

Paleoclimate



source: NASA

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Link to Slides



Yesterday's Summary

- Ice cores for climate science
- The time machine
 - decay series dating
 - cosmogenic nuclide dating
 - application examples
 - surface exposure dating
- Abrupt climate change during the last glacial cycle
 - Dansgaard-Oeschger Events
 - Bipolar seesaw
 - Heinrich Events
 - Pa/Th proxy for ocean circulation rate

Lecture Progress

Monday	Introduction	Earth History
Tuesday	Proxies I	Cenozoic Hot & Warm House
Wednesday	Specific Climate System components	Pleistocene G-IG climate
Thursday	Proxies II & Climate System Interactions	Abrupt Climate Change
Friday	Current Climate Change	Future & Synthesis

Today's Overview

- Climate Modelling
- Climate Feedbacks and Tipping Points
- The Human Influence
 - human civilisation
 - human emissions
 - other influences
- IPCC AR6 projections

Climate Modelling

Climate Modelling

- Numeric modelling is used very often in (paleo)climate
- Useful to test magnitudes and interactions
- Help us understand and quantify complex outcomes
- Can be used to e.g.
 - extrapolate from sparse observations
 - turn proxy results into meaningful numbers
 - test hypotheses
 - project into future
- However, they are only as good as the concepts
- Bullshit in → bullshit out!

Climate Modelling

- Climate System Models (CSM) are most comprehensive
- Computationally intensive, depending on resolution
- Different resolutions for different problems
- Spatial and Temporal resolutions are correlated
- Everything happening below model scale needs to be parameterised
- For focus on specific domains others can be simplified
- Models with dynamic interactions between domains are called (fully) coupled → much more costly

Climate Modelling

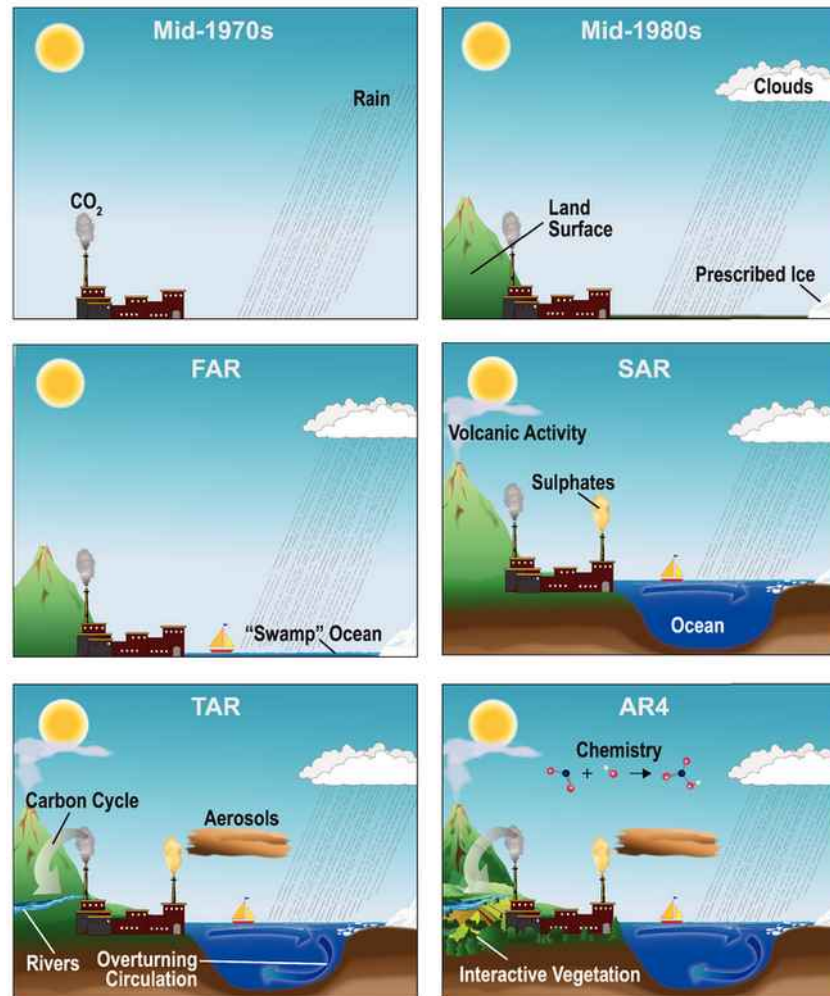
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Climate Modelling

- No model is perfect
 - choose the right design for each question
- Model “verification” via
 - modern data
 - historical or paleo data
 - model intercomparison
 - Coupled Model Intercomparison Project
 - Paleo Model Intercomparison Project

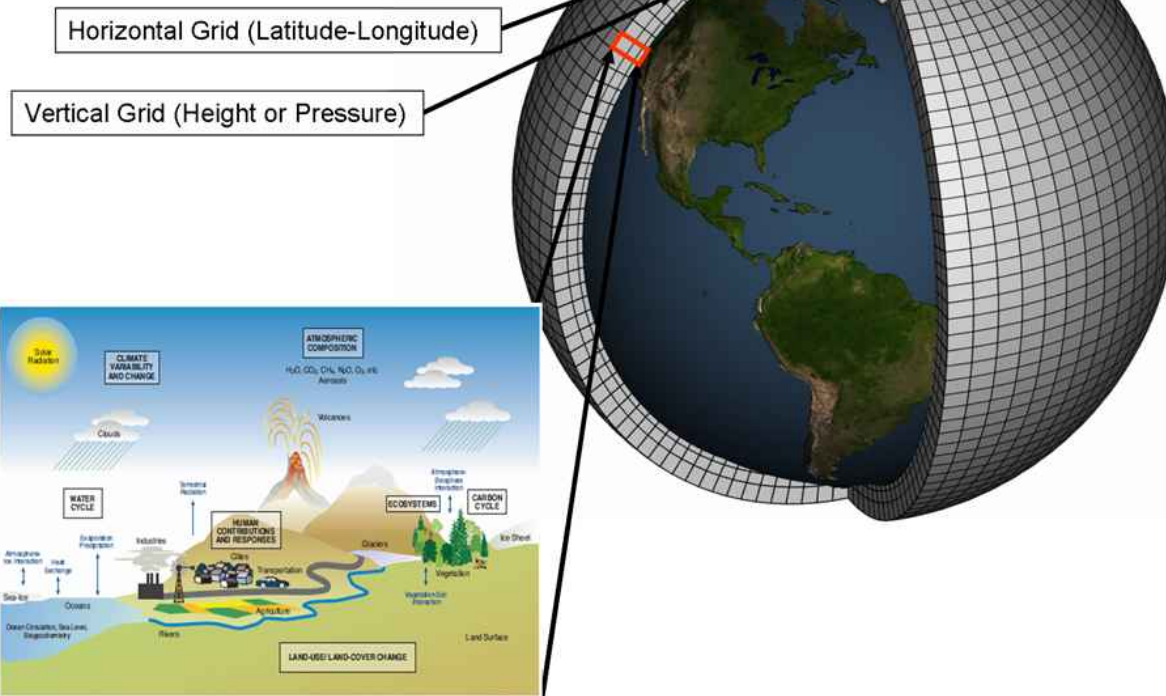
Climate Modelling

The World in Global Climate Models

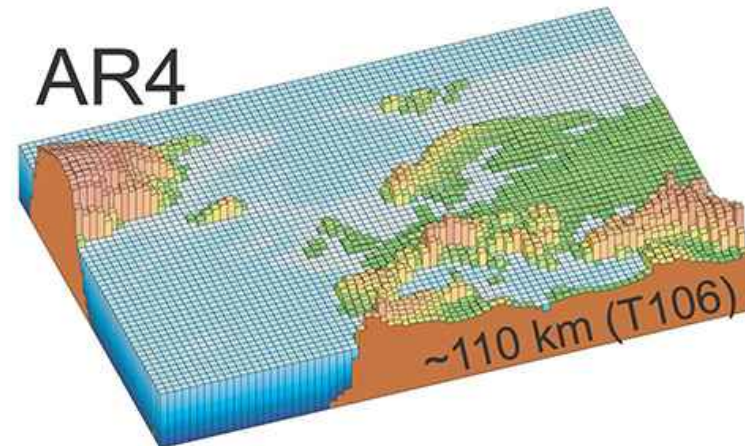
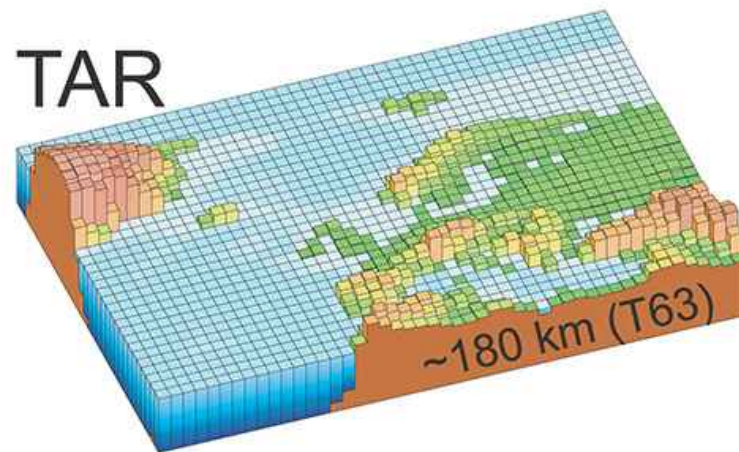
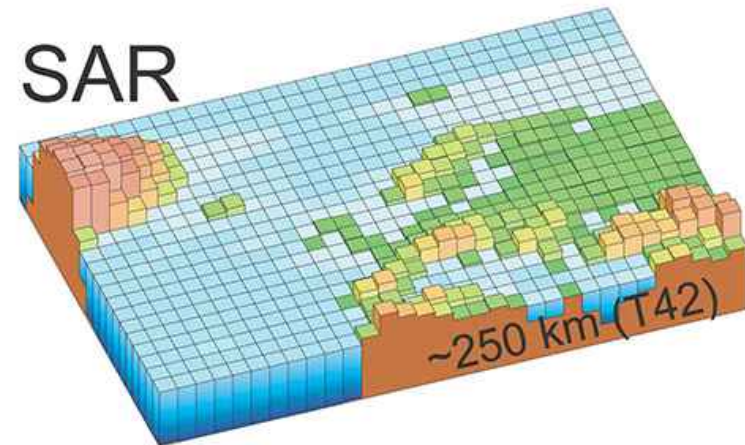
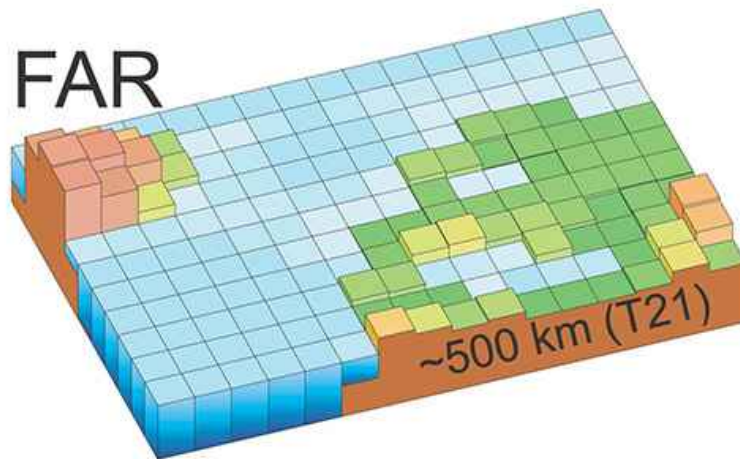


Climate Modelling

Schematic for Global Atmospheric Model



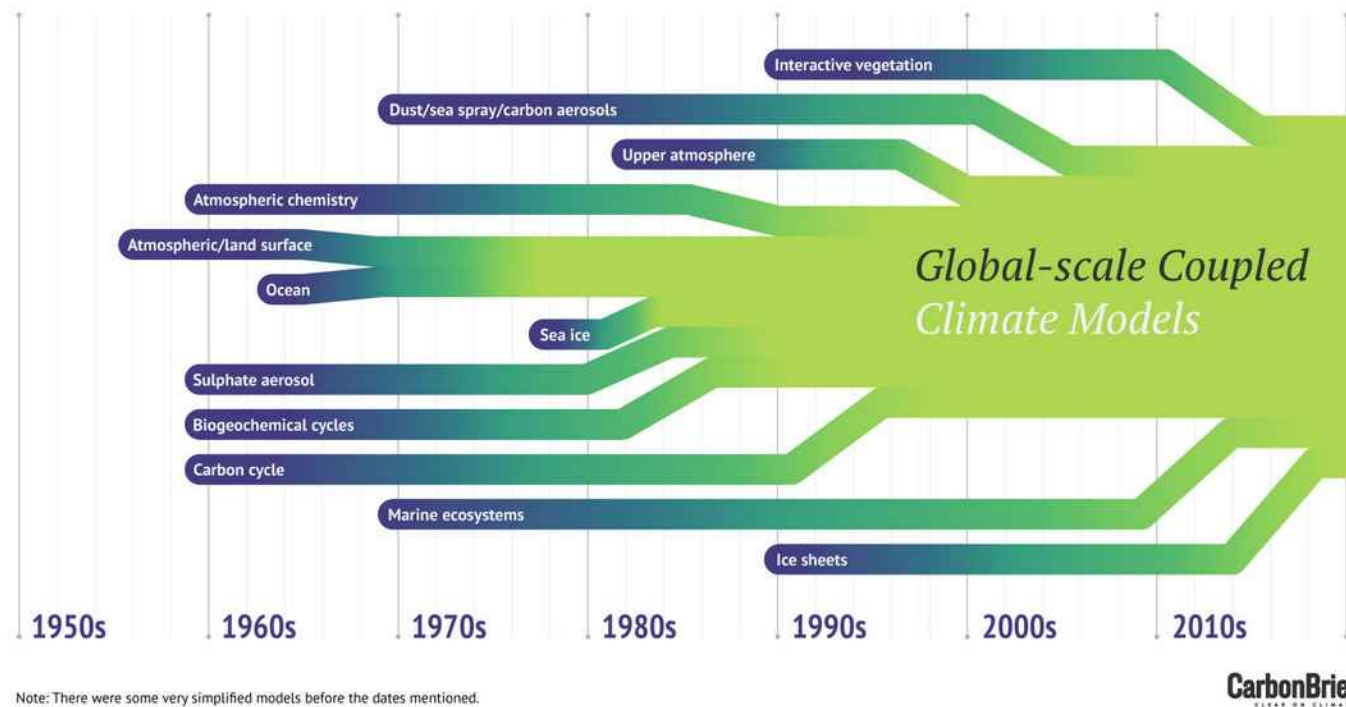
Climate Modelling



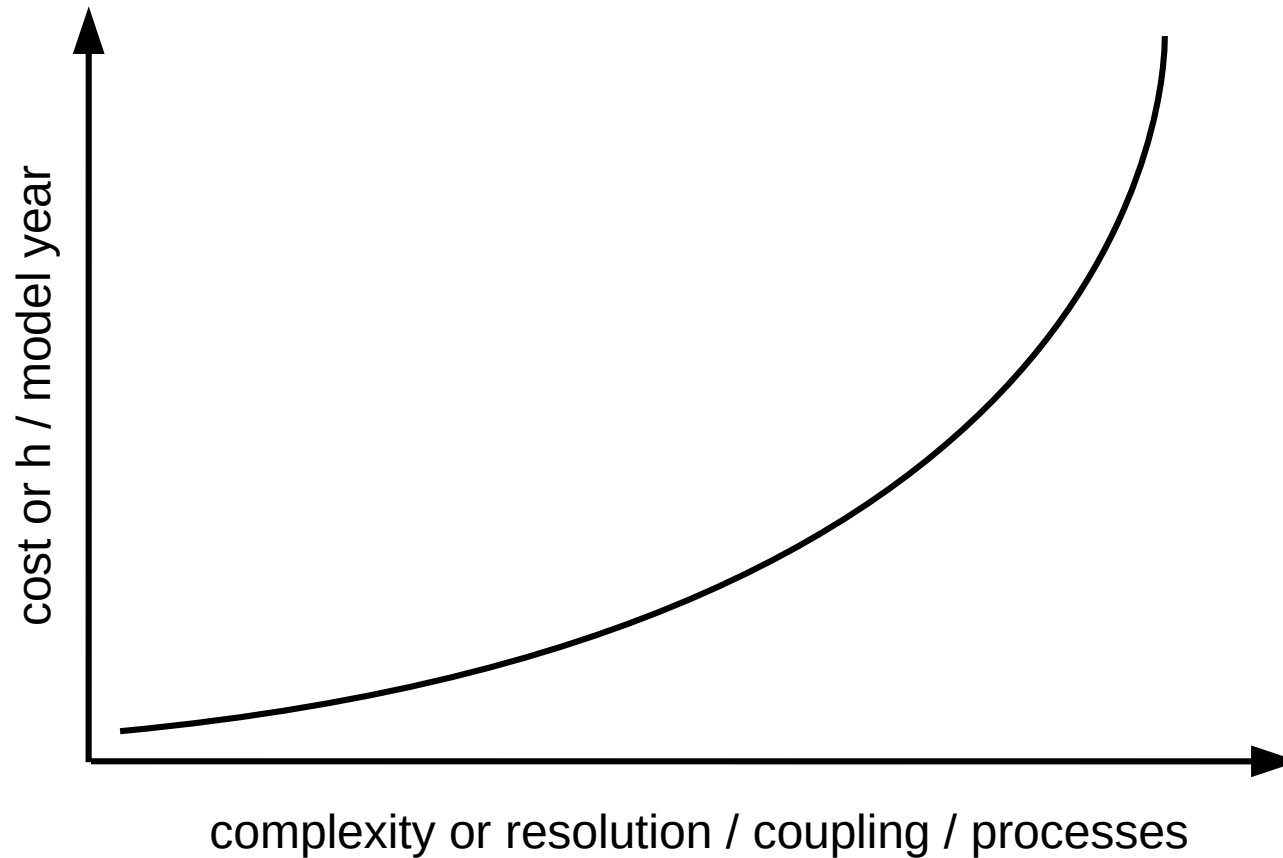
Climate Modelling

Climate models

For decades scientists have been using **mathematical models** to help us learn more about the Earth's climate. Known as climate models, they are driven by the fundamental physics of the atmosphere and oceans, and the cycling of chemicals between living things and their environment. Over time they have increased in complexity, as separate components have merged to form **coupled systems**.



