K36: The Ocean / Atmosphere Connection and Climate

Most of the Past 60 years of Global Warming Has Gone into the Oceans

- **The Ocean has absorbed approximately 93% of the warming of the Earth system that has occurred since 1955**.
- The top 700m ocean layer accounted for approximately 2/3 of the warming of the 0-2000m layer of the World Ocean.
- The thermosteric component (*i.e.* the component due to expansion of the seawater due to its higher temperature) of sea level rise was 0.54 ±.05 mm per year for the 0-2000m layer and 0.41 ±.04 mm per year for the 0-700m layer of the World Ocean for 1955-2010. (IPCC AR4 2007)

93%. Has this Raised the Ocean's Temperature Greatly?

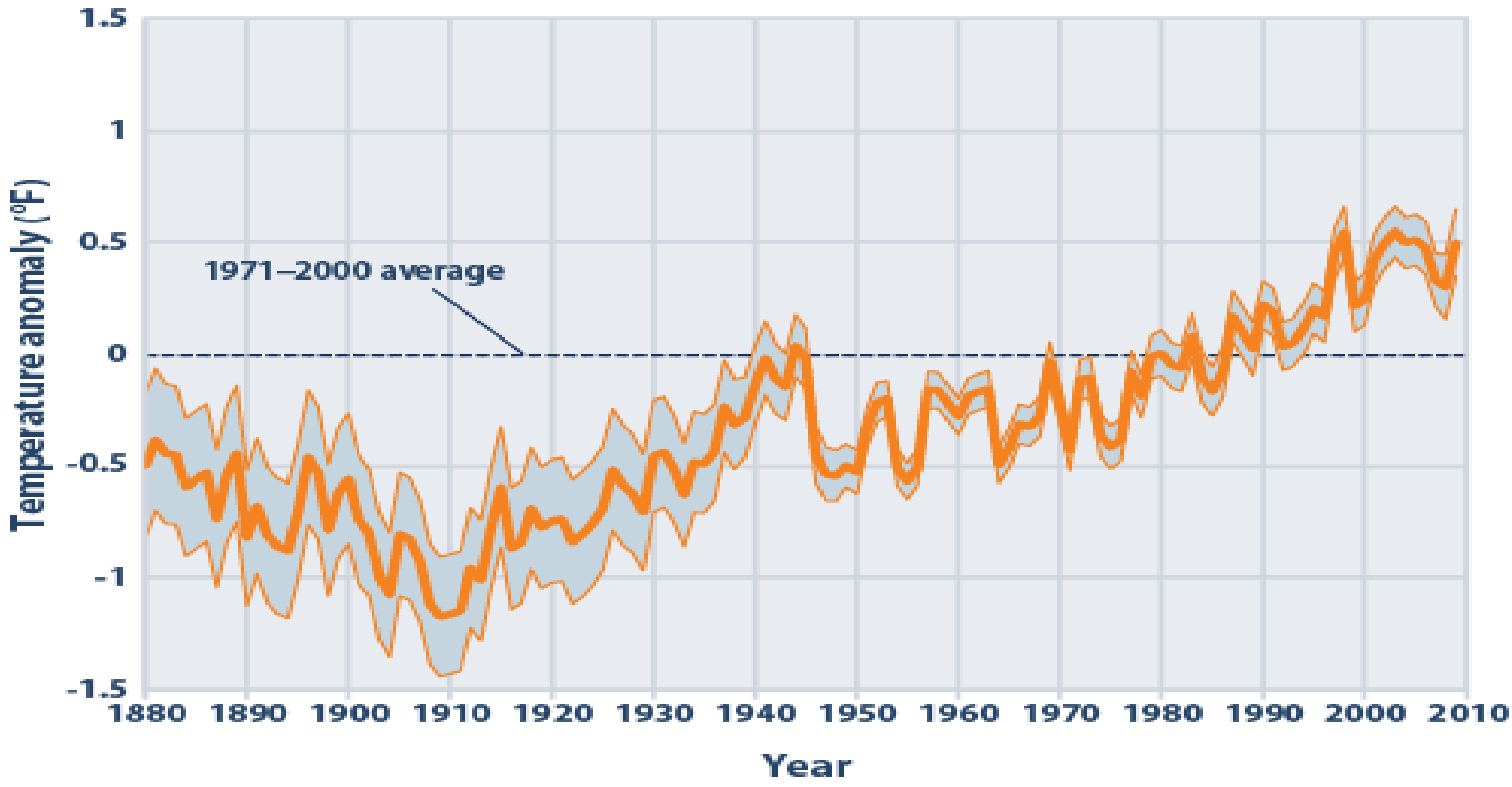
- **Not much.** The thermal capacitance of water is very high. Water is a polar molecule, with one side net positive and the opposite net negative, and this causes strong bonding with neighboring molecules in complementary positionings ("hydrogen bonds"). These bonds can absorb a lot of energy without raising the kinetic energy of the molecule itself.
- **High thermal capacitance;** means it can absorb and give off a lot of heat without much temperature change.

The Thermal Capacitance of the Air is Much Less than that of Water

- Why? It is dominated by diatomic molecules (N_2, O_2), which have fewer internal degrees of freedom (vibrations) able to be excited.
- This means energy added to the atmosphere goes more directly into increasing its temperature, not so for water.
- Observational data as of 2016 indicate that ocean surface has warmed only about 0.6 C, compared to the total land+ocean+cryosphere surface system, which has warmed +1.2C, since pre-industrial times.

Sea Surface Temperatures Have Risen Only ~Half as Much as Air Temperatures During Current Climate Change (note these are Fahrenheit degrees) (source: NOAA)

Figure 1. Average Global Sea Surface Temperature, 1880–2009



The Ocean's Thermal Mass is 700 Times Larger the Thermal Mass of the Atmosphere…

- The entire thermal capacity of the atmosphere is equivalent to just the top 3.5m (about **12 feet**) of the ocean.
- Without the ocean to absorb our greenhouse gas heating, our atmosphere would have warmed by **+68F**, rather than the actual 2F, or almost 40 times larger temperature difference,
- …and we'd all be dead. But as we'll see: *The Ocean Giveth, and the Ocean will Taketh Away*

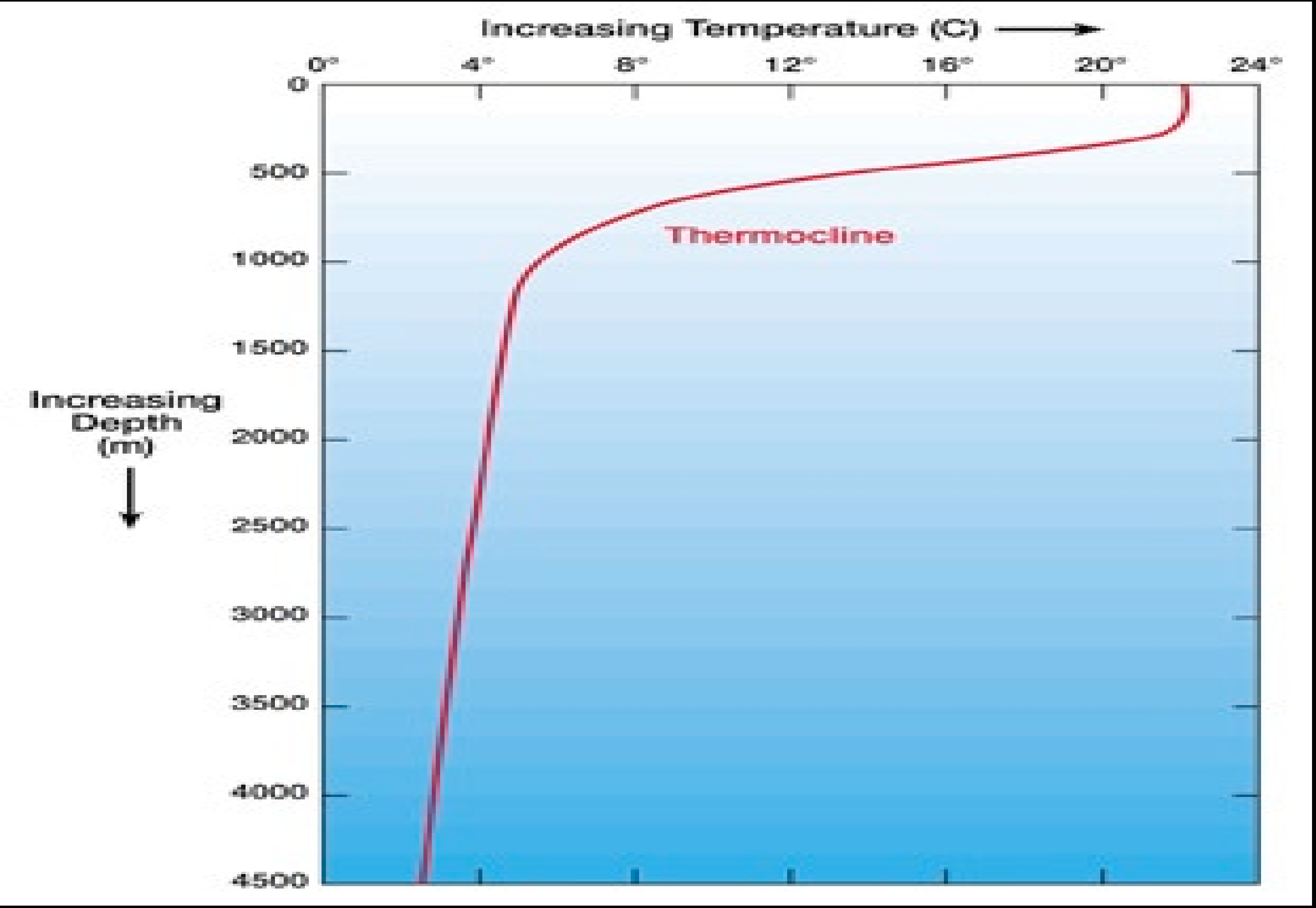
Water Vapor

- On average, Earth's atmosphere contains about 0.8% water vapor (enough to make **1 inch of liquid water around the planet**)
- Because hotter air will hold more water vapor, at 120F temperature and 100% relative humidity, water vapor would make up fully 4% of the mass of the atmosphere.

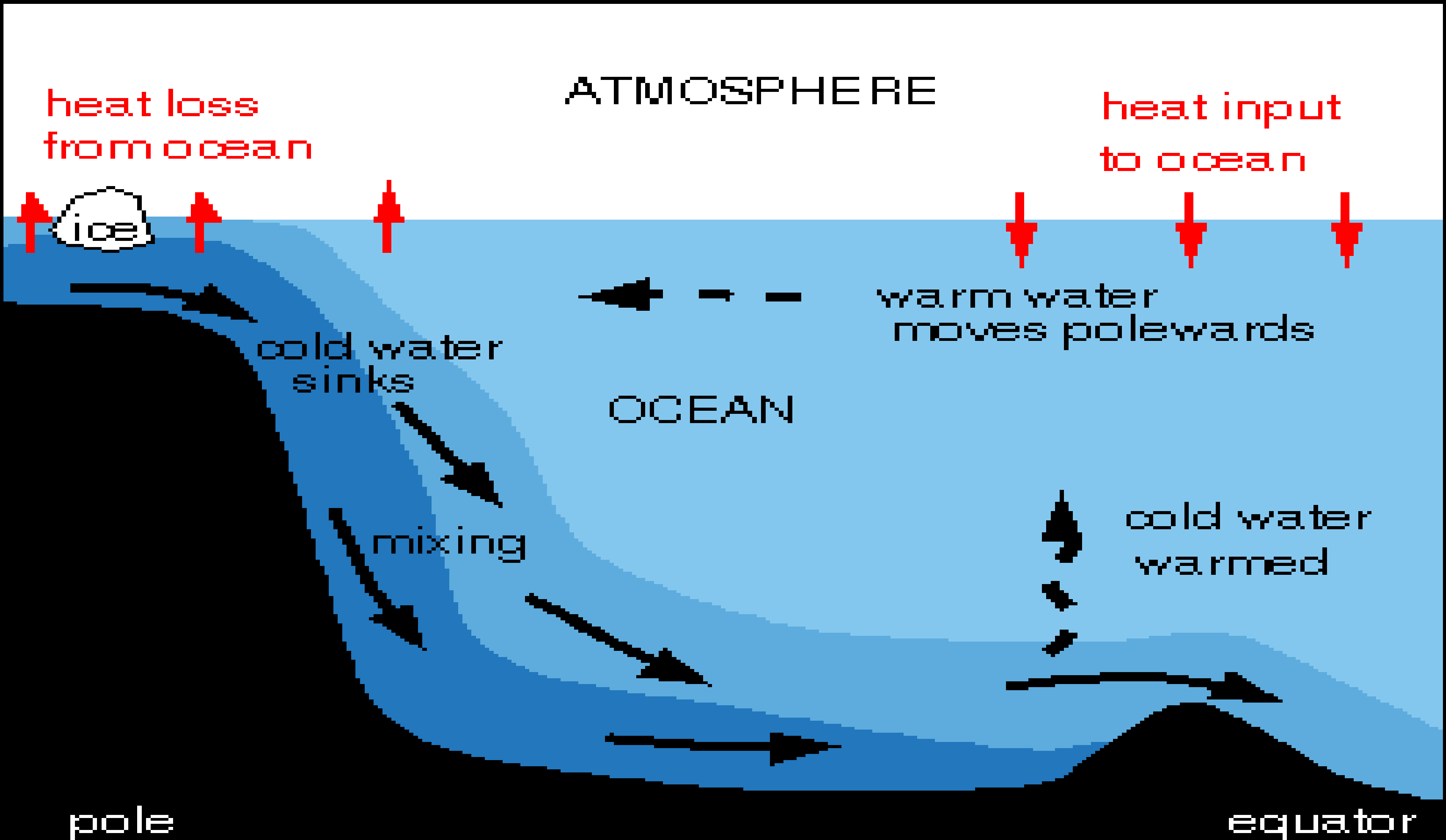
The Ocean Responds to Forcings SLOWLY

- The total ocean responds to forcings (*e.g.* heat input, CO2 transport in/out) **slowly**, because of its sheer mass and slow currents.
- It does not mix itself rapidly.
- **On average, the ocean is well mixed in summer to only 20m depth, and to only 90m depth in winter** (more storm turbulence in winter). For a 90m mixing depth, the ocean takes fully **6 years** to reach some sort of equilibrium to a temperature change at the surface.
- Mixing of the ocean which goes all the way to the bottom (avg of 3800 meters depth) takes much longer; **about 1000 years**, because the **thermocline boundary** (see next slide) must be crossed and this is a very stable boundary, significantly crossed only at 4 places around the world.
- In other words, the slow currents of the ocean must move 10's of thousands of miles before slowly moving downward or upward to communicate ocean bottom waters with ocean surface waters

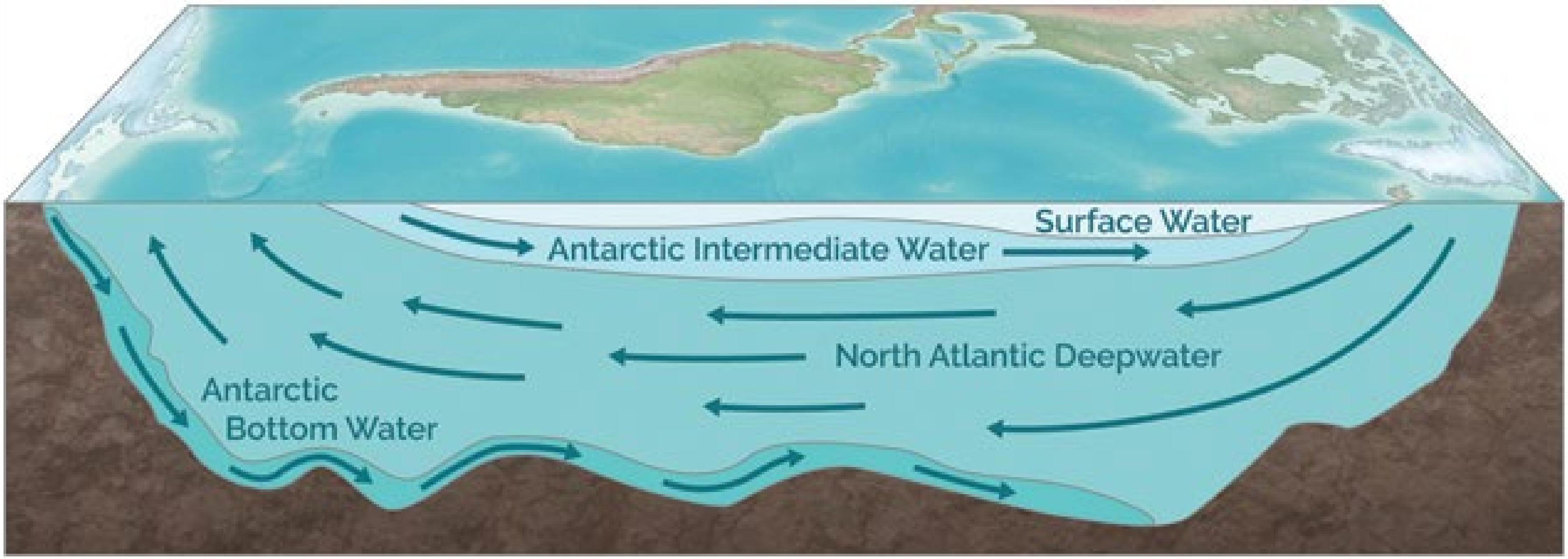
The Thermocline: A relatively narrow range of depth where the ocean temperature rises significantly and hence the density decreases significantly, strongly inhibiting convective mixing across this layer. ~90% of the ocean volume is below the Thermocline



