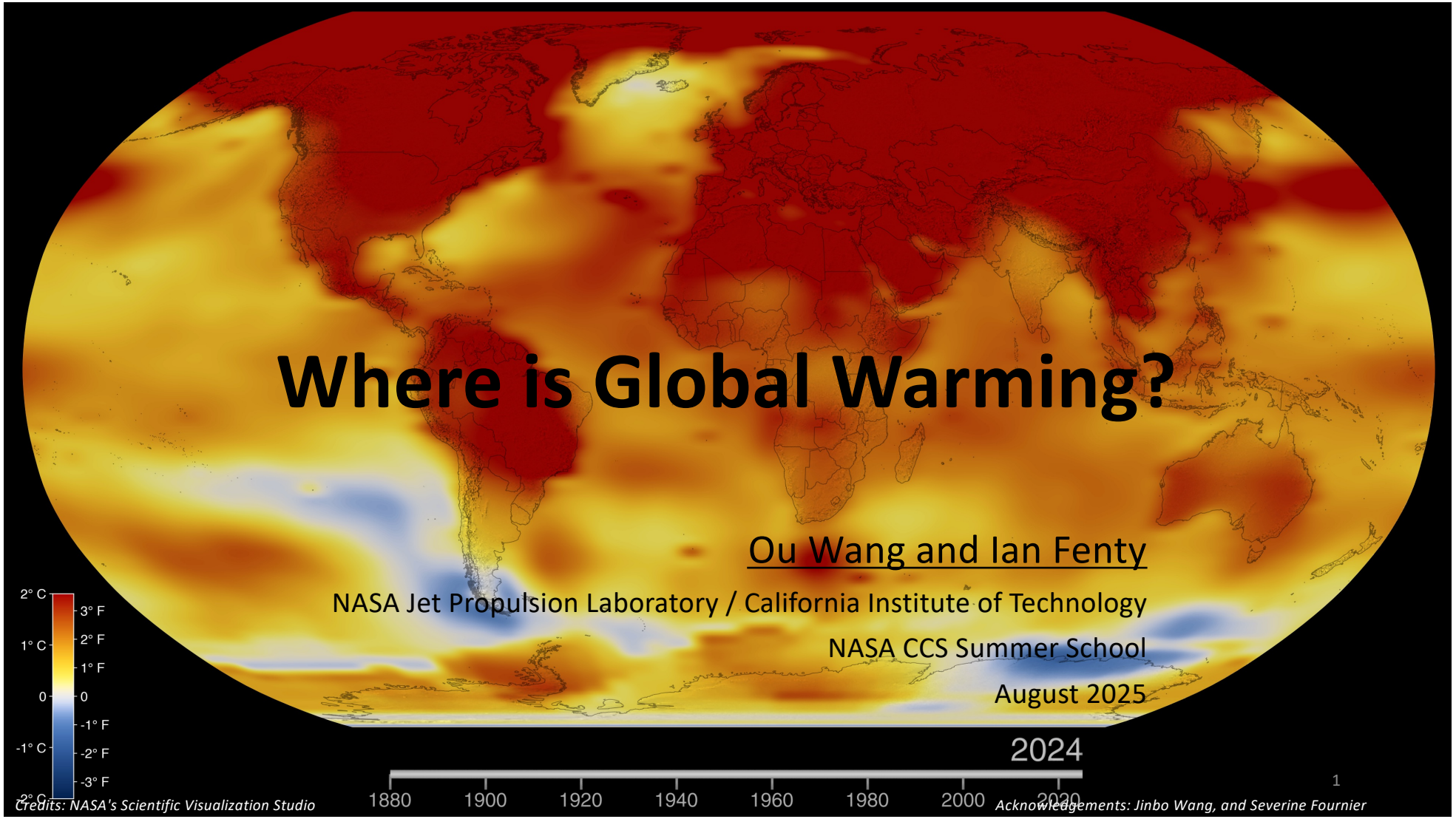

Where is Global Warming?