Climate Modelling



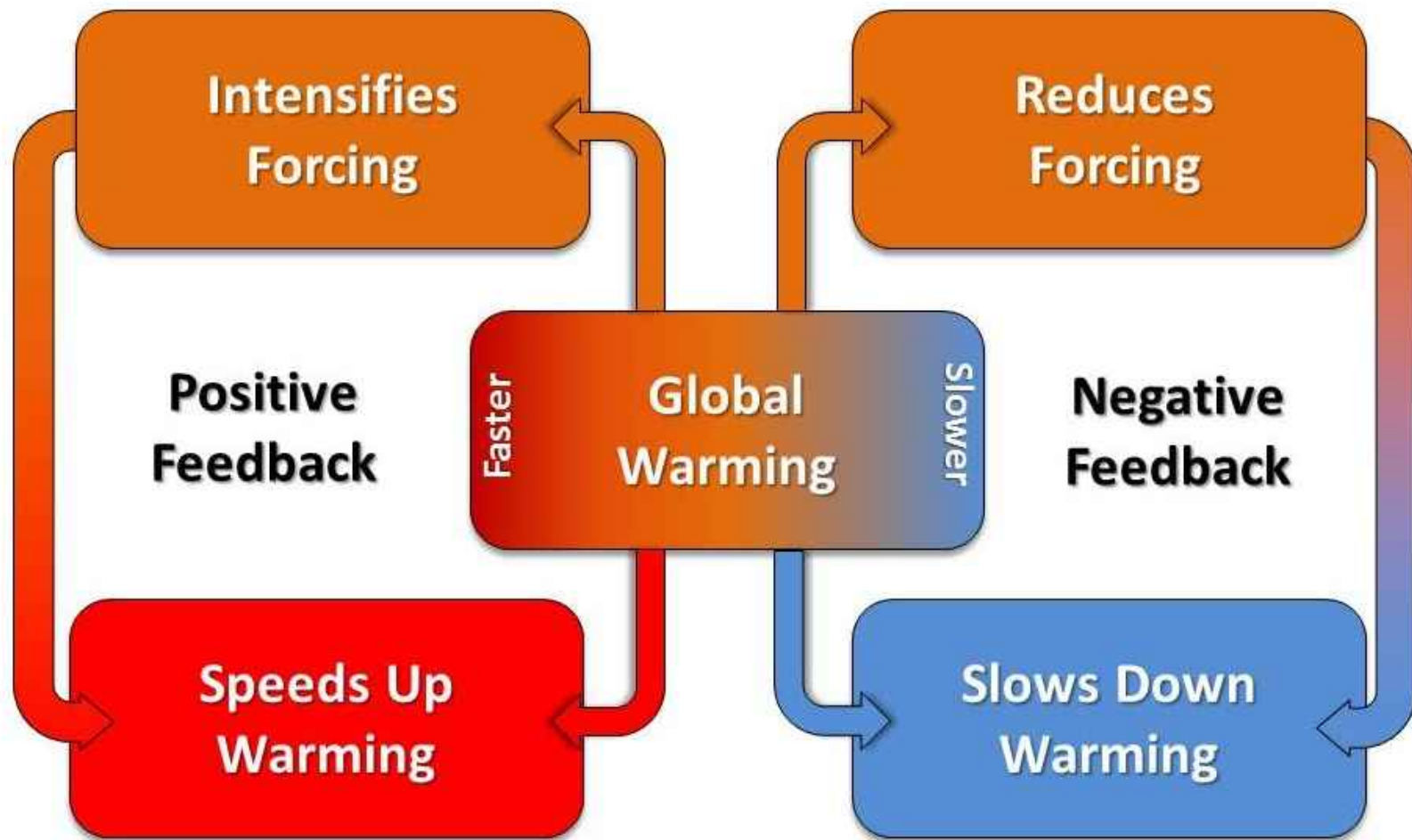
Climate Modelling

**All models are wrong,
but some are useful.**

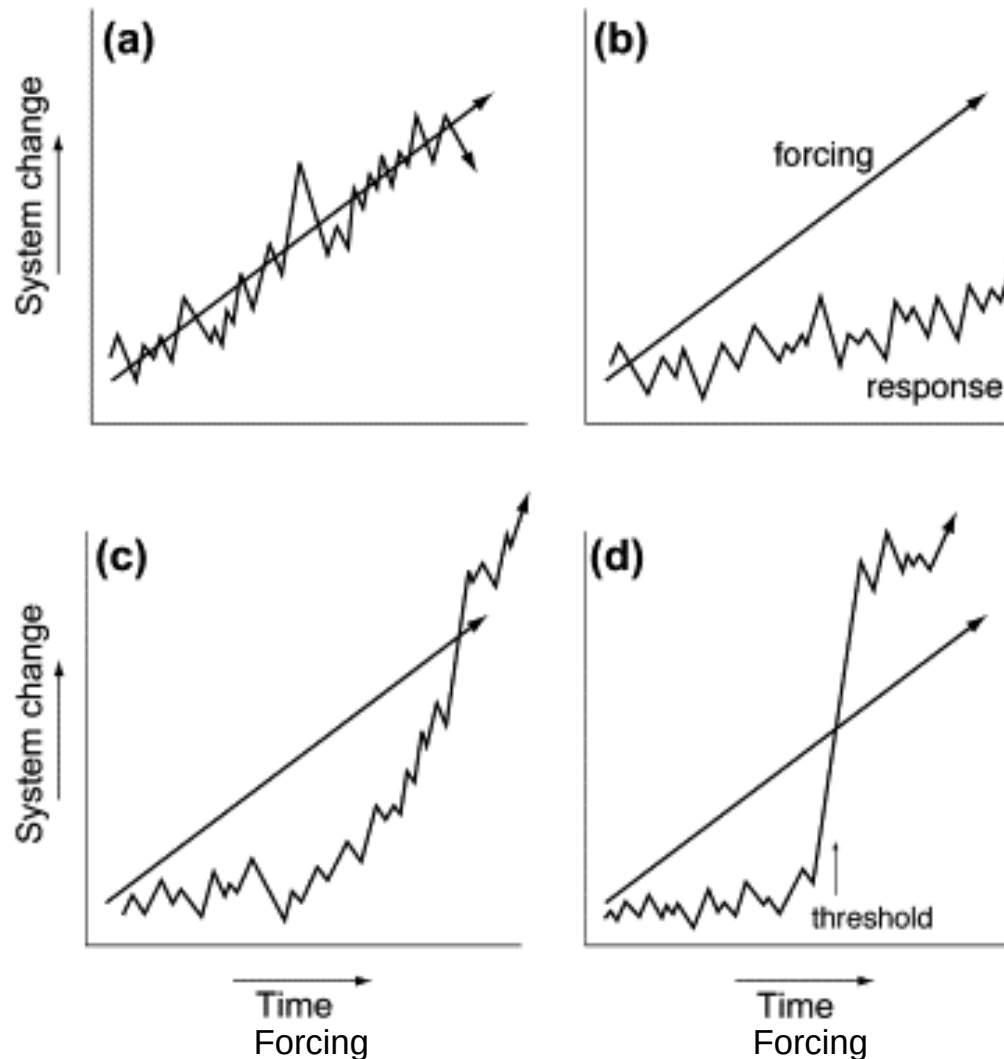
George Box

Feedbacks and Tipping Points

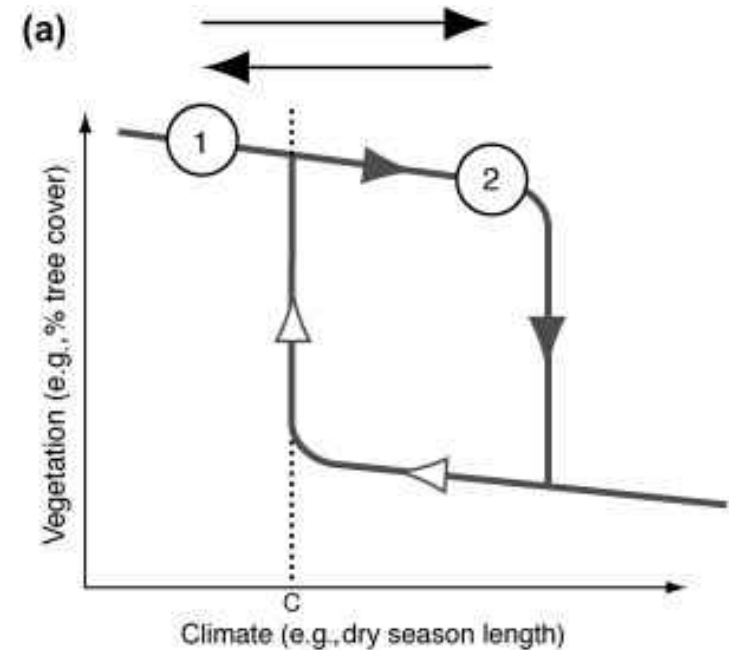
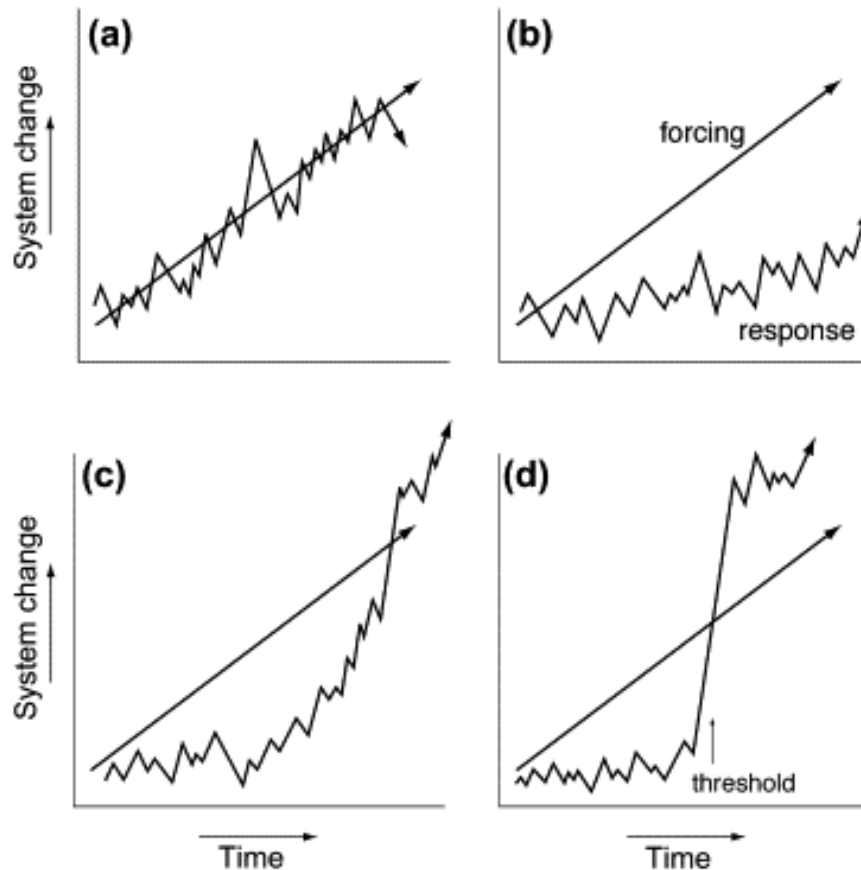
Feedbacks and Tipping Points



