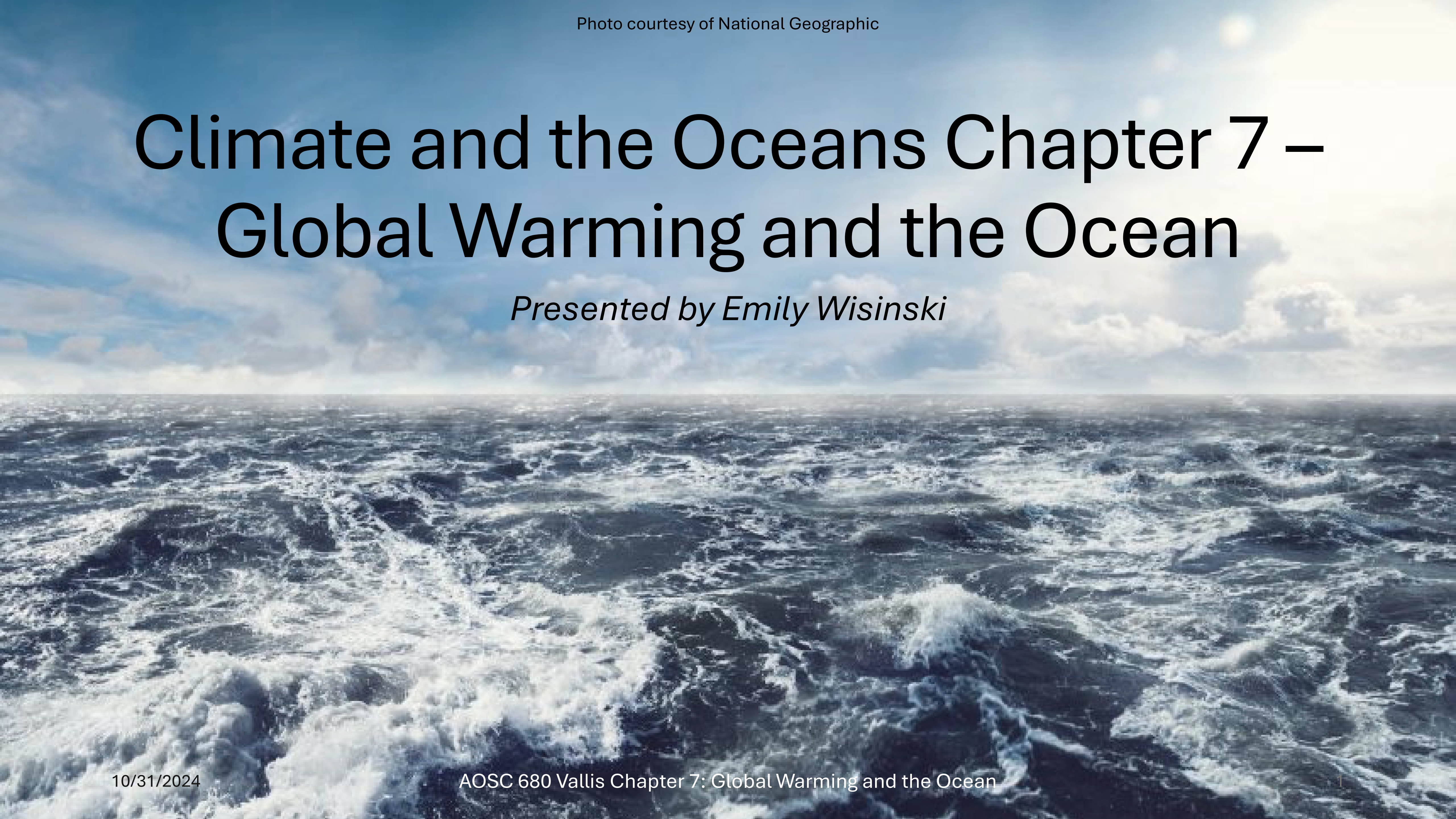


Photo courtesy of National Geographic

Climate and the Oceans Chapter 7 – Global Warming and the Ocean

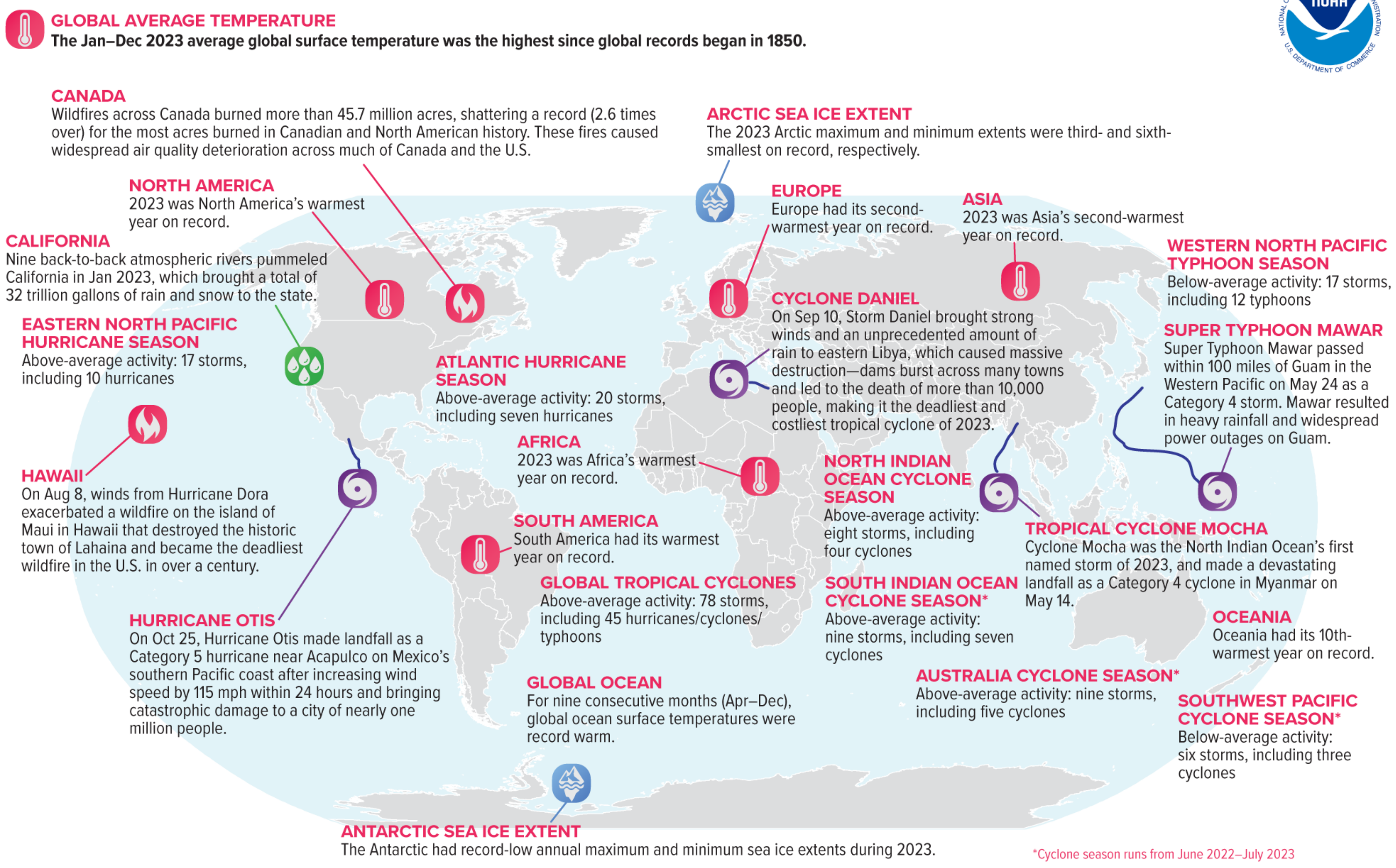
Presented by Emily Wisinski

Learning Outcomes

- ✓Discuss sources of error in the global surface temperature records
- ✓The modern thermometer
- ✓How satellites collect temperature measurements
- ✓How proxy data is used for temperature reconstructions
- ✓Human fingerprints of carbon dioxide
- ✓How ocean heat content is measured
- ✓How the deep ocean will equilibrate
- ✓Fingerprint of AMOC weakening
- ✓Sea level rise by thermal expansion and melting of ice sheets
- ✓How we track sea ice extent and concentration

Selected Significant Climate Anomalies and Events: Annual 2023

"The name "global warming" is useful…No where will be unaffected, nothing will be impervious, no one will be immune."
-Vallis

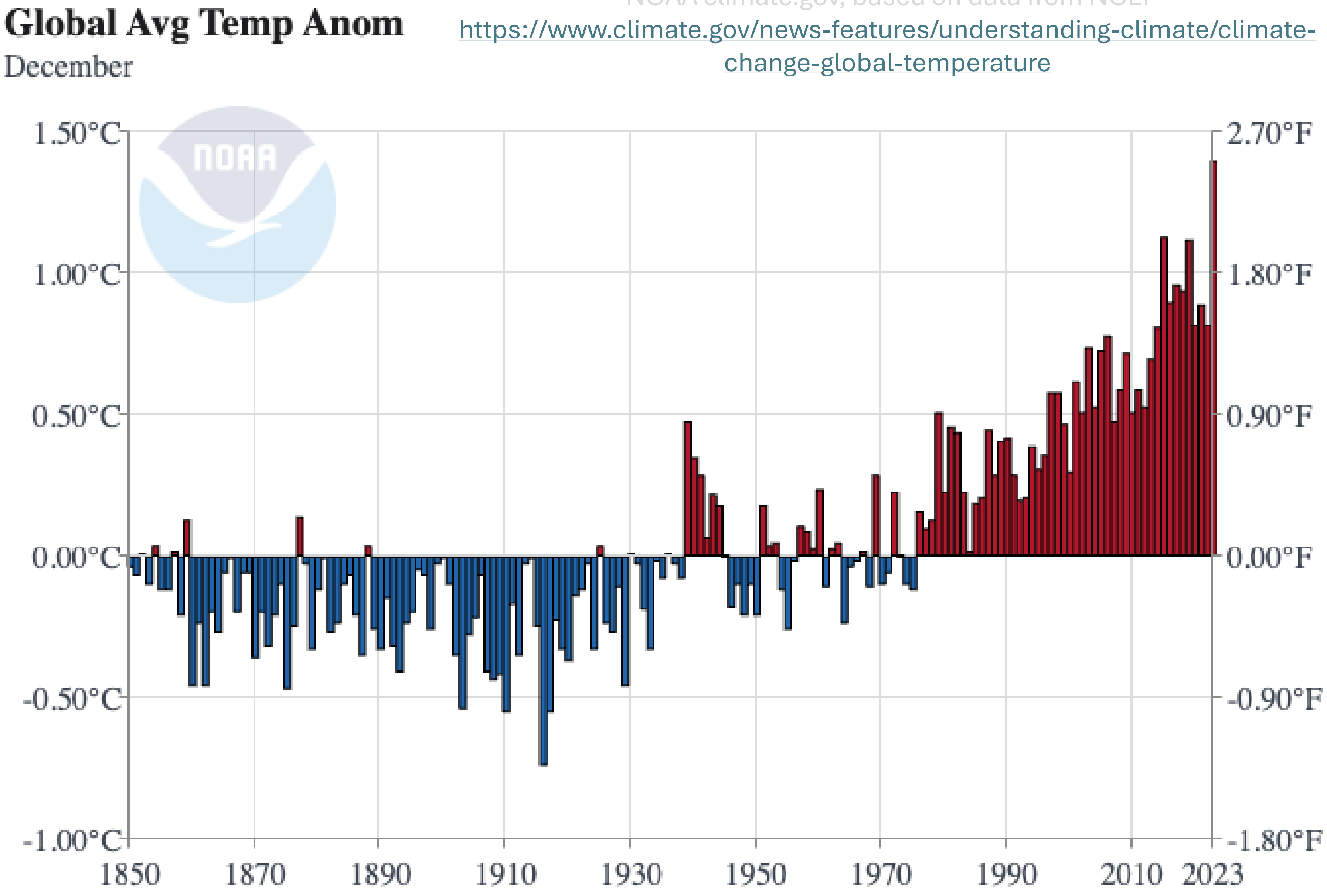


Please note: Material provided in this map was compiled from NOAA's State of the Climate Reports. For more information please visit: https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/

Observed Global Average Surface Temperature

What overall trend do we see here?

Updated Figure 7.1 from Vallis Ch 7. (1850-2023)
NOAA climate.gov, based on data from NCEI
https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature



Observed Global Average Surface Temperature

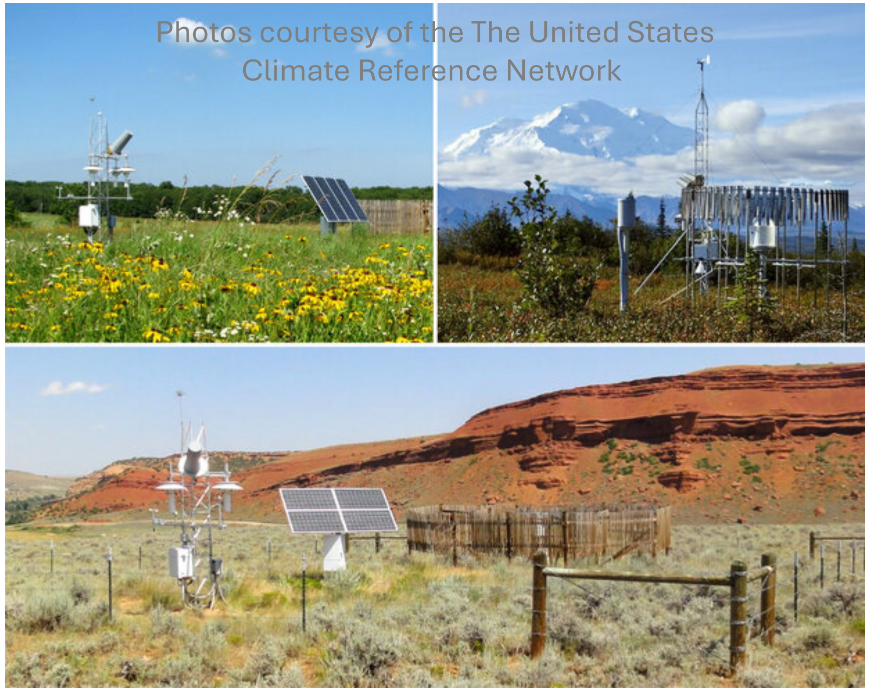
Weather stations collect data 1-2x daily across the globe

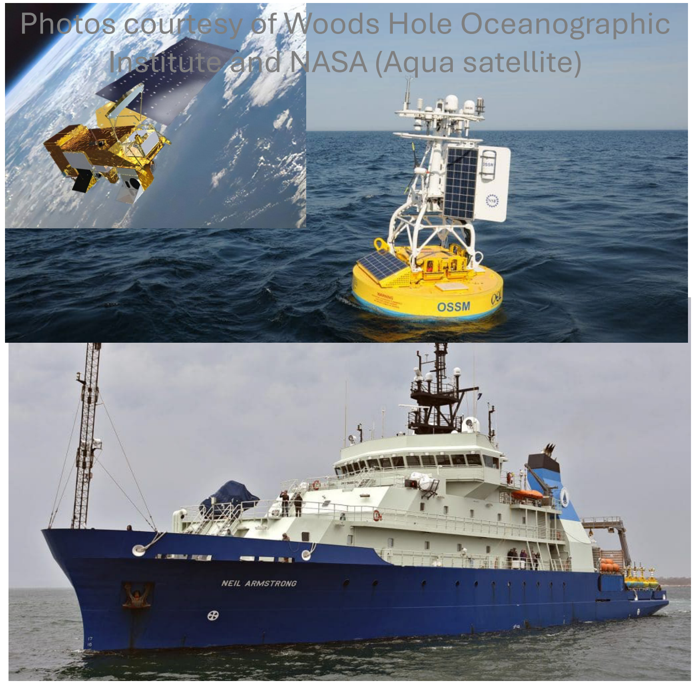
→

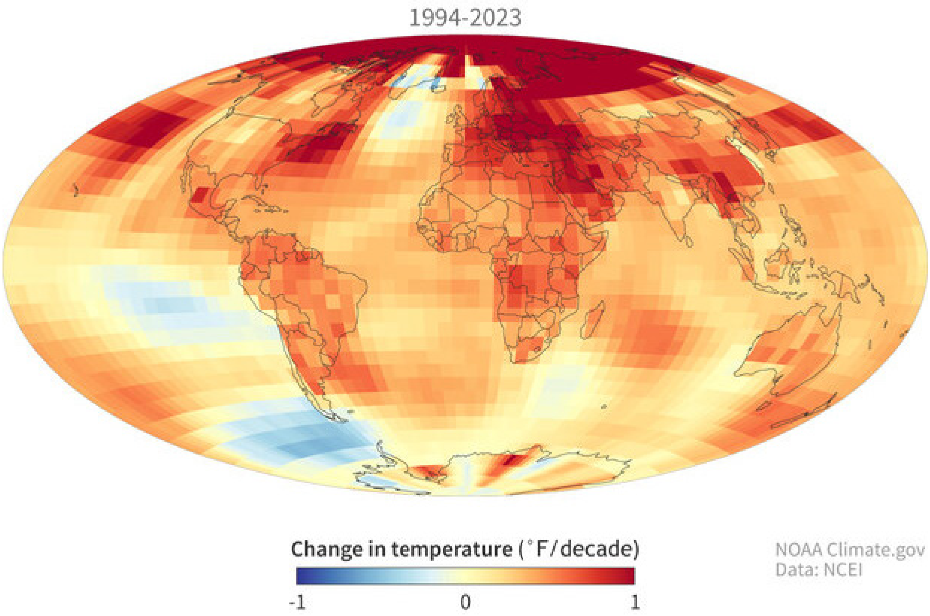
Ocean data comes from in-situ observations (e.g., ships, buoys, & satellites)

