Earth's climate has always changed; human civilization is new.

- 12,000 years ago glaciers receded
- Unusually long stable climate period
- <0.5°C change, globally

- Sudden development of humans from Stone Age hunter-gatherers to modern societies
  - agriculture
  - permanent dwellings
  - growth of villages, specialization of roles
  - megafaunal extinctions?

Lascaux cave painting, 20,000 ybp, Field Museum. This image is in the public domain.

Now there's a lot more in harm's way.

Human culture advances on order of magnitude time scales (YBP):

- 2,500,000 - first evidence of stone tool use
- 200,000 - development of *Homo sapiens*
- 12,000 - development of agriculture, society, permanent residences
- 200 - development of industry, use of fossil fuels
- 20 - internet

Pre-industrial climate change

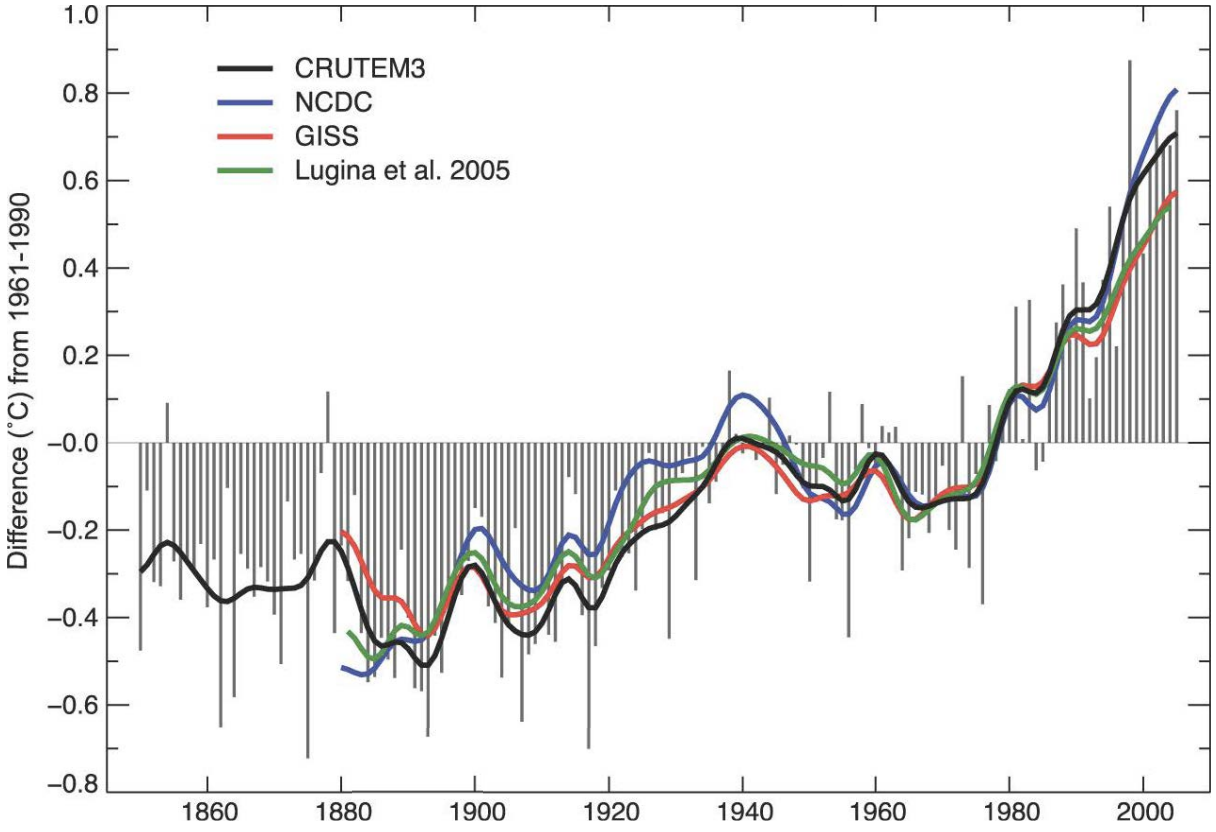
Humans began altering the climate.

- Evidence that early agriculture increased atmospheric CO_2 and CH_4 as early as 5000 YBP
- Rice irrigation began 5000 YPB, increase in irrigated area correlates with CH_4 rise
- Europe, Asia, deforestation for agriculture already widespread by 1086, likely earlier

Climate Change since 1850

Information sources:

- Instrumental records
- Satellite observations
- Sea level rise + attribution

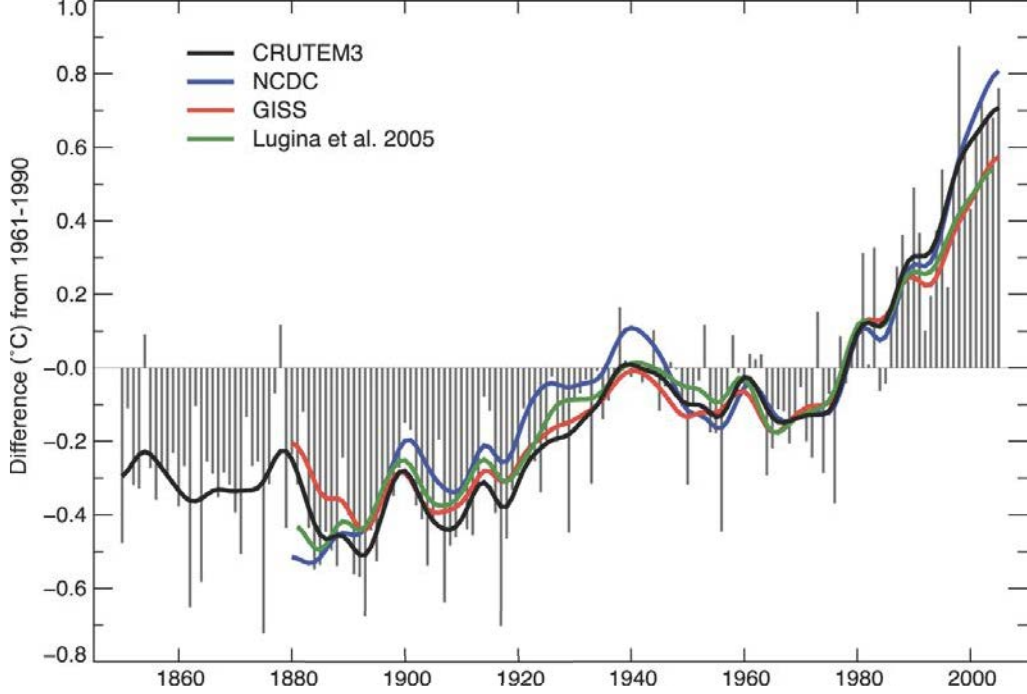


IPCC AR4, Fig. 3.1

Climate Change since 1850

Information sources:

- Instrumental records
- Satellite observations
- Sea level rise + attribution



IPCC AR4, Fig. 3.1

Complications in interpreting records: climate oscillations

- El Niño Southern Oscillation
- Pacific Decadal Oscillation
- North Atlantic Oscillation

Instrumental records

- Surface thermometers
- Radio sondes
- Subsurface ocean temperatures
- Widespread melt of mountain glaciers

