Lab experience

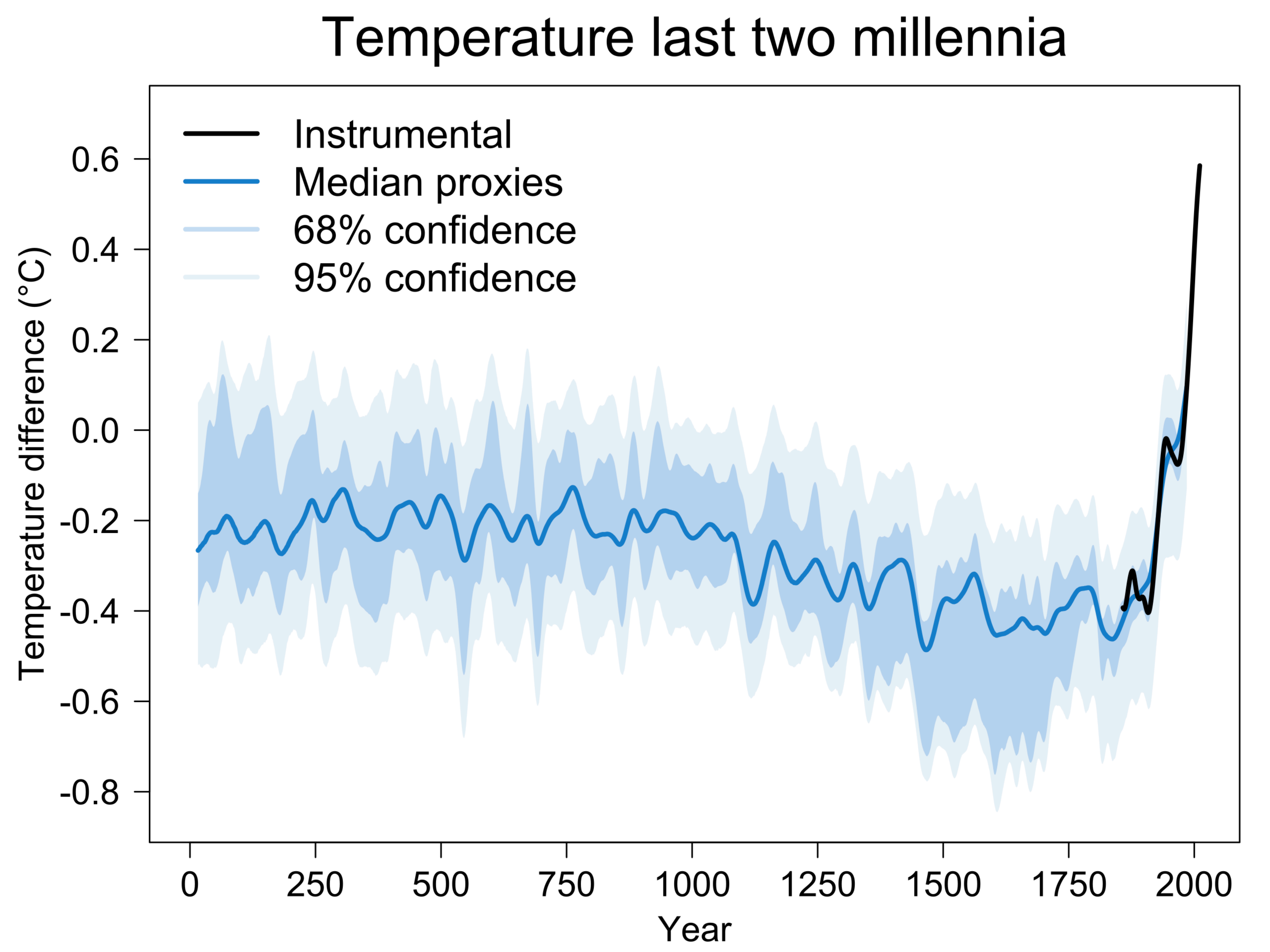
Global warming

LABORATORY EXPERIENCE 3

GLOBAL WARMING

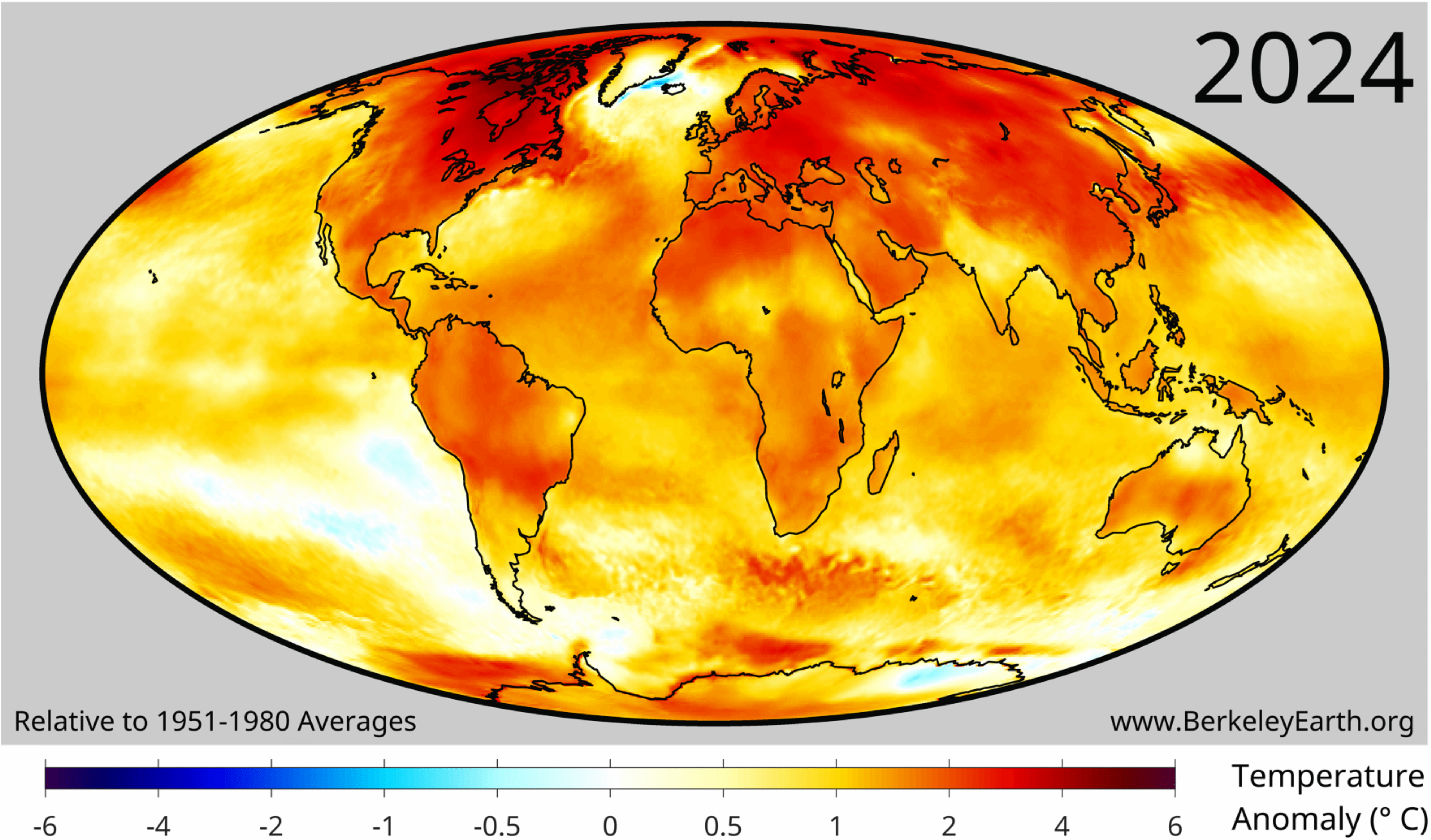
Mean global temperature record

- Since 1850, we have global historical **record measurements** of the mean Earth temperature
- For older dates, we need to resort to **temperature proxies**:
  - **Tree rings** widths (dendroclimatology) for the last ~1000 years
  - **Ice cores** can identify temperature changes from the abundance of oxygen isotopes (last 800 kyr)
  - Fossils, sediments, and geologic studies for even older periods


Temperature last two millennia
Instrumental
Median proxies
68% confidence
95% confidence
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
Temperature difference (°C)
0
250
500
750
1000
1250
1500
1750
2000
Year

Global Warming

and local changes



Thermal equilibrium

- Earth's temperature is determined from an **equilibrium condition**: heat received from the Sun is equal to heat dispersed into space
- In the simplest model, both quantities can be computed using **Stefan-Boltzmann's law**
- In the computation, one needs to take into account the **albedo**, that is the amount of light reflected into space (for example because of the clouds).