Colder water is denser, as is saltier water (ice formation excludes salt, leaving remaining water saltier). Both contribute to overcoming the thermocline, so cold freezing dense salty waters can sink, migrate towards equator where heating and trade winds drive surface waters away, to be replaced by rising waters from the depths

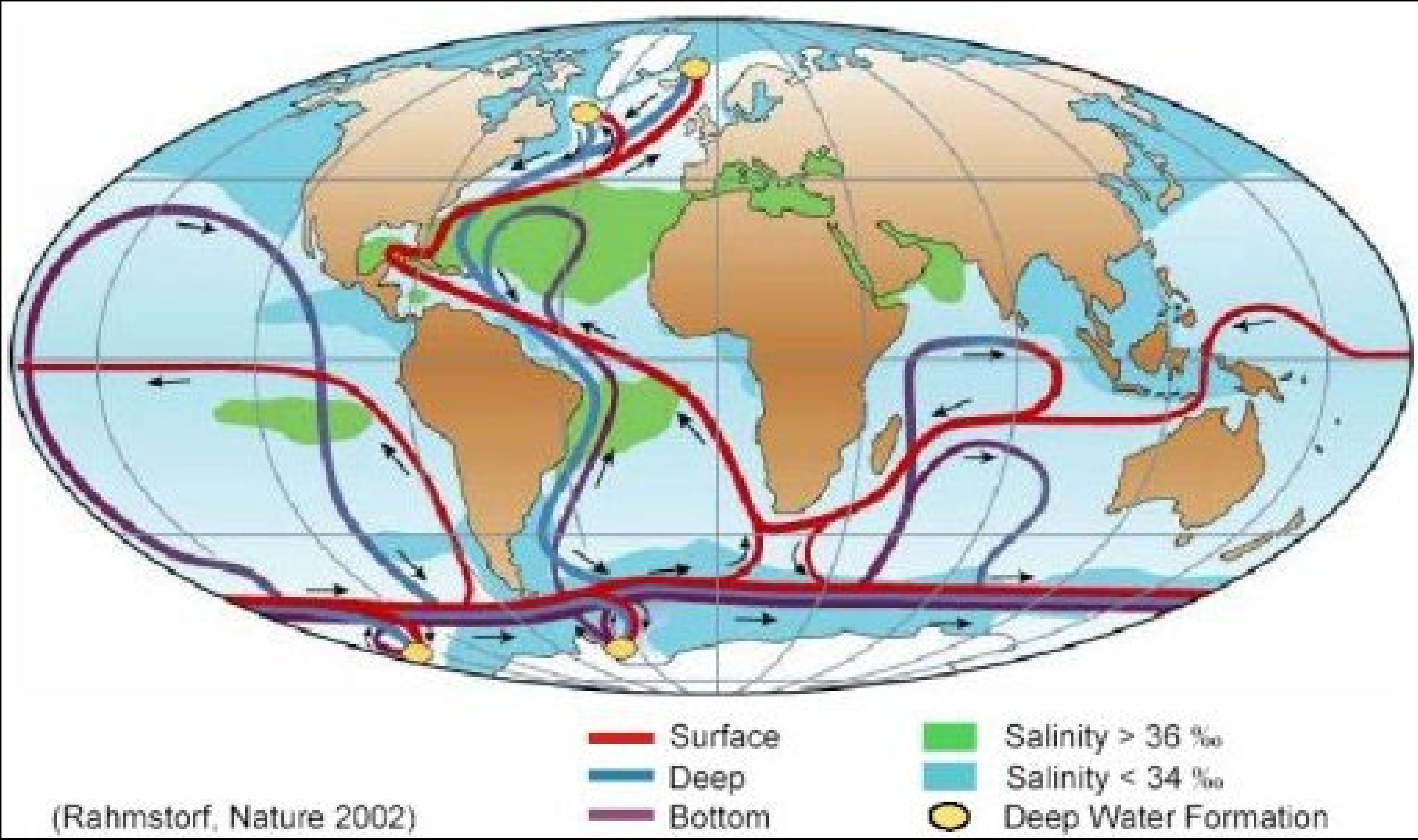


The closer you look, the more complex the currents are. At different depths move in different directions: It's a 3-D ocean circulation



Starting at the surface in the Northern Hemisphere, surface waters chilled in the frigid Labrador and Nordic seas become denser and sink, forming North Atlantic Deepwater. At the bottom of the North Atlantic, this water mass turns south, flowing at depth above north-flowing Antarctic Bottom Water (AABW), for approximately 100 years until it meets the waters around Antarctica. Credit: K. Cantner, AGI.

The Global Thermohaline Circulation Currents



There are Only Two Places in the Northern Hemisphere Where the Surface Waters Return to the Deep

- **…And both are near Greenland.** Only here is there a forceful northern flow of water which can get far enough north to cool enough to break through the Thermocline
- But, the rapid melting of Greenland and the Arctic now is causing the surface waters to freshen
- This fresher water is less dense, more bouyant than salty water, and this inhibits its ability to sink, causing the warm surface waters to have to go FARTHER north before getting cold enough to sink.
- **This warmth farther north accelerates Arctic ice melt. Another positive climate feedback**
- And, the thermohaline circulation is beginning to slow

Ocean Circulation, as Indicated by the Atlantic Meridional Overturning Circulation (AMOC), is Already Weakening

- Rahmstorf *et al.* 2015 and discussed here, and at Realclimate.org find AMOC has weakened by **~17%,** much larger than climate models had predicted, and unprecedented in at least a thousand years
- Strong polar ice melt means fresh water, which is less dense than salty water, almost no matter what its temperature is. Thus, it can't get dense enough to fall through the thermocline.

The AMOC weakening is predicted to accelerate with further climate change

- But recall – the Coriolis force pushes northward currents like the AMOC eastward. And if this force lessens with a slower AMOC…
- …this will raise sea levels on the Eastern North American coasts by several extra inches, and as much as a full meter if the AMOC were to halt altogether, due to the reduced Coriolis force.

AMOC Current Strength (proxy), and 20th Century Direct Measurements.

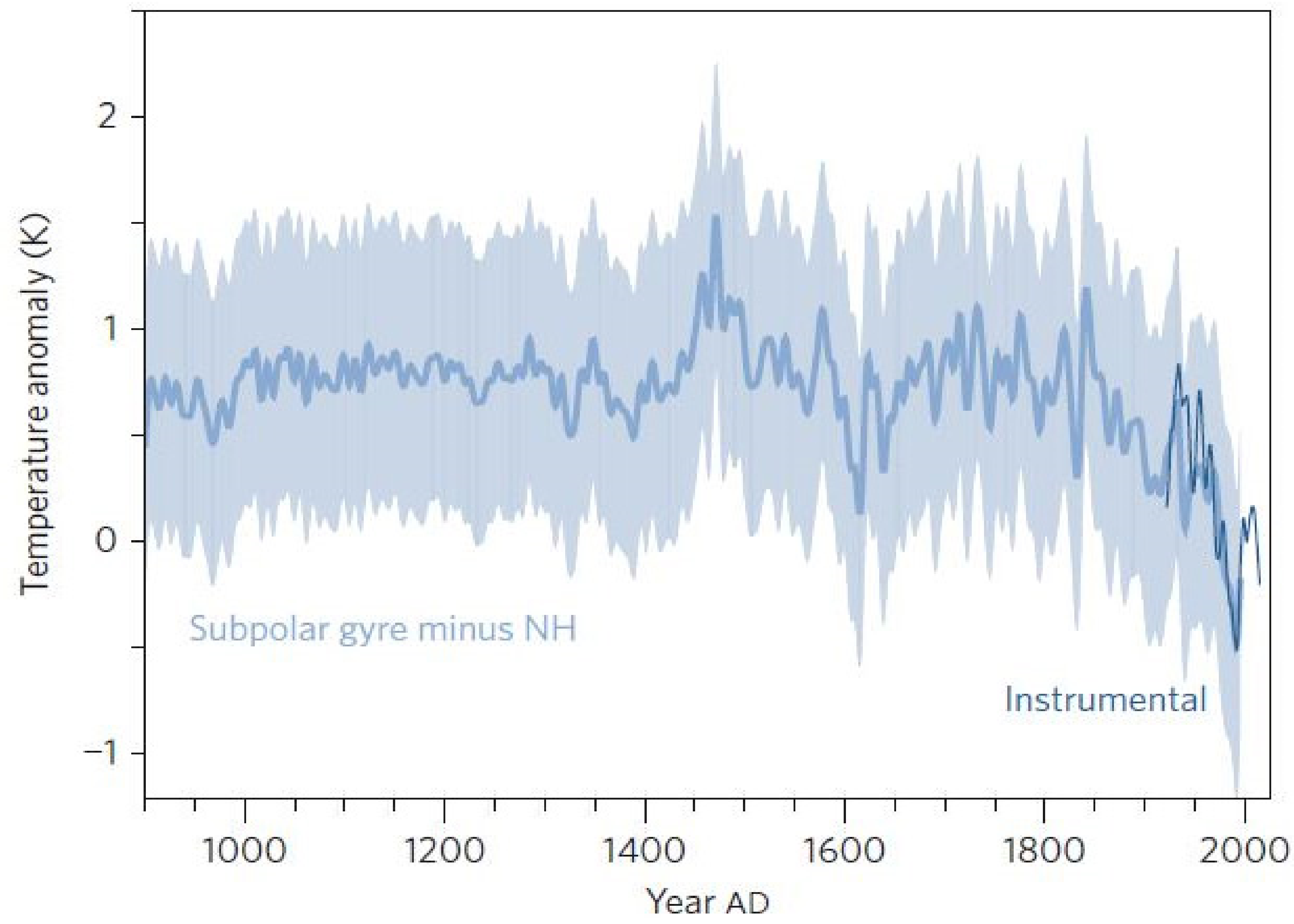
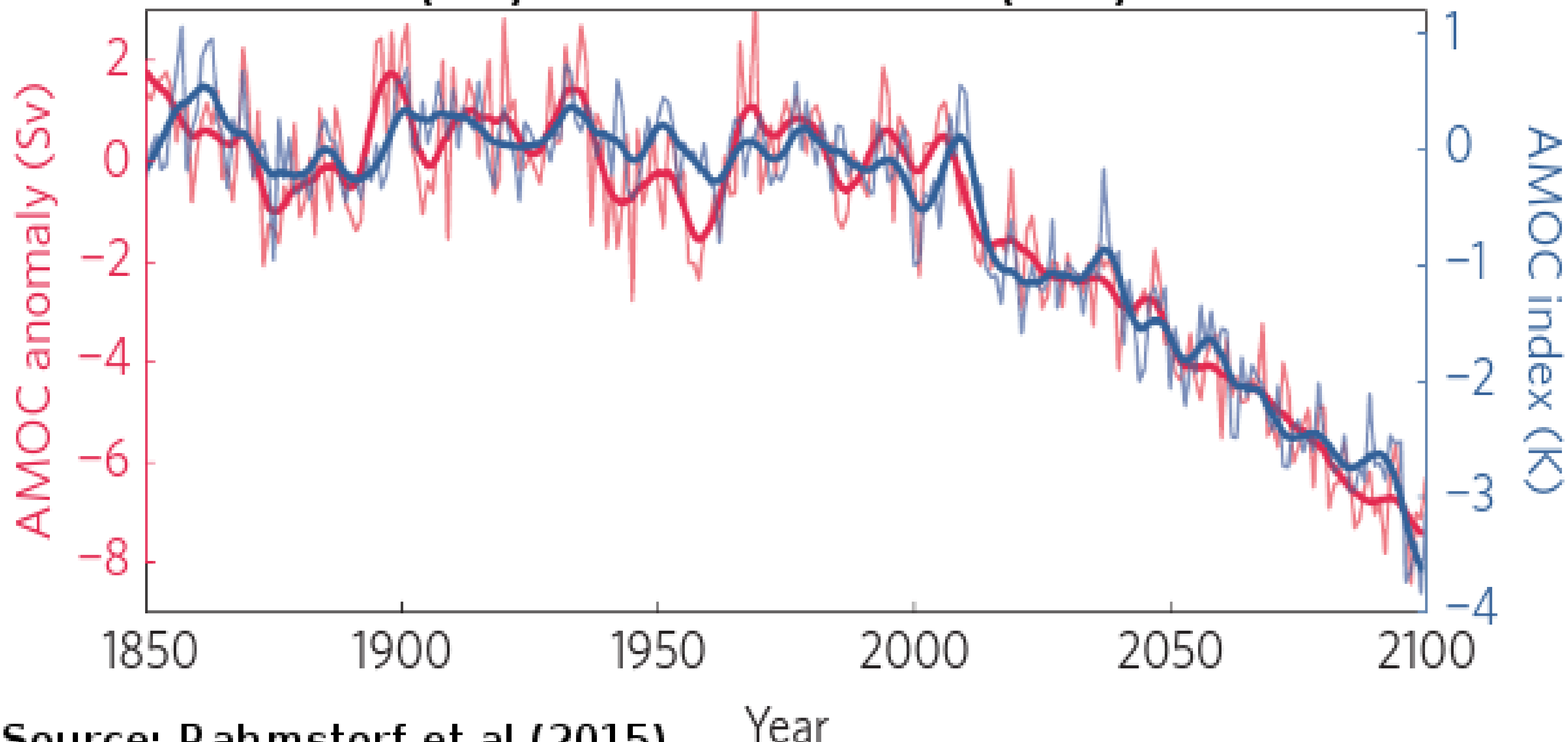


Fig. 3 *Time series of the temperature difference between the subpolar North Atlantic and the entire northern hemisphere, which can be interpreted as an indicator of the strength of the Atlantic circulation.*

The Atlantic Meridional Overturning Current is Expected to Continue to Slow

Time series of the maximum overturning stream function (red) and the AMOC index (blue).



Source: Rahmstorf et al (2015)

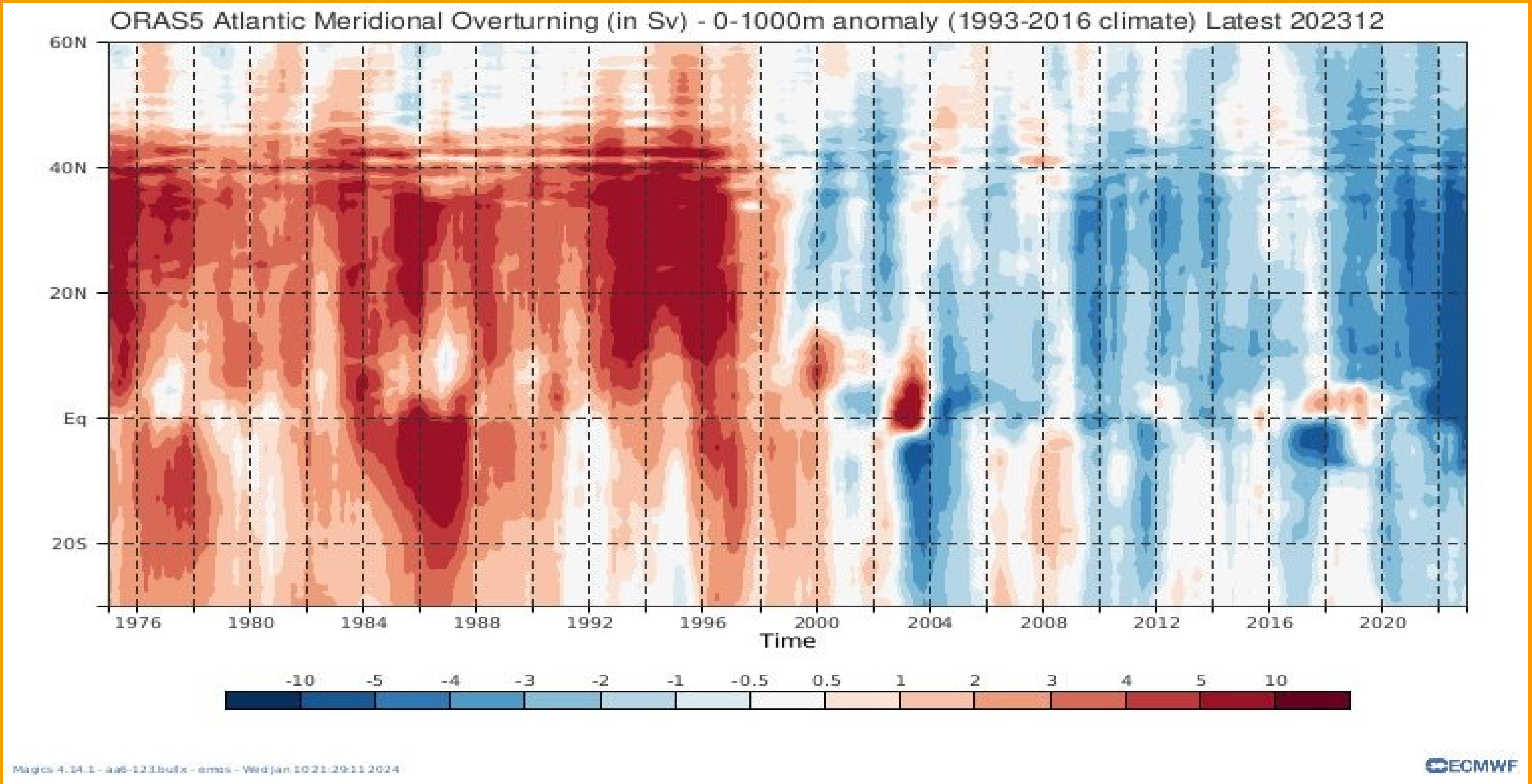
Does the AMOC Have a Tipping Point?