Instrumental records

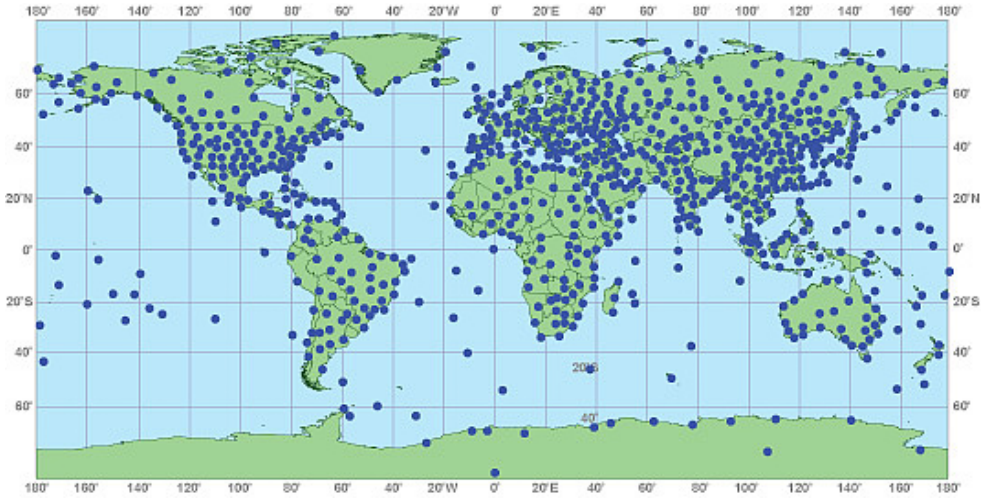
Surface thermometers

- Coverage has increased significantly since 1800’s
- Must be corrected for urban heat island effect (many stations are near population centers)
- Historical sea surface temps must be calibrated to modern methods (buckets, engine rooms)
- Global average increase of 0.9°C since 1900

Radiosonde or weather balloon

- Instrument package includes temp, humidity, pressure, GPS coordinates; transmit data to ground station in real time during ascent
- Can ascend up to 35 km, ~2 hr flight
- Launched 2x/day at over 800 locations globally; data shared through international agreements
- Record adjusted for solar heating on instrument casing (daylight launches only)

Radiosonde being launched by NOAA Earth System Research Lab



Radiosonde locations worldwide

Instrumental records

Subsurface ocean temperatures

- “Surface” = top 100m, typically well-mixed
- Measurements since ~1955
- Heat moved by diffusion, sinking water masses
- 0.07°C increase since 1950s represents large amount of heat storage (more than 10x atmospheric storage)

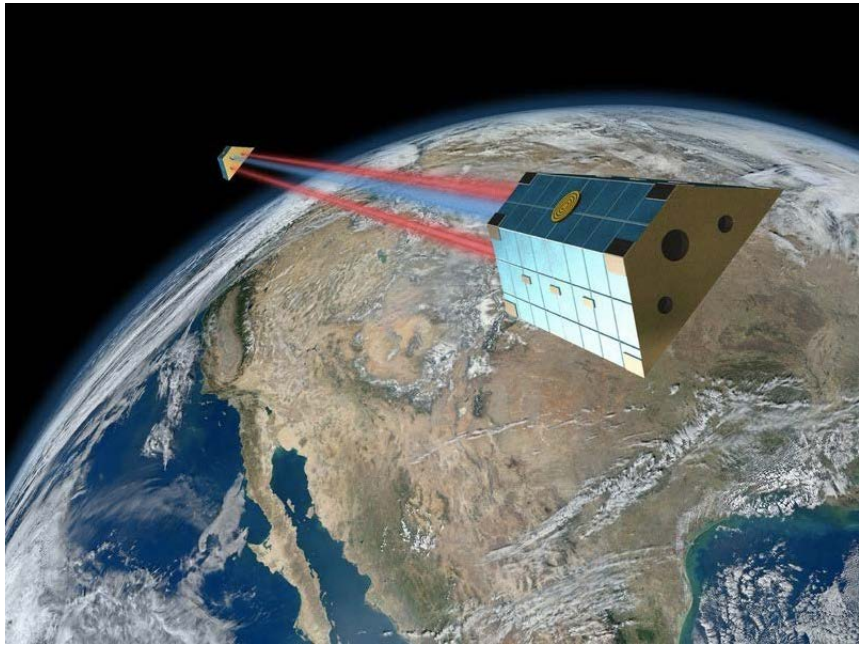
Instrumental records

Widespread melt of mountain glaciers

- Mountain glaciers = 4% of surface land ice
- Glaciers measured from 1860 – 1900 already showed retreat
- Almost every glacier measured is retreating; some have melted entirely
- Global average of 1.5 km of retreat since 1800s
- In 1850, 150 glaciers in Glacier National Park. By 2015, only 26 remain

Satellite Observations

- Arctic warming
- Melting ice sheets
- Disagreement between satellite and ground stations: resolved



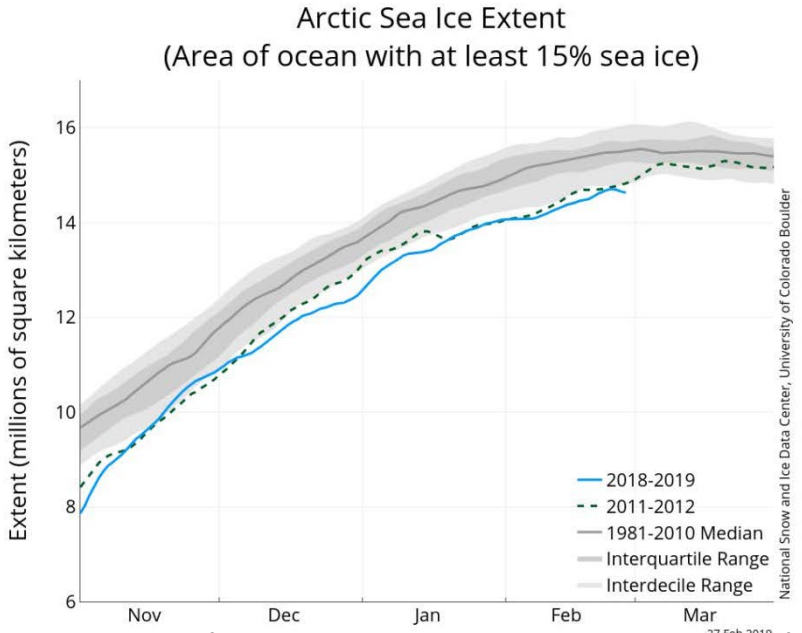
NASA GRACE satellite, artist's rendition (NASA/JPL)

Disko Bay, Greenland (NASA), Ian Joughin, University of Washington

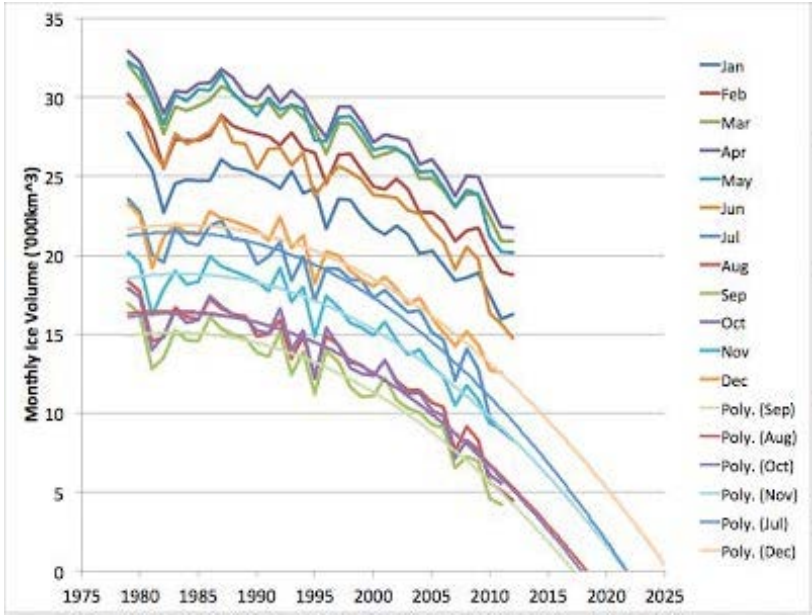
Satellite Observations

Arctic warming

- Arctic is warming 2x faster than global average
- Sept. sea ice reduced by 40% since 1970s
- Reductions in both cover and thickness of ice
- Growing season in Alaska two weeks longer now than in 1960s
- Northwest Passage now open in fall months



Figures courtesy of the National Snow and Ice Data Center, University of Colorado, Boulder. This content is in the public domain.