Exercise. Suppose the Earth has an albedo of $A = 0.3$ (that is, 30% of the Sun light is reflected back into space). What is its equilibrium temperature?

Solution

$$P_{\mathrm{in}} = \sigma T_\odot^4 (1 - A) \frac{R_\odot^2}{a^2} \pi R_\oplus^2 = \sigma T_\oplus^4 \cdot 4\pi R_\oplus^2 = P_{\mathrm{out}}$$

and therefore

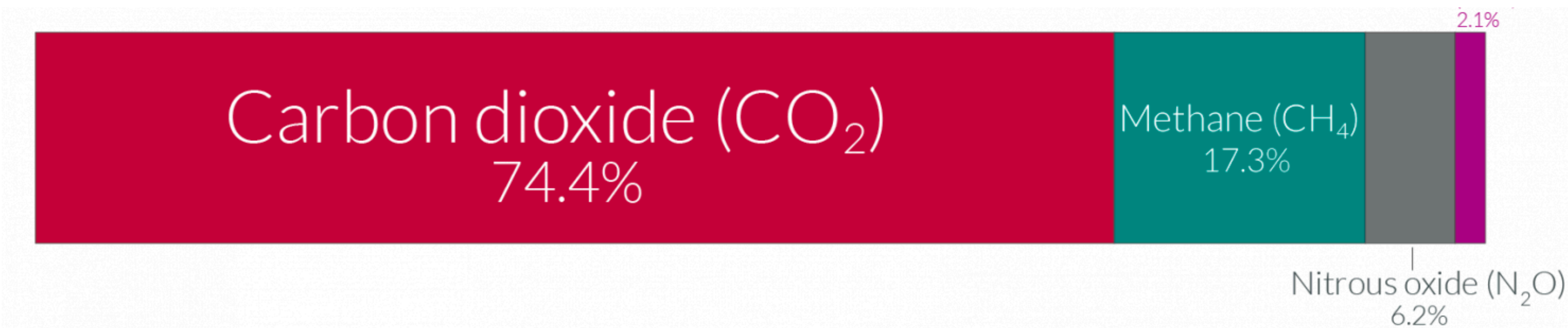
$$T_\oplus = T_\odot \sqrt[4]{1 - A} \sqrt{\theta/2} \simeq 255\,\mathrm{K}$$

where $\theta \equiv R_\odot / a = 0.00465$ is the angular radius of the Sun expressed in radians.

Observation. This result is, somewhat surprisingly, about $33\,\mathrm{K}$ less than the average global temperature on Earth. Can you explain this difference?

Greenhouse effect!

- This temperature difference is mostly due to the **greenhouse effect**
  - Some gases (CO_2, CH_4 e N_2O) in the atmosphere are transparent in the visibile radiation, but are **opaque in the infrared (IR)**



  - The Sun radiation P_{in} (mostly in the visible) arrives mostly undisturbed; however, the emitted radiation P_{out} (in the IR) is mostly reflected back to the Earth
- Although the whole problem is very complex, we can describe the main characteristic with a simple model…

Troposphere and stratosphere

- The atmosphere is made of various layears. For our purposes, we just need to consider two of them:

  Troposphere: occupies the first 11 km and has a lapse rate of 6.5 °C / km; it is relatively dense and opaque in the IR