- Lenton *et al.* (2008) find that below a certain strength, the AMOC breaks down entirely.
- While the IPCC AR5 estimated the odds of this at only 10% this century, they used inadequate models (Hoffman and Rahmstorf 2009), and…
- A survey of 16 climatologists who specialize here find more realistic odds are ~40% given strong global warming of ~+6C, which is quite possible even if we act strongly.
- This would be **bad**

Consequences of a Significantly Slowed or Halted AMOC

- Rise in sea level from warmer waters in mid/low latitudes
- Strong rise in sea level along Eastern US, due to weakened Coriolis Force. This could be as much a 1 meter if the AMOC shuts down altogether
- Anoxic ocean, as upwelling ceases. Widespread kills in plankton and all surface species due to lack of nutrients, especially oxygen.
- Ocean and air currents would change significantly, leading to very different rainfall patterns, climate change in other ways difficult to predict

Now in the 2020's, The AMOC Strength Has Taken Another Sharp Turn Lower. Tipping Point?



Compare Thermal Mass of Oceans to Continental Land Surfaces…

- Rock and soil has only about ¼ of the heat capacitance of ocean water. It obviously does not mix itself either, and it has low thermal conductivity.
- The seasonal cycle of temperatures only penetrates about 2 meters below the surface. Beneath 2 meters, the temperature is essentially constant over the day/night and summer/winter time cycling.
- Over longer time frames, the depth below which temperature change does not happen, is deeper.
- **Bottom Line: The amount of Continental thermal mass affected by annual climate is small, a thin layer only 2 meters thick which can be heated and cooled quickly (lower heat capacitance) compared to the oceans**.

For today's climate change, while it is the atmosphere which is being directly forced, *via* greenhouse gases, it transfers this heat to the ocean surface fairly efficiently, and much more slowly to the deeper layers, (below, from IPCC AR4), as seen by the large and strongly accelerating energy content growth in the oceans (compare pink to blue. Blue is 40 last years, pink final 10 yrs – rapid acceleration of change into 2003. This graph ends in 2003. More acceleration since then.

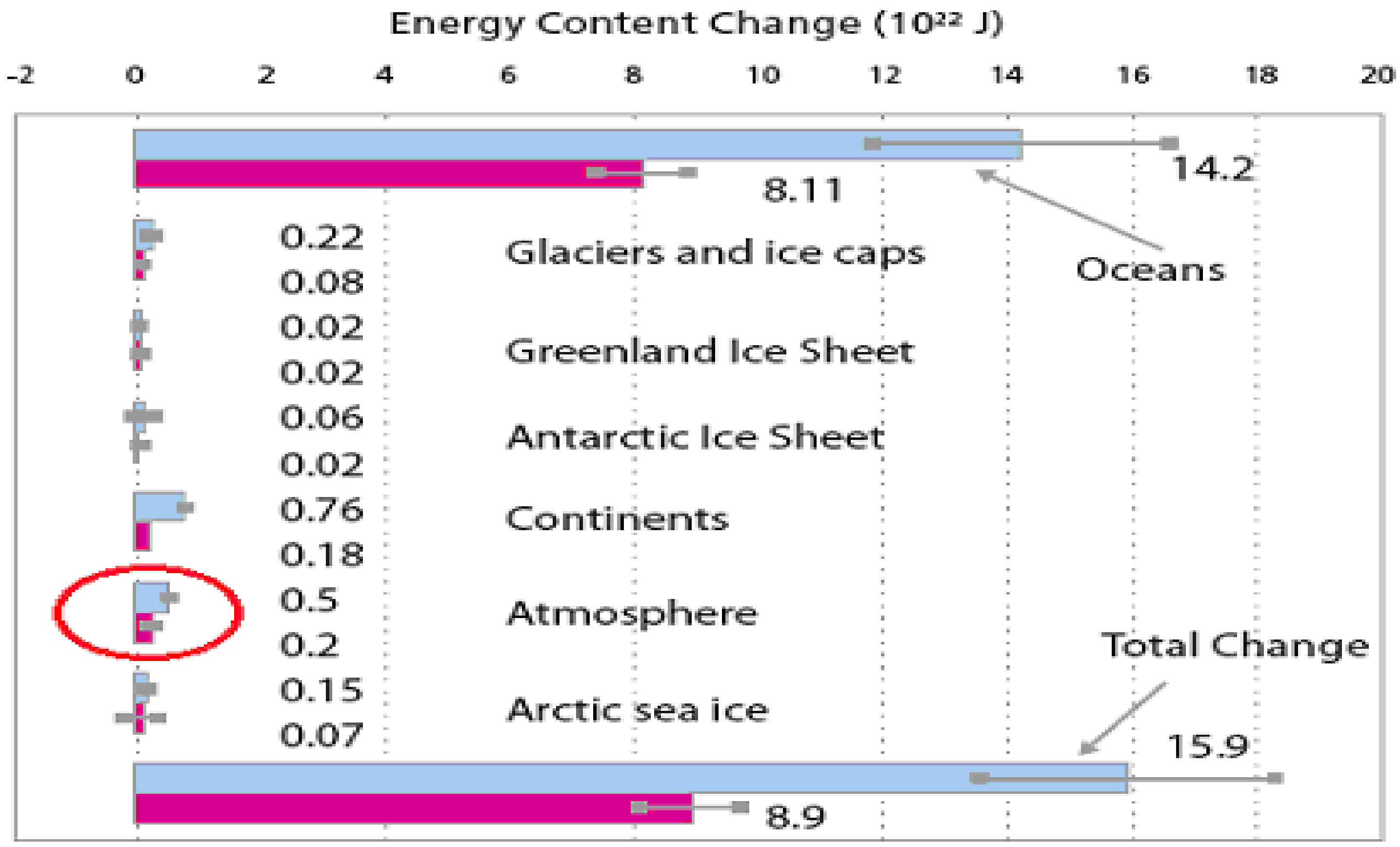
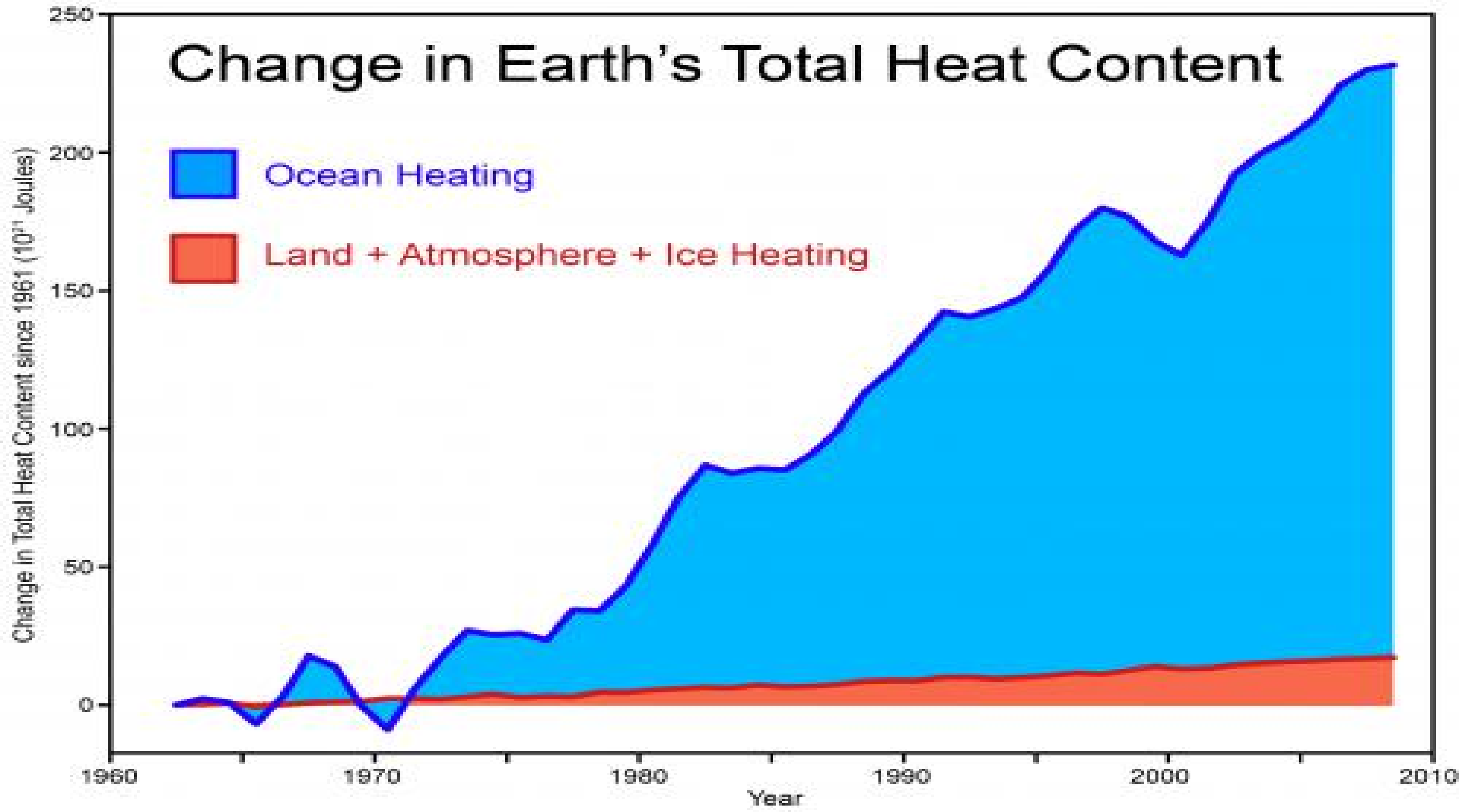
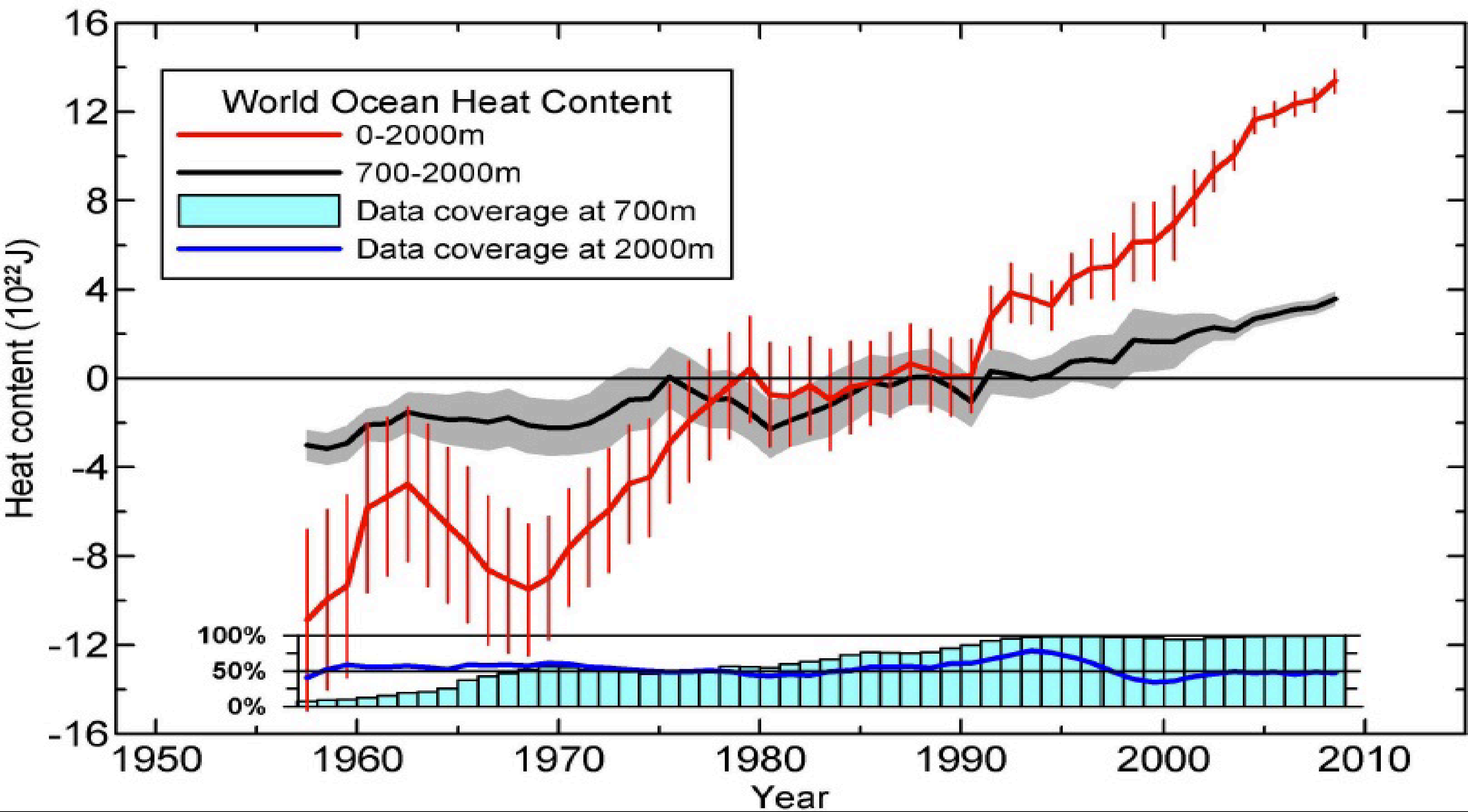


Figure 2

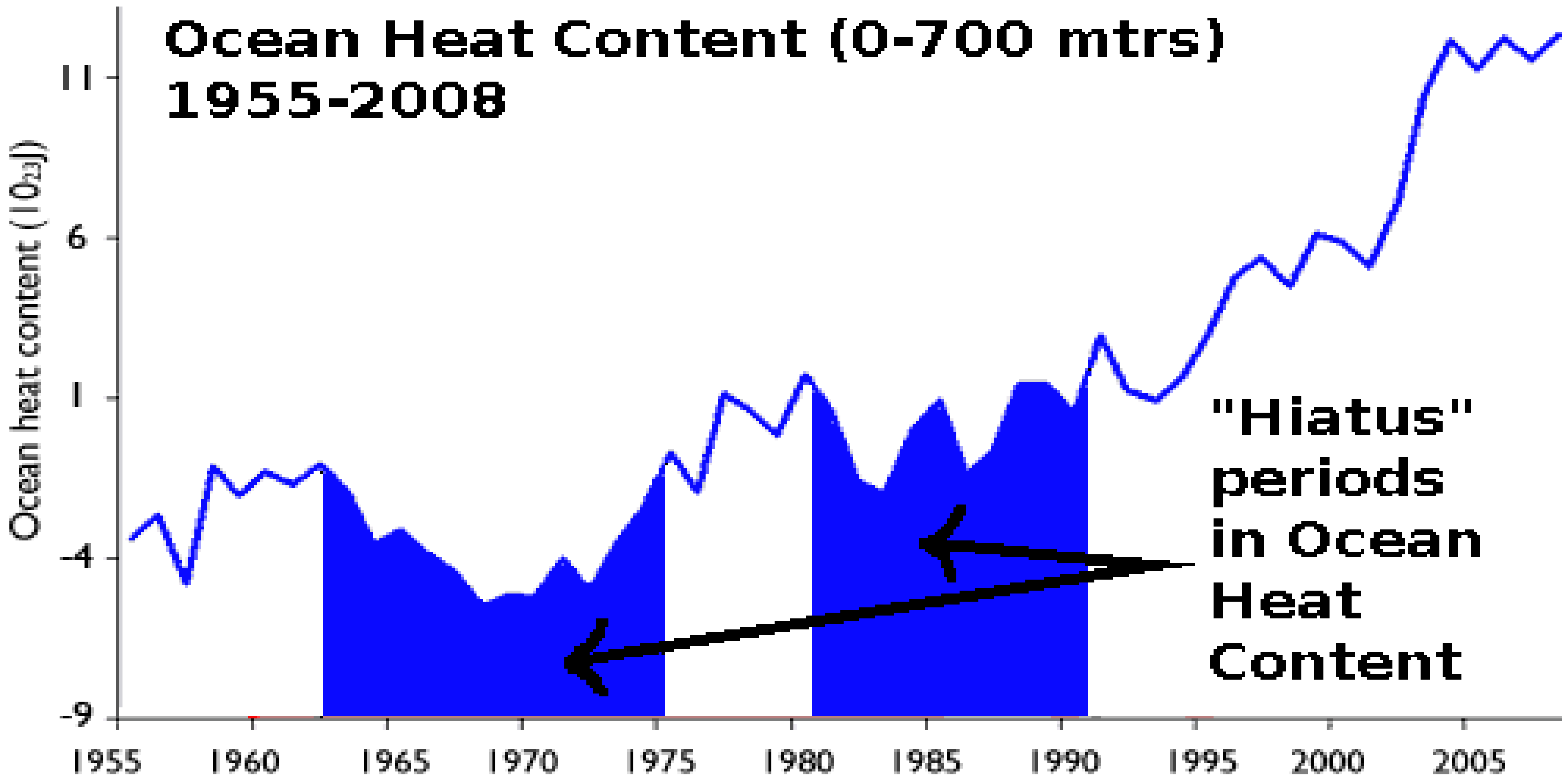
The change in energy content in different components of the Earth System for two periods: 1961-2003 (blue bars) and 1993-2003 (pink bars)[2] (figure 5.4).