→

Data is interpolated onto a regular grid for temperature constructions

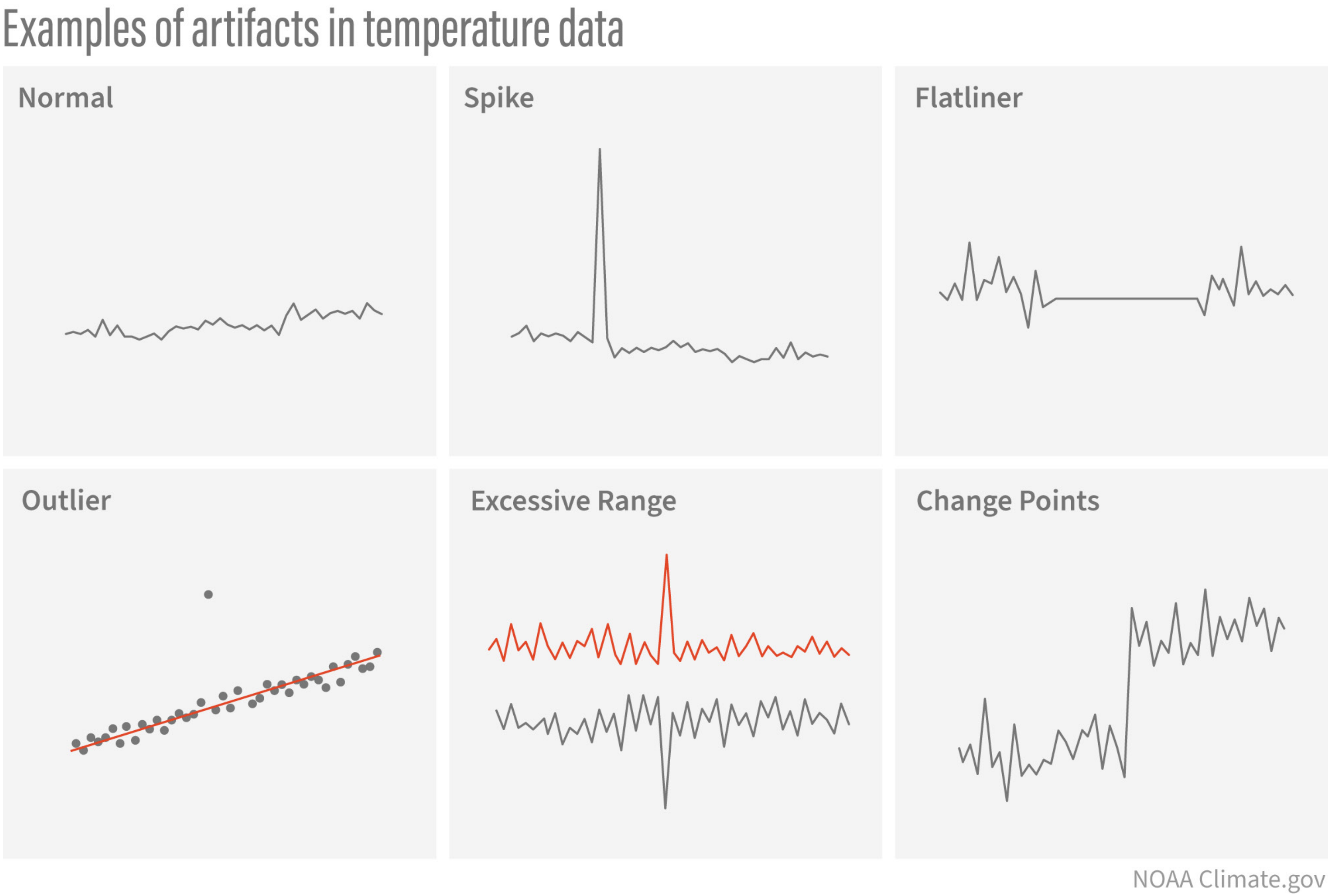


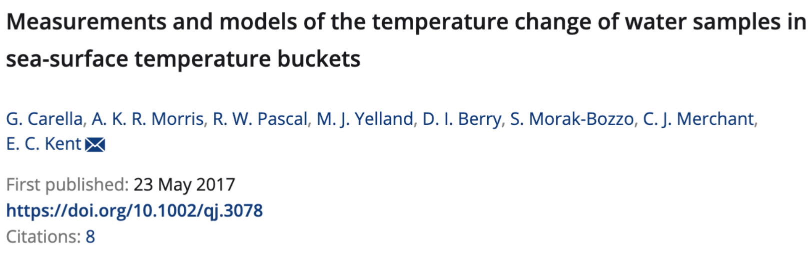


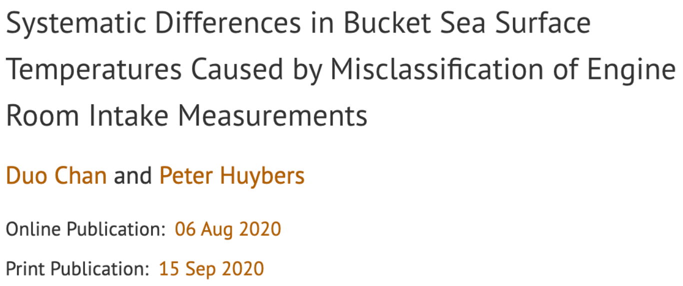


Sources of Error

What are three potential sources of error Vallis discusses?



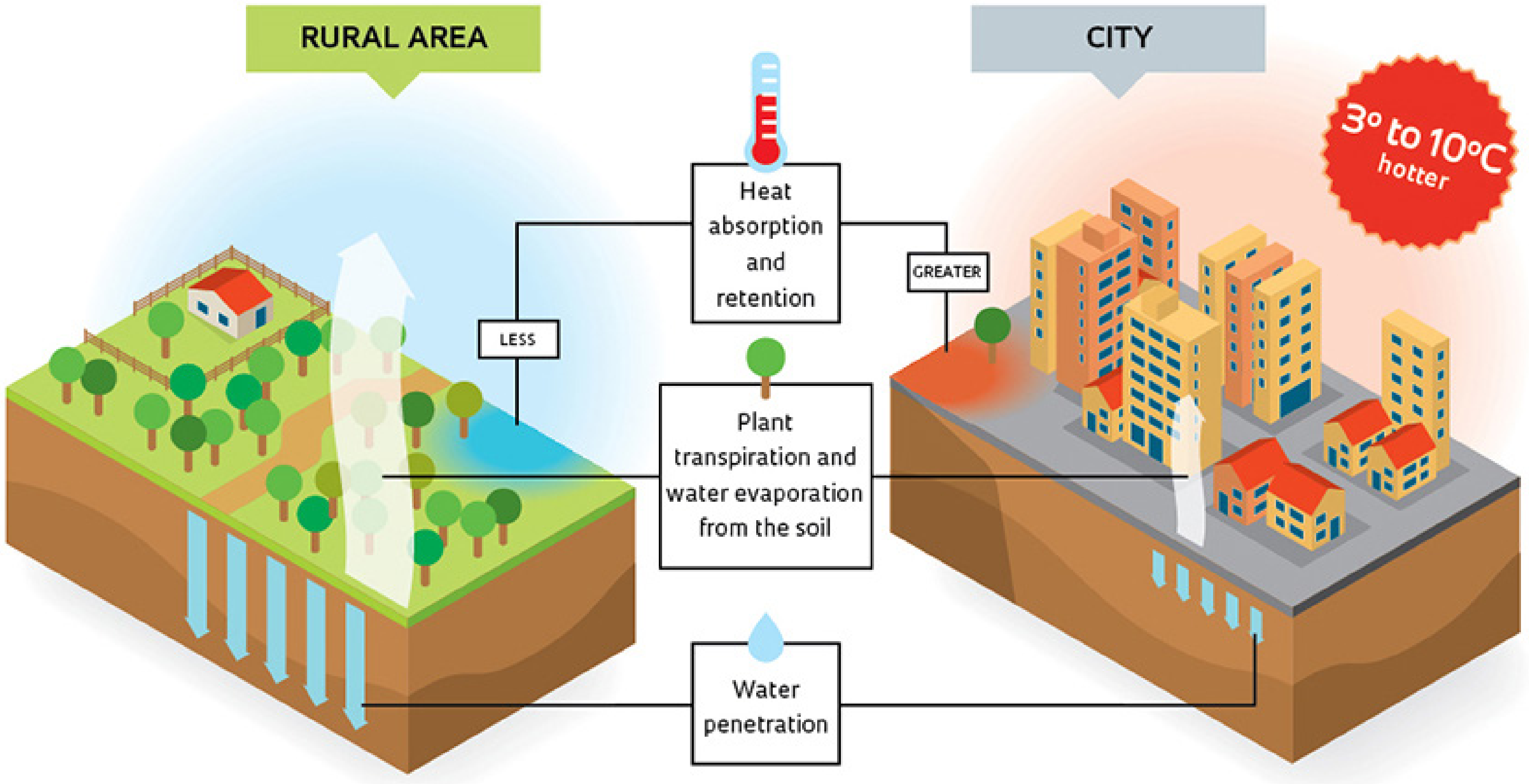




Urbanization / The Urban Heat Island Effect

How do scientists disentangle the actual warming of a localized region impacted by urbanization?

Urban Heat Island Effect graphic, Alexandre Affonso



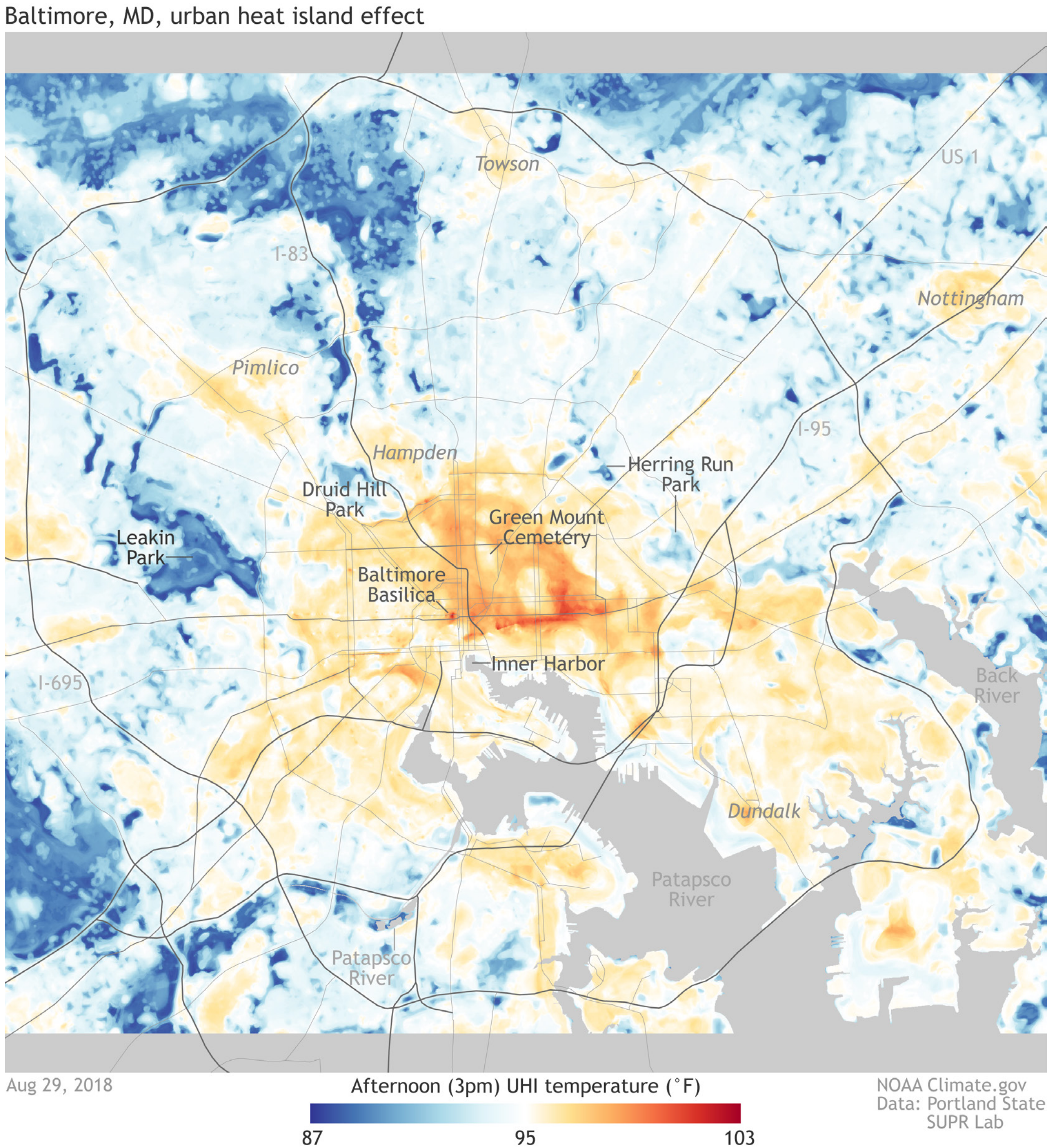
Research Article | Open Access

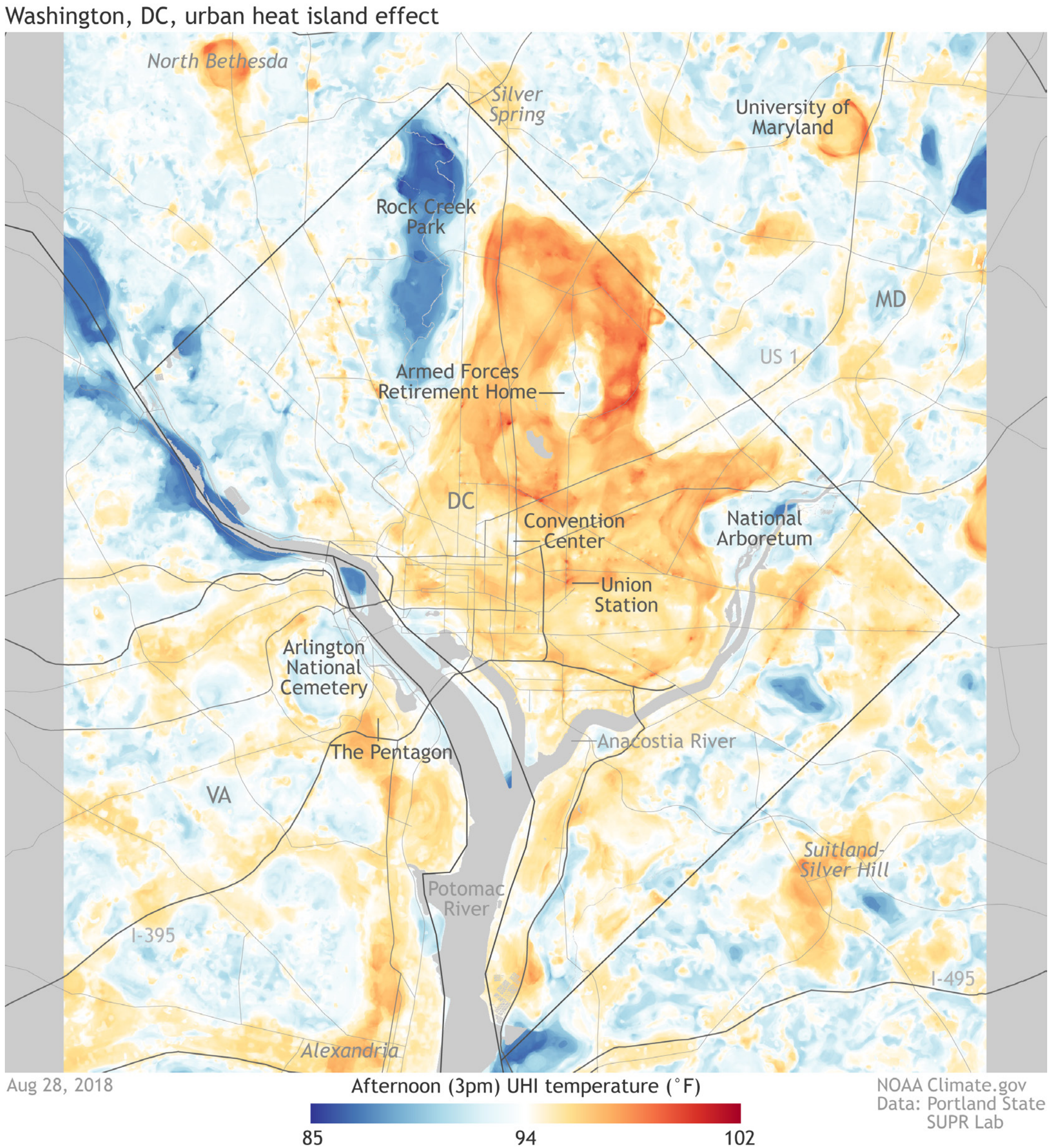
Urbanization Contributes Little to Global Warming but Substantially Intensifies Local and Regional Land Surface Warming

Decheng Zhou, Jingfeng Xiao, Steve Frolking, Liangxia Zhang, Guoyi Zhou

First published: 04 May 2022 | https://doi.org/10.1029/2021EF002401 | Citations: 15

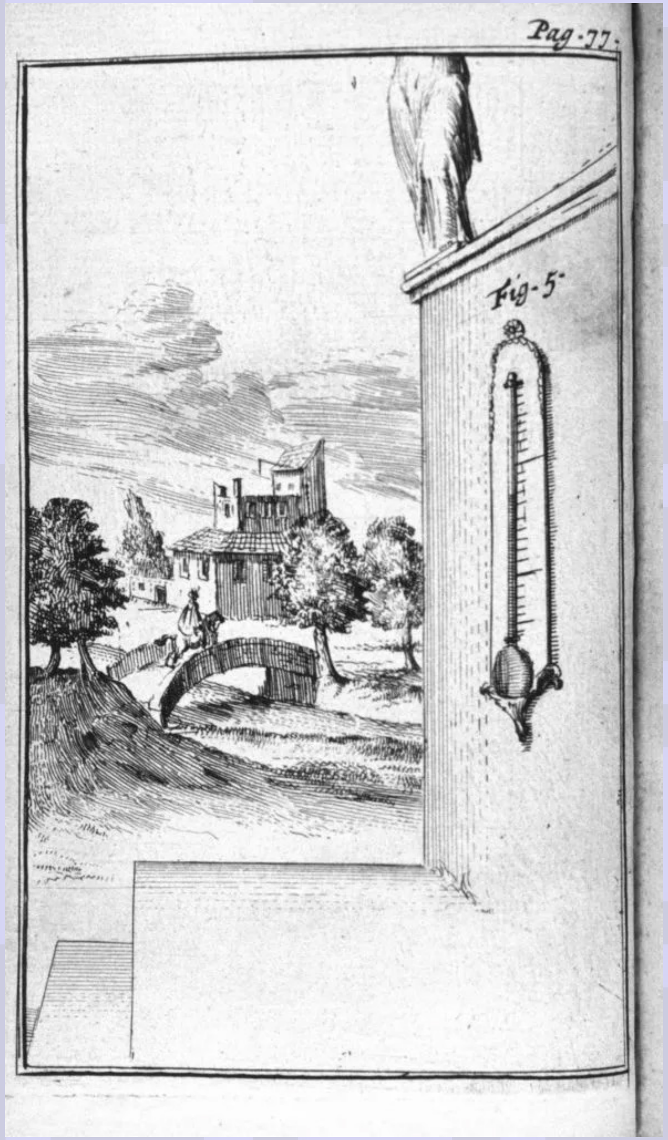
Urbanization / The Urban Heat Island Effect





The Thermometer

- ***Who invented the first thermometer with a scale? What year?***
- ***Who invented the first thermometer calibrated to the freezing and boiling points of water? What year?***
- ***Who invented the thermometer design with mercury? What year?***
- ***Lastly, who invented the thermometer calibrated to the freezing and boiling points of water at sea level? What year?***



Thermometer on an outside wall in 1688, Joachim d'Alence
https://time.com/6053214/thermometer-history/

The Modern Thermometer

- Invented by Daniel Gabriel Fahrenheit in 1714, mercury glass tube with a standardized scale running up the side
- The thermometer, barometer, and hygrometer were key parts of the formal weather station (Stevenson screens), first installed in Europe and the US in the 1800s
- Our temperature record begins in 1850

A Stevenson screen, containing meteorological instruments. Credit: Universal Images Group North America LLC / DeAgostini / Alamy Stock Photo.