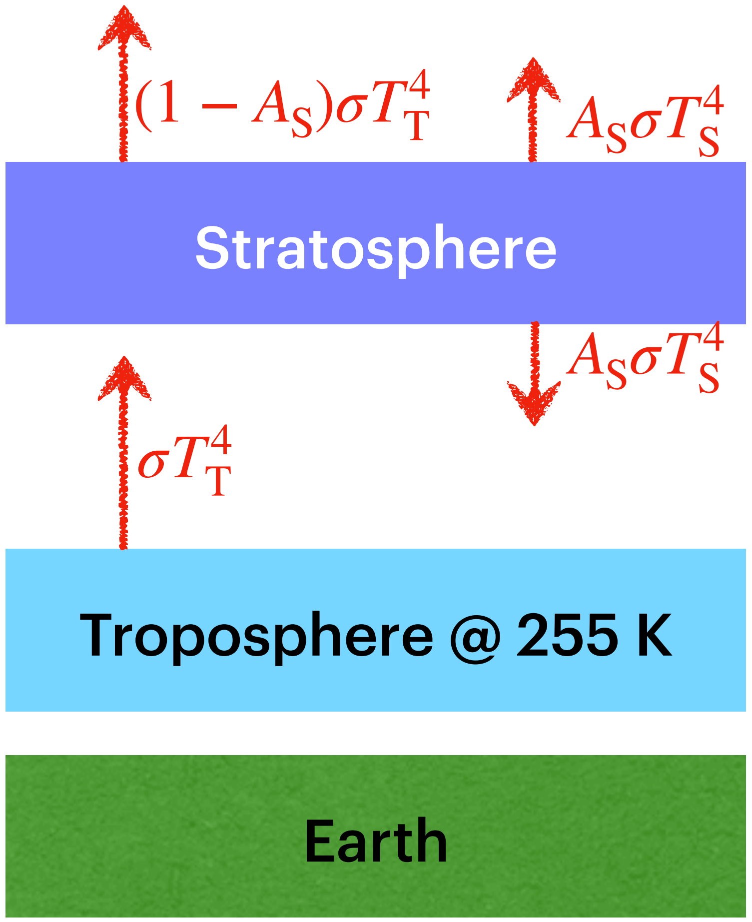
  Stratosphere: reaches 50–60 km and is a far less dense layer; its is separate by the troposphere by the **tropopause**

- The stratosphere, not very dense and essentially without greenhouse gases, is transparent to the IR: for this reason its **temperature is constant**

Two-layer model

- The top of the troposphere has an effective temperature $T_\mathrm{T} = 255\,\mathrm{K}$, i.e. the temperature we computed earlier

- Assuming an albedo A_S for the stratosphere, its temperature T_S can be obtained from the energy balance:



$$A_\mathrm{S}\sigma T_\mathrm{T}^4 = 2A_\mathrm{S}\sigma T_\mathrm{S}^4 \implies T_\mathrm{S} = 214\,\mathrm{K}$$

