Meridional Overturning Circulation, Ocean Heat Transport and Climate Change

2023-2024

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

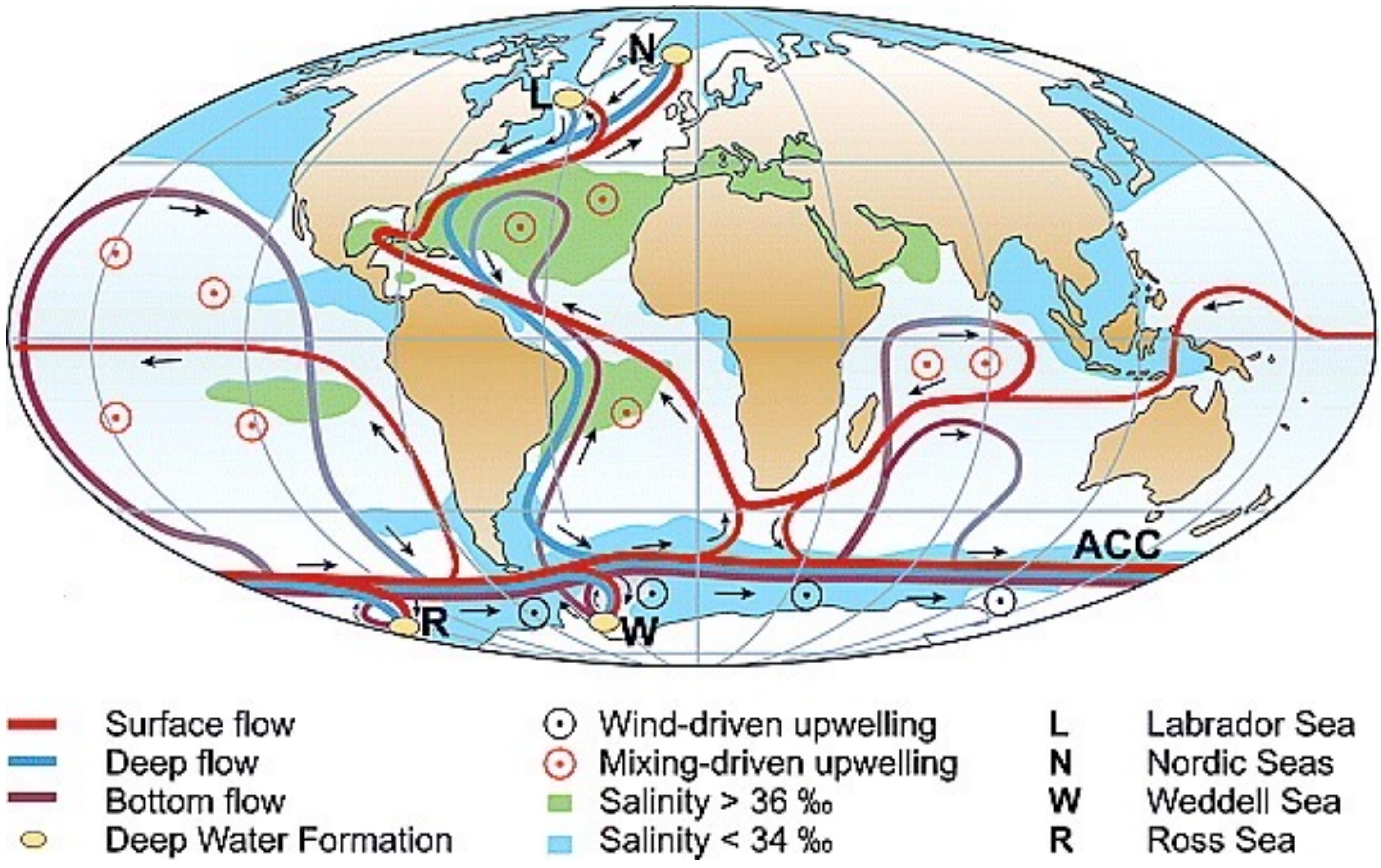
Controversy on names:

"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.

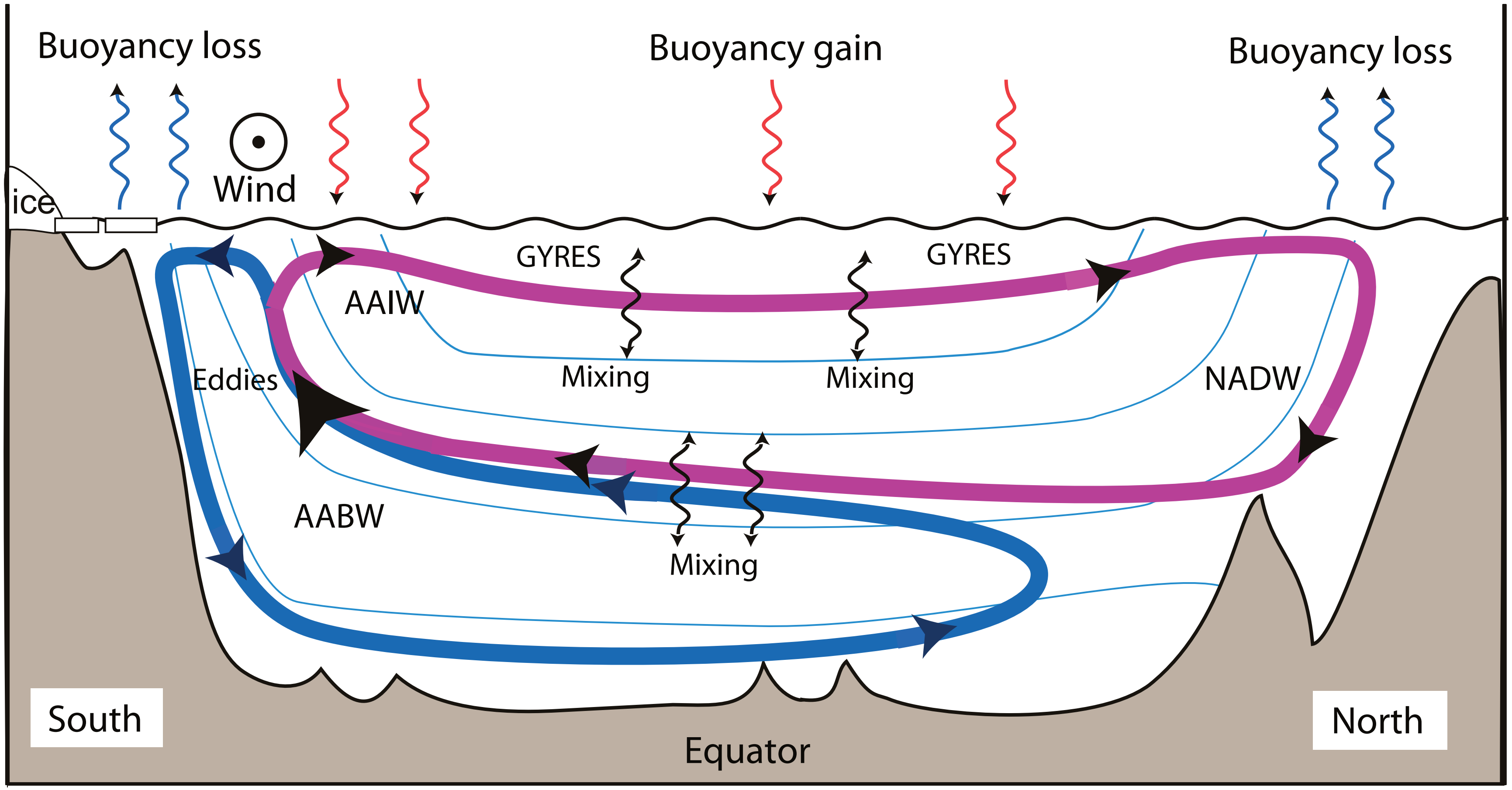
In physical oceanography, we also refer to "abyssal circulation" when discussing the theory of deep circulation (*See Stommel-Aaron's Model*)

"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

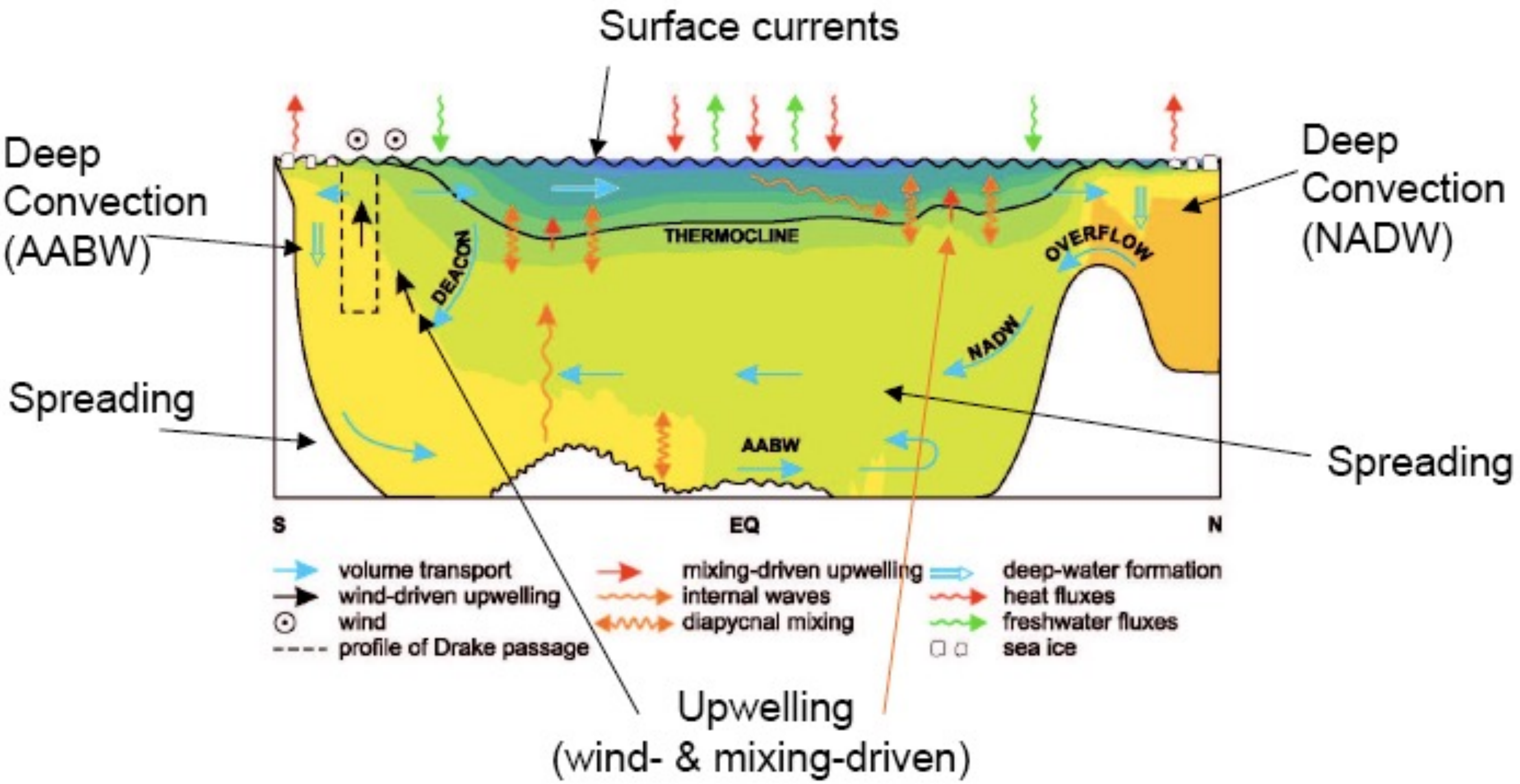


Buoyancy and Wind-driven MOC



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.



Surface currents

Deep Convection (AABW)

Deep Convection (NADW)

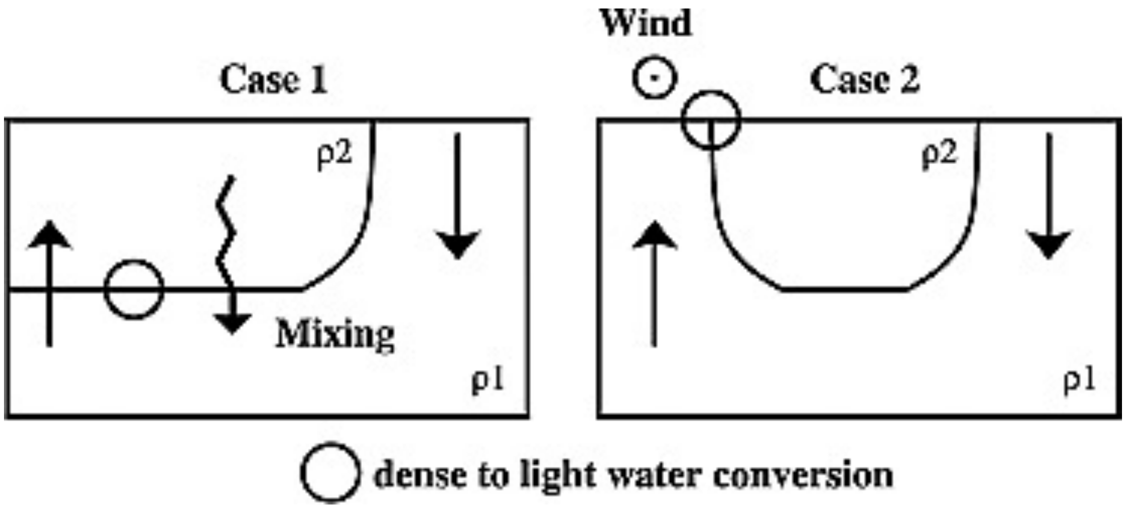
Spreading

Spreading

Upwelling
(wind- & mixing-driven)

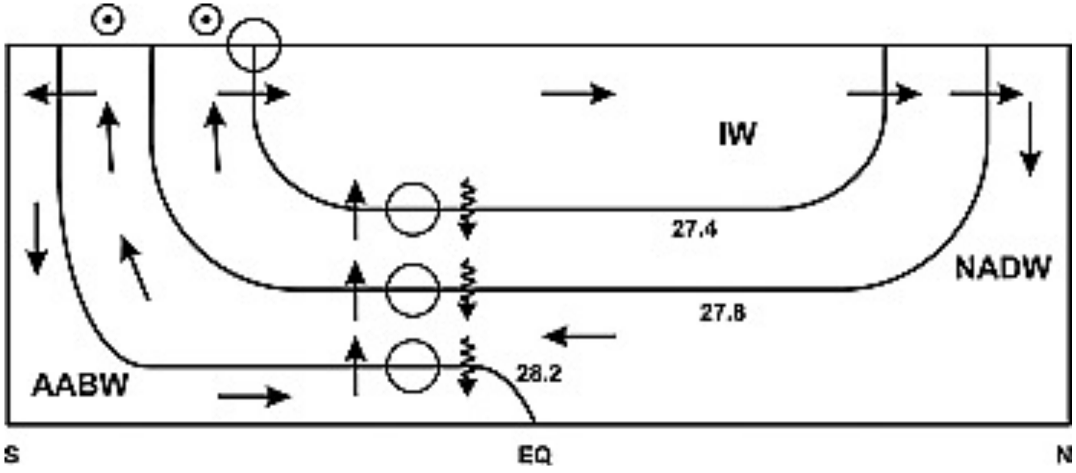
Its drivers are: (a) turbulent diapycnal mixing,
(b) wind-driven upwelling in the Southern Ocean

Mixing & Winds

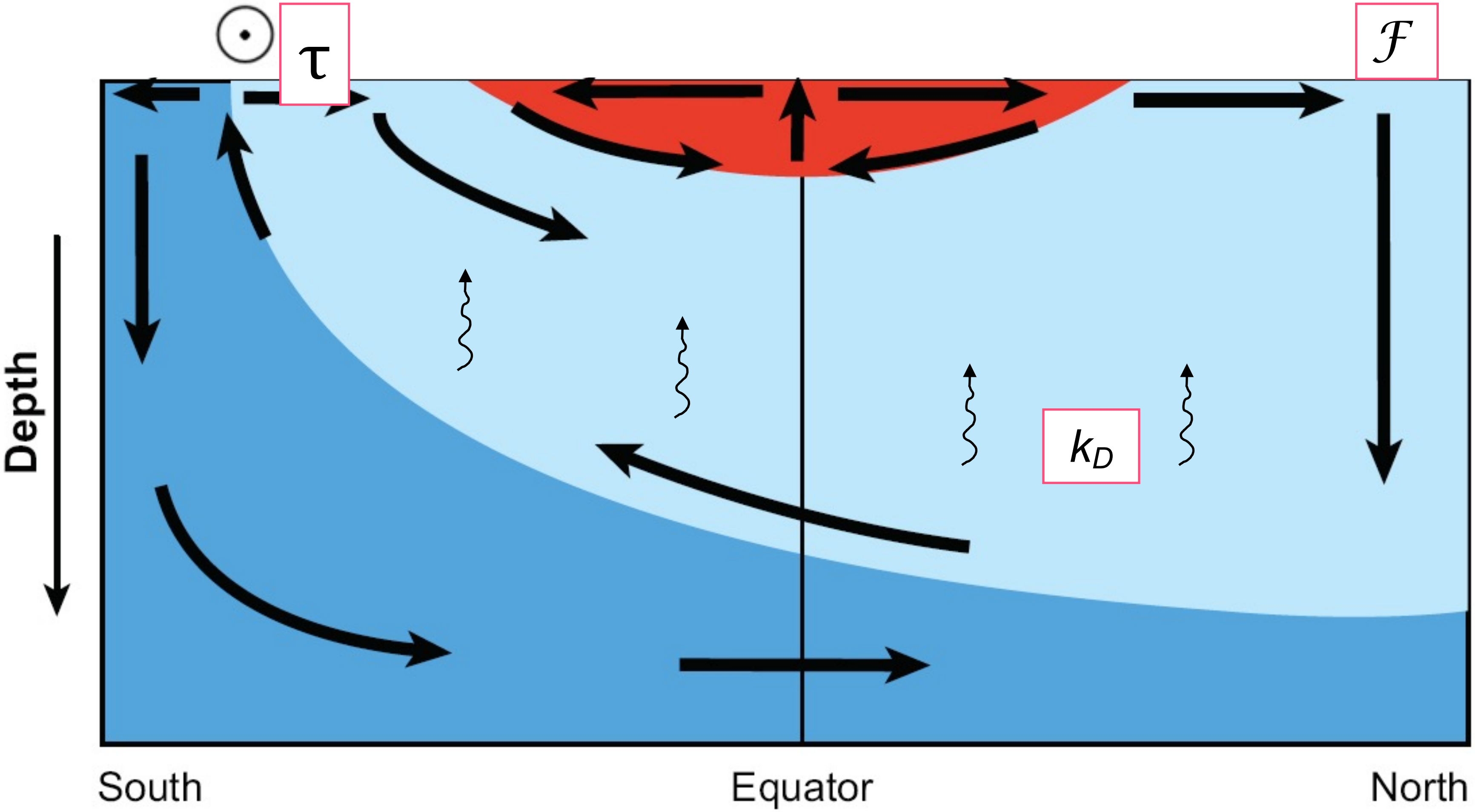


Sketch of the two extreme cases: “only diapycnal mixing” (case 1) and “only wind-driven upwelling” (case 2). The curved line indicates the thermocline that separates denser from lighter waters. The open circles indicate regions of dense-to-light conversion of water masses.

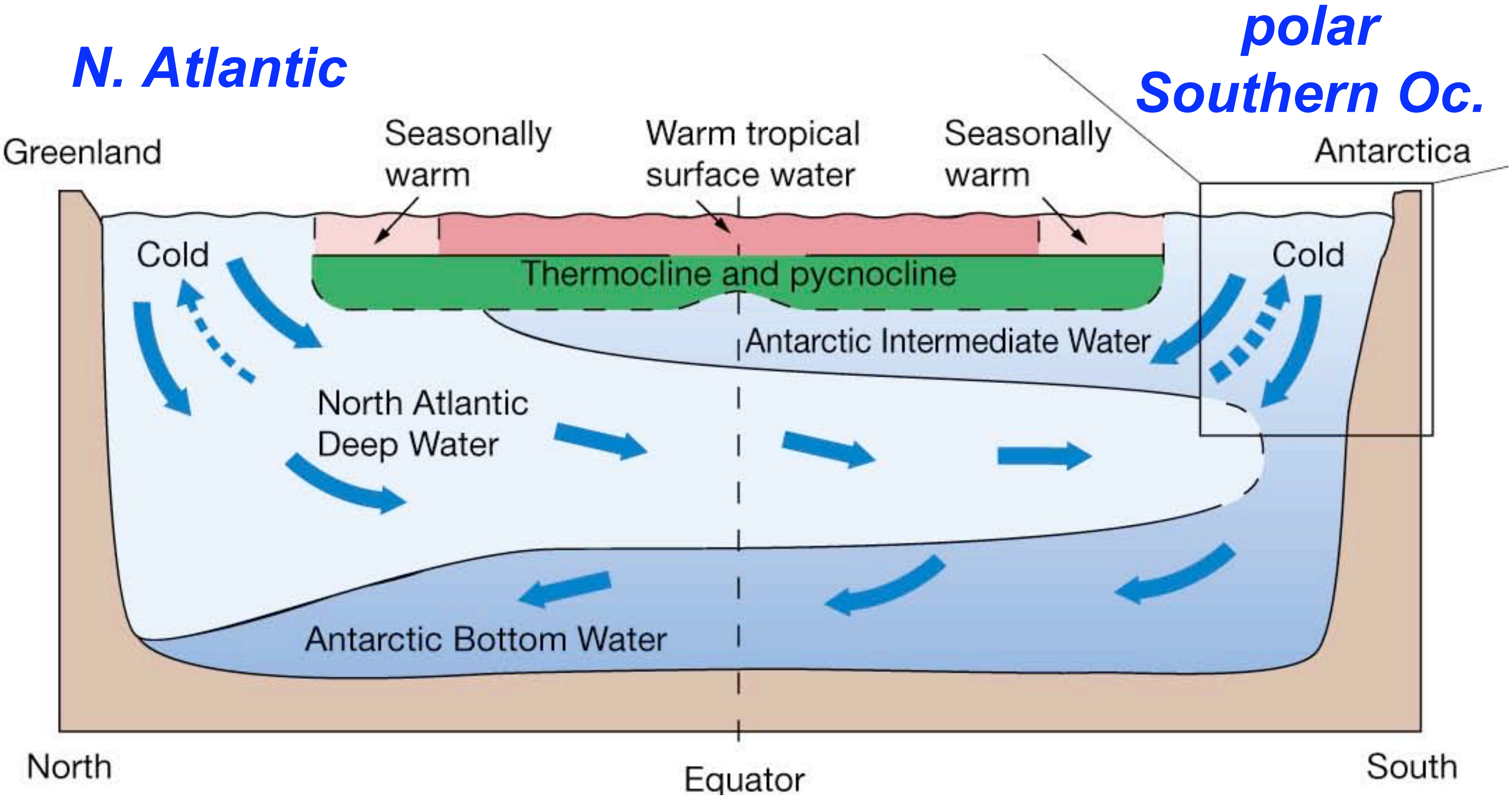
Schema of the AMOC. The two cells are driven by both diapycnal mixing and wind-driven upwelling.