Same Result, from later study (Church *et.al.* 2011). Pink curve shows sum heating of land+ice+atmosphere. It is the atmosphere being forced, but the oceans which takes most of the resulting heat. **Without the oceans to dump into, the atmosphere would have heated by about ~68F, not the ~2F we have seen so far**





Time series for the World Ocean of ocean heat content (units of 10^22 J) for the 0-2000m (red) and 700-2000m (black) layers based on running pentadal (five-year) analyses. Reference period is 1955-2006. Each pentadal estimate is plotted at the midpoint of the 5-year period. The vertical bars represent +-2 standard deviations (S.E.) about the pentadal estimate for the 0-2000m estimates and the grey-shaded area represent +/- 2*S.E. about the pentadal estimate for the 700-2000m estimates. The blue bar chart at the bottom represents the percentage of one-degree squares (globally) that have at least four pentadal one-degree square anomaly values used in their computation at 700m depth. Blue line is the same as for the bar chart but for 2000m depth. From Levitus et al. (2012)



Hiatus Periods: Periods when the surface ocean is efficiently transporting heat from shallow to deeper layers, so air temp rise is muted.

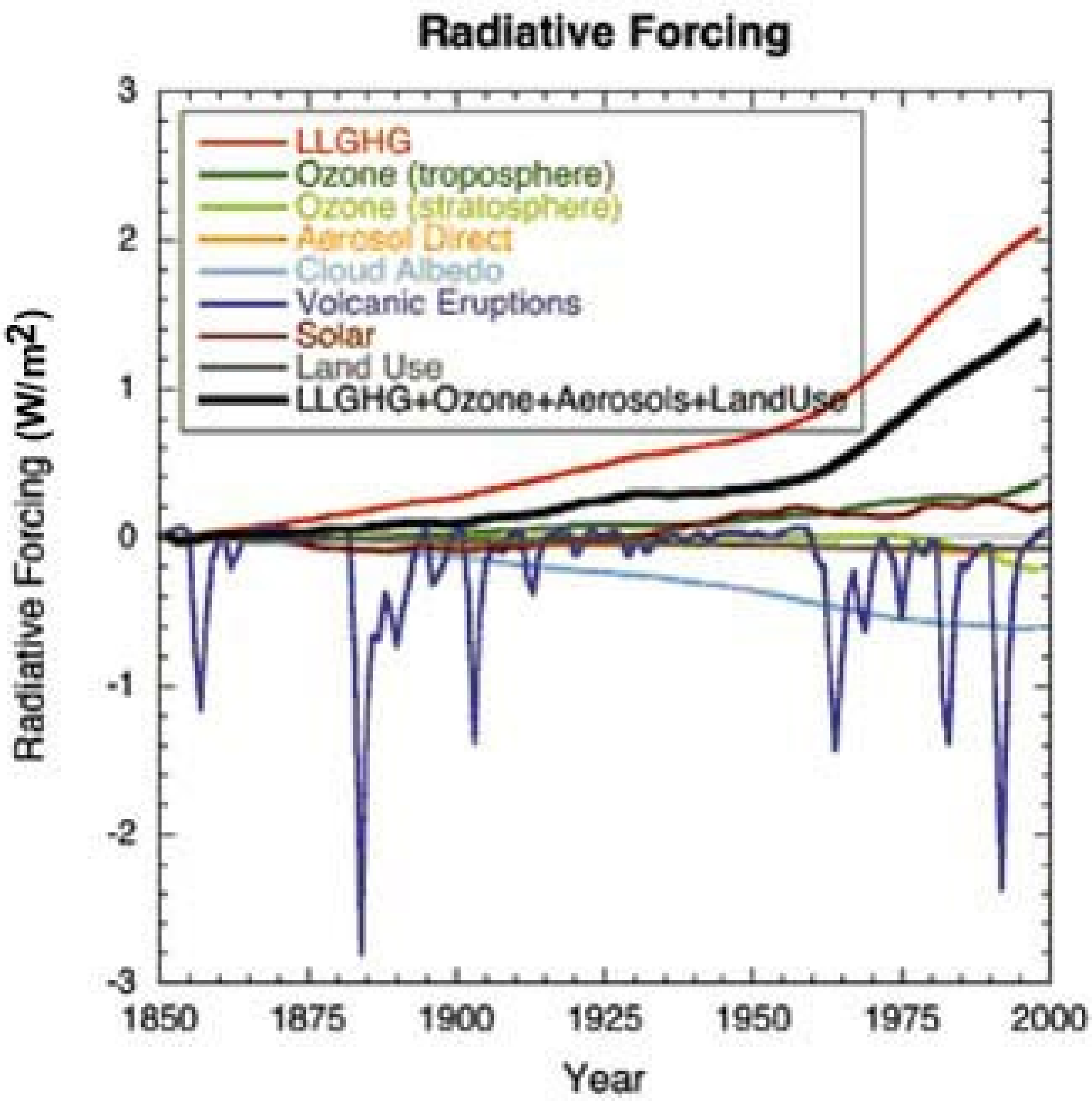
When the warm waters are not able to transfer to deeper levels, they remain hotter, less able to accept heat from atmosphere to the ocean, and so the atmosphere is hotter than it would have been…

The AMO: Atlantic MultiDecadal Oscillation

- This is a slower oscillation defined strictly by sea surface temperatures (SST's) in the North Atlantic, and showing an oscillation time scale of more than a decade typically
- **Because the AMO is *defined* by sea surface temperatures's (SST's), then it is dangerous to simply assume AMO *causes* Global Warming, when in fact the physics says it's the other way around**
- This basic and rather obvious fact was ignored in a paper several years back which showed a correlation between AMO and global surface temps and concluded the AMO might be causing a significant amount of global warming (seized on by climate denial bloggers with a vengeance).

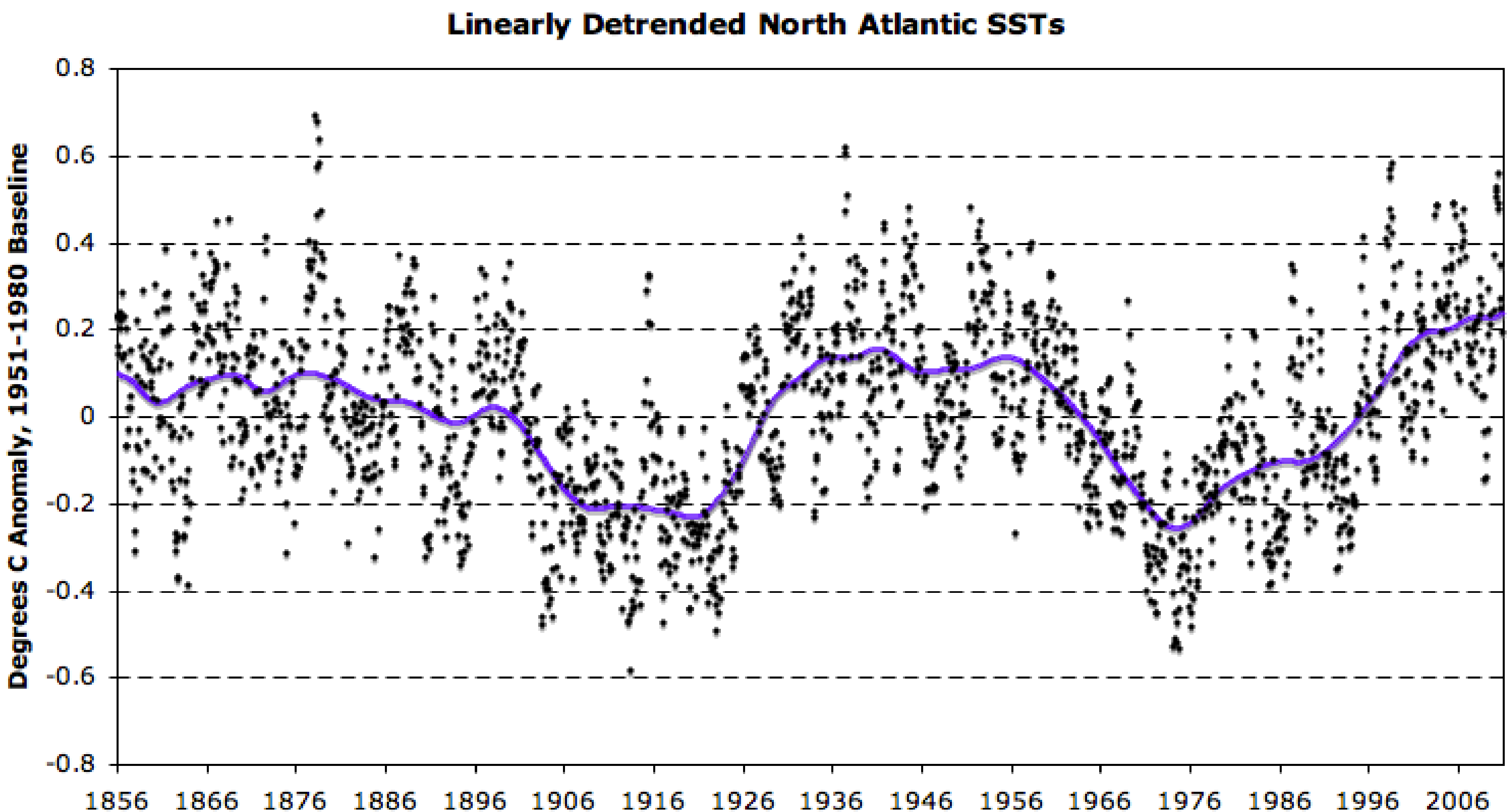
Trend *vs.* Oscillation in the AMO

- Those who try to argue that the AMO accounts for most or all of global average temperature rise also make a fatal mistake in taking out the LINEAR trend before defining the oscillation (the linear upward trend due to human greenhouse warming. if you want to wade into the academics, here is the author *vs.* other climate scientists)
- But it is obvious from the CO2 graphs and the resulting Earth radiative forcing (next slide) that this anthropogenic forcing is NOT linear, but instead steeply weighted to recent years and decades. When de-trended this way (Trenberth and Shue), the AMO is seen to be a simple oscillation which in fact has been in a negative overall trend during the 100 or so years we have data for.
- Great discussion here

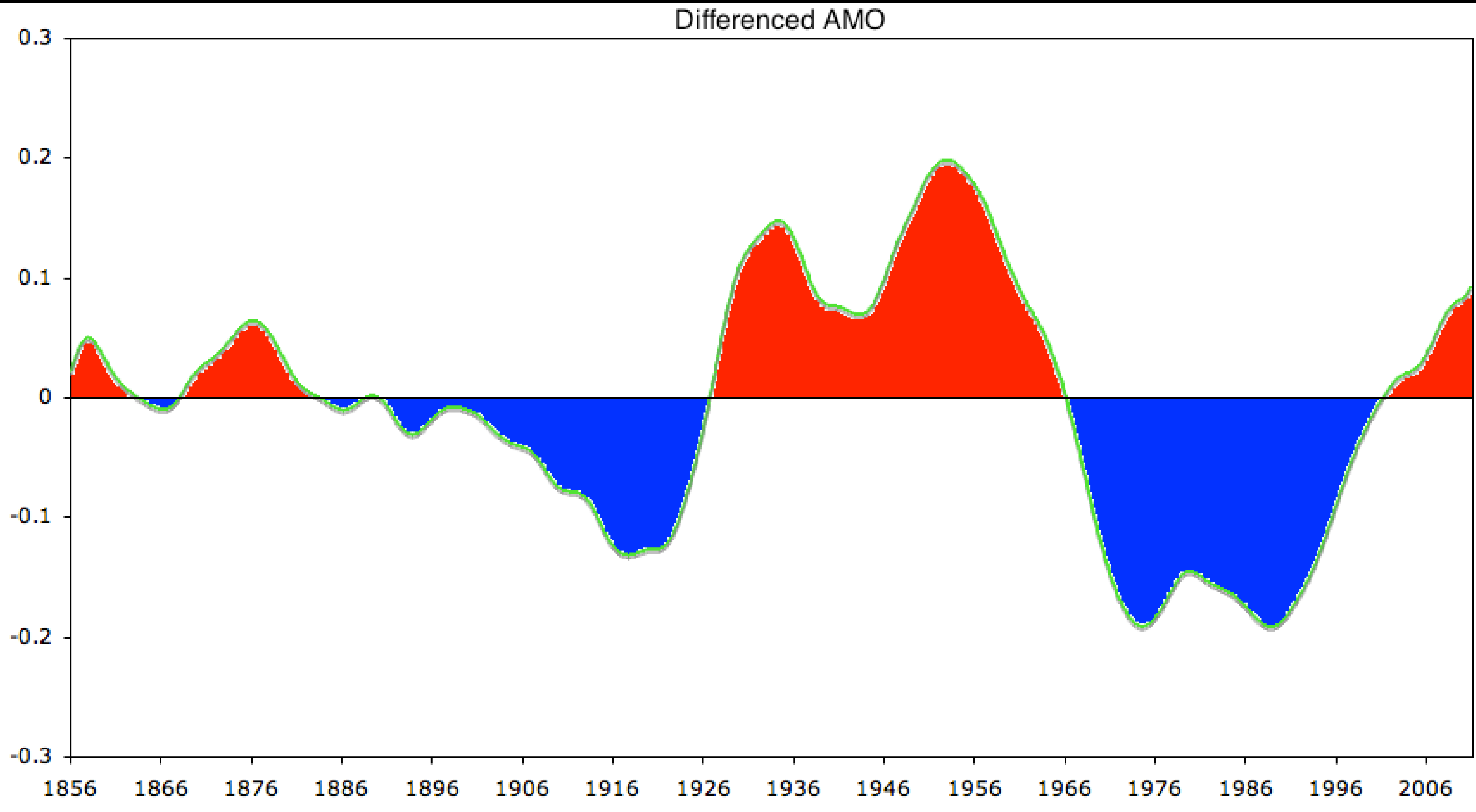


Human generated long-lived greenhouse gases (LLGHG) sharply dominate climate especially since ~1970

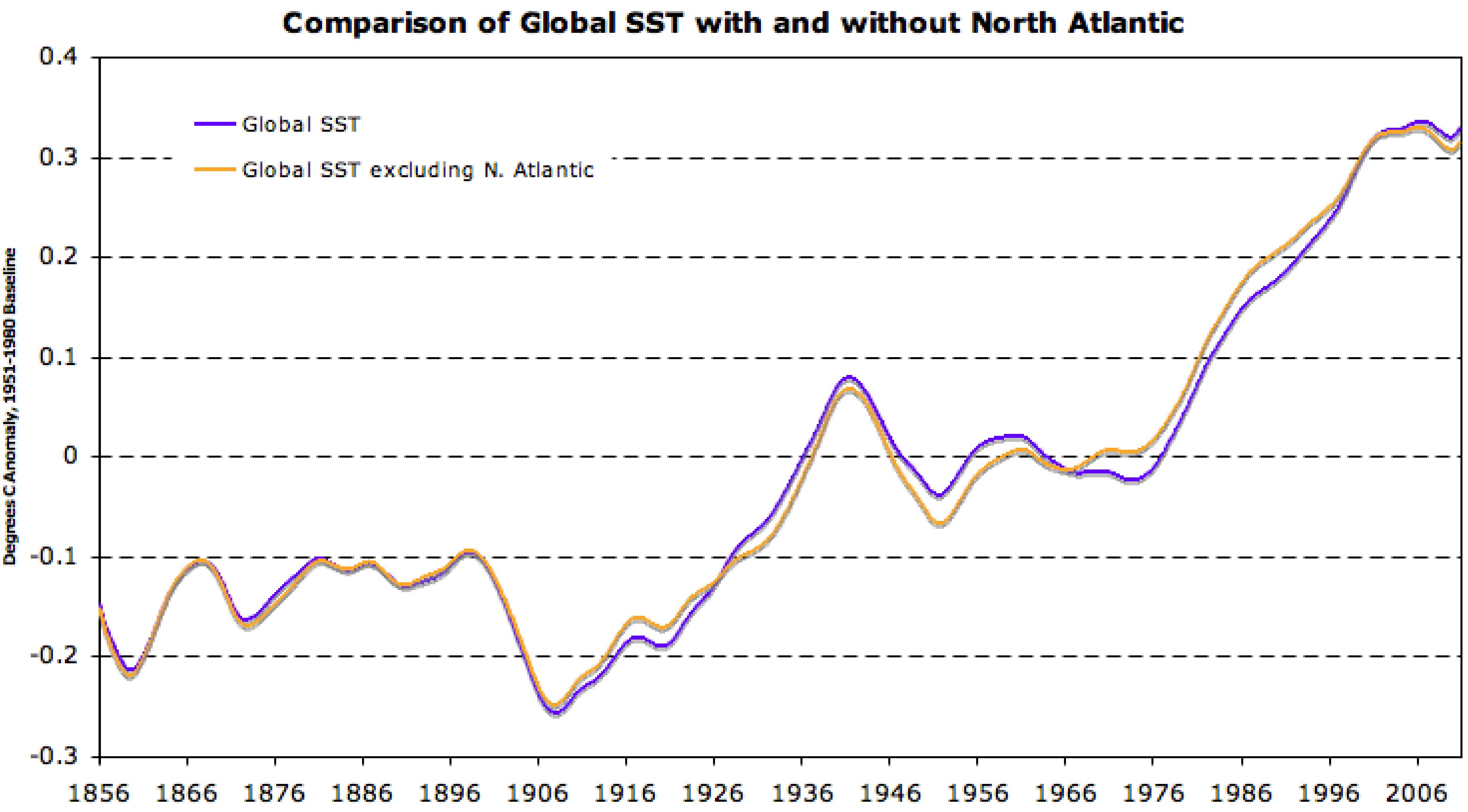
The AMO with simple linear trend removed. The significant post-1970 rise would have the casual reader believe some of global warming is AMO. But not so….



