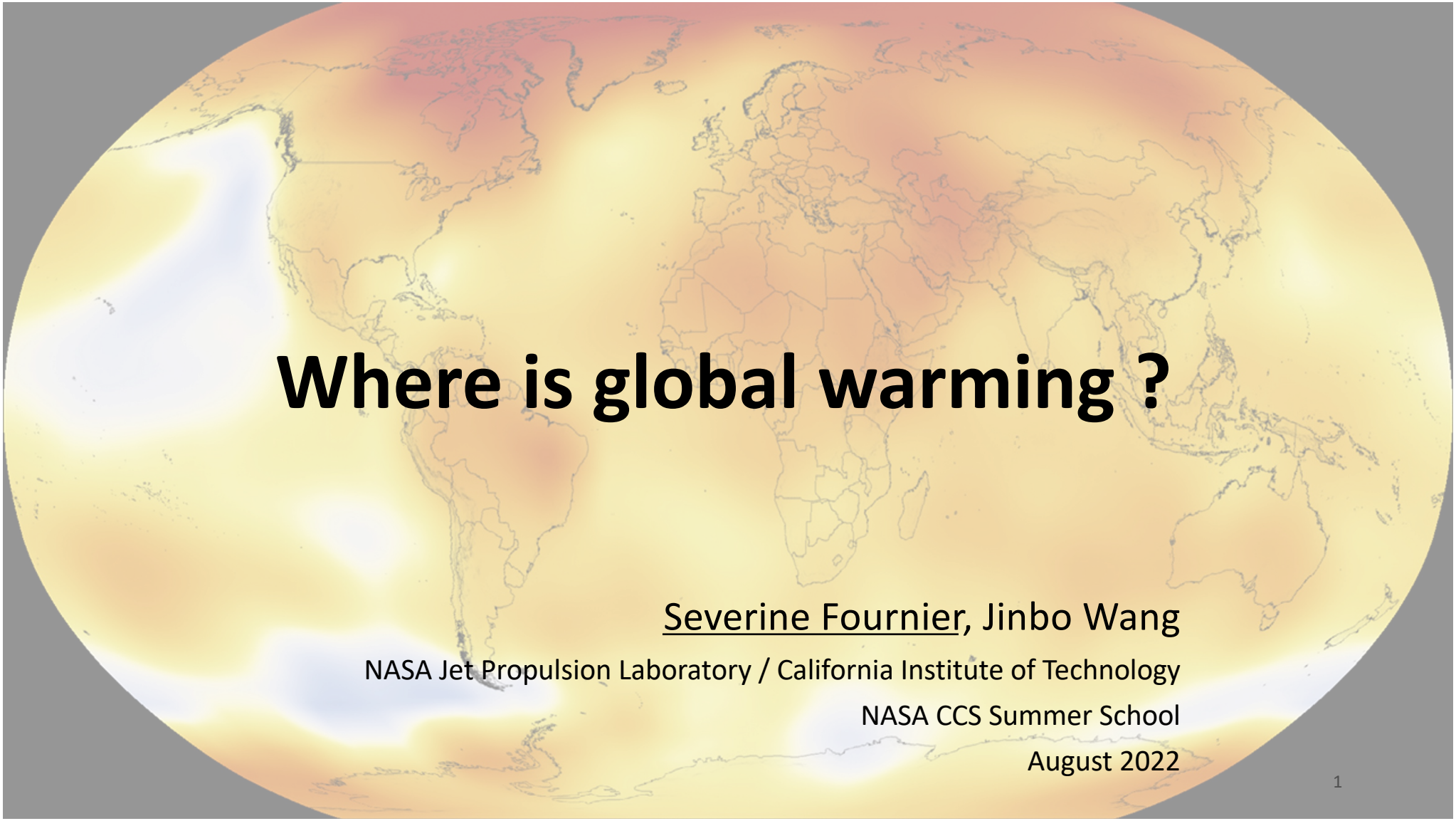

Where is global warming ?