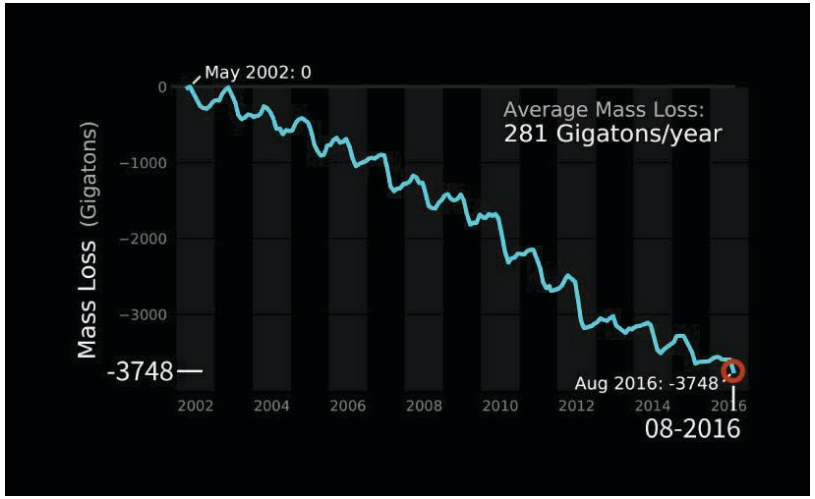


Seasonal trends in Arctic sea ice volume, with hypothetical projections. NSIDC/Staniford

Satellite Observations

Melting ice sheets

- Since 2002, measured with GRACE satellites; measures gravitational pull, essentially “weighs” ice sheets
- Greenland shows decline and increasing *rate* of decline
- Antarctica is more variable, higher uncertainty (also order of magnitude more ice than Greenland



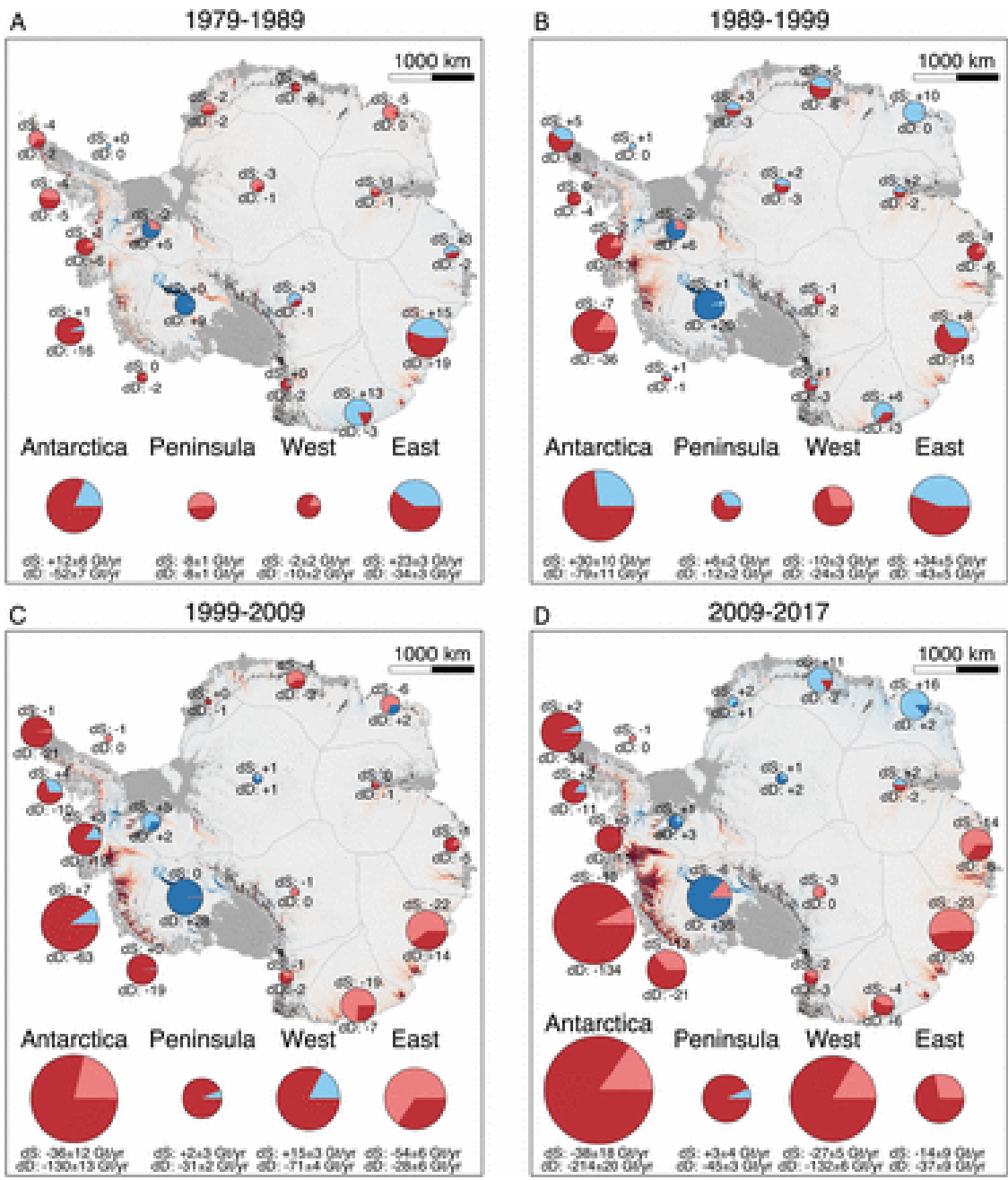
Loss of ice mass from Greenland as measured by GRACE

Courtesy of NASA. Image is in the public domain.

Satellite Observations

Melting ice sheets

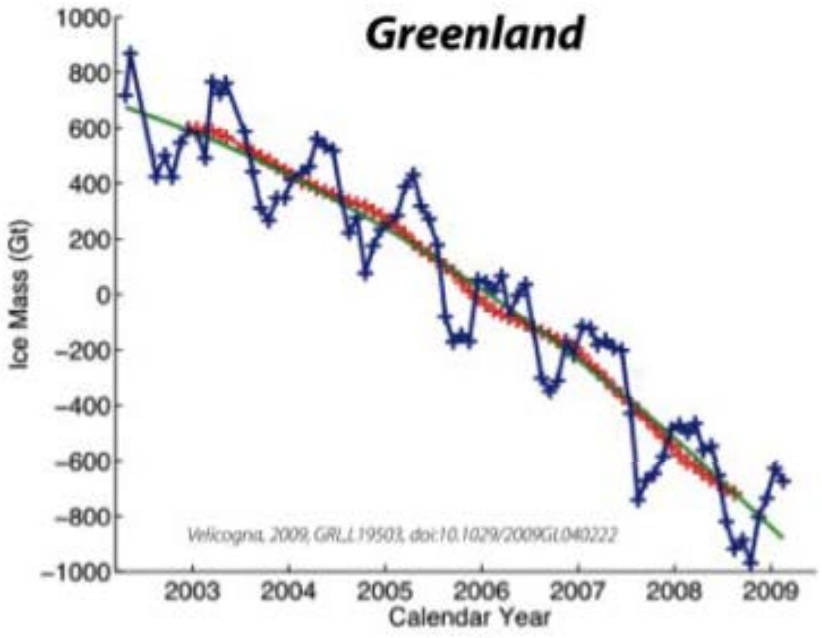
- Since 2002, measured with GRACE satellites; measures gravitational pull, essentially “weighs” ice sheets
- Greenland shows decline and increasing *rate* of decline
- Antarctica is more variable, higher uncertainty, but melt rate appears to be increasing there too