Important parameters: τ – *wind stress in the Southern ocean*
k_D– *diapycnal diffusivity*
$\mathcal{F}$ – *surface freshwater fluxes*

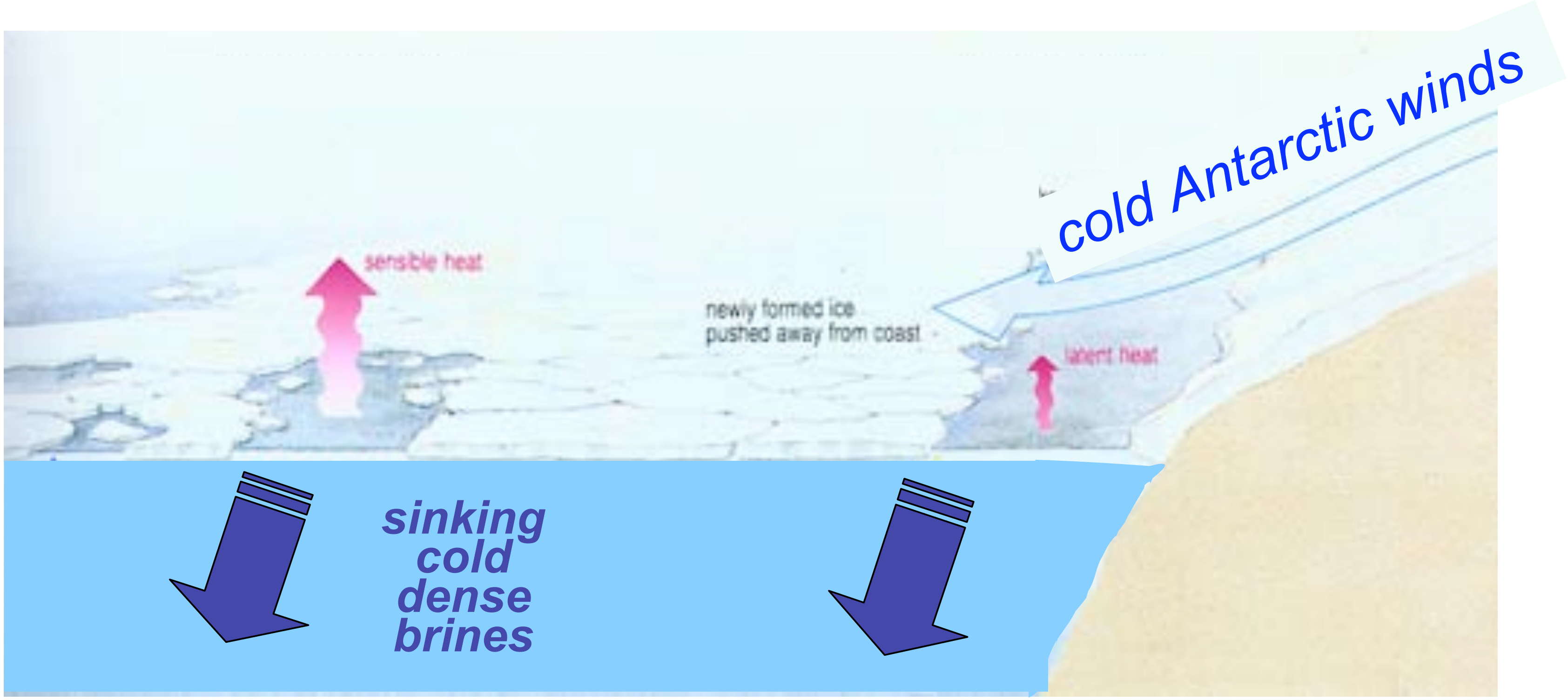


polar sources of deep water



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

the Antarctic sea-ice factory



cold Antarctic winds

**sinking
cold
dense
brines**

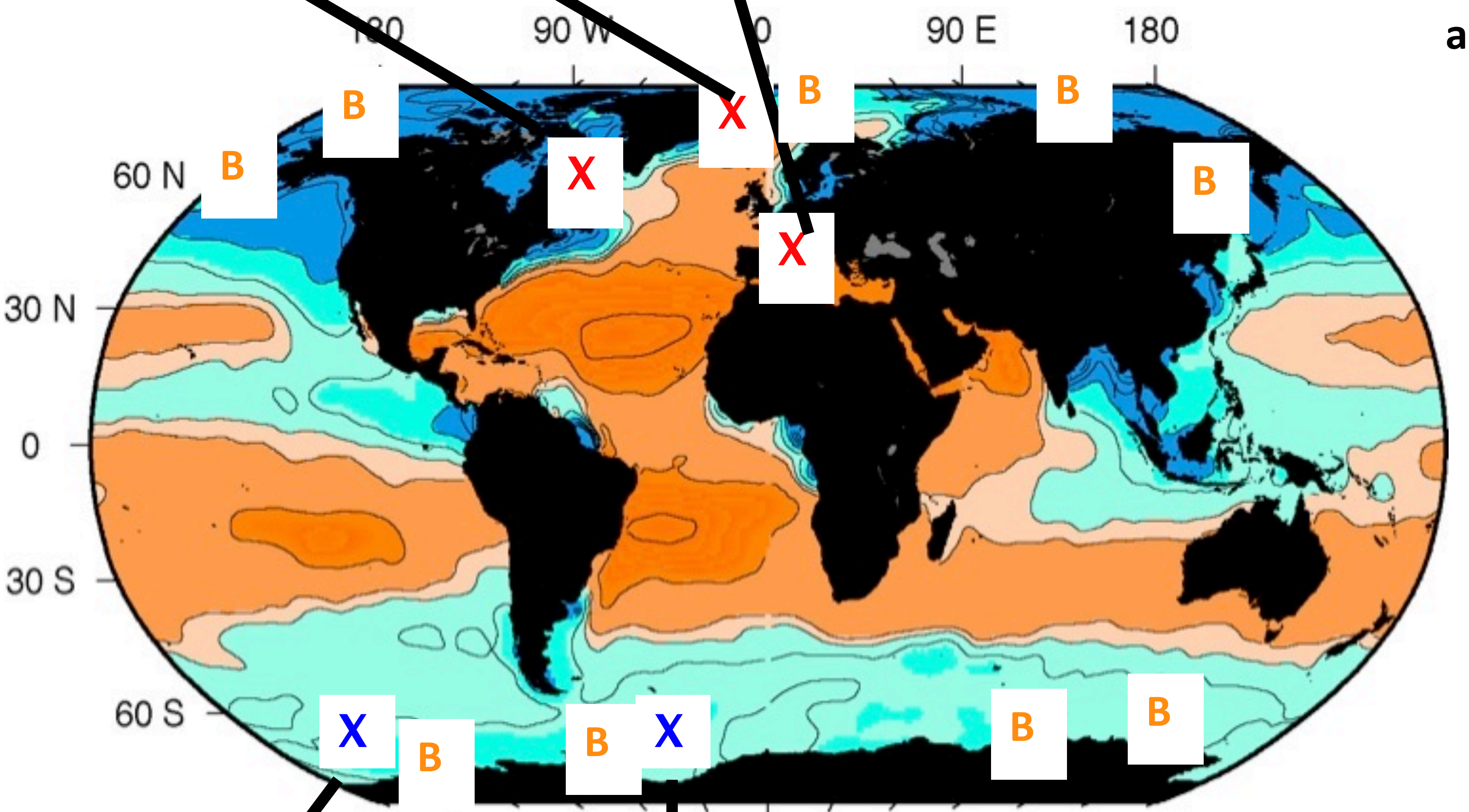
cold winds blow sea-ice out to sea as it formed, allowing continual formation of new sea ice… as sea ice is formed from sea water, salt is rejected, enriching salt content below

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

Deep convection and brine rejection sites

Labrador Sea Greenland Sea Mediterranean Sea

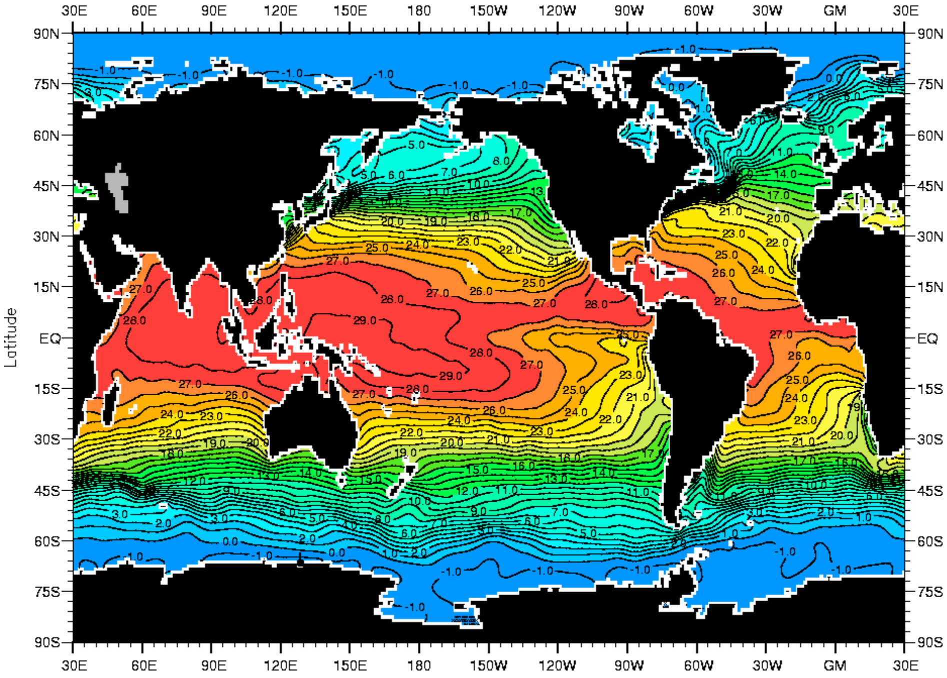
Brine rejection in all sea ice areas



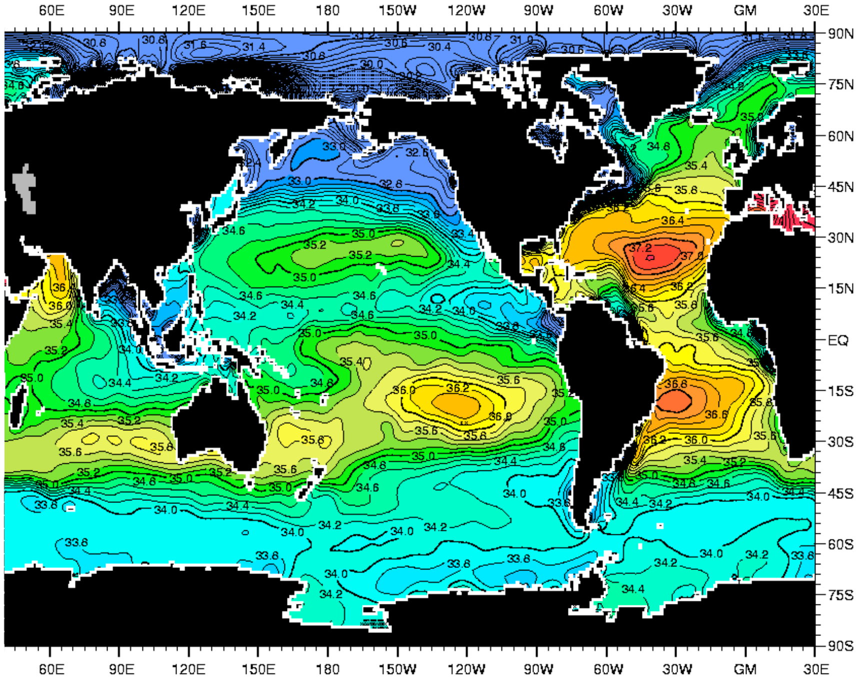
Ross Sea Weddell Sea

clicker question:

temperature



salinity

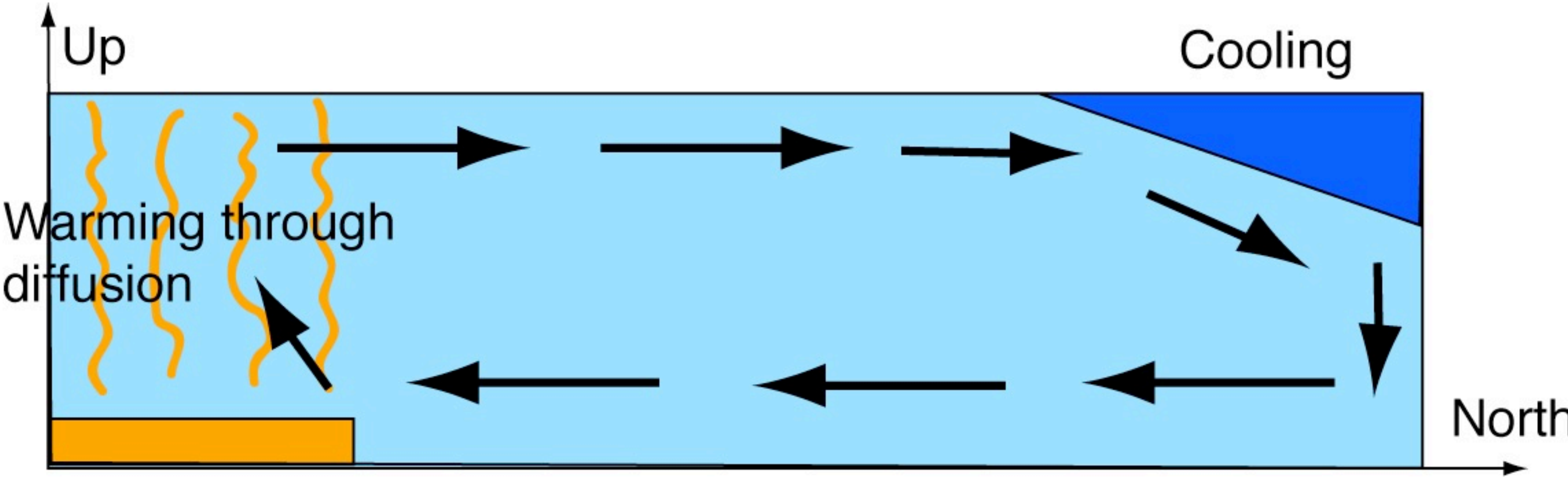


surface waters are cold throughout the high latitudes, so why might deep water formation occur in the N. Atlantic but not in the N. Pacific?

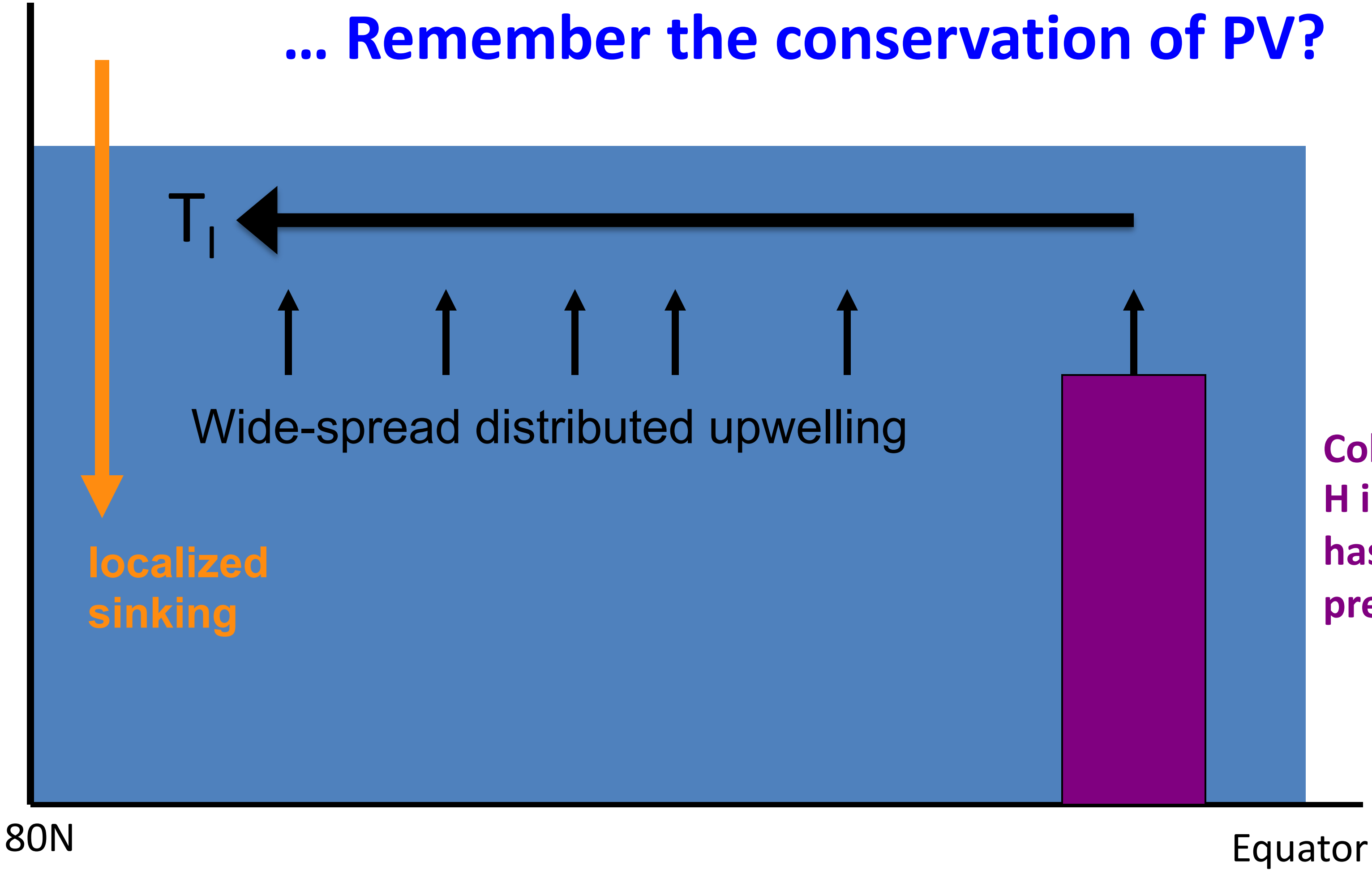
a) not *really* cold in N. Pac, b) not windy enough, c) Coriolis wrong direction, d) not salty enough, e) too sunny

Abyssal circulation dynamics

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



… Remember the conservation of PV?



T_l

Wide-spread distributed upwelling

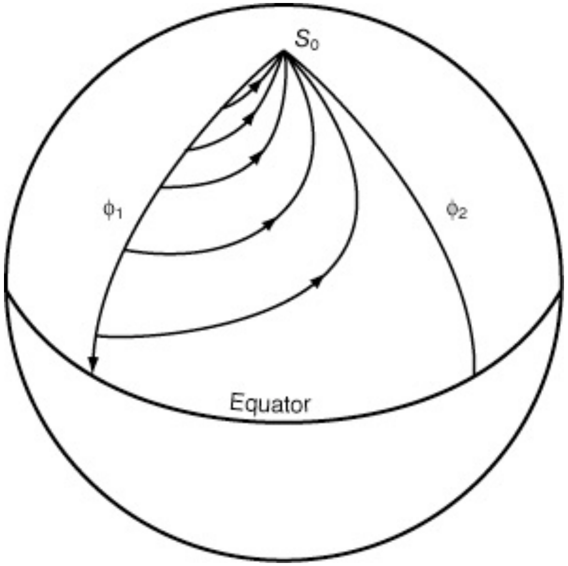
localized sinking

80N

Equator

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

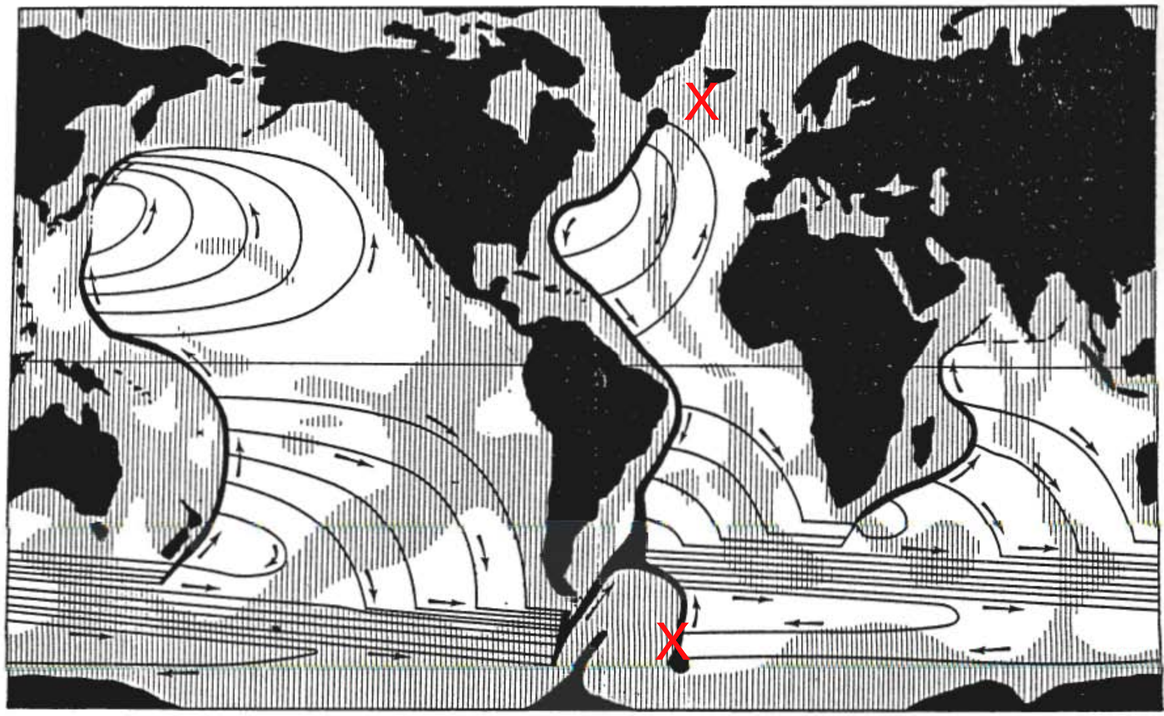
Abyssal circulation: Stommel-Aarons model



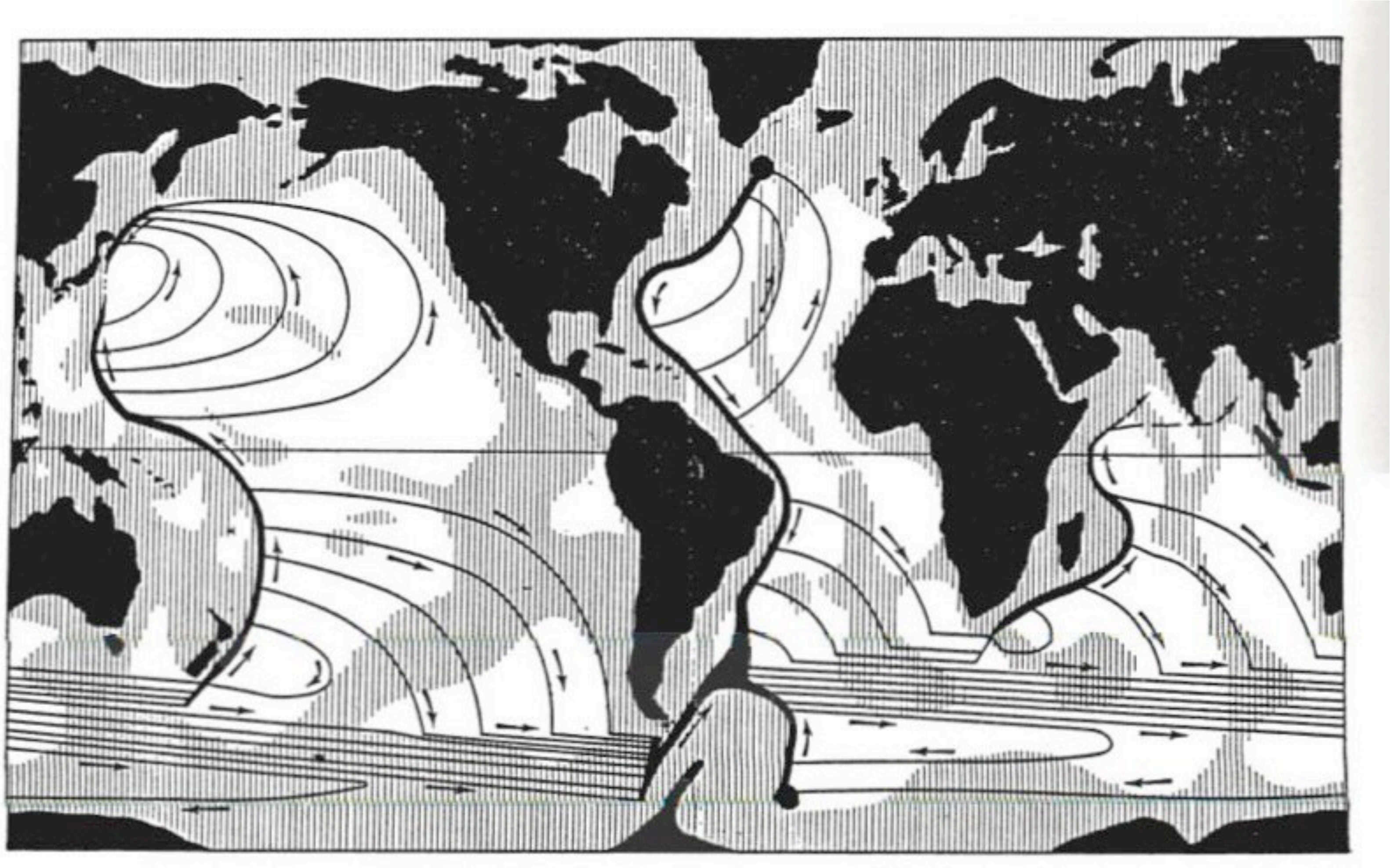
Local deep water sources

General upwelling

Yields poleward interior flow, connected with Deep Western Boundary Currents



Very idealized model of global DWBCs (Stommel, 1958)