Isolating <u>only</u> the North Atlantic SST's (*i.e.* subtracting from Global SST's all but AMO-relevant North Atlantic SST's shows a much smaller strict AMO with no trend



In Fact, Global SST's Change very little whether or not North Atlantic temps removed. AMO has little effect. So something else must be driving Global SST's: It is external human influences like CO2

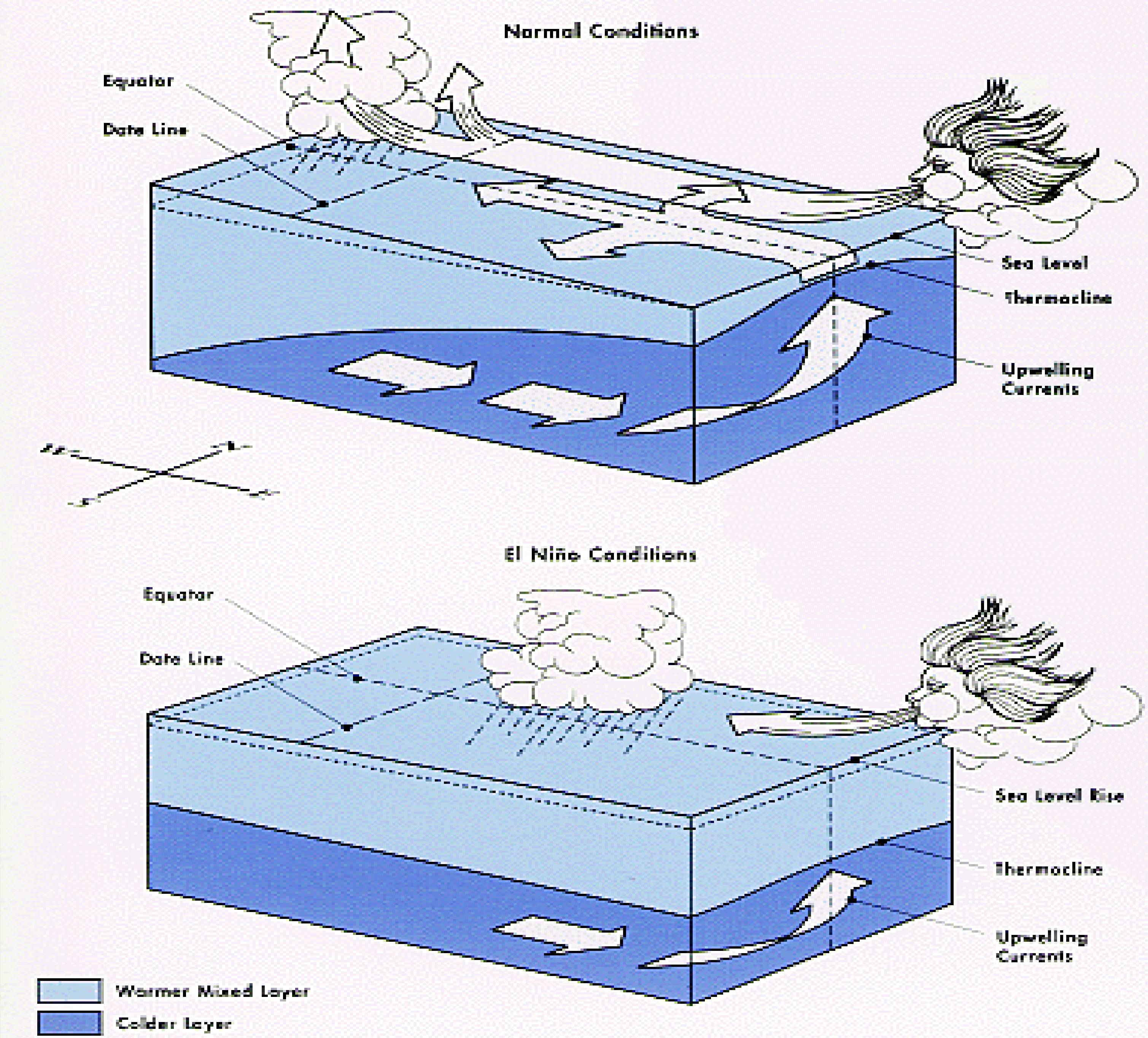


Oscillations in Ocean Currents Means Oscillations in the Heating of the Oceans

- World's largest ocean is the Pacific. Because of its size, the oscillation period over which currents will be modulated by winds is longer than the seasonal period: The **El Nino – Southern Oscillation** (**ENSO**) cycle
- When the winds blow strongly westward at the equator, you have cold upwelling off South America which is then blown as surface cool water to the west. By the time it arrives in Indonesia, it's pretty warm. When those Trade Winds weaken, the cold upwelling weakens and the hot surface waters, now a "hill" at Indonesia, sloshes back by gravity, eastward, flooding the equator with warm water.
- **These warm surface water periods prevent heat take-up from the atmosphere – the "El Nino" phenomenon – which raises atmosphere temperatures at a rate faster than the longer term average.**

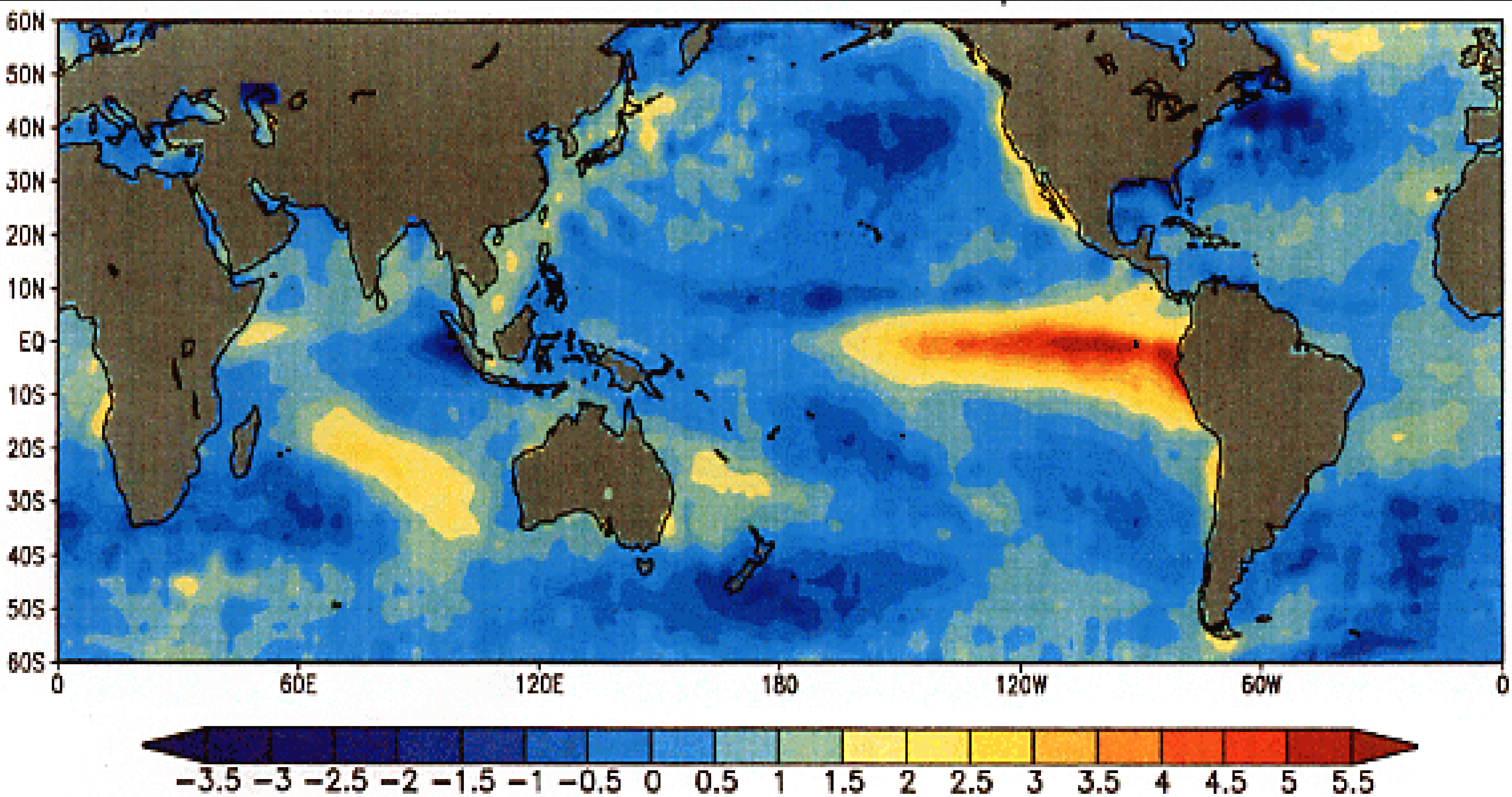
La Nina *vs.* El Nino

- So…
- **La Nina:** Strong trade winds blow equatorial waters westward, driving cold upwelling and cooler equatorial water
- **El Nino:** Weak or absent trade winds, warm built-up surface water off Indonesia sloshes back Eastward, and this extensive hot water on the surface can't absorb more heat from the hot atmosphere



Normal Conditions
Equator
Date Line
Sea Level
Thermocline
Upwelling
Currents
El Niño Conditions
Equator
Date Line
Sea Level Rise
Thermocline
Upwelling
Currents
Warmer Mixed Layer
Colder Layer

<u>El Nino Warming Map</u>: Temperature difference from long term average at sea surface, in Celsius, during El Nino warming. Equatorial Pacific and North American west coast waters warm

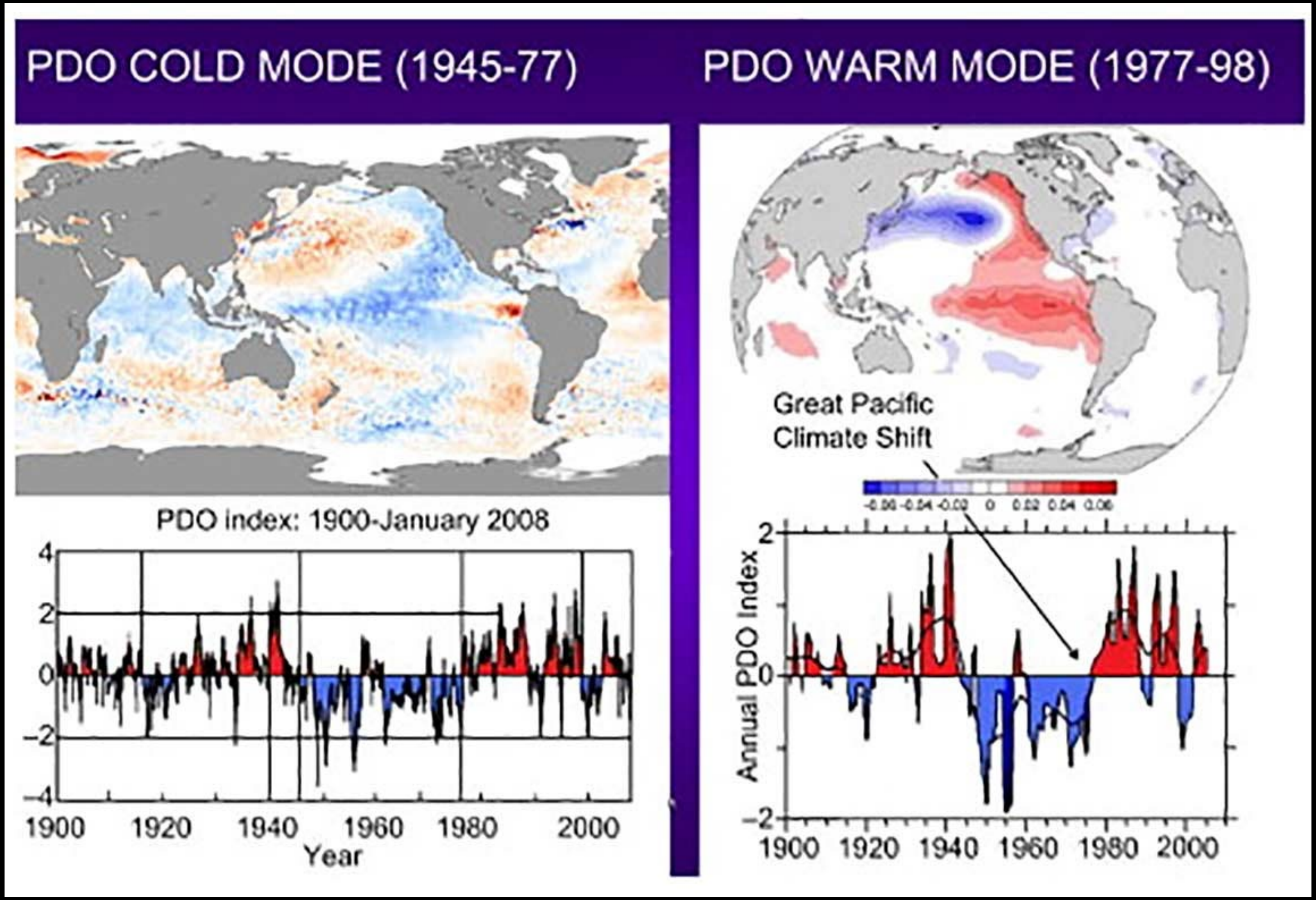


Typically the period between El Nino phases is <u>very</u> roughly <u>5 years</u> (but not periodic) – Anyway, longer than the yearly seasonal cycle.

- Since the ocean has so much more heat than the atmosphere, the El Nino (warm surface water) phase can be associated with significant short-term heating of global atmosphere, but still smaller than greenhouse forcing.
- The much smaller Indian Ocean shows no similar ENSO cycle, only a smaller cycle (monsoons), with a period of one year (*i.e.* seasonal).
- Must average climate over time scales much larger than ENSO in order to get clear idea of secular global warming.
- Climate denialists are fond of starting their “cherry picked” time intervals at El Nino’s in order to claim “See? No more global warming!” 1997/98 was the most powerful El Nino warming in decades, for example. More on this when we get to climate denialism.