Severine Fournier, Jinbo Wang

NASA Jet Propulsion Laboratory / California Institute of Technology

NASA CCS Summer School

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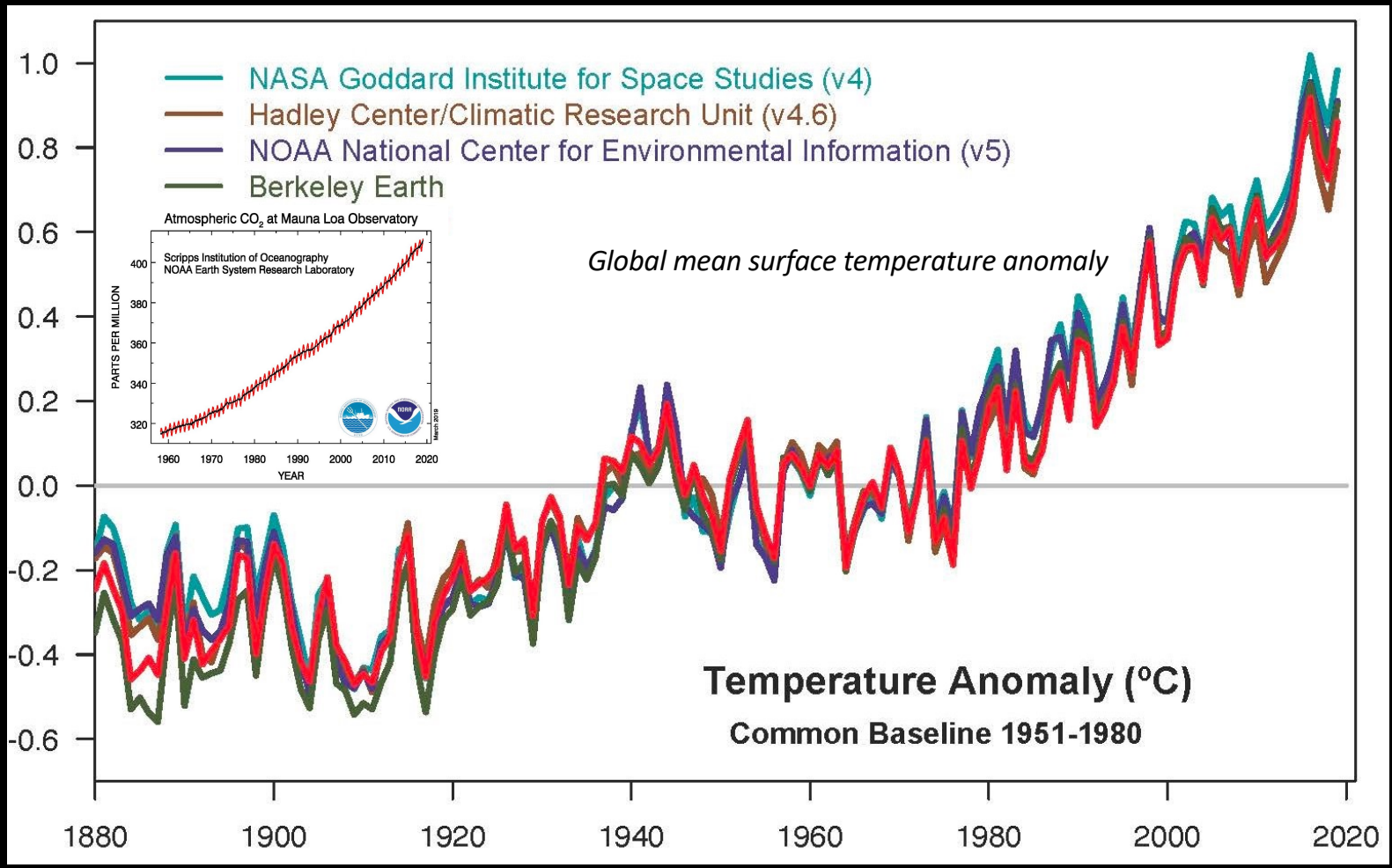
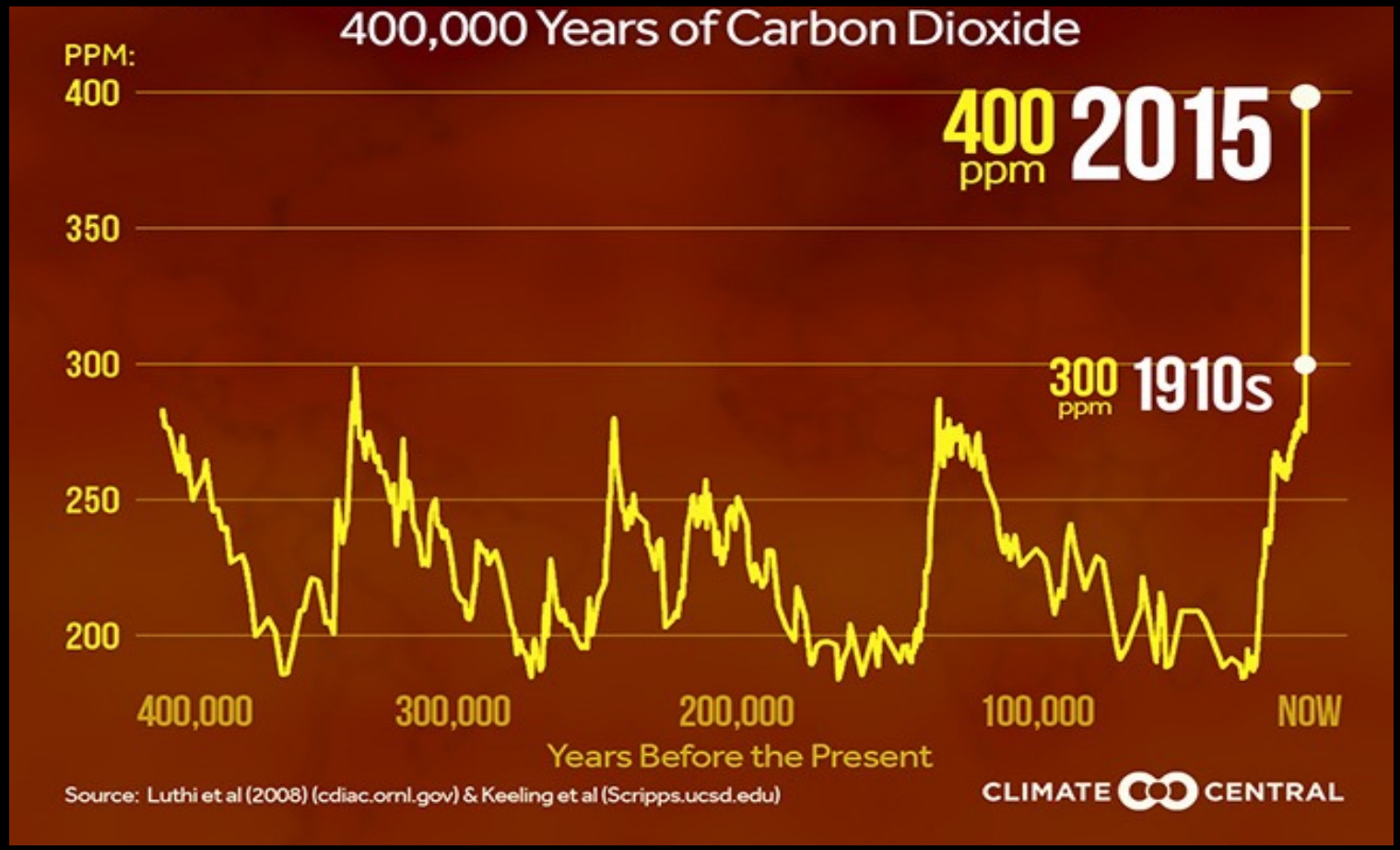
The Earth is warming