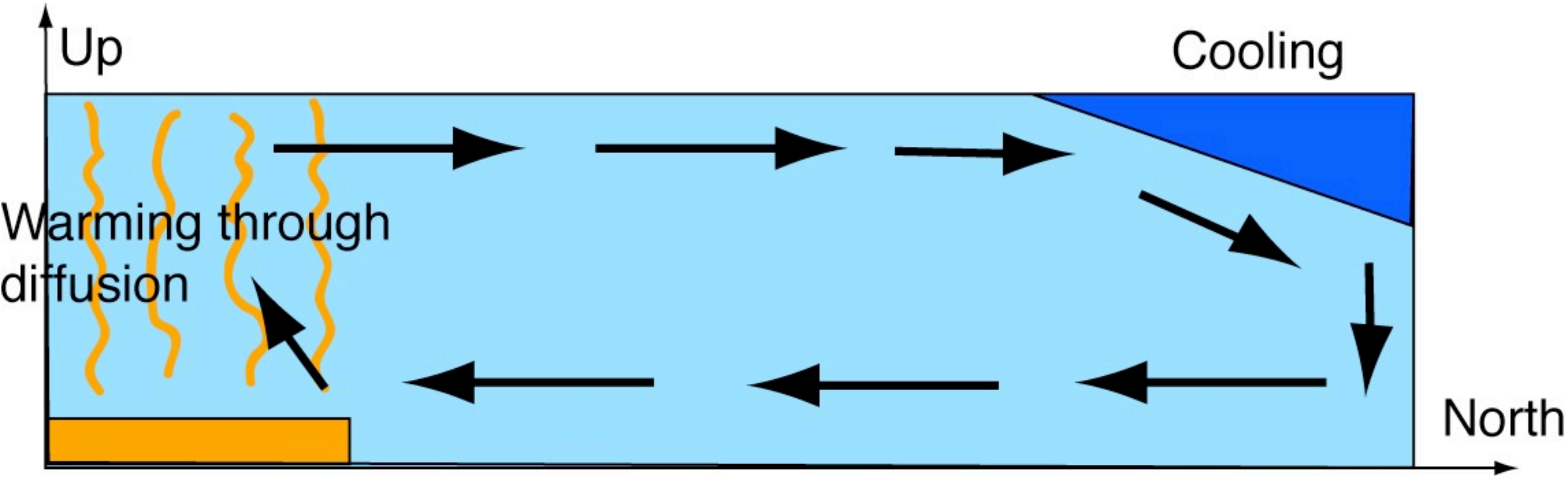


No topography

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 numerical 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)

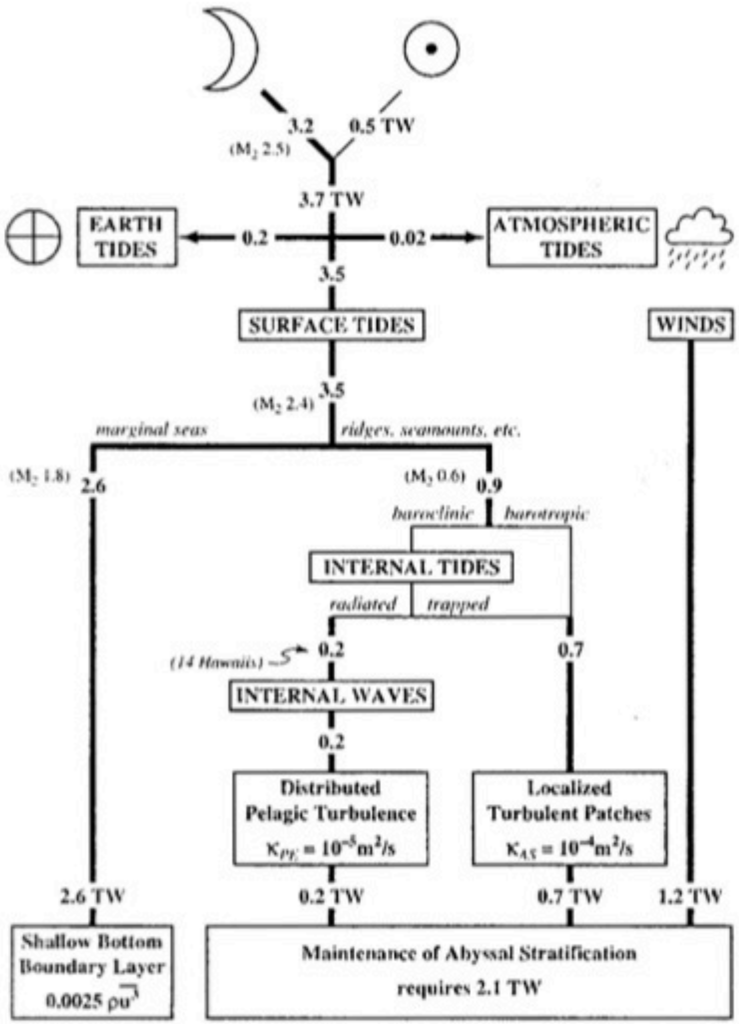


Fig. 4. An impressionistic budget of tidal energy flux. The traditional sink is in the bottom boundary laye (BBL) of marginal seas. Preliminary results from Egbert (1997) based on TOPEX/-POSEIDON altimetr suggest that 0.9 TW (including 0.6 TW of M_2 energy) are scattered at open ocean ridges and seamounts 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 availabl 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

⇓

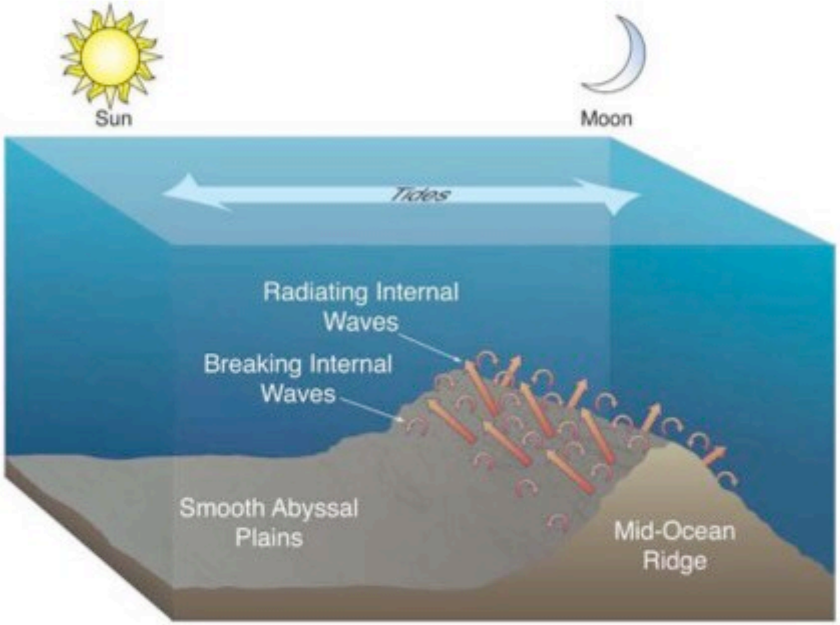
Turbulence due to breaking internal waves

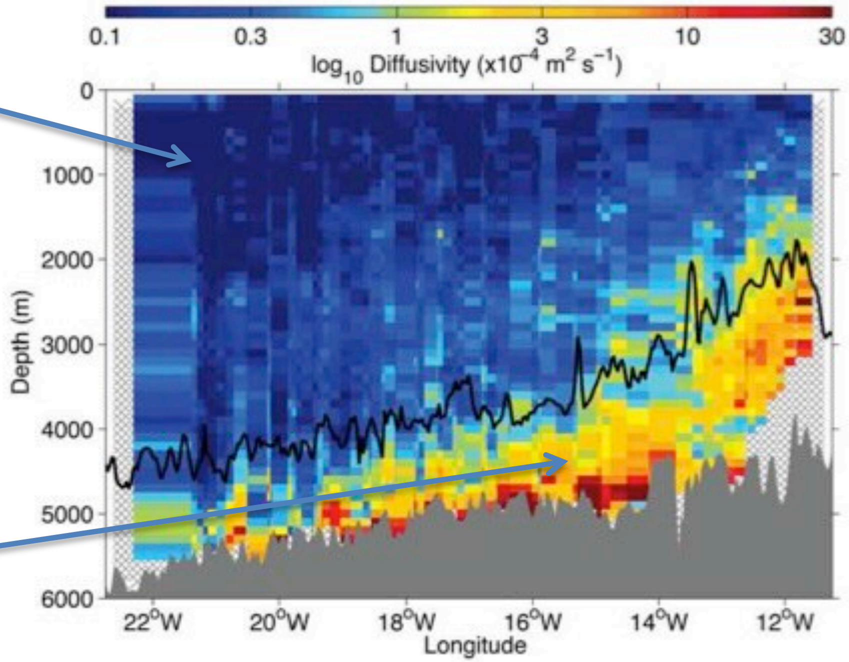
⇓

Mixing temperature, salinity & tracer fields

⇓

Ocean circulation & Sea level

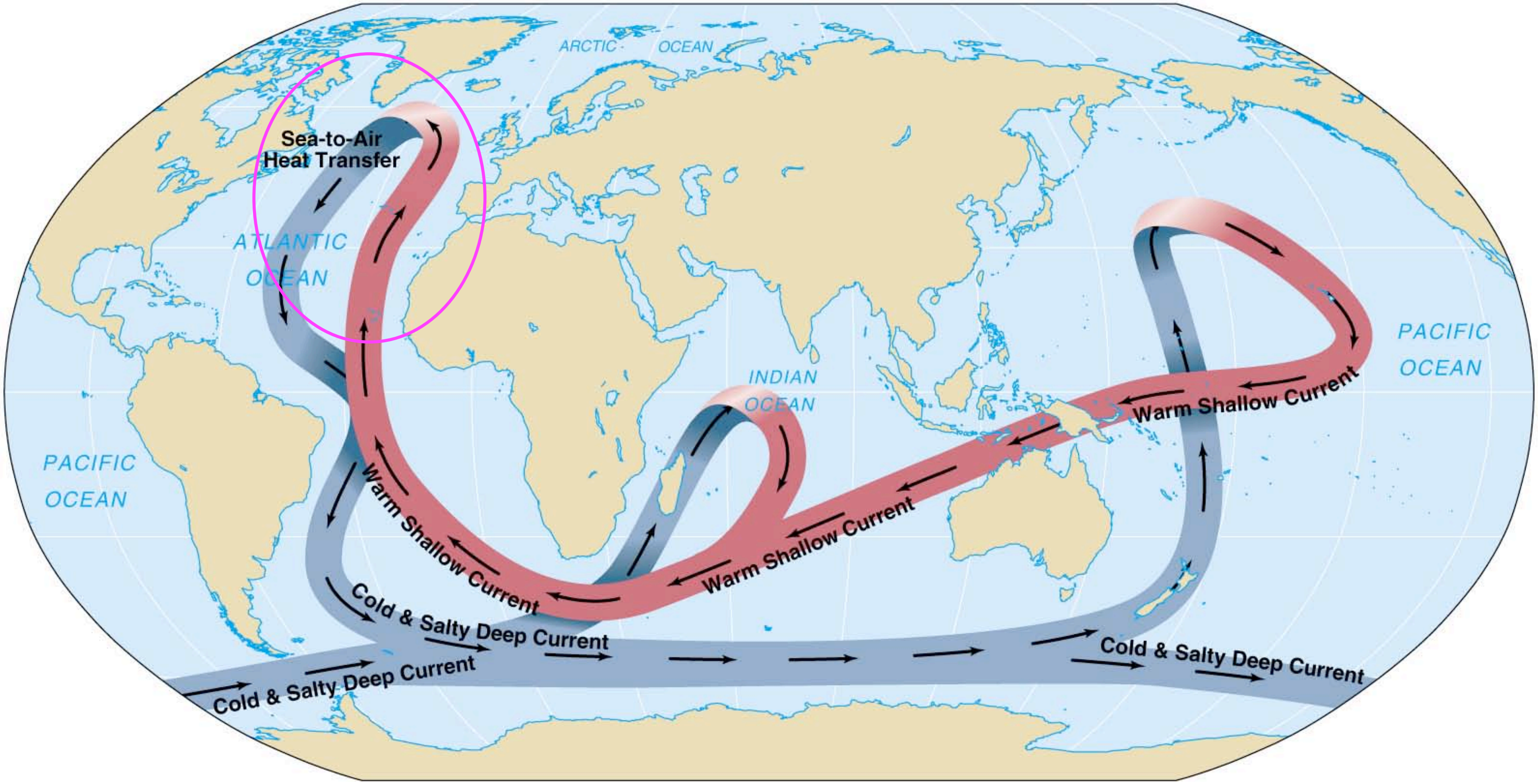




Kv = 10^{-5}

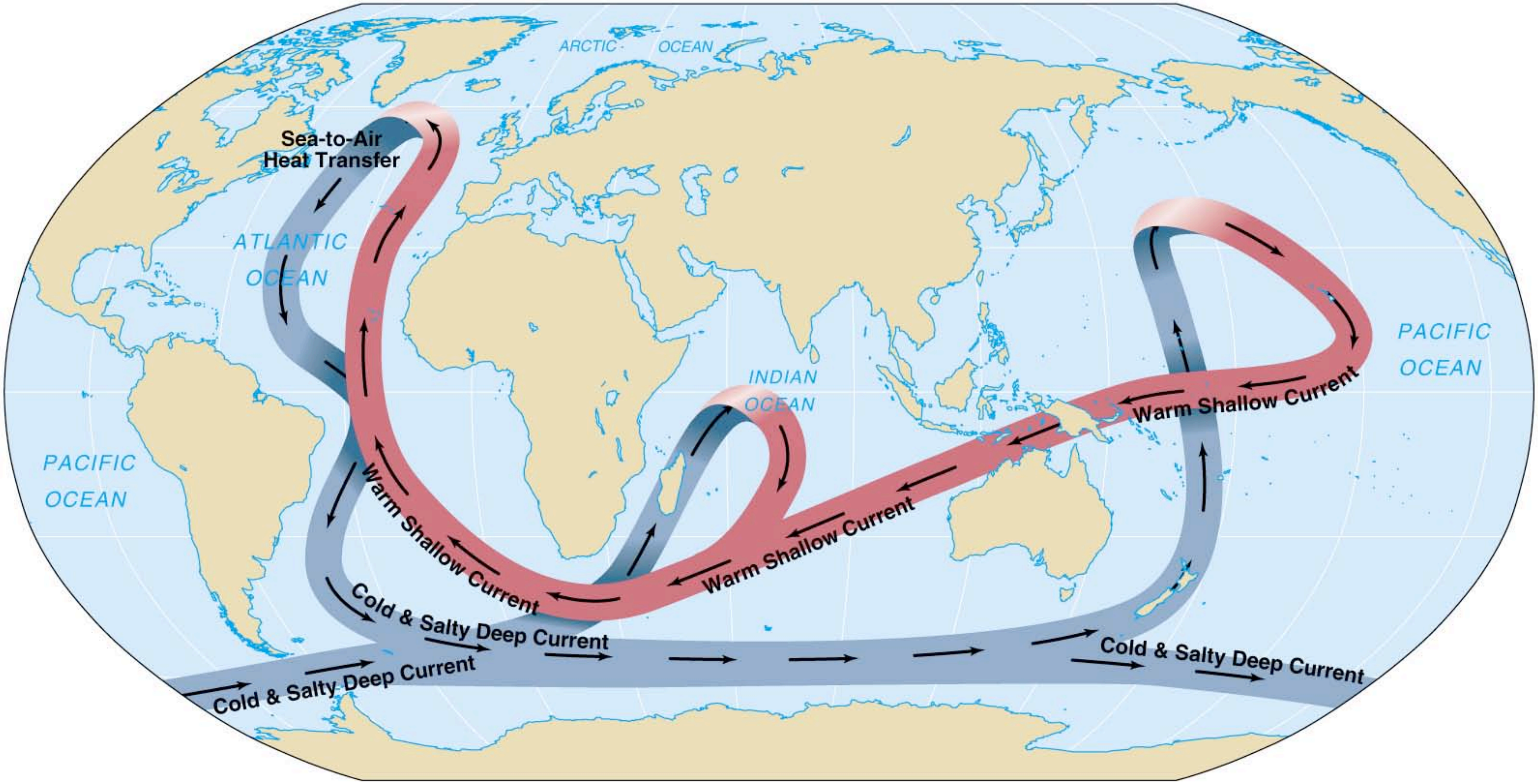
Kv = 10^{-3}

the ocean “conveyor belt”



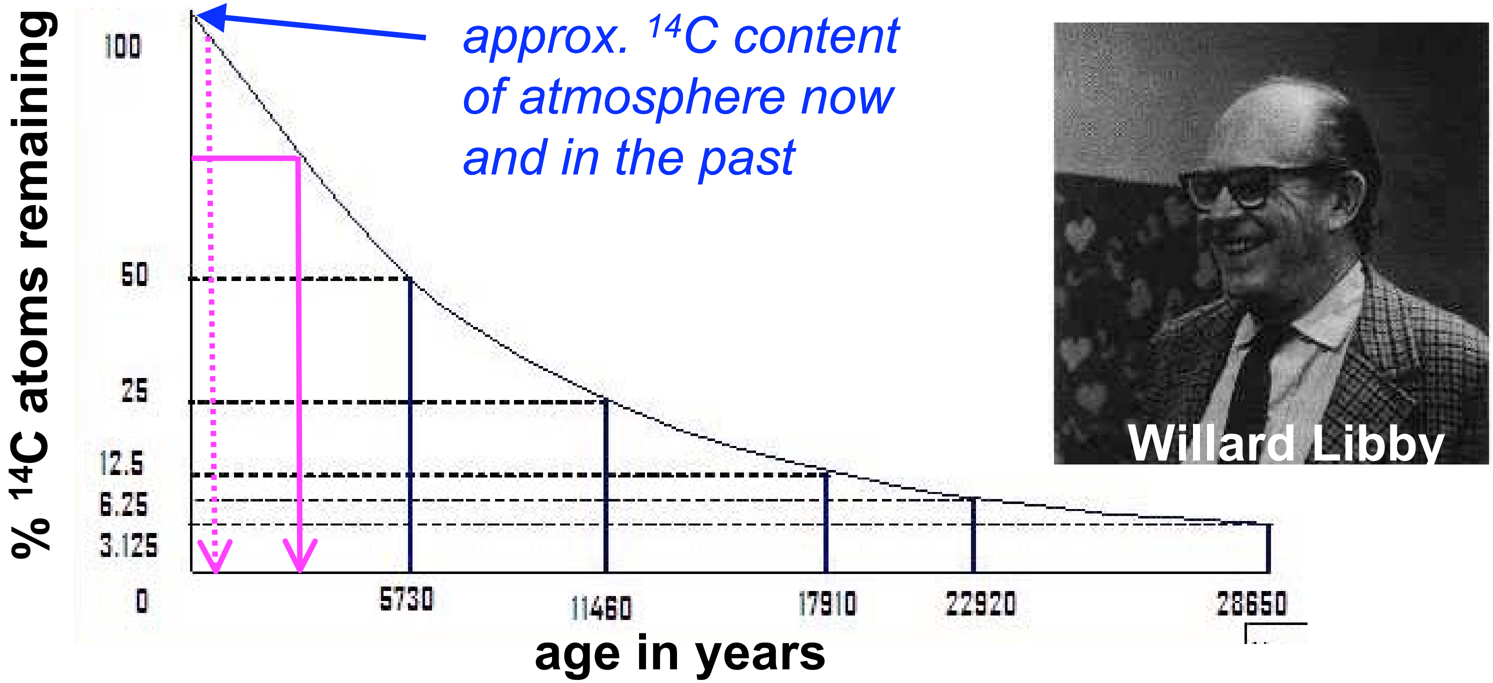
deep circulation dominated by a continuous circuit associated with formation of deep water in the N. Atlantic (i.e. NADW)
“what goes around comes around”

the ocean “conveyor belt”



long route implies long time to complete circuit
how long?

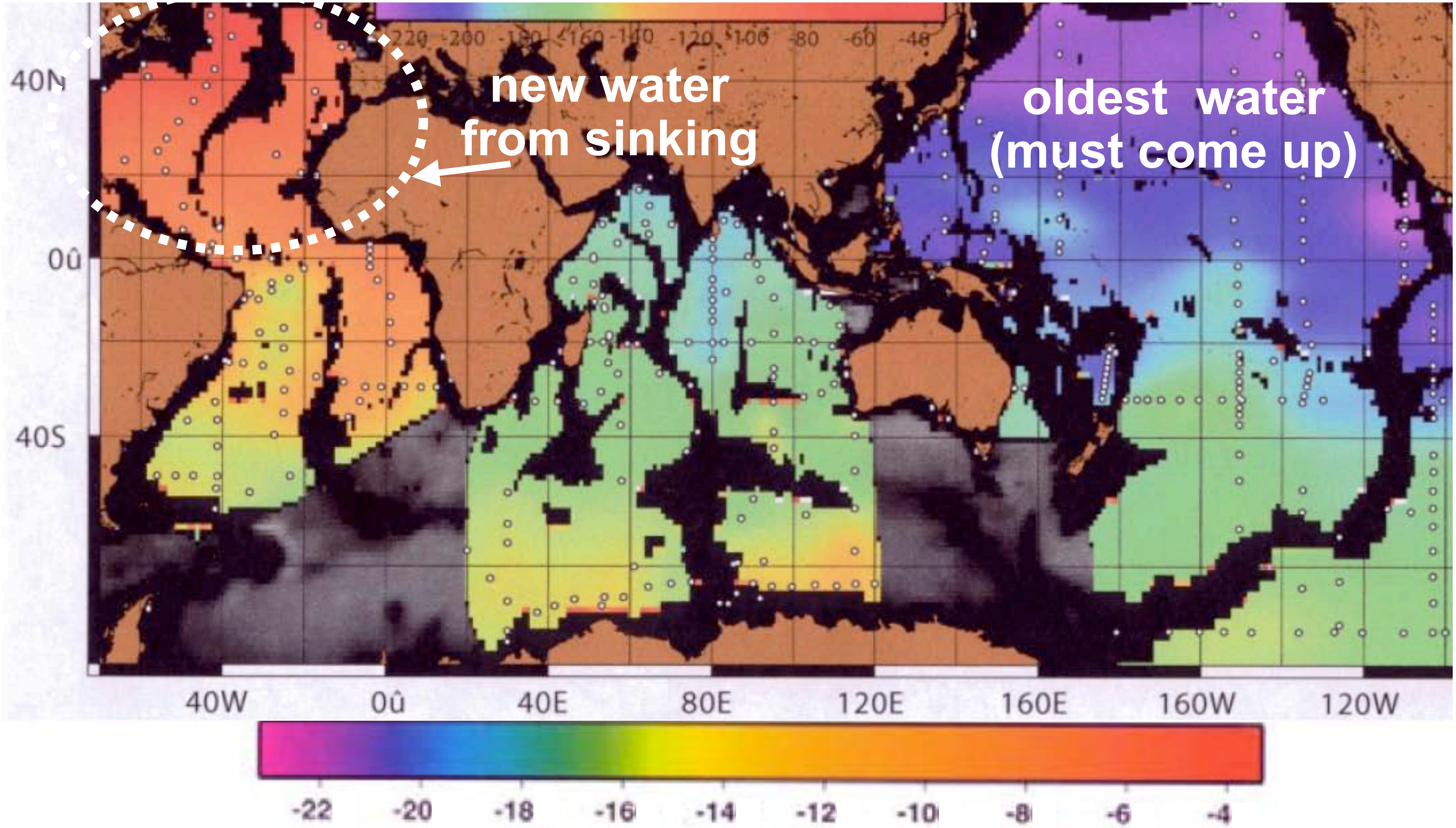
how old is the deep ocean?