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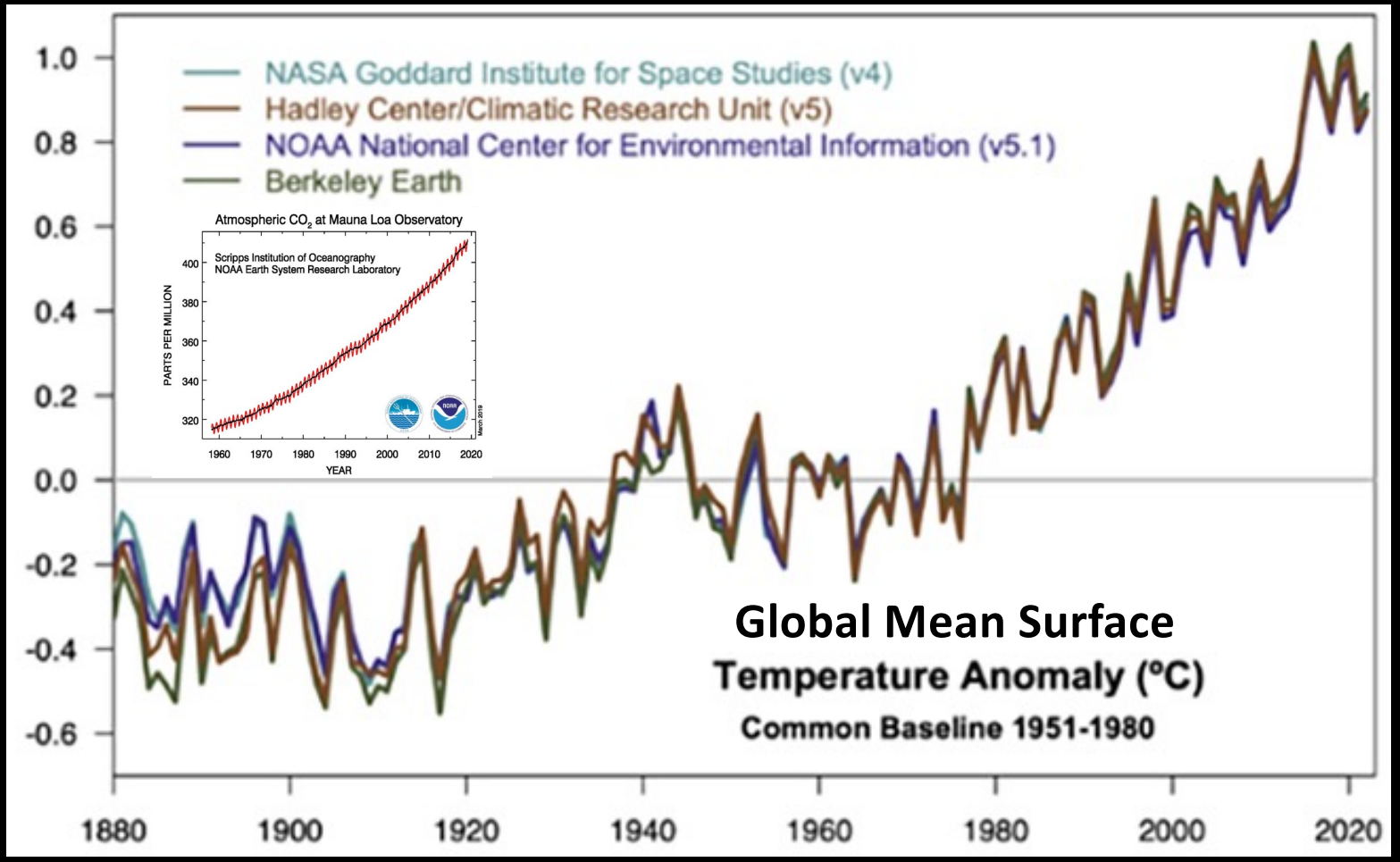
NASA CCS Summer School

August 2025

Credits: NASA's Scientific Visualization Studio

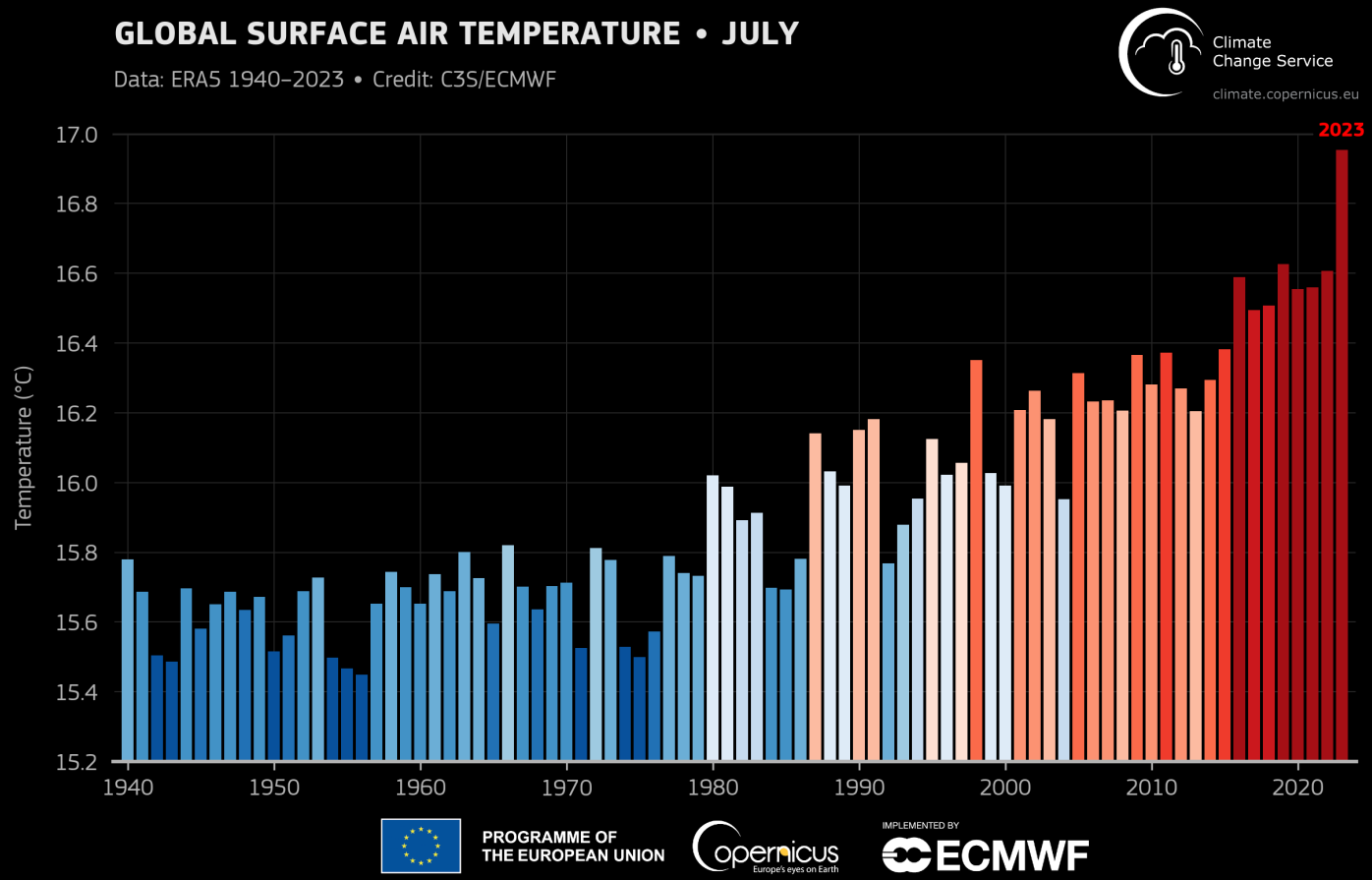
Acknowledgements: Jinbo Wang, and Severine Fournier

