally, heat storage by the climate system cannot compensate for the net radiative flux imbalance at the top of the atmosphere and, annually, the balance is nearly entirely achieved by heat transport from regions with a positive net radiative flux to regions with a negative net radiative flux. When the balance is averaged over latitudinal circles (zonal mean), this corresponds to a meridional heat transport from equatorial to polar regions
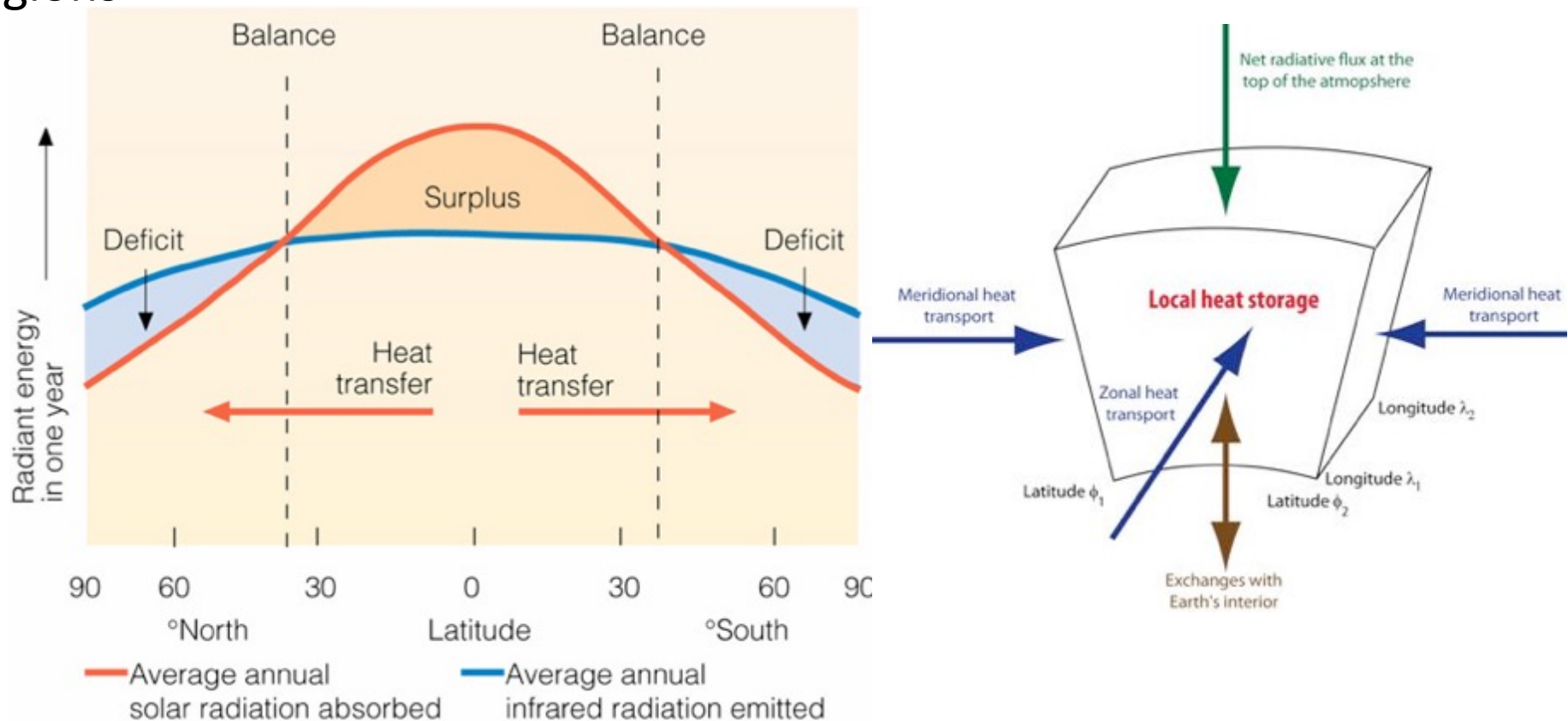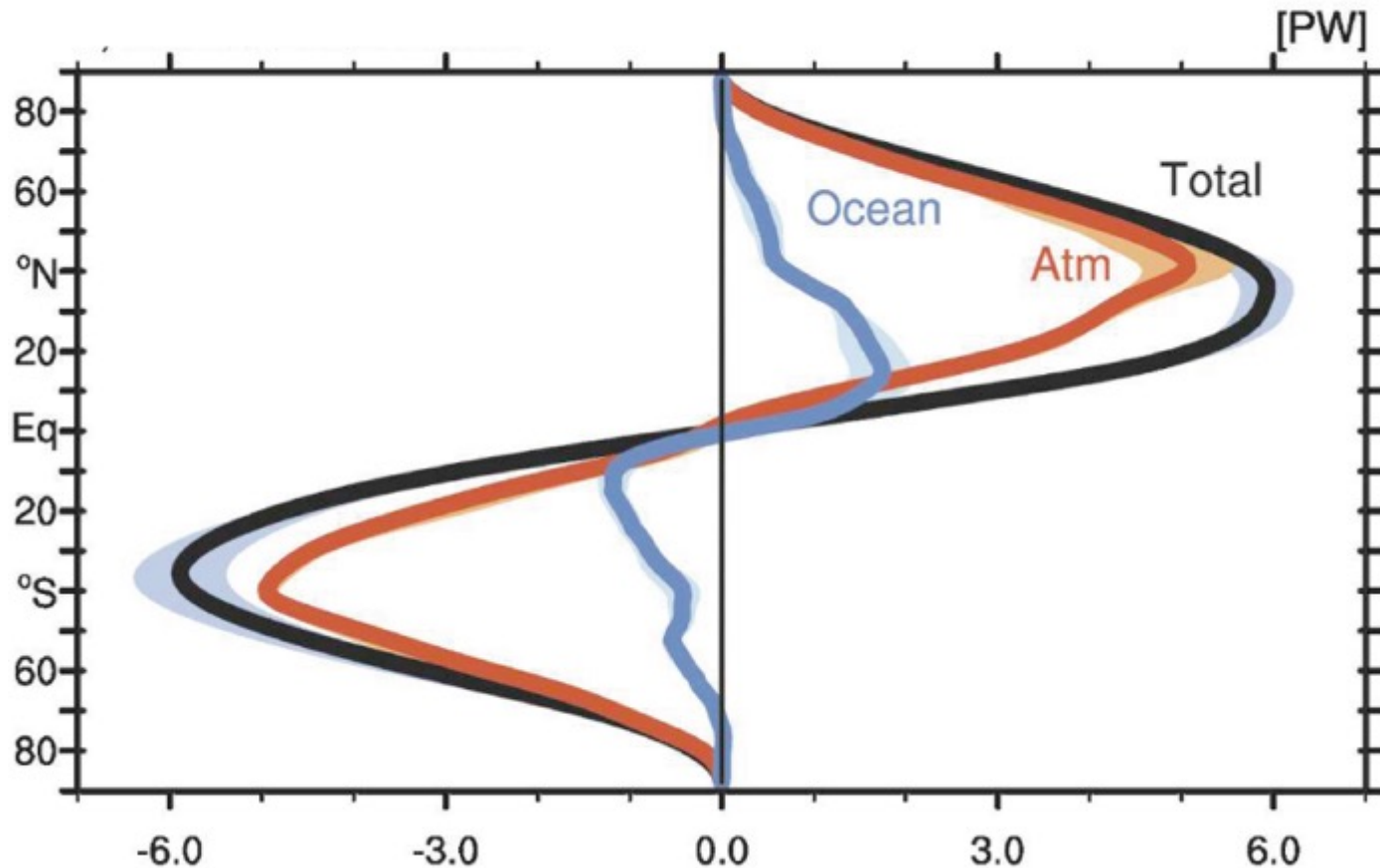
# Ocean Heat Transport

- Most of the incoming radiation occurs in the tropical and equatorial regions, so there is more incoming radiation than outgoing radiation for latitudes less that 35 degree. There is more outgoing radiation than incoming radiation in subpolar and polar regions.
- To maintain the heat budget at each latitude, the ocean + atmosphere must transport heat poleward away from tropical regions toward polar regions.



Trenberth and Stepaniak (2004)

The heat transport obtained is nearly zero at the equator, rising to ~ 6PW at about 35°, before declining again towards zero at the poles.
It can be divided into an oceanic and an atmospheric contribution.
The horizontal transport on continental surface being negligible.