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

- 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 ^{14}C means older water!



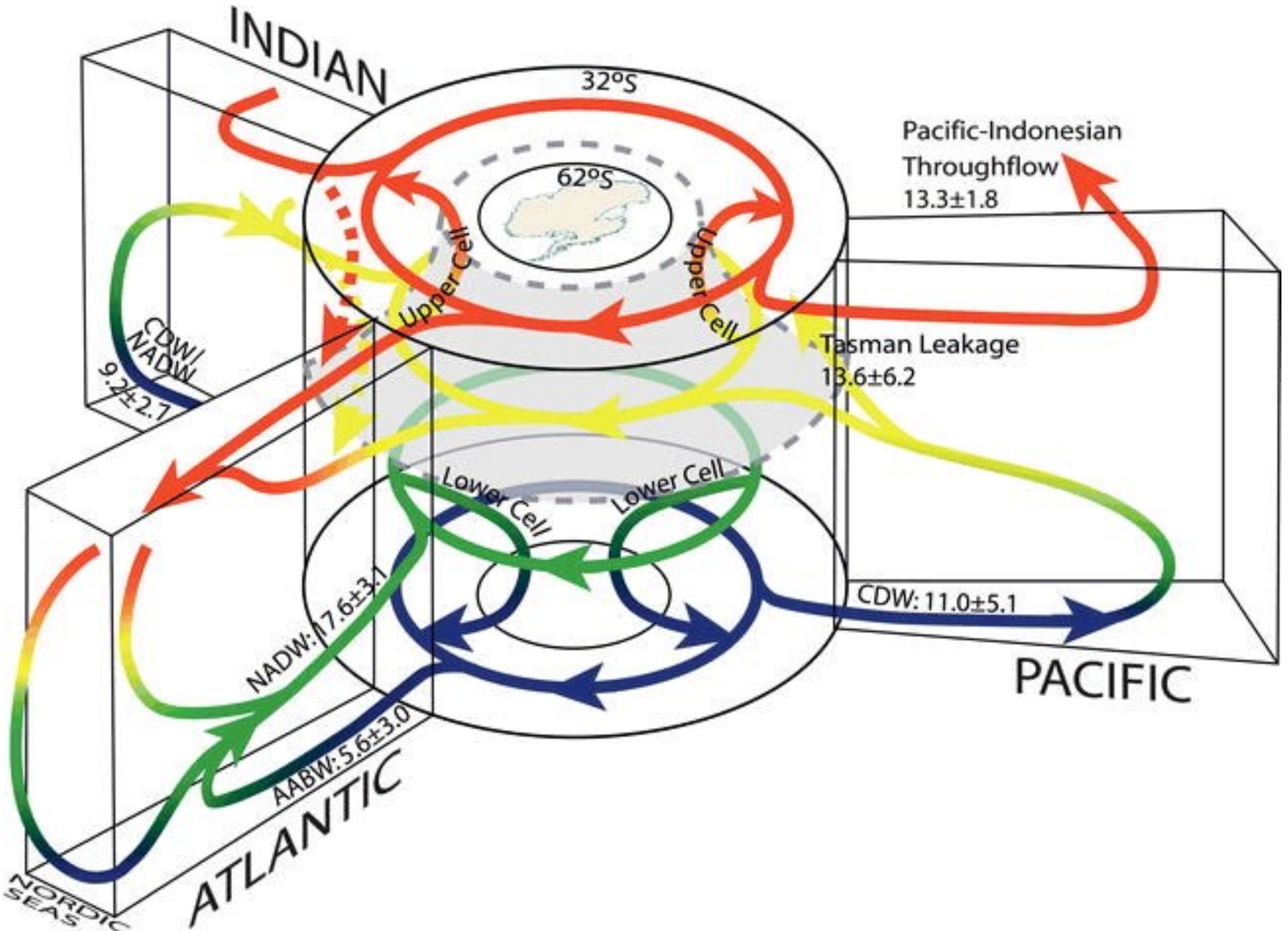
new water
from sinking

oldest water
(must come up)

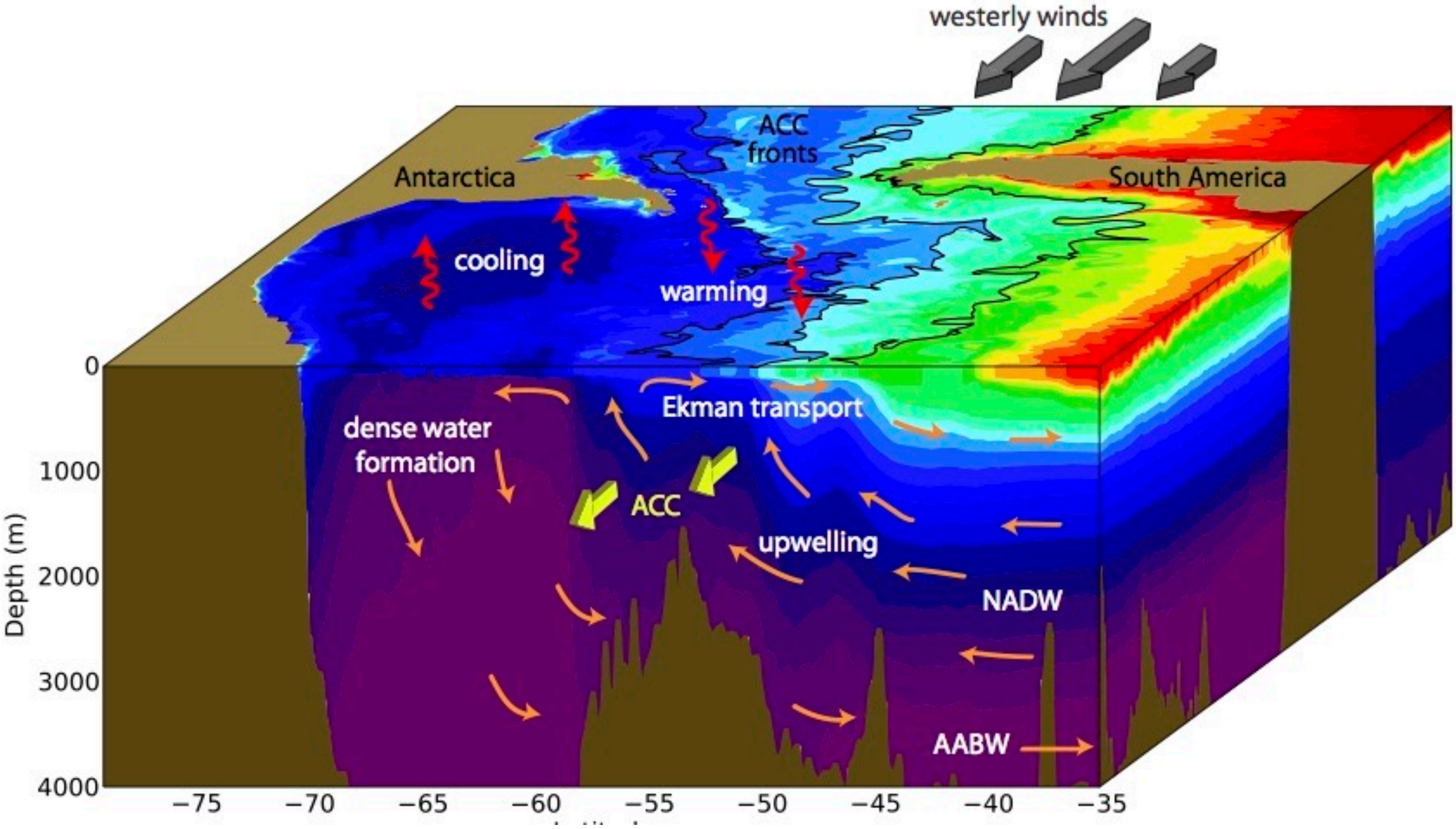
near bottom ^{14}C (% deviation from modern)

can estimate avg. timescale of deep circulation is 1000 years!

The Southern Ocean: a pivotal role

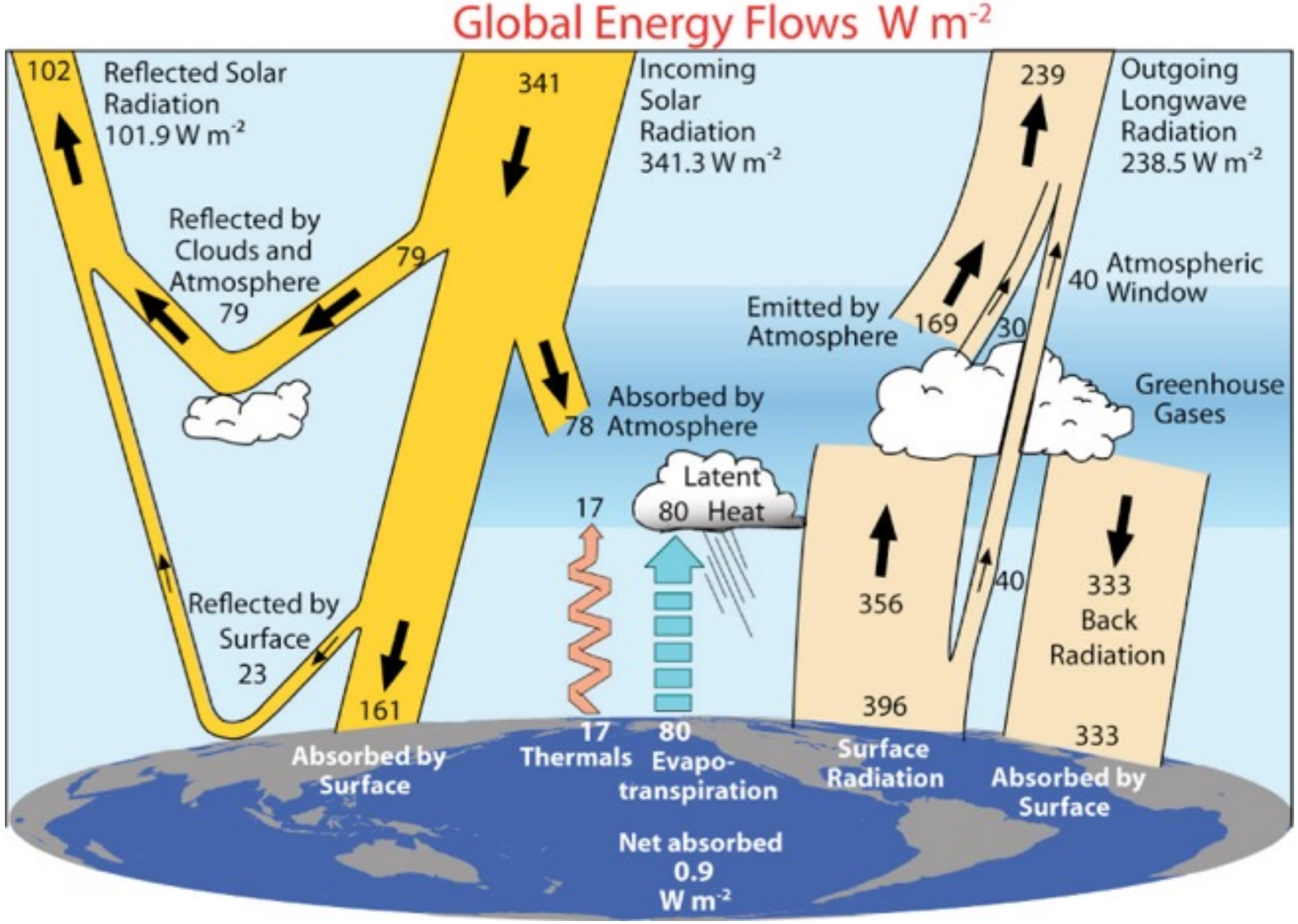


The Southern Ocean



Ocean Heat Transport

Earth’s Heat Budget



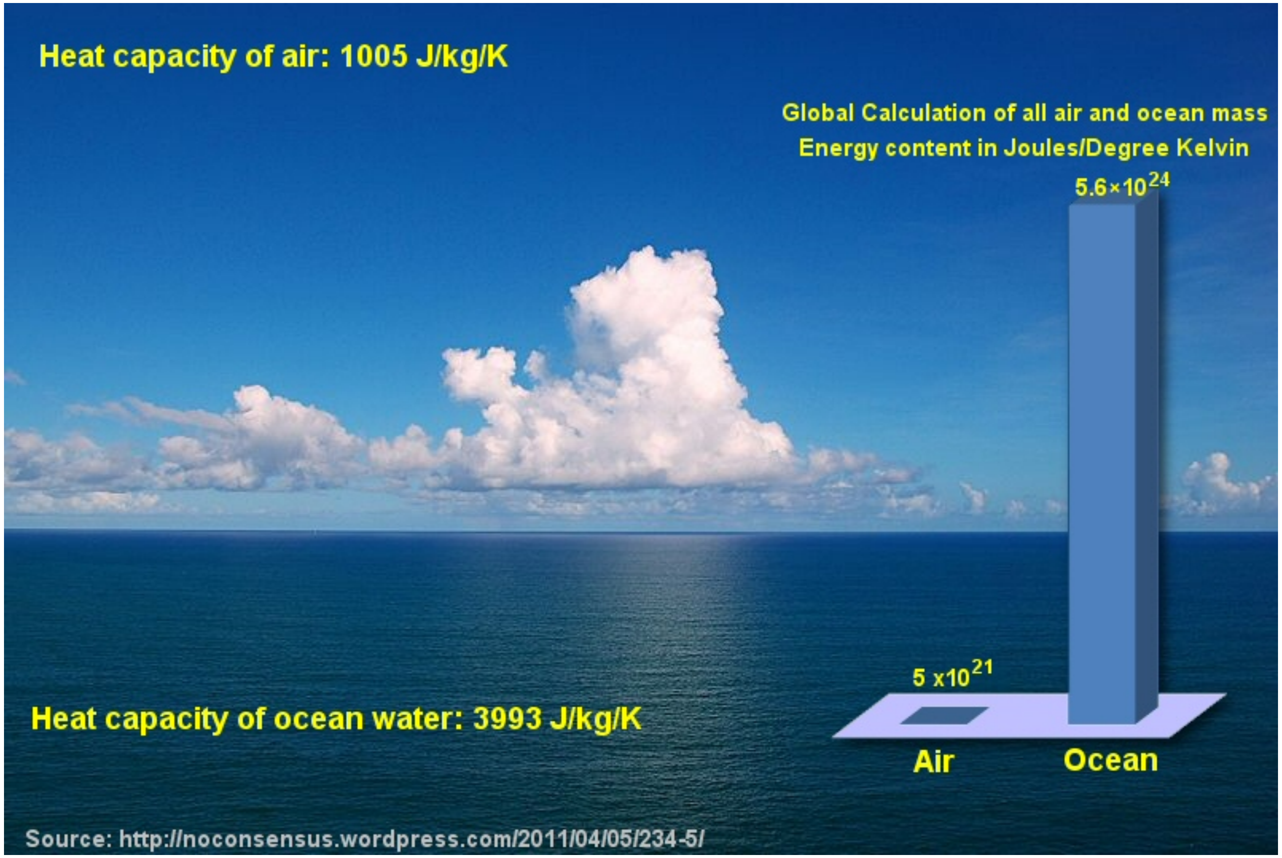
Notice that insolation balances infrared radiation at the top of the atmosphere

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

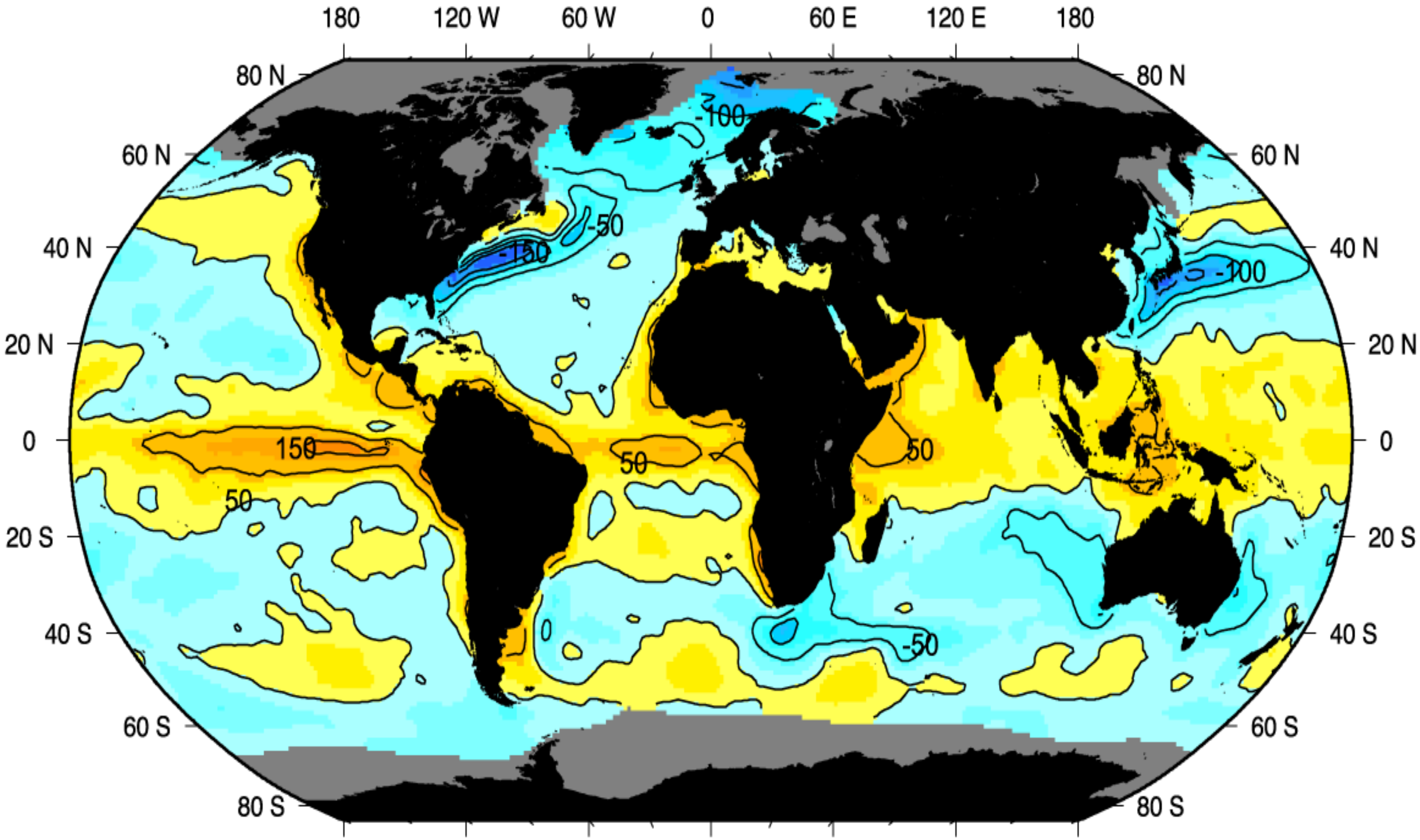
- **The heat capacity of the ocean is about 1000 times larger than the heat capacity of the atmosphere**
- **The top 3.5 meters of the ocean hold as much energy as all of the air on the planet**
- **The ocean is by far the largest reservoir of heat in the climate system**



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.