Earth is warming



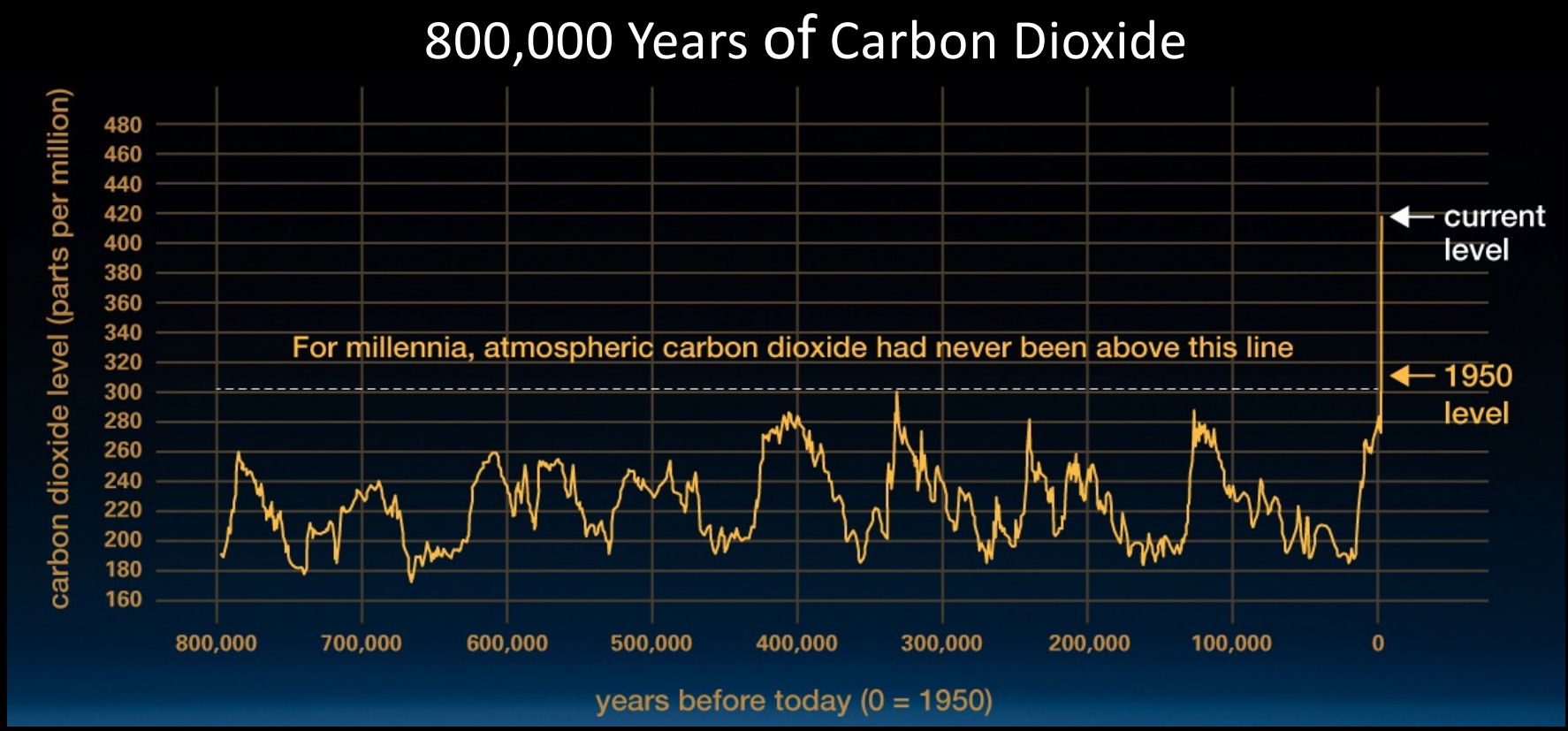
Credits: NASA GISS

July 2023, the warmest month on record

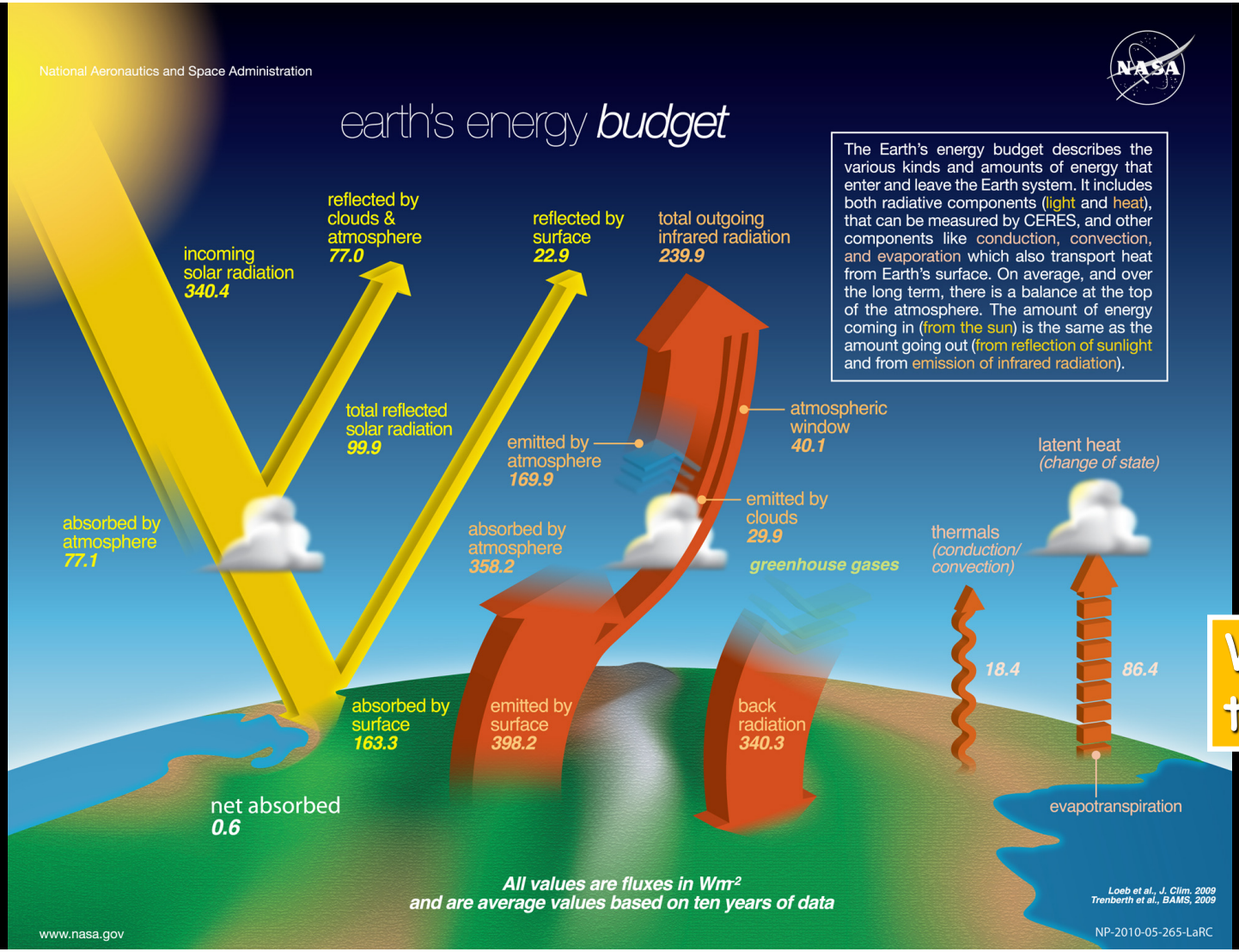


Credit: C3S/ECMWF

What really causes global warming?



Credits: climate.nasa.gov



~0.6W/m² energy imbalance (receiving more than emitting)

What happens to the heat?

Energy balance model

$$\rho C_p \frac{dT}{dt} = Source - Sink$$

Credits: NASA/JPL-Caltech