The PDO: Pacific Decadal Oscillation

- The PDO is a semi-periodic oscillation in the North Pacific currents and air patterns which lead to oscillations in the sea surface temperatures
- It is caused by several forcings happening in tandem (see purple slide for more)
- It definitely affects climate, the “cool phase” associated with cooler global temps, “warm phase” with warmer global temps

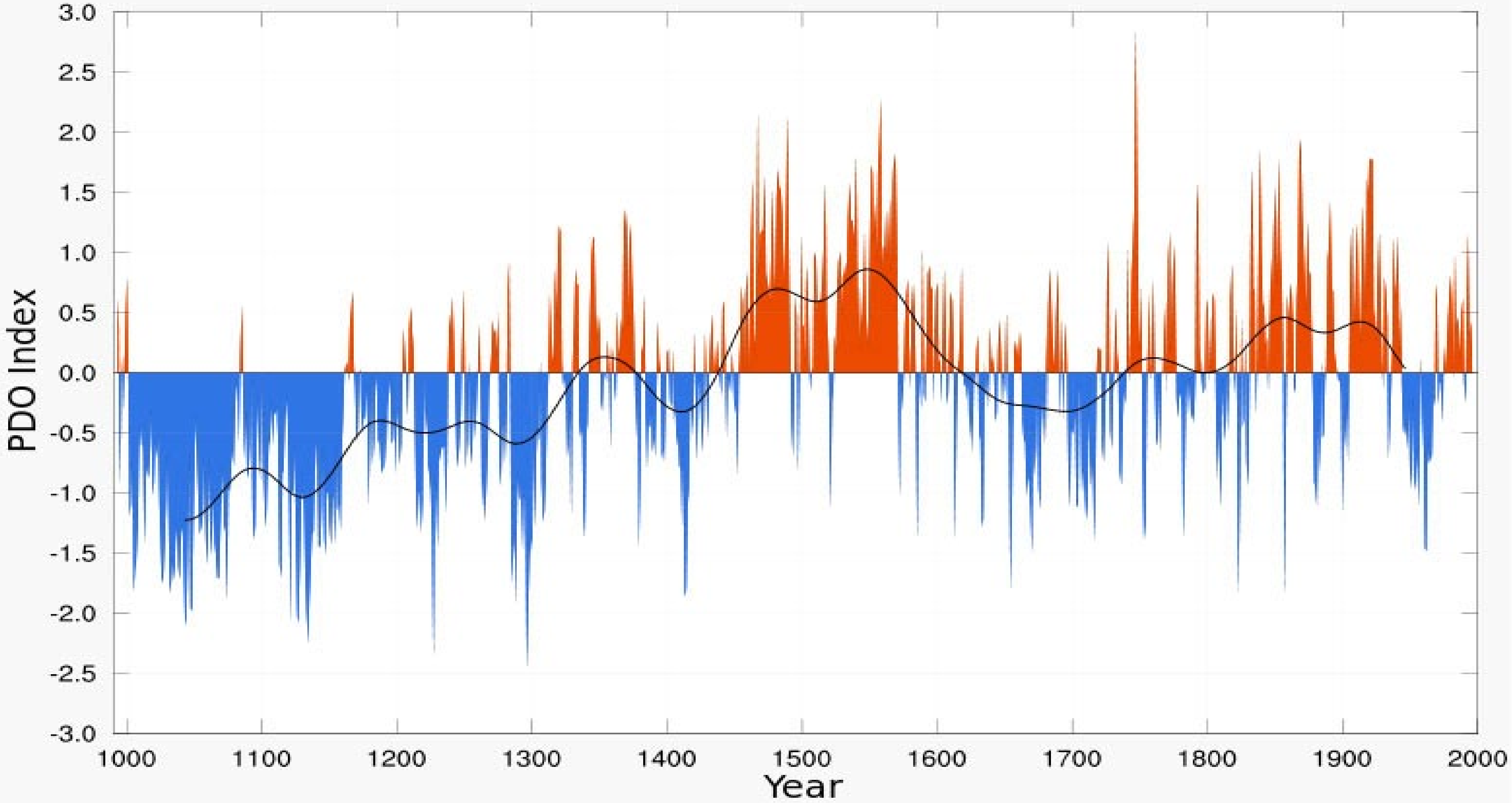


- The **PDO index** is defined as the excess average sea surface temperature in the North Pacific, after removing the monthly global mean sea surface temperature.
- It therefore explicitly removes **global** sea surface temperature long term trends, and therefore clearly cannot be invoked as the cause of "**global** warming".
- There's a conservation of Energy law here: You can't explain a constantly rising ocean temperature by appealing to an oscillation!

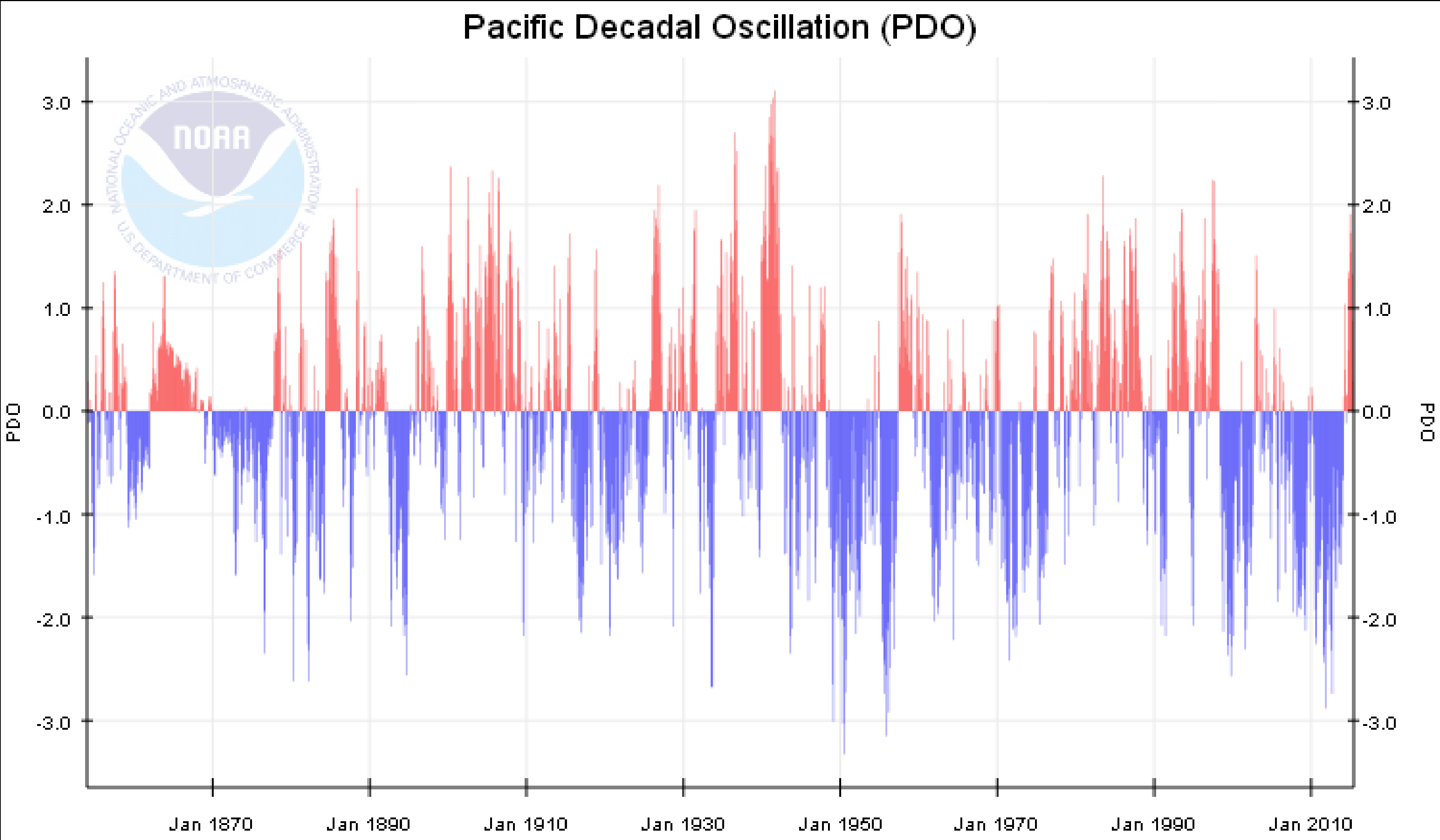
If it sounds messy, that's right.

The PDO pattern is consistent with the atmospheric forcing associated with fluctuations of position and strength of the Aleutian Low (an atmospheric low pressure area south of the Aleutian Islands). In the central North Pacific, a deepened Aleutian low decreases sea surface temperatures by advection of cool and dry air from the north, by increases of westerly winds and ocean-to-atmosphere turbulent heat fluxes, and by strengthened equatorward advection of temperature. In the eastern regions, a deepened Aleutian low enhances poleward winds and leads to warm anomalies of surface temperature.

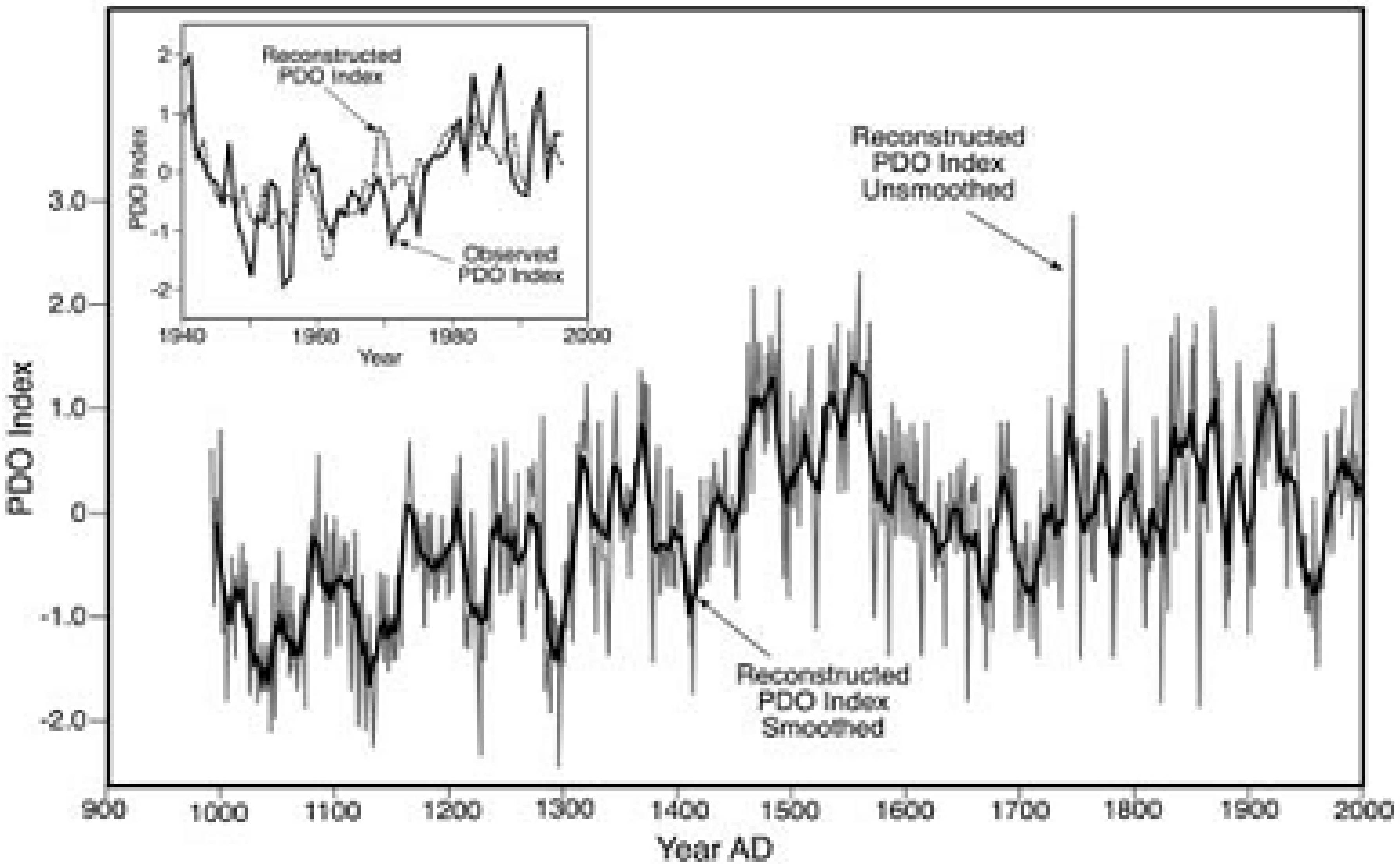
It can be reasonably well modelled only by including 3 different forcings – the El Nino/Southern Oscillation, random forcings from storms on short time scale, and changes in the North Pacific ocean gyre rotational energy



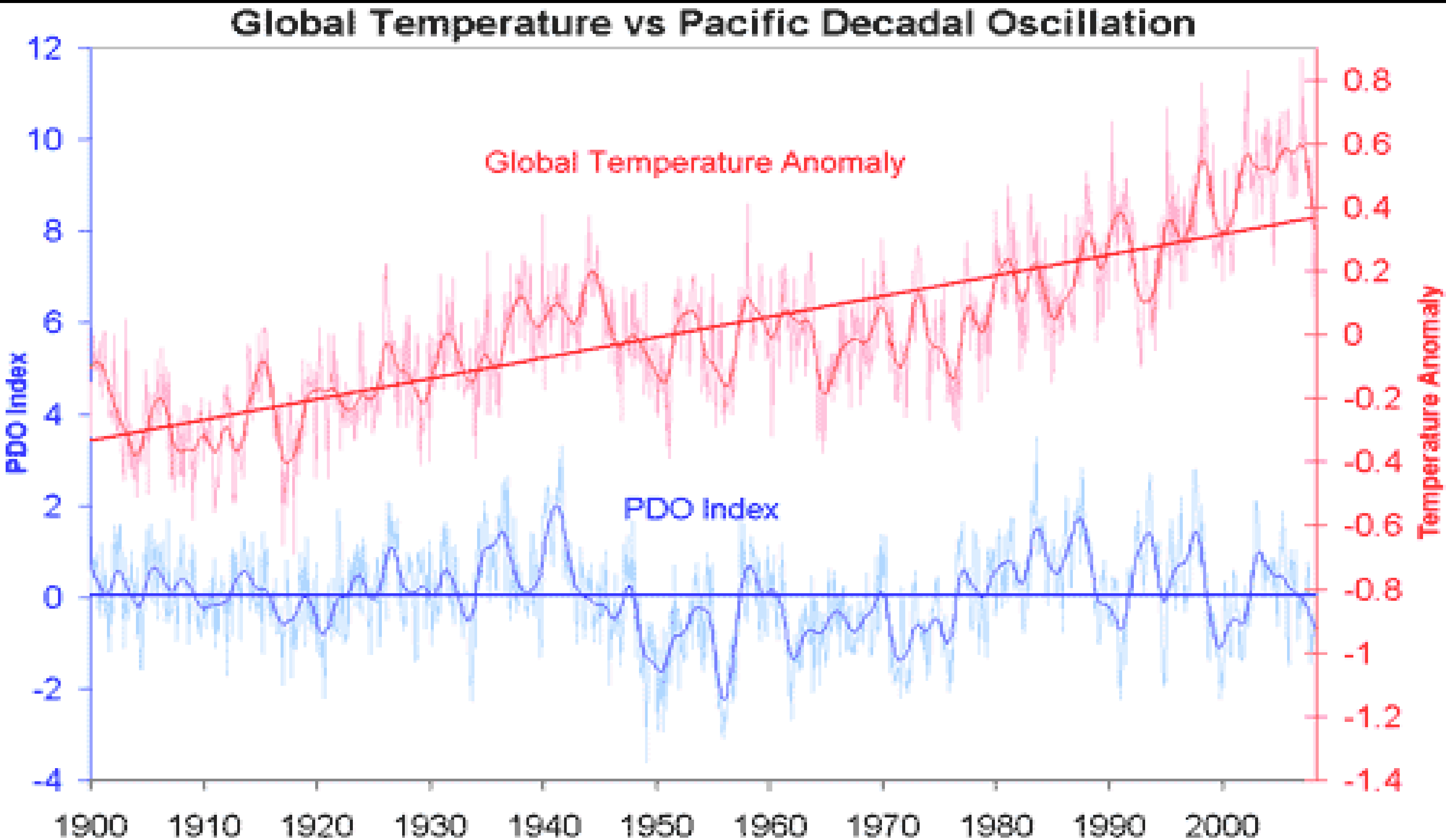
PDO Index - Last 1000 years w/ Proxies: The PDO affects mostly western North America's climate. Using tree ring data from Baja California, calibrated by data in the past century, a proxy for the PDO index can be calculated for the past millenium. It shows little consistent periodicity, and no net trend for the past 700 years.