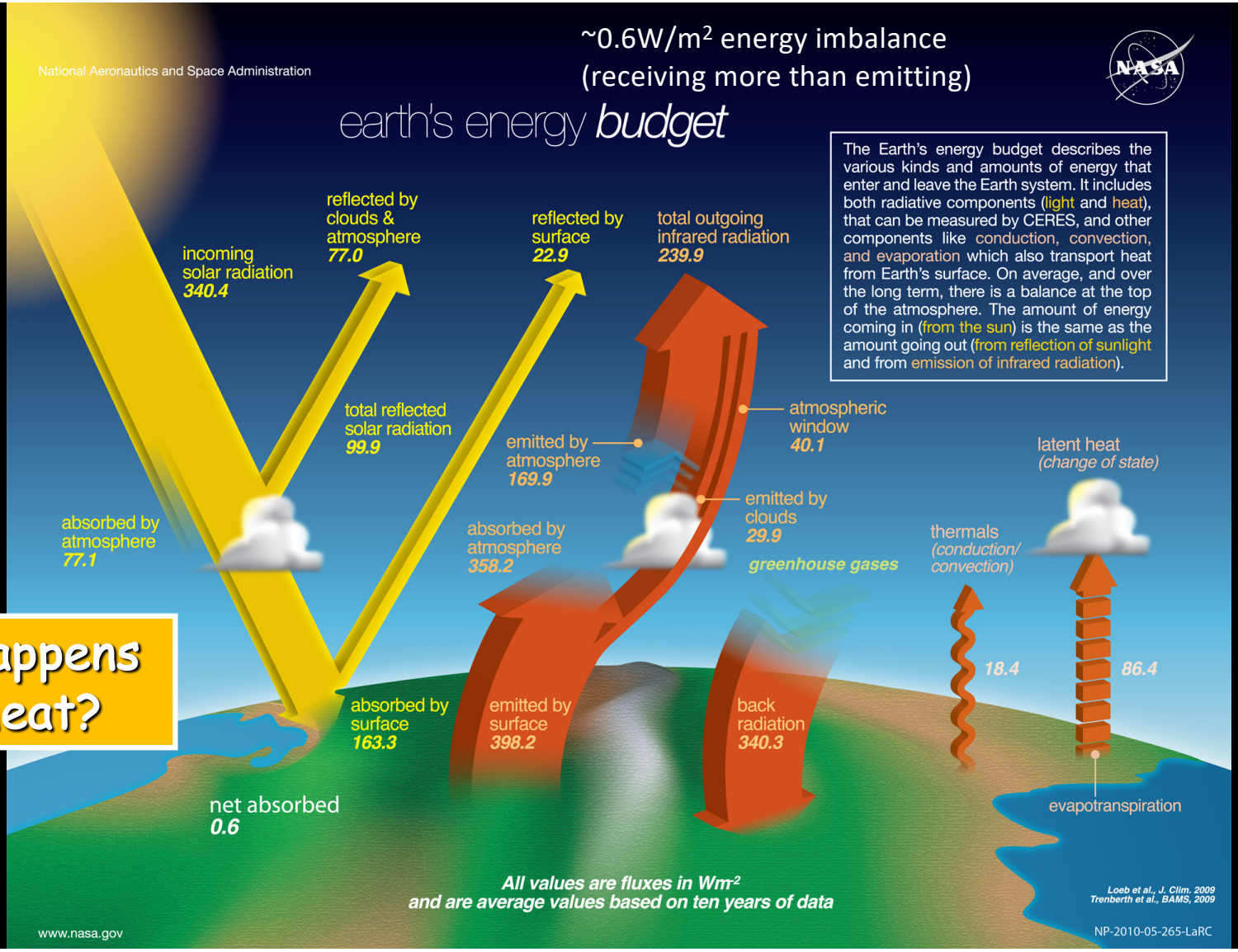


Credits: NASA GISS/Gavin Schmidt

What really causes global warming?