Is 0.6W m^{-2} energy imbalance significant

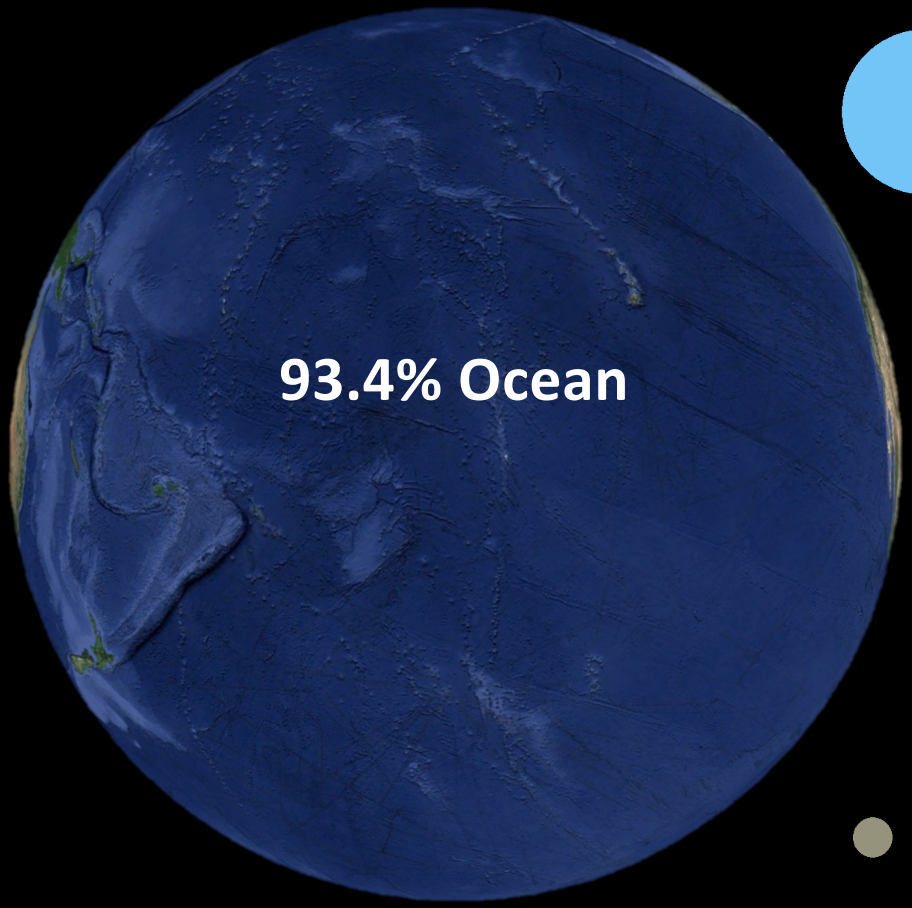
A ~0.6W/m^2 energy imbalance might seem small compared to the incoming solar radiation (340.4 W/m^2). But is it significant?

It certainly is, given the vast global surface area of Earth: 5.1x10^{14} m^2.

Each year, the global energy imbalance is more than 10 times the total energy consumed globally by humanity.