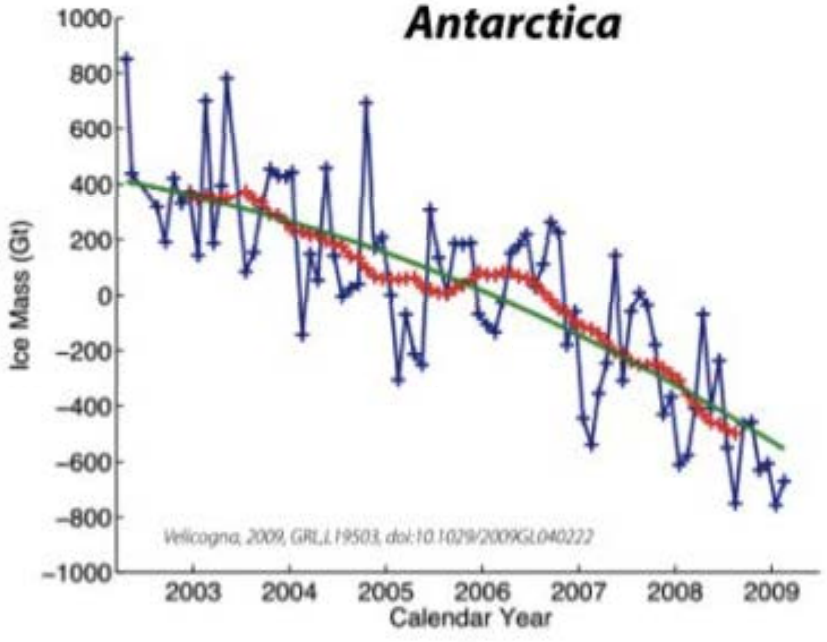


Rignot et al. 2019. Red = ice loss, blue = ice gain; size of circle proportional to absolute magnitude of anomaly.

Satellite Observations

Melting ice sheets





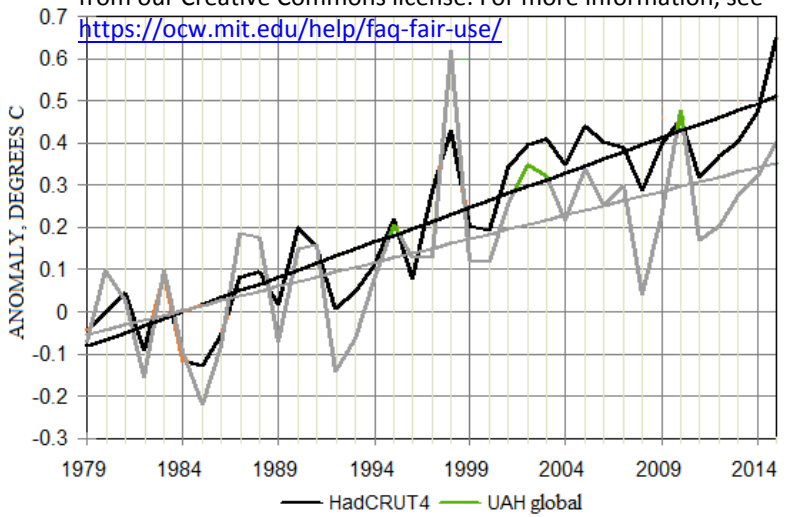
NASA GRACE findings for change in mass of Greenland and Antarctic ice sheets; note different scale on y-axis.

Image is in the public domain.
NASA / R. Braithwaite

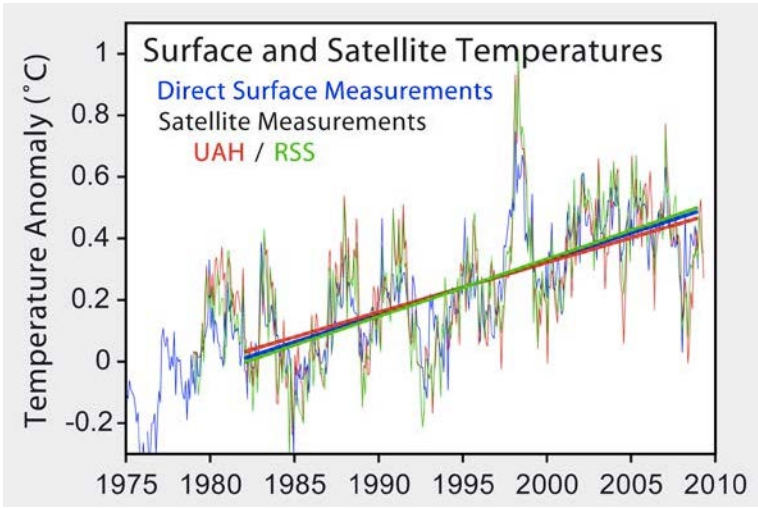
Satellite Observations

Disagreement between satellite and ground stations: resolved

- Satellites measure temperatures throughout air column; ground stations measure ground temps
- Satellites measure energy emissions of O_2, correlated with air temperature; requires substantial correction and calibration
- As satellite data analysis has improved, agreement with ground data increased



Uncorrected satellite data (UAH global) compared with land/sea surface measurements (HadCRUT4); satellite data show lower warming trend. From EuanMearns.com



Corrected satellite data correlate well with land/sea surface measurements.

Sea Level Rise

- Since there have been oceans, sea level has been in flux (e.g., 125m lower during last glaciation, but 7m higher during previous interglacial warm period)
- Melting Greenland's ice sheet would result in global SLR of 7m
- Melting Antarctica's ice sheets could result in global SLR of 57m

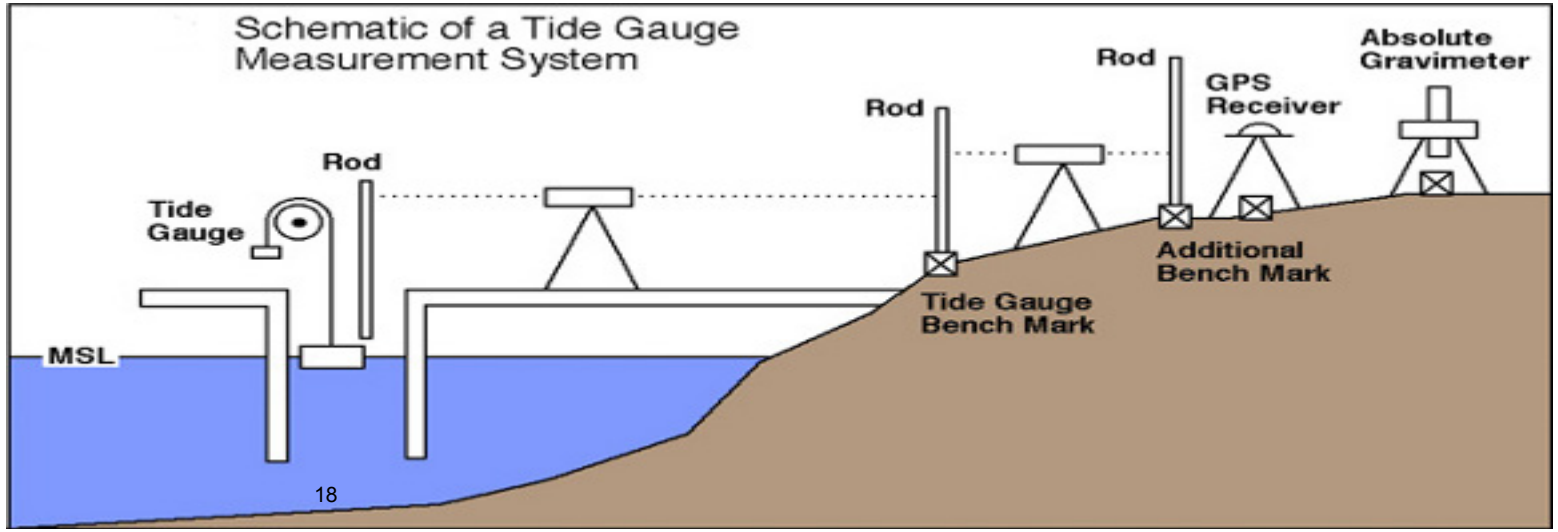
How do we measure SLR?