# Ocean Heat Transport
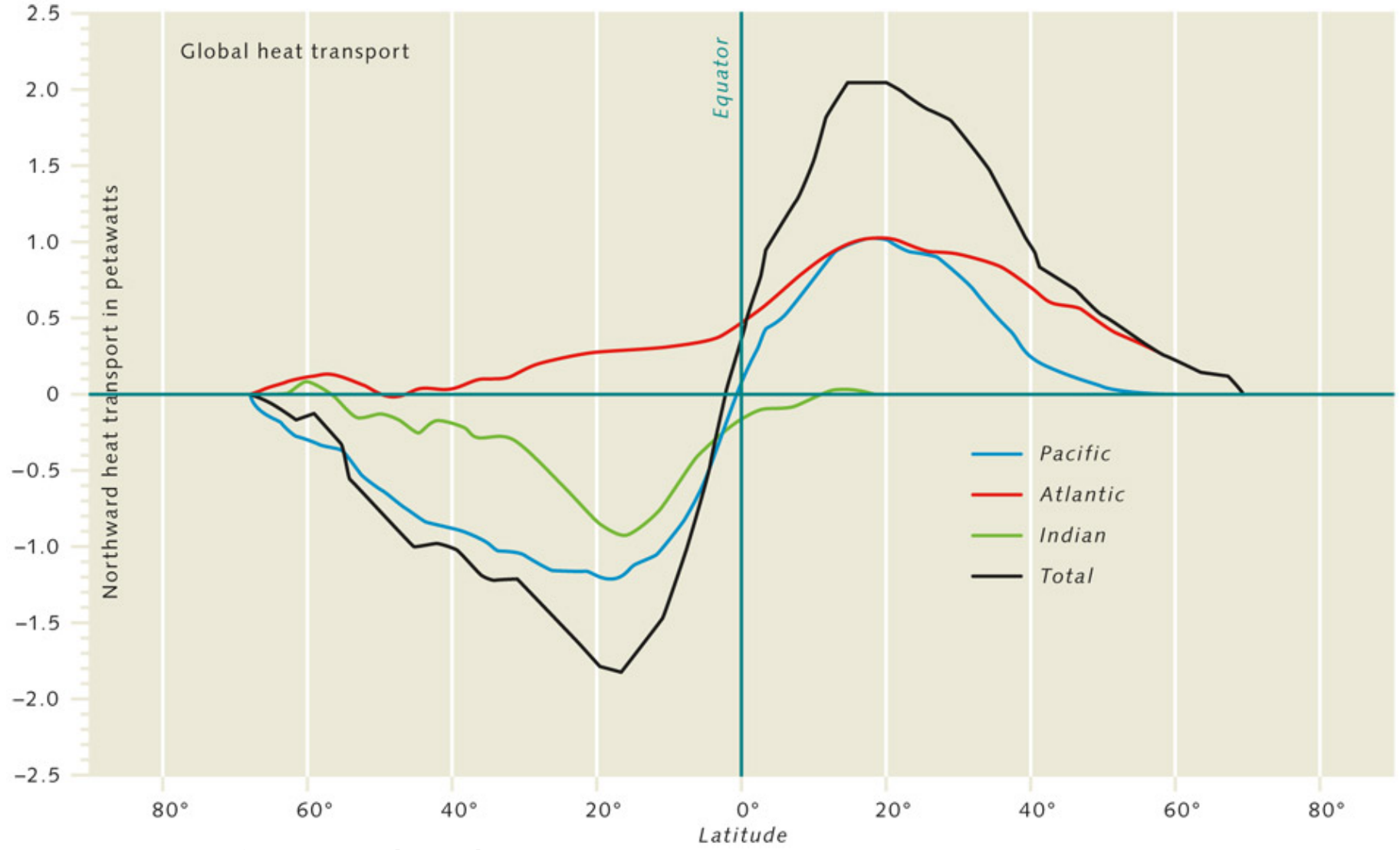


**Trenberth and Solomon (1994)**
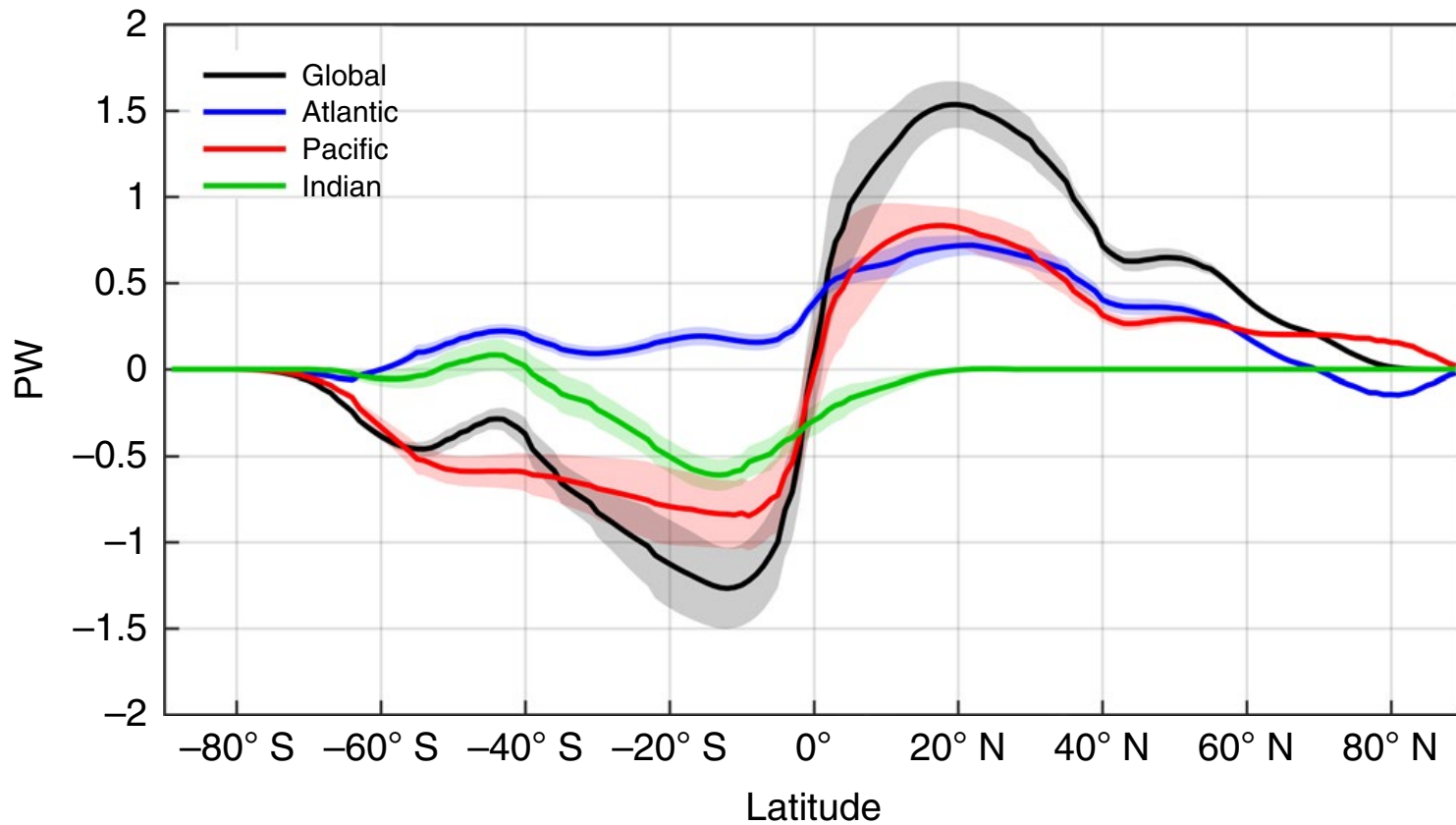
(a) Global

(b) Atlantic

(c) Indo-Pacific
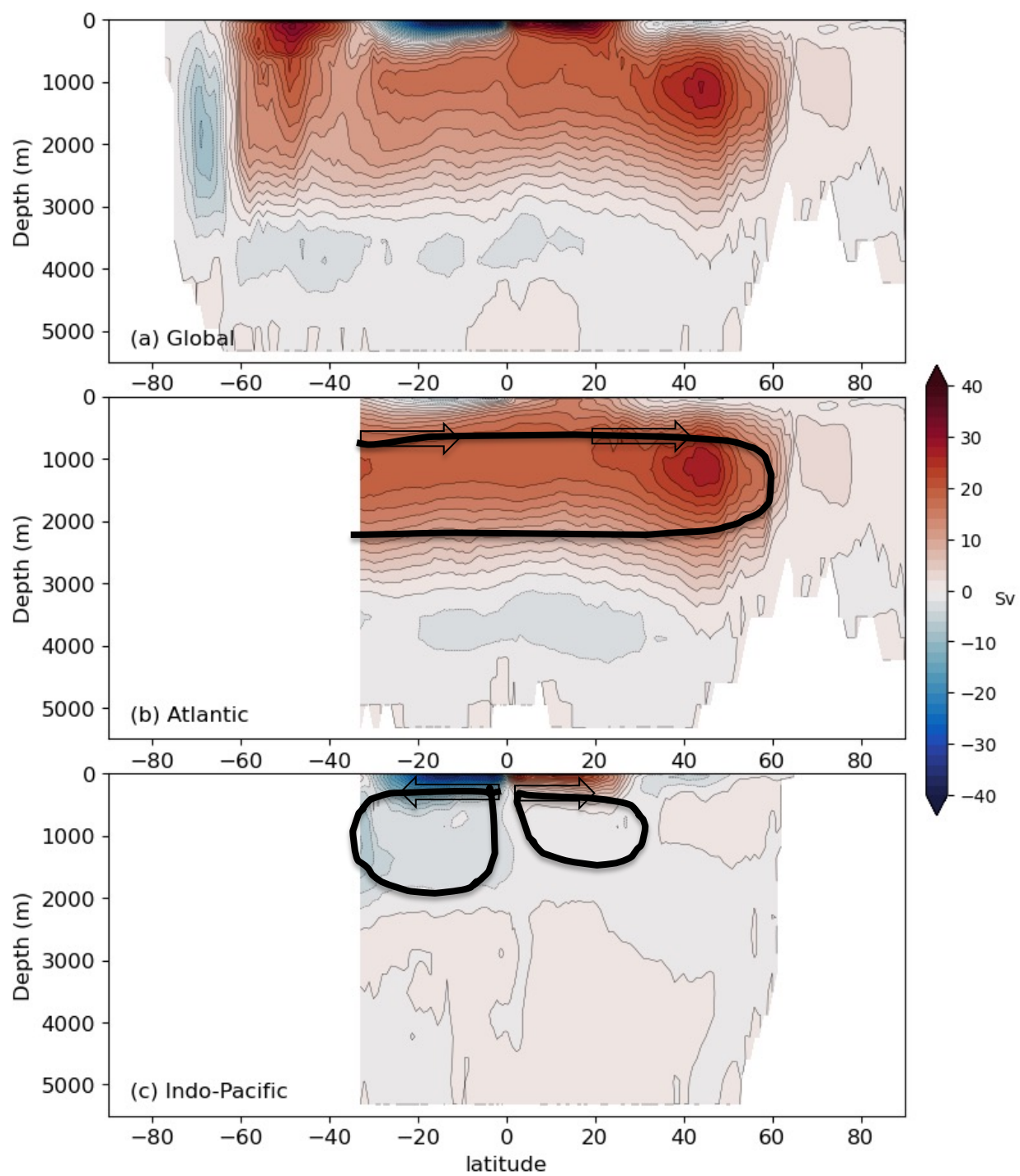
**Fig. 2 | Meridional effective OHT.** The global ocean case is depicted in black. Meridional effective OHT for the Atlantic (blue), Pacific (red) and Indian (green) sectors is also shown. The thick lines denote the 1992–2011 time average and the shaded ranges reflect ±1 standard deviation among annual means.
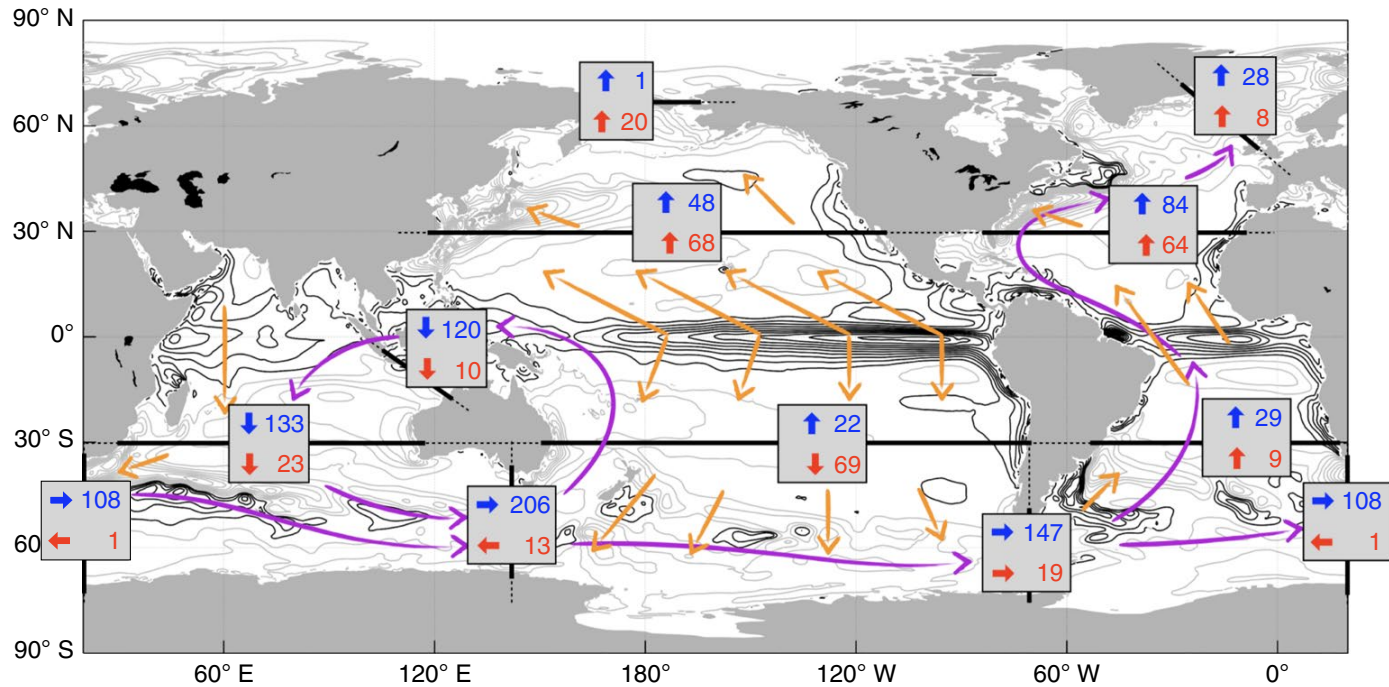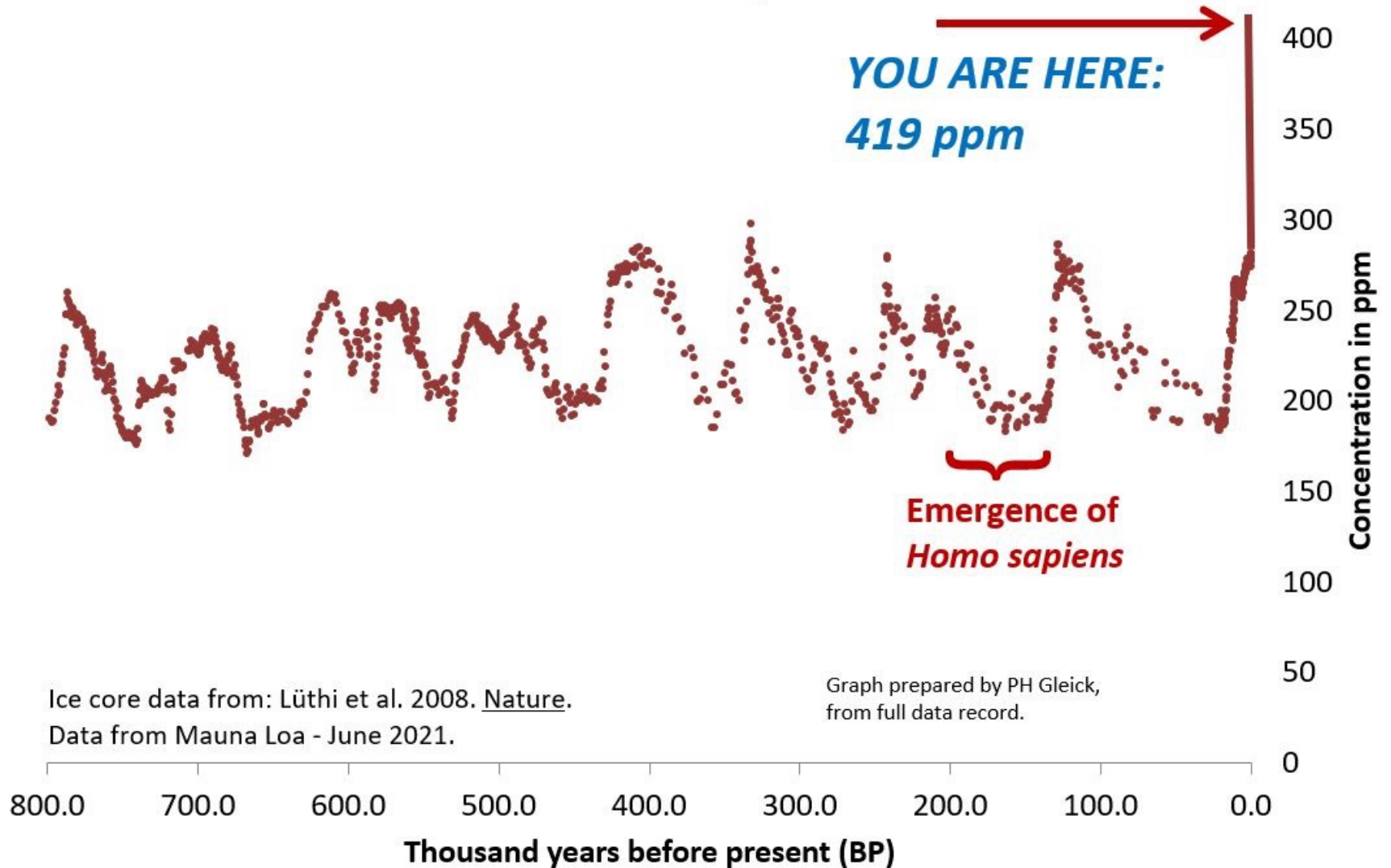
Forget and Ferreira, 2019