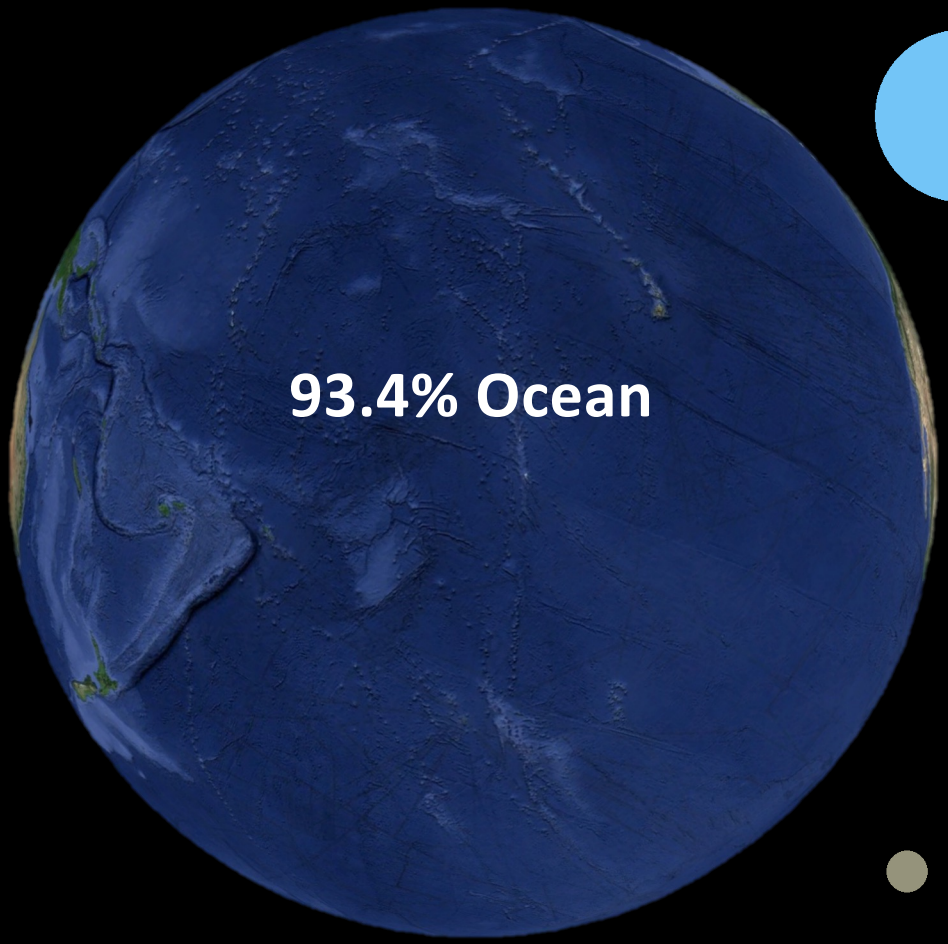


~0.6W/m^2 energy imbalance
(receiving more than emitting)



What happens to the heat?