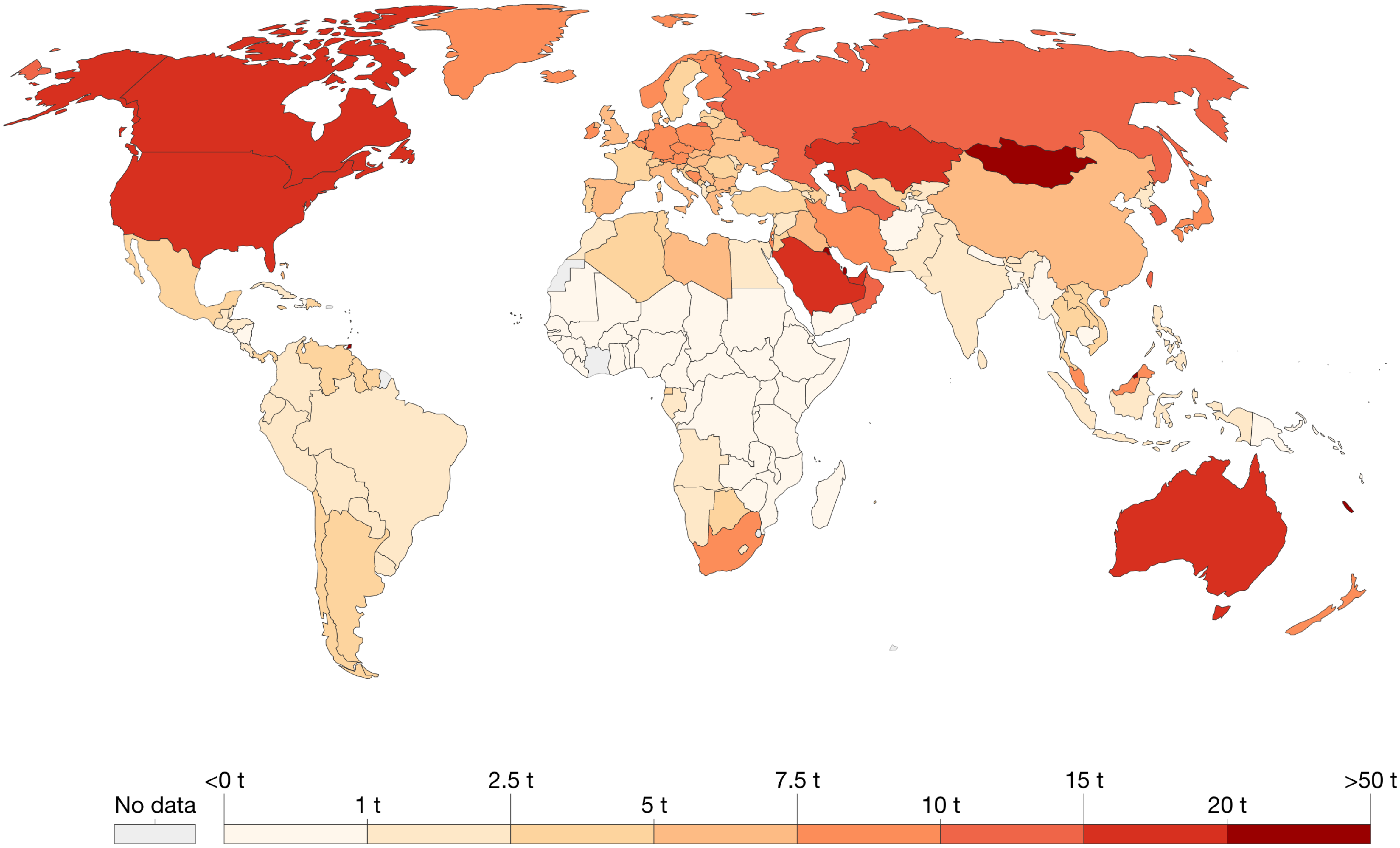
- The Earth surface temperature is computed using the lapse rate and the height off the troposphere:

$$T_\oplus = T_\mathrm{S} + 6.5 \times 11 = 286\,\mathrm{K}$$

Per capita CO_2 emissions, 2019

Carbon dioxide (CO_2) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.