**Fig. 1 | OHT as estimated through sections that separate ocean basins and delimit the tropics for the 1992–2011 time average.** Values (in 0.01 PW = $10^{13}$ Watts) of plain OHT (rotational + divergent components; OHT0) and effective OHT (divergent component alone; OHT∇) are charted in blue and in red, respectively. The thin lines with arrowheads are a schematic of internal ocean heat loops (purple) and effective OHT patterns (orange). The black contours (respectively, grey contours) represent the rate of OHT divergence (respectively, convergence), which corresponds to heat uptake from (respectively, heat release to) the atmosphere. These rates are contoured every 15 W m⁻² starting from ±5 W m⁻².

$(OHT_{R,0})$

Forget and Ferreira, 2019

Carbon Dioxide in the Atmosphere for the Past 800,000 Years

YOU ARE HERE: 419 ppm

Emergence of Homo sapiens

Ice core data from: Lüthi et al. 2008. Nature.
Data from Mauna Loa - June 2021.

Graph prepared by PH Gleick, from full data record.

Concentration in ppm

Thousand years before present (BP)
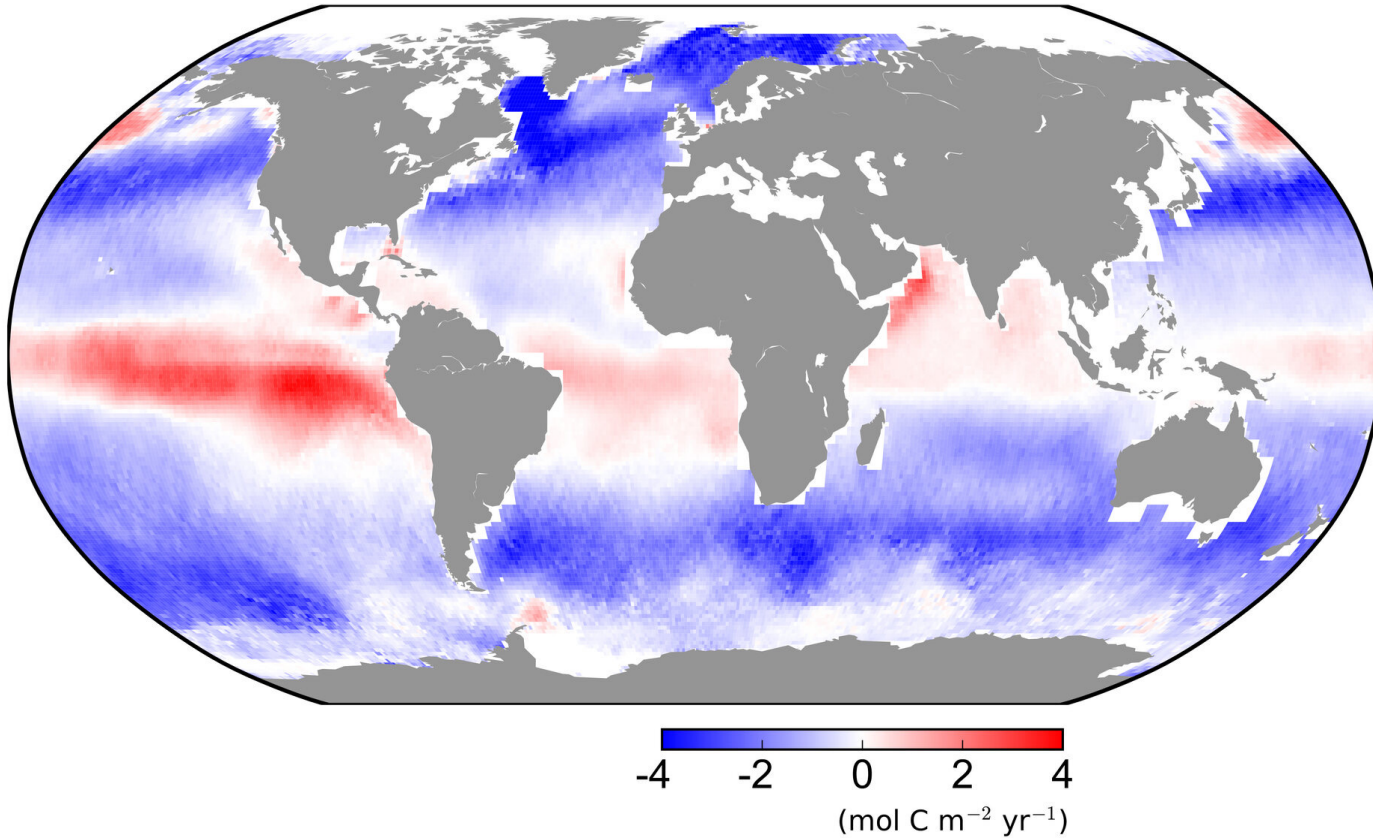
Carbon dioxide continually flows into (blue) and out (red) of the ocean. The oceans store carbon for thousands of years, so most of the carbon dioxide coming out of the ocean within the equatorial pacific was previously in the atmosphere before the time of the industrial revolution.
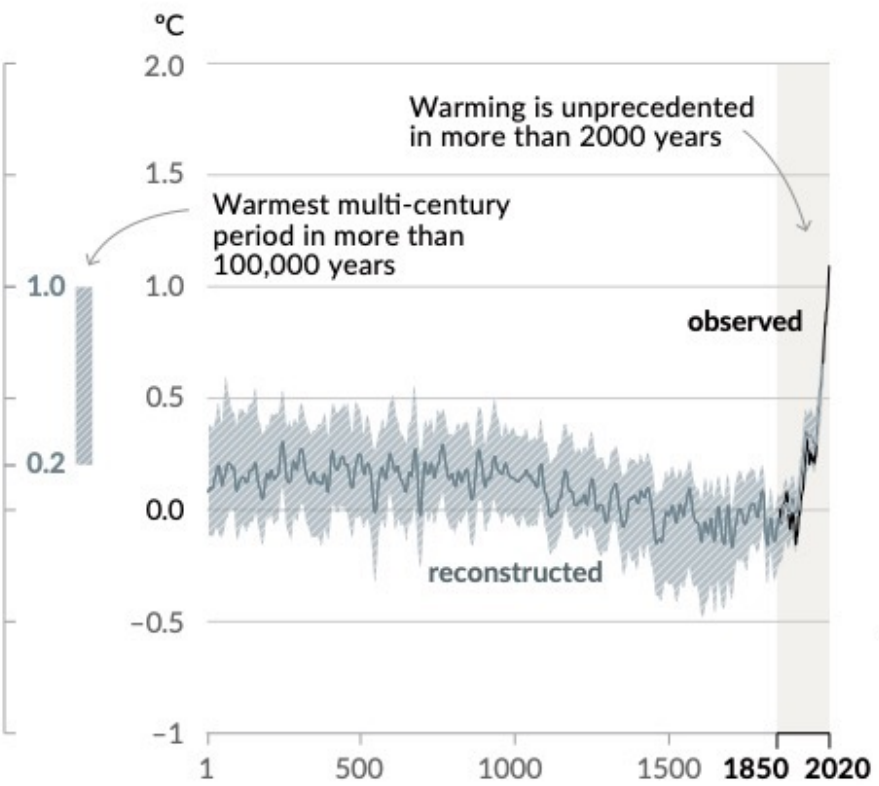
# The Atlantic Ocean plays a central role in transporting mass, heat and other tracers
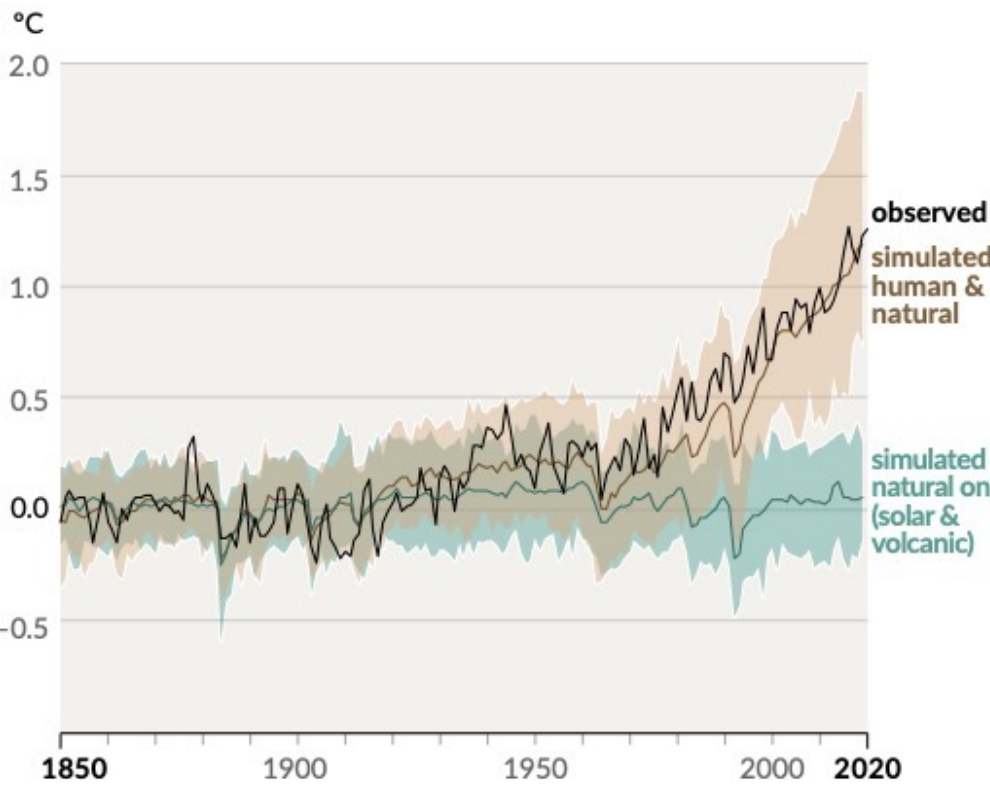