Credits: NASA

Where is all the heat going?



Atmosphere
2.3%

Continents
2.1%

Glaciers
0.9%

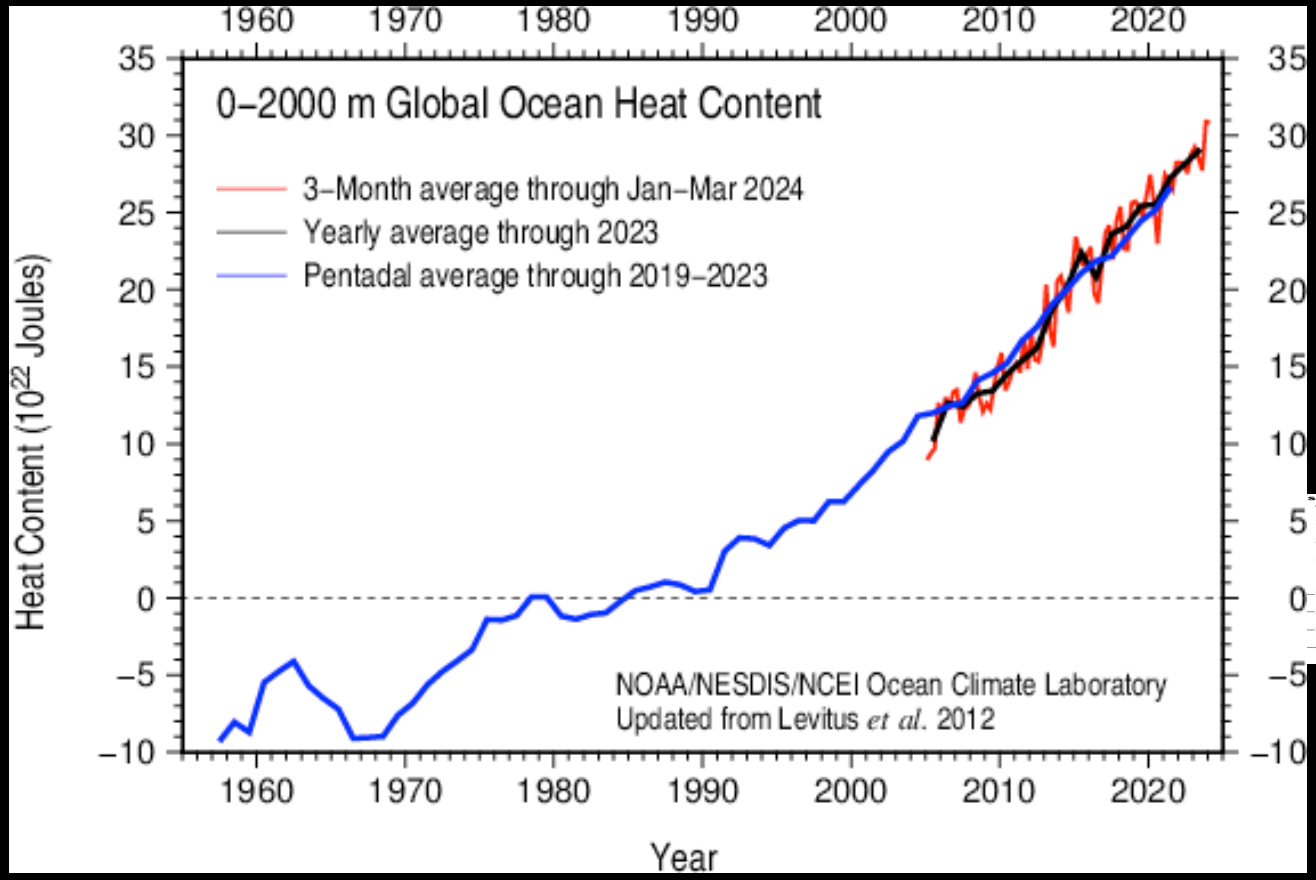
Arctic sea ice
0.8%

Greenland Ice Sheet
0.2%

Antarctic Ice Sheet
0.2%

Credit: IPCC

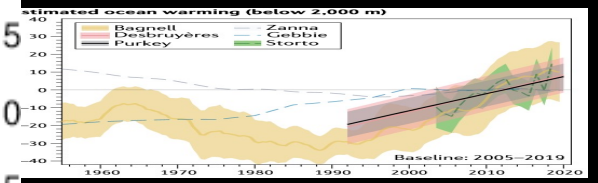
Ocean heat has steadily increased



Global ocean heat content has steadily increased. The heat is mainly gained in the upper 2,000 m.