Satellite Measurements

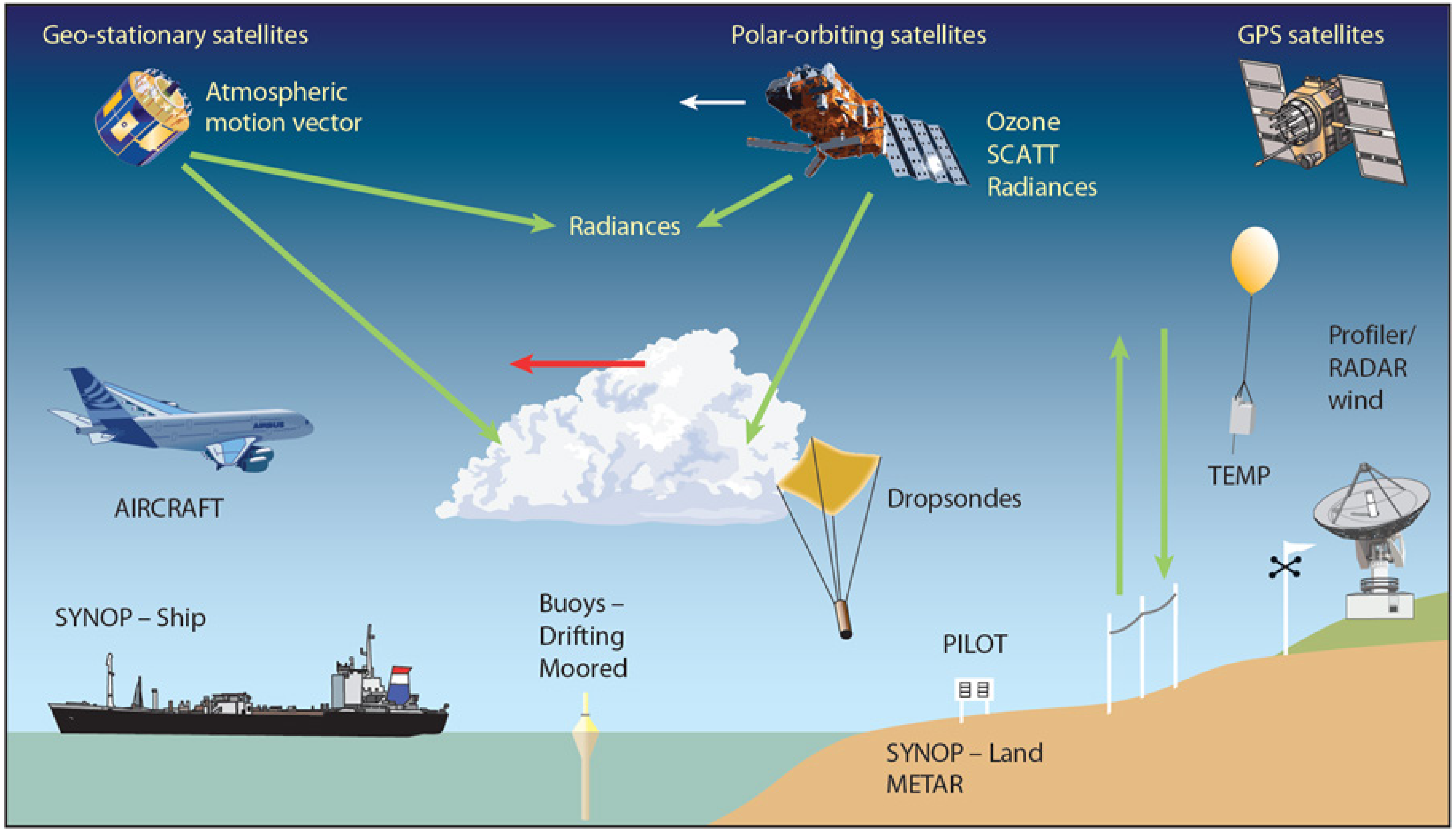
What are some pros and cons of satellite measurements?

Pros	***Cons***

How Do Satellites Measure Temperature?

- → Measurements taken with a microwave and infrared sounder
- → The brightness in each band is sensitive to temperature and water vapor
- → Multiple bands creates a temperature profile

Figure courtesy of ECMWF



Satellite Measurements

What trends do you notice?

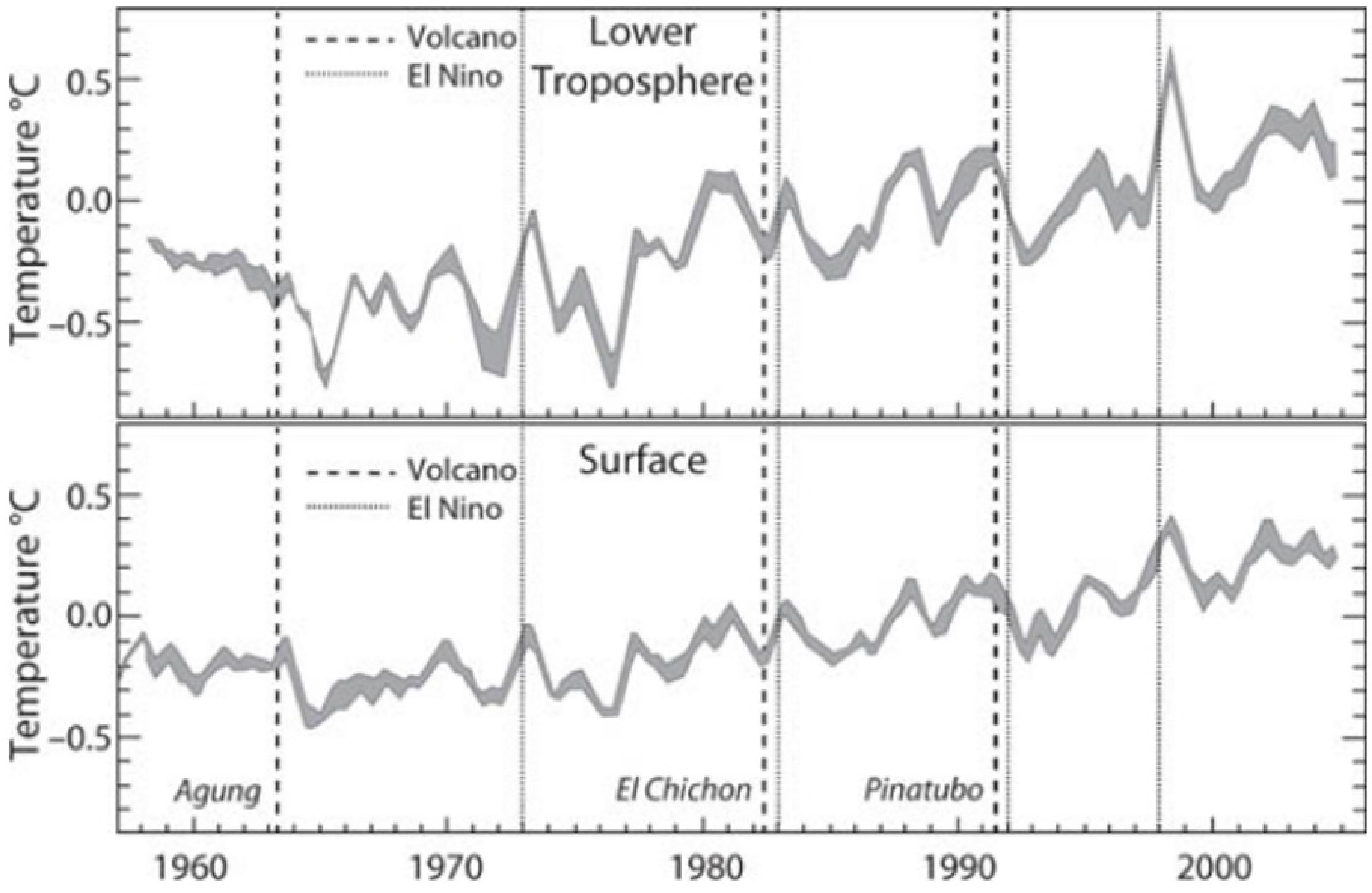
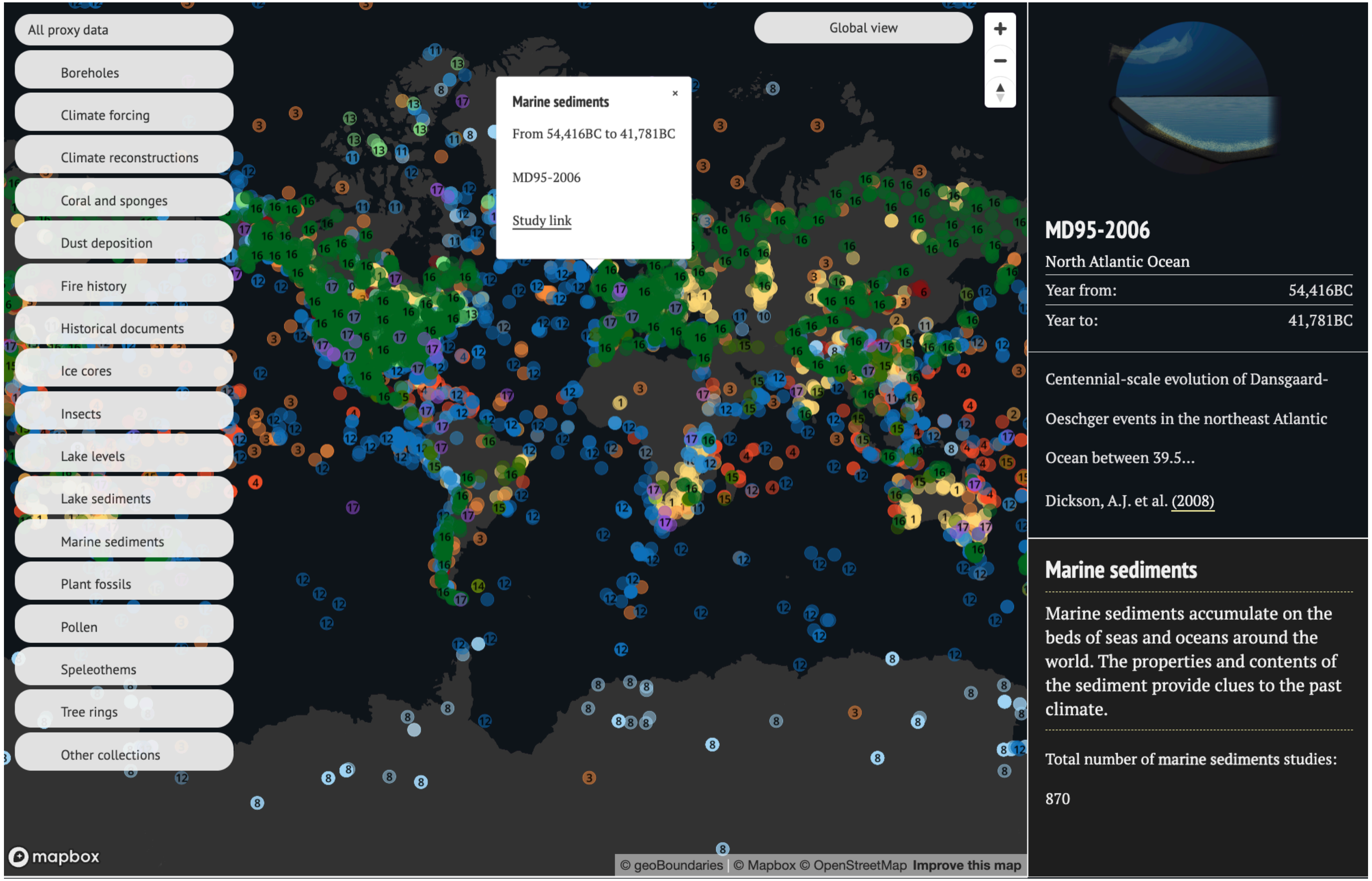


Figure 7.2. Top: Lower troposphere temperature as measured by various satellites and by radiosondes; the gray shading indicates the spread between all measurements. Bottom: Surface temperature records from NOAA, NASA, and UKMO, with gray shading again indicating the spread. Records are monthly means, smoothed with a seven-month running mean filter, and are relative to 1979–1997 mean. Adapted from Solomon et al., 2007.

Proxy Data

Amazing interactive tool to learn about proxy data! https://interactive.carbonbrief.org/how-proxy-data-reveals-climate-of-earths-distant-past/ NCEI Paleoclimatology data (10,000 proxy datasets): https://www.ncei.noaa.gov/products/paleoclimatology

What sources are used for reconstruction?



‘Hockey Stick’ Graph

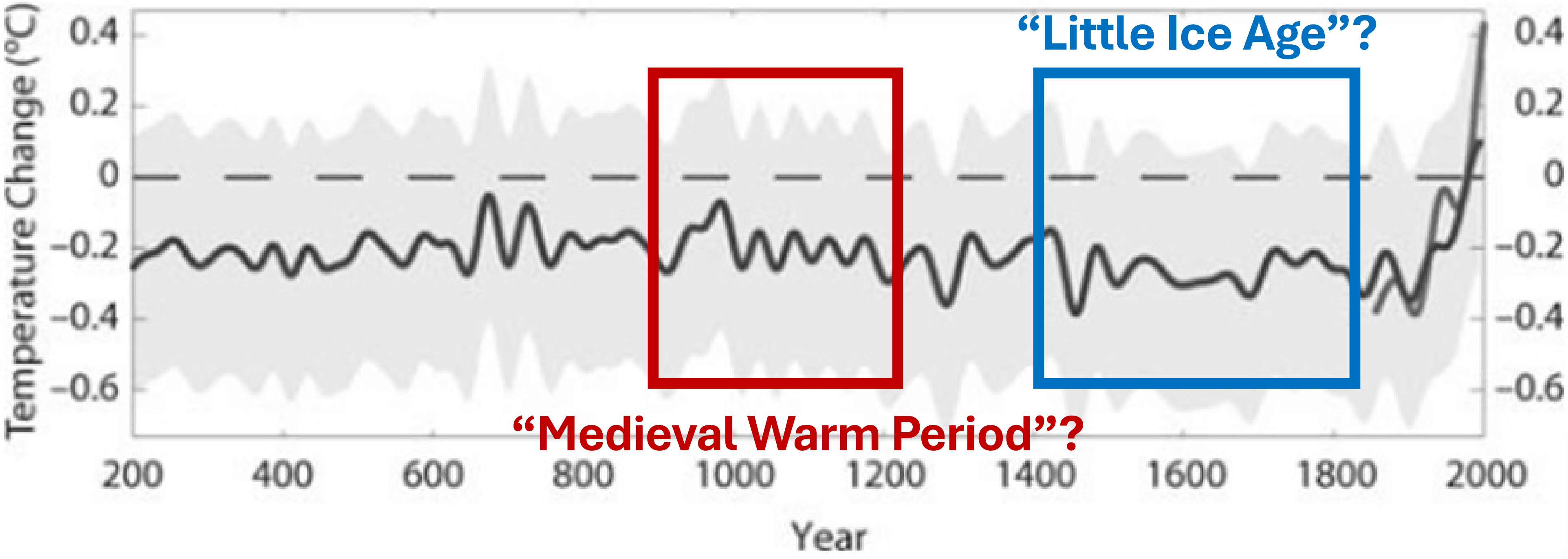


Figure 7.3. Global mean surface temperatures of the past 1,800 years. The lighter solid curve extending from about 1850 to 2000 shows the instrumental record. The longer solid curve is an estimate of temperature over the entire period using proxy reconstructions, and the gray shading is an error estimate (the 95 percent confidence interval). The series are smoothed to remove fluctuations of periods shorter than 40 years, and the temperatures represent anomalies in °C from a late twentieth century value. Source: Adapted from Jones and Mann (2004).

Proxy Data – ‘Hockey Stick’ Graph

What properties do we assume to be true when using proxy data?