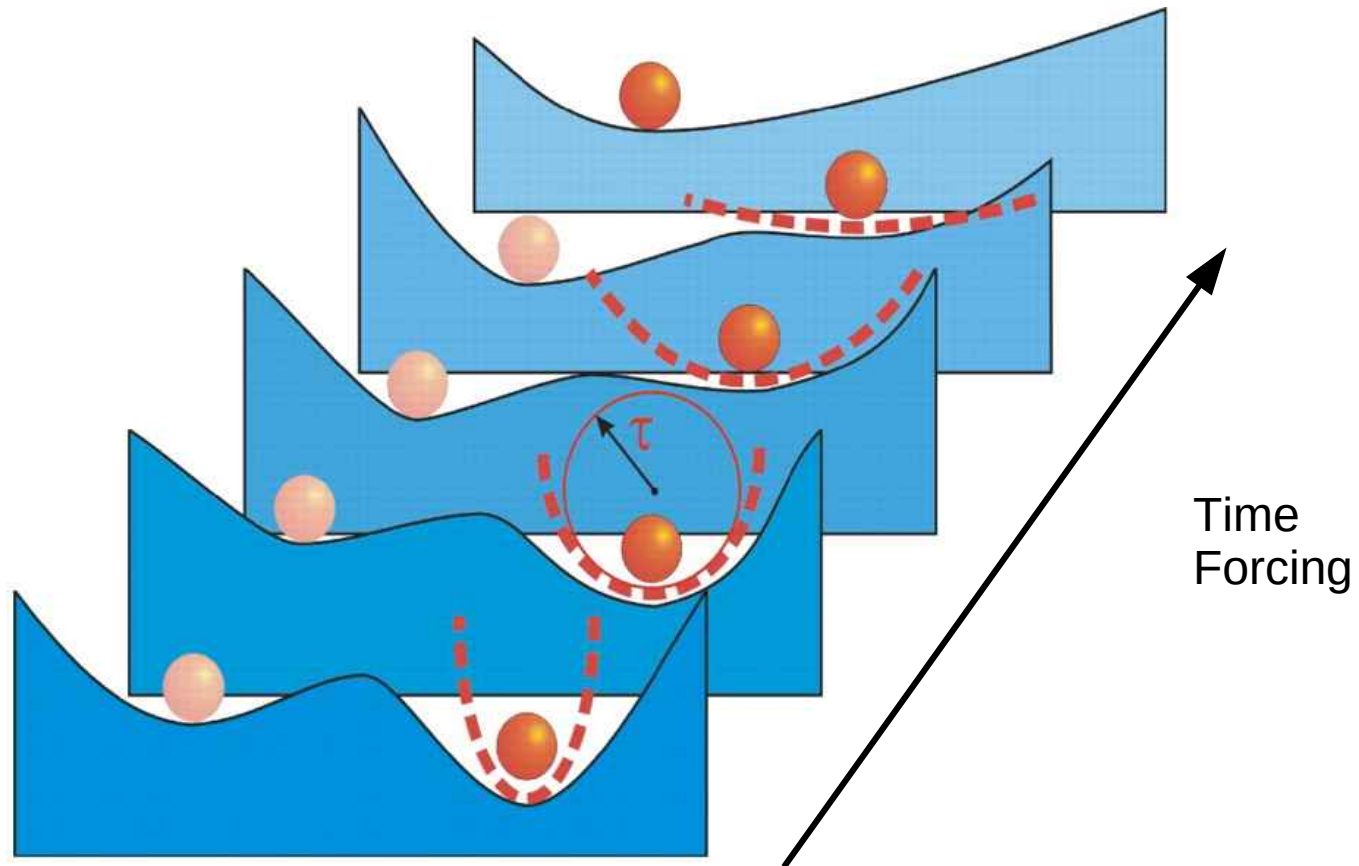
Feedbacks and Tipping Points



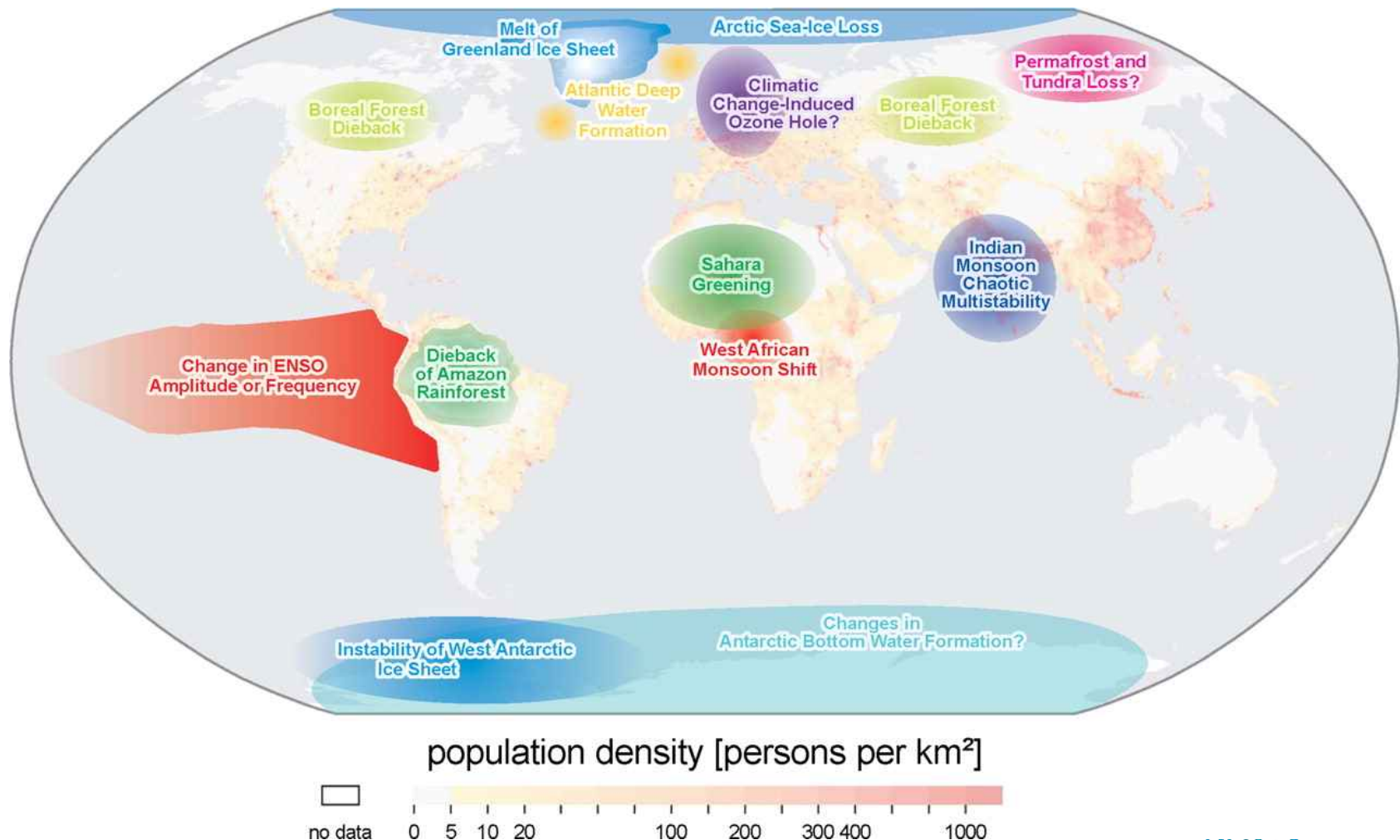
Feedbacks and Tipping Points



Feedbacks and Tipping Points



Feedbacks and Tipping Points

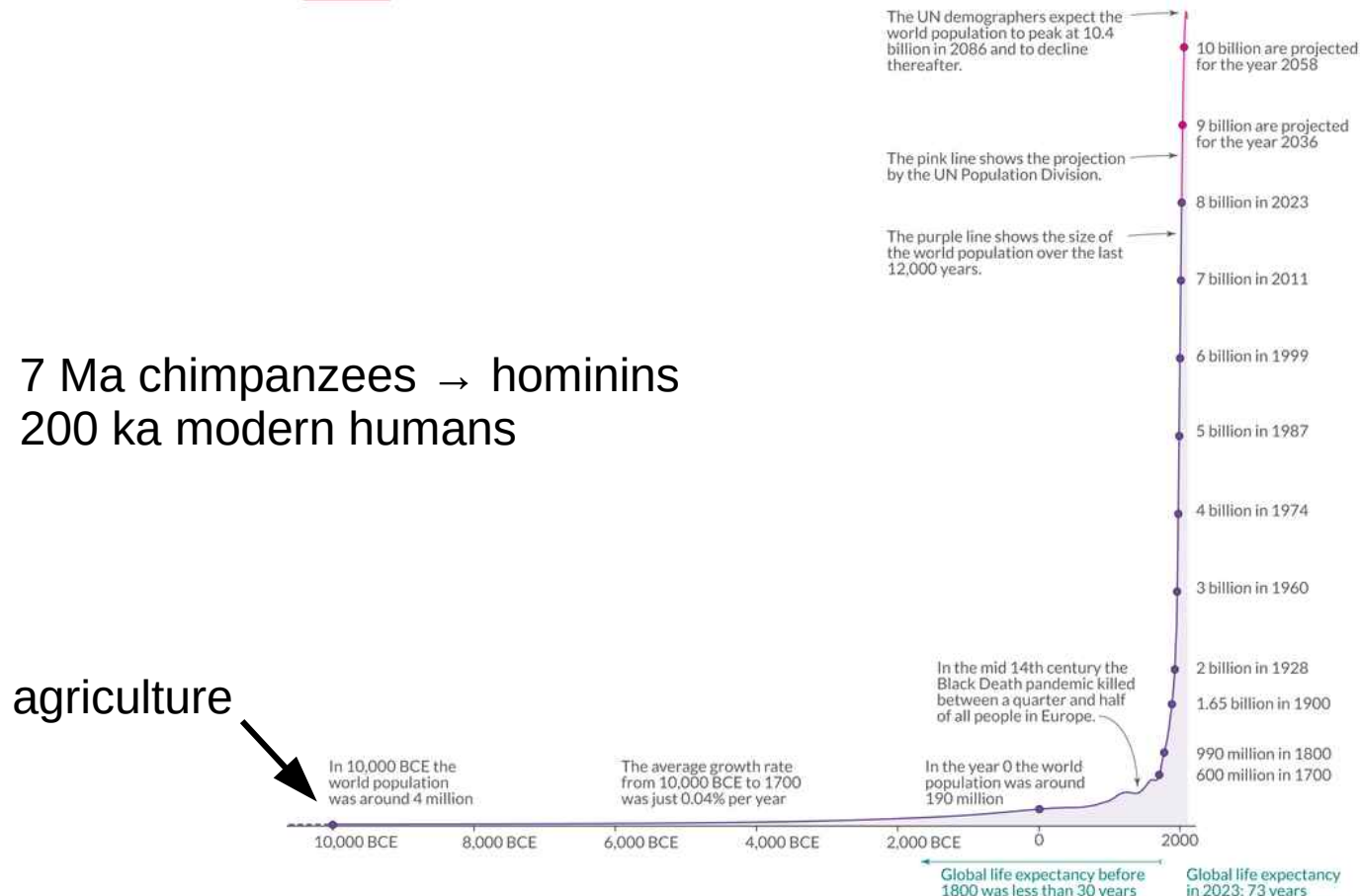


Human Influence

Human Influence

Our World
in Data

The size of the world population over the long-run



Based on estimates by the History Database of the Global Environment (HYDE) and the United Nations.

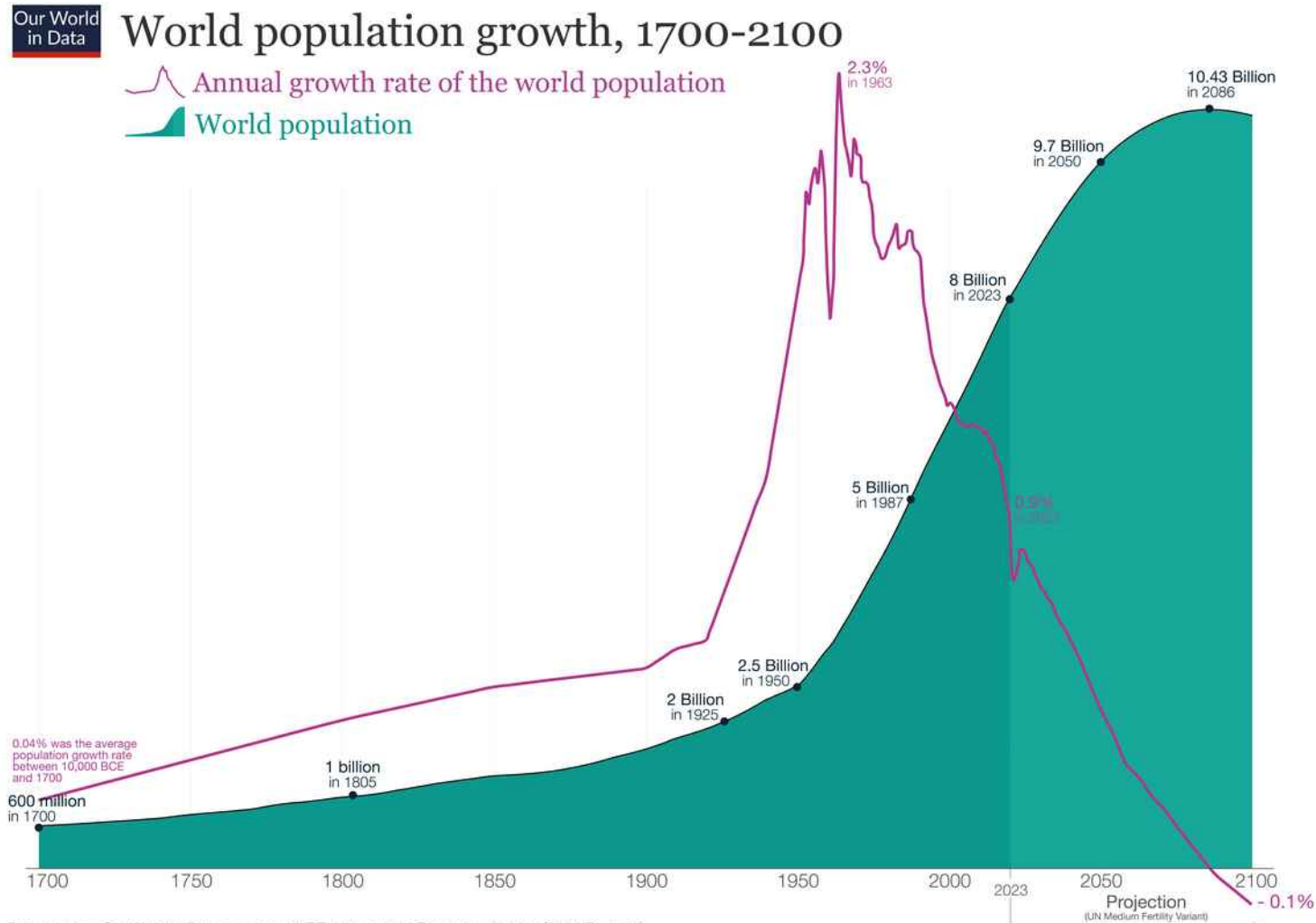
This is a visualization from [OurWorldinData.org](https://www.ourworldindata.org).

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Human Influence



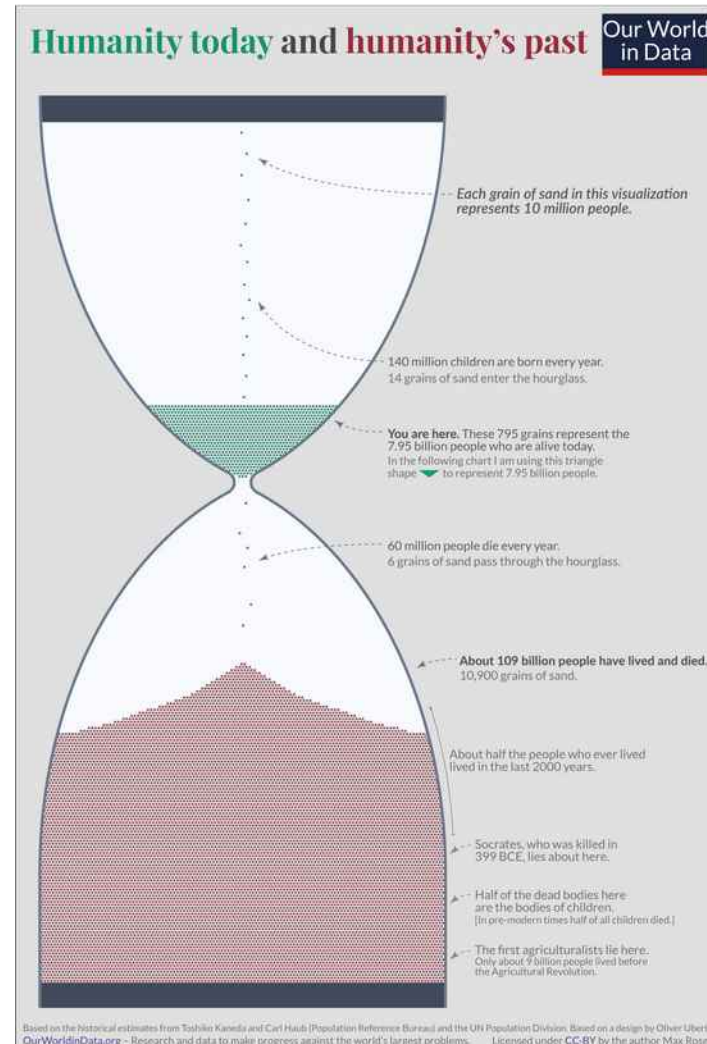
Data sources: Our World in Data based on HYDE, UN, and UN Population Division [2022 Revision]
This is a visualization from [OurWorldinData.org](https://ourworldindata.org), where you find data and research on how the world is changing.

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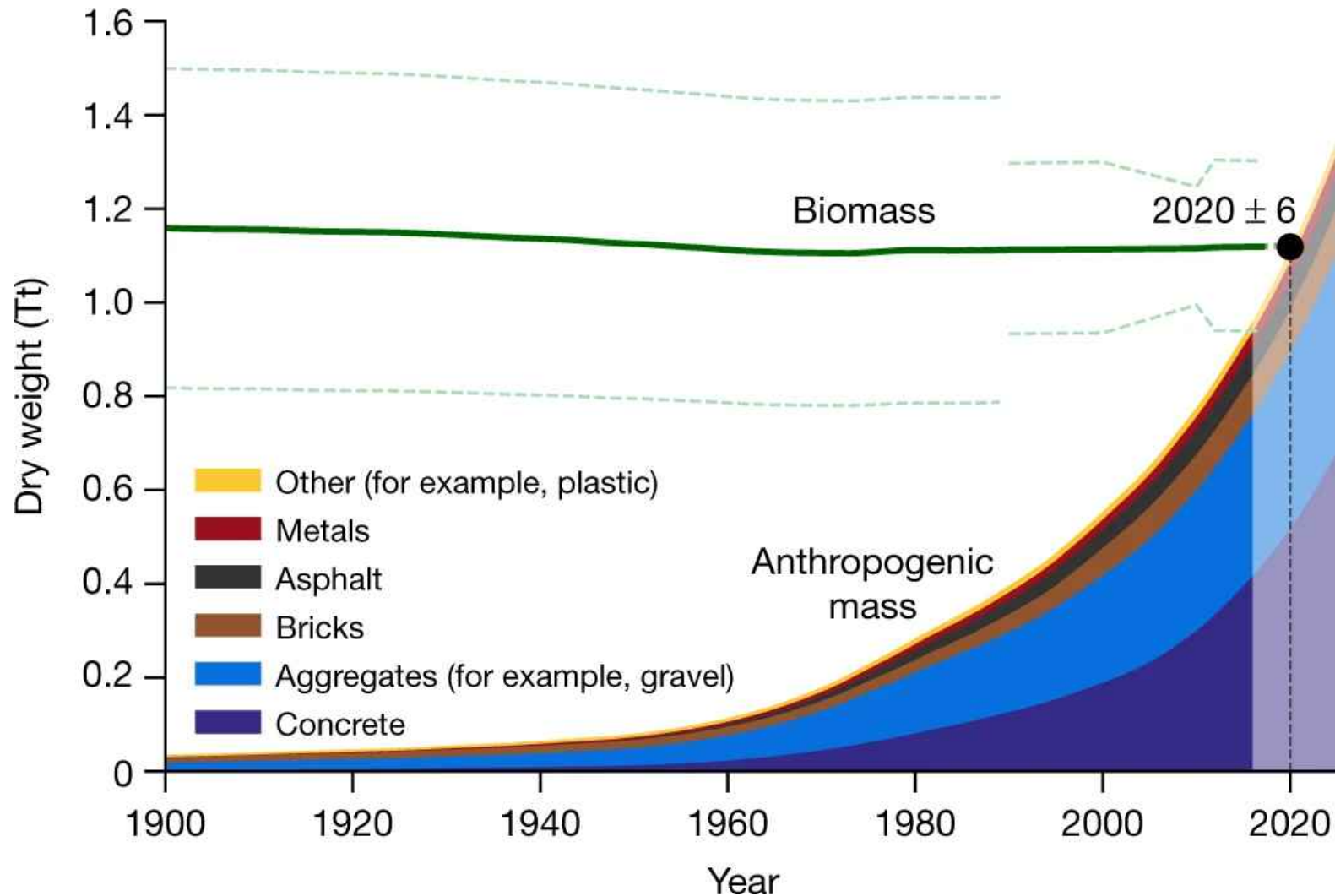
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Human Influence



Human Influence



Human Influence



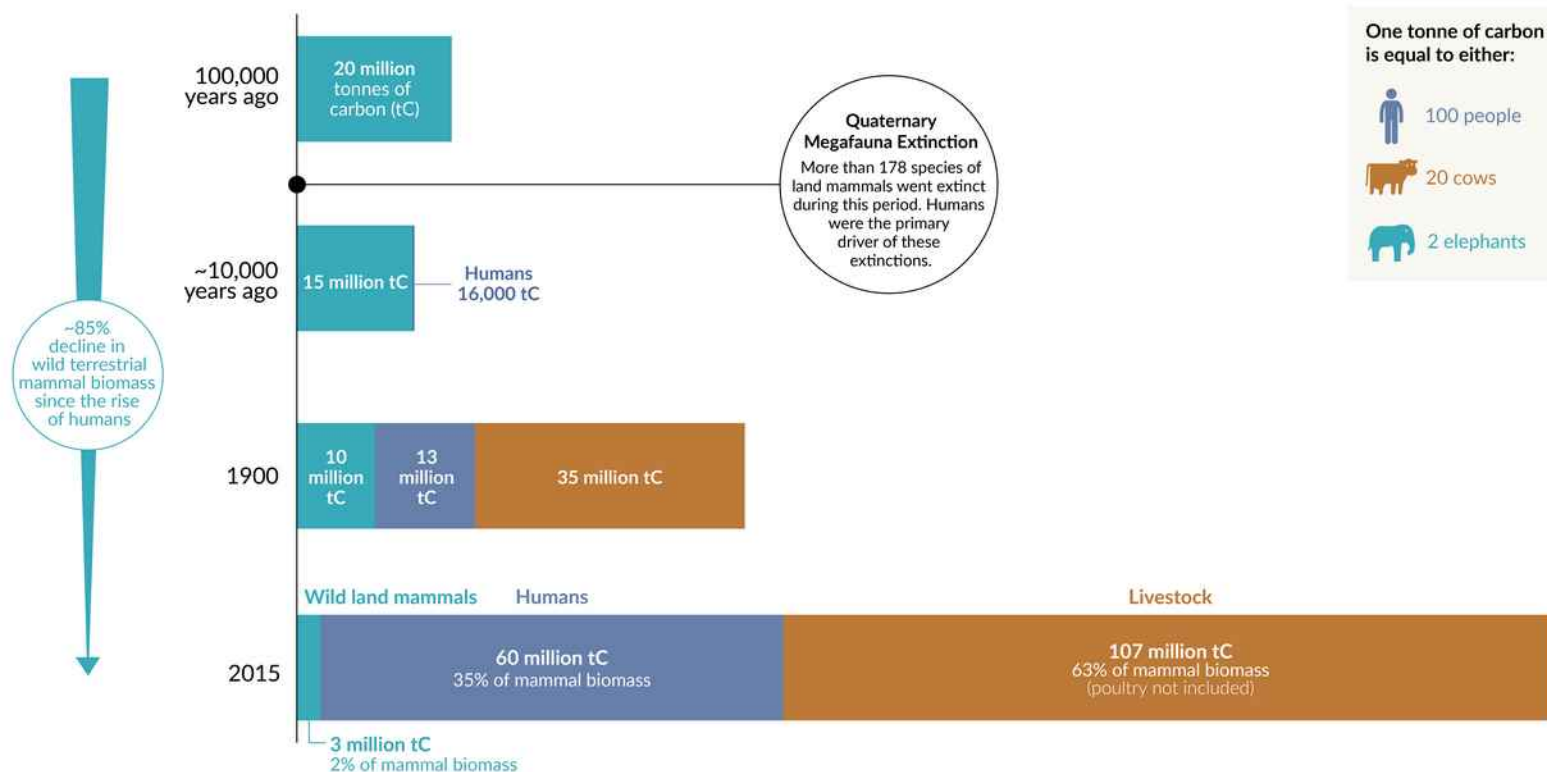
Current epoch:
The Anthropocene

Human Influence

Changing distribution of the world's land mammals

Mammals are compared in terms of biomass, measured in tonnes of carbon.

Our World
in Data



Note: Estimates of long-term biomass come with significant uncertainty, especially for wild mammals 100,000 and 10,000 years ago.