(a)

Simplified global overturning circulation
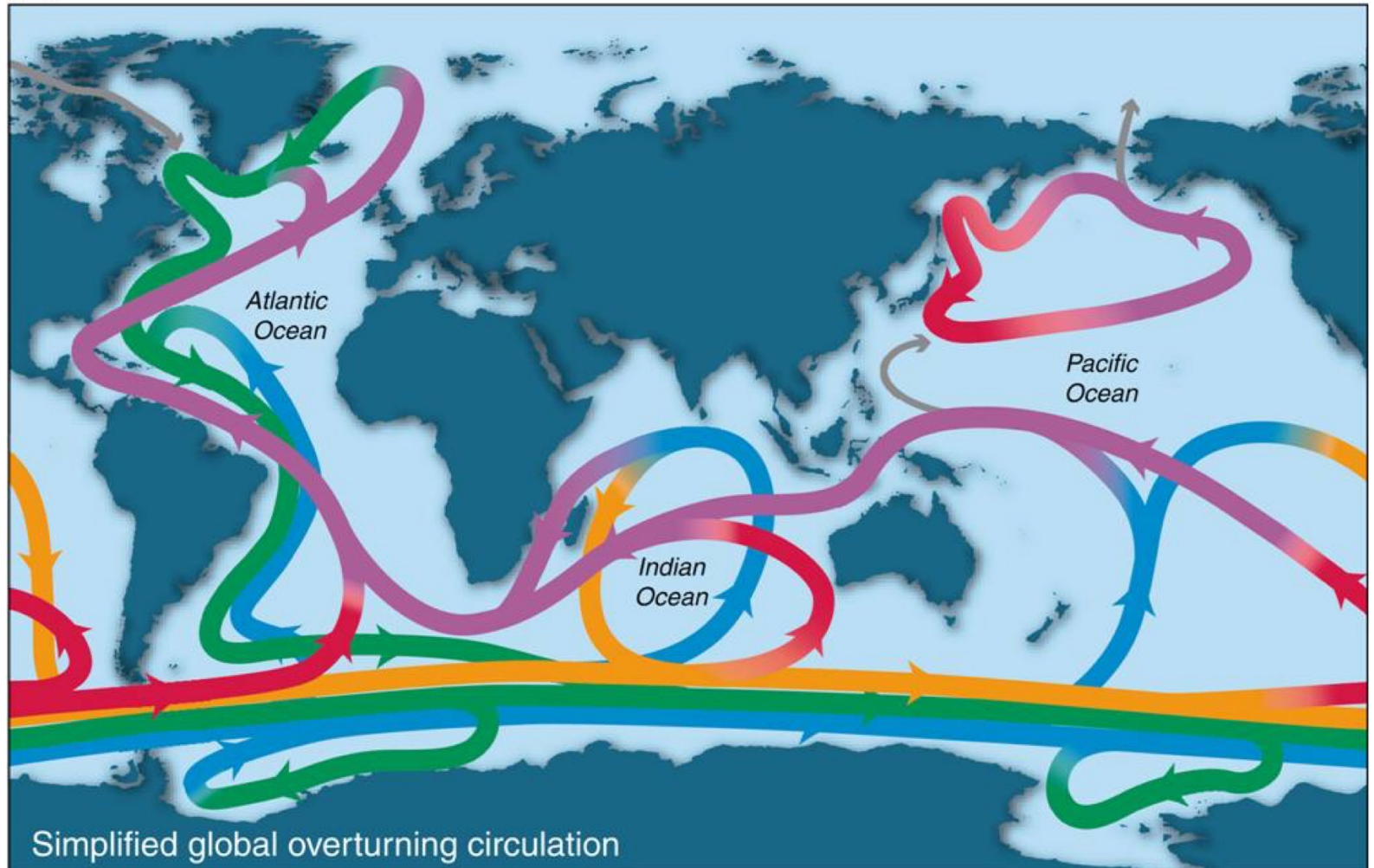
# Changes in global surface temperature relative to 1850–1900



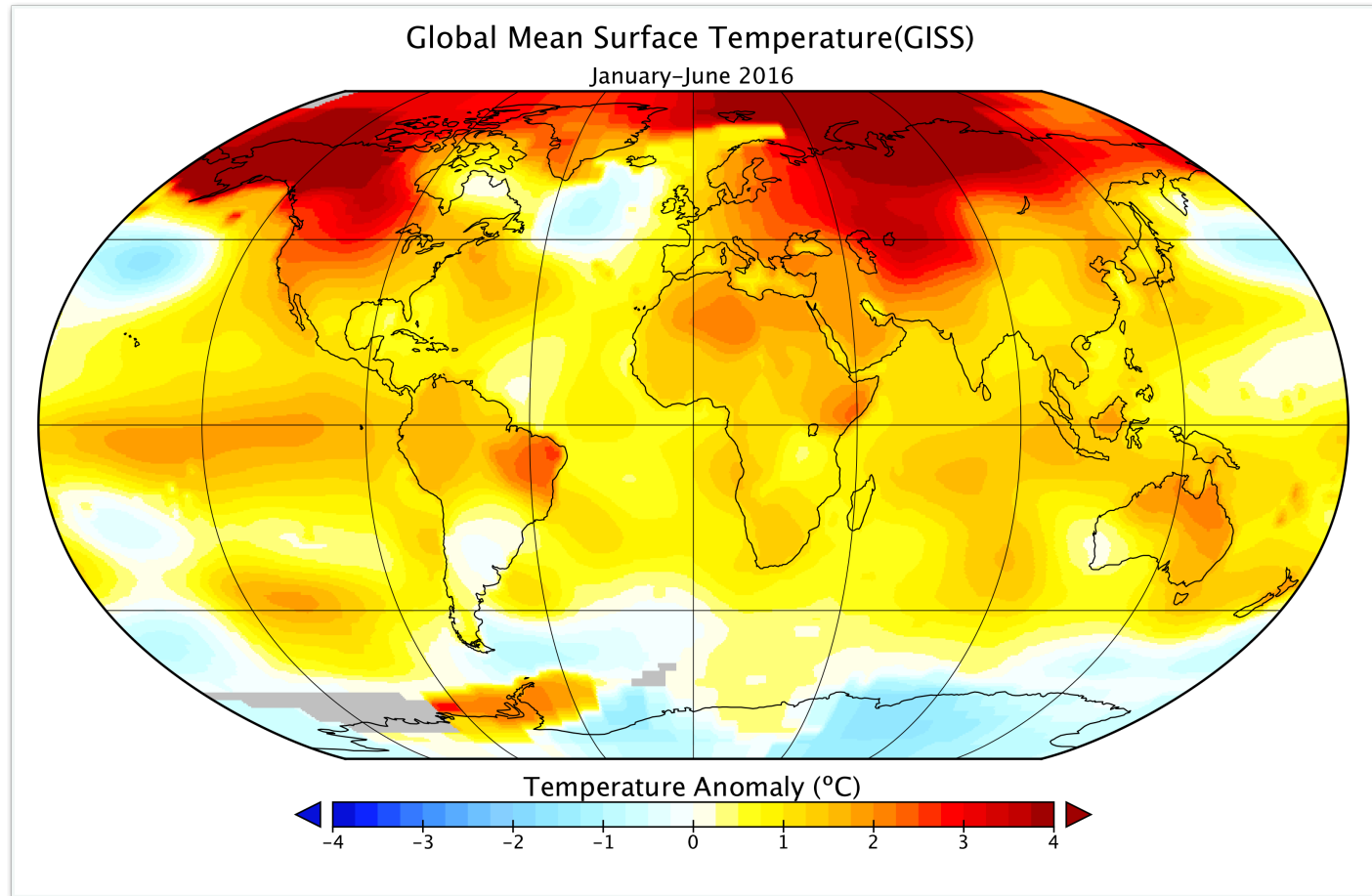(a) Change in global surface temperature (decadal average) as reconstructed (1–2000) and observed (1850–2020)

(b) Change in global surface temperature (annual average) as observed and simulated using human & natural and only natural factors (both 1850–2020)