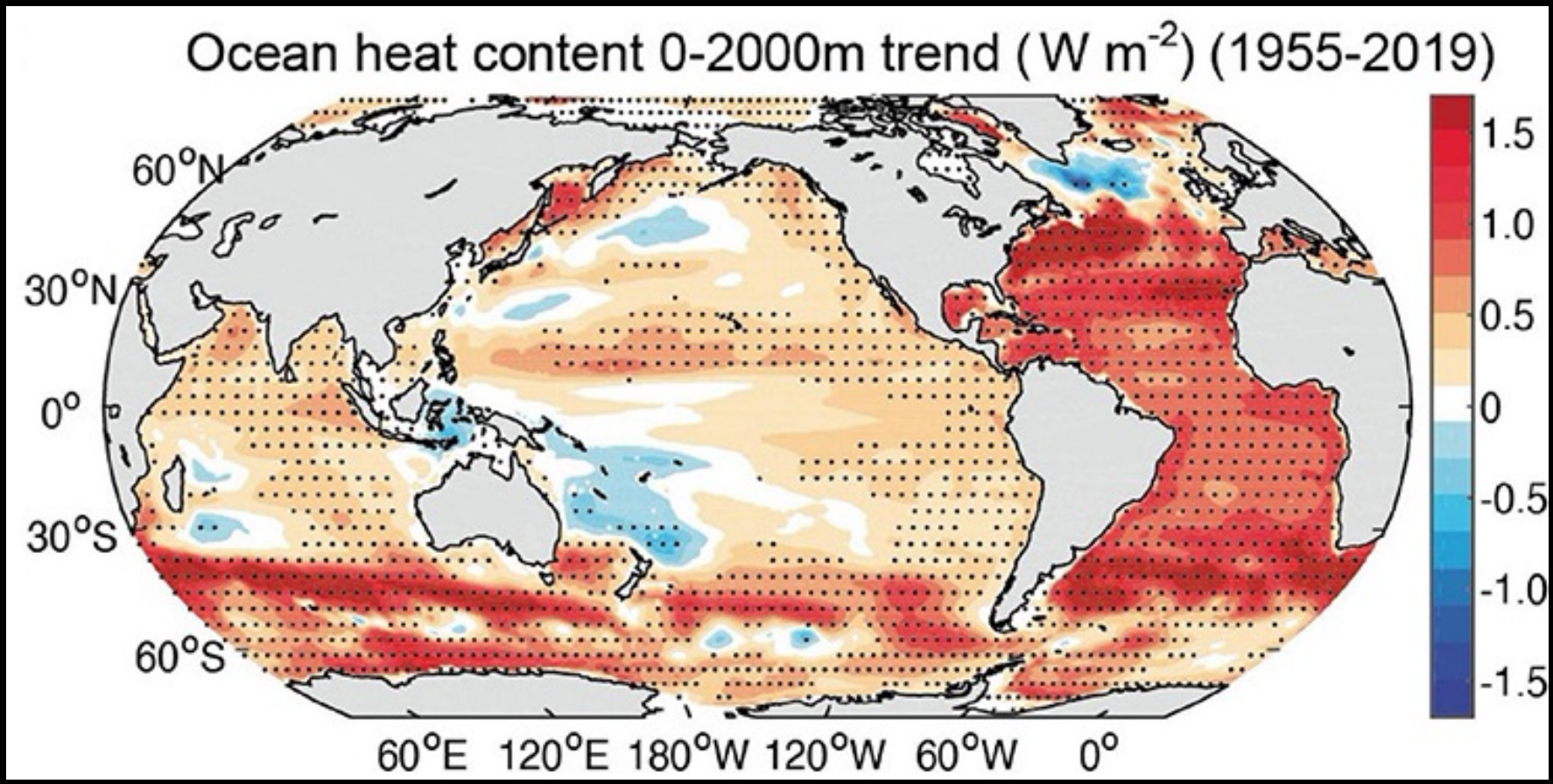
Since 2003, Argo floats have revolutionized the measurements of ocean properties at depth.

Below 2000 m



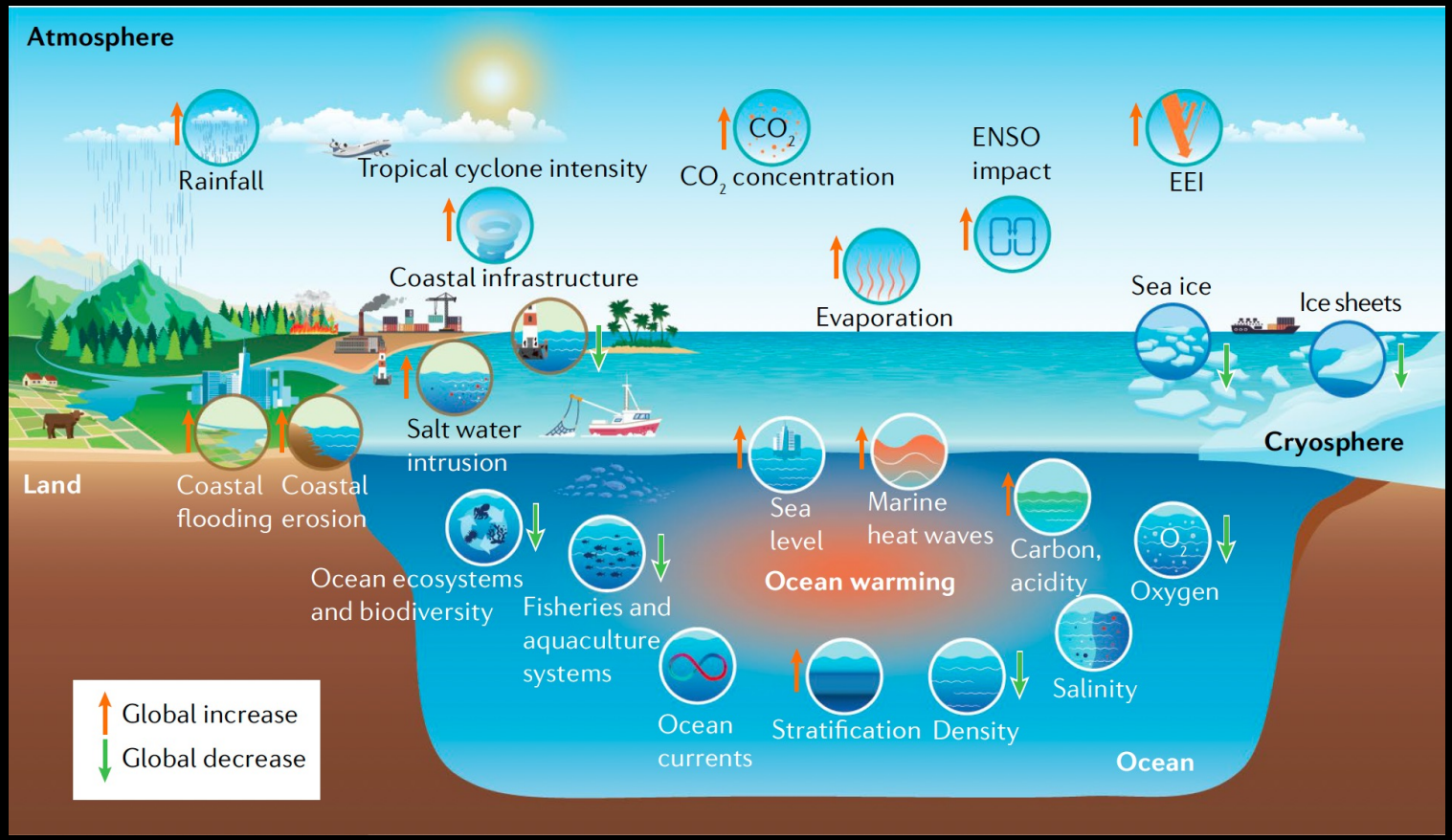
Cheng et al. (2022, Nature)