Sources: Barnosky (2008); Smil (2011); and Bar-On et al. (2018).

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

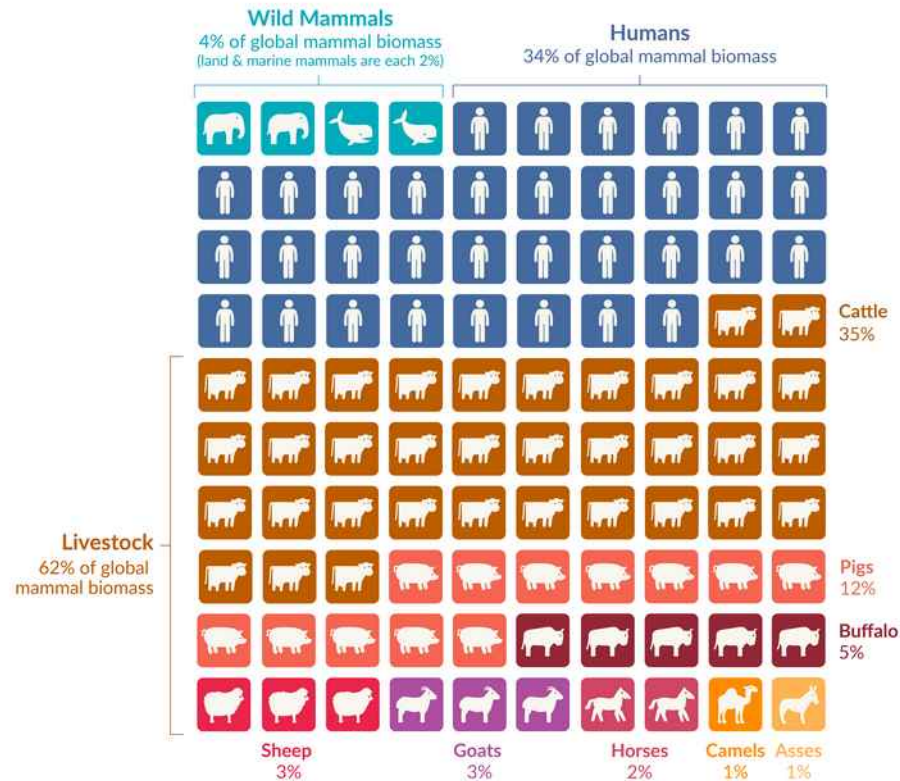
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Human Influence

Distribution of mammals on Earth

Mammal biomass is measured in tonnes of carbon, and is shown for the year 2015. Each square corresponds to 1% of global mammal biomass.

Our World
in Data



Note: An estimate for pets has been included in the total biomass figures, but is not shown on the visualization because it makes up less than 1% of the total.

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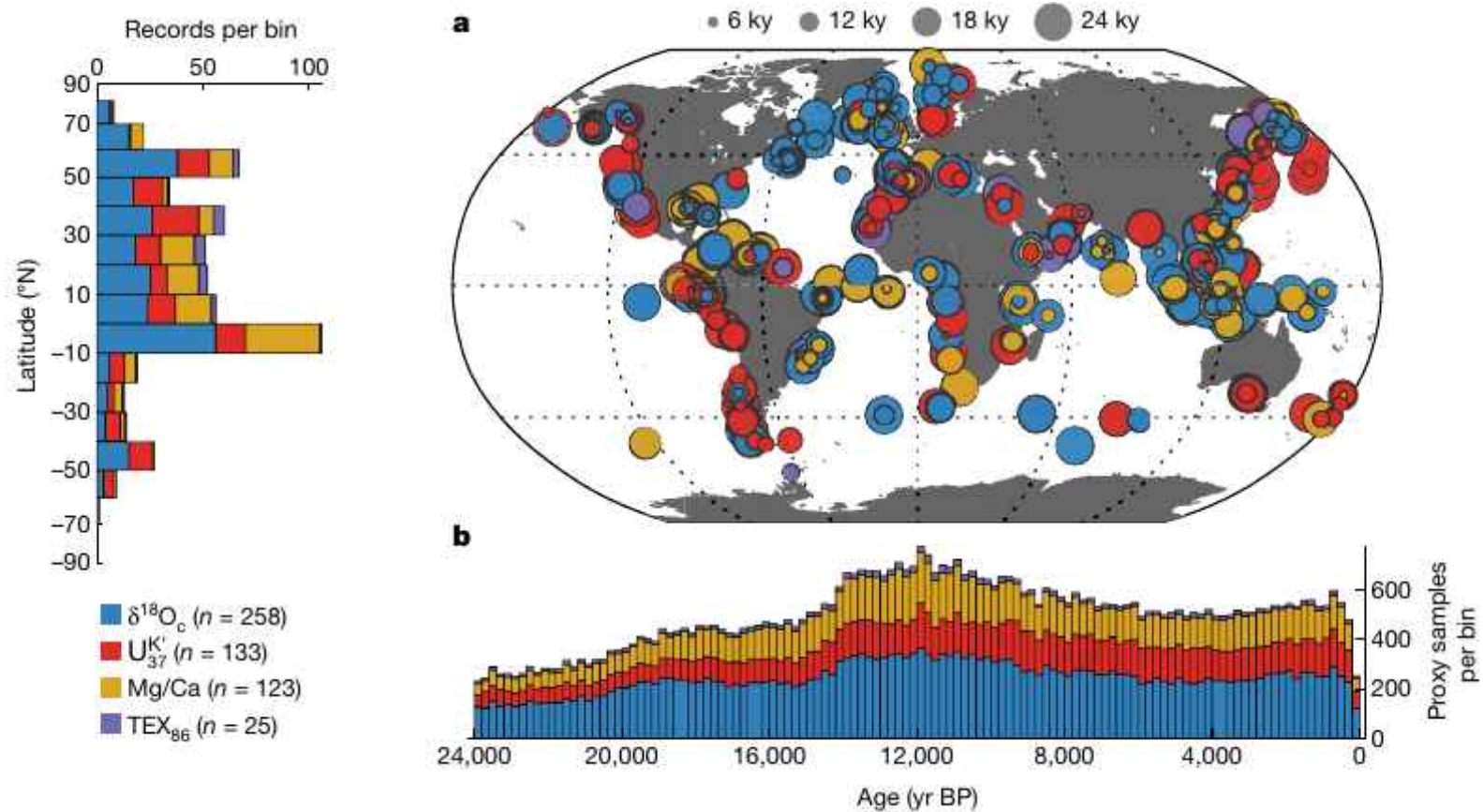
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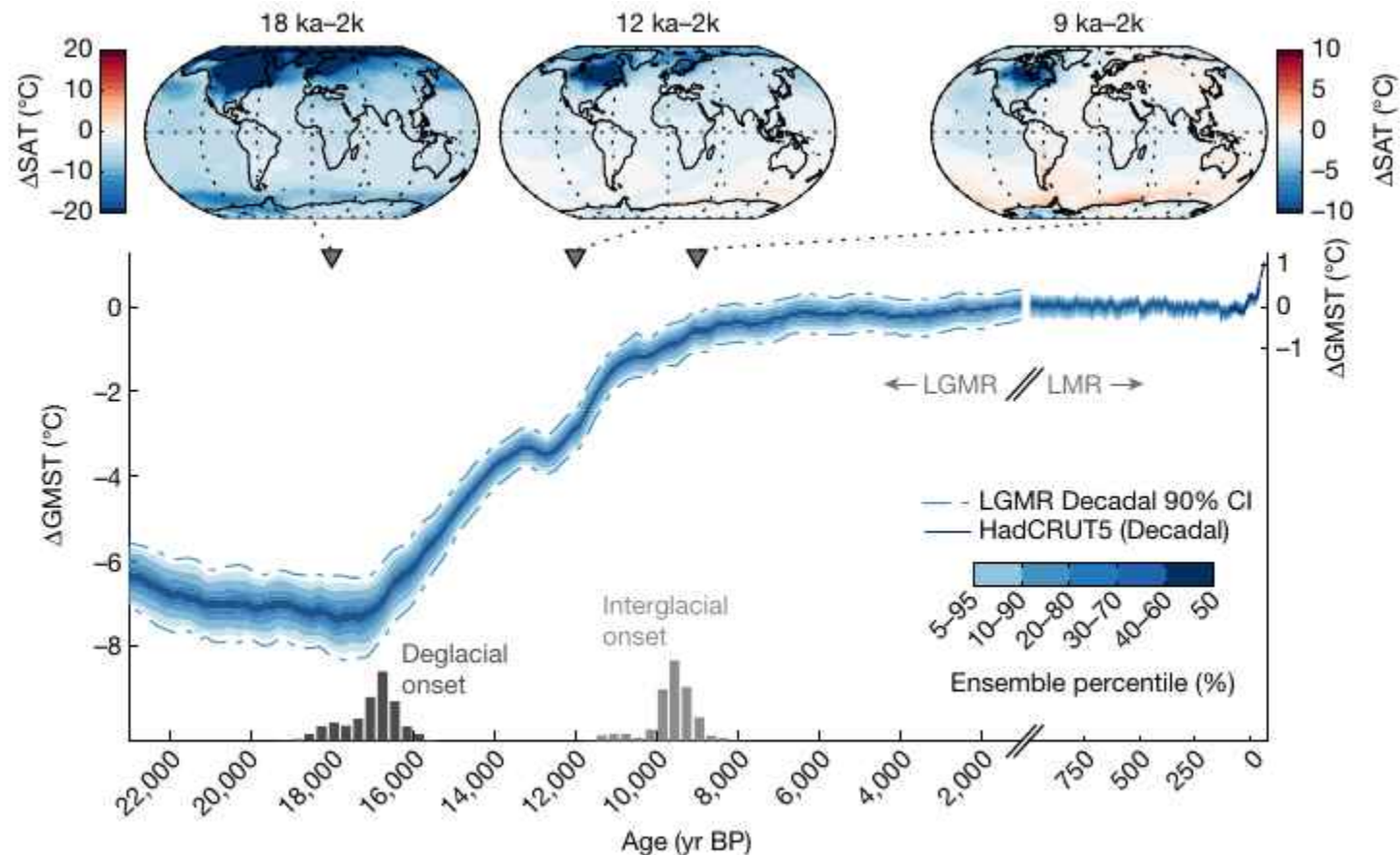
Human Influence

Global Climate during Human Civilization



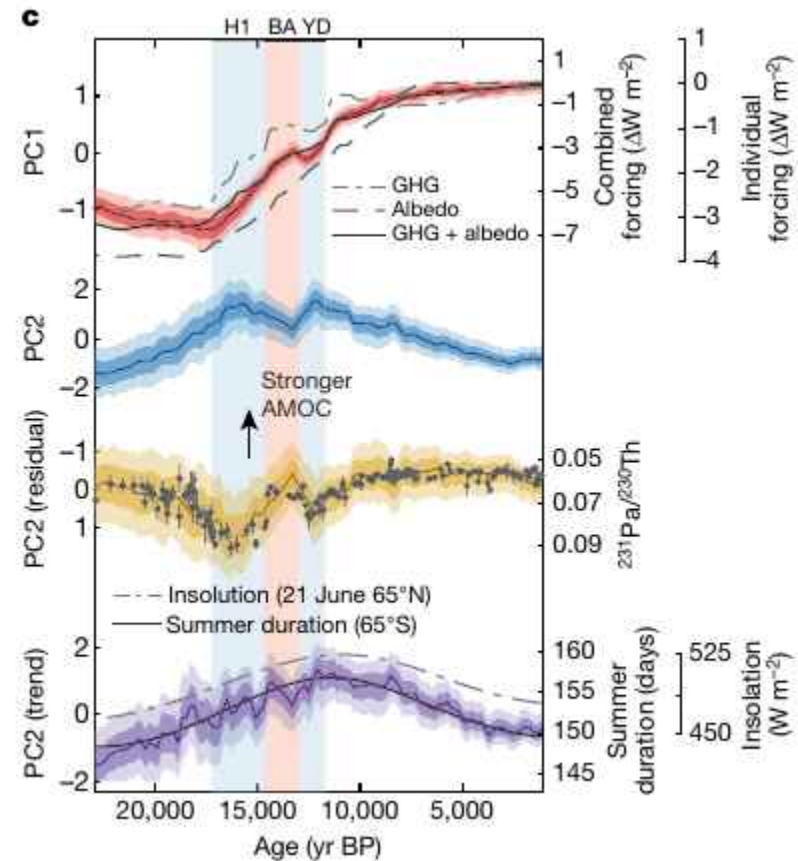
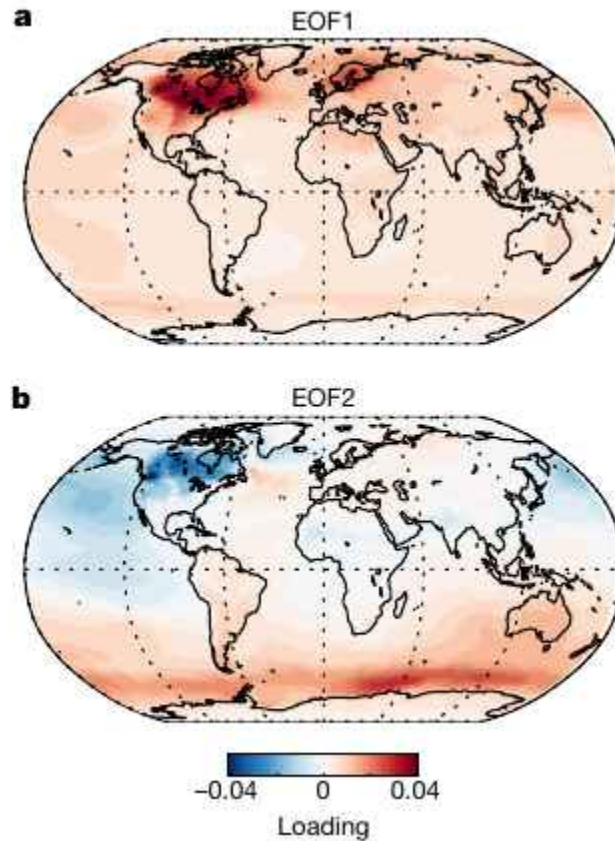
Human Influence

Global Climate during Human Civilization



Human Influence

Global Climate during Human Civilization



Human Influence

Global Climate during Human Civilization

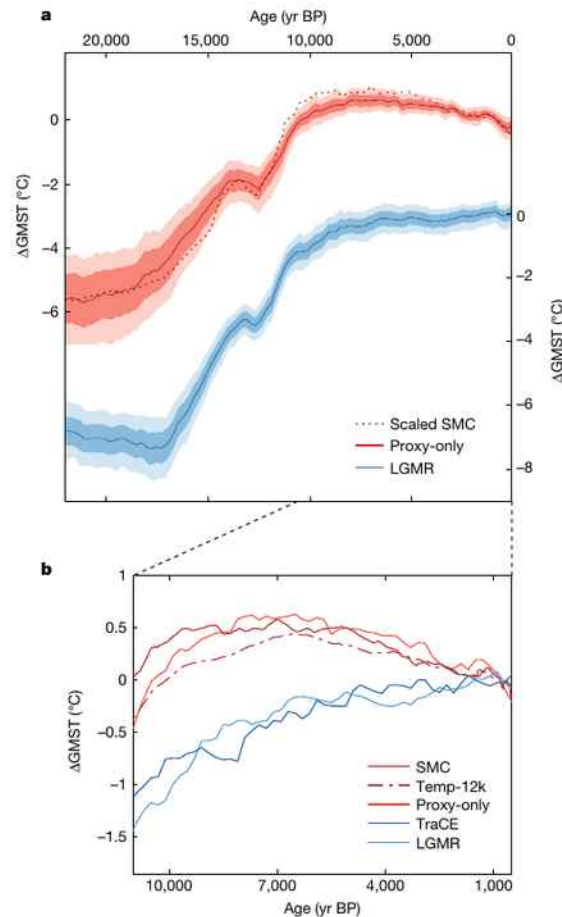


Fig. 4 | Comparison of LGM-to-present surface temperature reconstructions.