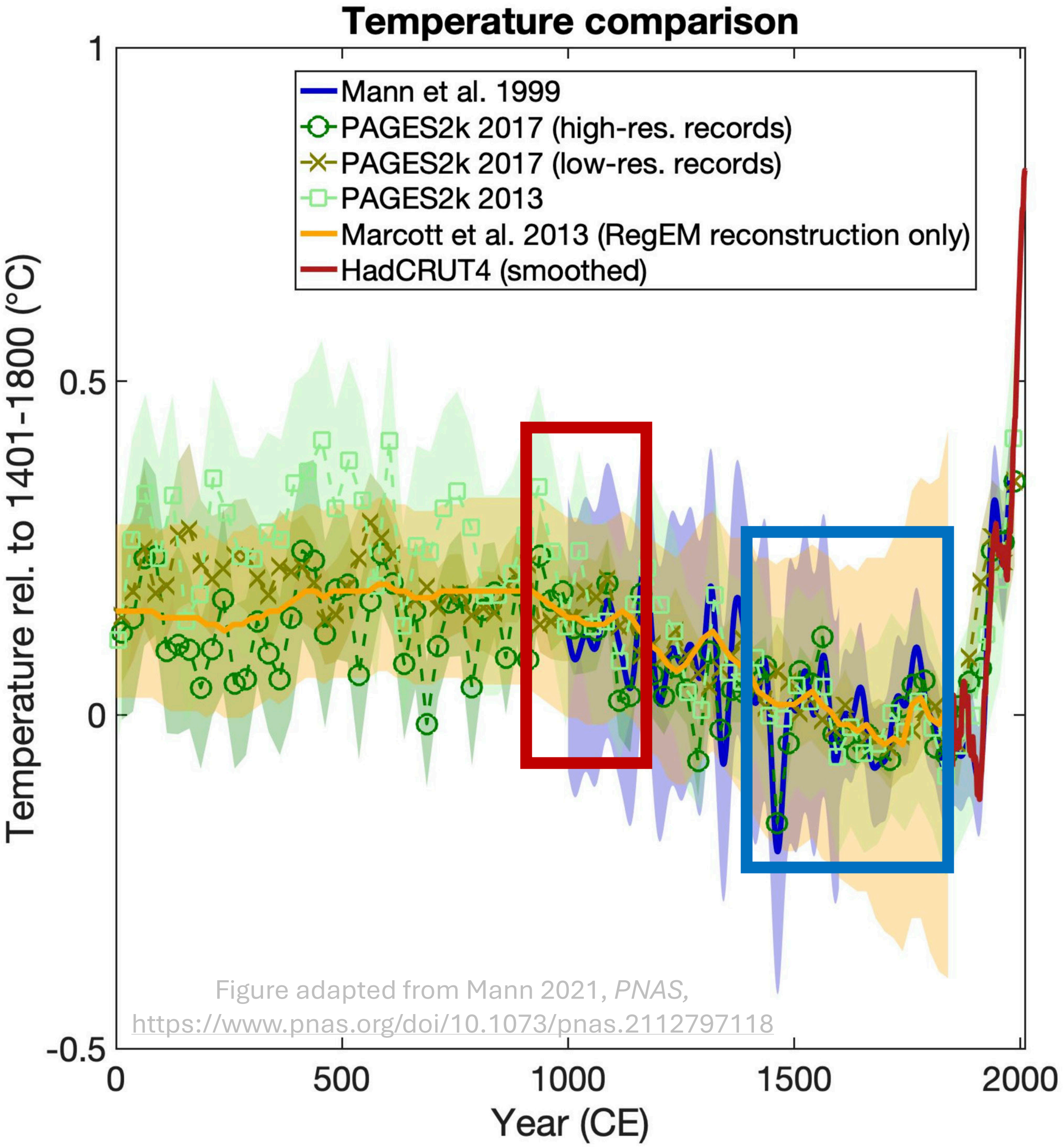


Figure adapted from Mann 2021, *PNAS*, https://www.pnas.org/doi/10.1073/pnas.2112797118

Greenhouse Gases and Global Temperatures

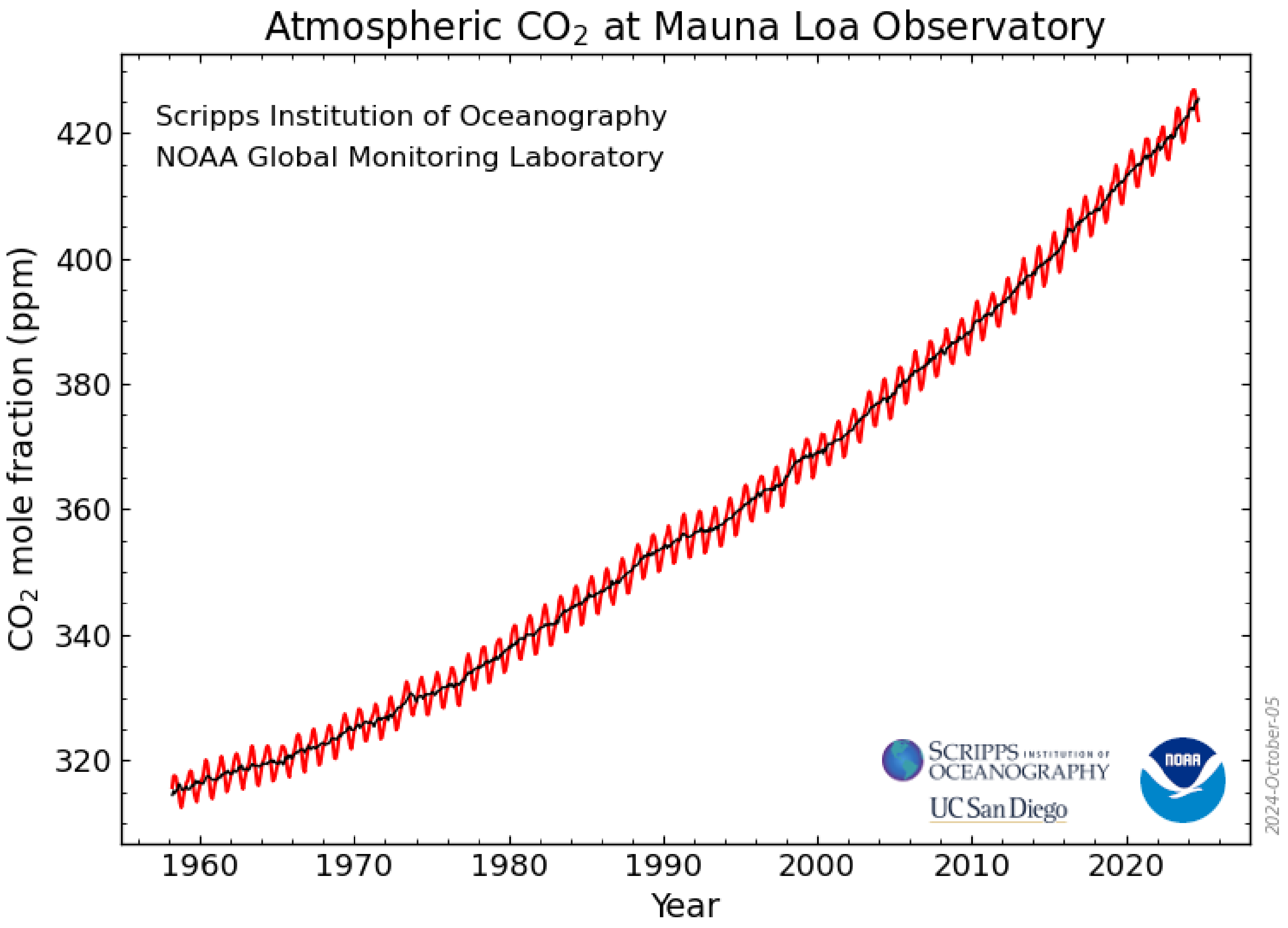
Review:

What is the most important naturally occurring greenhouse gas in Earth's atmosphere?

What is the most important anthropogenic greenhouse gas in Earth's atmosphere?

Greenhouse Gases and Global Temperatures

What are the two distinctive features of the Keeling Curve?



Latest reading: 421.95 ppm

Human Fingerprints of Carbon Dioxide

How do we know the increase in carbon dioxide is caused by the burning of fossil fuels (per Vallis)?

How do we know the increase in carbon dioxide is caused by the burning of fossil fuels (per Beacon of Hope)?

The Likely Culprit of Global Warming

Main Takeaways:

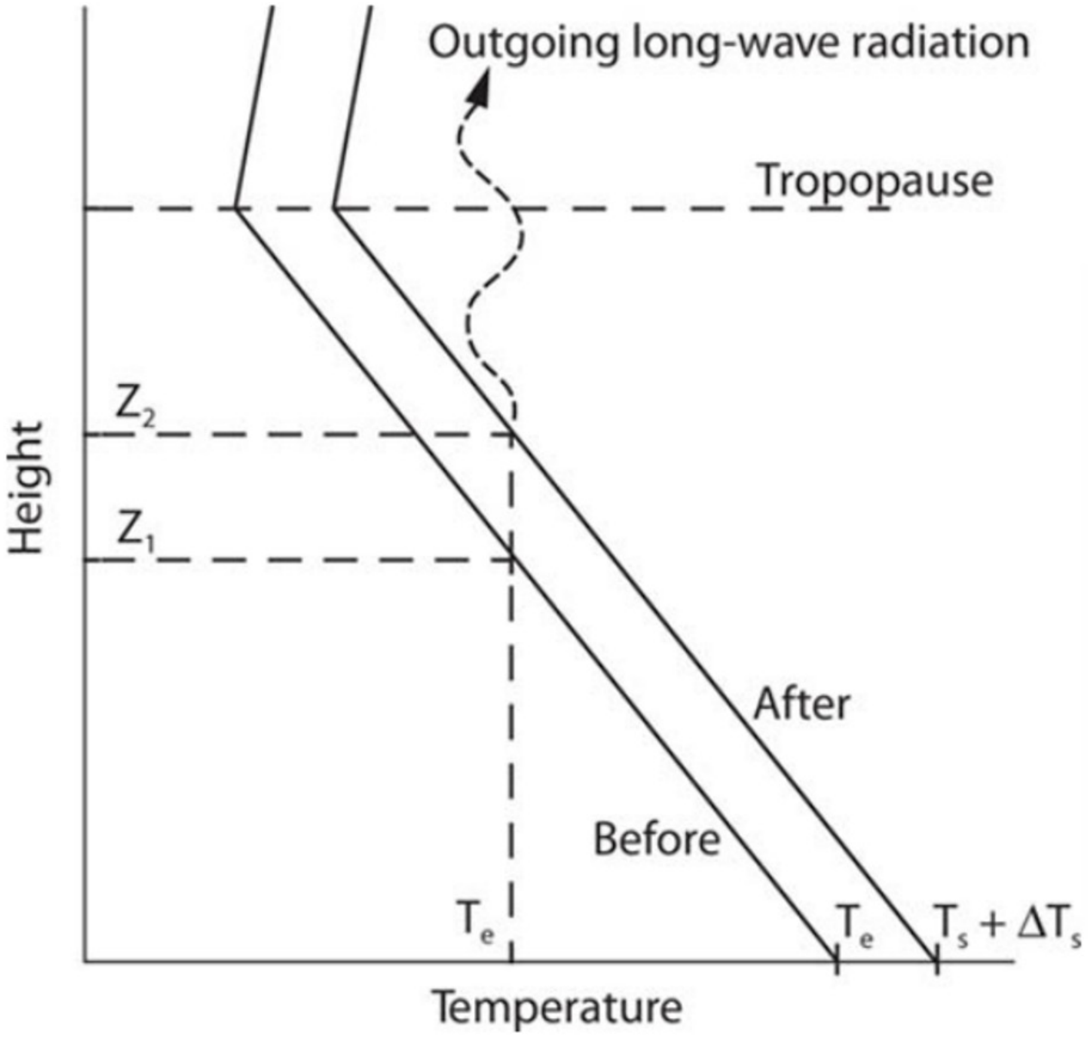


Figure 7.5. Schematic of temperature profiles before and after the addition of greenhouse gases. The total outgoing longwave radiation must remain the same because this radiation balances the incoming solar radiation, and so the emissions temperature, T_e, stays the same. However, the emissions height must increase (from Z_1 to Z_2 because of the increased absorptivity of the atmosphere. Hence, if the temperature gradient in the vertical remains similar, the surface temperature must increase.

Has the Ocean Warmed?

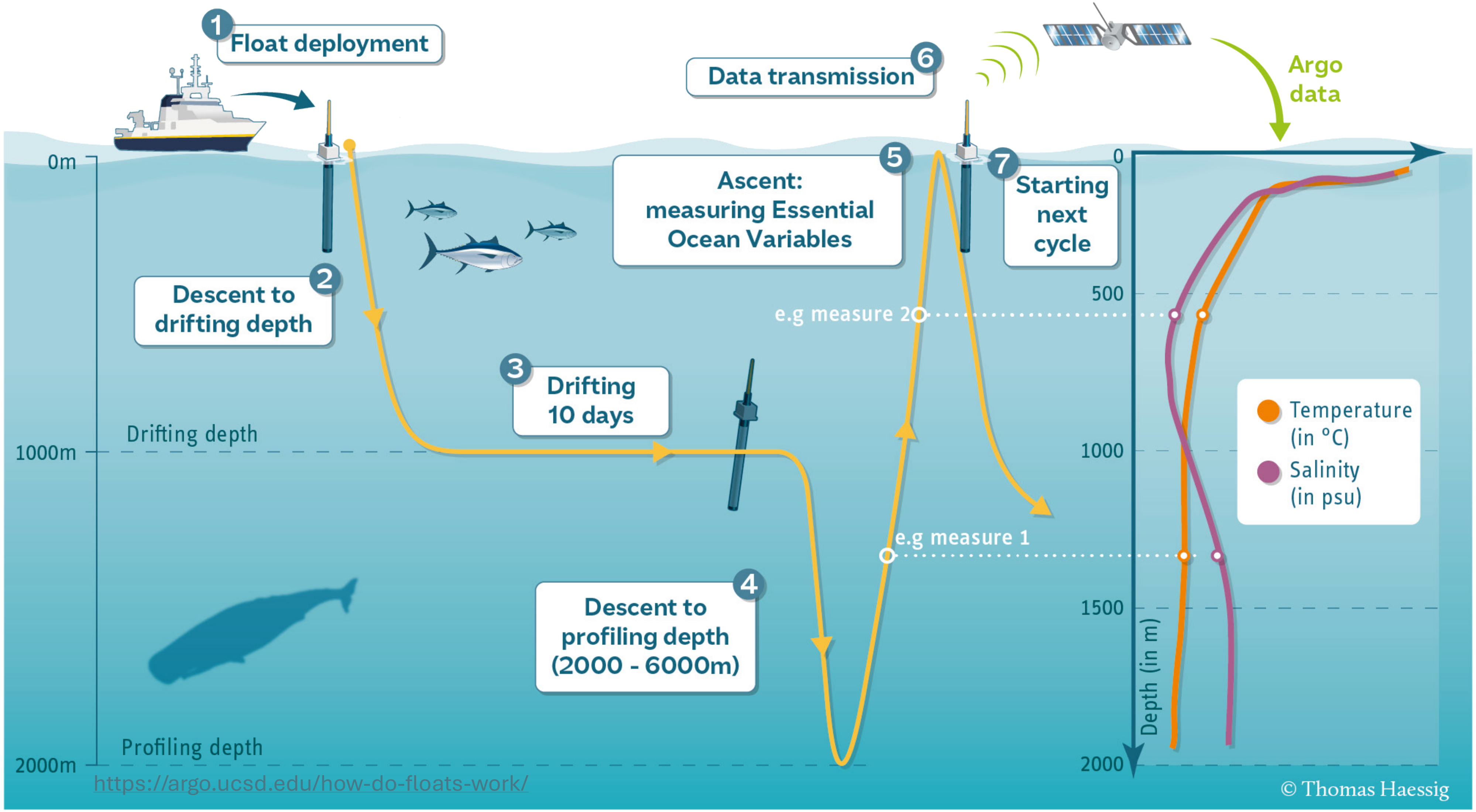
Section 2

What is Ocean Heat Content (OHC)?

”… defined as the heat capacity of seawater multiplied by the change in temperature, integrated over the entire mass of the world’s oceans.”

How Do We Measure OHC In-Situ?

Fun fact: Argo was named because of the program's partnership with the Jason earth observing satellites → in Greek mythology, Jason sailed on his ship the Argo