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%

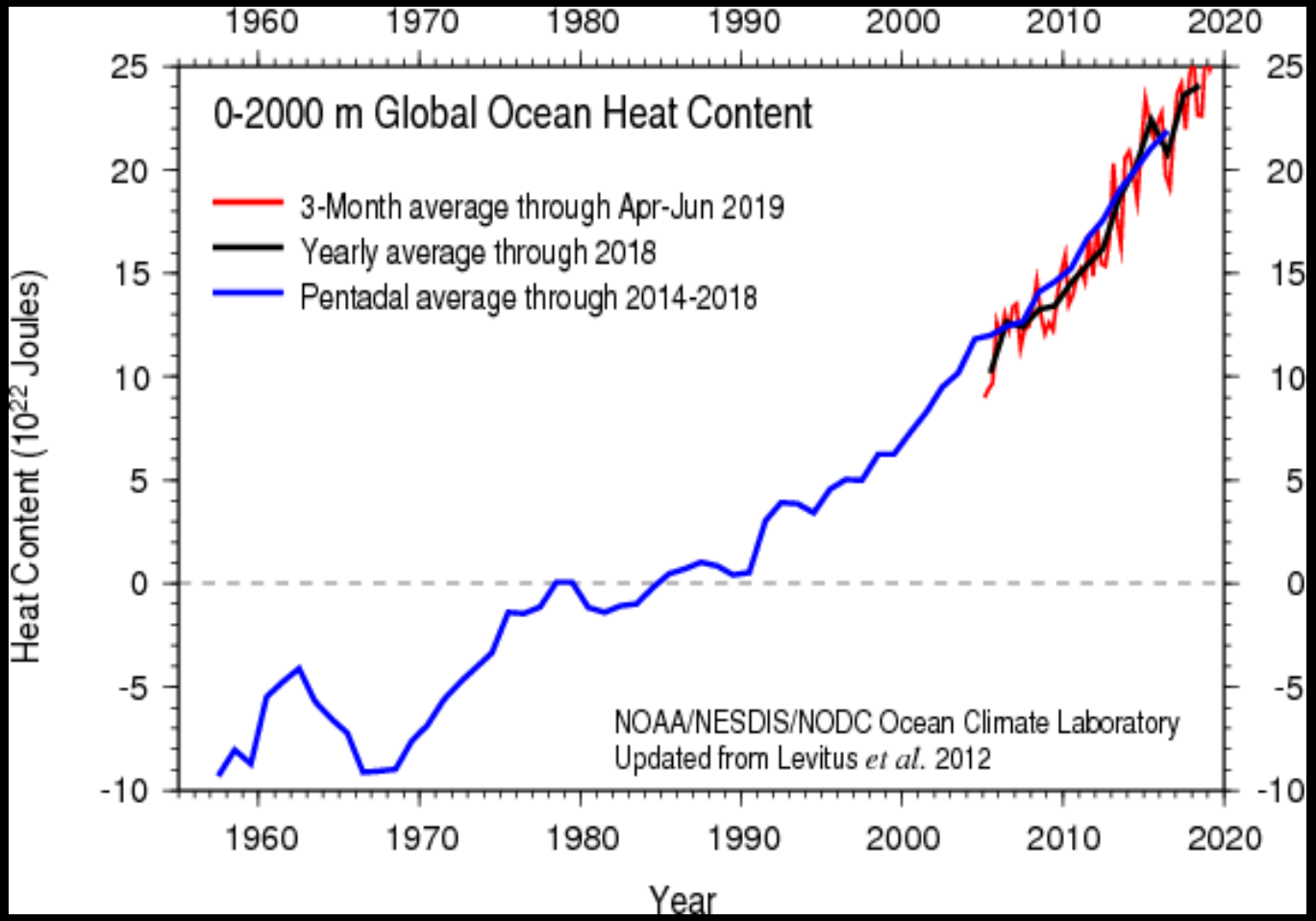
Antarctic Ice Sheet
0.2%