From: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf
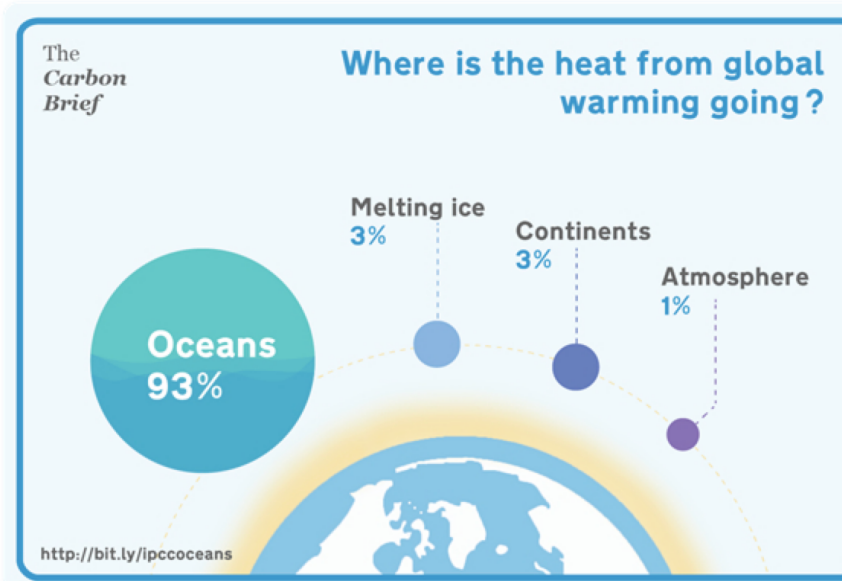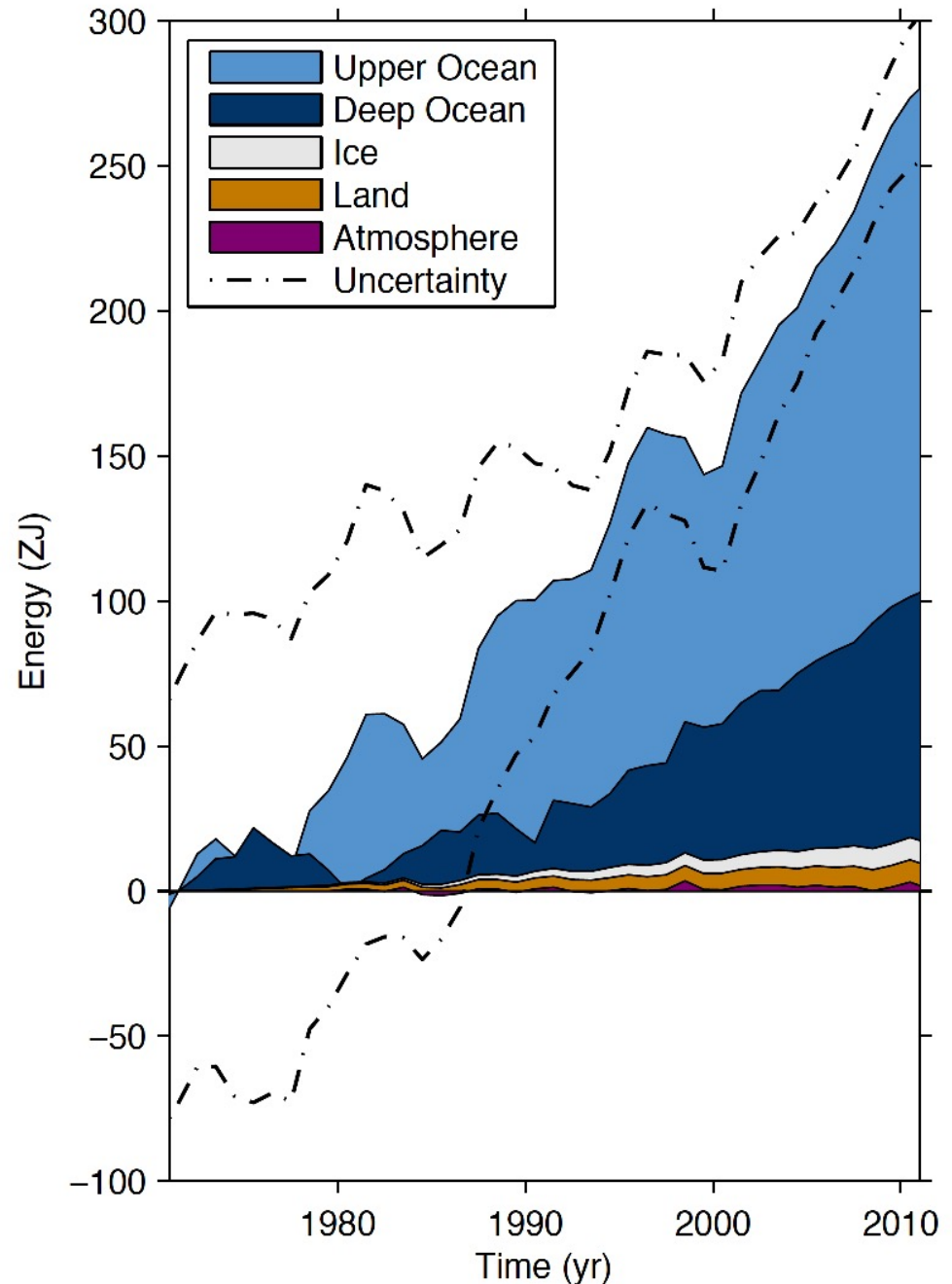
# Climate change = Ocean change



Global surface temperature anomalies for the period January 2016 through June 2016. Higher than normal temperatures are shown in red and lower then normal termperatures are shown in blue.
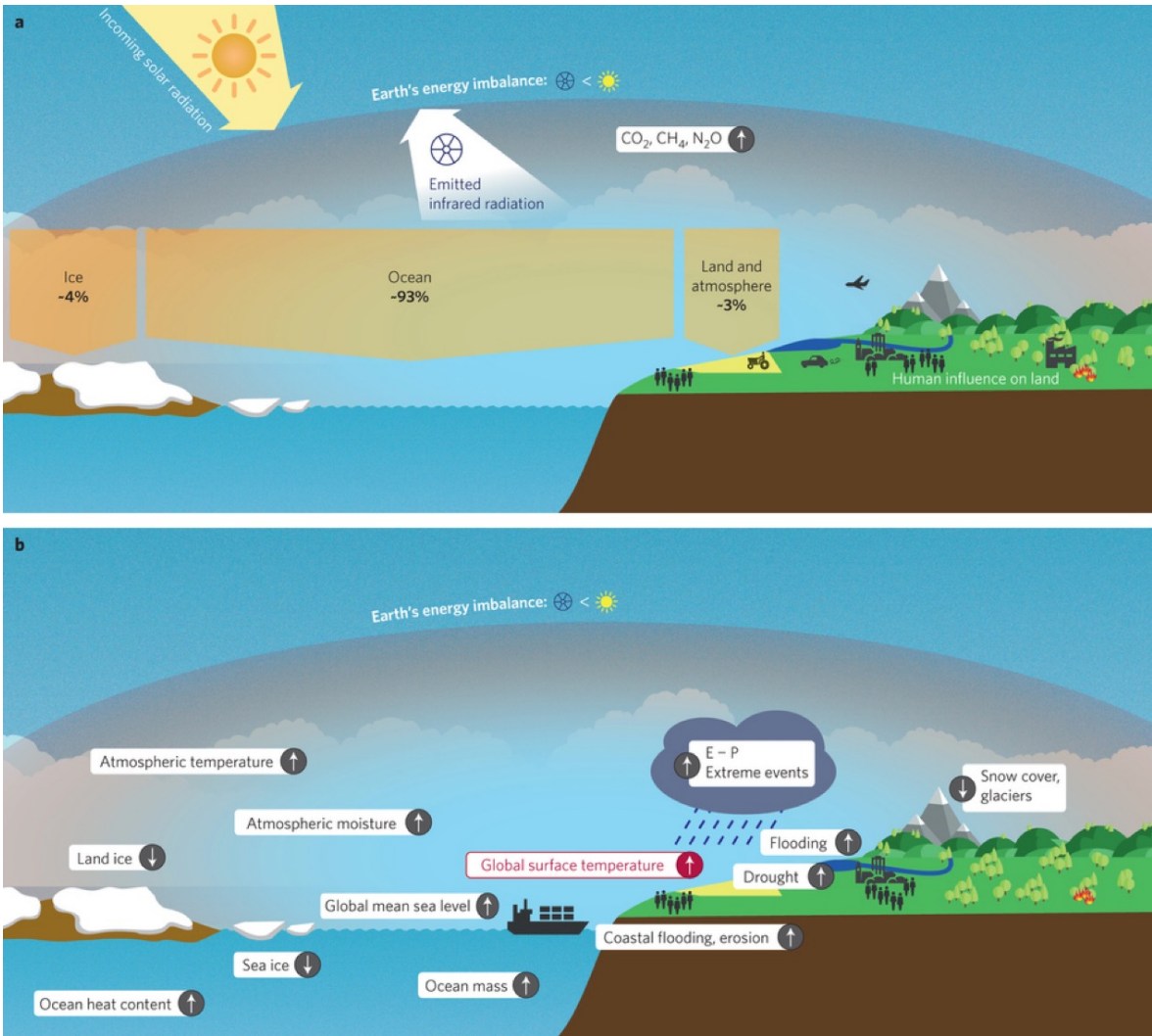Credit: NASA/GISS

# Where is all the extra energy going?



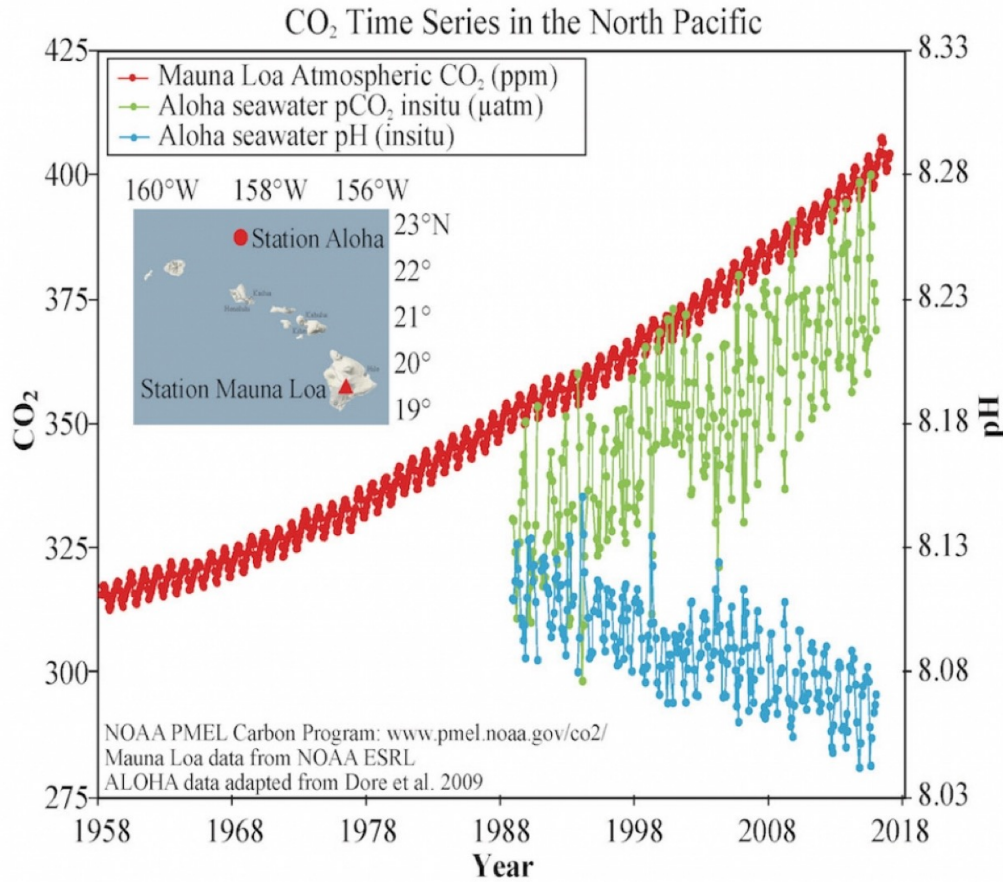Source: Rosamund Pearce, Carbon Brief

# The Ocean is the major heat reservoir, with about 90% of Earth's Energy Imbalance stored. The rest goes into warming the land and atmosphere, and melting ice.



'Symptoms' of positive EEI, including rises in Earth's surface temperature, ocean heat content, global mean sea level, atmospheric temperature and moisture, drought, flooding and erosion, increased extreme events, and evaporation – precipitation, decrease in land and sea ice, snow cover and glaciers.

# Climate change = Ocean change



CO$_2$ Time Series in the North Pacific

- Mauna Loa Atmospheric CO$_2$ (ppm)
- Aloha seawater pCO$_2$ insitu (µatm)
- Aloha seawater pH (insitu)

Station Aloha
Station Mauna Loa

NOAA PMEL Carbon Program: www.pmel.noaa.gov/co2/
Mauna Loa data from NOAA ESRL
ALOHA data adapted from Dore et al. 2009

Data: Mauna Loa (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2.txt)
Ref: J.E. Dore et al, 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc Natl Acad Sci USA* **106**:12235-12240.