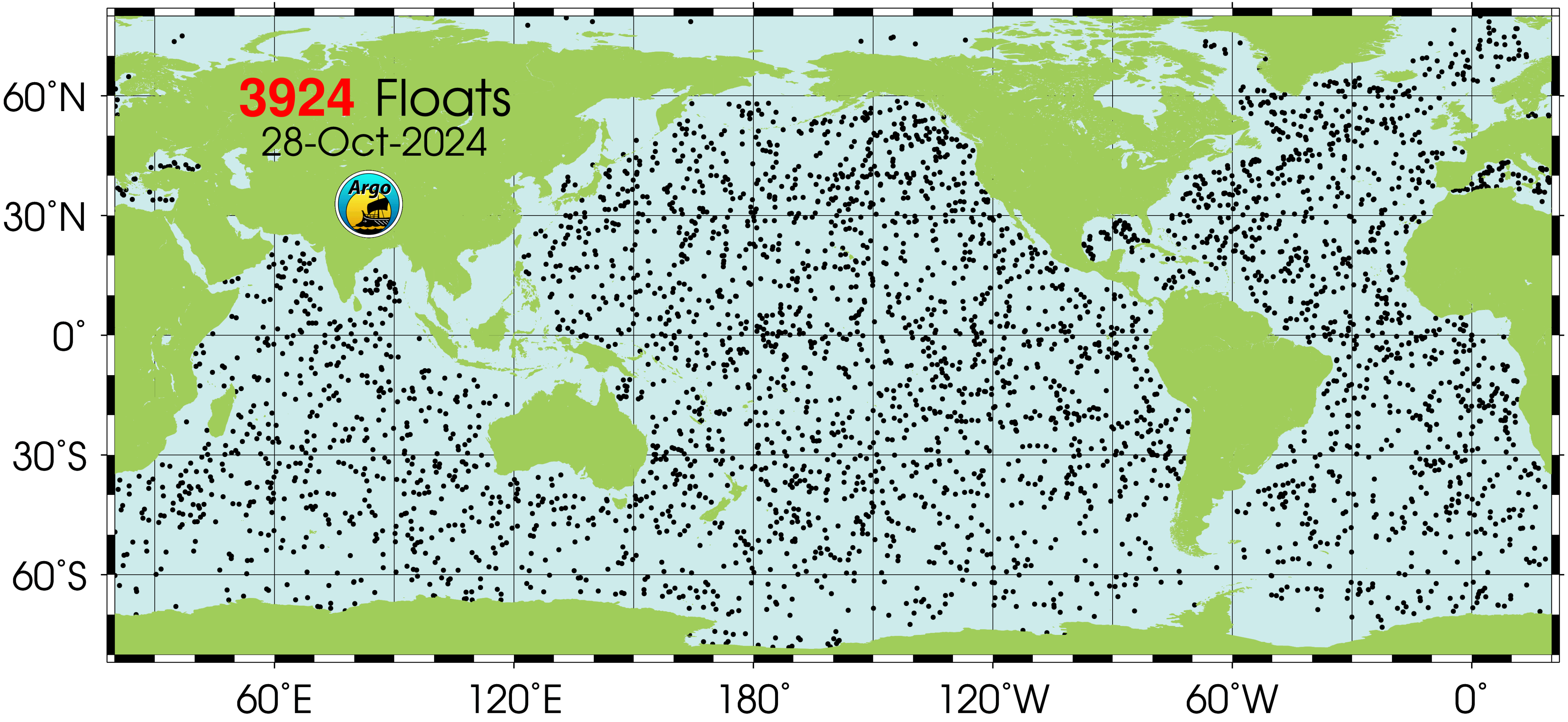


https://argo.ucsd.edu/how-do-floats-work/

Argo Float Distribution, Oct 2024

https://argo.ucsd.edu/about/status/

There are still regions that need to be gap filled



3 Ocean Heat Content Indicators

0-300 meters, Ocean-atmosphere interface, shows greatest warming

0-700 m, Standard measure of OHC, historical measurements collected here

0-2000 m, Important for long-term energy imbalance and heat storage

https://marine.copernicus.eu/ocean-climate-portal/ocean-heat-content

OHC

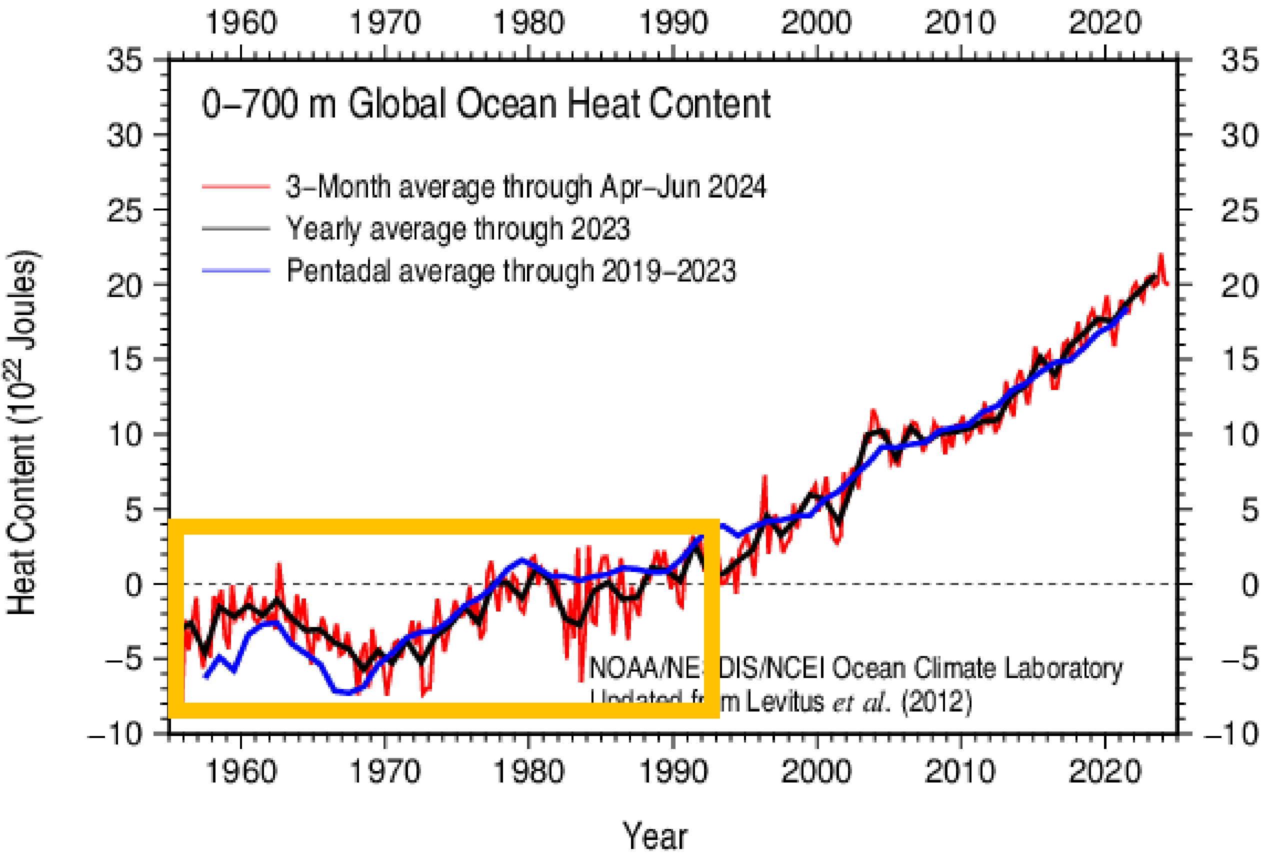
Where has the ocean experienced the most temperature increase?

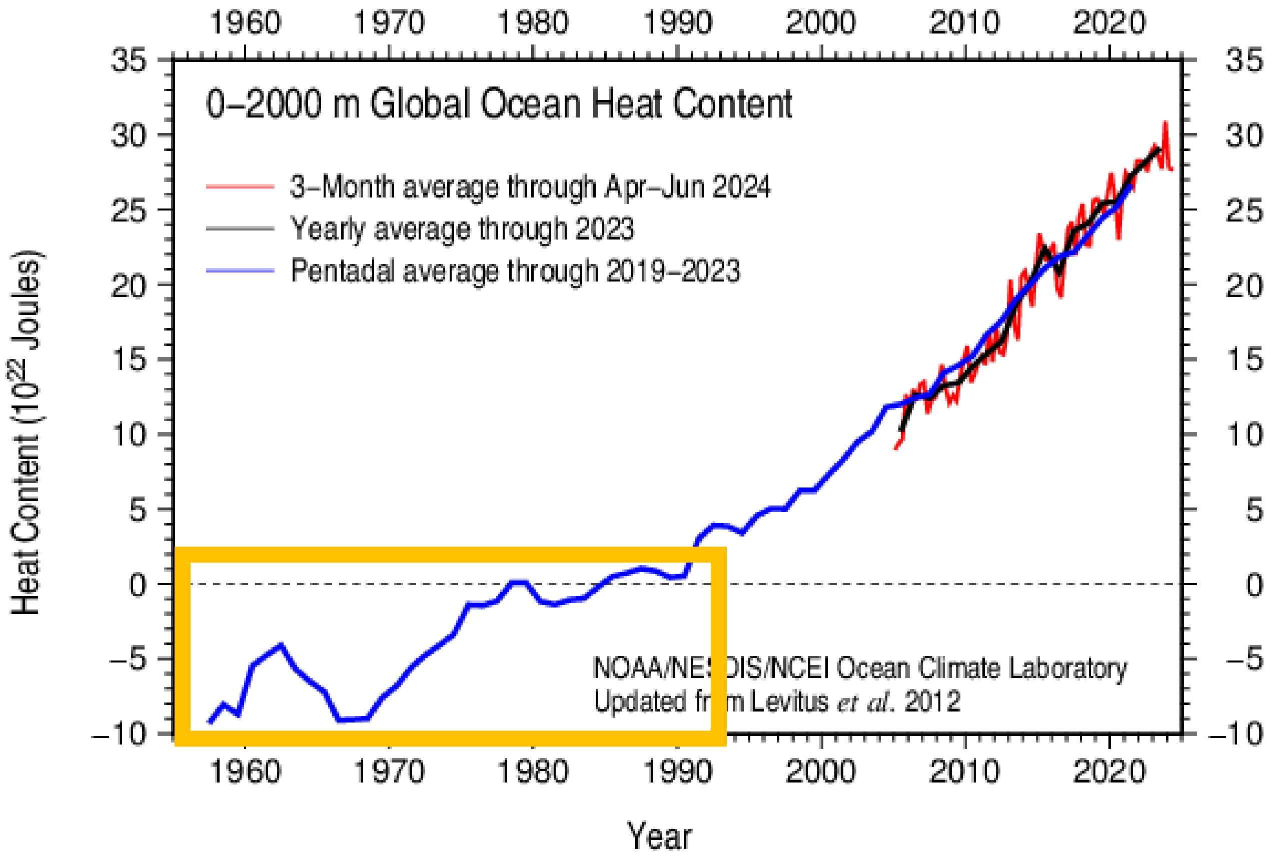
What about the negative trend in the Northeastern Atlantic?

Change in ocean heat content from 1993 to 2023 https://climate.copernicus.eu/climate-indicators/ocean-heat-content			
Ocean depth		**Global ocean**	**Northeastern Atlantic**
0–2000 m	W/m²	**1.30** ± 0.01 W/m²	**0.22** ± 0.1 W/m²
	°C	**0.22** ± 0.004°C	**0.04** ± 0.01°C
0–700 m	W/m²	**0.83** ± 0.01 W/m²	**0.39** ± 0.04 W/m²
	°C	**0.40** ± 0.005°C	**0.18** ± 0.02°C
700–2000 m	W/m²	**0.47** ± 0.02 W/m²	**-0.16** ± 0.13 W/m²
	°C	**0.12** ± 0.005°C	**-0.04** ± 0.03°C

OHC

Is there anything surprising in these figures?

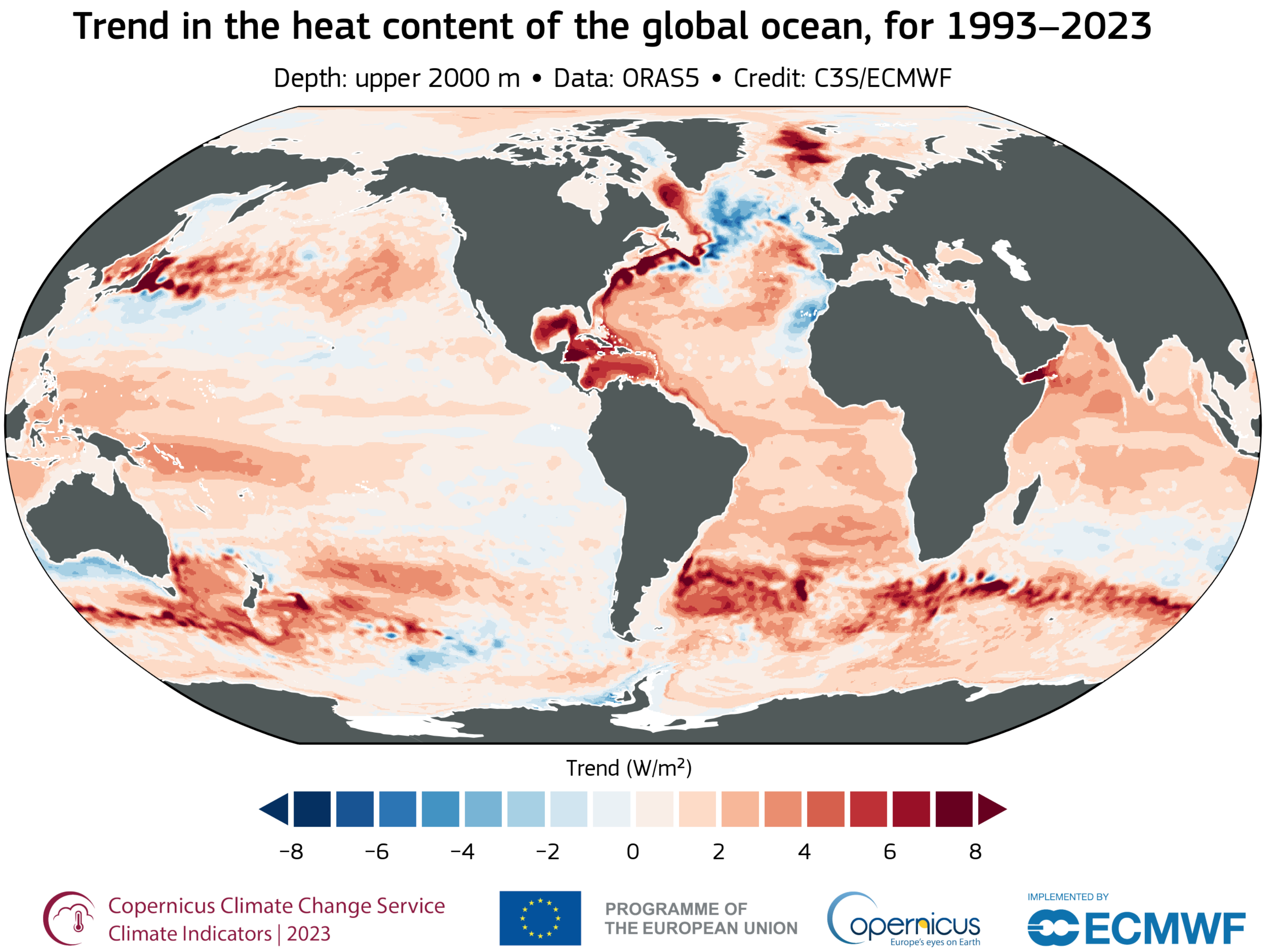




OHC

Why do some regions exhibit cooling trends?

Do you notice anything about the western boundary currents?



More Effects of and on the Ocean

The 4 potential effects Vallis includes are:

Effect #1: The Slowing of Global Warming

- There is a slower oceanic response compared to the atmosphere
- The mixed layer is in equilibrium with the forcing levels in the atmosphere about a decade ago

Timescale of a few years

Timescale of thousands of years

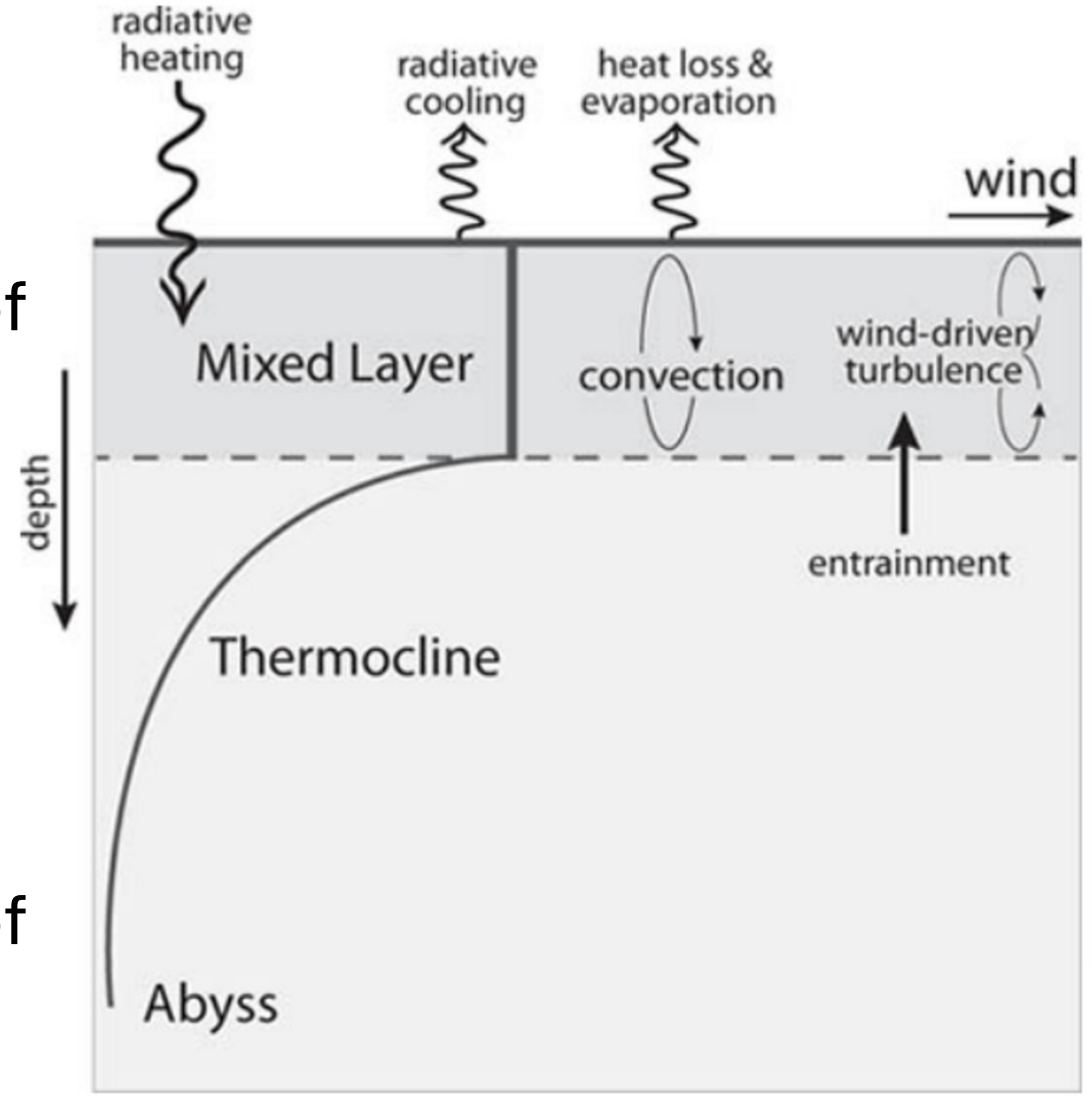


Figure 2.5. Schematic of the vertical structure of the ocean, emphasizing the mixed layer. In the mixed layer, typically 50–100 m deep, turbulence and convection act to keep the temperature relatively uniform in the vertical. Below this layer, temperature changes over a depth of a few hundred meters, in the *thermocline*, before becoming almost uniform at depth, in the *abyss*. Adapted from Marshall and Plumb, 2007.

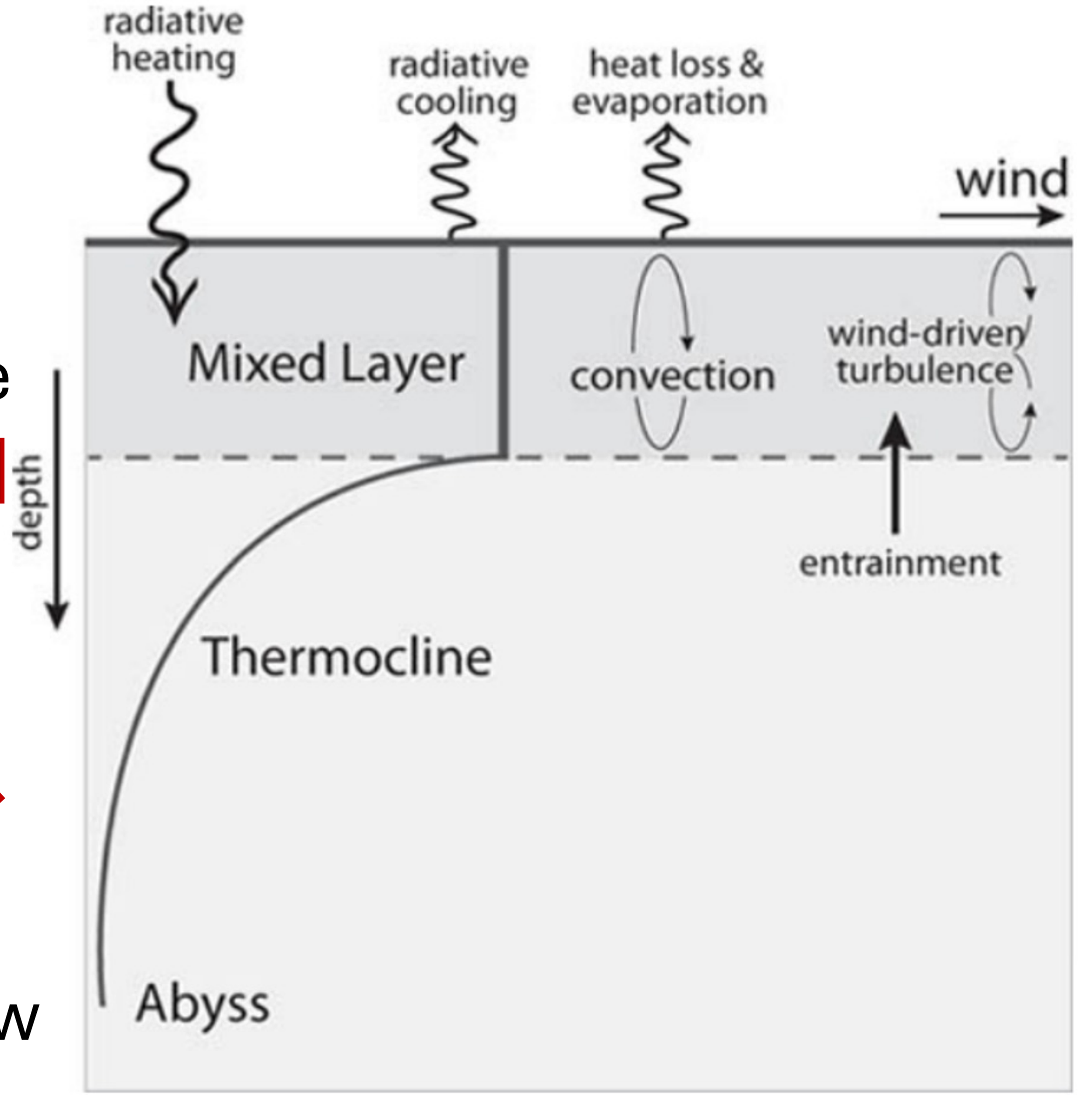
Effect #1

Main takeaway:

"As the deep ocean warms, the mixed layer can give up LESS of its heat to the ocean below, and so can only balance the radiative forcing by further INCREASING its temperature, so that it gives its heat BACK to the atmosphere." - Vallis

Increase in temperature

Warms the ocean below over many centuries



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Effect #1

Is the deep ocean in equilibrium?