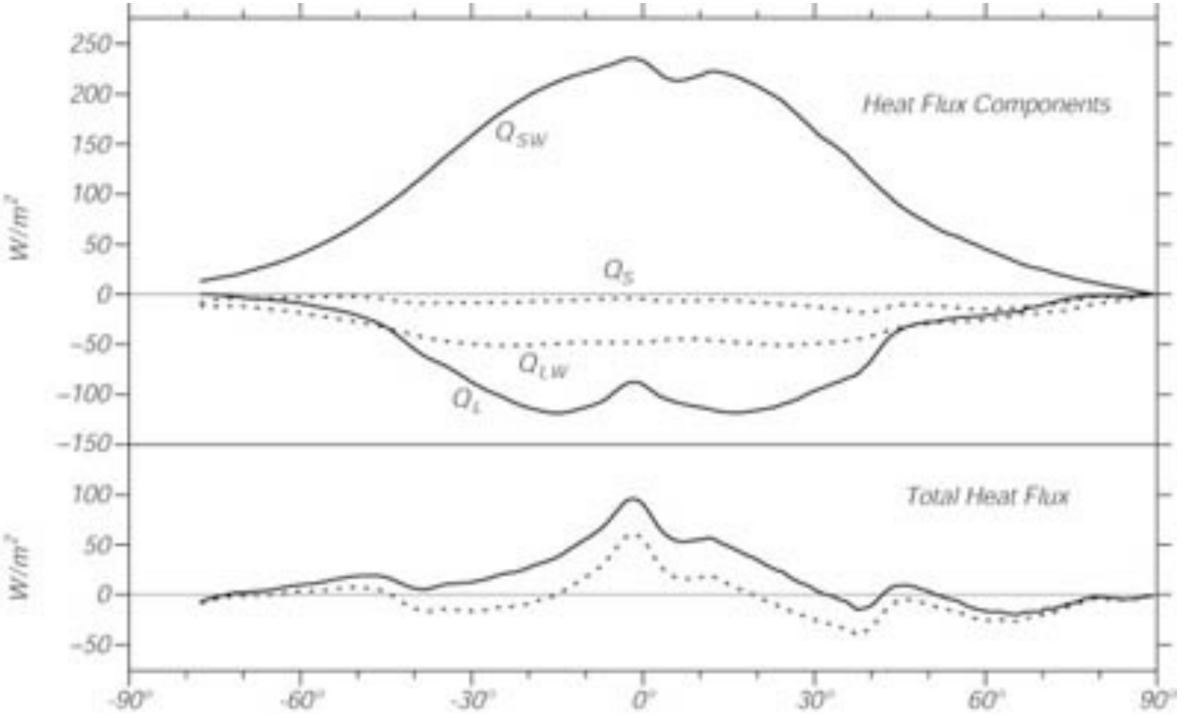
Surface heat flux ($\mathrm{W / m^2}$) into ocean



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

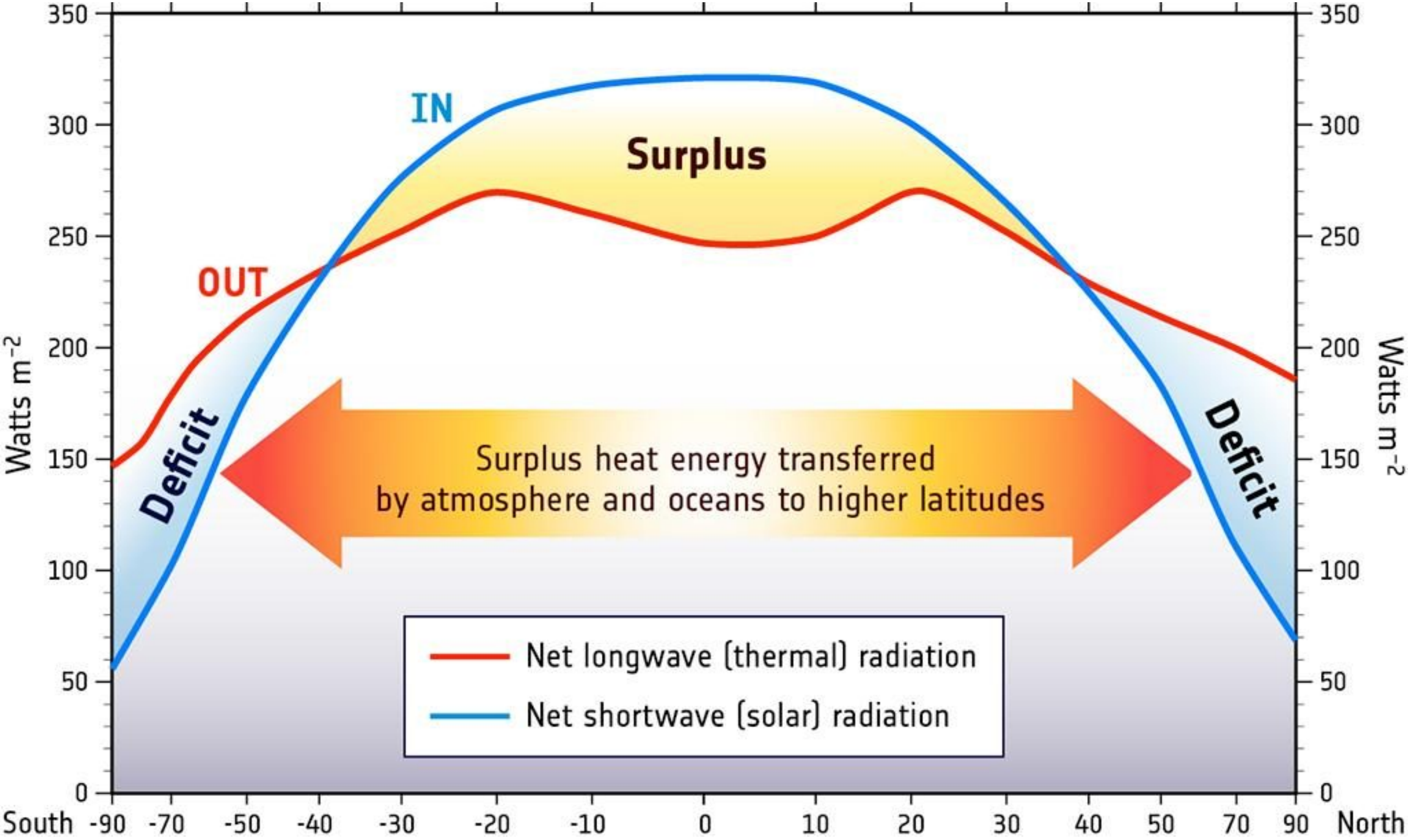


The zonal average of the oceanic heat-budget terms shows that insolation is greatest in the tropics, that evaporation balances insolation, and that sensible heat flux is small

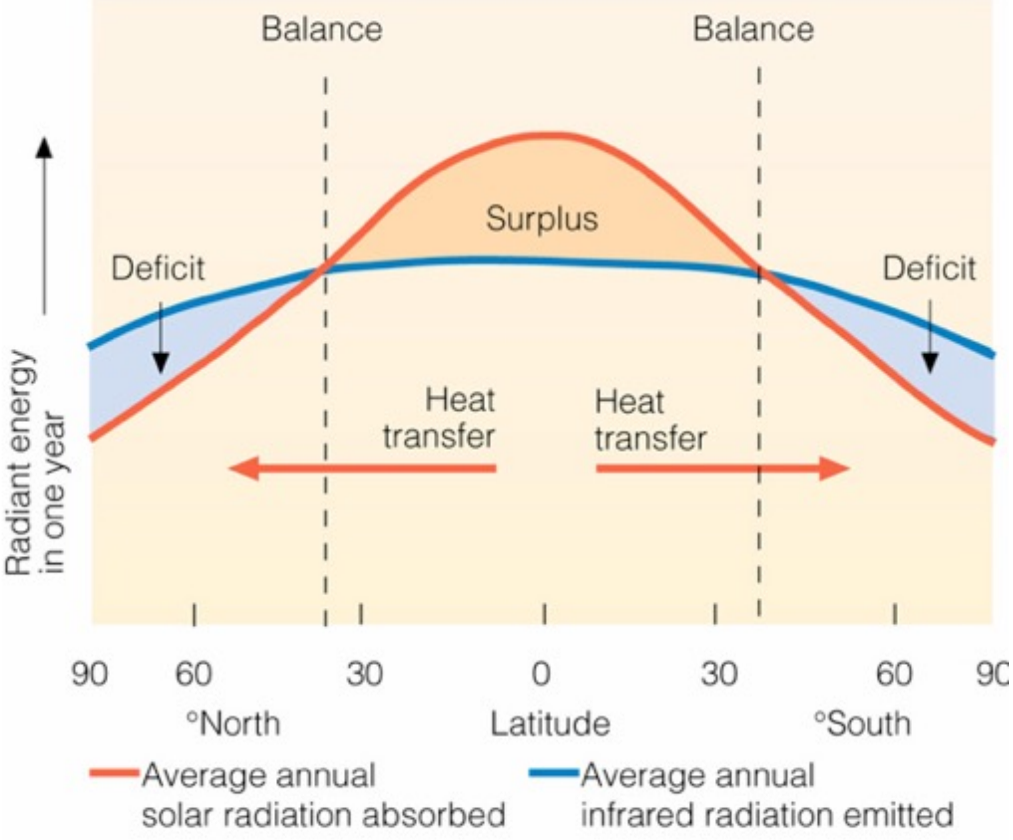
The earth's Radiation Balance

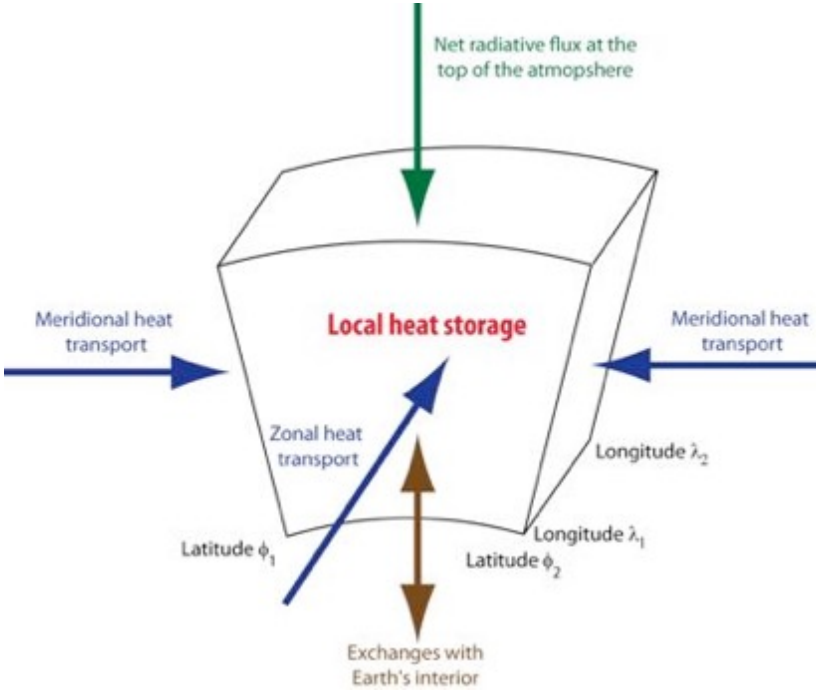
- A balance between incoming solar radiation and outgoing long-wave radiation
- The incoming radiation is “sunlight”, shortwave radiation, some of which is reflected back to space.
- The percentage of energy reflected is called the albedo, and the albedo is higher over lighter areas like snow and lower 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



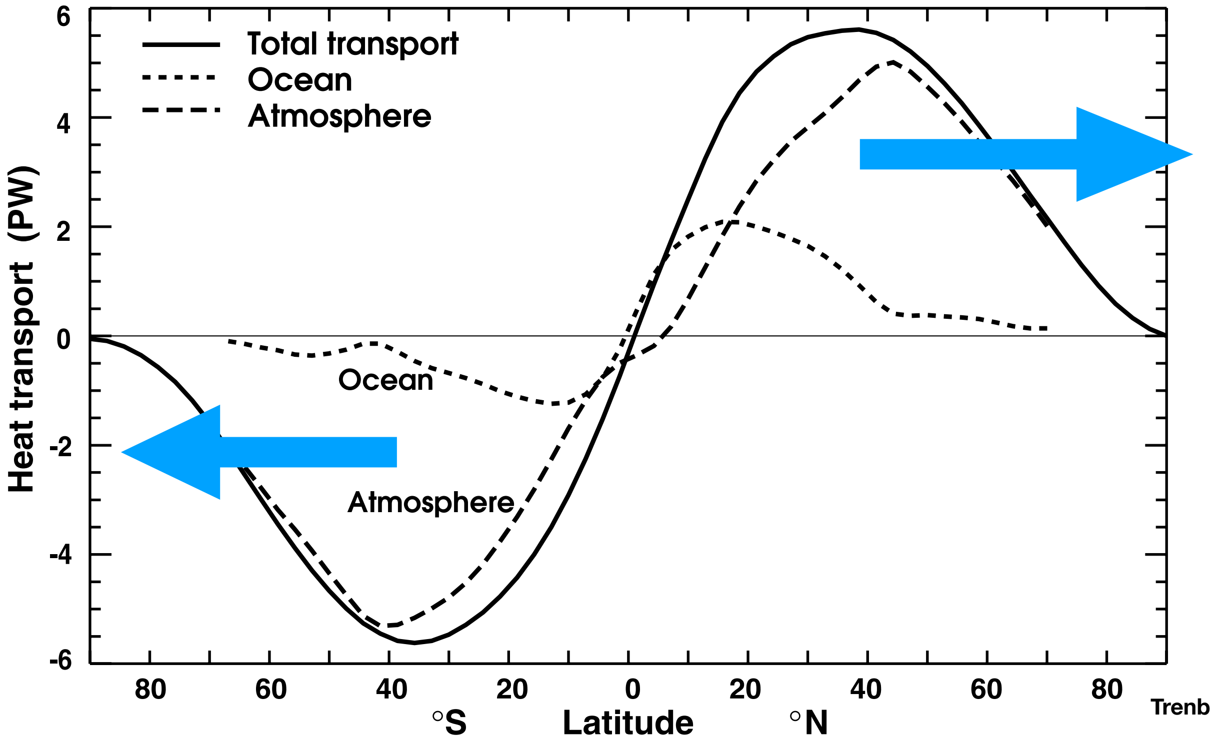
Locally, heat storage by the climate system cannot compensate for the net radiative flux imbalance at the top of the atmosphere and, annually, the balance is nearly entirely achieved by heat transport from regions with a positive net radiative flux to regions with a negative net radiative flux. When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





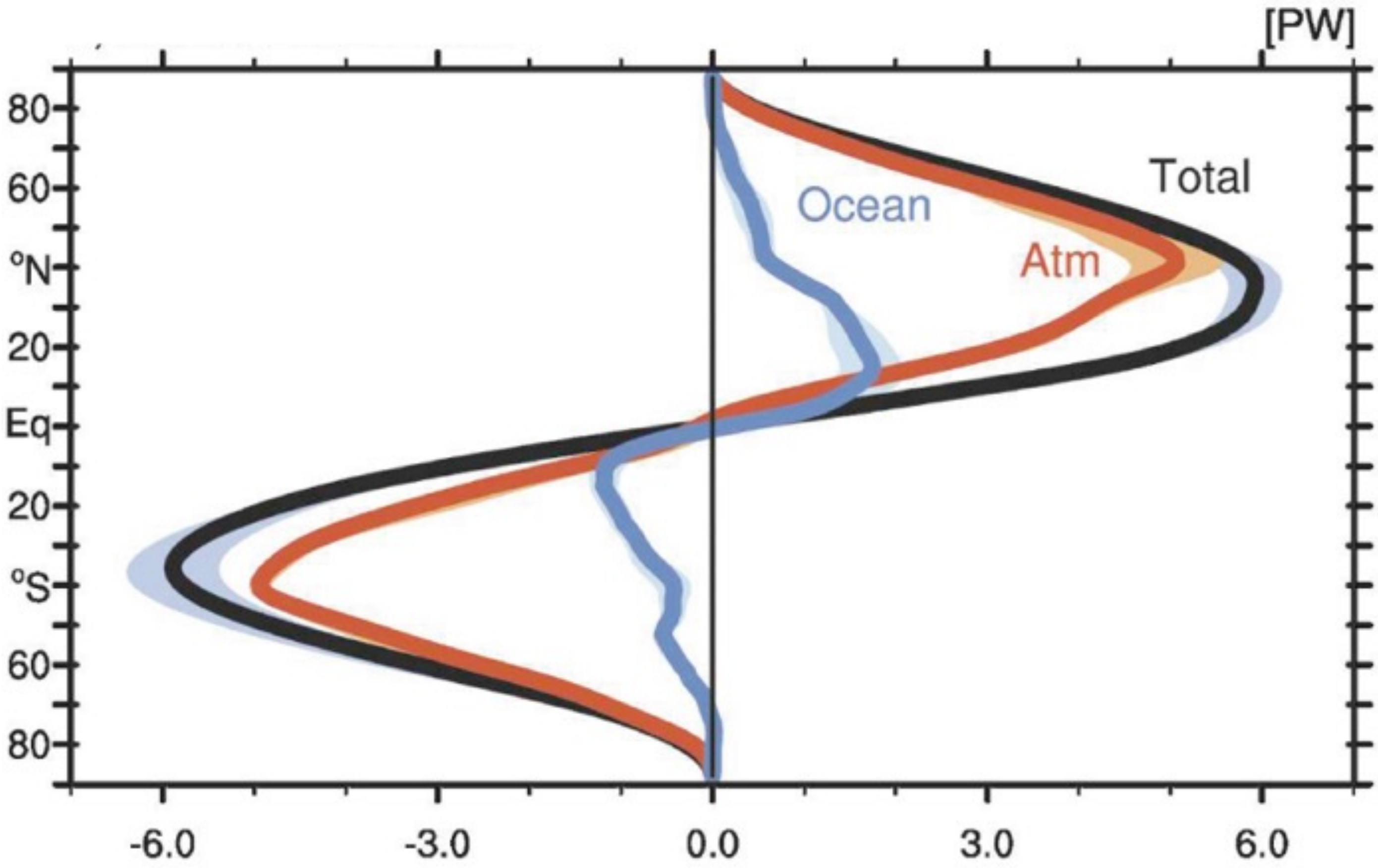
Ocean Heat Transport

- 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.

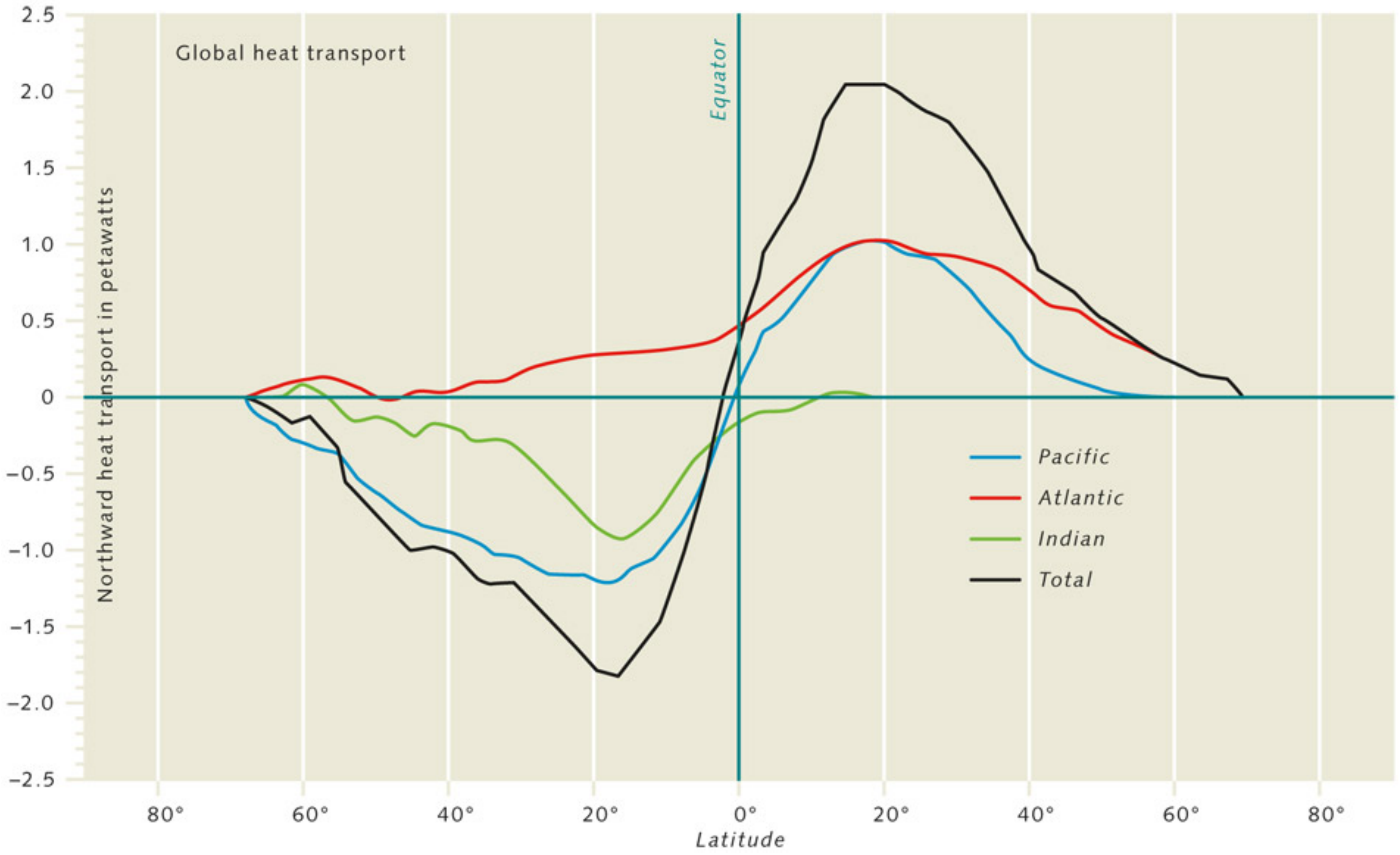


Trenberth and Stepaniak (2004)

The heat transport obtained is nearly zero at the equator, rising to more than 5PW at latitudes of 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. This shows that, except in tropical areas, the atmospheric transport is larger thanthe oceanic transport.



Ocean Heat Transport



Trenberth and Solomon (1994)

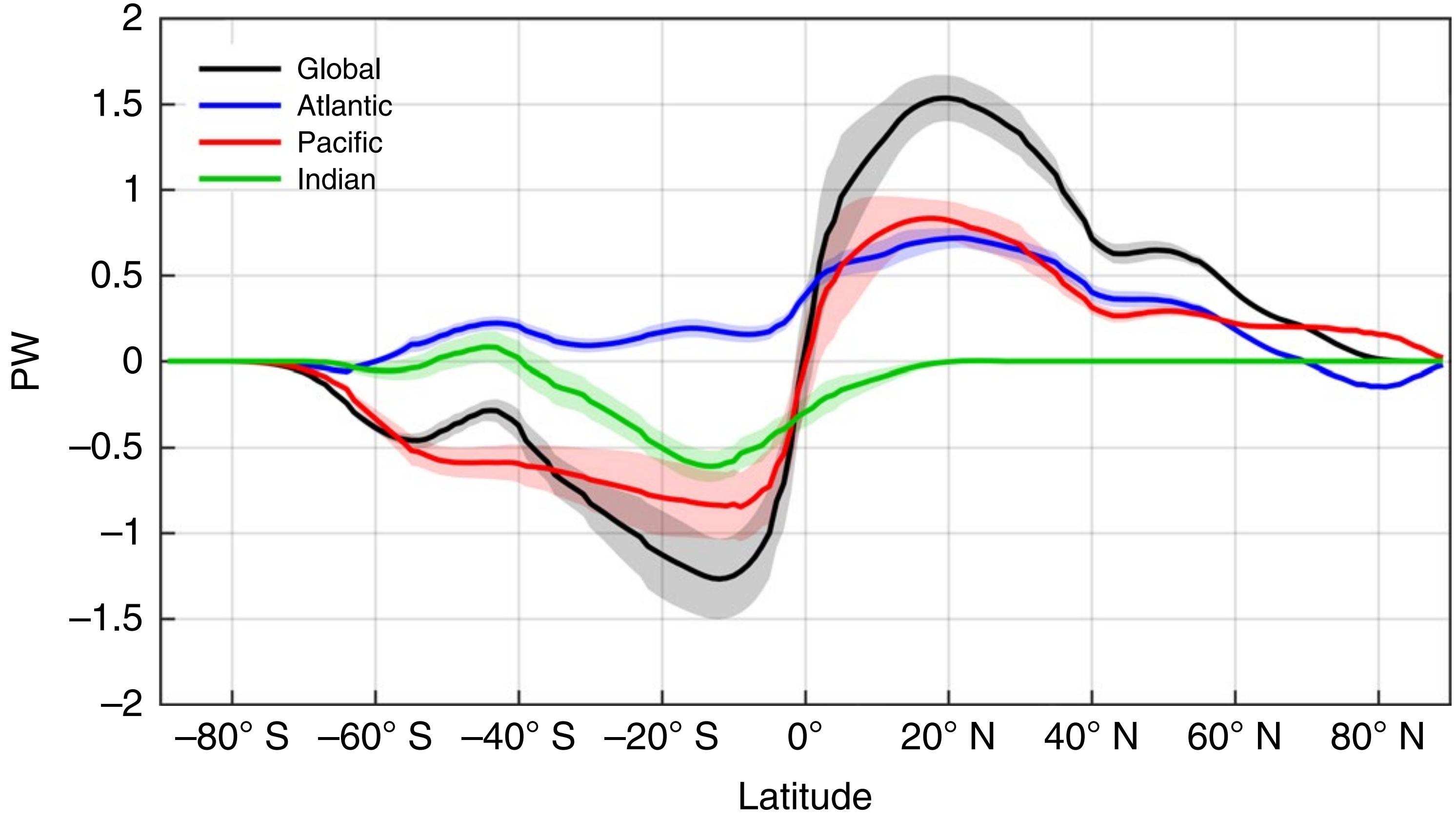


Fig. 2 | Meridional effective OHT. The global ocean case is depicted in black. Meridional effective OHT for the Atlantic (blue), Pacific (red) and Indian (green) sectors is also shown. The thick lines denote the 1992–2011 time average and the shaded ranges reflect ±1 standard deviation among annual means.