PDO Index for the past century. **If somehow the PDO, not CO_2, were responsible for rising global temperatures, you'd expect a forcing pattern – the PDO exceeding global temperatures during the past 60 years. In fact, during the past ~25 years, with the best data, the PDO actually had been weakening and only in 2015 re-entered the warm phase**

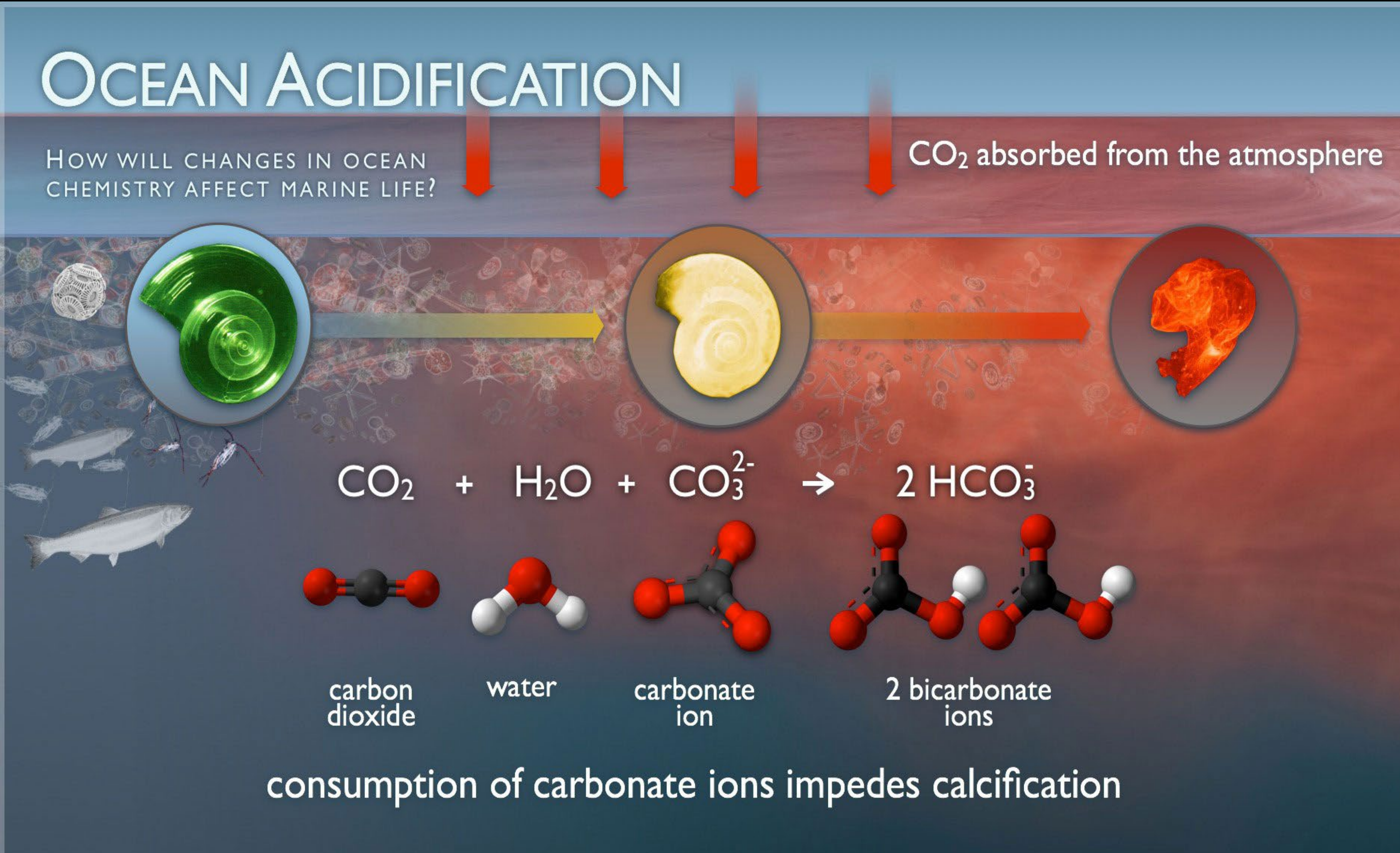


Observed *vs.* proxy PDO, for the past 1100 years. Pretty good match; proxies look good.

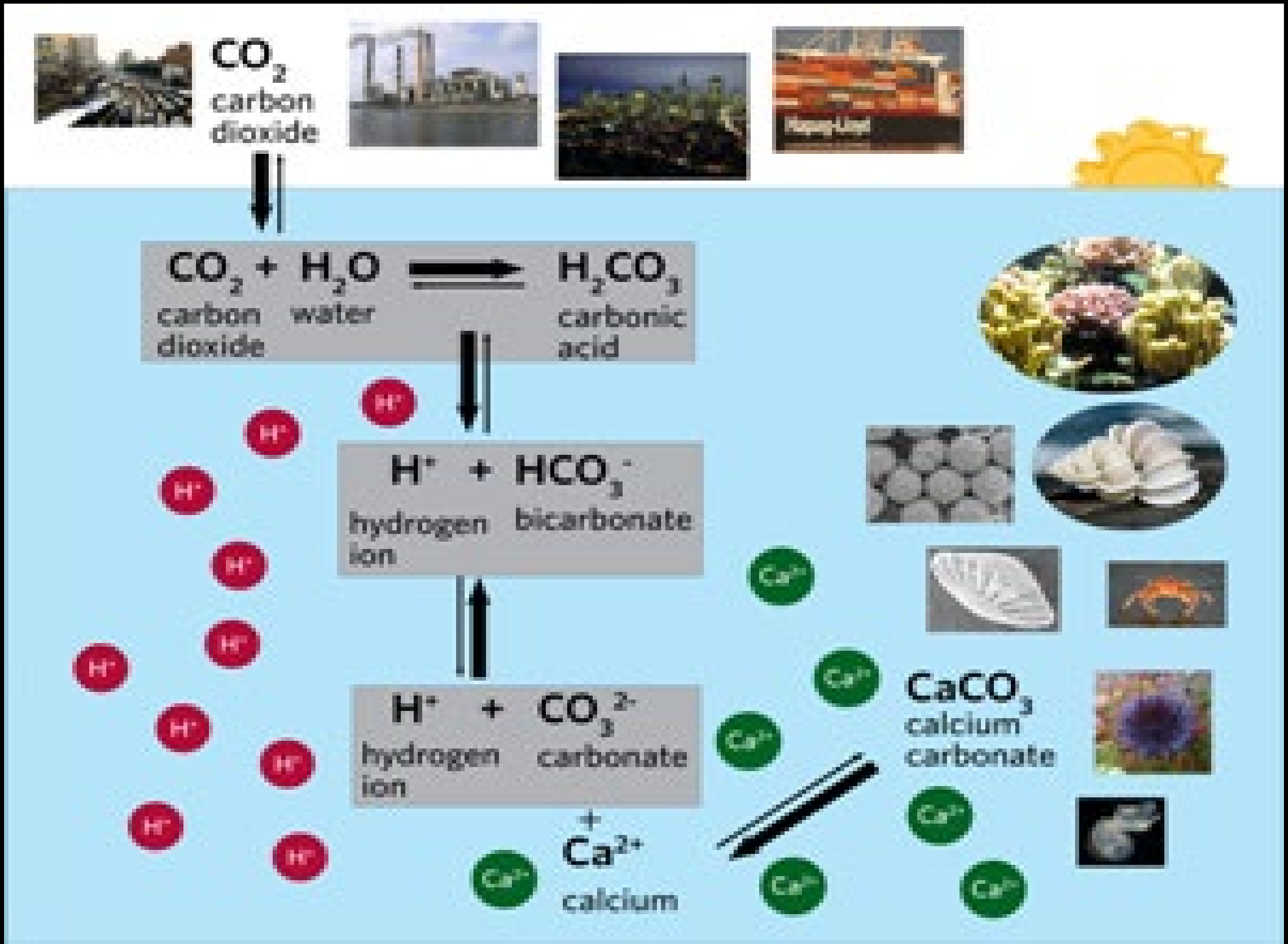


As CO_2 levels rise and more completely dominate climate changes, the mild correlation between the PDO and global temperatures weakens by the mid '80s. Conclusion: PDO influence on climate is much smaller than the 20^th Century main driver: Greenhouse Gases

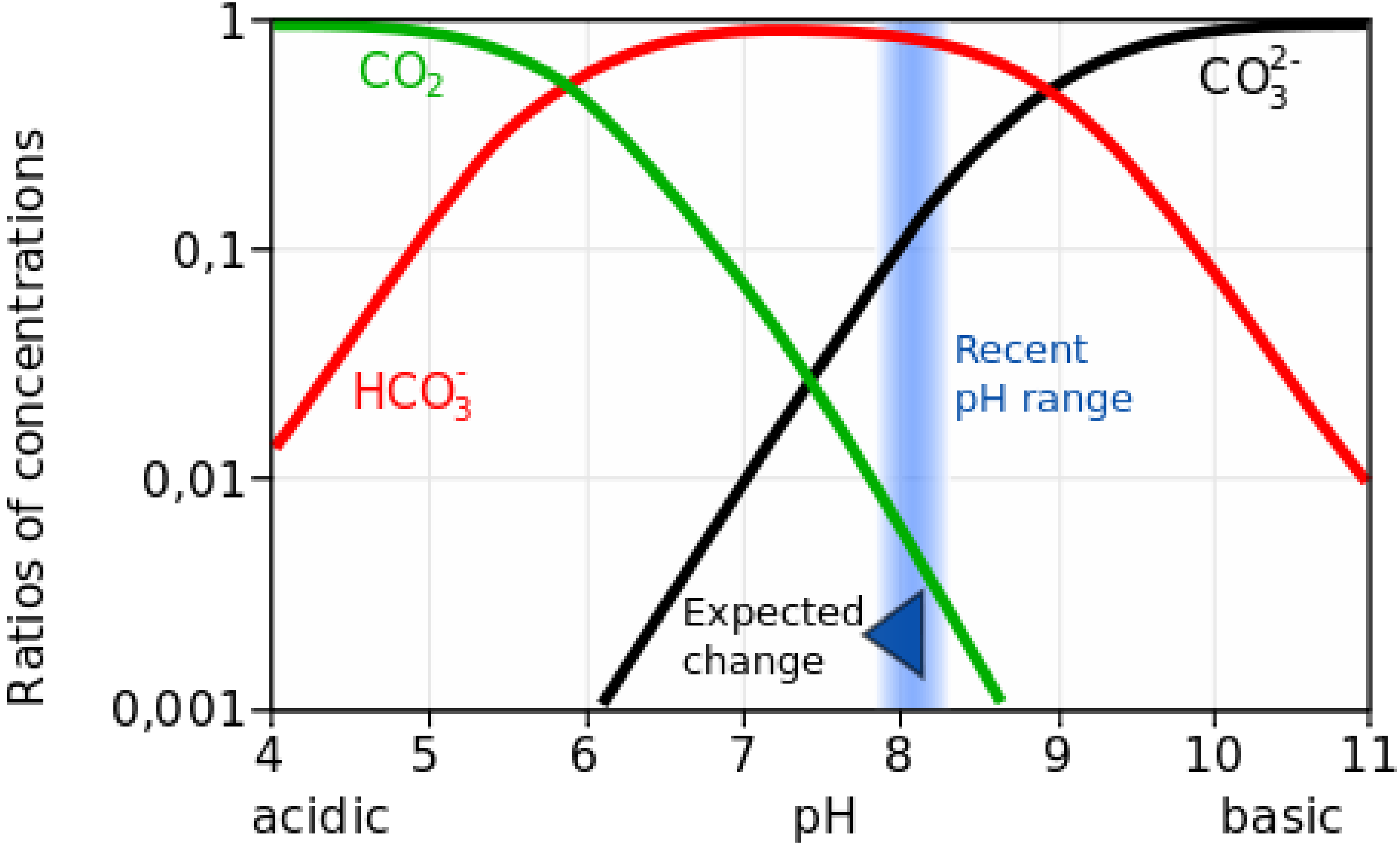
Chemical Interactions - Oceans And the Atmosphere



Raising ocean acidity means more H+ ions, which combine with carbonate ions to produce bicarbonate, and thus prevent those carbonate ions from instead combining with Ca in metabolism of phytoplankton, algaes, and sea animals to produce CaCO3 = seashell

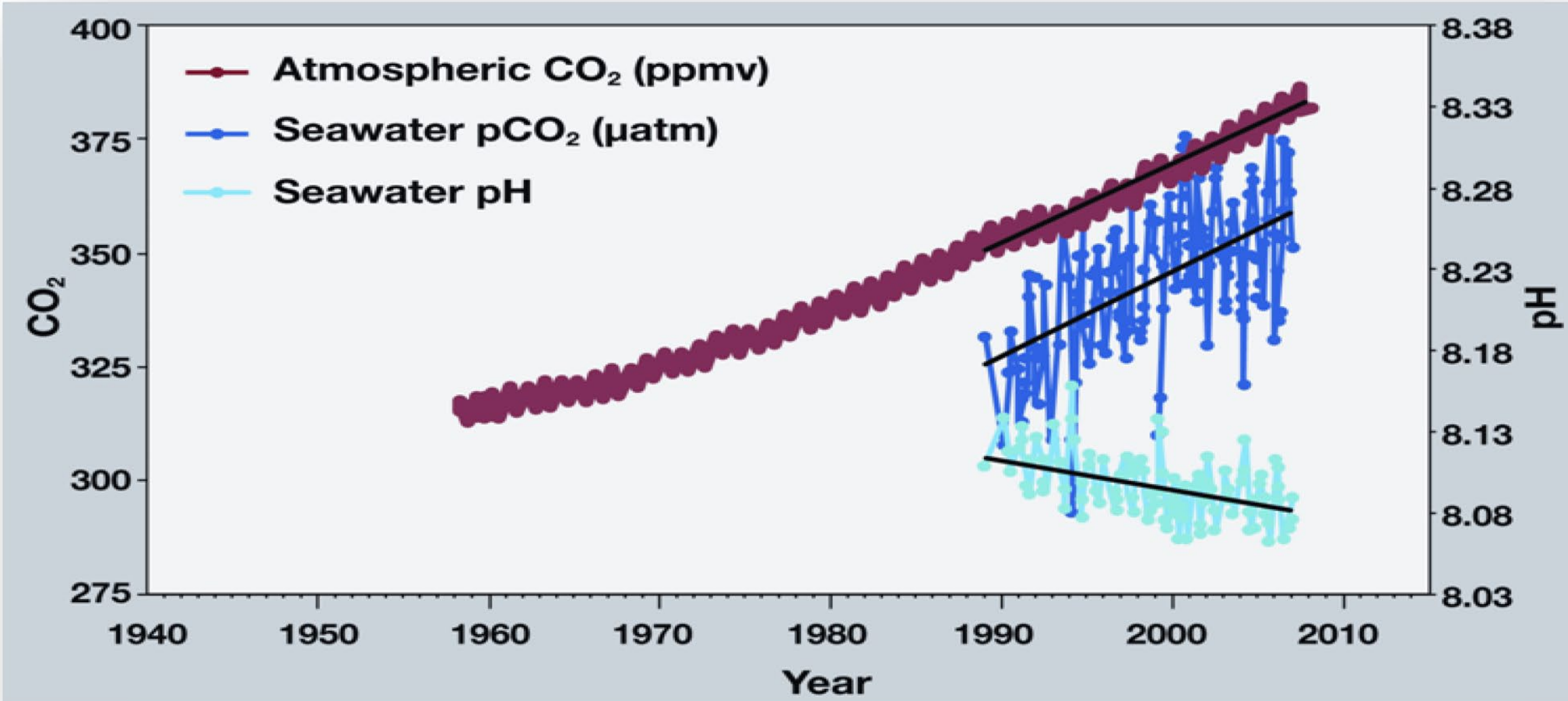


At increasing acidity, equilibrium shifts away from formation of carbonate and towards CO2 + carbonic acid