Our World in Data



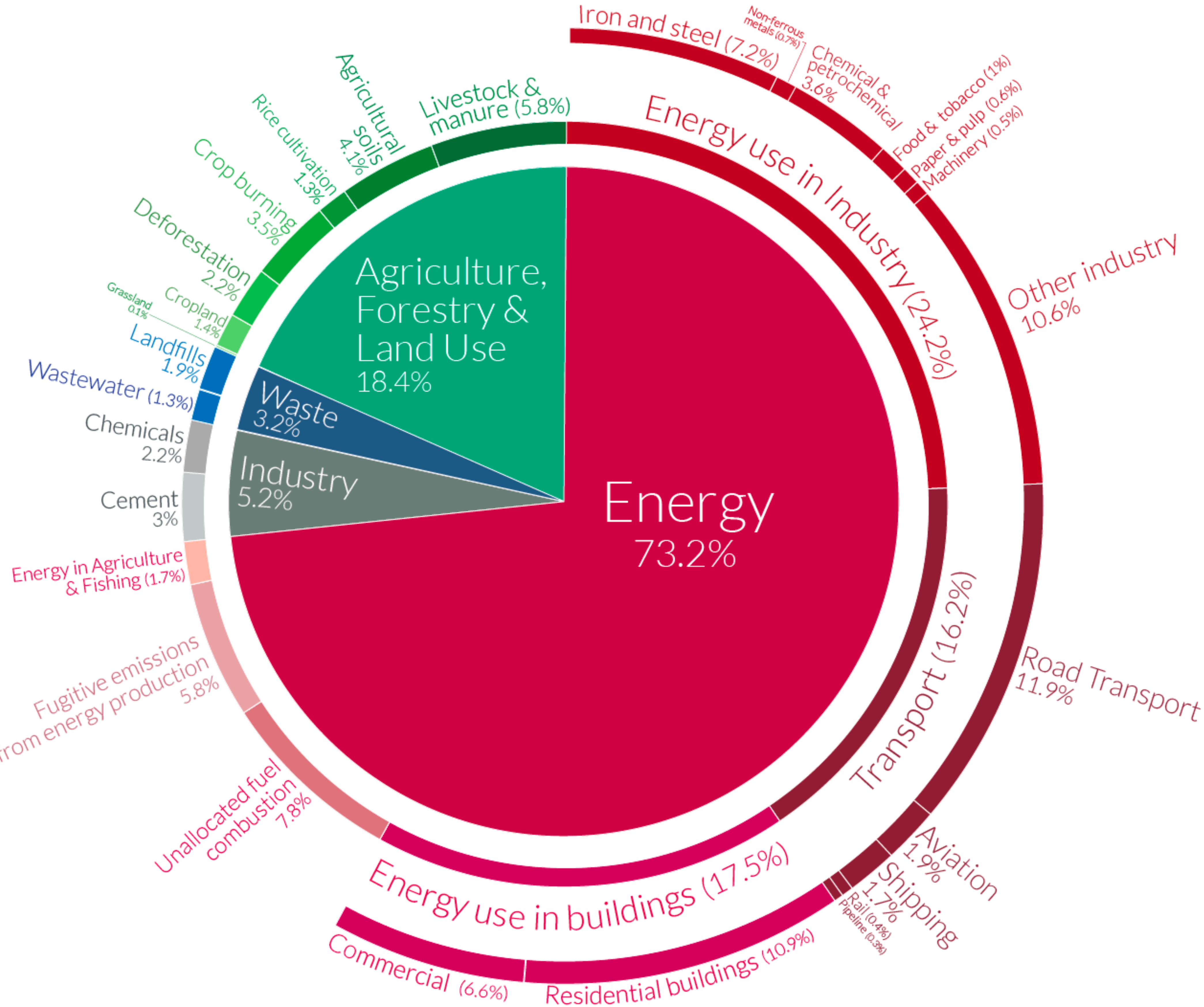
Source: Our World in Data based on the Global Carbon Project; Gapminder & UN

Note: CO_2 emissions are measured on a production basis, meaning they do not correct for emissions embedded in traded goods.