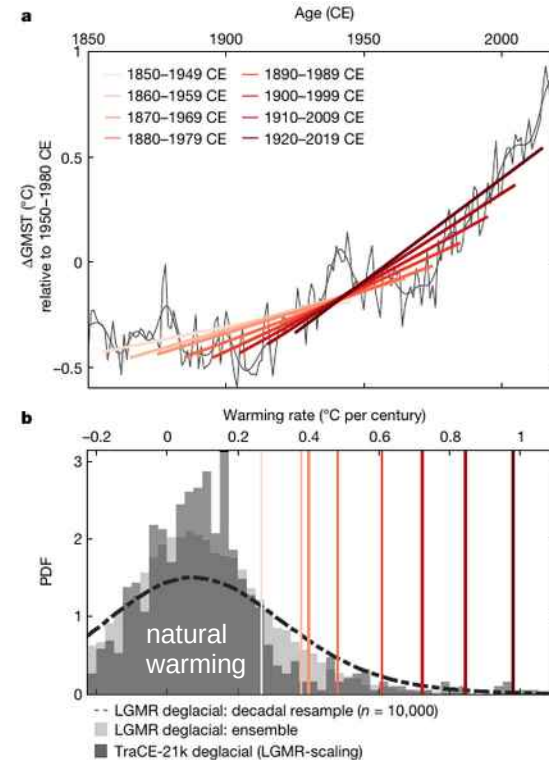
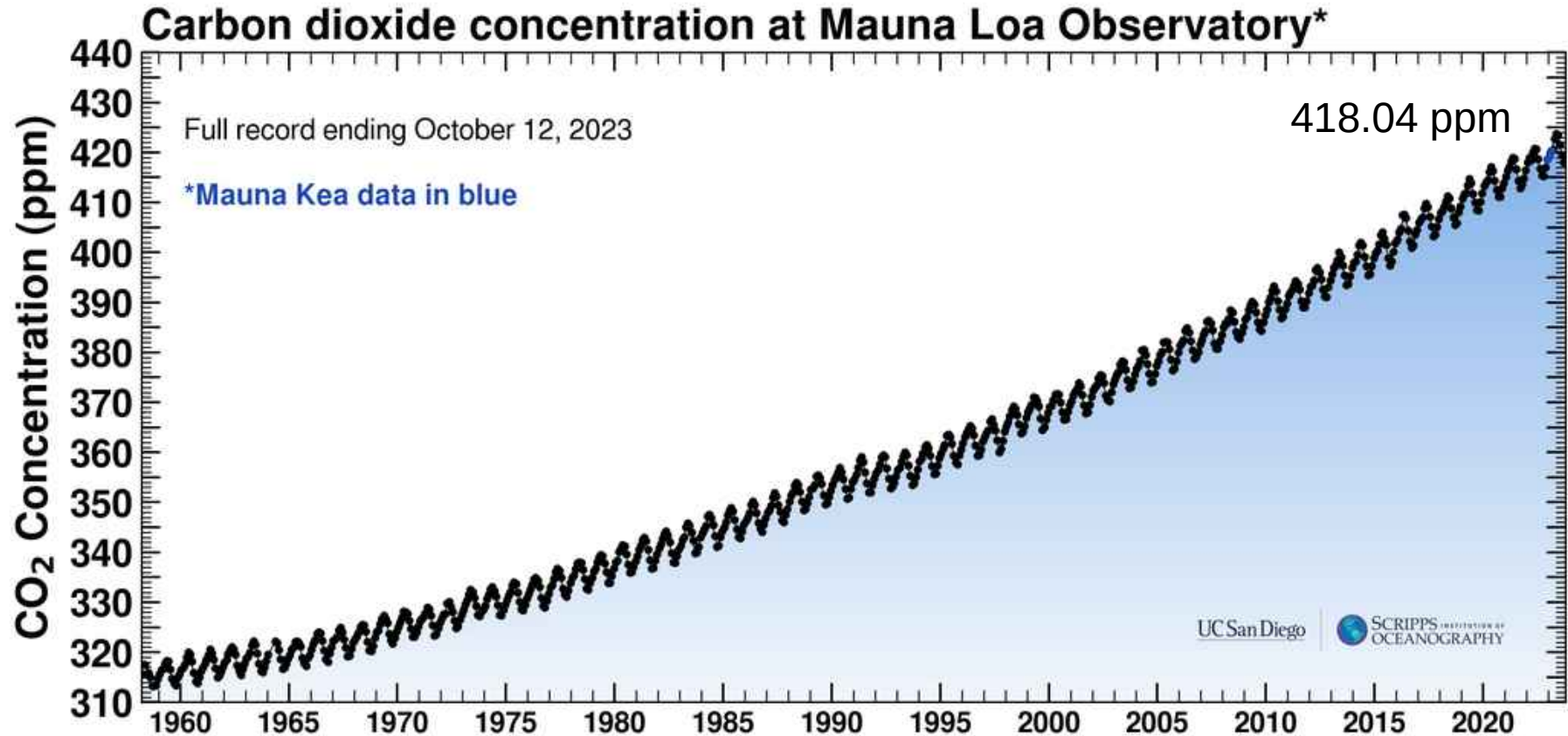


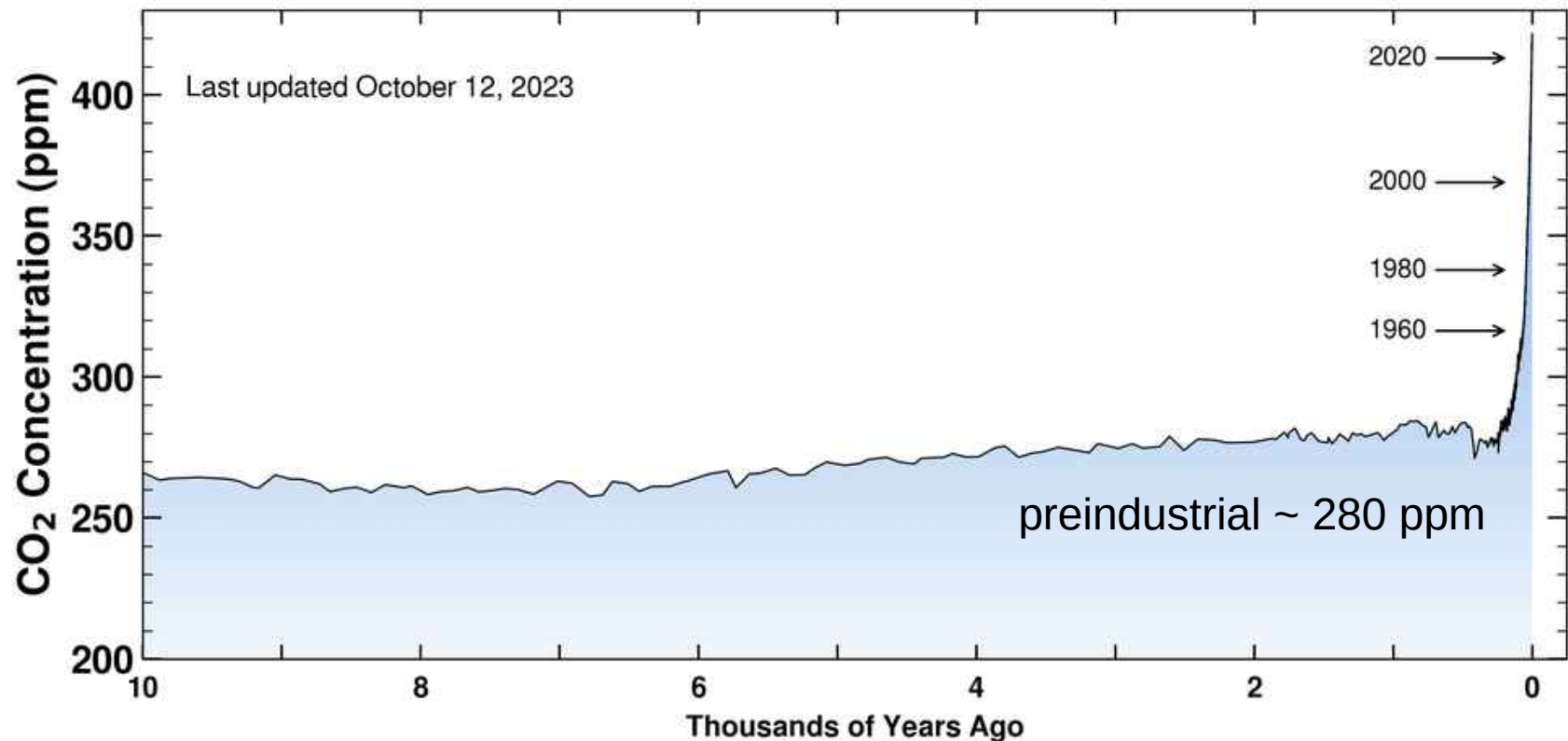
Fig. 5 | Contextualizing rates of modern warming. **a**, Observed rates of centennial GMST warming stepped decade-wise to present based on HadCRUT5 observations¹. **b**, Comparison of HadCRUT5 warming rates (vertical red lines) to the distribution of deglacial warming rates from (1) the LGMR ensemble ($n = 500$ posterior means); (2) the decadal variance-inflated LGMR ensemble ($n = 10,000$ randomly drawn samples; see Methods and Fig. 2); and (3) the TraCE-21k simulation¹ scaled to reflect the magnitude of LGMR deglacial warming (Supplementary Information). Observed centennial warming rates after 1910 CE exceed the

recent warming

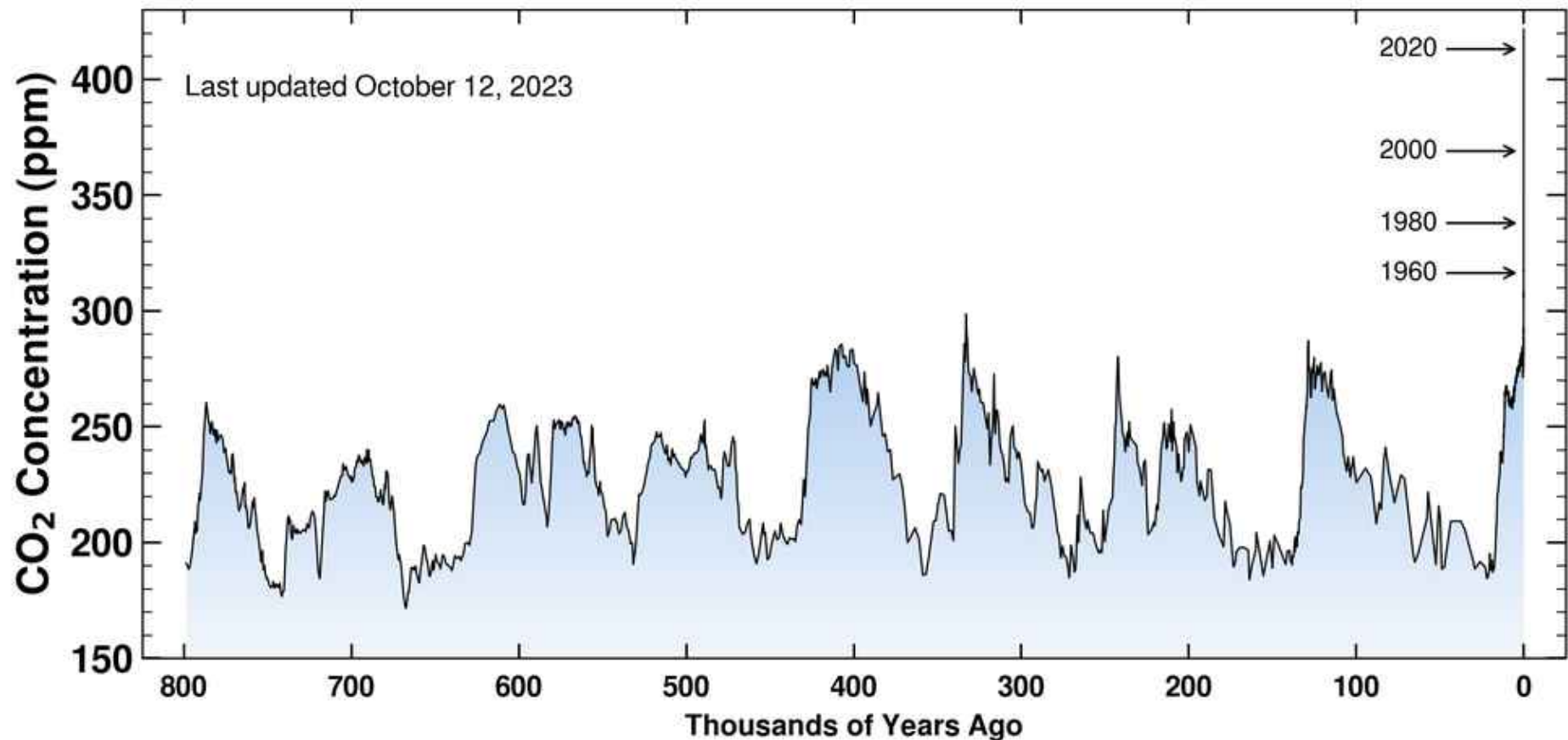
Human Influence



Human Influence



Human Influence



Human Influence

Fourier,
Tyndall,
et al.:

absorption &
GHG

Arrhenius

Glacial
Cycles

~ 5.5 °C

next ice
age
coming?

nope,
that's
cancelled

global
warming
coming

yep,
it's here

just as
we
projected

it really
is here

call it
climate
change

your turn

mid 19th C.

end 19th C.

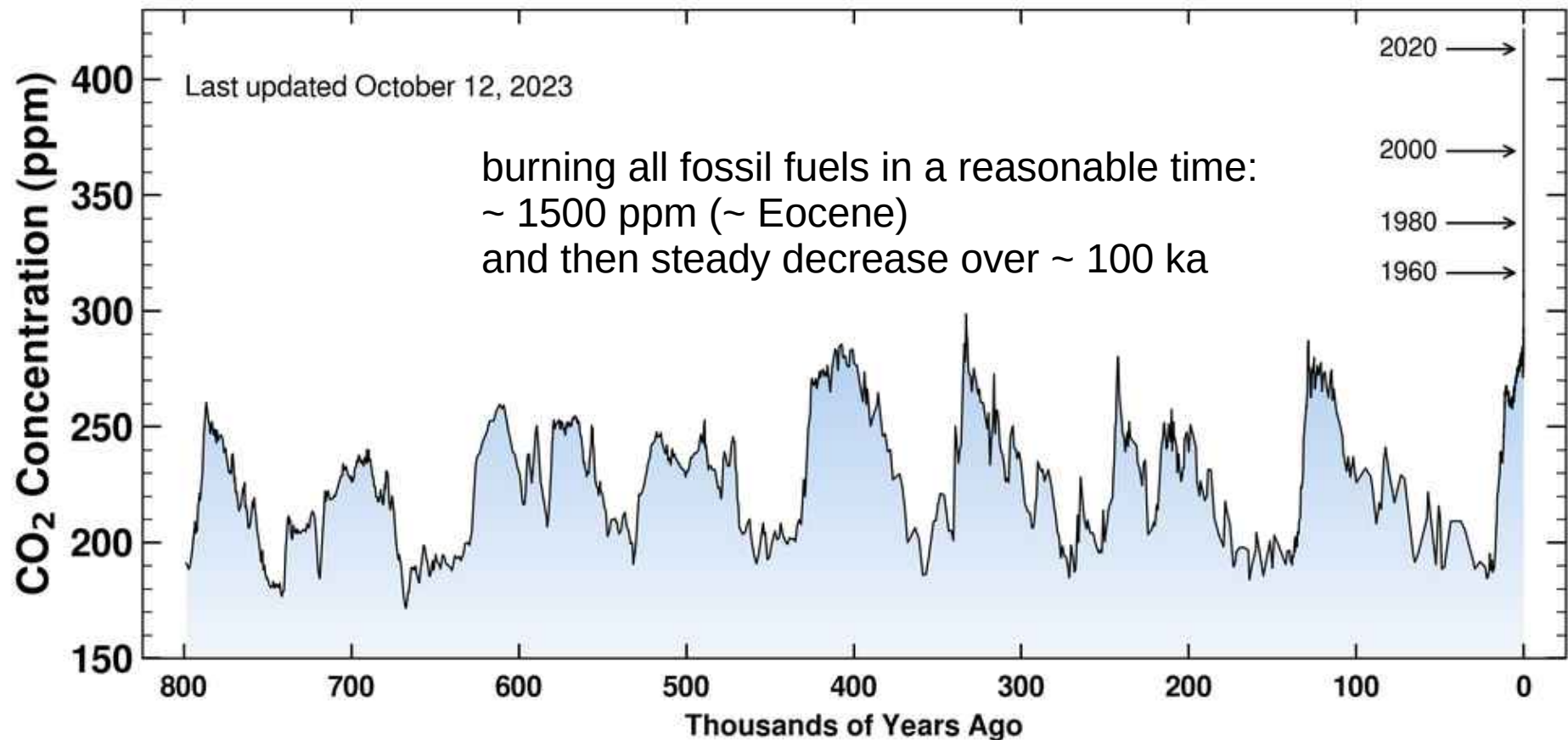
1950s

1970s

1990s

2020s

Human Influence



Human Influence

Who has contributed most to global CO₂ emissions?

Our World
in Data

Cumulative carbon dioxide (CO₂) emissions over the period from 1751 to 2017. Figures are based on production-based emissions which measure CO₂ produced domestically from fossil fuel combustion and cement, and do not correct for emissions embedded in trade (i.e. consumption-based). Emissions from international travel are not included.

North America

457 billion tonnes CO₂
29% global cumulative emissions



Asia

457 billion tonnes CO₂
29% global cumulative emissions



EU-28

353 billion tonnes CO₂
22% global cumulative emissions



Europe

514 billion tonnes CO₂
33% global cumulative emissions

Africa

43 billion tonnes CO₂
3% global emissions

South America

40 billion tonnes CO₂
3% global emissions

Oceania

20 billion tonnes CO₂
1.2% global emissions

Figures for the 28 countries in the European Union have been grouped as the 'EU-28' since international targets and negotiations are typically set as a collaborative target between EU countries. Values may not sum to 100% due to rounding.

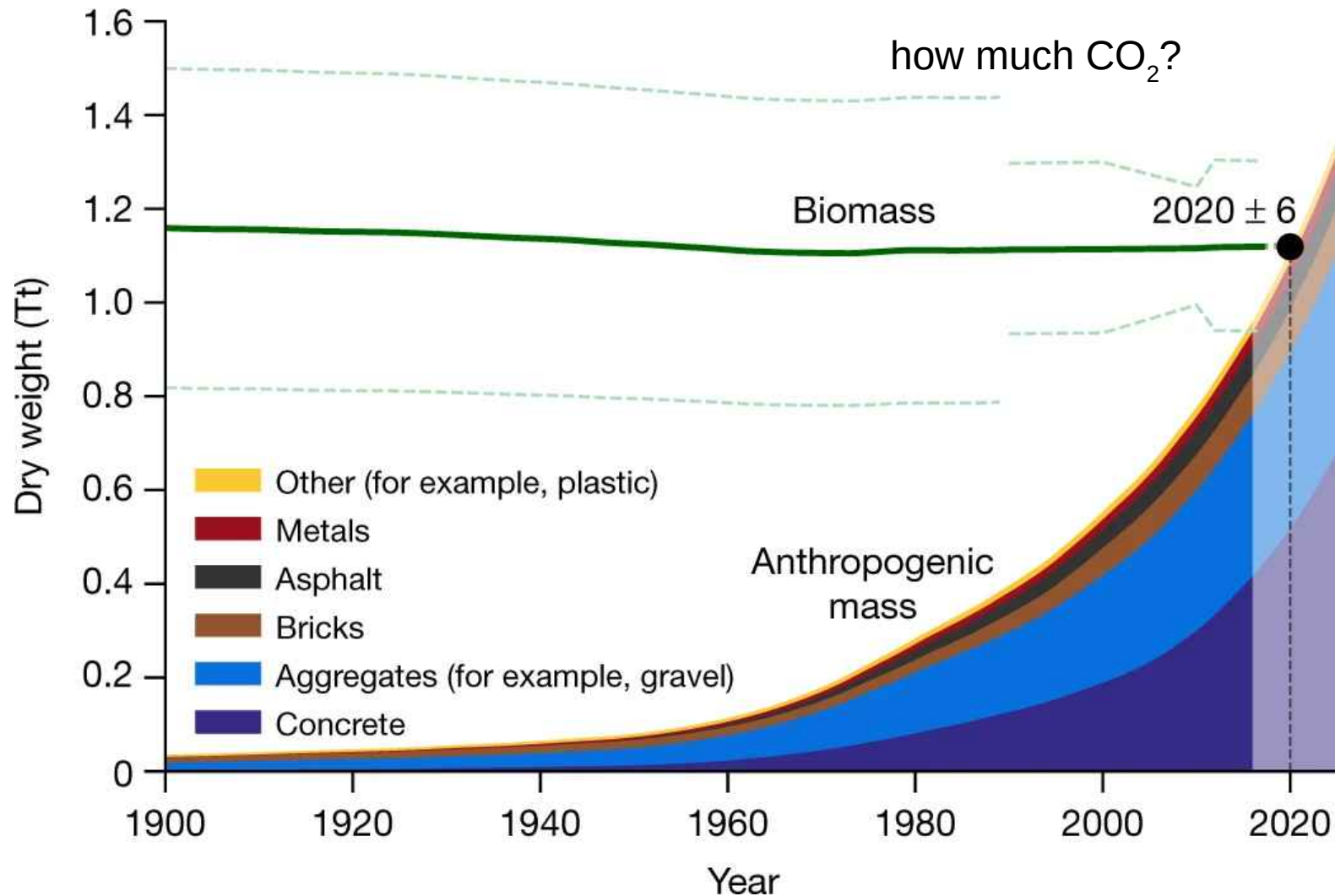
Data source: Calculated by Our World in Data based on data from the Global Carbon Project (GCP) and Carbon Dioxide Analysis Center (CDIAC). This is a visualization from OurWorldinData.org, where you find data and research on how the world is changing.