The Oceans have absorbed **~45%** of global anthropogenic carbon dioxide emissions

- The Oceans have absorbed **~80%** of the excess heat caused by climate change with serious and irreversible consequences for marine ecosystems and natural resources

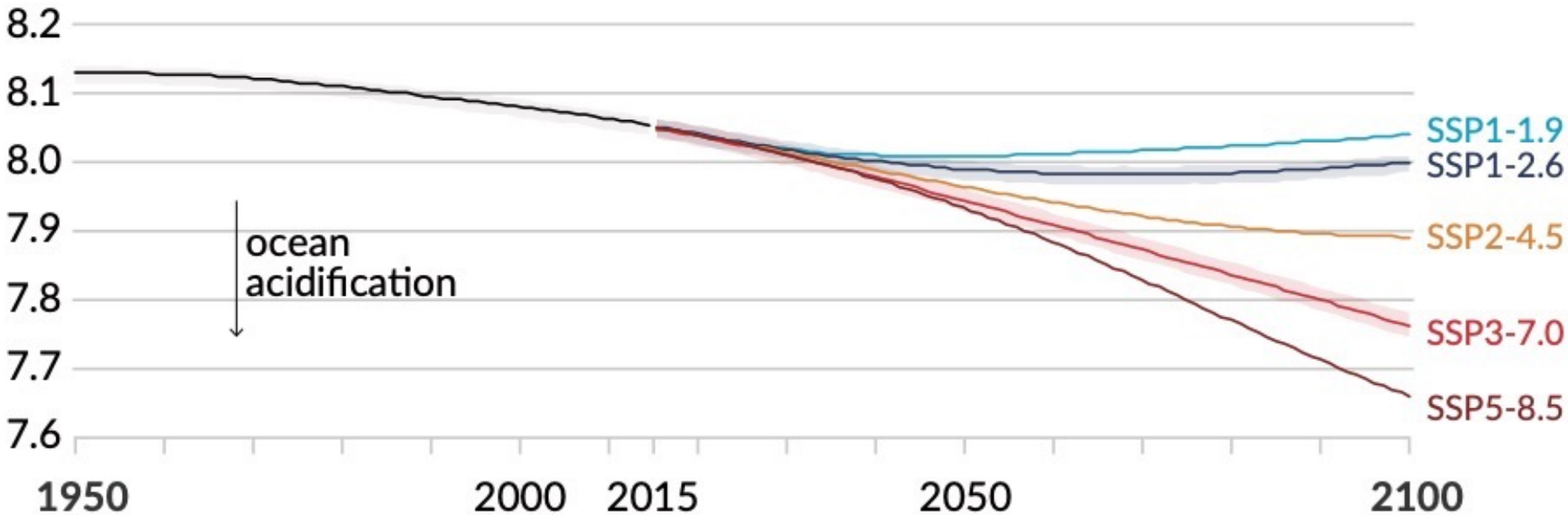## (a) Global surface temperature change relative to 1850–1900
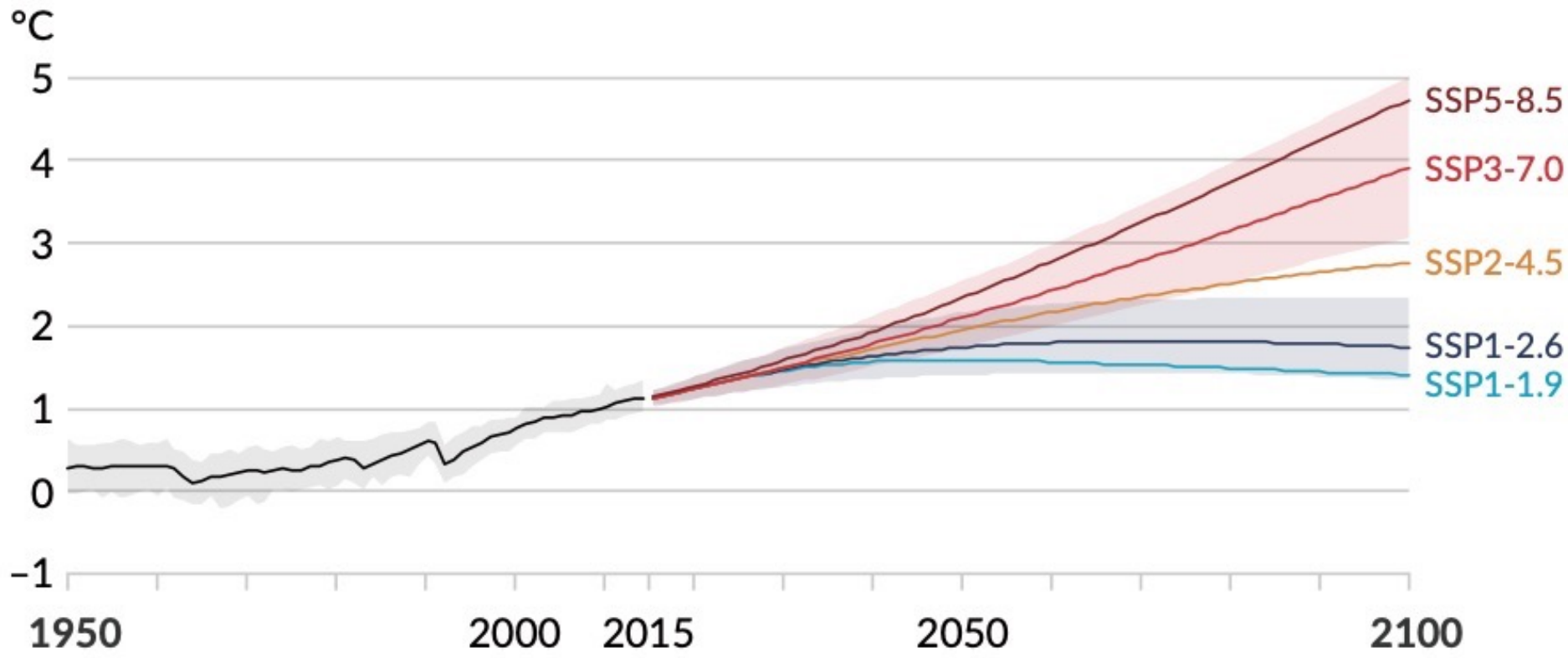
From: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf
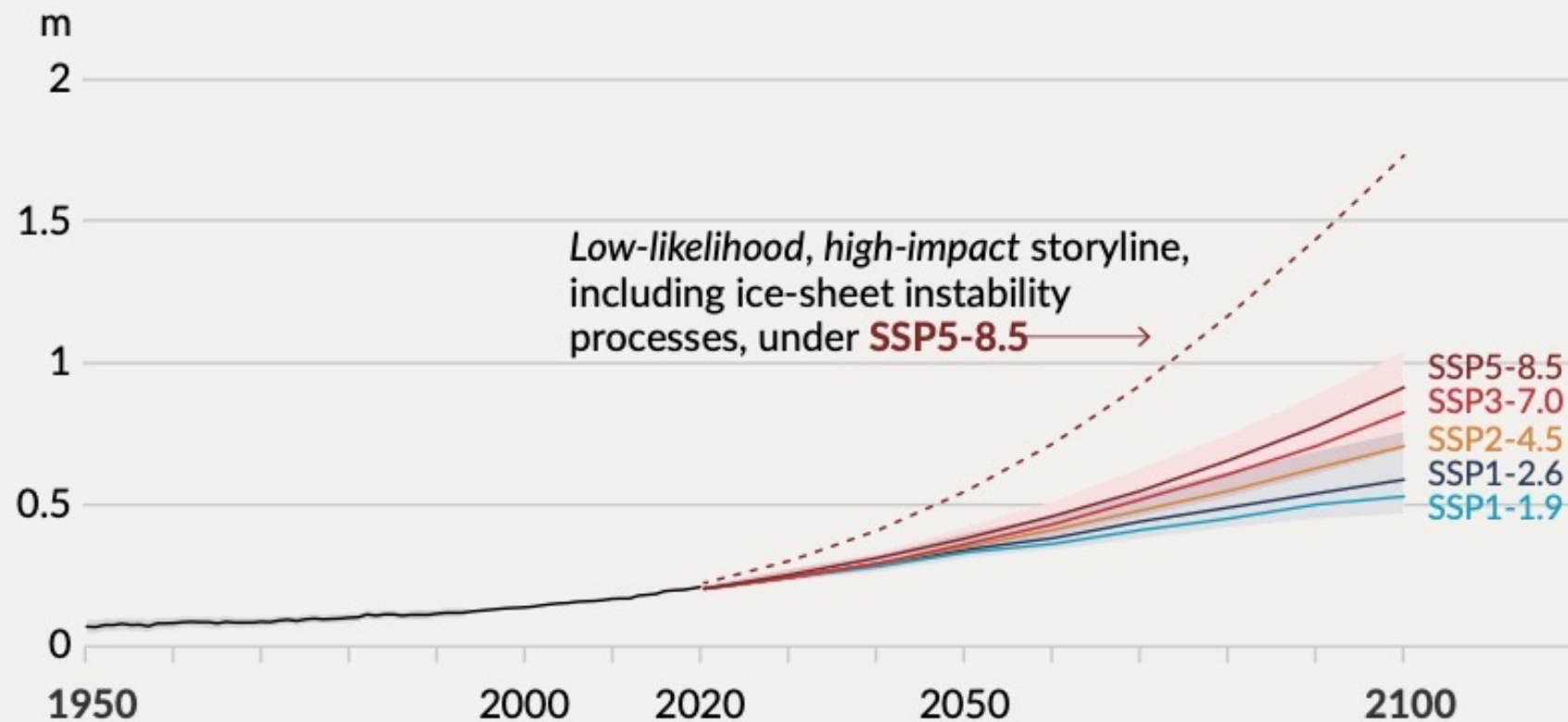
# (b) September Arctic sea ice area

$10^6$ km²

SSP1-1.9
SSP1-2.6
SSP2-4.5
SSP3-7.0
SSP5-8.5

Practically ice-free
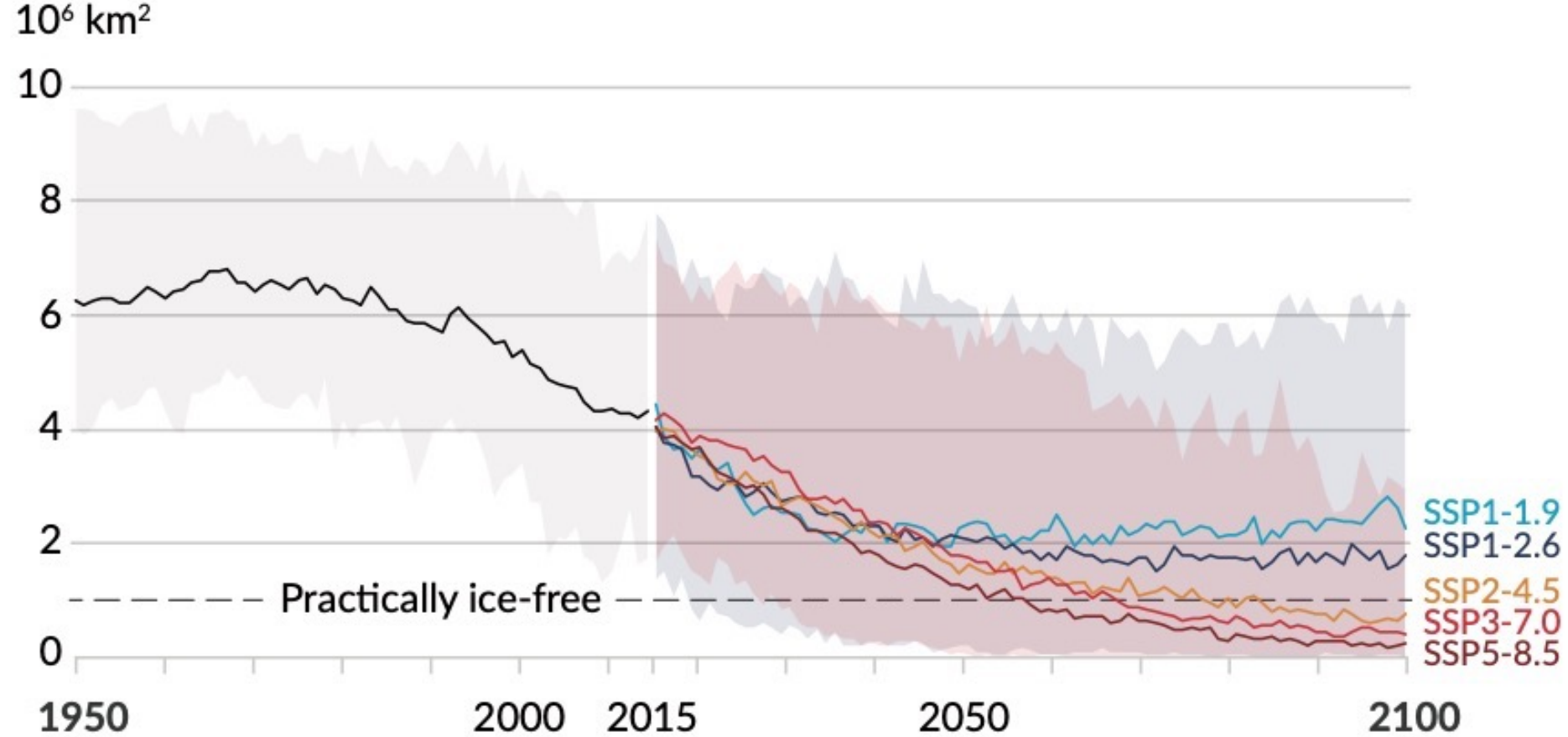
From: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