Effect #1

What stands out in this figure?

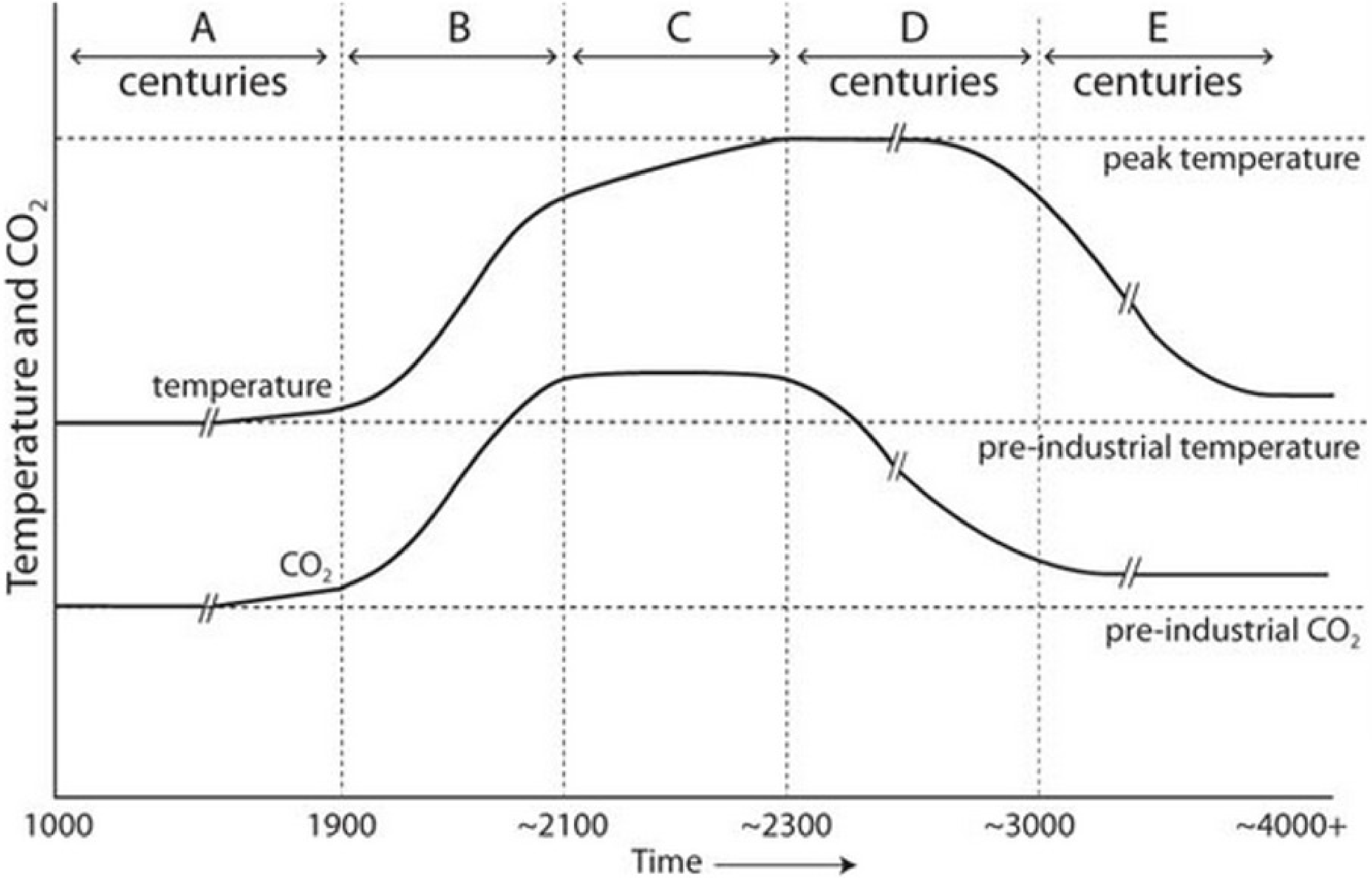


Figure 7.7. Schema of a CO_2-temperature scenario. Carbon dioxide levels increase from 1900 to 2100 (period B) before leveling off (period C) because of controls on emissions. Temperature increases rapidly in period B, then more slowly in period C. At the end of period C (the year 2300 in the figure), anthropogenic emissions go to zero, and the level of CO_2 slowly diminishes through periods D and E back to levels close to, but probably a little above, the preindustrial period. In period D, temperature stays roughly constant for centuries before it too eventually falls back to near pre-industrial levels in period E. Many plausible scenarios can be adapted from this plot by changing 2100 and 2300 to other dates and calibrating the y-axis.

Effect #2: Circulation Changes and a Thermohaline Shutdown

Will the winds change their basic structure?

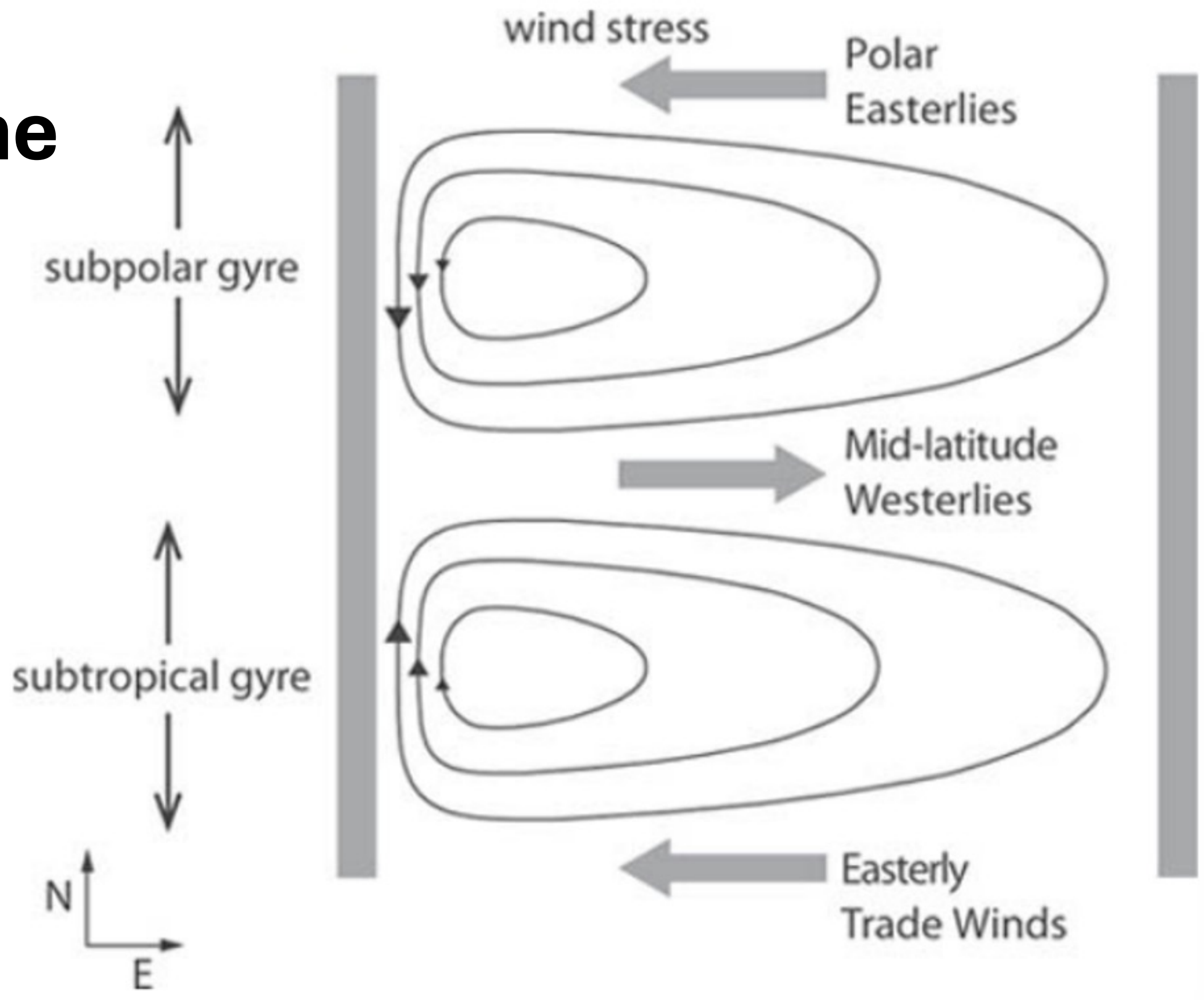


Figure 4.1. An idealized gyre circulation in a rectangular ocean basin in the Northern Hemisphere, showing the subtropical gyre (lower, typically extending from about 15°N to 45°N), the subpolar gyre (upper), and the intense western boundary currents on the left.

Effect #2:

One controlling factor in the intensity of the overturning circulation is *the meridional buoyancy gradient at the ocean surface*

Surface waters here are sufficiently dense and sink in convective plumes

Warmer, less dense waters travel from the tropics to the high latitudes

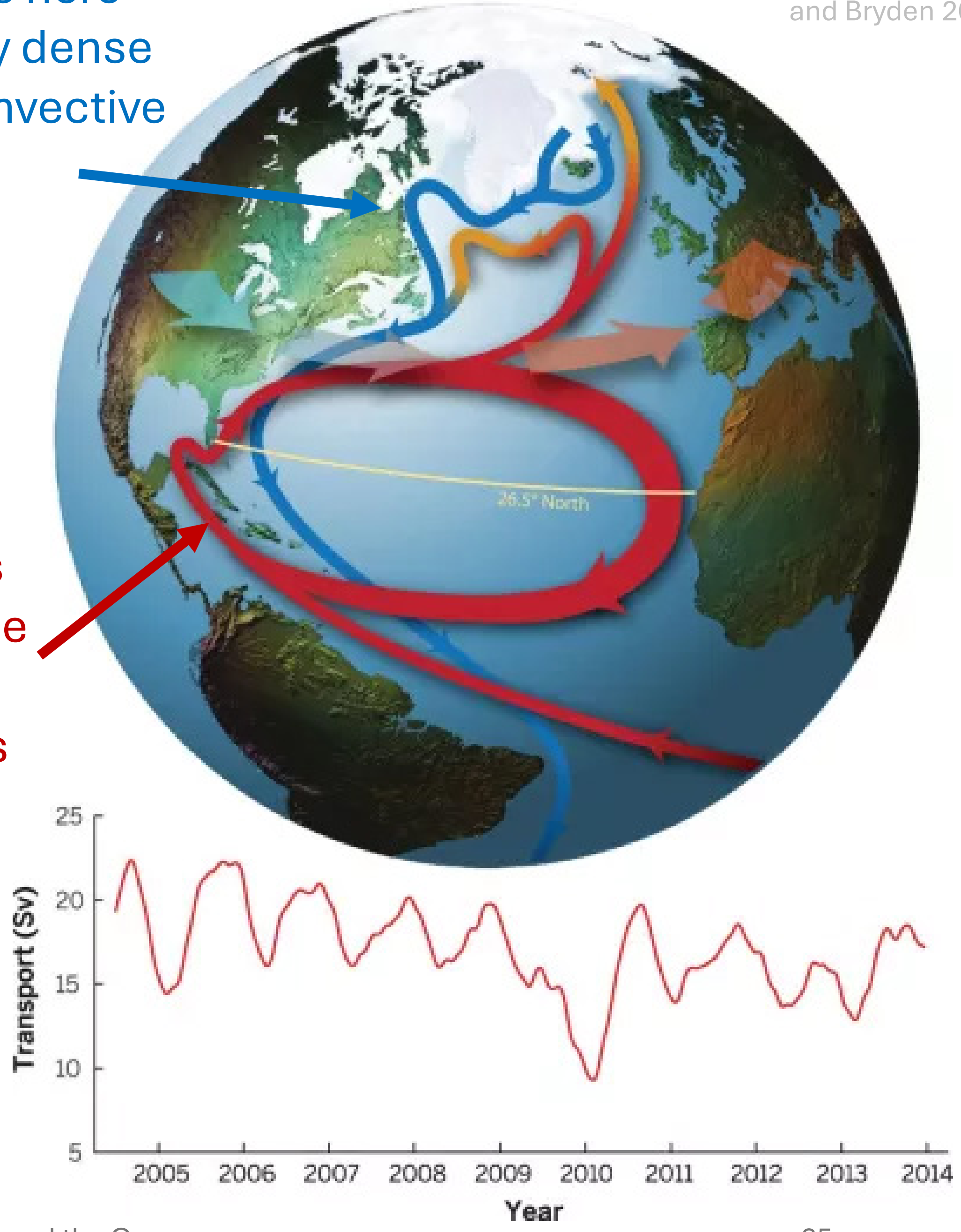
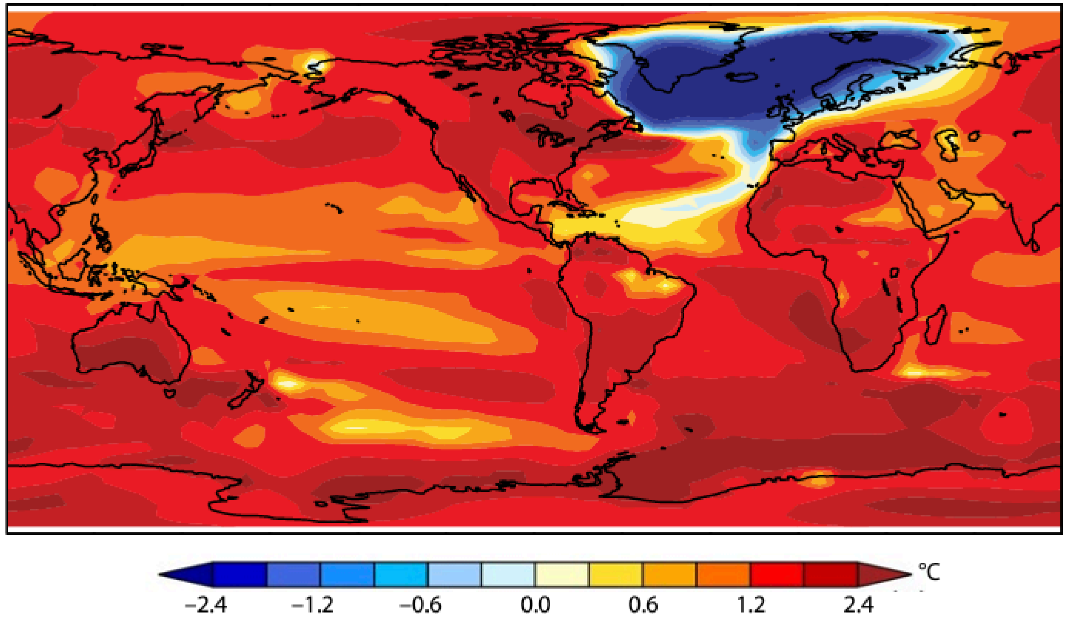
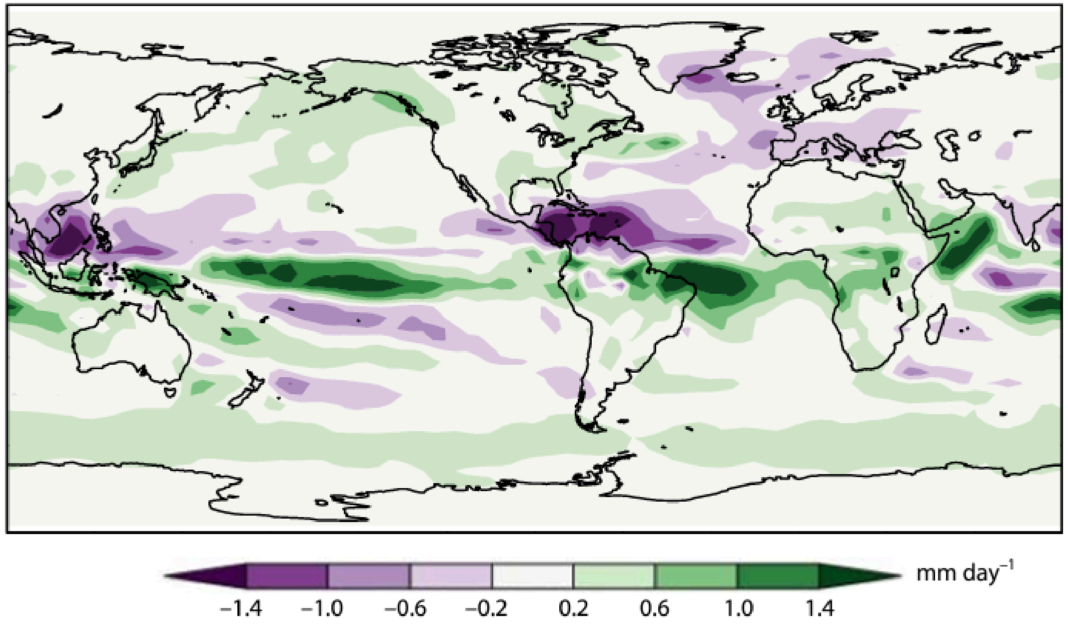


Figure courtesy of Srokosz and Bryden 2015

Effect #2:

What 2 things can bring AMOC to a halt?