Licensed under CC-BY by the author Hannah Ritchie.

nil

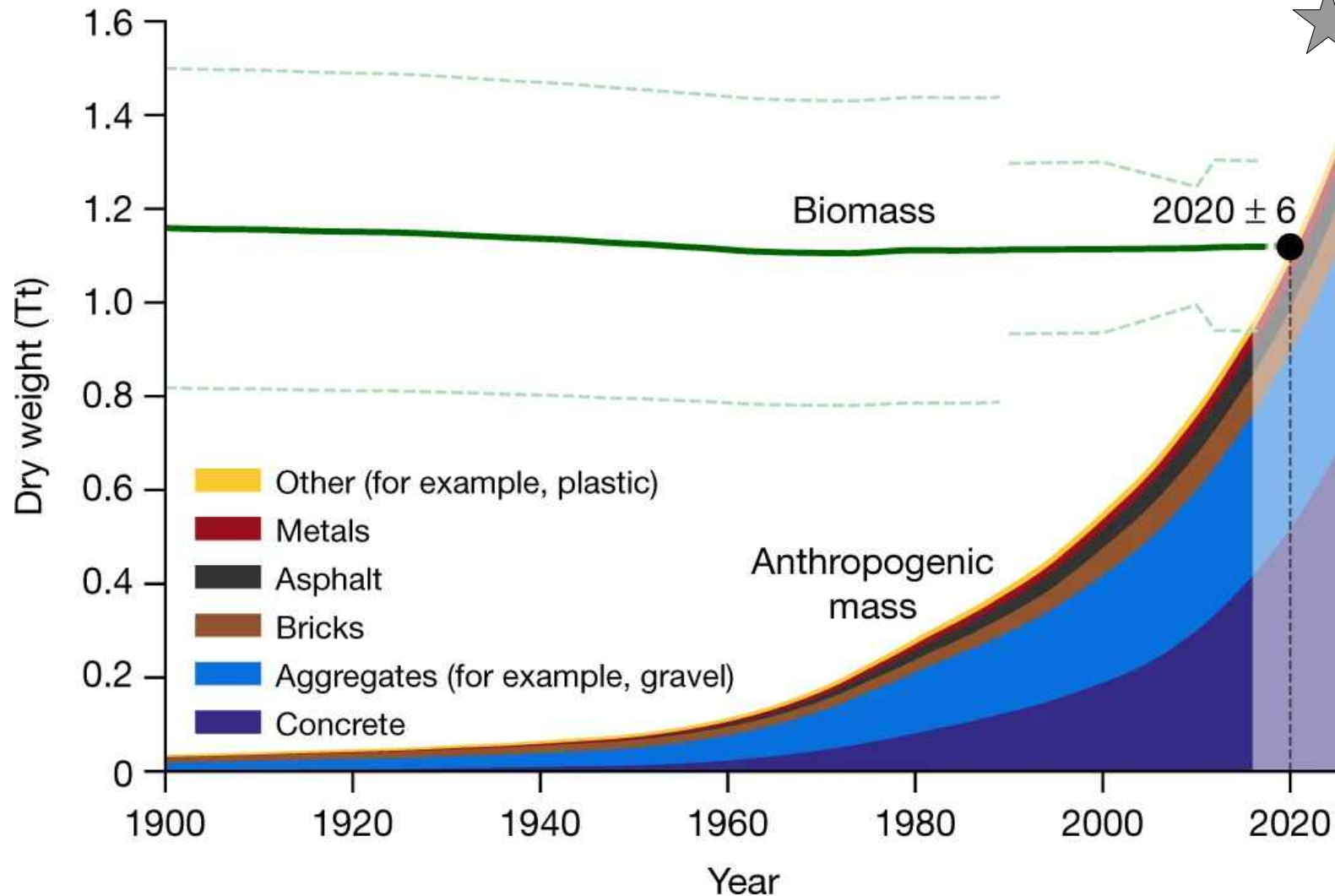
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Human Influence



Human Influence

CO₂:
1.7 Tt



Human Influence

where did all the CO₂ go?

Human Influence

where did all the CO₂ go?

<https://youtube.com/watch?v=dwVsD9CiokY>

Human Influence

Global warming potential of greenhouse gases over 100-year timescale

Global warming potential¹ measures the relative warming impact of one unit mass of a greenhouse gas relative to carbon dioxide.

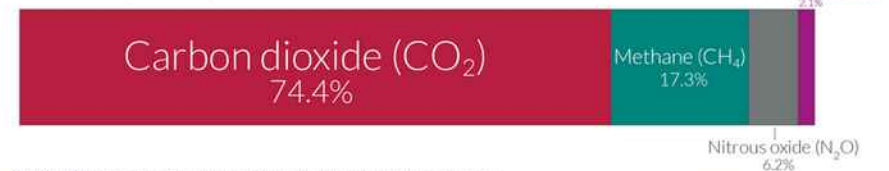
Our World
in Data



Global greenhouse gas emissions by gas

Greenhouse gas emissions are converted to carbon dioxide-equivalents (CO₂eq) by multiplying each gas by its 100-year 'global warming potential' value; the amount of warming one tonne of the gas would create relative to one tonne of CO₂ over a 100-year timescale. This breakdown is shown for 2016.

Our World
in Data



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

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Source: IPCC, 2014: Climate Change 2014: Synthesis Report.

OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

1. Global warming potential: Global warming potential (GWP) measures the amount of heat absorbed by a greenhouse gas relative to the same mass of carbon dioxide (CO₂). It measures the amount of warming a gas creates compared to CO₂. Carbon dioxide is given a GWP value of one. If a gas had a GWP of 10 then one kilogram of that gas would generate ten times the warming effect as one kilogram of CO₂. Since greenhouse gases spend different amounts of time in the atmosphere, their global warming potential depends on the length of time that it's measured over. For example, GWP can be measured as the warming effect over 20 years, 50 years, or 100 years. Potent but short-lived greenhouse gases – like methane, for example – will have a higher GWP when measured over 20 years than over 100 years. The GWP value for methane over 100 years (GWP₁₀₀) is 28. This means one kilogram of methane would cause 28 times the warming of one kilogram of CO₂.

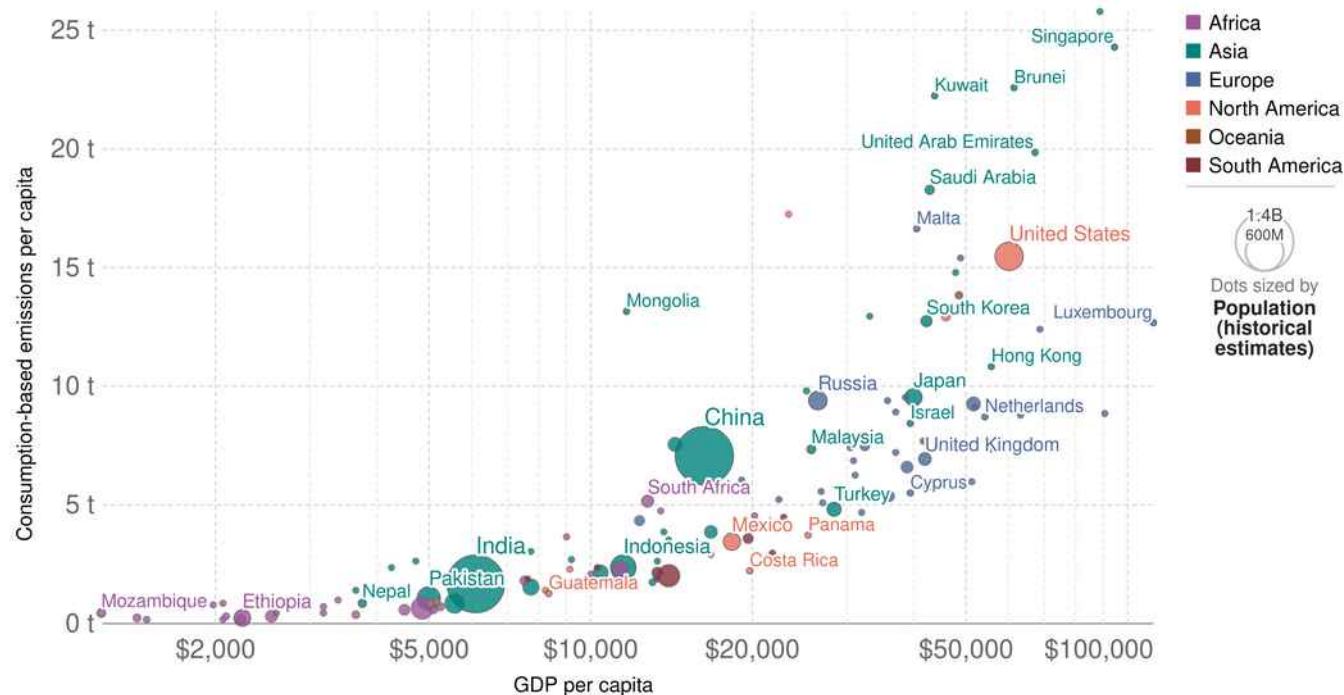
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Human Influence

Consumption-based CO₂ emissions per capita vs. GDP per capita, 2020

- Consumption-based emissions¹ are national emissions that have been adjusted for trade. It's production-based emissions minus emissions embedded in exports, plus emissions embedded in imports.
- GDP per capita is adjusted for price differences between countries (PPP) and over time (inflation).

Our World
in Data

Source: Global Carbon Project (2022); Population based on various sources (2023); Data compiled from multiple sources by World Bank
OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

1. Consumption-based emissions: Consumption-based emissions are national or regional emissions that have been adjusted for trade. They are calculated as domestic (or 'production-based' emissions) emissions minus the emissions generated in the production of goods and services that are exported to other countries or regions, plus emissions from the production of goods and services that are imported. Consumption-based emissions = Production-based – Exported + Imported emissions

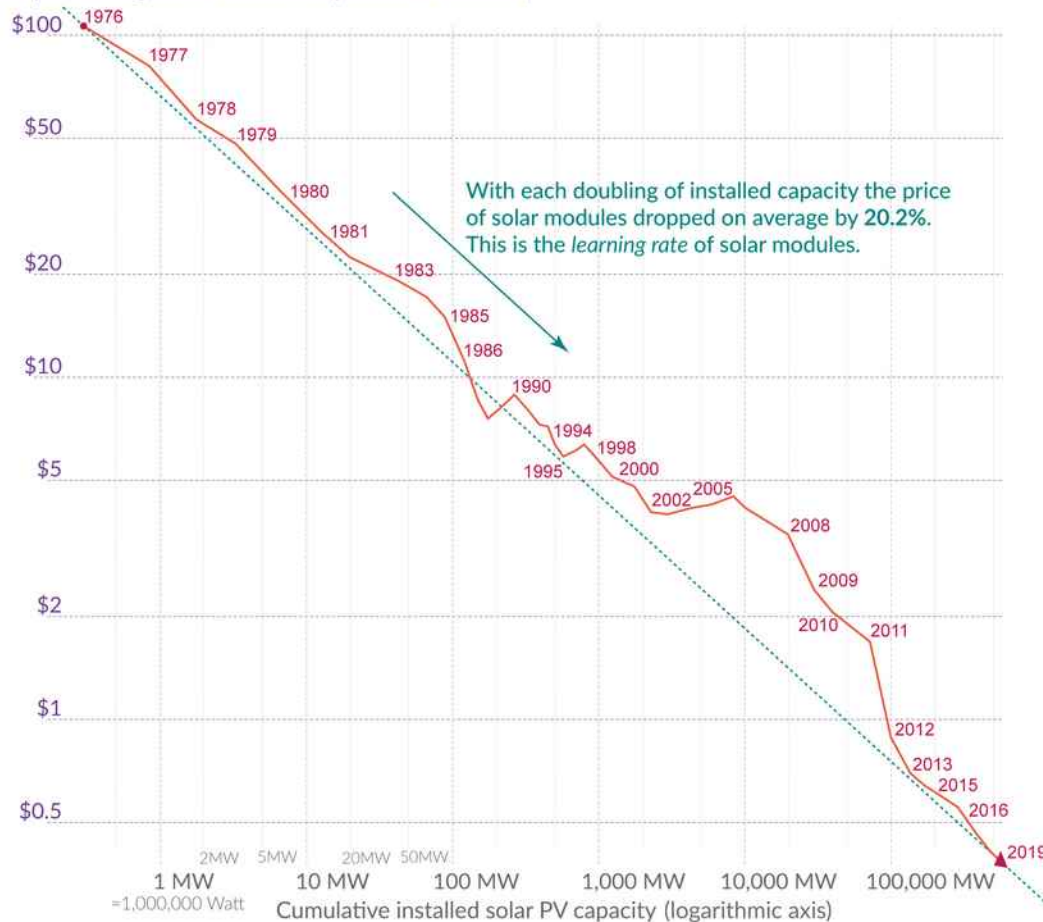
Human Influence

The price of solar modules declined by 99.6% since 1976

Our World
in Data

Price per Watt of solar photovoltaics (PV) modules (logarithmic axis)

The prices are adjusted for inflation and presented in 2019 US-\$.



Data: Lafond et al. (2017) and IRENA Database; the reported learning rate is an average over several studies reported by de La Tour et al (2013) in Energy. The rate has remained very similar since then.
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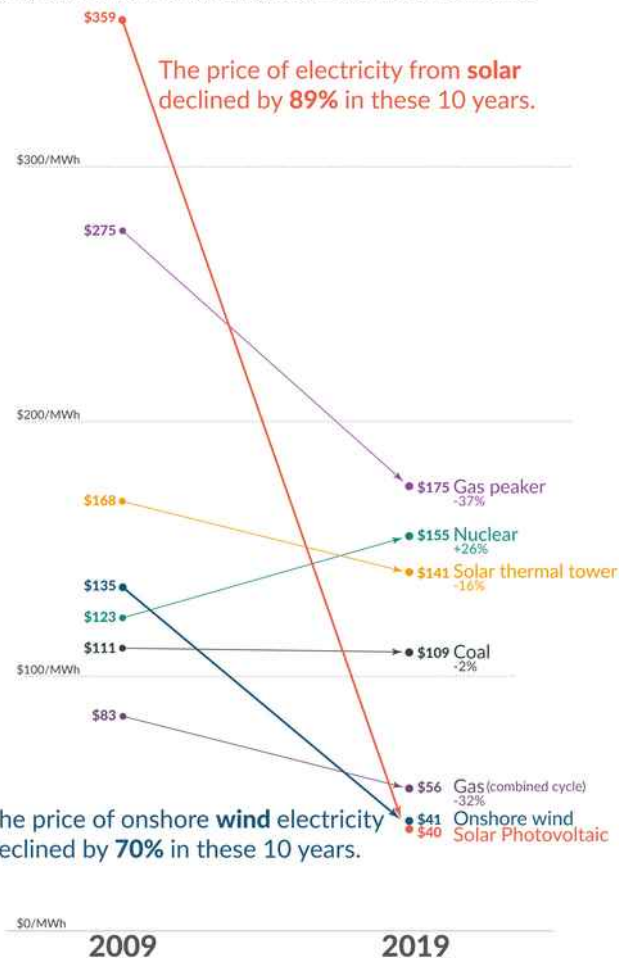
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The price of electricity from new power plants

Electricity prices are expressed in 'levelized costs of energy' (LCOE). LCOE captures the cost of building the power plant itself as well as the ongoing costs for fuel and operating the power plant over its lifetime.