## (c) Global ocean surface pH (a measure of acidity)



From: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf
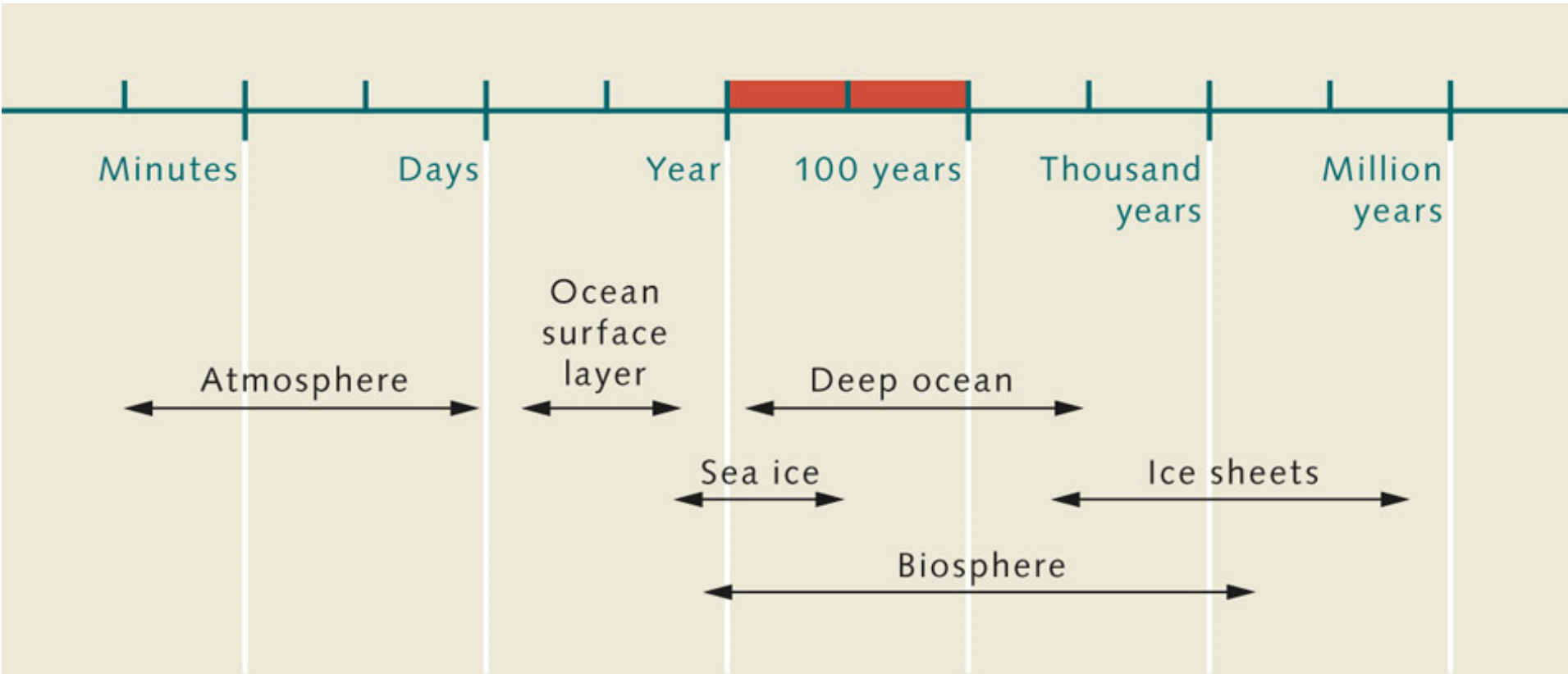
From: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

# But in order to understand climate change we need to understand climate (ocean) natural (decadal) variability
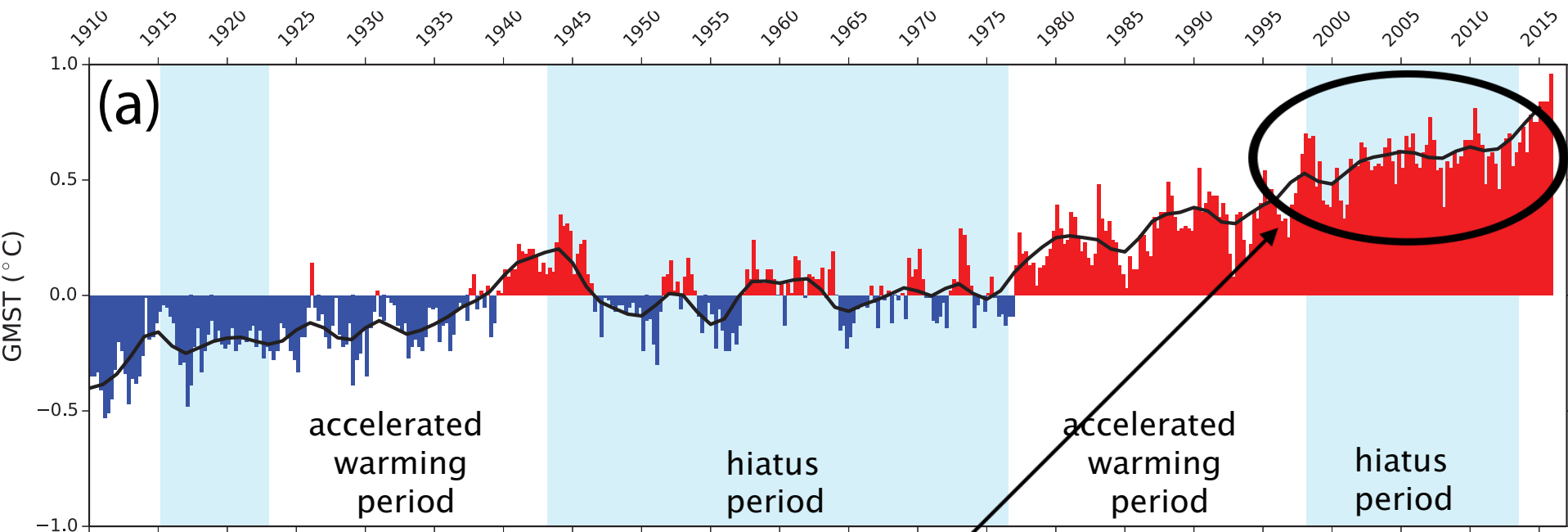


Sources of uncertainty in projected global mean temperature
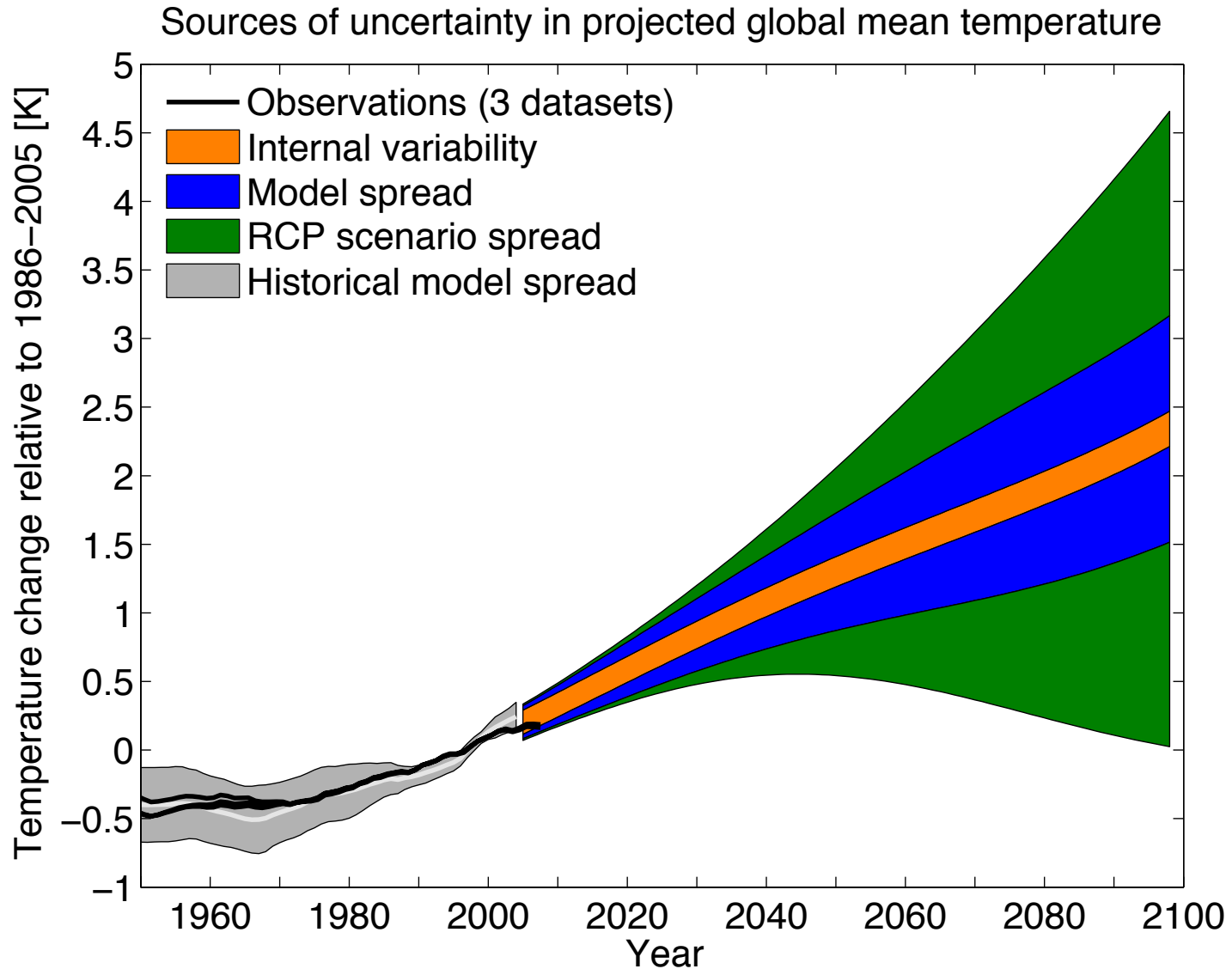
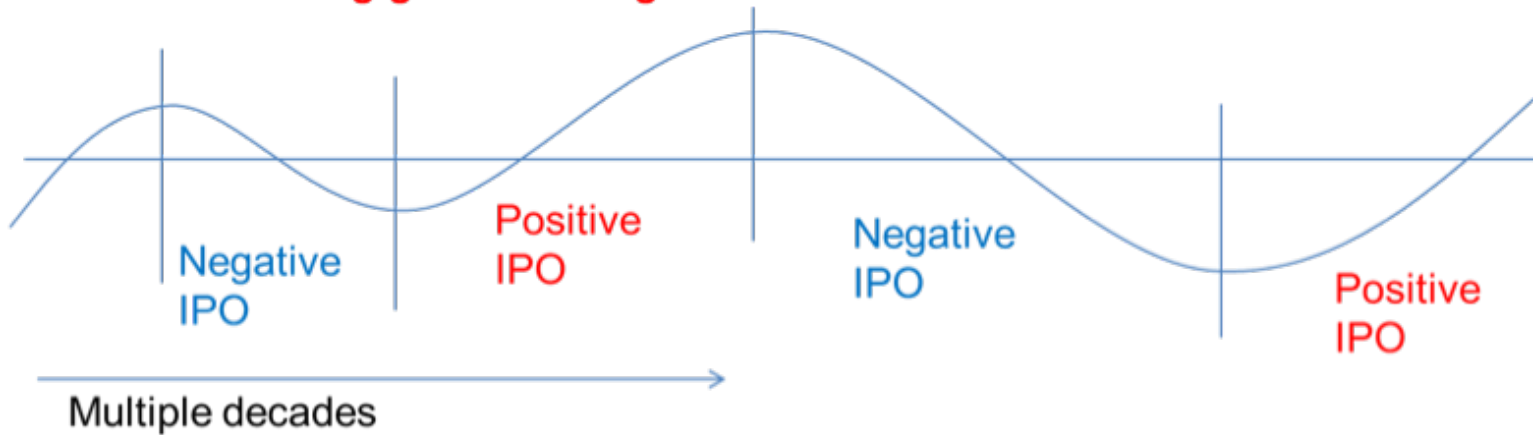# Global Warming is coexisting with internal variability of the deep ocean