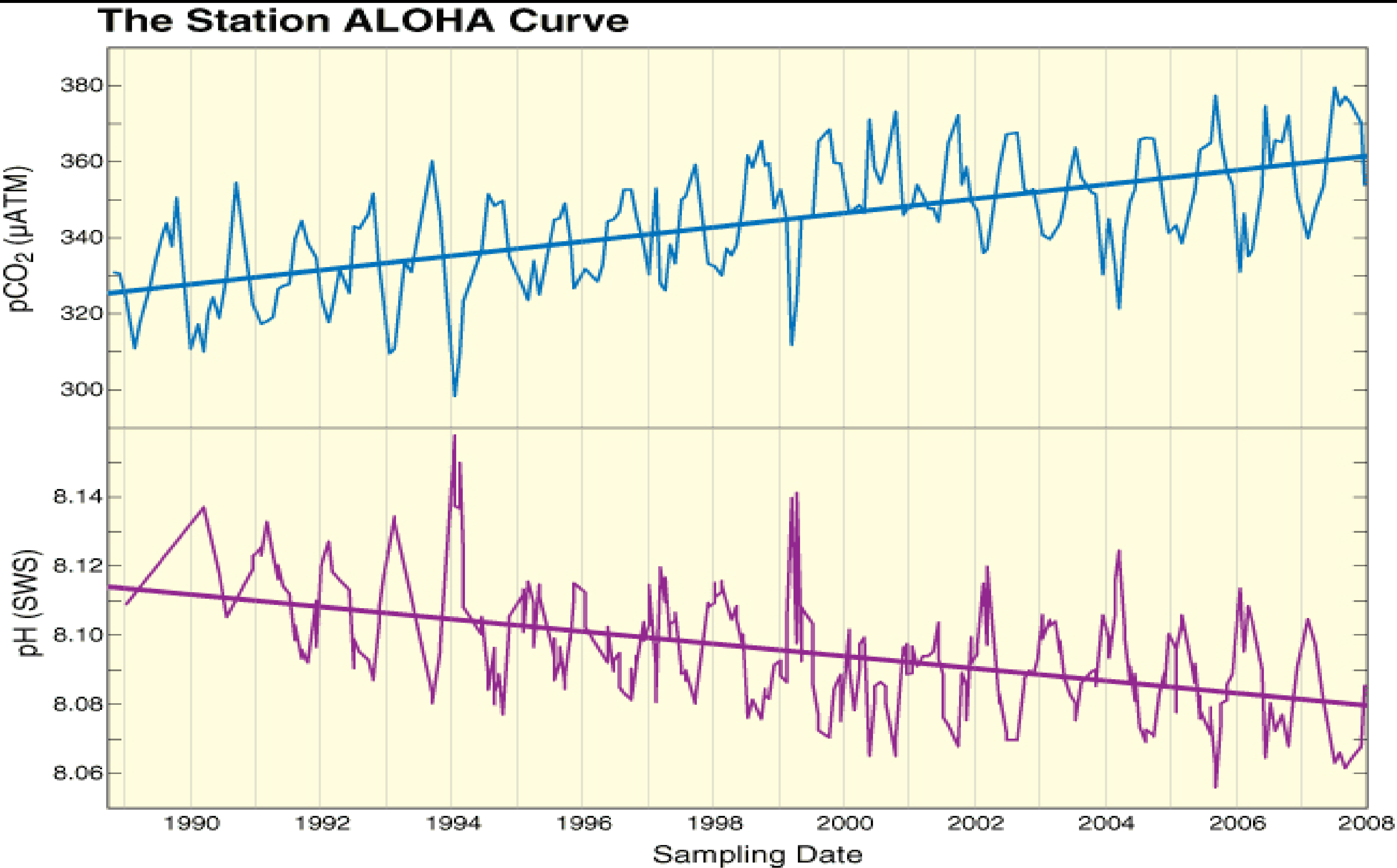
Some Web Links To Check Out

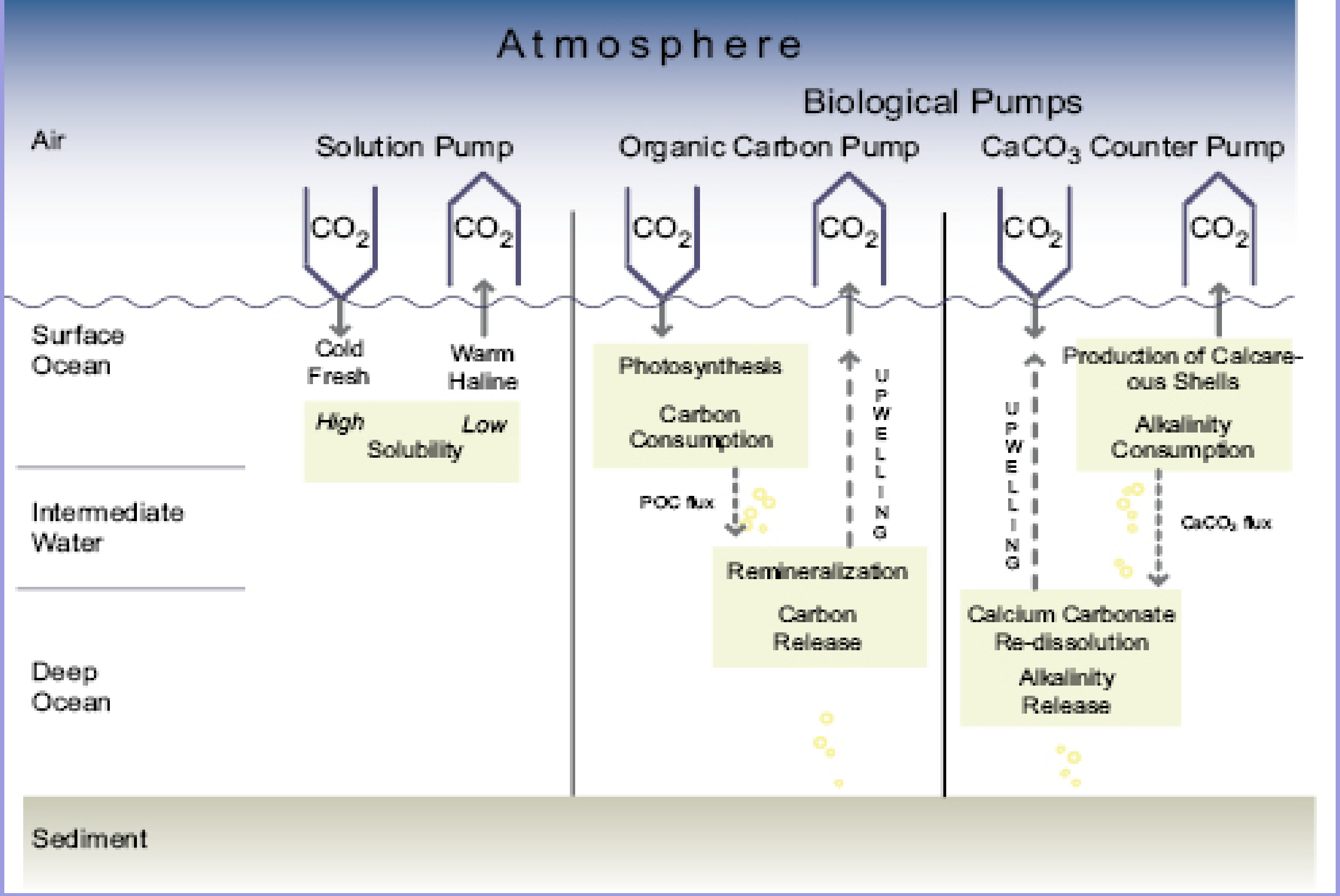
- Good primer from NOAA on how rising CO2 raises the level of acidity of the oceans
- 4 min Video on acidification; data, consequences
- The current rate of change in the ocean's pH is 100 times faster than any time in the last few hundred thousand years and is most likely unprecedented in the Earth's history (oceana.org)



This graph shows the correlation between rising levels of carbon dioxide (CO_2) in the atmosphere at Mauna Loa with rising CO_2 levels in the nearby ocean at Station Aloha. As more CO_2 accumulates in the ocean, the pH of the ocean decreases. (Modified after R.A. Feely, Bulletin of the American Meteorological Society, July 2008)

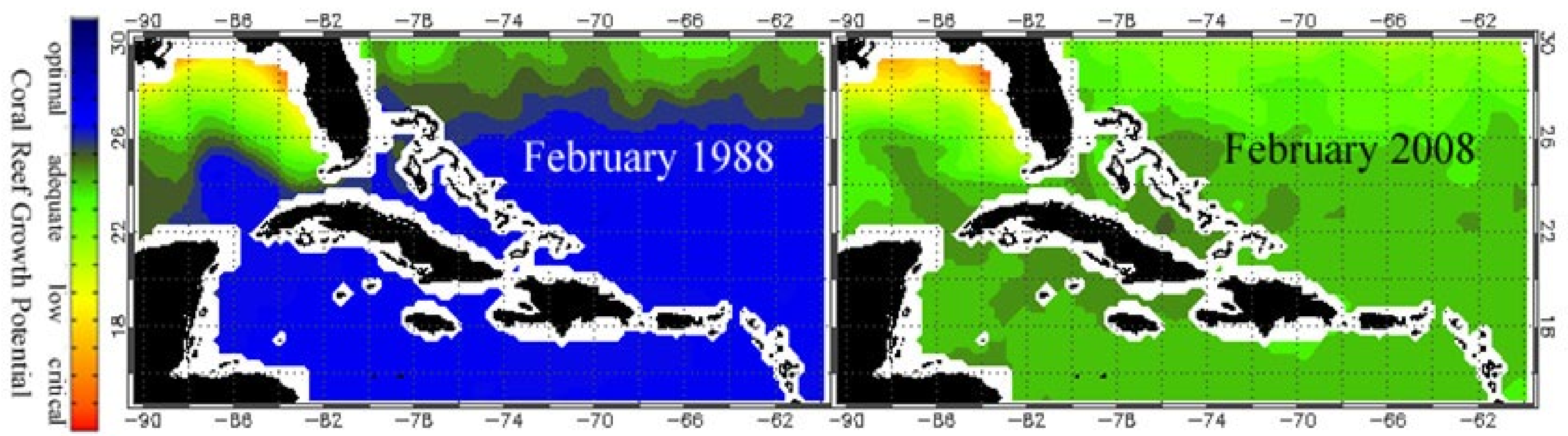
Rising CO2 goes with falling (more acidic) pH: Partial pressure of CO2 in the ocean *vs.* ocean pH (note seasonal oscillations due to phytoplankton blooms, mostly). CO2 pressure has risen by fully 10% in just the past 18 years, as pH falls. Strong correlation even on very short time scales, at the surface

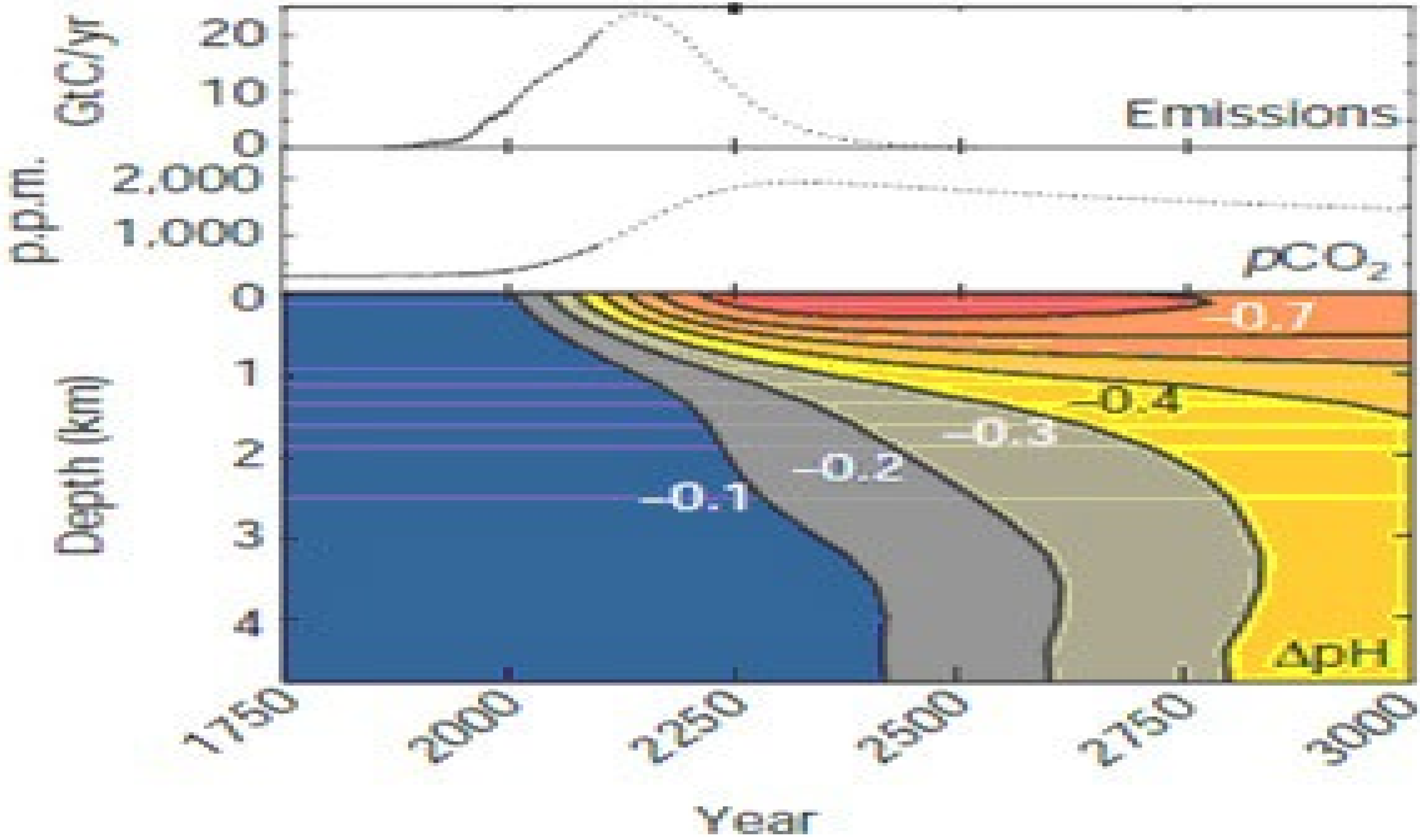




Three main ocean carbon pumps govern the regulation of natural atmospheric CO2 changes by the ocean (Heinze *et al.,* 1991): the solubility pump, the organic carbon pump and the CaCO3 'counter pump'. The oceanic uptake of anthropogenic CO2 is dominated by inorganic carbon uptake at the ocean surface and physical transport of anthropogenic carbon from the surface to deeper layers. For a constant ocean circulation, to first order, the biological carbon pumps remain unaffected because nutrient cycling does not change. If the ocean circulation slows down, anthropogenic carbon uptake is dominated by inorganic buffering and physical transport as before, but the marine particle flux can reach greater depths if its sinking speed does not change, leading to a biologically induced negative feedback that is expected to be smaller than the positive feedback associated with a **slower physical downward mixing of anthropogenic carbon.** Reprinted with permission, copyright 1991 American Geophysical Union.

pH in the Caribbean Sea; prime habitat for coral reefs – past 20 years. Clearly, becoming more acidic. Large shift in marine species to be expected in our future, as corals and other aragonite-forming species disappear. See more in "Current Climate Change" PowerPoint series





pH of the ocean *vs* depth, for the next 1,000 years, with CO2 emission “business as usual” scenario, until we run out of economical fossil fuels in a ~century. Acidity slowly percolates to the deep ocean on long time scales. Source: Carnegie Institute

Long Term Effects on Ocean/Atmosphere Carbon Transport and Biology?

- Biological feedback is complex and poorly understood….
- What species will take over niches occupied by aragonite species?
- How well will they sequester carbon? Likely not as well as mineralized $CaCO_3$ now
- As the thermohaline boundary is expected to become stronger due to both melting continental ice freshening and lightening surface waters and also heating/expansion of surface waters, this will further inhibit vertical transport, and may well shut down the entire ocean thermohaline circulation
- Likely – large turnover in species occupying ocean, primary productivity changes for the worse.
- **-> A very different ocean environment.** These processes implicated in the Permian Mass Extinction – the biggest mass extinction in Earth's history, with 95% of all life going extinct

Ocean's Oxygen Rapidly Dropping Due to Heat, Pollution

- New work (**Ito *et al.* 2017**) discussed **here**) find that oxygen levels are dropping in the ocean nearly 3x faster than models predicted.
- Likely cause – minerals from Asian air pollution covering ocean, seeding algae blooms whose secondary effect is rapid depletion of oxygen out of surface waters. Also, hotter water will hold less O_2 in solution.

A Look Ahead…at Harsh Justice

- The massively large amount of Human-generated greenhouse heat already absorbed by the ocean is a key reason why, if even if we halt CO_2 emissions, global temperatures will NOT be able to go back down for thousands of years – The ocean has 700 times more thermal capacity than the atmosphere
- **Nature's Lesson: The ocean absorb-ith (our heat), and the ocean re-give-ith (our heat) if we try to cool Earth.**
- ***"That which you sowed, so shall ye reap." (Galatians VI)***

K36 Key Points: Ocean/Atmosphere

- **93% of global warming heat since 1955 is now in the oceans
- Water's hydrogen bonds give it very high thermal capacitance; sea surface temps risen less than half as much as air temps
- Oceans well mixed for only the top <~90m (still takes ~6 yrs to equilibrate with atmosphere at this depth), and 1000 years to mix all throughout.
- **Without ocean heat uptake, human-induced greenhouse warming of atmosphere leads to raising surface temps not 1.5F but 36C= 65F – 45 times higher temperature change!
- **CO_2 solubility in seawater drops with increasing temperature – warming waters have decreasing ability to absorb atmospheric CO_2
- CO_2 we force into the atmosphere, some slowly dissolves in ocean, raising acidity.
- Rising acidity (=consumption of carbonate ions), inhibits carbonate formation within sea plants and animals.
- Thermocline – a boundary between top layer of warm temperature, lower density water which inhibits mixing of top with deep layers
- Ice formation raises ocean salinity as ice cannot incorporate salt. Saltier water is denser, aiding falling through thermocline at high cold latitudes – thermohaline ocean circulation, which distributes heat from tropics toward poles and across the globe. Melting ice LOWERS Salinity in the Arctic, making it less dense, and harder to push down through the Thermocline
- Wind changes a prime cause of ocean current changes. High mass of ocean means long period of these changes; one to several years – El Nino/Southern Oscillation
- AMO = Atlantic Multi-Decadal Oscillation: defined by sea surface temps alone (not winds etc) and proper calibration indicates it is at most a minor contributor to climate change warming in recent decades.
- Pacific Decadal Oscillation (PDO) has shown no net trend for more than a century, it is not responsible for Global Warming, only oscillates on top of it.
- El Nino/La Nina (ENSO) oscillation has very roughly 5 year period, much too short to account for century-long rise in global temperatures.
- El Nino: weaker equatorial winds-> inhibit upwelling->hotter surface ocean and Earth Climate
- Arctic melting should produce, on average, less salty and therefore less dense surface waters, inhibiting thermohaline circulation in general, and the Gulf Stream as an example.