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Data: Lazard Levelized Cost of Energy Analysis, Version 13.0

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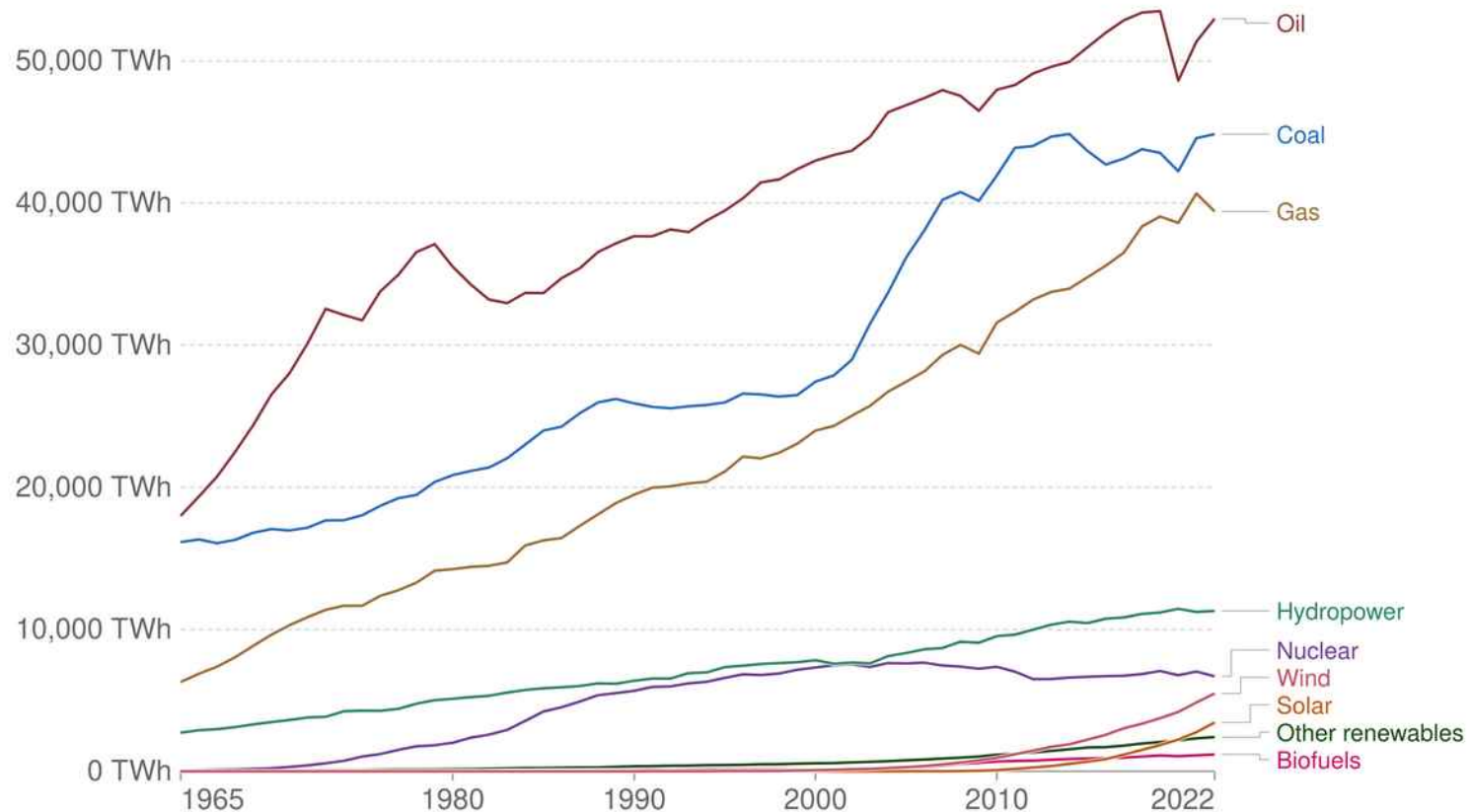
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Human Influence

Primary energy consumption by source, World

Primary energy is shown based on the 'substitution' method which takes account of inefficiencies in energy production from fossil fuels.

Our World
in Data



Source: Energy Institute Statistical Review of World Energy (2023)

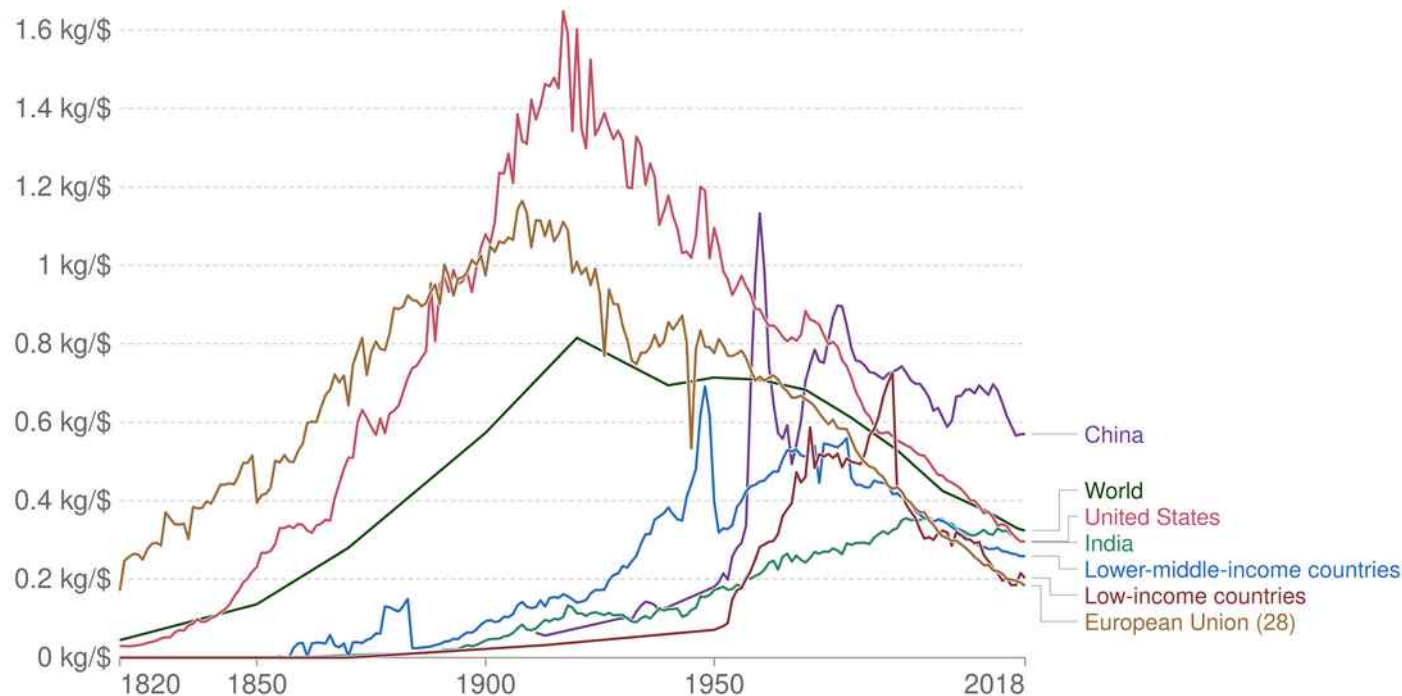
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Human Influence

Carbon intensity: CO₂ emissions per dollar of GDP

This is measured as the kilograms of CO₂ emitted per dollar of GDP. Emissions include fossil fuel and industry emissions¹. Land use change is not included. GDP data is adjusted for inflation and differences in the cost of living between countries.

Our World
in Data



Source: Maddison Project Database 2020 (Bolt and van Zanden, 2020); Global Carbon Project (2022)

Note: GDP data is expressed in international-\$² at 2011 prices.

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Human Influence

examples on fossil fuels

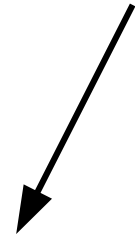
Human Influence

- average energy intensity EU ~ 0.2 kg CO₂ per € spent
 - how much is 0.2 kg CO₂?
 - @ 20°C ideal gas ~ 24 litres / mole
 - 0.2 kg CO₂ ~ 4.5 moles
 - ~ 100 litres CO₂ gas
- (that's a nice bath in a small tub)

Human Influence

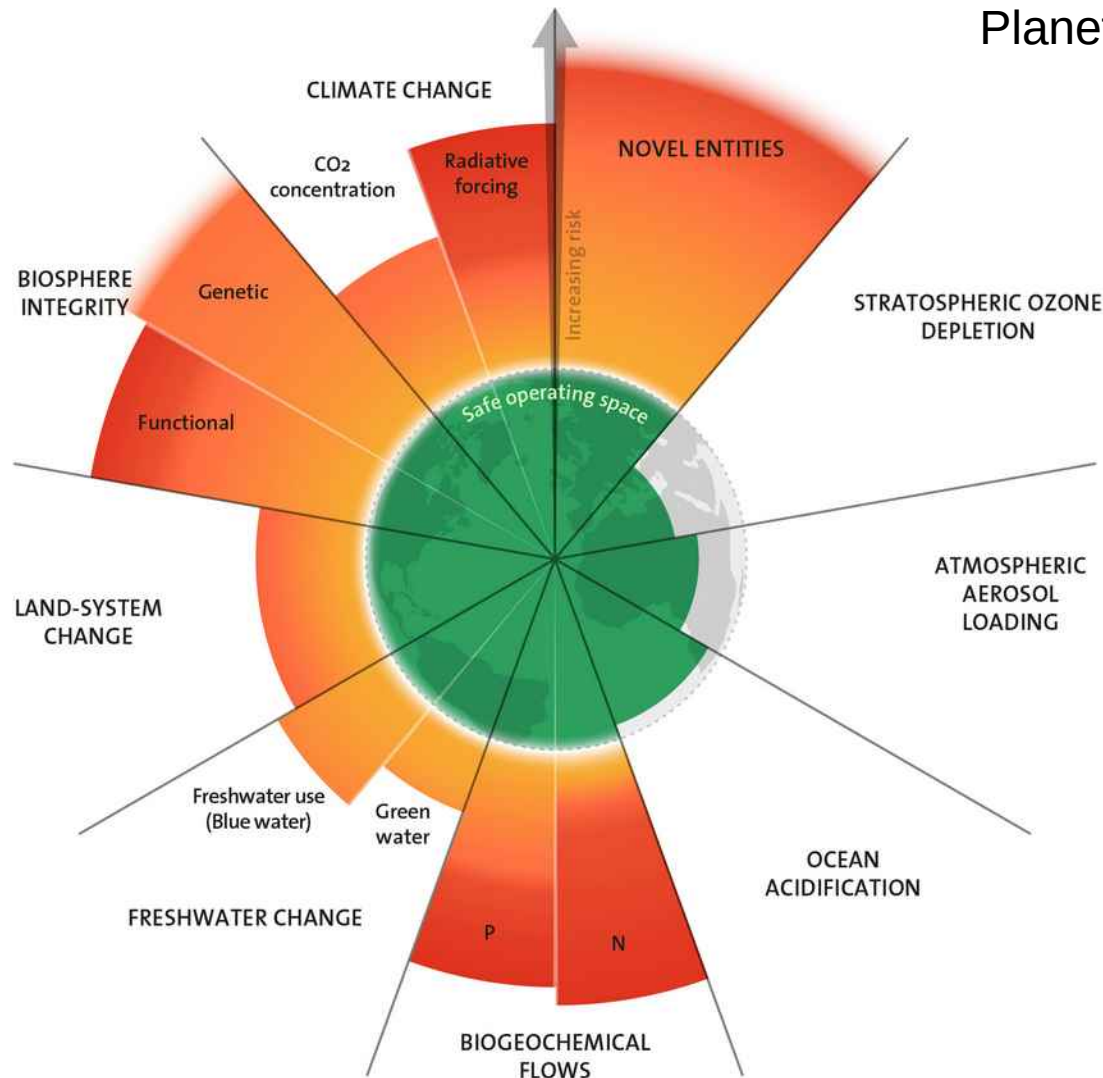
- how much does burning coal heat the planet vs. e.g. your house?
- 1 kg coal: 30 MJ heating value (8 kWh), 3.2 kg CO₂
- 70 ppm CO₂ increase ~ climate forcing of 2.5 W/m²
- Earth surface ~ 510.000.000 km² → 1.3 * 10¹⁵ W
- ~ 800 Gt C in atmosphere (3000 Gt CO₂)
- 3.2 kg CO₂ from coal ~ 10⁻¹⁵ of atm. CO₂ ~ 1W
- 8000 h ~ 333 d ~ 1 year
- over 100 years ~ 100 x more heating in atmosphere

same as spending
average 16 €!



Human Influence

Planetary Boundaries

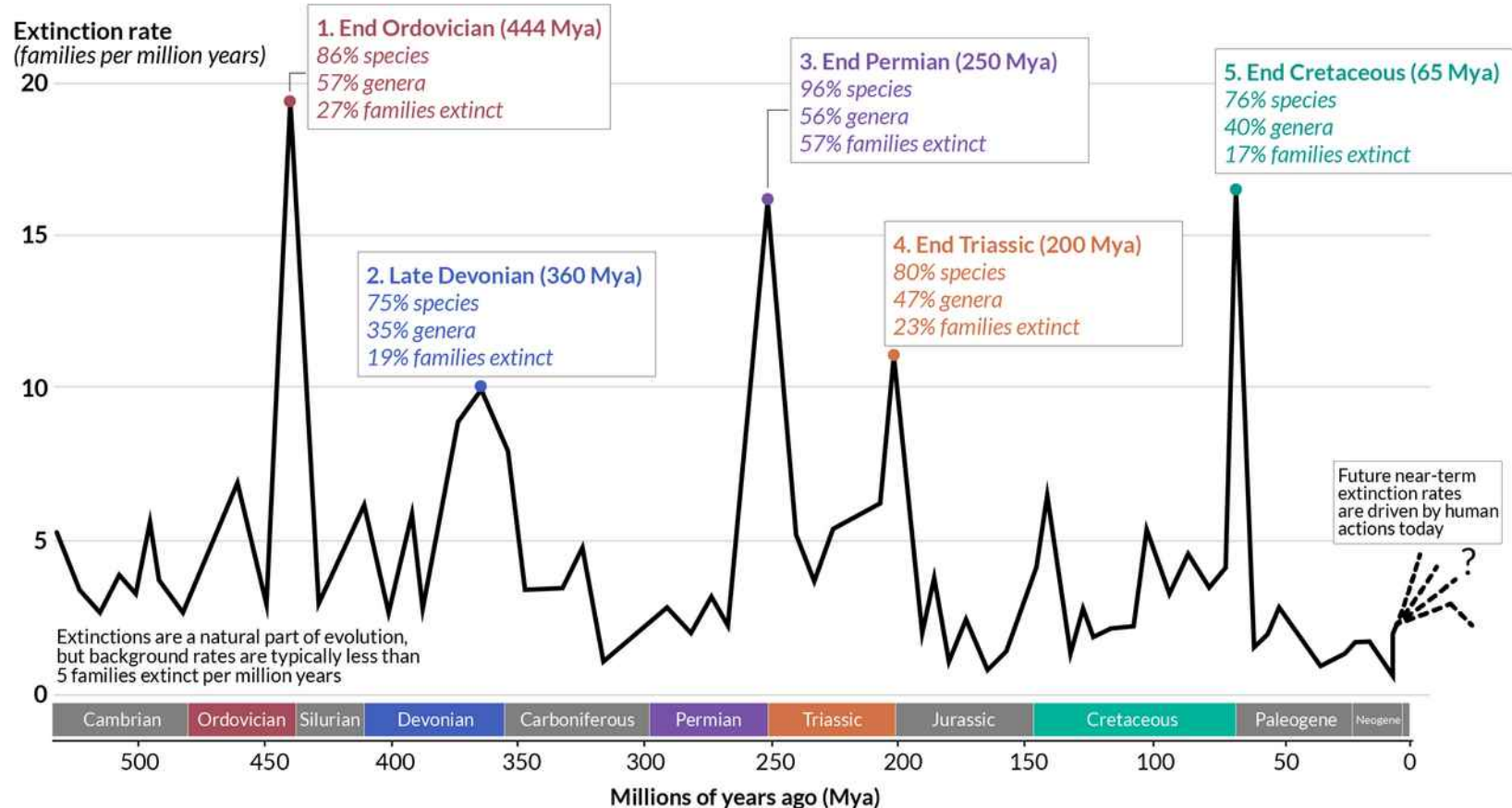


Human Influence

'Big Five' Mass Extinctions in Earth's History

A mass extinction is defined by the loss of at least 75% of species within a short period of time (geologically, this is around 2 million years).

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in Data



Sources: Barnosky et al. (2011); Howard Hughes Medical Institute; McCallum (2015). Vertebrate biodiversity losses point to a sixth mass extinction.
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IPCC

Intergovernmental Panel on Climate Change

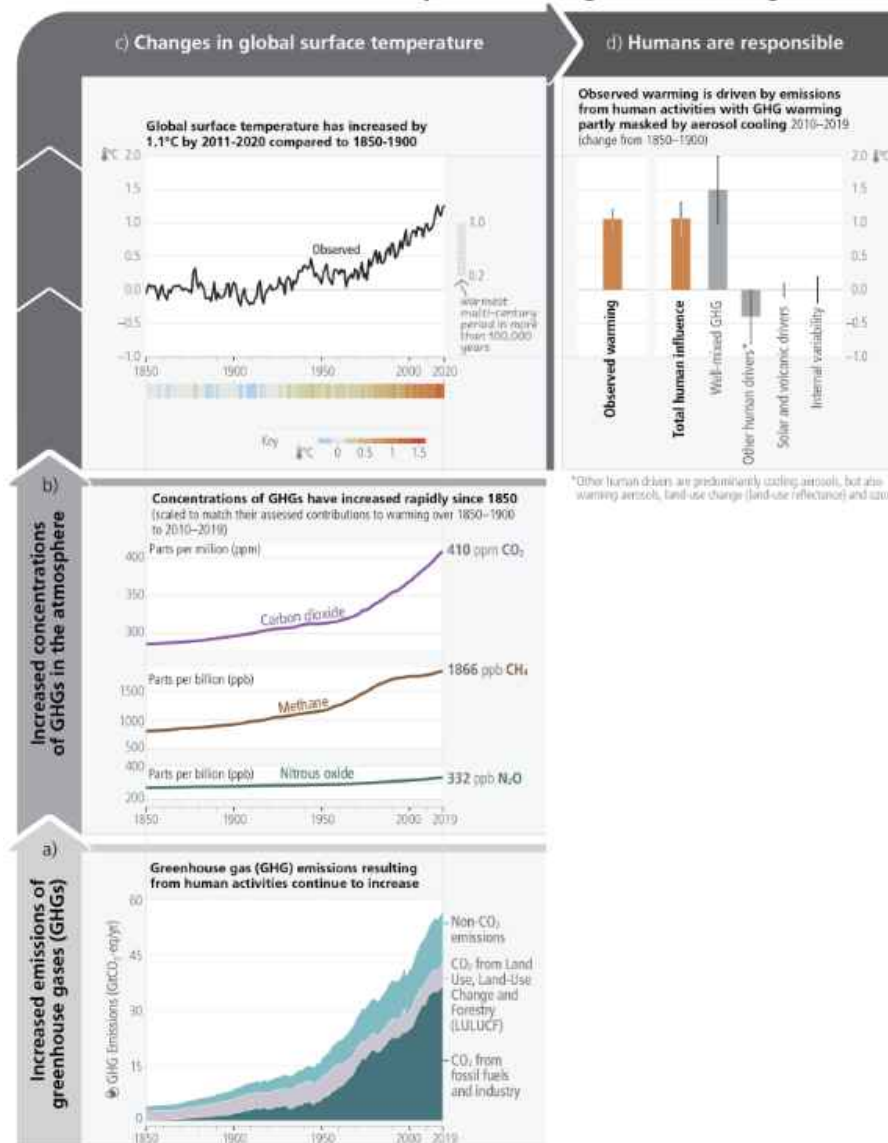
IPCC

Projections based on
Representative Concentration Pathways (RCP)

- RCPX has climate forcing of $X \text{ W/m}^2$ in 2100
- does not consider feedbacks on emissions
- RCP2.6: peak @ 490 ppm in 2020
- RCP4.5: rise to 650 ppm in 2100
- RCP6.0: stabilising 800 ppm in 2100
- RCP8.5: > 1370 ppm in 2100