# Global Mean Surface Temperature Anomalies:
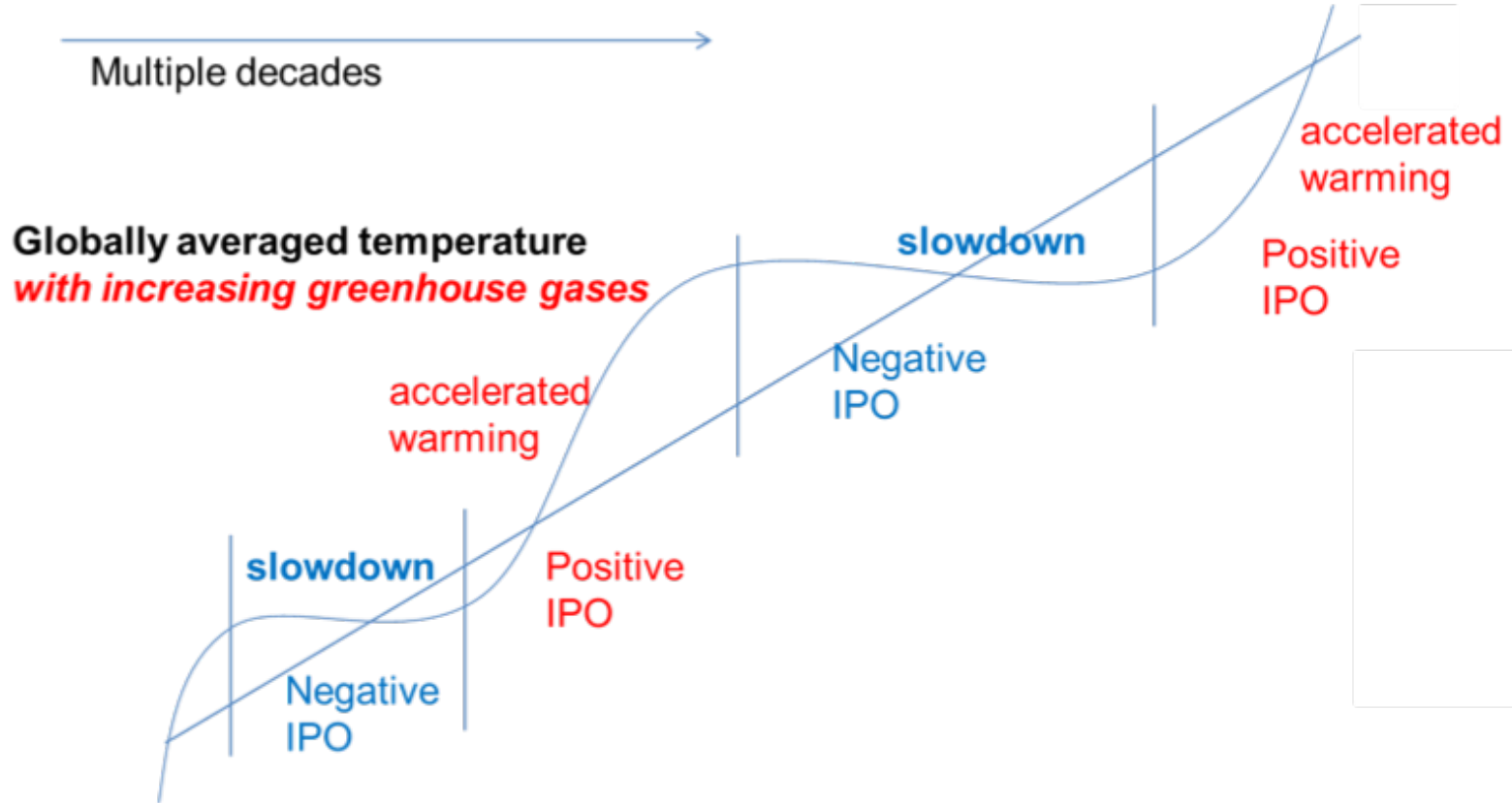## A hiatus (a.k.a. global warming slow-down?)

The slower rise in temperatures from 1998 to 2012 has repeatedly been cited by climate sceptics as a sign that the climate is less sensitive to greenhouse gases than previously thought

(a)

GMST (°C)

accelerated warming period

hiatus period

accelerated warming period

hiatus period

from 1998 until 2012

# Global Mean Surface Temperature Anomalies:
# A hiatus (a.k.a. global warming slow-down?)



**Globally averaged temperature**
*without increasing greenhouse gases*

Negative IPO

Positive IPO

Negative IPO

Positive IPO

Multiple decades

Multiple decades

**Globally averaged temperature**
*with increasing greenhouse gases*

accelerated warming

slowdown

Positive IPO

Negative IPO

slowdown

Negative IPO

Positive IPO

accelerated warming

Positive IPO

**Globally averaged temperature**
*without increasing greenhouse gases*

Negative IPO

Positive IPO

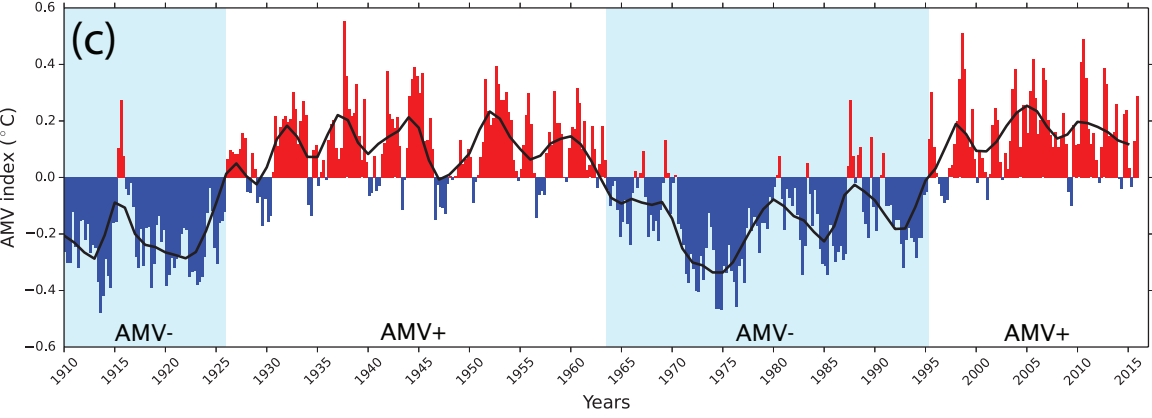Negative IPO

Positive IPO

Multiple decades

Just Natural Variability of the Ocean!
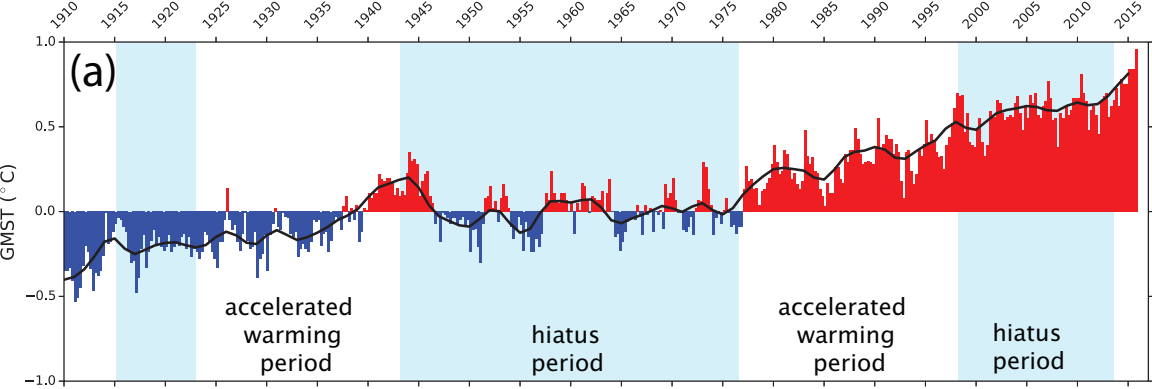
(a) Two signals superimposed: the effect of global warming + natural fluctuations of the ocean
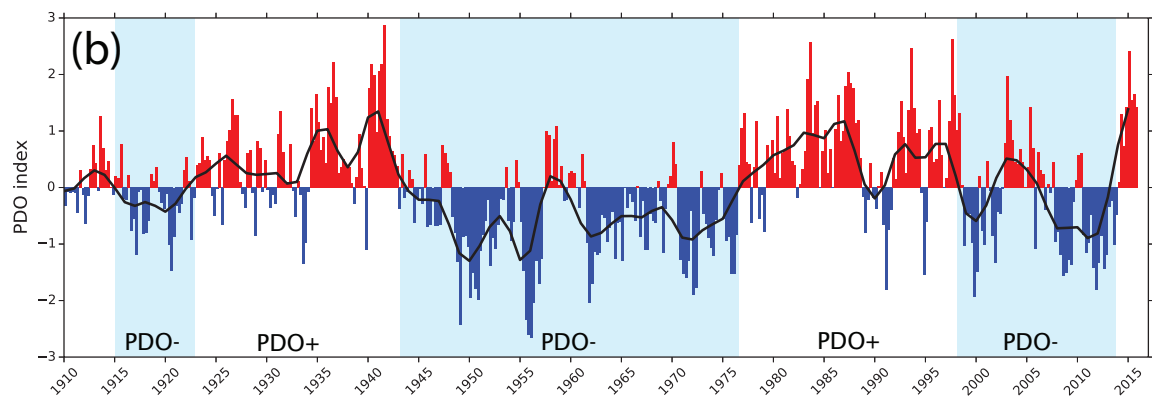
(b) Pacific Decadal Oscillation

(c) Atlantic Multidecadal Variability

Farneti (2017)