Global greenhouse gas emissions by sector

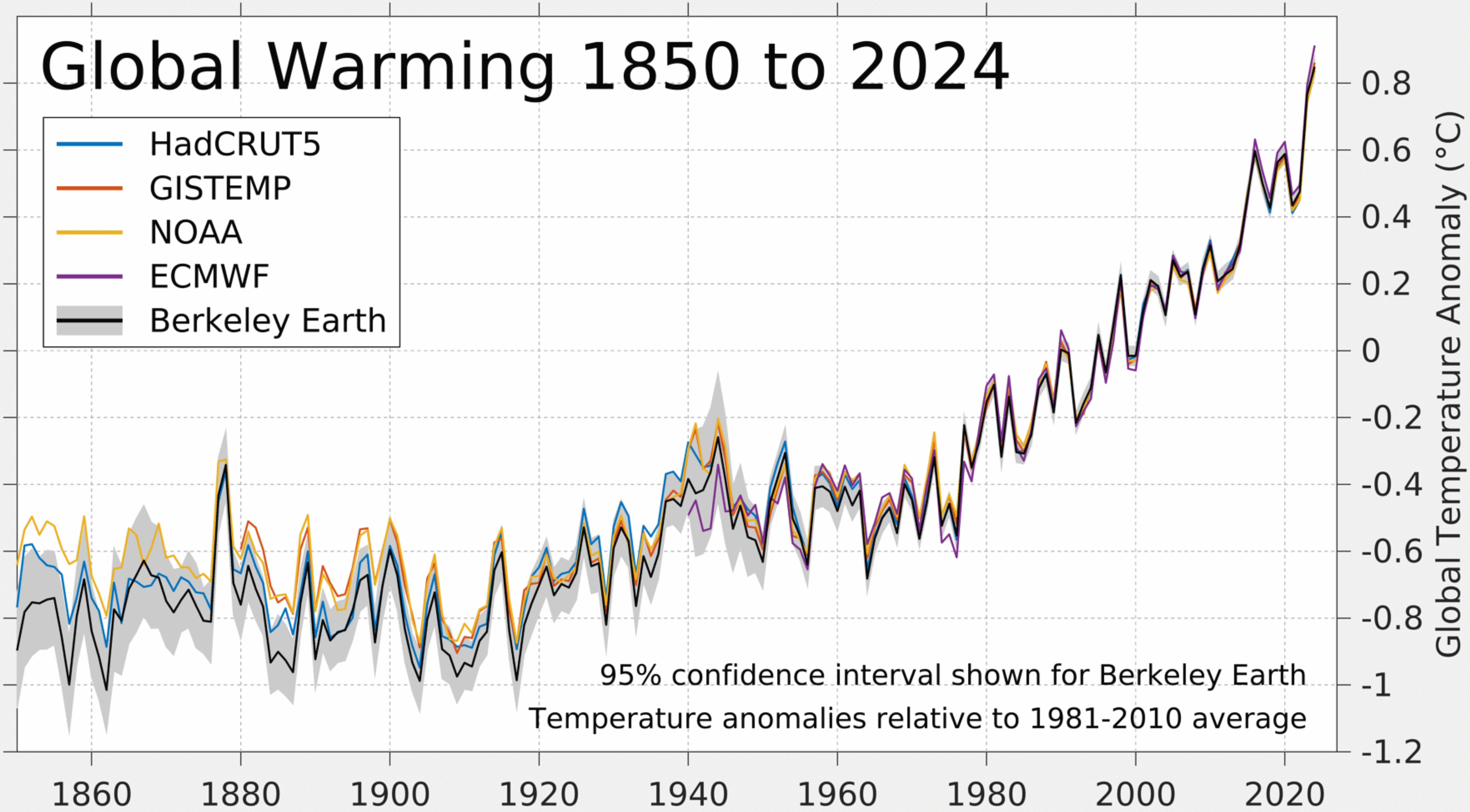
Our World in Data

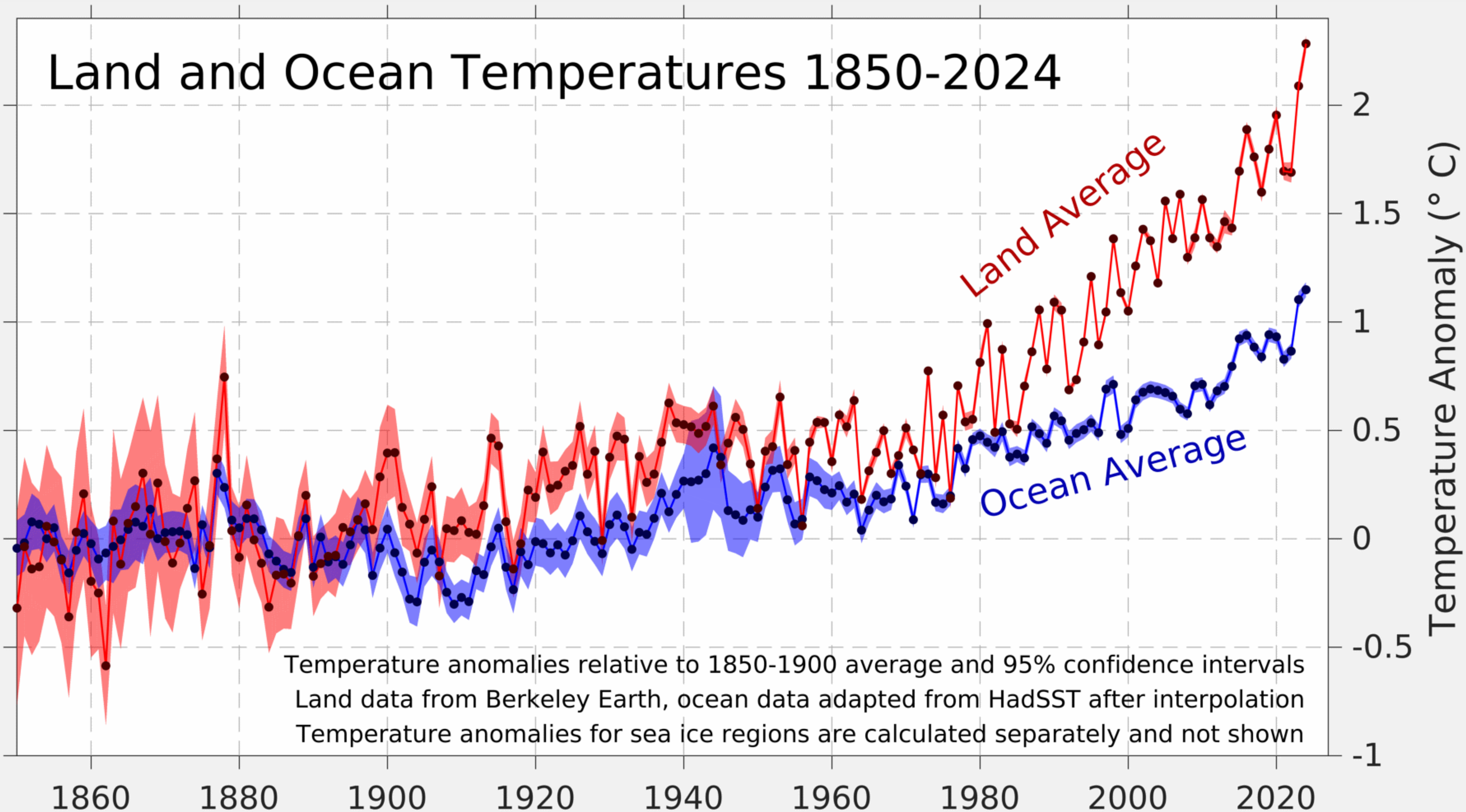
This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO_2eq.