Forget and Ferreira, 2019

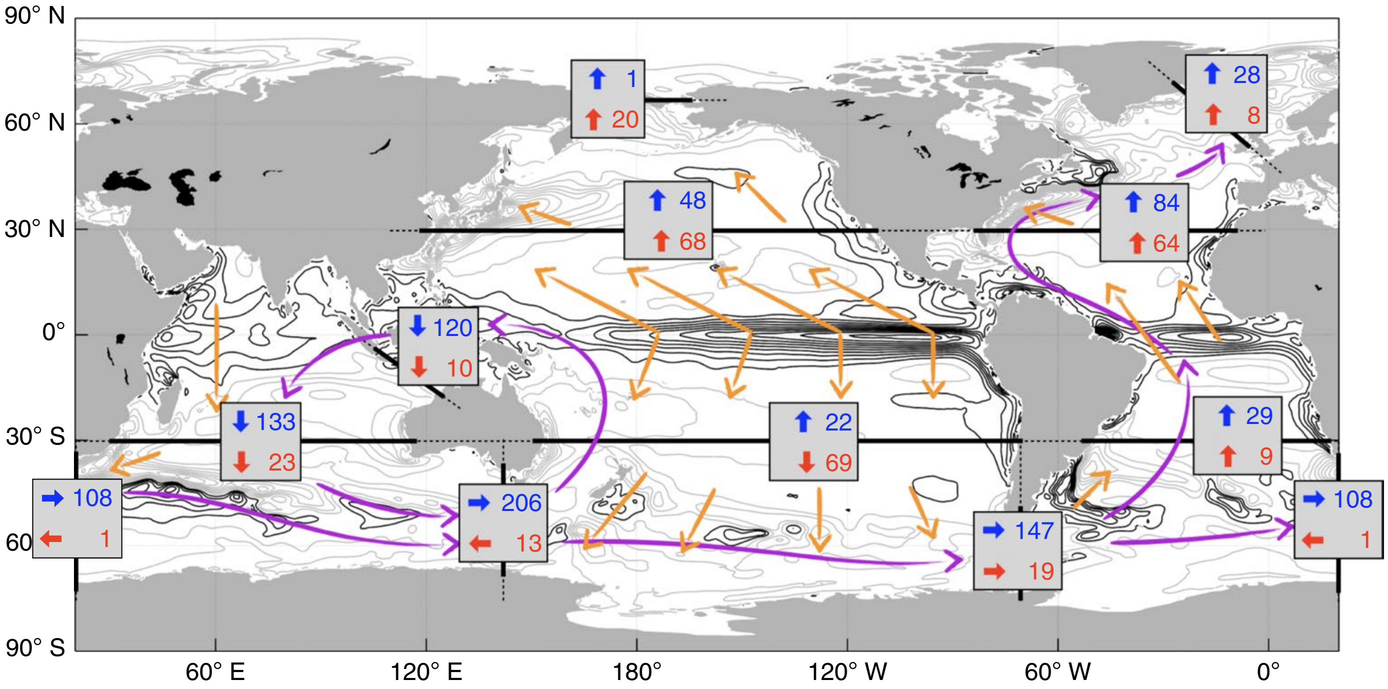
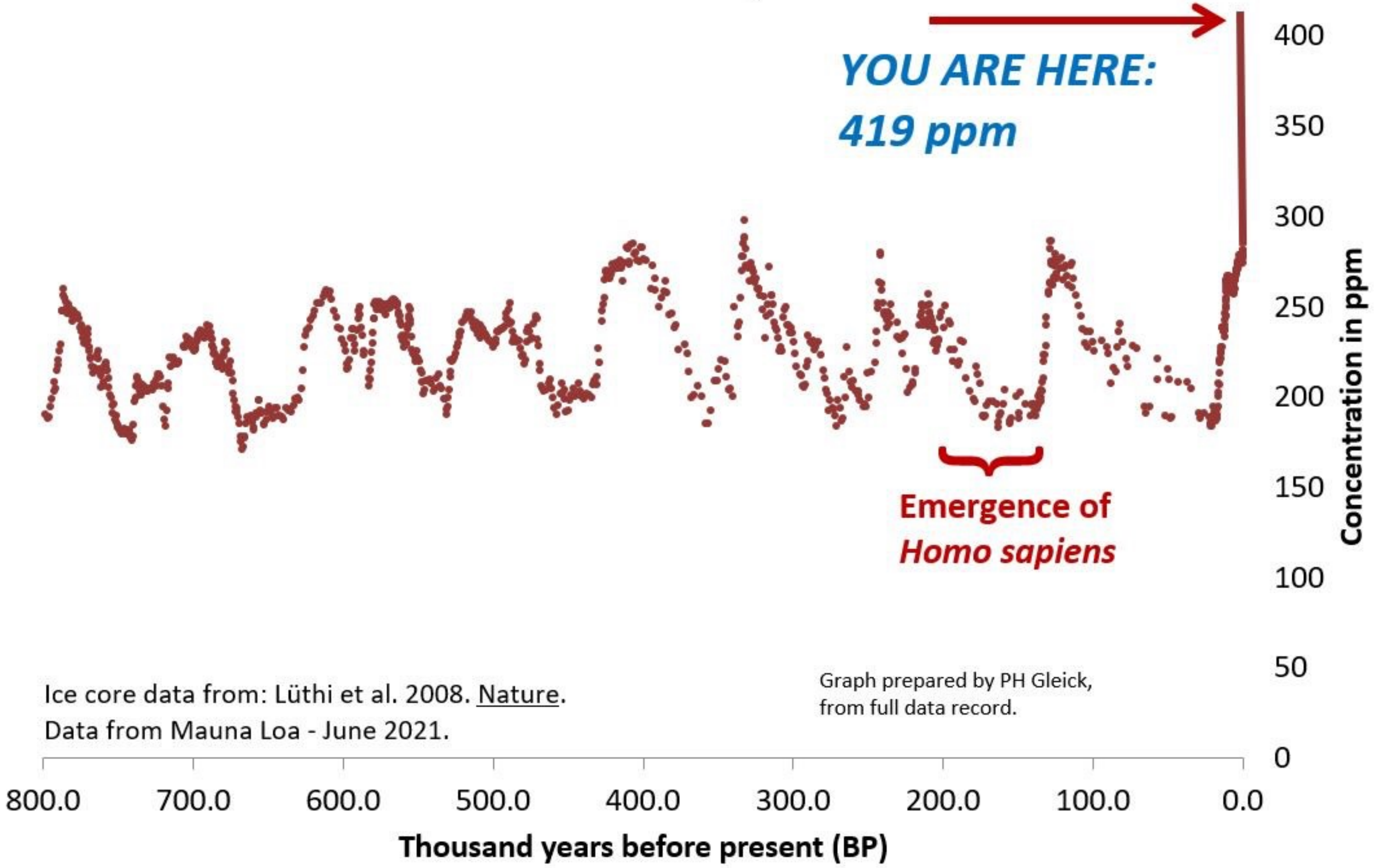


Fig. 1 | OHT as estimated through sections that separate ocean basins and delimit the tropics for the 1992–2011 time average. Values (in 0.01 PW= 10^{13} Watts) of plain OHT (rotational + divergent components; OHT0) and effective OHT (divergent component alone; OHT∇) are charted in blue and in red, respectively. 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}.

Forget and Ferreira, 2019

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

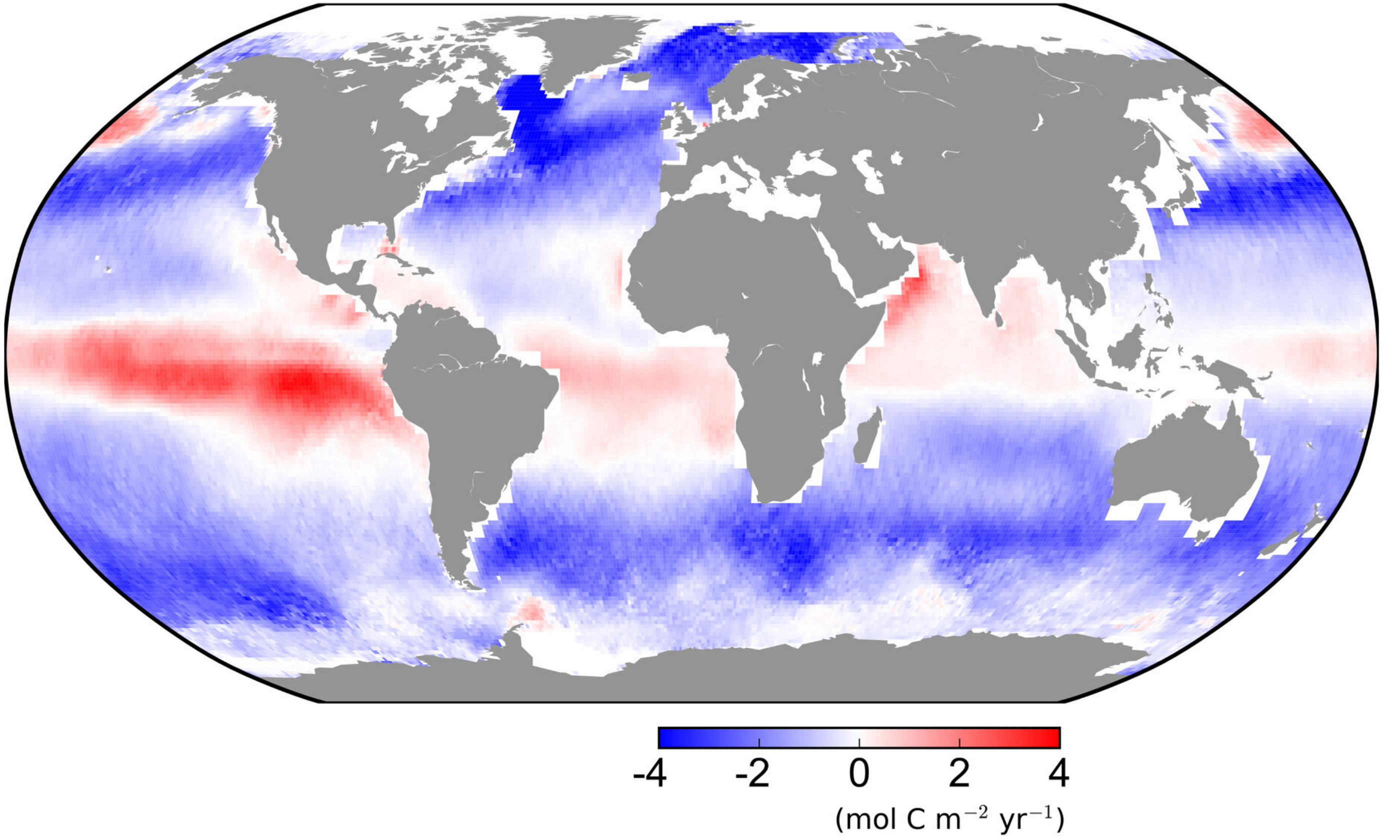


YOU ARE HERE: 419 ppm

Emergence of *Homo sapiens*

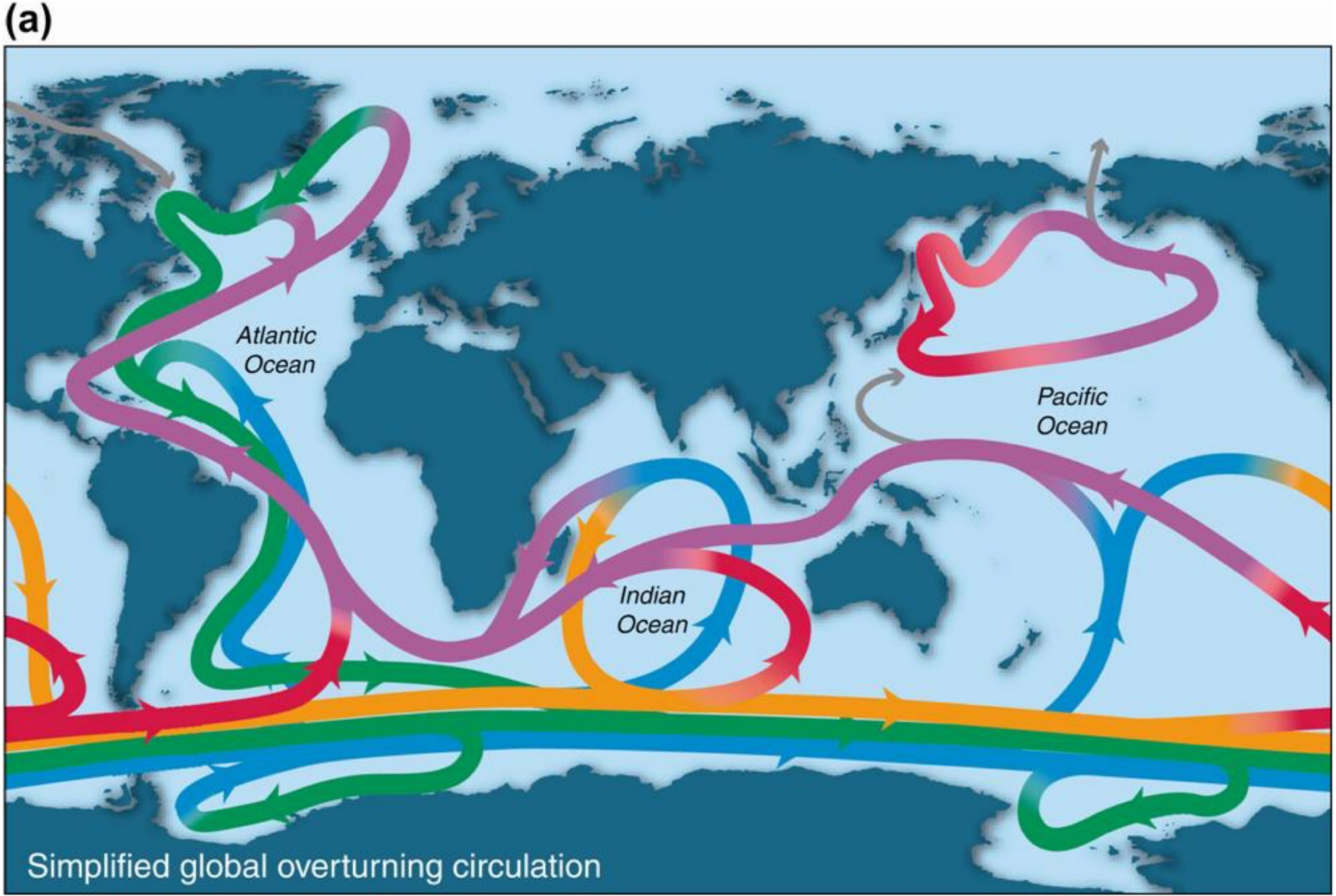
Ice core data from: Lüthi et al. 2008. Nature.
Data from Mauna Loa - June 2021.

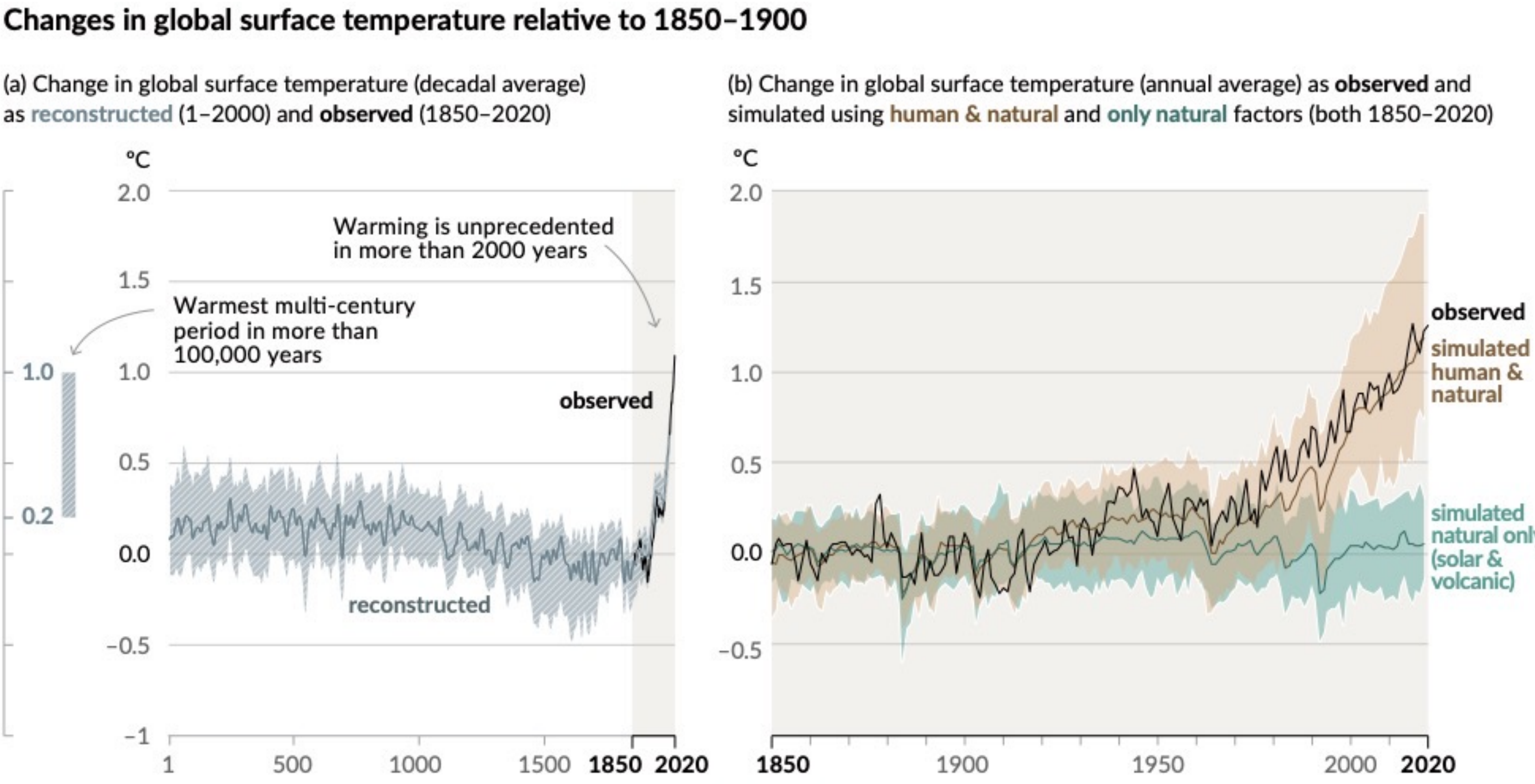
Graph prepared by PH Gleick, from full data record.



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





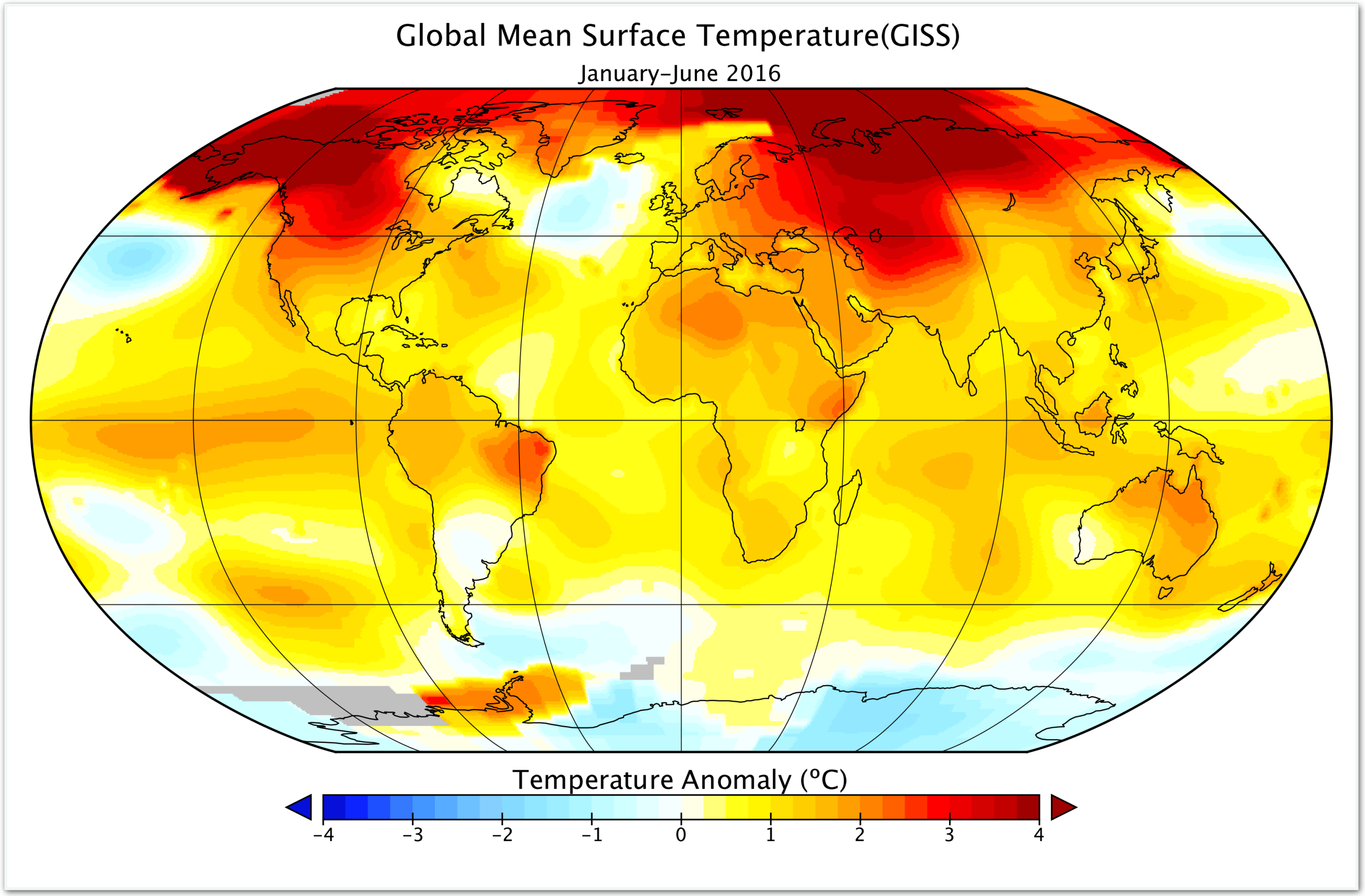
Changes in global surface temperature relative to 1850–1900

(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)

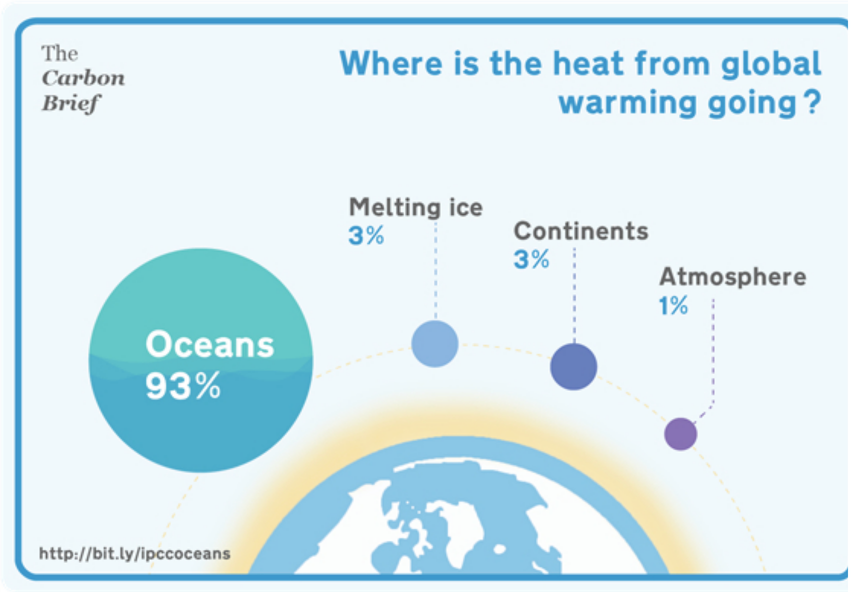
From: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf

Climate change = Ocean change

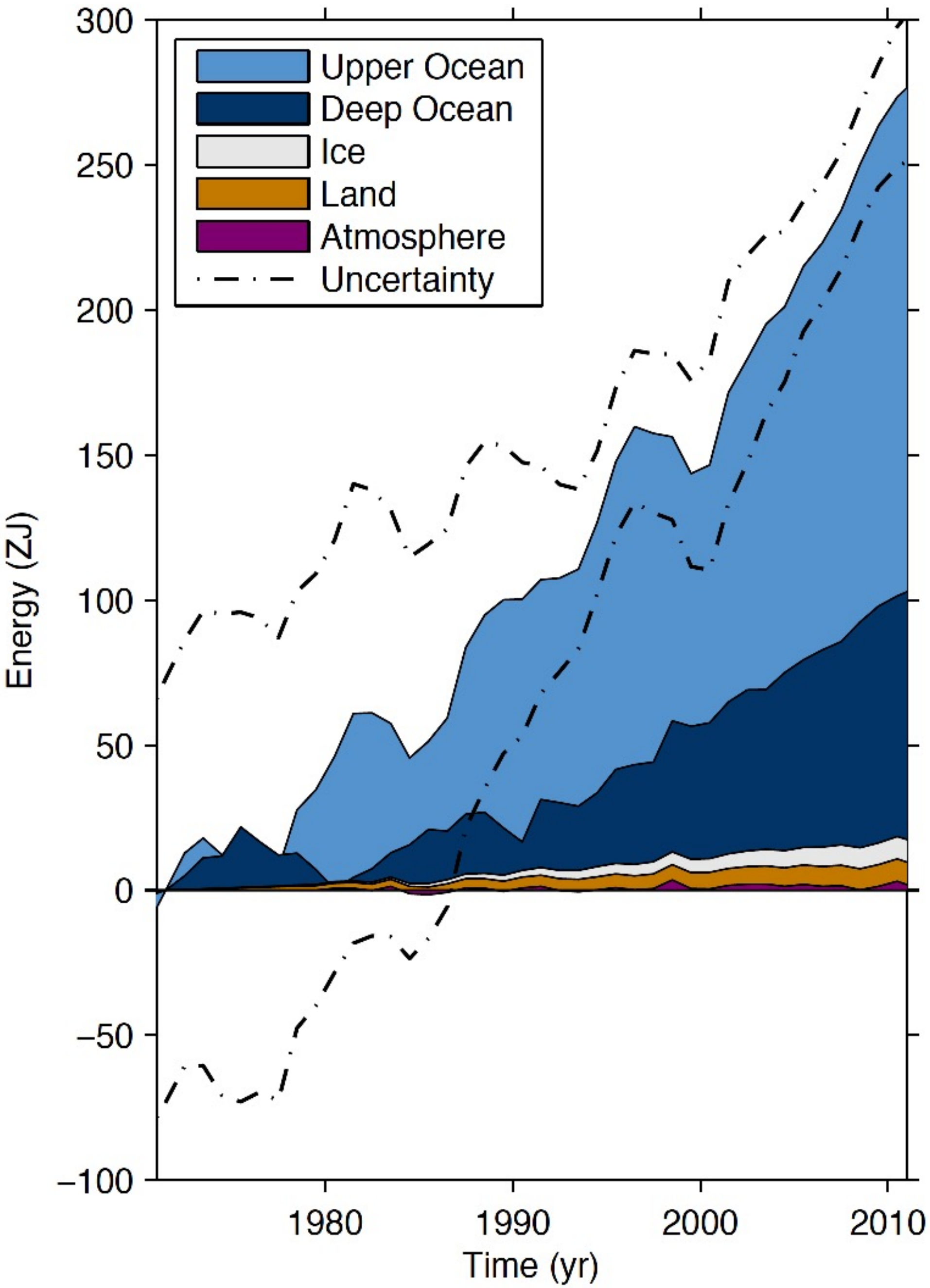


Global surface temperature anomalies for the period January 2016 through June 2016. Higher than normal temperatures are shown in red and lower then normal termperatures are shown in blue.
Credit: NASA/GISS

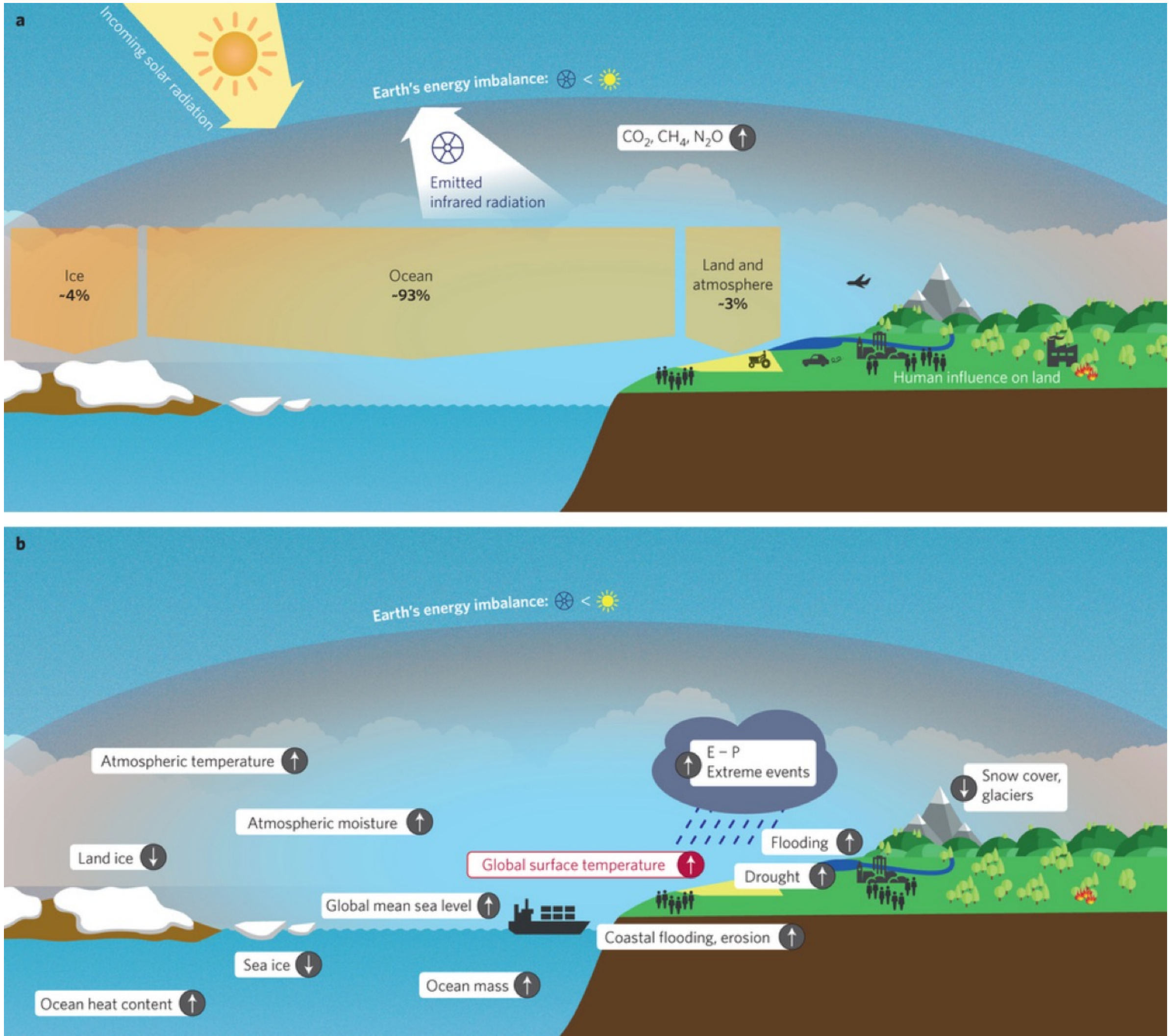
Where is all the extra energy going?



Source: Rosamund Pearce, Carbon Brief

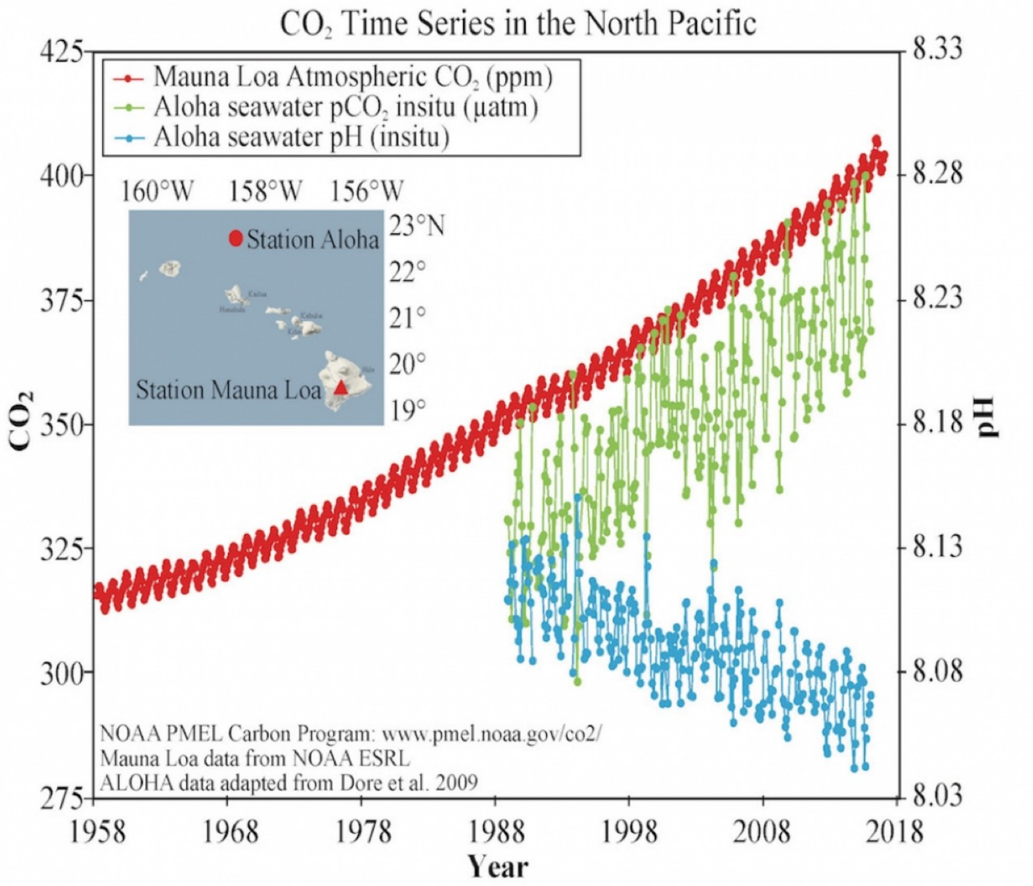


The Ocean is the major heat reservoir, with about 90% of Earth's Energy Imbalance stored. The rest goes into warming the land and atmosphere, and melting ice.



'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.

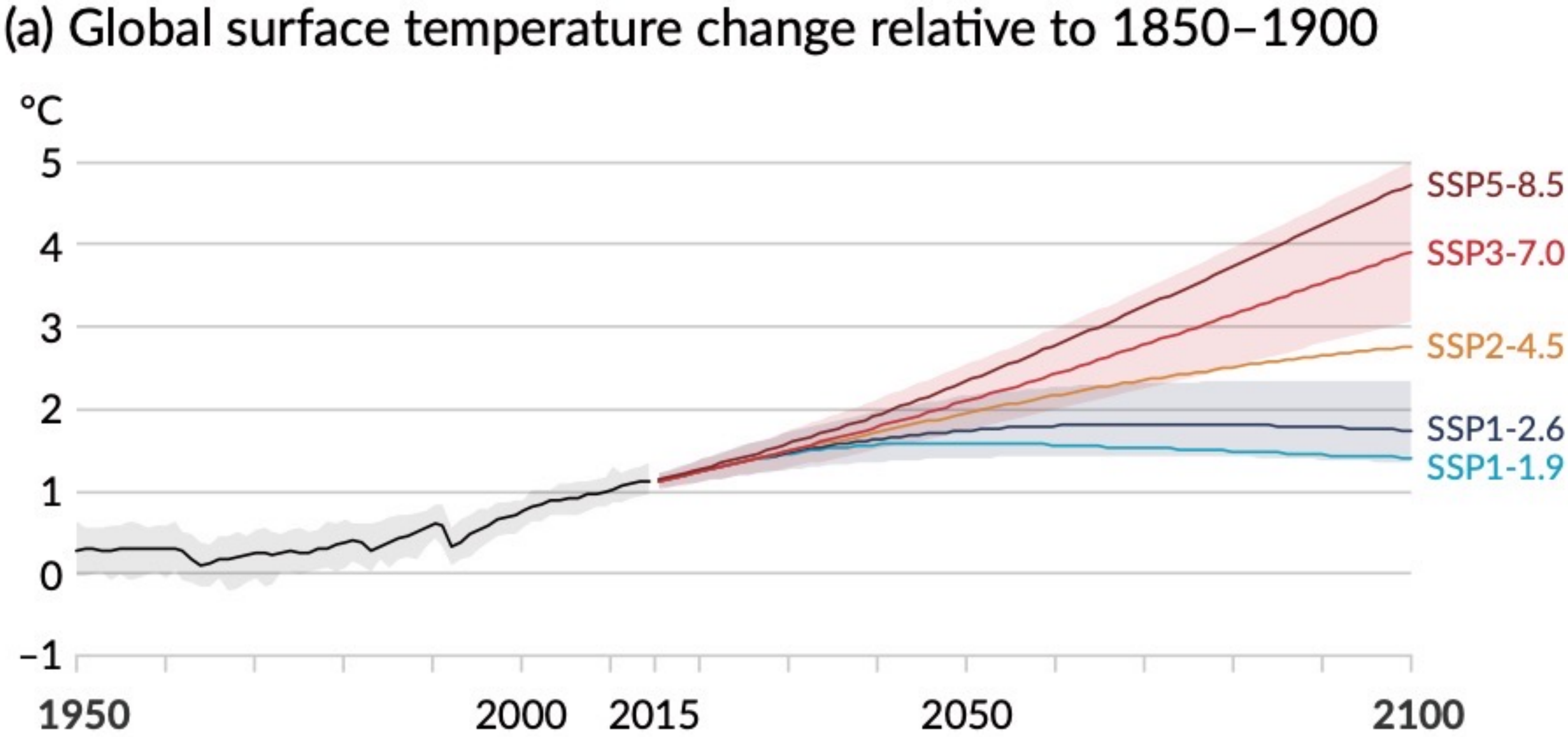
Climate change = Ocean change



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.

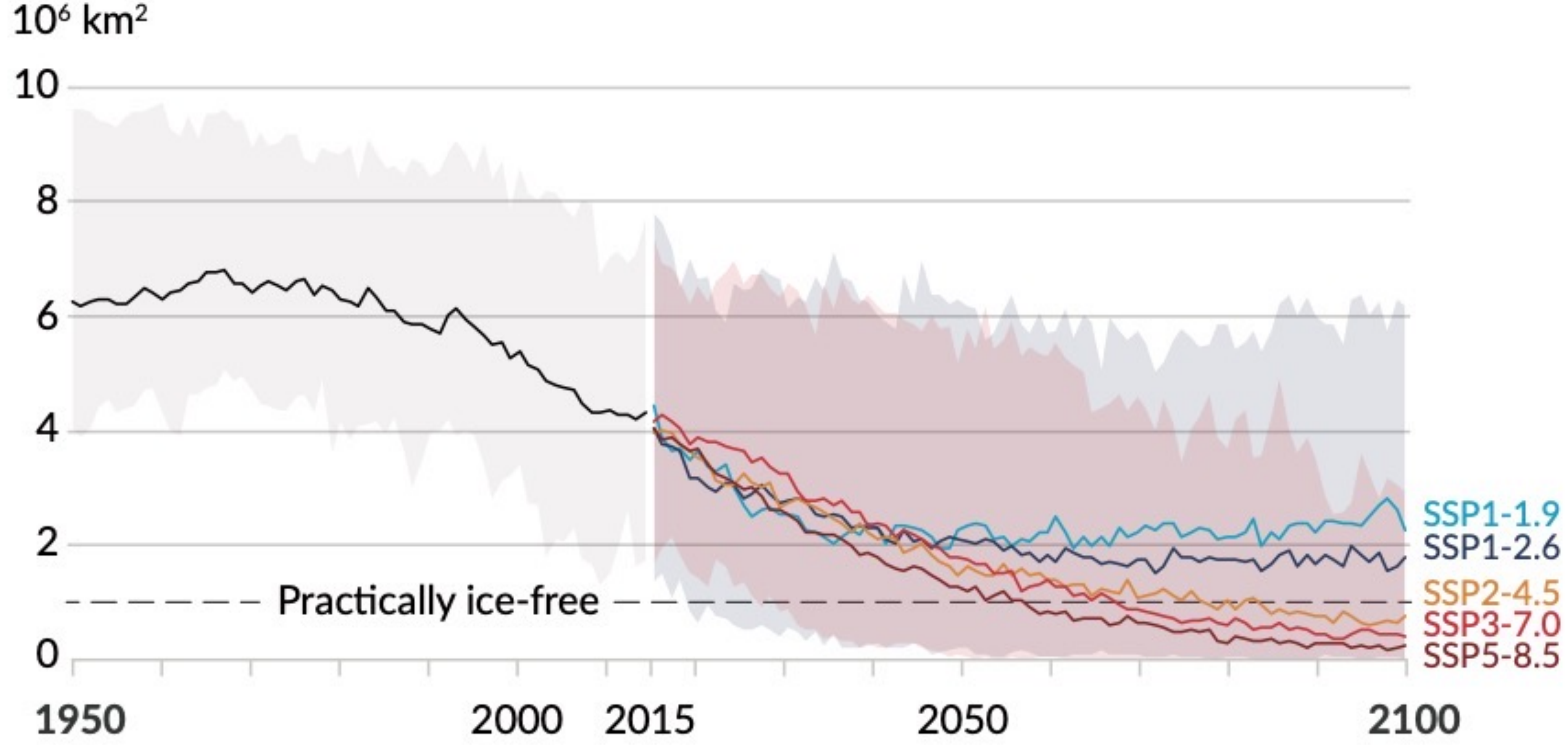
The Oceans have absorbed **30%** of global anthropogenic carbon dioxide emissions

- 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

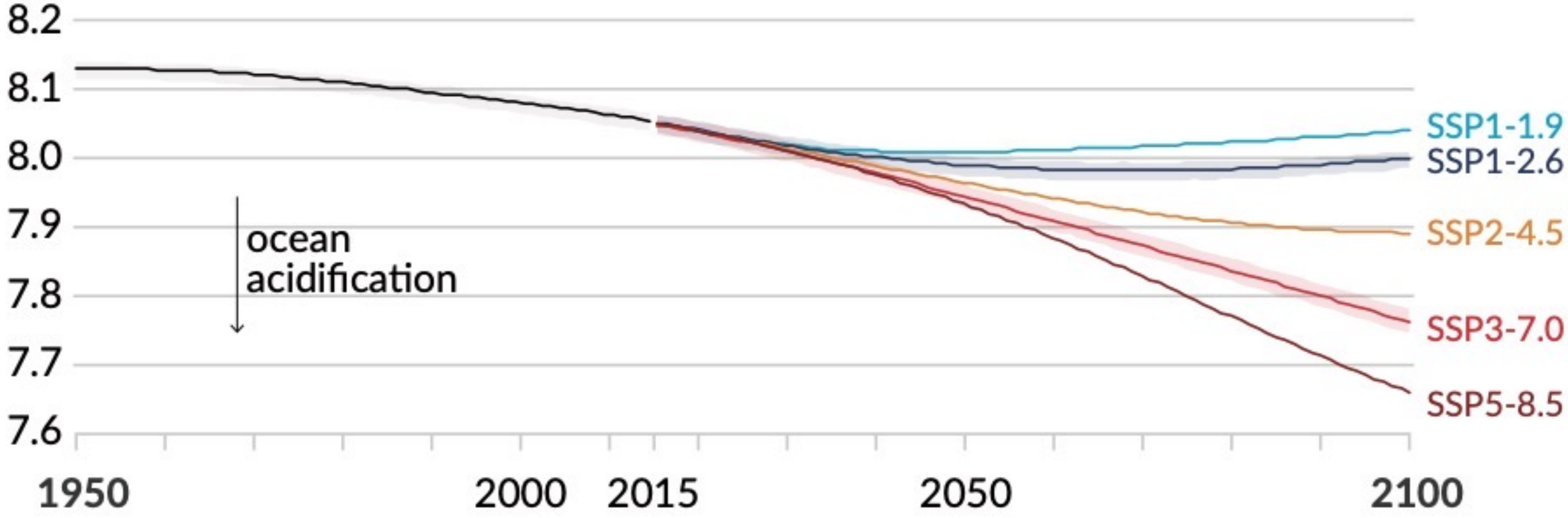
From: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf



(b) September Arctic sea ice area

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)