Figures adapted from Liu et al. 2017
Top figure shows near-surface air temperature change resulting from carbon dioxide doubling and AMOC breakdown. Bottom figure shows the southward shift of the tropical Pacific rainfall belts.
https://www.science.org/doi/10.1126/sciadv.1601666

Effect #2:

Fingerprint of AMOC weakening:

→ Cold blob off the coast of Greenland, warming off the East Coast of the US

→ Reminder: OHC and temperature are directly related

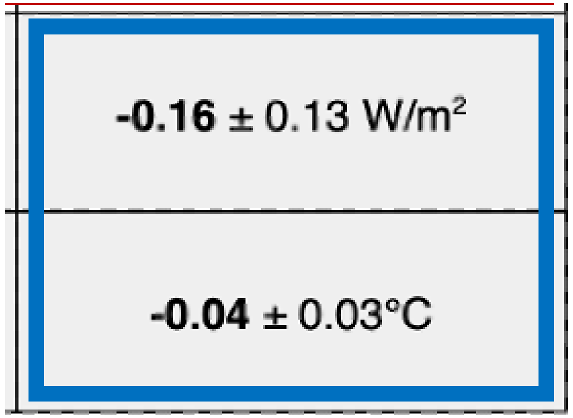
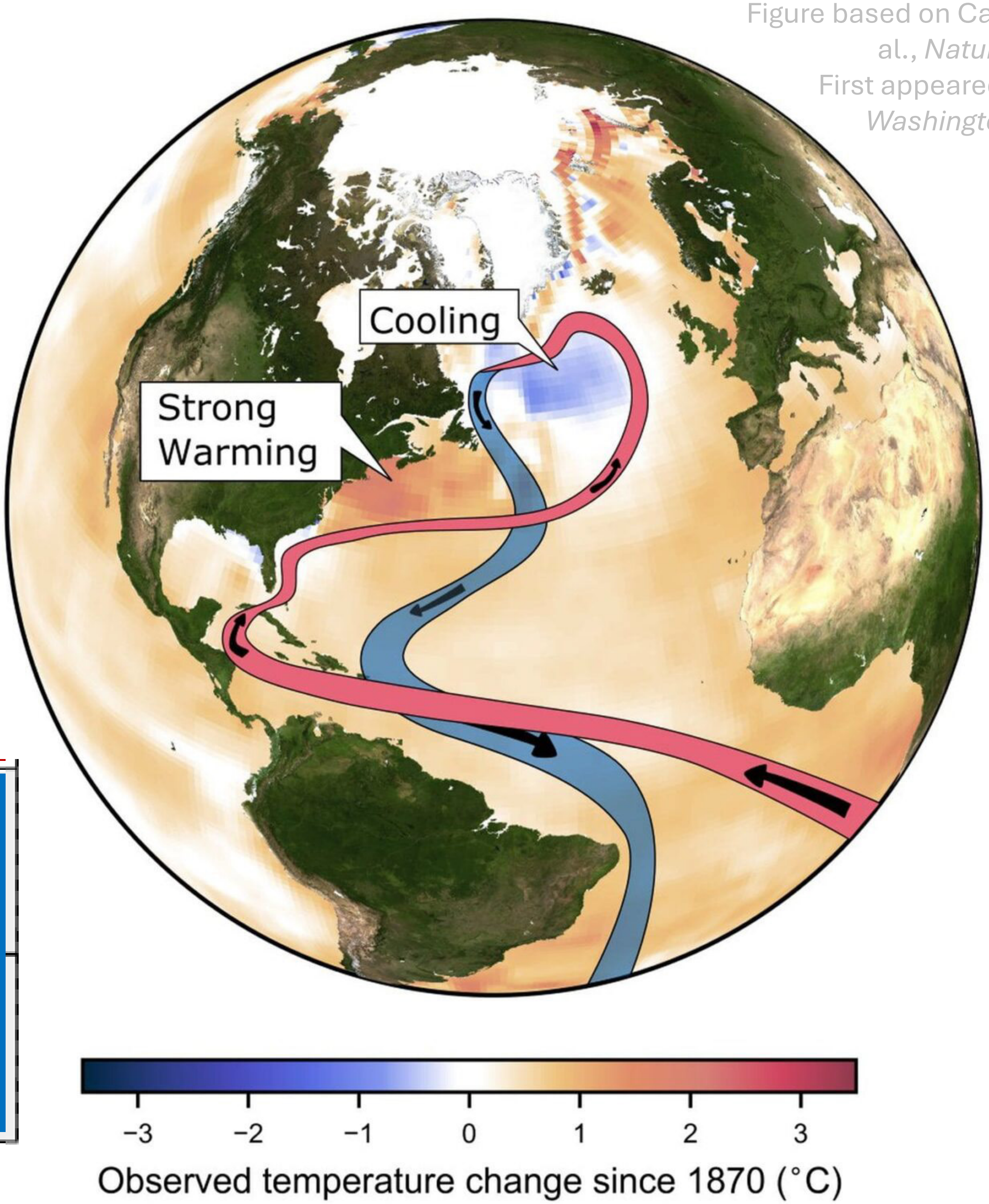


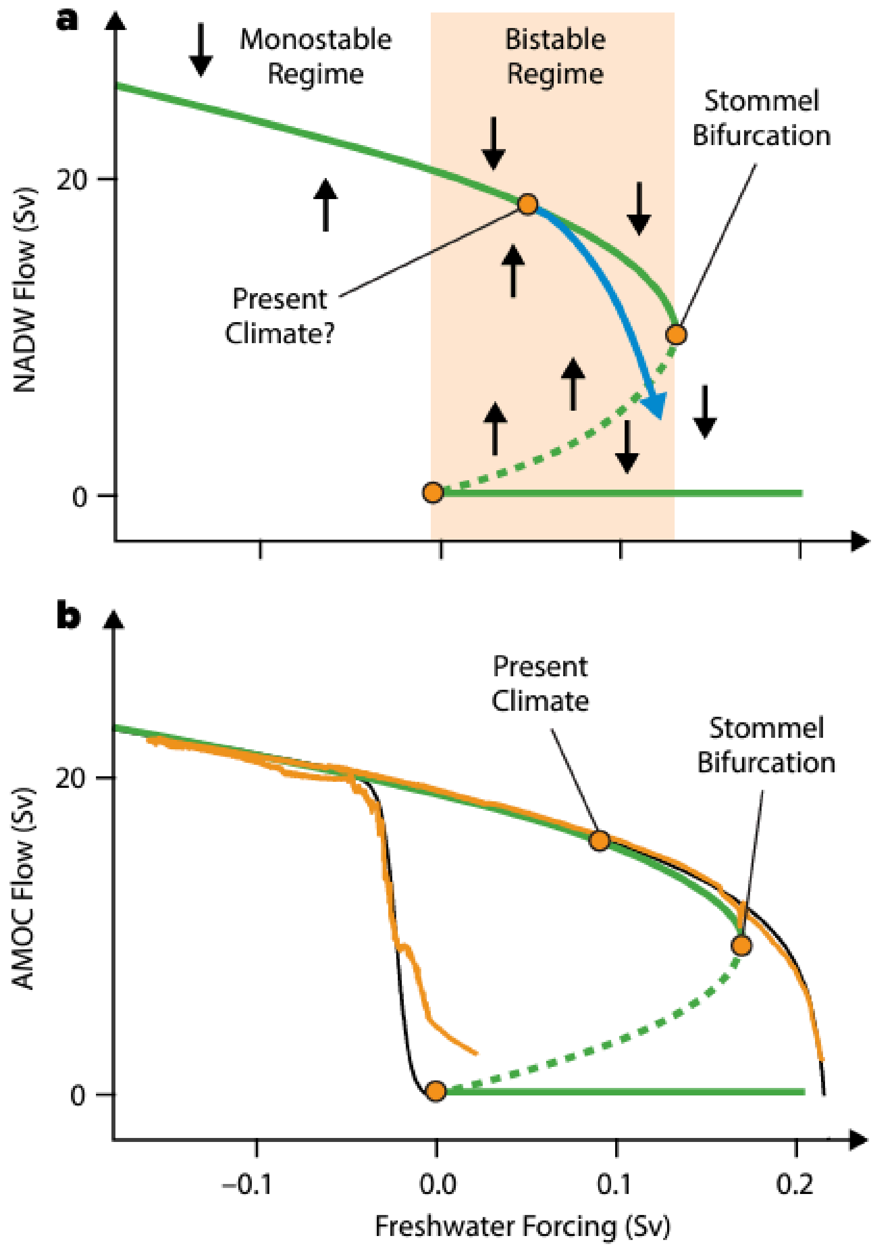
Figure based on Caesar et al., *Nature 2018*
First appeared in the *Washington Post*



Effect #2:

AMOC has a tipping point:

- Decline of AMOC gets steeper as freshwater forcing increases
- When the green curve bends back on itself, the tipping point has been reached

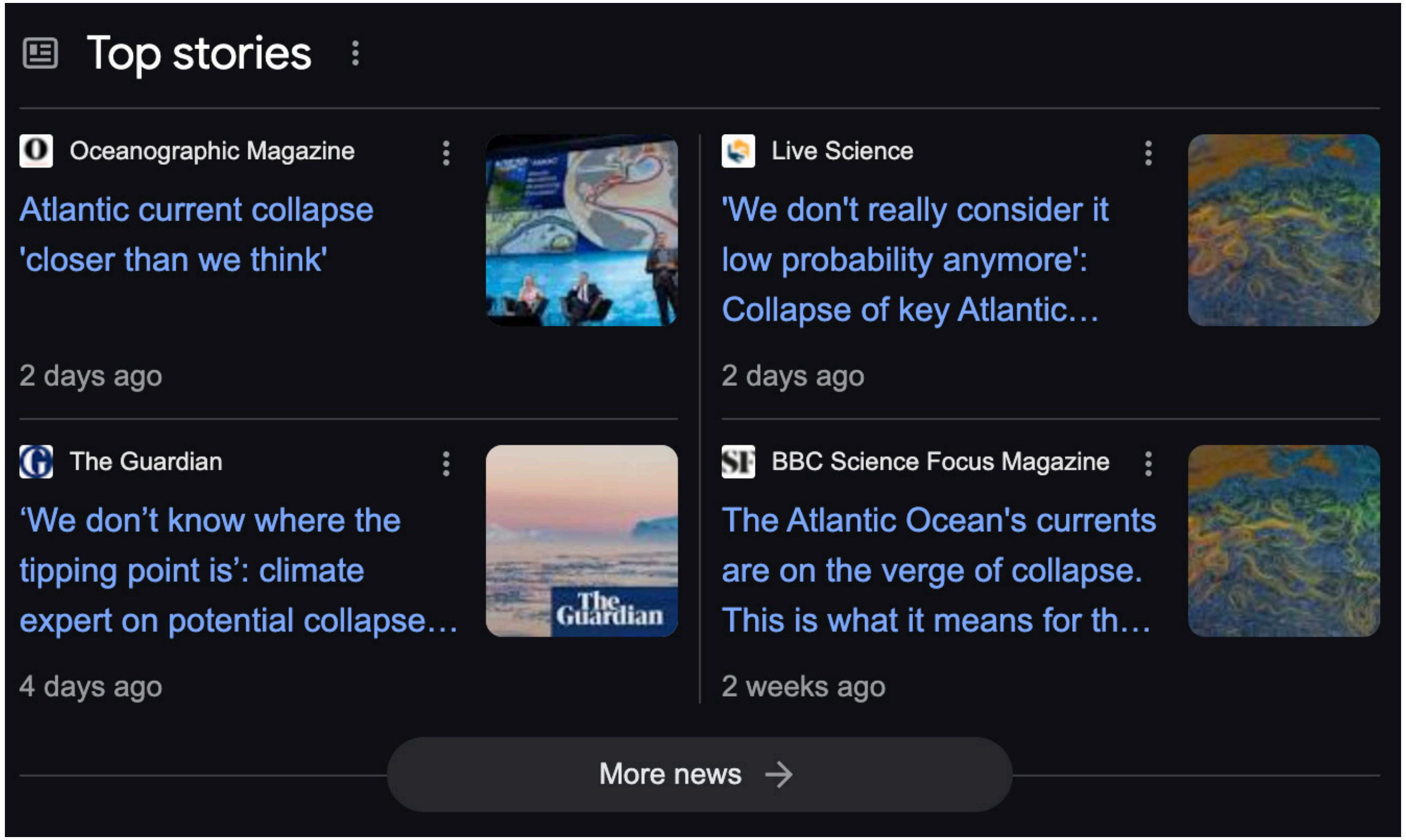


Top figure displays the stability diagram in Stommel's box model, with the solid green line indicating the stable equilibrium regime and the dashed green line indicating the unstable equilibrium regime. The blue line represents the path leaving the equilibrium state under climate change. The bottom figure displays the AMOC equilibrium in a three-dimensional global ocean circulation model. The top orange line indicate AMOC "on" and the bottom line indicates AMOC "off".
https://link.springer.com/article/10.1007/s003820050144
https://www.nature.com/articles/nature01090

Effect #2

Effect #2

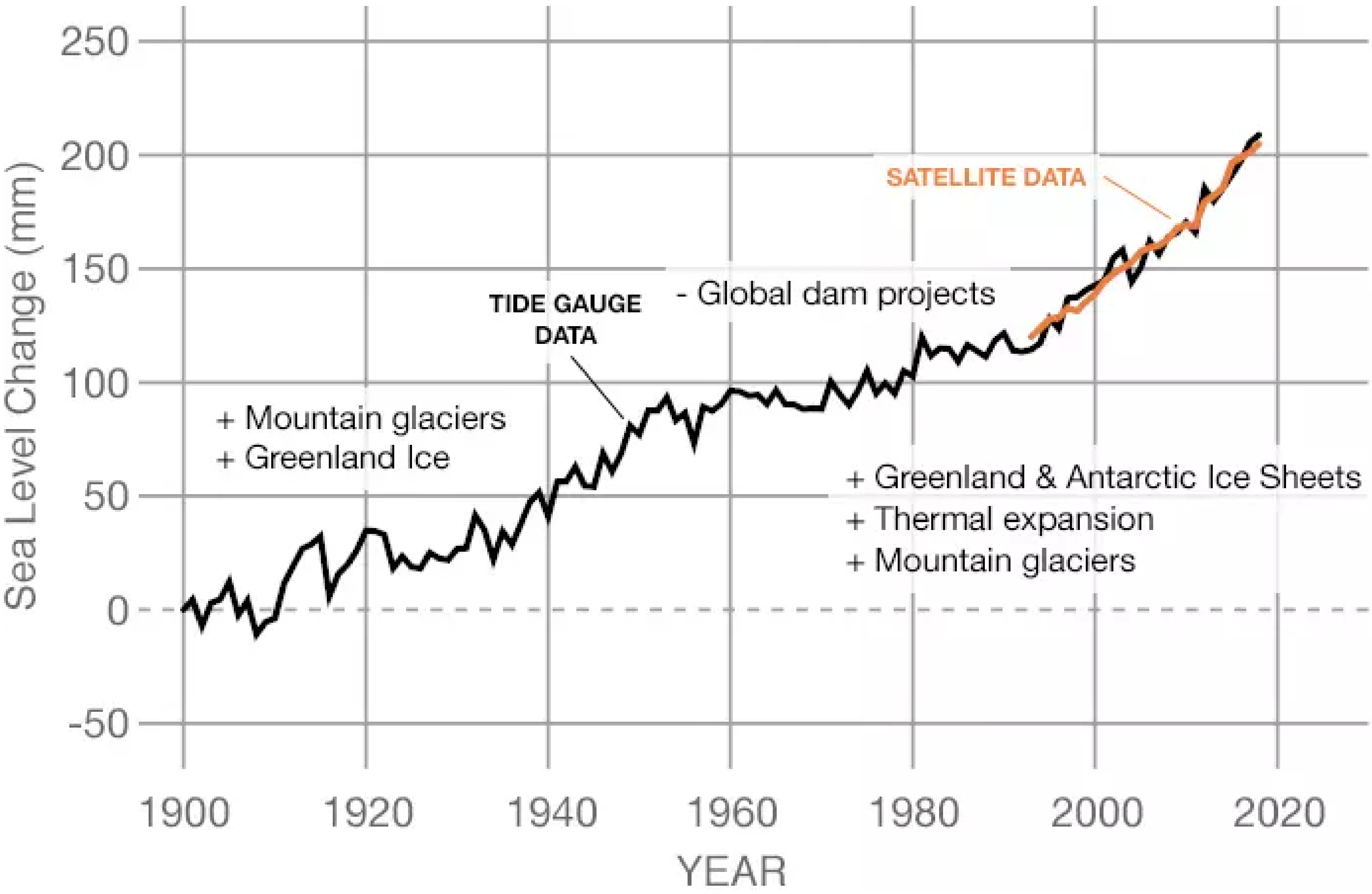
What is the current state of the science?
<u>AMOC is weakening, possible collapse around mid-century (dependent on model parameters used)</u>



Data source: Frederikse et al. (2020)
Credit: NASA's Goddard Space Flight Center/PO.DAAC
Items with (+) indicates contribution to sea level rise while (-) indicates contribution to a decline in sea level rise

Effect #3: Sea Level Rise (SLR)

Since 1993, SLR has risen by 101.9 mm (about 4 inches)