Credit: IPCC

Energy balance model

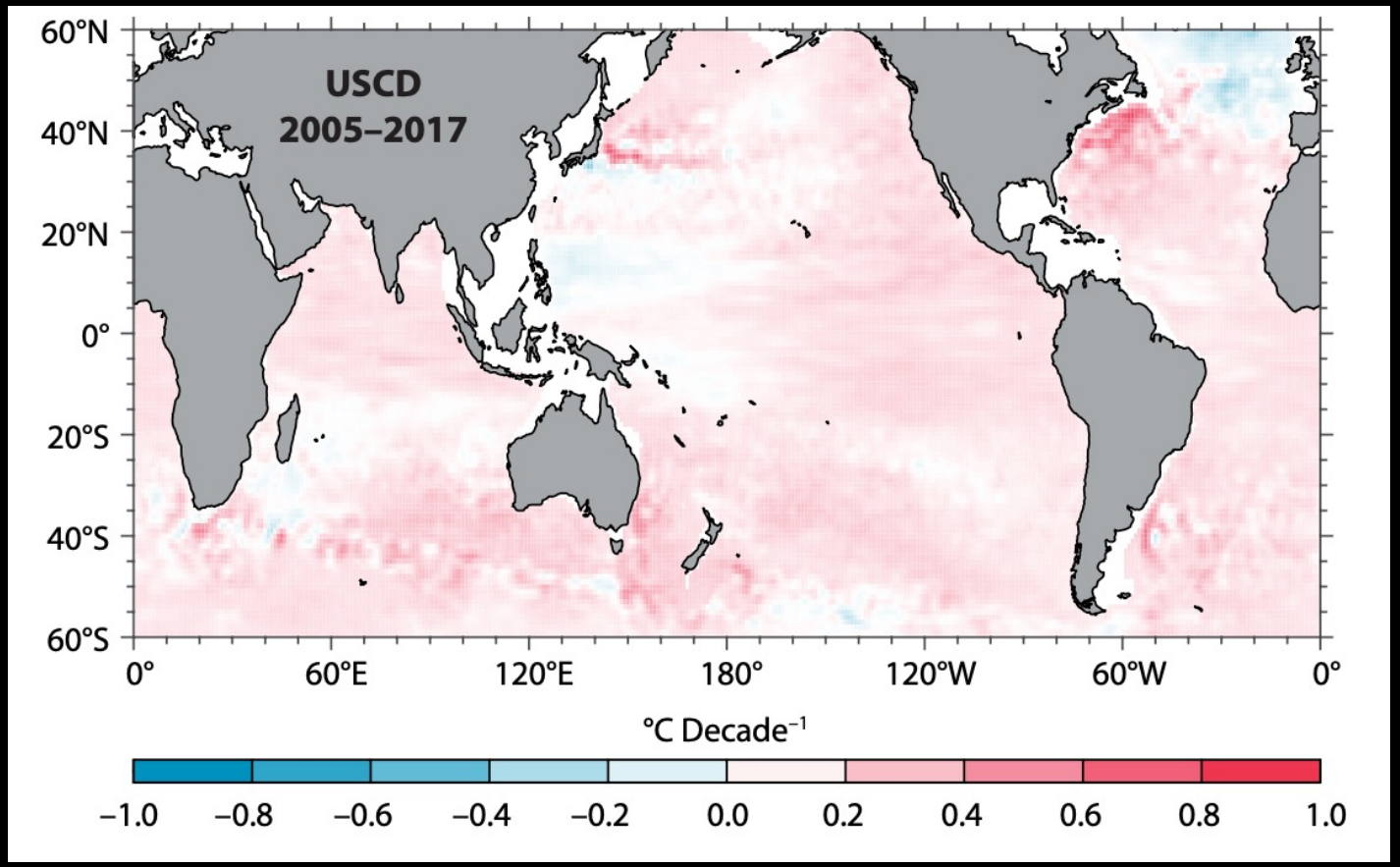
$$\rho C_p \frac{dT}{dt} = Source - Sink$$