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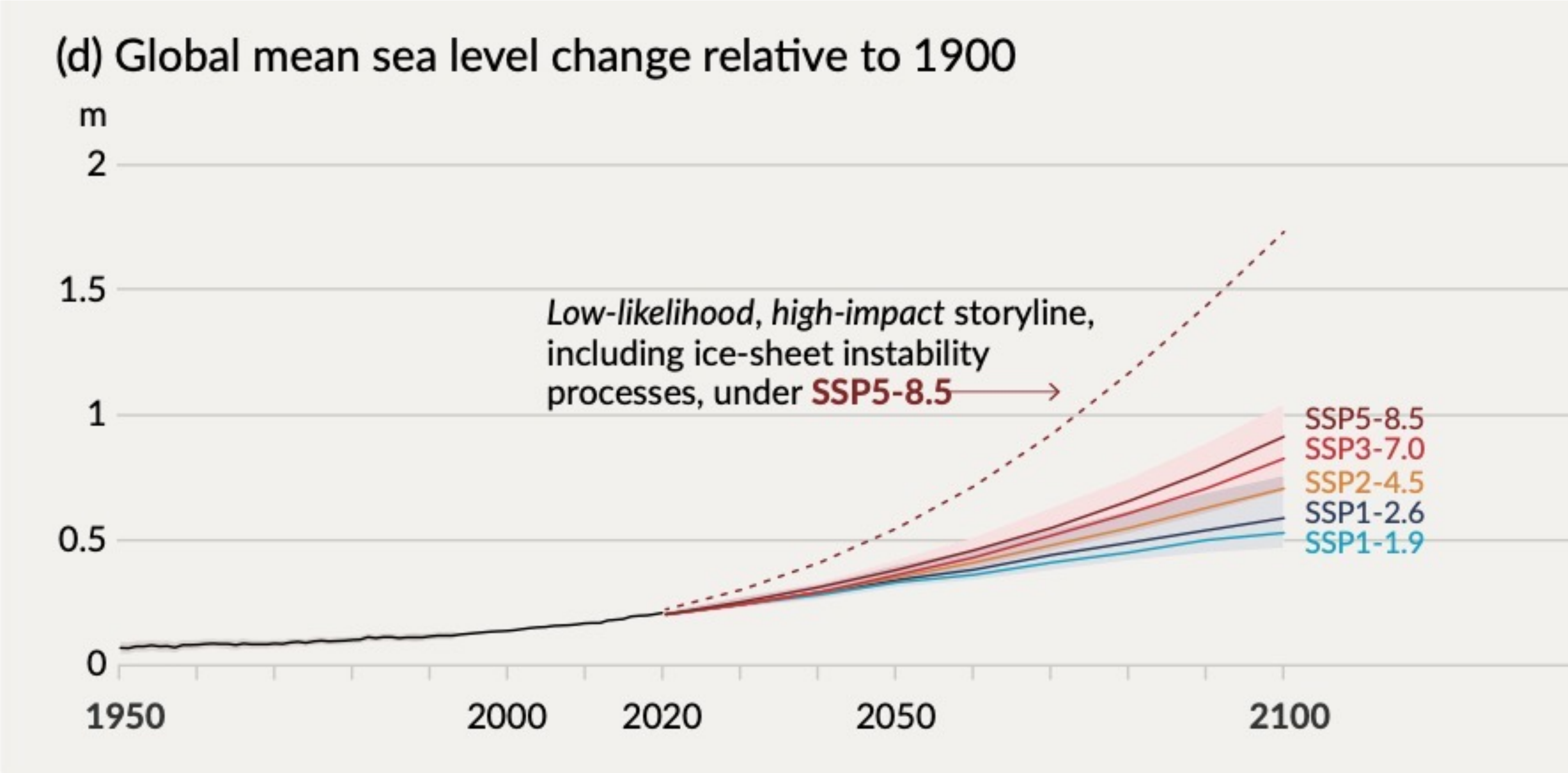
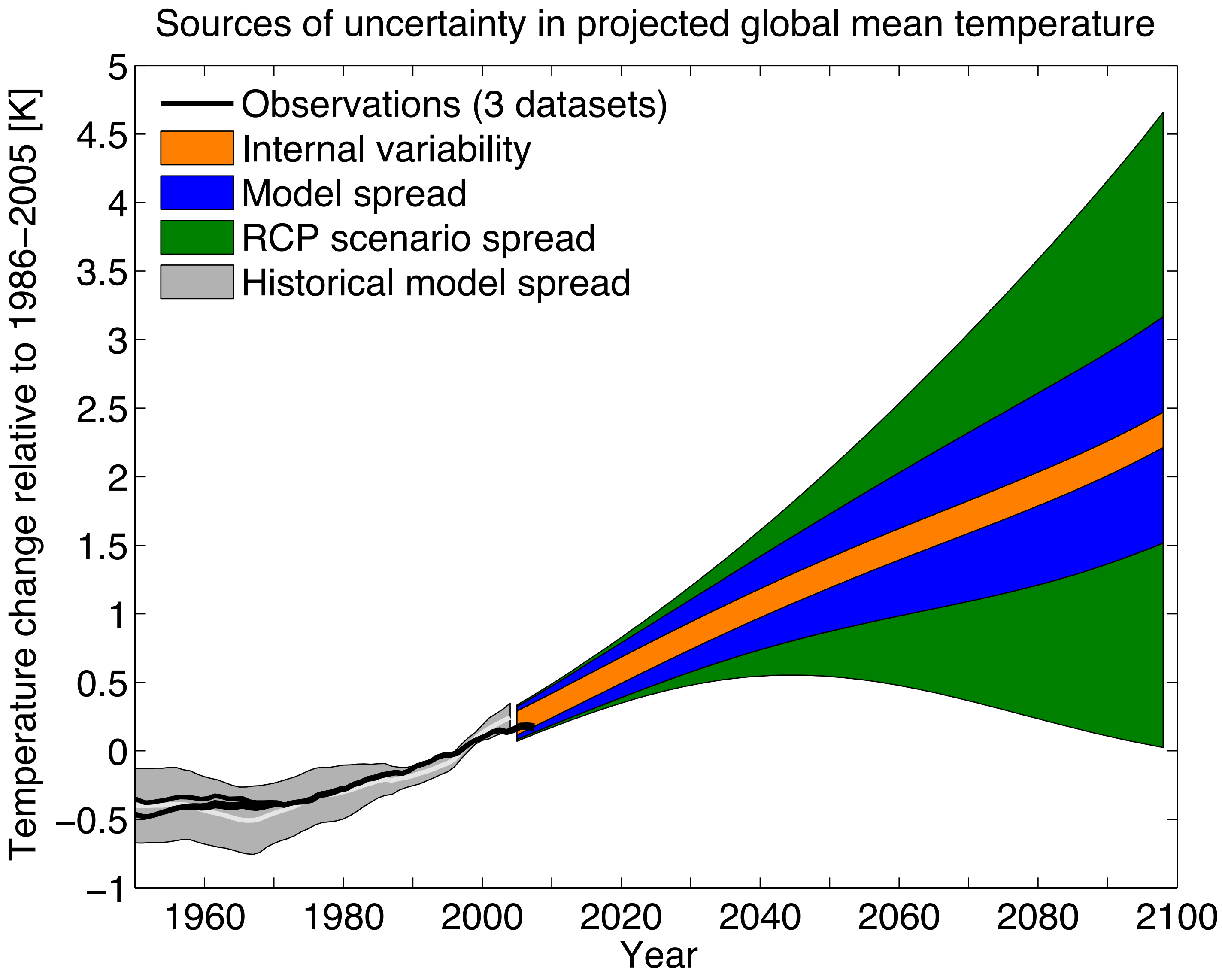


(d) Global mean sea level change relative to 1900

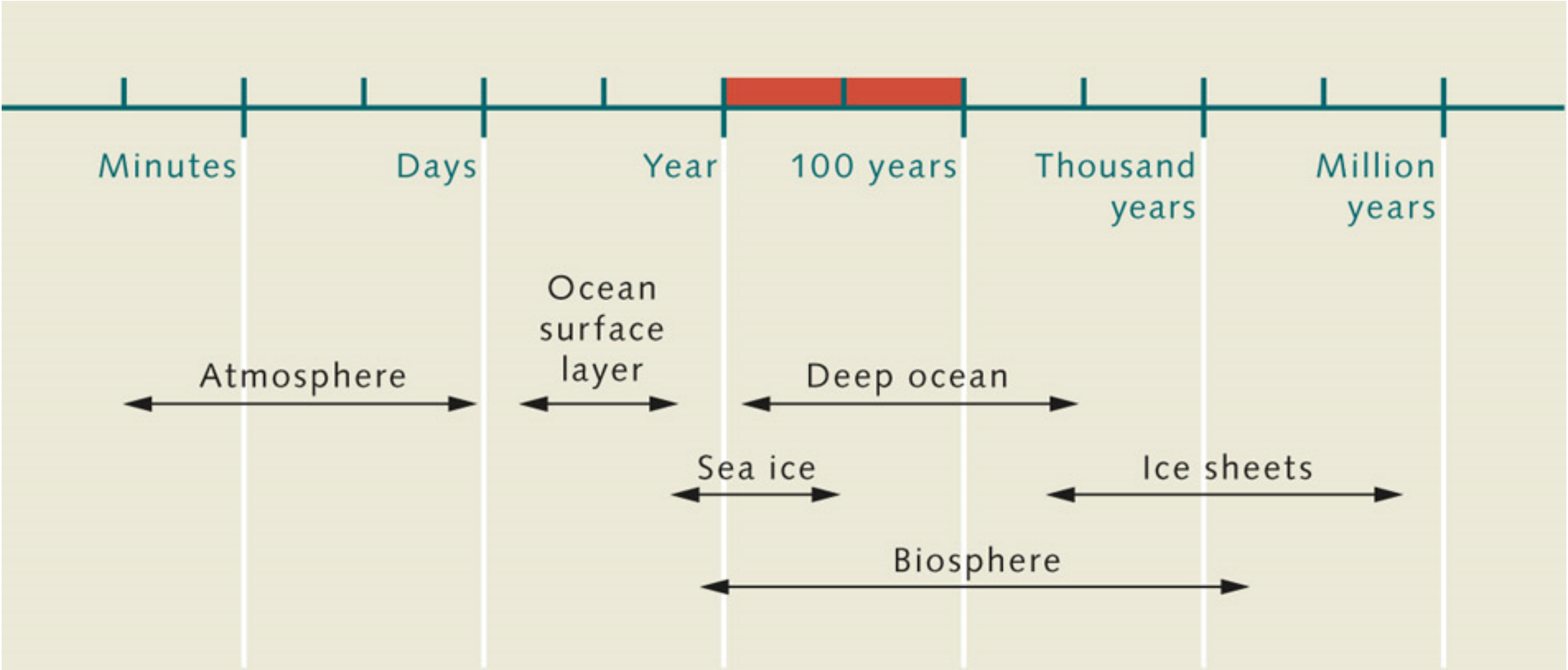
Low-likelihood, *high-impact* storyline, including ice-sheet instability processes, under **SSP5-8.5** →

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

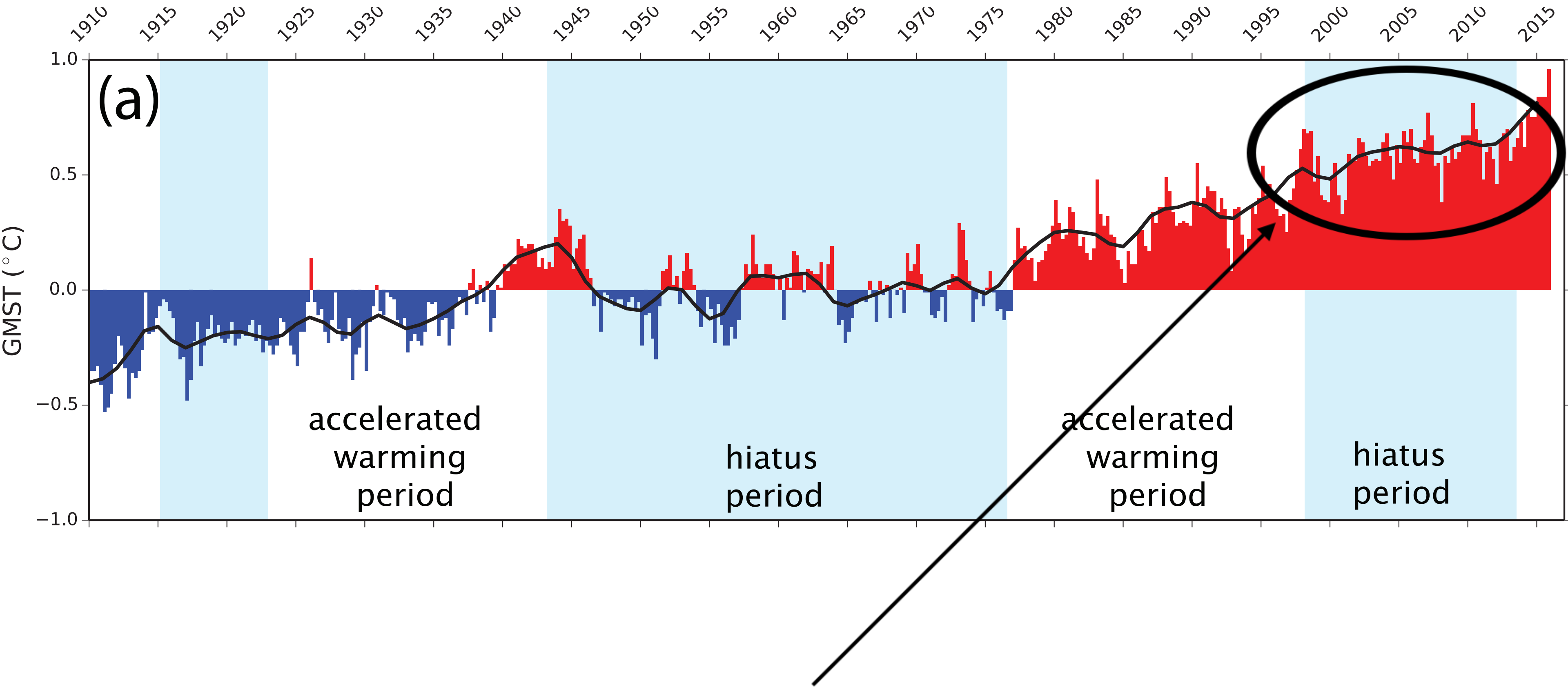


Global Warming is coexisting with internal variability of the deep ocean



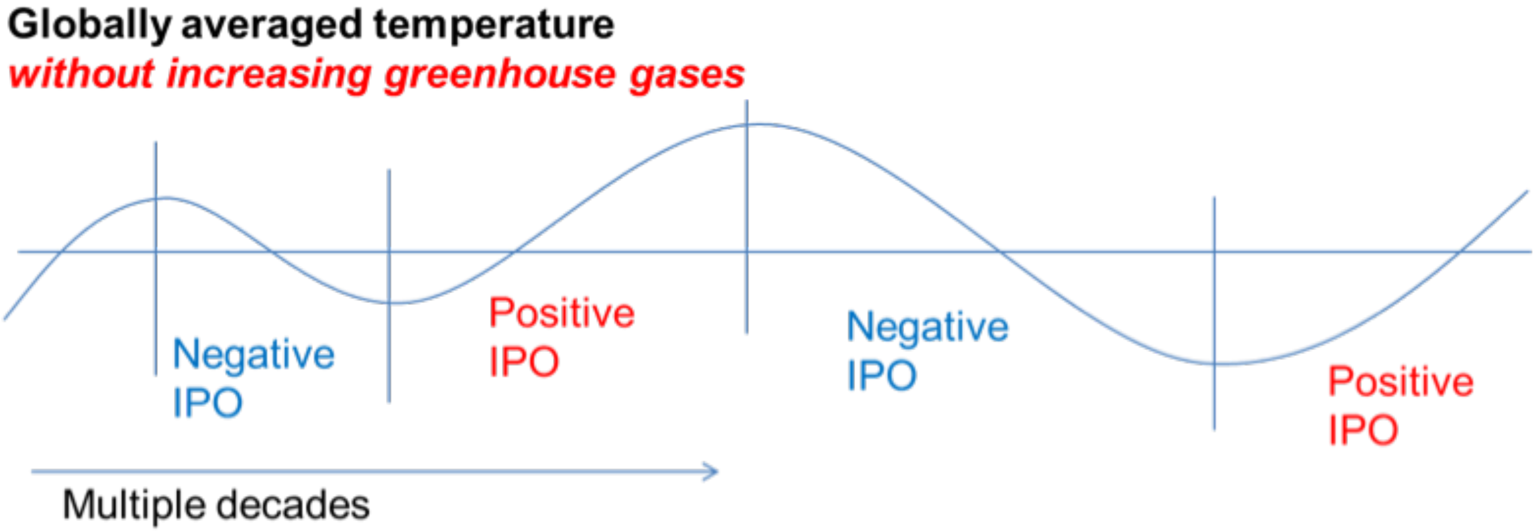
Global Mean Surface Temperature Anomalies: A hiatus (a.k.a. global warming slow-down?)

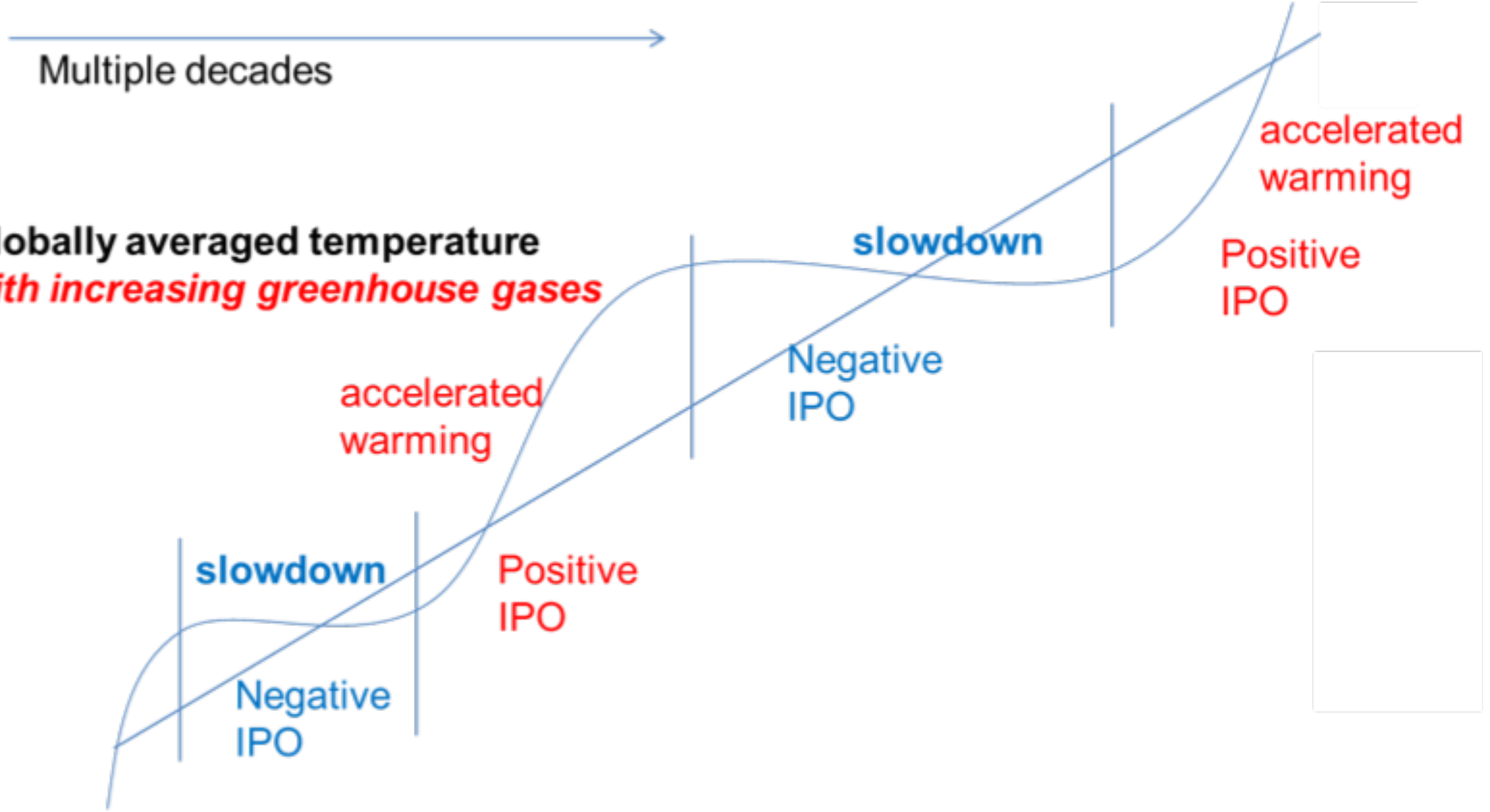
The slower rise in temperatures from 1998 to 2012 has repeatedly been cited by climate sceptics as a sign that the climate is less sensitive to greenhouse gases than previously thought



from 1998 until 2012

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





Multiple decades

Globally averaged temperature
with increasing greenhouse gases

slowdown

Negative
IPO

accelerated
warming

Positive
IPO

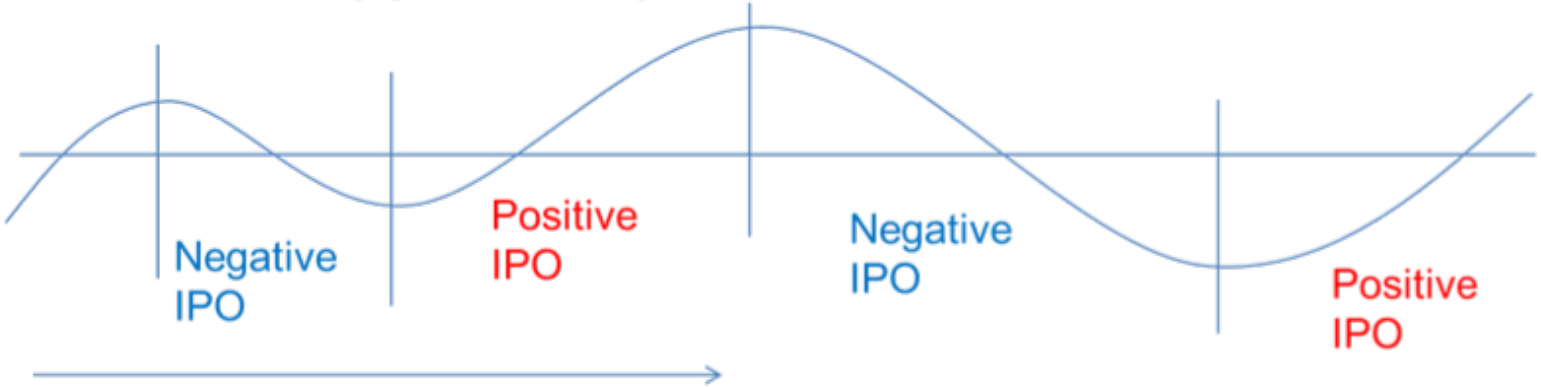
slowdown

Negative
IPO

accelerated
warming

Positive
IPO

Globally averaged temperature
without increasing greenhouse gases



Negative
IPO

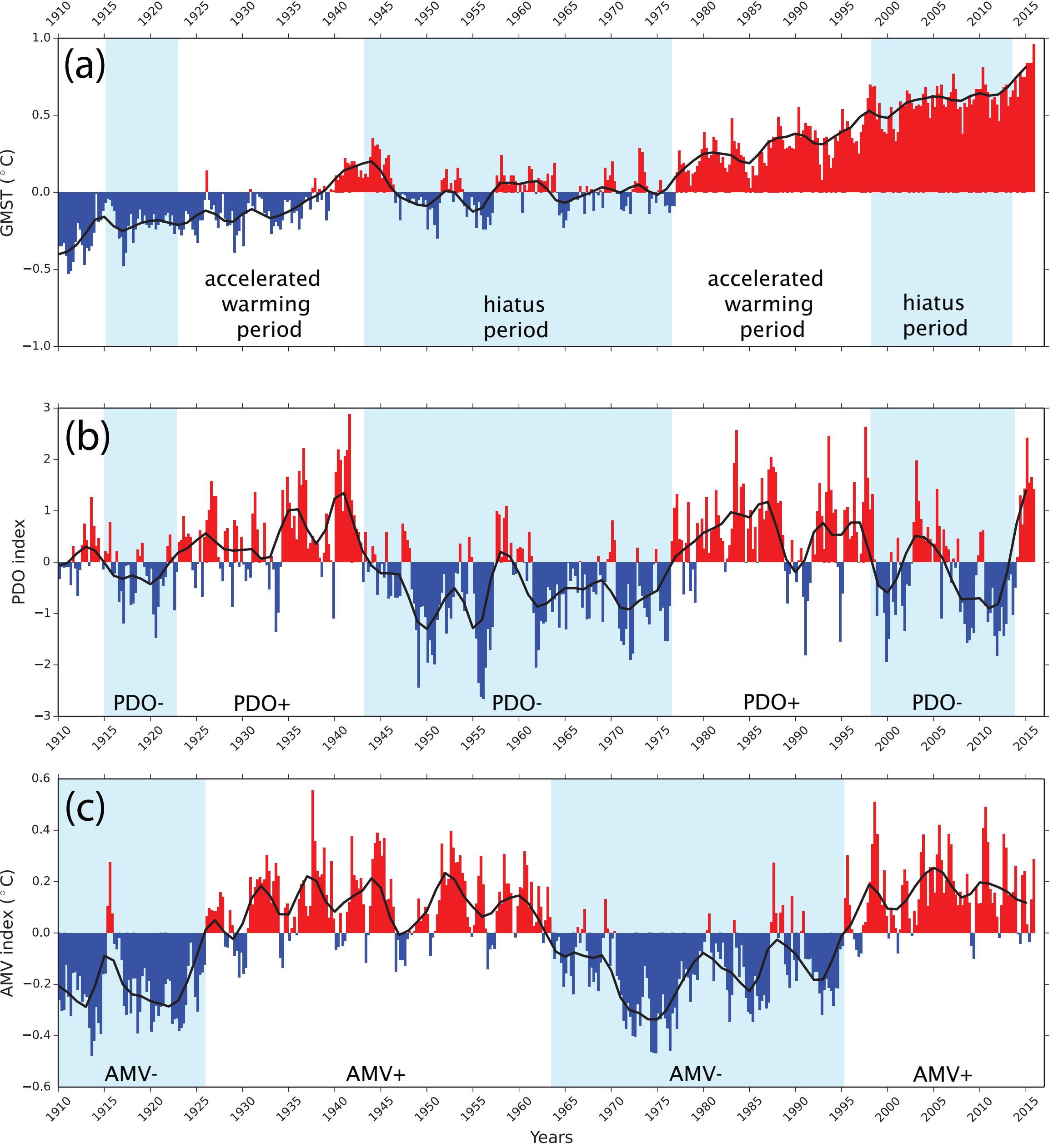
Positive
IPO

Negative
IPO

Positive
IPO

Multiple decades

Just Natural Variability of the Ocean!



Two signals superimposed:
the effect of global warming +
natural fluctuations of the ocean

Pacific Decadal Oscillation

Atlantic Multidecadal Variability

Farneti (2017)