Effect #3: SLR

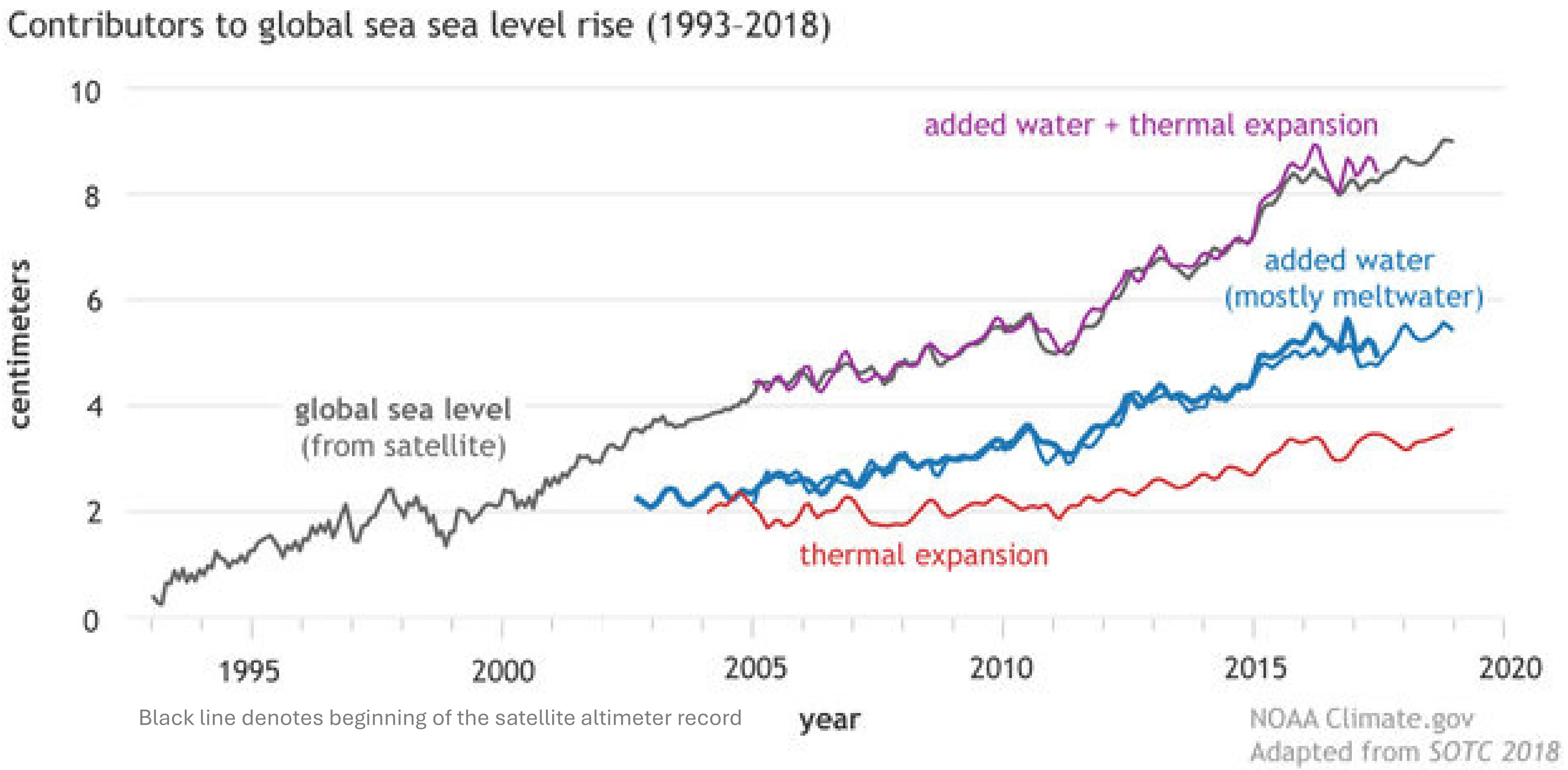
Based solely on thermal expansion, we find an *increase in temperature of 1 C contributes to ~ 0.5 m in SLR*

If temperatures reach 3 C for a prolonged period, an increase of 1.5 m in SLR is likely, purely by thermal expansion (no contribution from melting ice sheets)

$$\frac{\Delta V}{V} = \beta_T \Delta T$$

Effect #3: SLR

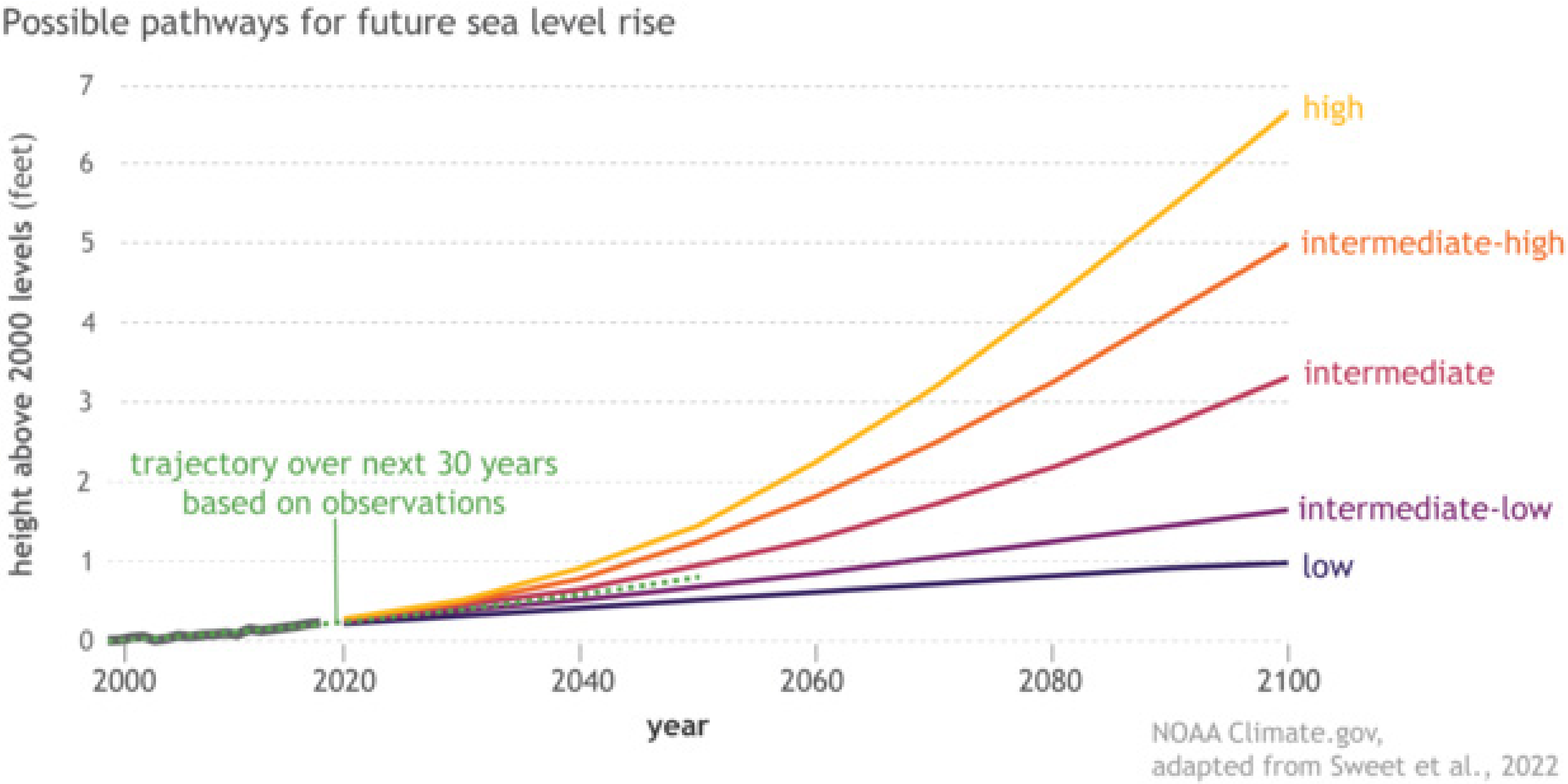
Vallis states, "thermal expansion of the oceans is estimated to have contributed a little more than half of the total sea-level rise ... climate models project that a global sea-level rise due to mainly thermal expansion..."



Black line denotes beginning of the satellite altimeter record

Effect #3: SLR

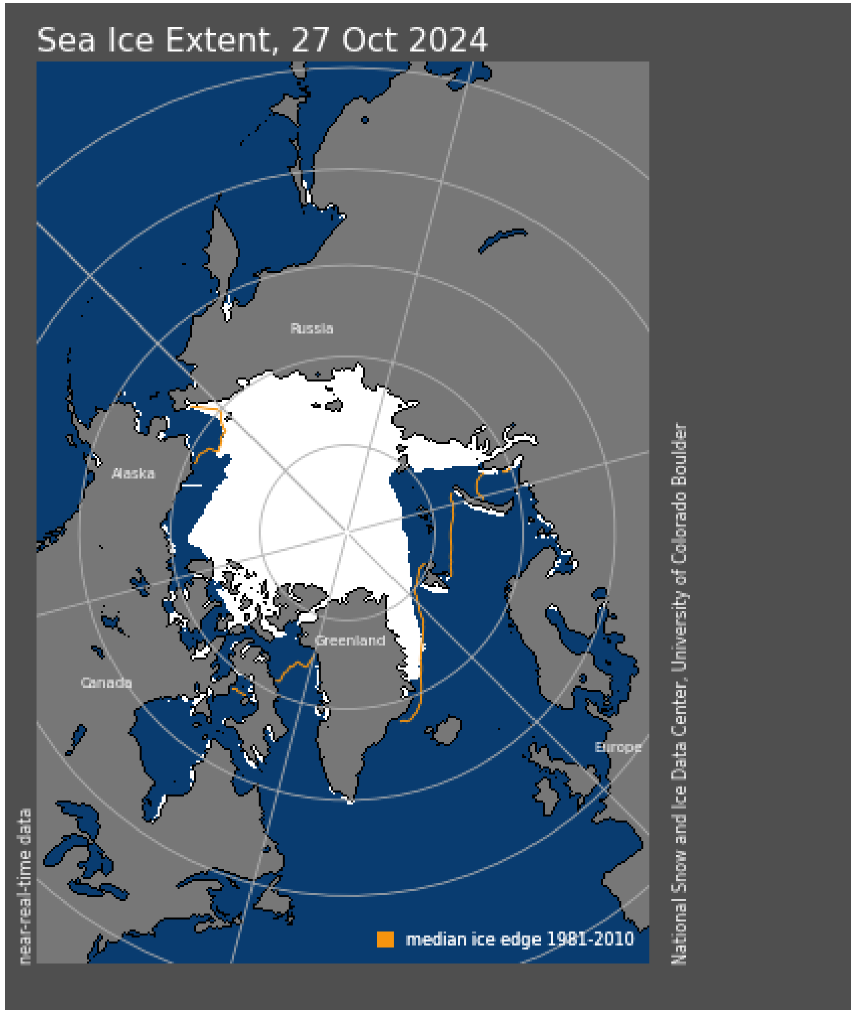
- Low-lying nations would be most impacted by SLR
- About 40% of the global population lives within 100 km of the coast (https://www.unep.org/topics/ocean-seas-and-coasts/regional-seas-programme/coastal-zone-management)

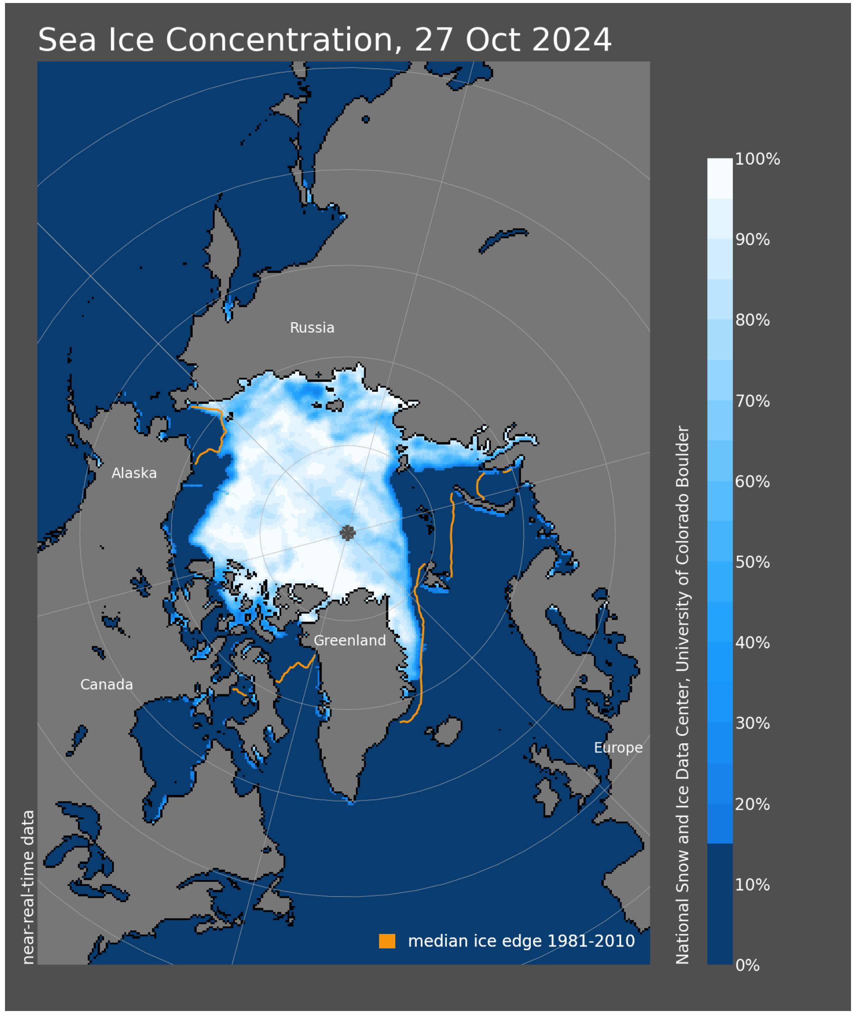


Effect #3: Loss of Sea Ice

Why is sea ice important?

https://nsidc.org/sea-ice-today

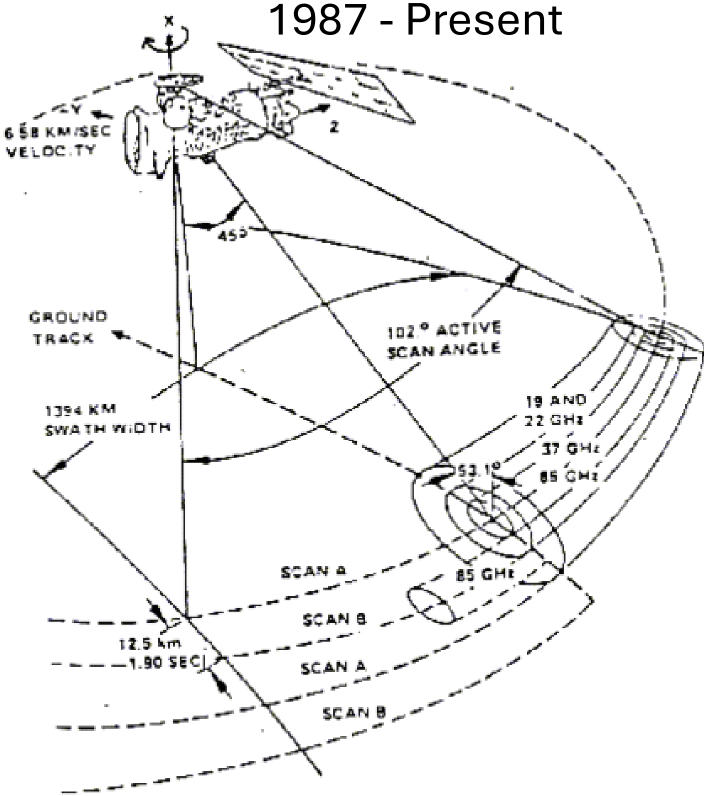




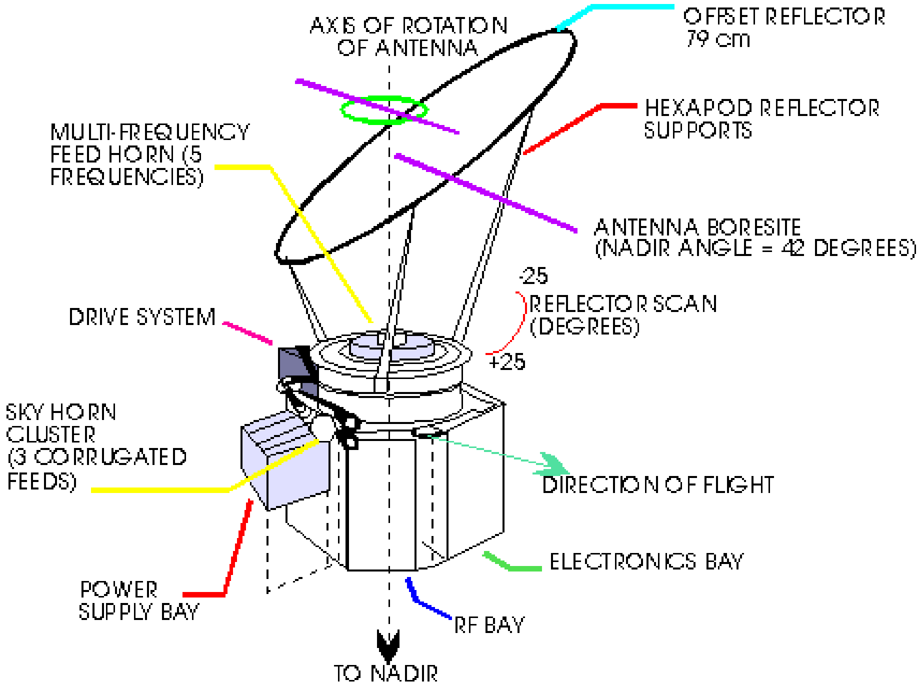
Effect #3: Loss of Sea Ice

Why do we use microwave radiation to monitor sea ice?

1987 - Present



1978 - 1987



The record of sea ice began in 1978 with the the launch of the NASA Scanning Multichannel Microwave Radiometer (SMMR) (right) and then continued with the Special Sensor Microwave Imager/Sounder (SSMI/SSMIS) (left). Other satellites, like AMSR, ICESat/ICESat-2 and CryoSat/CryoSat-2 have continued and enhanced the sea ice record. More information: https://www.remss.com/missions/ssmi/

Additional Readings and Resources

- How do we measure weather and climate? https://www.climate.gov/maps-data/climate-data-primer/how-do-we-observe-todays-climate
- How do weather observations become climate information? https://www.climate.gov/maps-data/climate-data-primer/how-do-weather-observations-become-climate-data
- The contribution of the UHI to global warming: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021EF002401
- Urban heat island effects of Baltimore and Washington D.C: https://www.climate.gov/news-features/features/detailed-maps-urban-heat-island-effects-washington-dc-and-baltimore
- Beyond the Hockey Stick: https://www.pnas.org/doi/10.1073/pnas.2112797118
- Argo Status: https://argo.ucsd.edu/about/status/
- More about ocean heat content: https://climate.copernicus.eu/climate-indicators/ocean-heat-content
- AMOC talk by Stefan Rahmstorf: https://www.youtube.com/watch?v=k0FUZKQhU6U
- The consequences of AMOC shutting down: https://www.germanwatch.org/en/87910
- More about SAR, scatterometers, and radar for sea ice: https://www.meereisportal.de/en/learn-more/sea-ice-measuring-methods/measurements-from-space/active-microwave-sensors-radar
- More about sea ice: https://nsidc.org/sea-ice-today

Learning Outcomes

✓Discuss sources of error in the global surface temperature records
✓The modern thermometer
✓How satellites collect temperature measurements
✓How proxy data is used for temperature reconstructions
✓Human fingerprints of carbon dioxide
✓How ocean heat content is measured
✓How the deep ocean will equilibrate
✓Fingerprint of AMOC weakening
✓Sea level rise by thermal expansion and melting of ice sheets
✓How we track sea ice extent and concentration