Ocean warming is not uniform



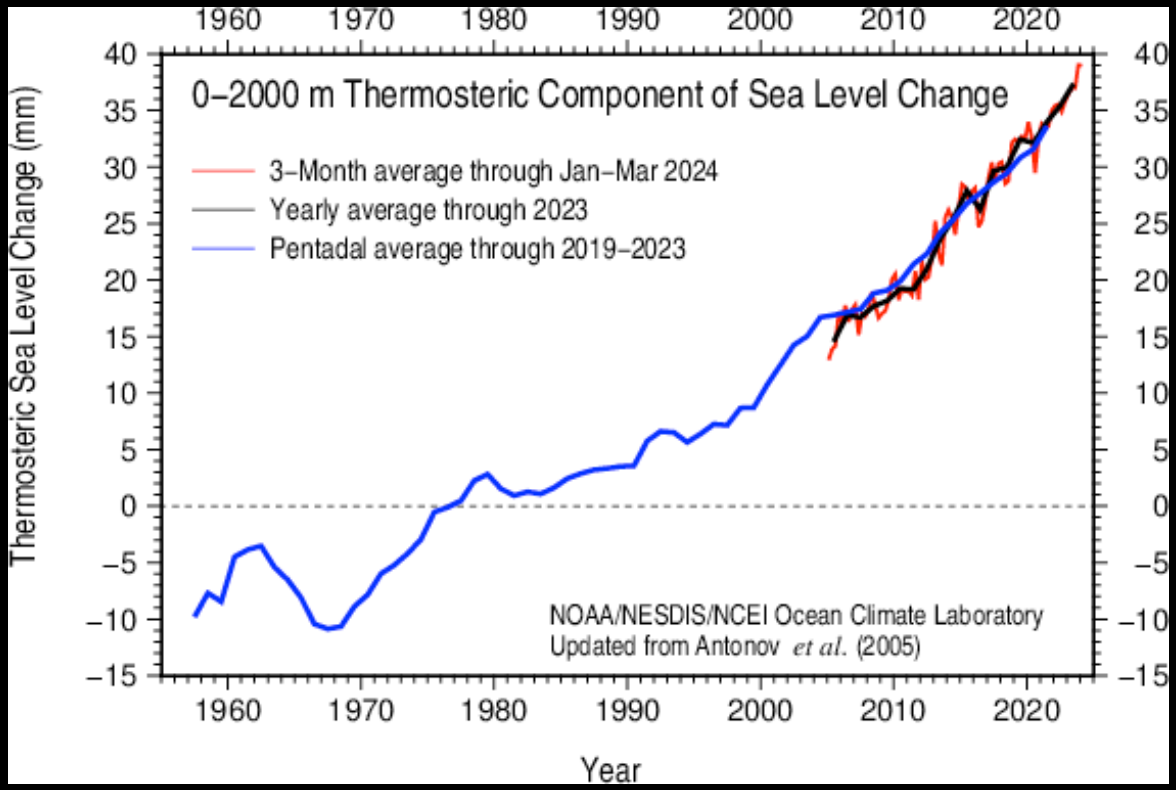
Garcia-Soto et al. (2021, Frontiers in Marine Science)

Linkage between ocean warming and changes in Earth system



Cheng et al. (2022, Nature)

Sea Level Rise, a consequence of global warming



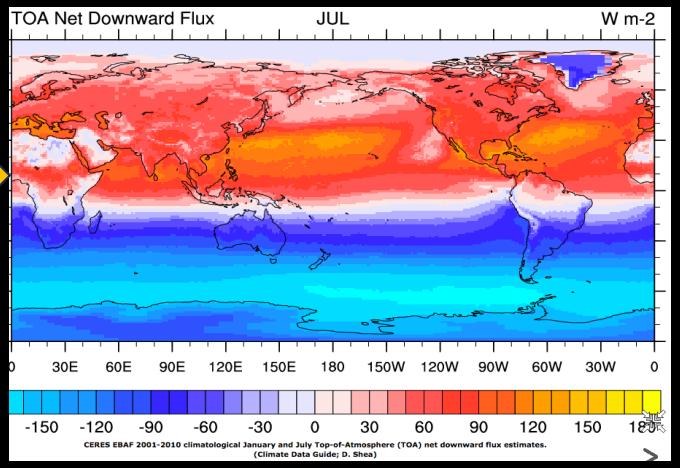
Since 1960: 5.5 inches global sea level rise:

1. The expansion of seawater associated with the warming ocean (thermal expansion) contributed about 1.8 inches (1/3)

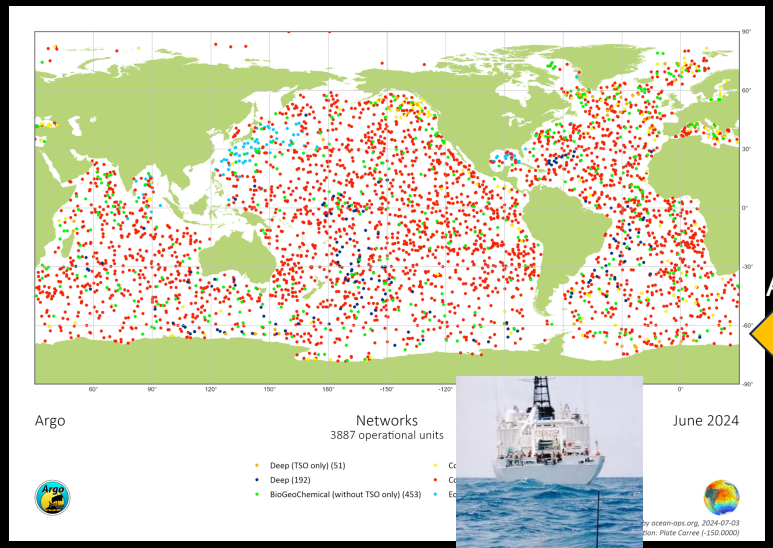
2. Melting of ice sheets and mountain glaciers have contributed about 3.7 inches (2/3)

How to quantify where the energy from Earth's net radiative imbalance is accumulating?

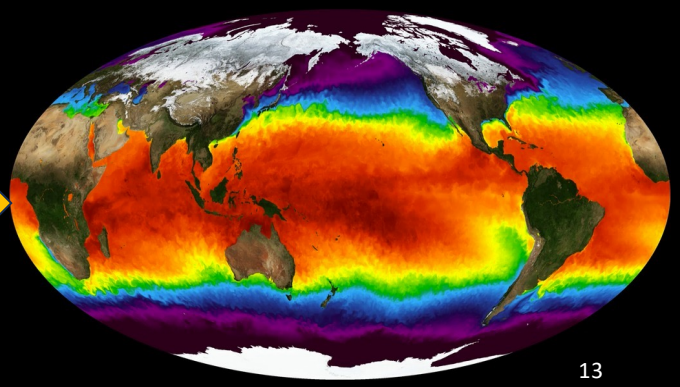
Top of atmosphere radiation
(Energy fluxes)



Argo global array of ocean profiling floats
(Ocean Interior Thermal Energy)



Satellite sea surface temperature
(Earth surface temperature)



Topic: Where is global warming?

- **Datasets**: TOA shortwave and longwave, AMSR-E sea surface temperature, Argo ocean temperature, sea level, and ocean mass
- **Geographic foci**: mid latitudes (+-60-30), low latitudes (+-30-0)
- **Introduction**: In 2015 the Earth crossed a major global warming milestone: the global mean surface air temperature was one degree Celsius warmer than the mid-19th century pre-industrial average. Yet, the road to this 1 degree of atmospheric warming was bumpy: air temperatures in 2012 were the same as 1998 and 2002. If we really want to see where the excess energy of global warming is going, we need to quantify changes in the energy storage in Earth's largest thermal reservoir: the ocean.
- **Bonus**: Global mean sea levels are rising because of two main factors: ocean thermal expansion (from seawater warming) and the addition of liquid mass (from melting land ice). Today, the ocean observing system allows us to 'close' the sea level budget, in other words to compare total observed sea level rise from satellite altimetry with the expected sea level rise from ocean warming (using Argo temperature data), and the measured increase in ocean mass. With the datasets provided, you can compare sea level rise is associated with ocean warming and where it is associated with ocean mass increase.

Contact Scientists: Dr. Ou Wang (Ou.Wang@jpl.nasa.gov) and Ian Fenty (Ian. Fenty@jpl.nasa.gov)

Topic: Where is global warming?

- **Questions:**
  1. Global warming is a consequence of an energy imbalance: more shortwave radiation absorbed at the top of the atmosphere (TOA) than re-emitted longwave and reflected shortwave. Calculate the global net radiative flux imbalance at the top of the atmosphere (TOA). How does this compare with published estimates? How has this number changed through time? *Note: when spatially averaging TOA fluxes, make sure you consider the fact that mapped grid cell areas change as a function of latitude.*
  2. If Earth's radiative flux imbalance were entirely absorbed in the troposphere (assume the lower 10 km of atmosphere), what would be the average annual increase in GMSAT? How does your predicted temperature change compare to the actual change through time? *Note: atmospheric density decreases with height*
  3. Repeat all parts of question (2) but instead consider that the entire radiative flux imbalance warms the upper 10 m, 100 m, 700 m, and 2000 m of the global ocean, respectively. Compare the predicted temperature changes against observed changes on a global scale. How do the actual warming trends of each of these depth categories compare against predictions?
  4. Divide the ocean into 4 basins: Pacific, Indian, Atlantic, and Southern Oceans. Which basins and which depths account for the greatest observed warming?
- **Notebooks:**
  - **Meet the data notebooks are complete and re-runnable. The other notebooks are placeholders, ready for you.**

  0. Project Introduction

  1a-d: Meet the data: CERES Top of Atmosphere Fluxes, Argo ocean Temperature, Satellite Sea Level Anomaly , and GRACE Liquid Water Equivalent

  2: TOA Energy Imbalance (CERES data)

  3. Ocean Heat Uptake (Argo data)

  4. Ocean Heat Uptake vs TAO (results from 2&3)

  5. Sea Level Budget (uses Sea Level, Ocean Mass, and Argo temperature)

  6. Regional Patterns (results from 1-5)

Contact Scientists: Dr. Ou Wang (Ou.Wang@jpl.nasa.gov) and Ian Fenty (Ian. Fenty@jpl.nasa.gov)