Ocean heat has steadily increased



Every year, the amount of new heat energy absorbed by the ocean is about 10 times the amount of energy harnessed from **every energy source used for all of humanity's endeavors across every single industrial and technological sector**

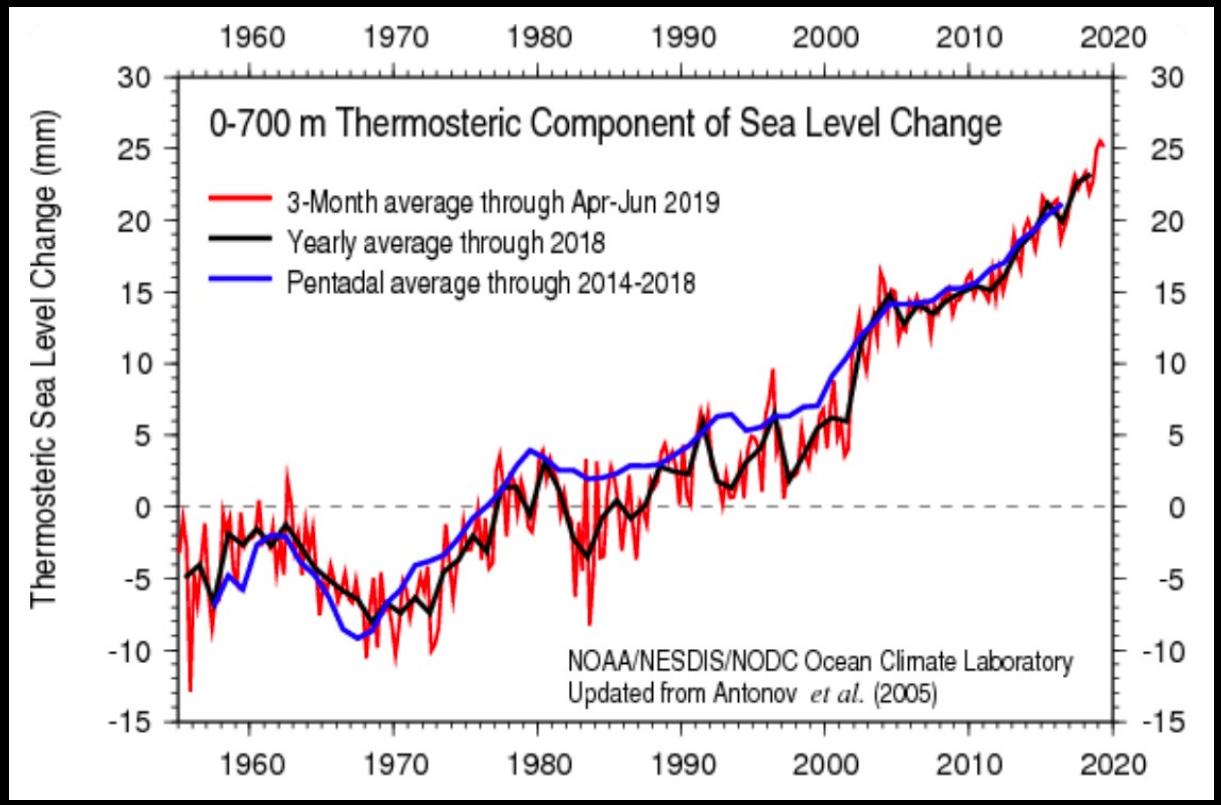
Ocean warming is not uniform



Depth-averaged warming trend from 2005 to 2017

Durack et al., 2018, Oceanography

Sea Level Rise, a consequence of global warming

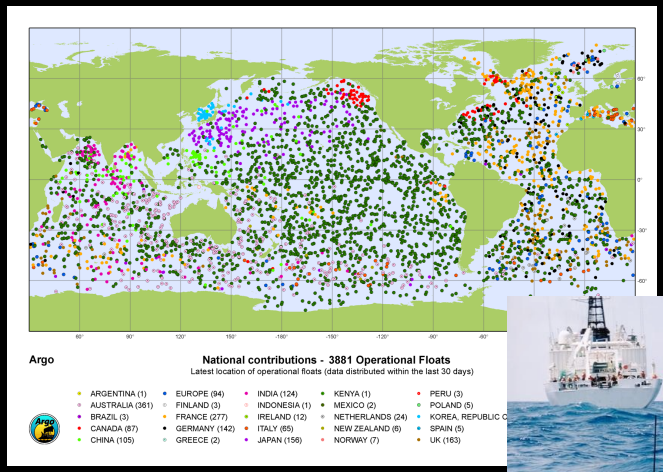


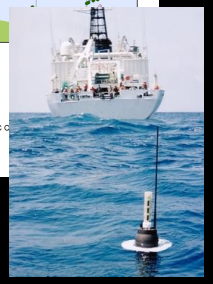
Since 1960: 5 inches global sea level rise:

1. The expansion of seawater associated with the warming ocean (thermal expansion) contributed about 1.6 inches (1/3)

2. Melting of ice sheets and mountain glaciers have contributed about 3.4 inches (2/3)

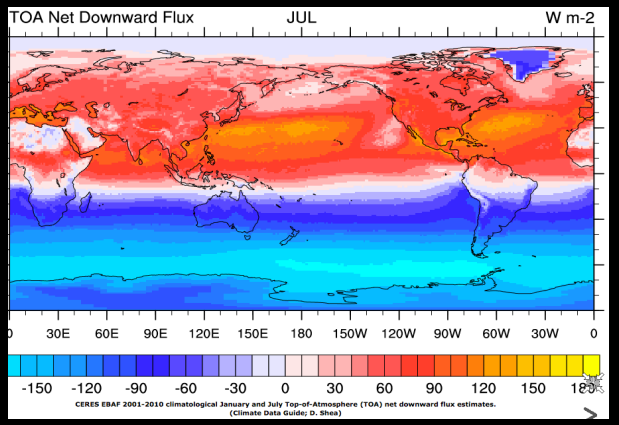
How to quantify where the energy from Earth's net radiative imbalance is accumulating?



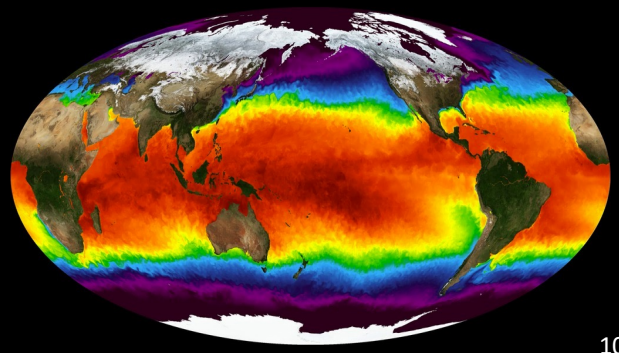


Argo global array of ocean profiling floats *(Ocean Interior Thermal Energy)*

Top of atmosphere radiation *(Energy fluxes)*



Satellite sea surface temperature *(Earth surface temperature)*



Topic #1 – Where is global warming?

- **Datasets**: ARGO ocean temperature, AMSR-E sea surface temperature, TOA shortwave and longwave
- **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 (GMSAT) 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: the GMSAT anomaly in 2012 was the same as 2002 and 1998. Because the heat capacity of the atmosphere is much smaller relative to the ocean, much of the year-to-year variability in GMSAT is driven by natural temperature variations of the ocean surface. 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.
- **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 the 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. Compare the predicted temperature changes against observations by using AMSR-E SST data as a proxy for the upper 10 m ocean temperature, and ARGO data for the upper 100, 700 and 2000 m. 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?
    5. Compare the year-to-year variations in GMSAT over the past 30 years with variations in the annual mean SST for each of the basins in Question 4. Which basin's SST is the most correlated with GMSAT?
- **Contact Scientist: Dr. Jinbo Wang (Jinbo.Wang@jpl.nasa.gov); Dr. Severine Fournier (severine.fournier@jpl.nasa.gov)**