Satellites since 1993 (Topex, Jasons 1,2,3)
Tide gauges since ~1870

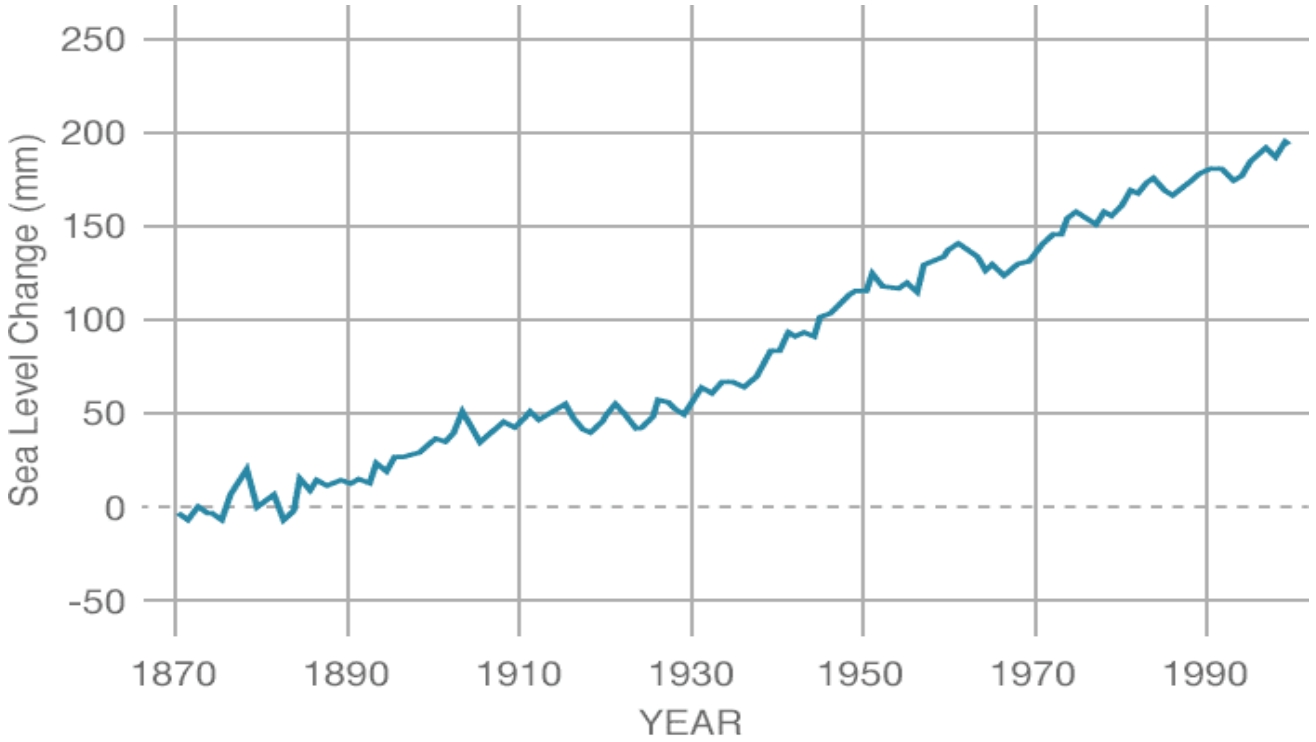
Relative SLR is sensitive to local conditions (uplift, subsidence, ocean bedrock sinking under weight of glacial meltwater)

“Relative” SLR is relative to benchmark on land

“Absolute” SLR is relative to the center of the earth

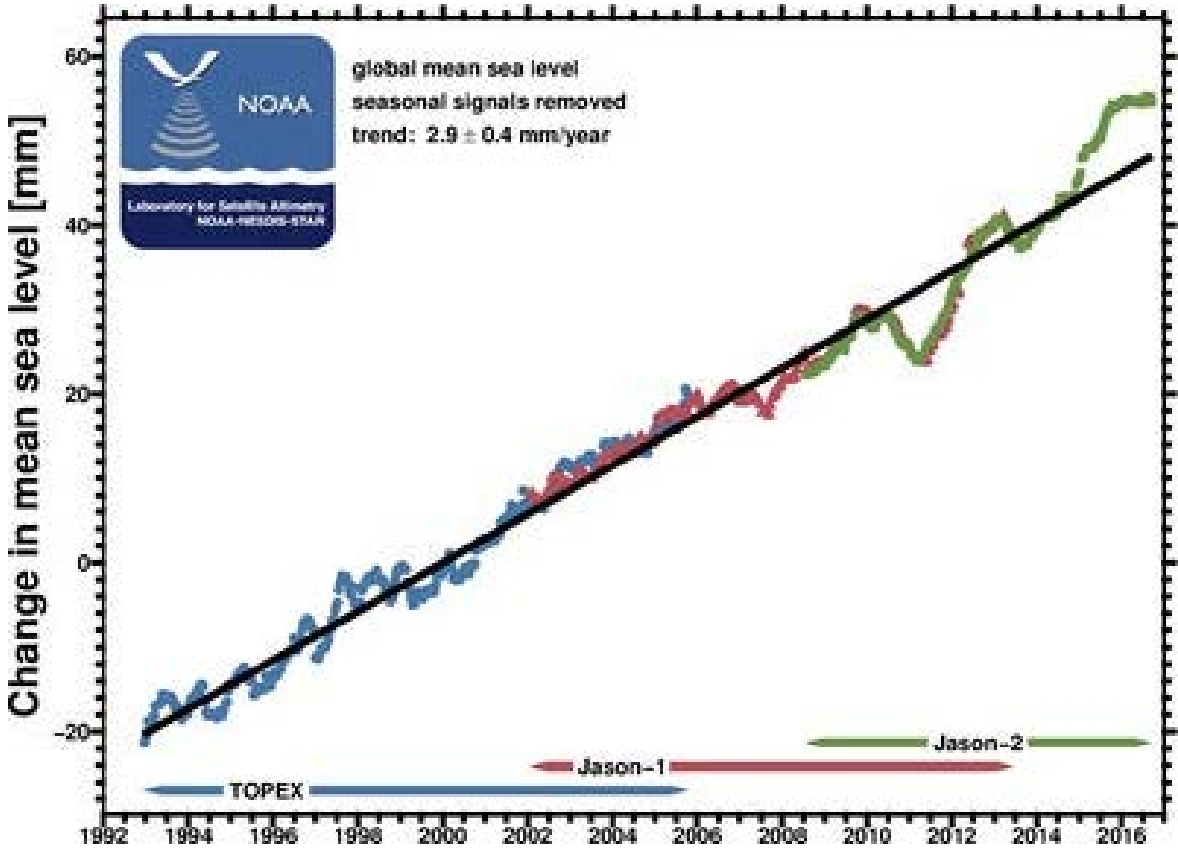


By any measurement, global sea levels are rising.



Global average sea level change as measured by tide gauges

Courtesy of NASA. Image is in the public domain.



Global average sea level change since 1992; NOAA/NESDIS

Courtesy of NOAA. This image is in the public domain.