OurWorldinData.org – Research and data to make progress against the world's largest problems.

Source: Climate Watch, the World Resources Institute (2020).


Global Warming 1850 to 2024
HadCRUT5
GISTEMP
NOAA
ECMWF
Berkeley Earth
95% confidence interval shown for Berkeley Earth
Temperature anomalies relative to 1981-2010 average
Global Temperature Anomaly (°C)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
1860
1880
1900
1920
1940
1960
1980
2000
2020


Land and Ocean Temperatures 1850-2024
Land Average
Ocean Average
Temperature Anomaly (° C)
2
1.5
1
0.5
0
-0.5
-1
1860
1880
1900
1920
1940
1960
1980
2000
2020
Temperature anomalies relative to 1850-1900 average and 95% confidence intervals
Land data from Berkeley Earth, ocean data adapted from HadSST after interpolation
Temperature anomalies for sea ice regions are calculated separately and not shown

Task

- Model the **global mean temperature historical record** (1850-present) with a number of models
  - Perform **Bayesian inference** on the models' parameters and **model inference** using the Bayesian evidence
  - Use at least the following models: constant temperature, linear growth, exponential growth, gaussian process with or without trend
- Data: **Berkeley Earth** "Land + Ocean (1850 – Recent)" data http://berkeleyearth.org/data/
- Inference library: **Ultranest** https://johannesbuchner.github.io/UltraNest/index.html
- Gaussian Process library: **George** https://george.readthedocs.io/en/latest/

Gaussian Processes

- **Informal definition**: a probability distribution over possible functions that fit a set of points
- A Gaussian Process (GP) is a sort of **interpolation**: given a set of evaluations $y_i = f(\boldsymbol{x}_i)$ of a real-valued function, estimate the function at some other points $\{\boldsymbol{x}_i^*\}$.
- However, a GP also provides **uncertainties** on the interpolated values
- It also naturally implements the idea of **smoothness** of the interpolated function through the covariance (**kernel**)

Gaussian Process for our model

- GPs can be used to interpolate the mean global temperature record…
  - Depending on the model, we can then obtain an estimate of the future trend
- A GPs interpolation also provides the evidence of the interpolation!
  - Useful to assess the merit of this specific model
- GPs do not need to assume a zero-mean: we can interpolate also a function with a trend
  - For example, in case of linear trend, one can infer at the same time the two parameters for the linear function (slope and intercept) together with the GPs kernel parameter

References on GPs

THE BOOK

Ramussen & Williams, “Gaussian Processes for Machine Learning”, MIT Press, 2006
http://www.gaussianprocess.org/gpml/chapters/RW.pdf

A nice tutorial
https://www.youtube.com/watch?v=92-98SYOdlY