The rate of SLR is increasing:

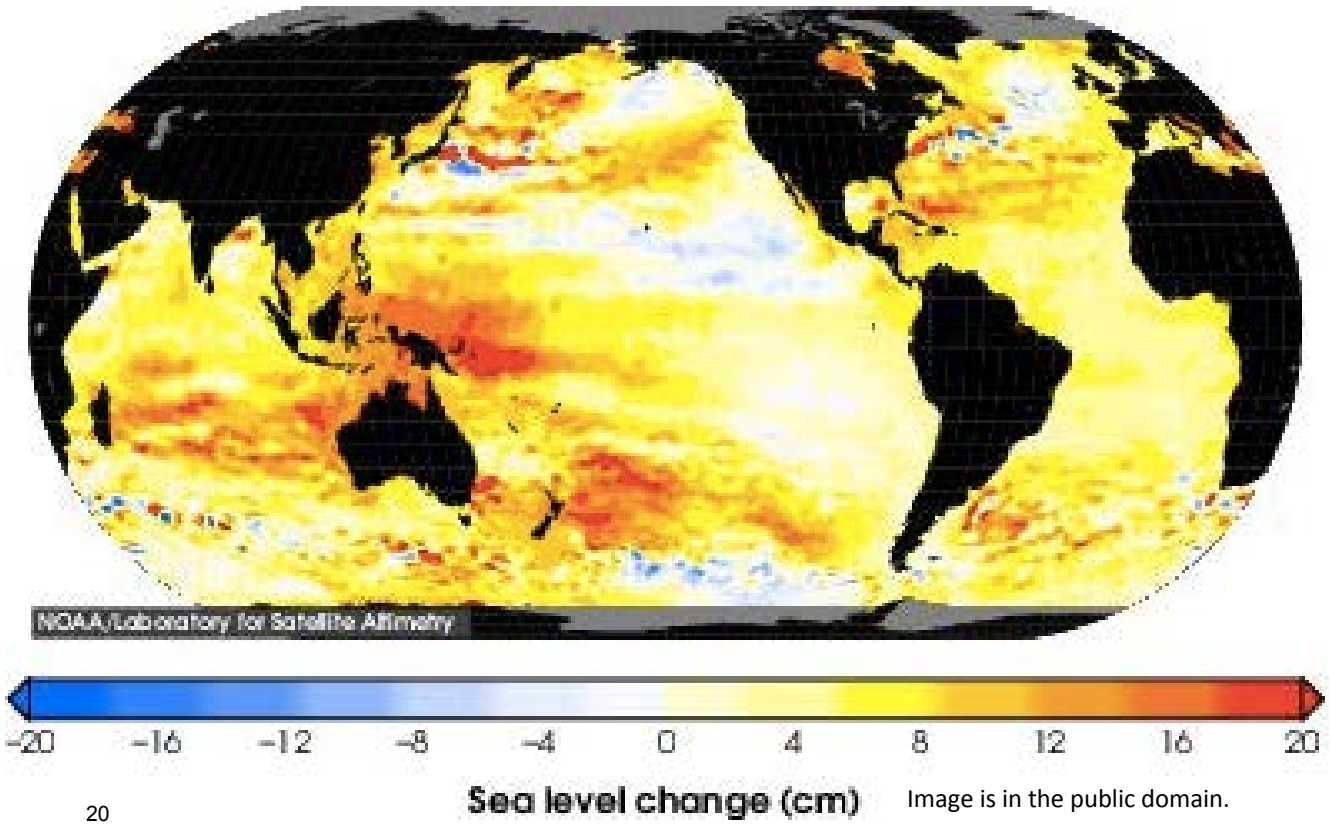
Rise since 1900: 20 cm

Current rate of rise: 3.2 cm/decade

Sea level rise is not uniform, and has multiple causes:

1. Thermal expansion of water
2. Melting of mountain glaciers
3. Greenland and Antarctic ice melt

As glaciers disappear and Greenland and Antarctica melt rates increase, this hierarchy will change.



Sea level change since 1993; NOAA/NESDIS

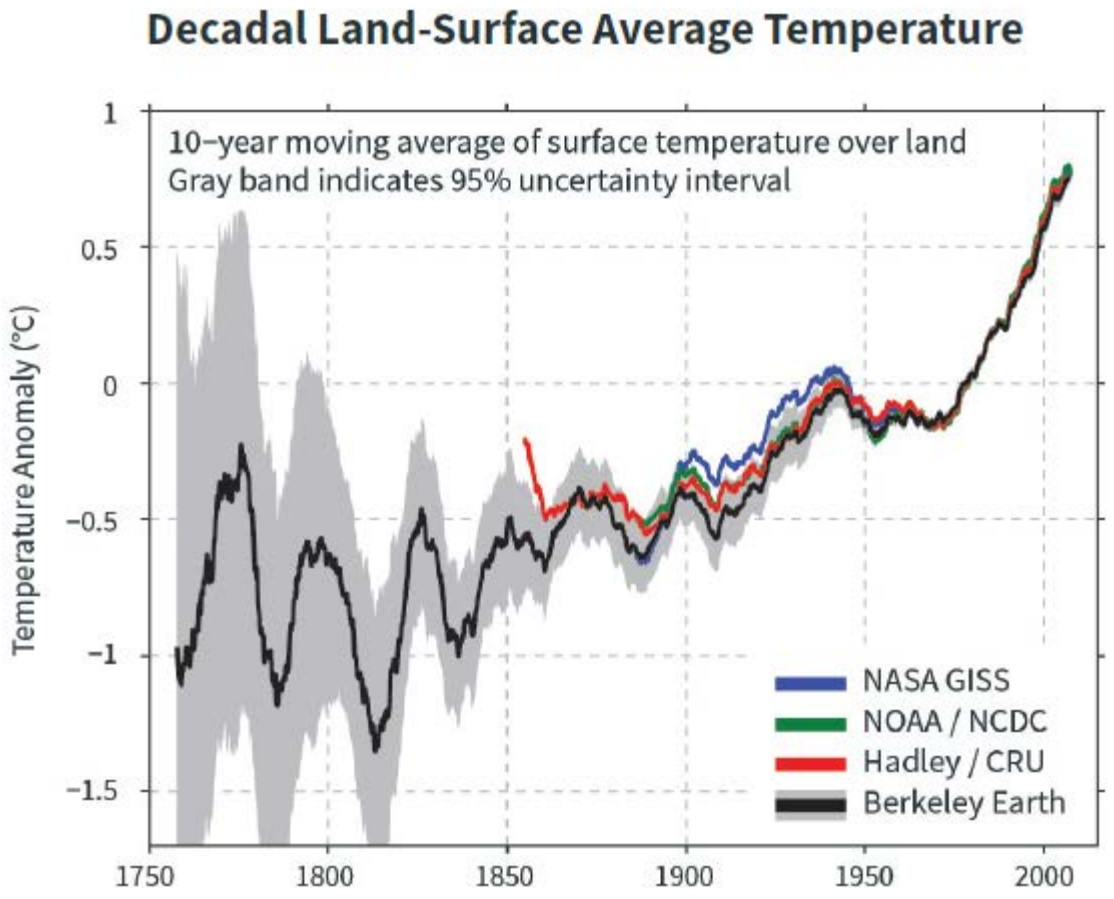
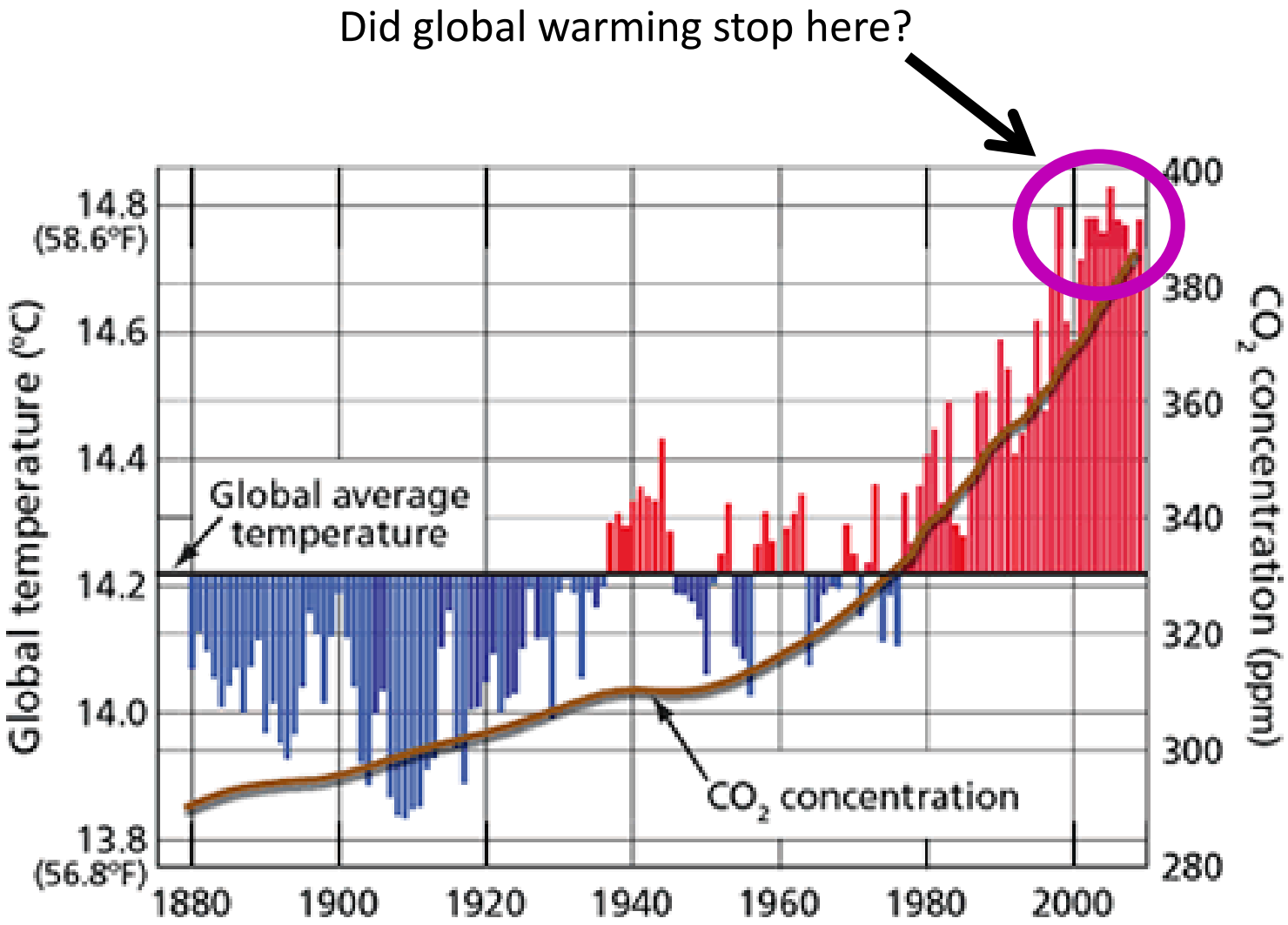


FIGURE 3: 10-year moving average of the global average temperature over land from 1750 to 2012. The blue curve is from the NASA Goddard Institute for Space Studies; the green, from NOAA's National Climatic Data Center; the red, from the United Kingdom Hadley Center's Climate Research Unit; and the black curve with gray uncertainty bounds, from the University of California's Berkeley Earth Project.

Multiple, independently calculated large data sets show a picture of rapid warming over last 100 years

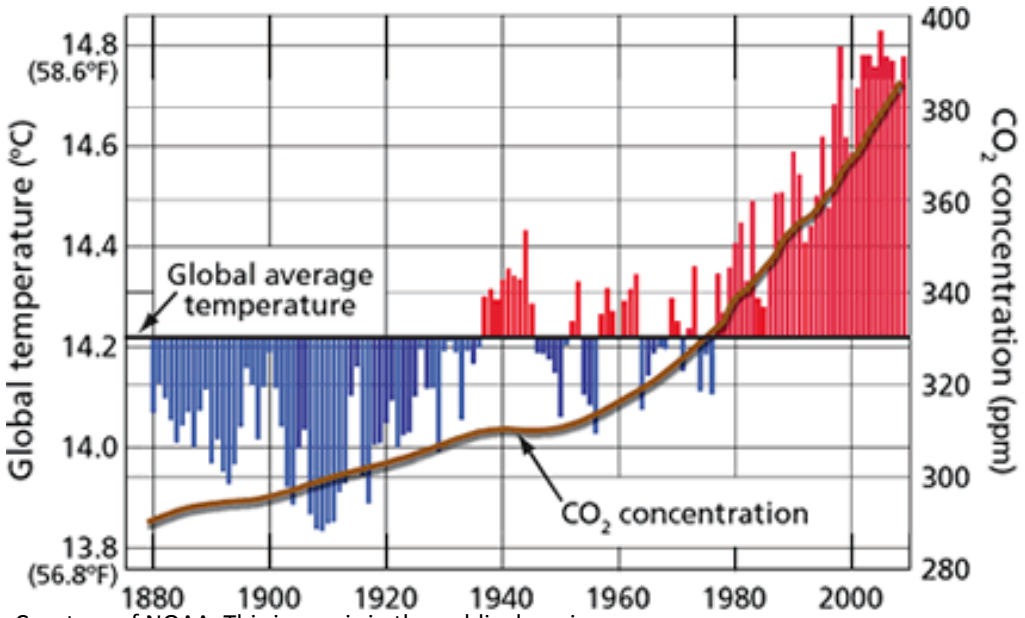
Emanuel, 2016

Modern direct measurements show close correlation between CO_2, and atmospheric temperature
(10 year time scales)



Courtesy of NOAA. This image is in the public domain.

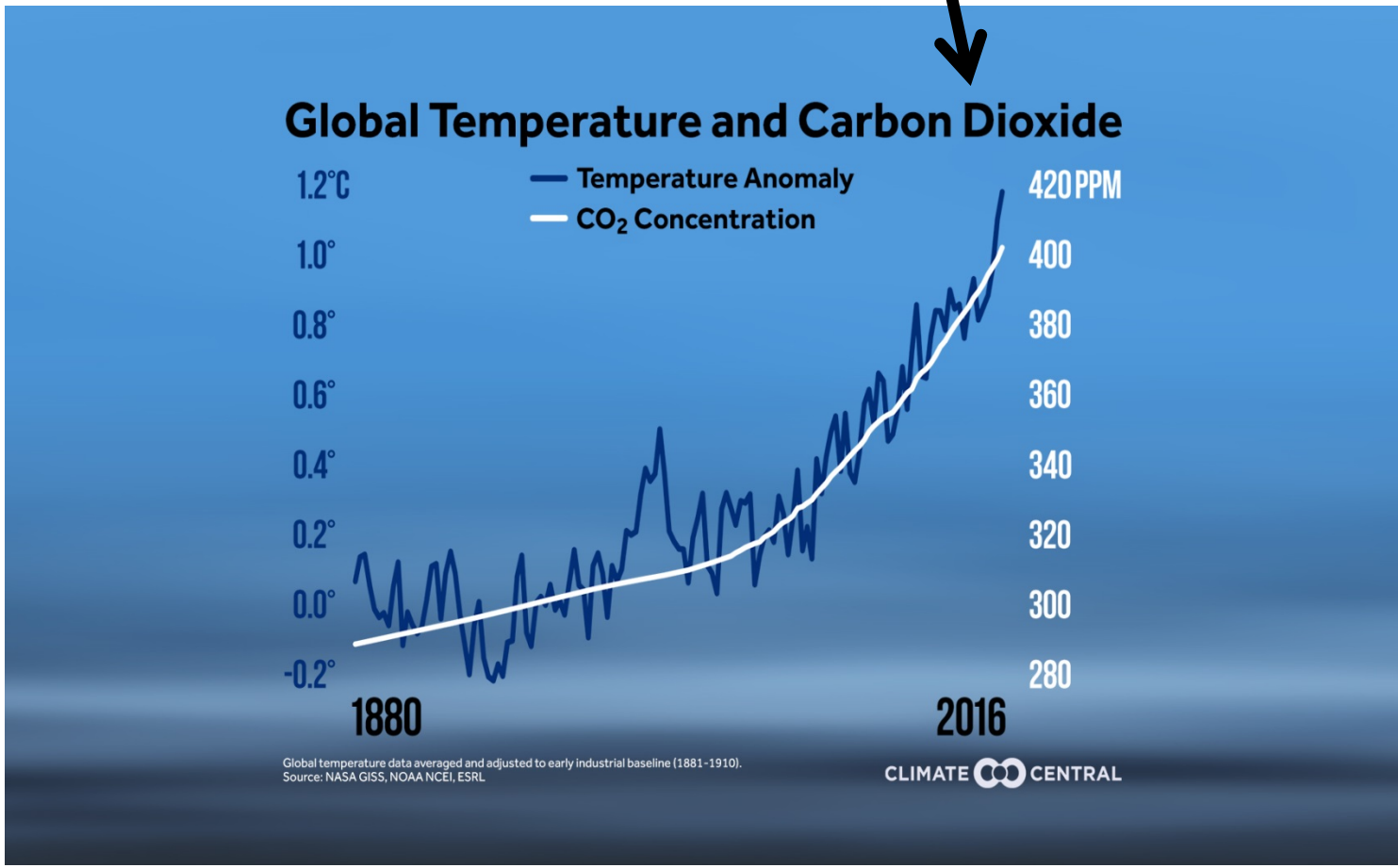
NOAA/NCDC



Courtesy of NOAA. This image is in the public domain.

NOAA/NCDC

Global warming did not stop there.



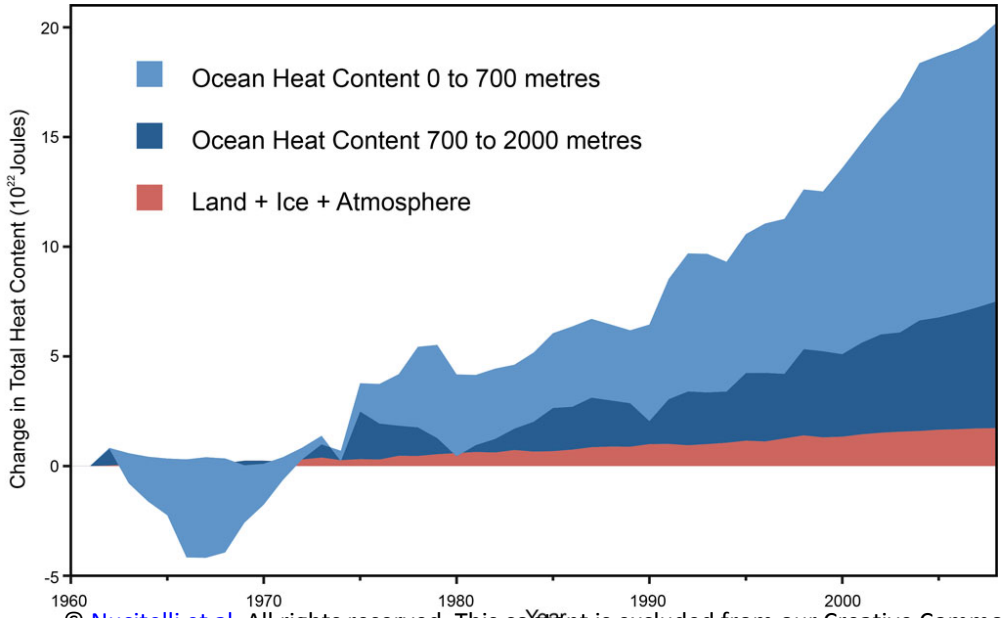
Courtesy of Climate Central. Used with permission.

Why has the warming been so small?

Delayed warming: ocean thermal inertia

Oceans have absorbed much of the heat

That heat is not “felt” by atmosphere yet



Upper ocean layer (0-100m depth) responds over years to decades

Deeper ocean responds over decades to centuries

Why has the warming been so small?

Cooling from aerosols:

- Industrial processes emit SO_2 aerosols
- particles scatter light, reflect incoming radiation
- nucleate clouds, reflect radiation
- may offset up to 25% of GG forcing
- Lots of uncertainty.

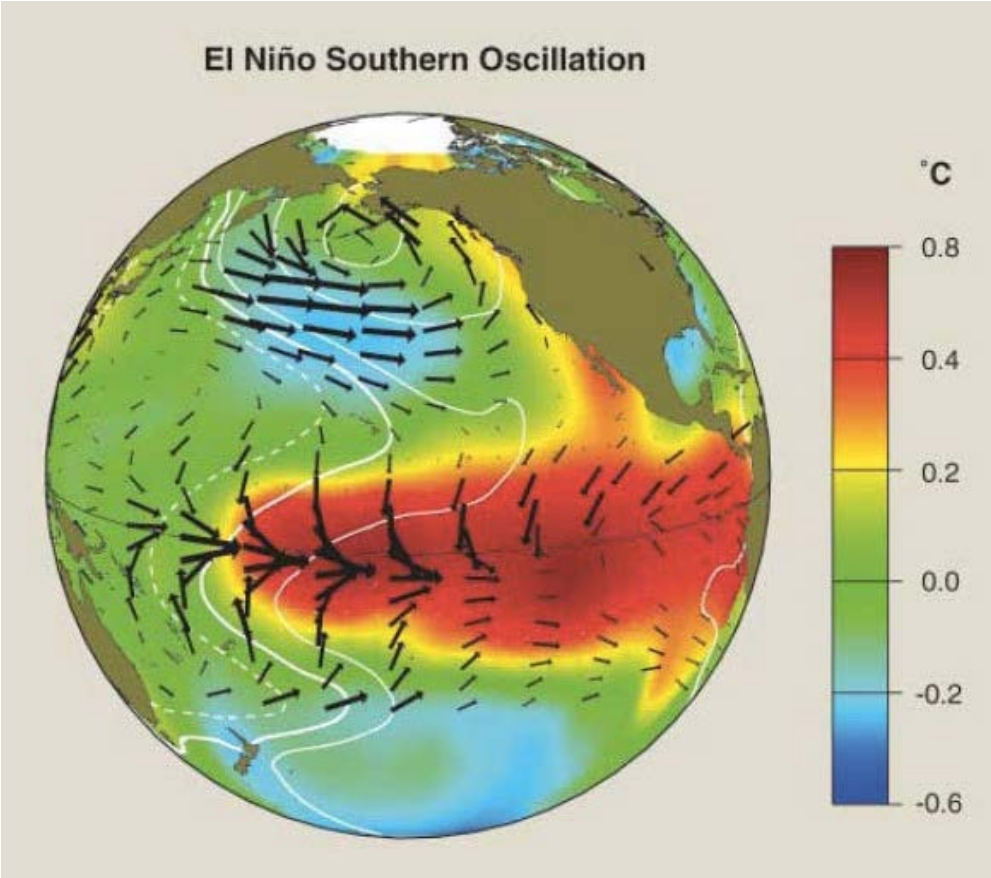
[Ruddiman Fig. 19-18 removed due to copyright restrictions. Ruddiman, William F. Earth's Climate: Past and Future. 3rd Edition. W.F. Freeman and Co., New York. 2014.]

Climate Oscillations

El Niño Southern Oscillation

- Warm ocean temps in east-central tropical Pacific
- Reduced precipitation in west tropical Pacific
- Irregular, 2-7 year recurrence
- Typically results in elevated global avg. temps

NOAA Pacific Marine Environmental Lab



Climate Oscillations

Pacific Decadal Oscillation

- Flips between “positive” and “negative” phases
- Positive means warm ocean temps in eastern Pacific, cooler temps in northwestern Pacific
- Negative has opposite pattern
- Years to decades time scale

[Ruddiman Fig. 18-22; A: positive PDO phase, B: time scale of oscillation removed due to copyright restrictions. Ruddiman, William F. Earth’s Climate: Past and Future. 3rd Edition. W.F. Freeman and Co., New York. 2014.]

Climate Oscillations

North Atlantic Oscillation

- Also flips between “positive” and “negative” phases, with varying strength
- Positive means warmer, wetter weather in North Atlantic, cooler in tropics
- Negative has opposite pattern (-ish… it’s complicated)
- Years to decades time scale

[Ruddiman Fig. 18-23 removed due to copyright restrictions. Ruddiman, William F. Earth’s Climate: Past and Future. 3rd Edition. W.F. Freeman and Co., New York. 2014.]

EC.719 D-Lab: Weather, Climate Change, and Health
Spring 2019