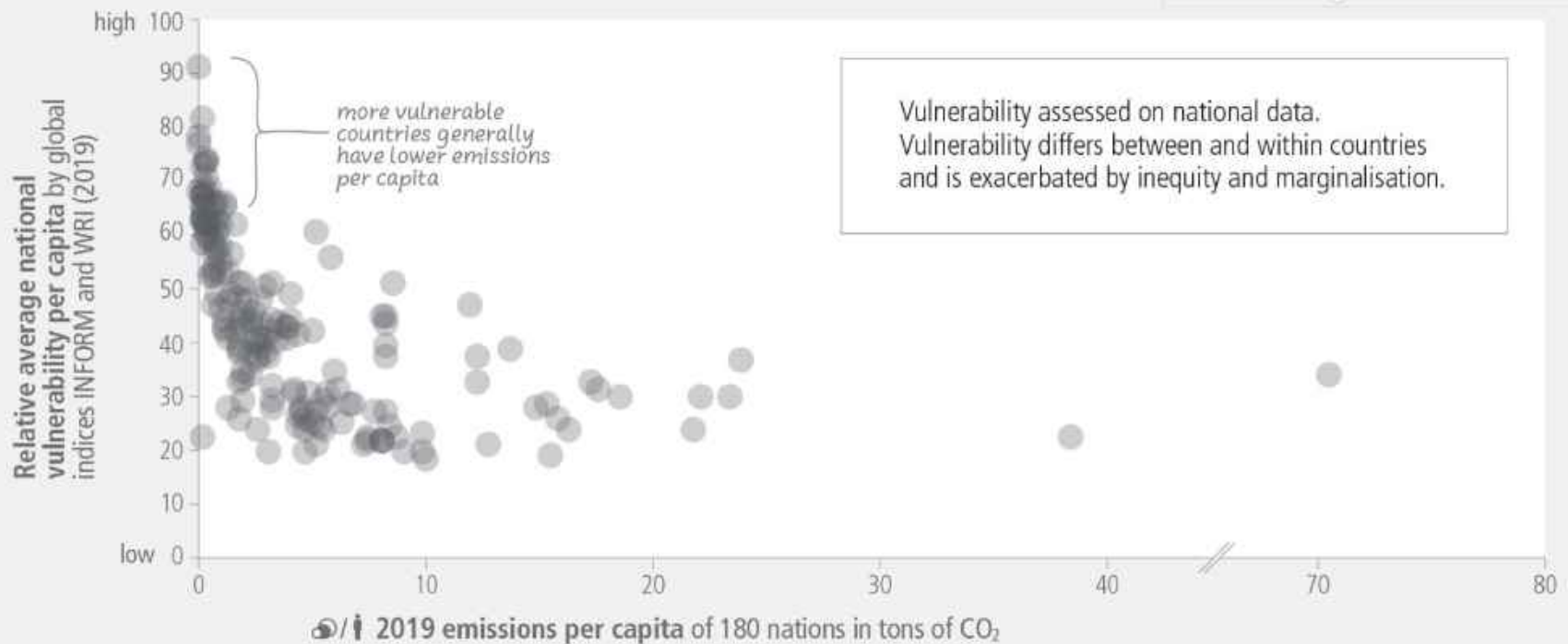
IPCC AR6

Human activities are responsible for global warming

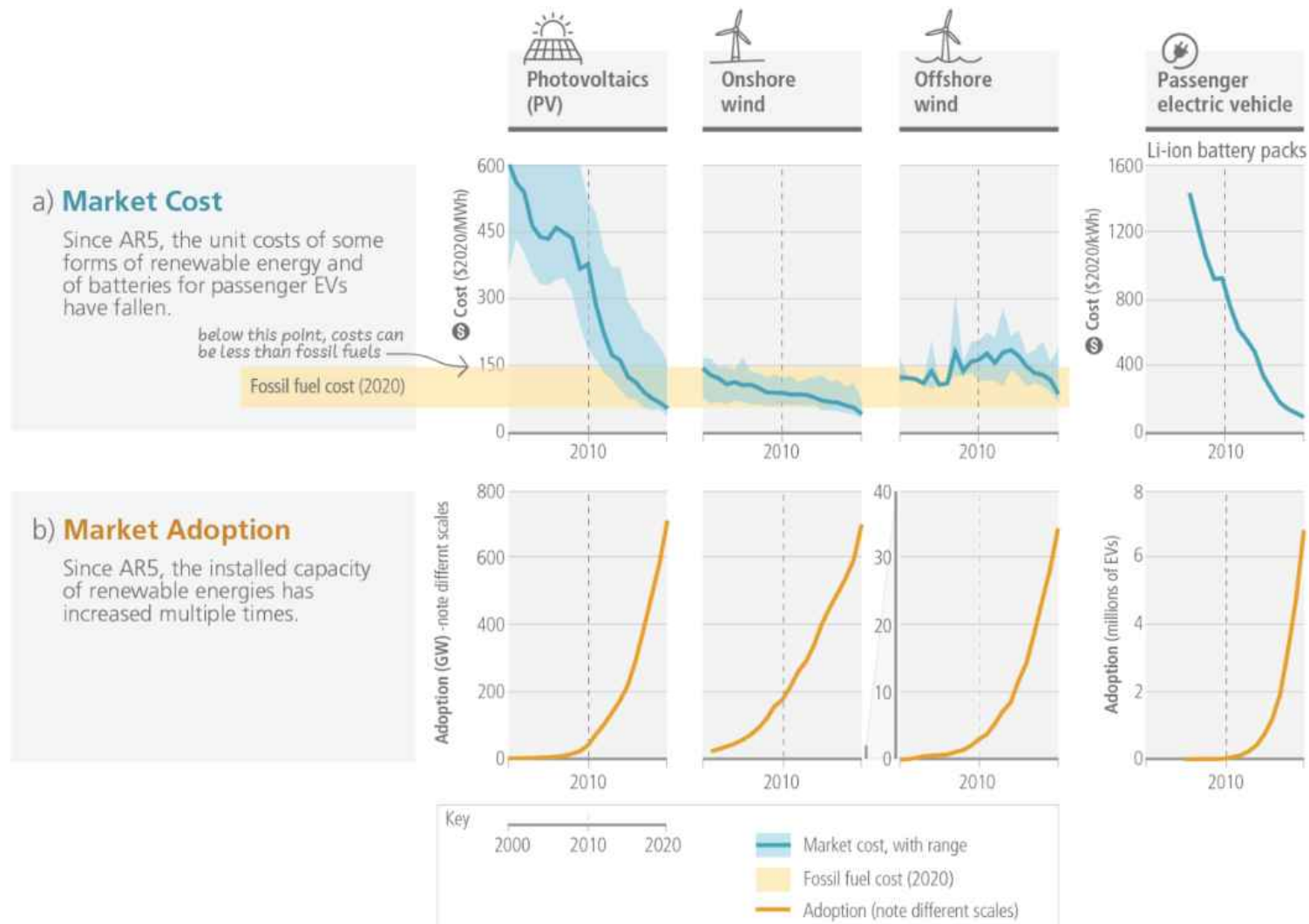


IPCC AR6

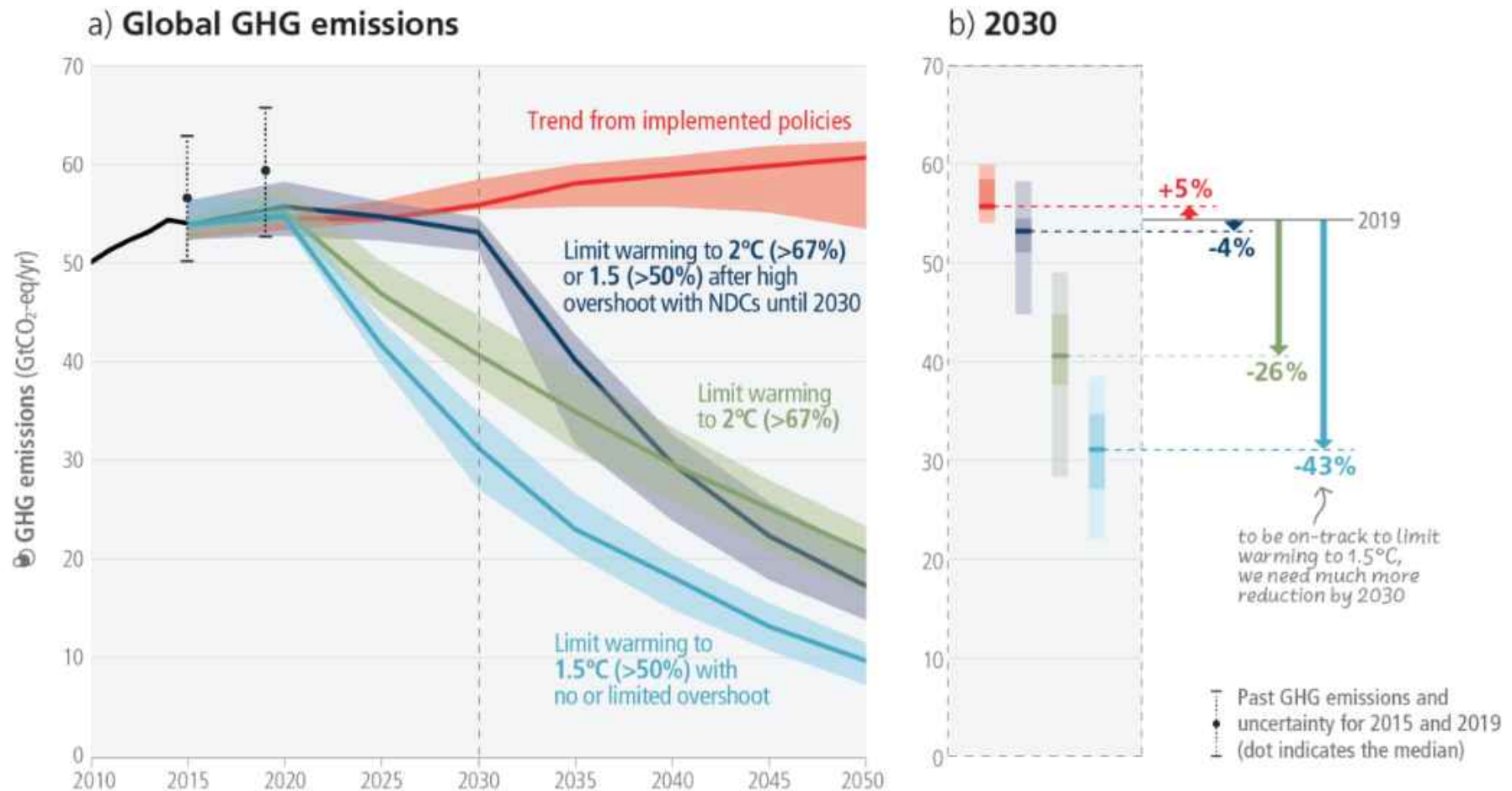
b) Vulnerability of population & per capita emissions per country in 2019



IPCC AR6

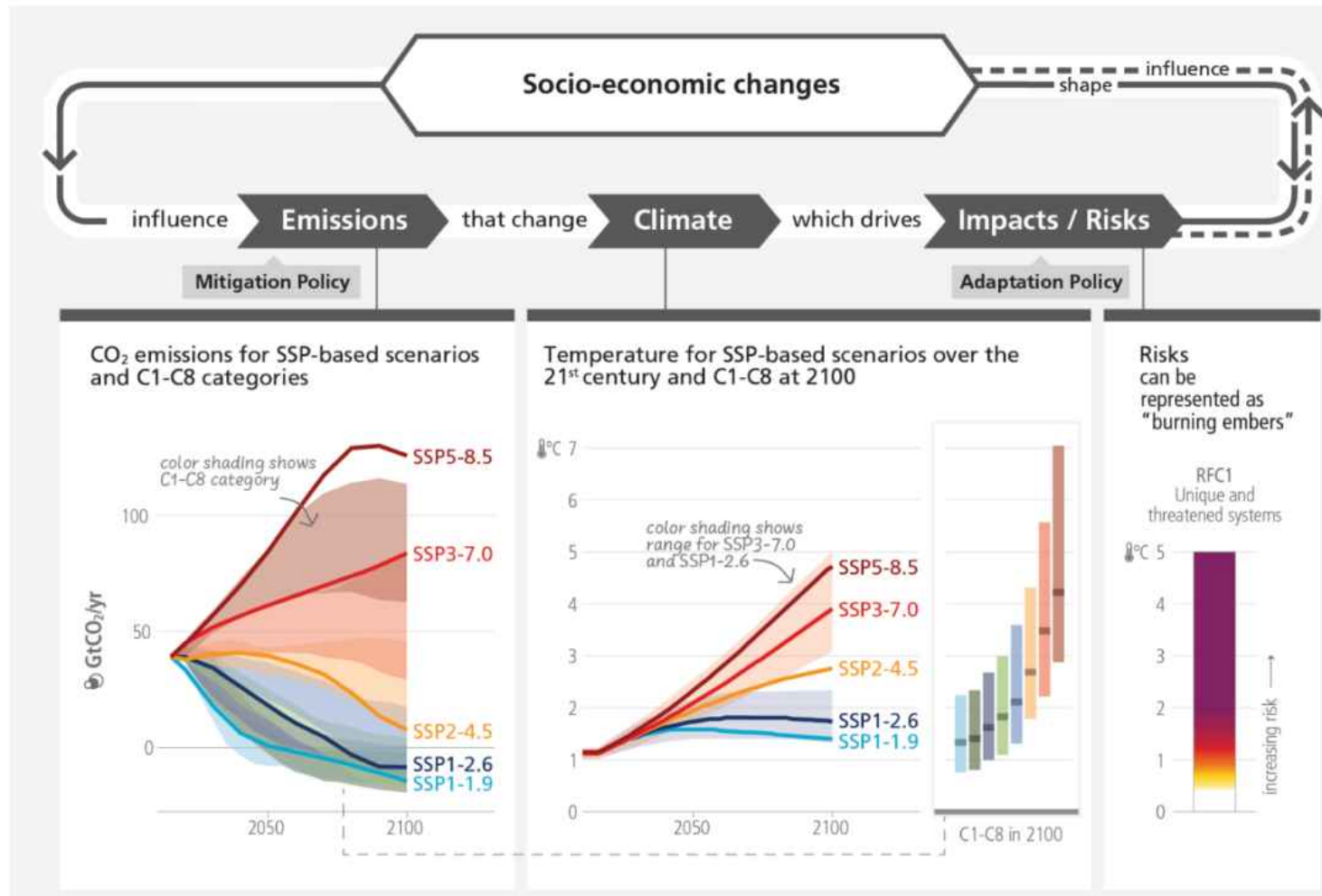


IPCC AR6

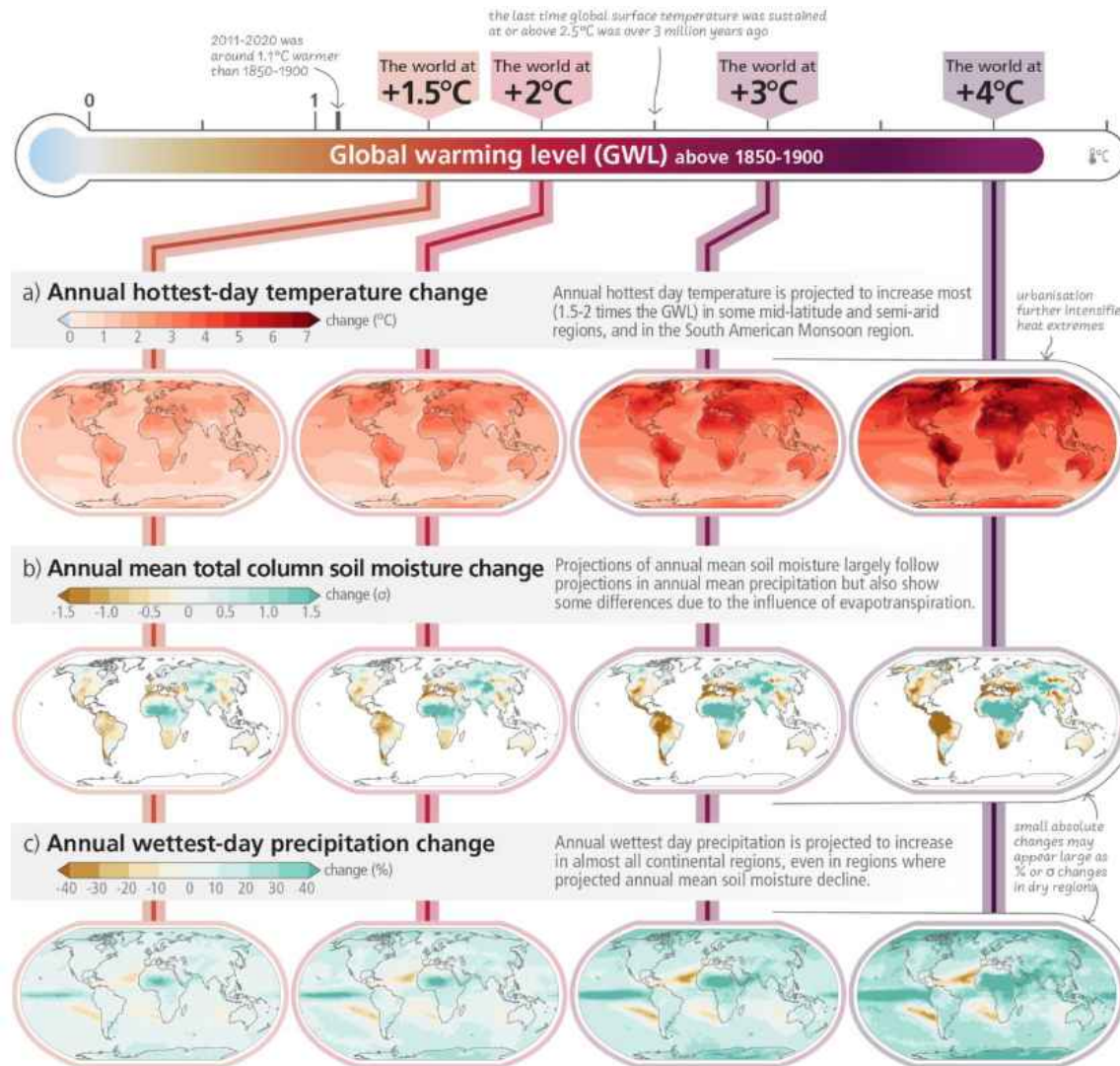


IPCC AR6

a) AR6 integrated assessment framework on future climate, impacts and mitigation

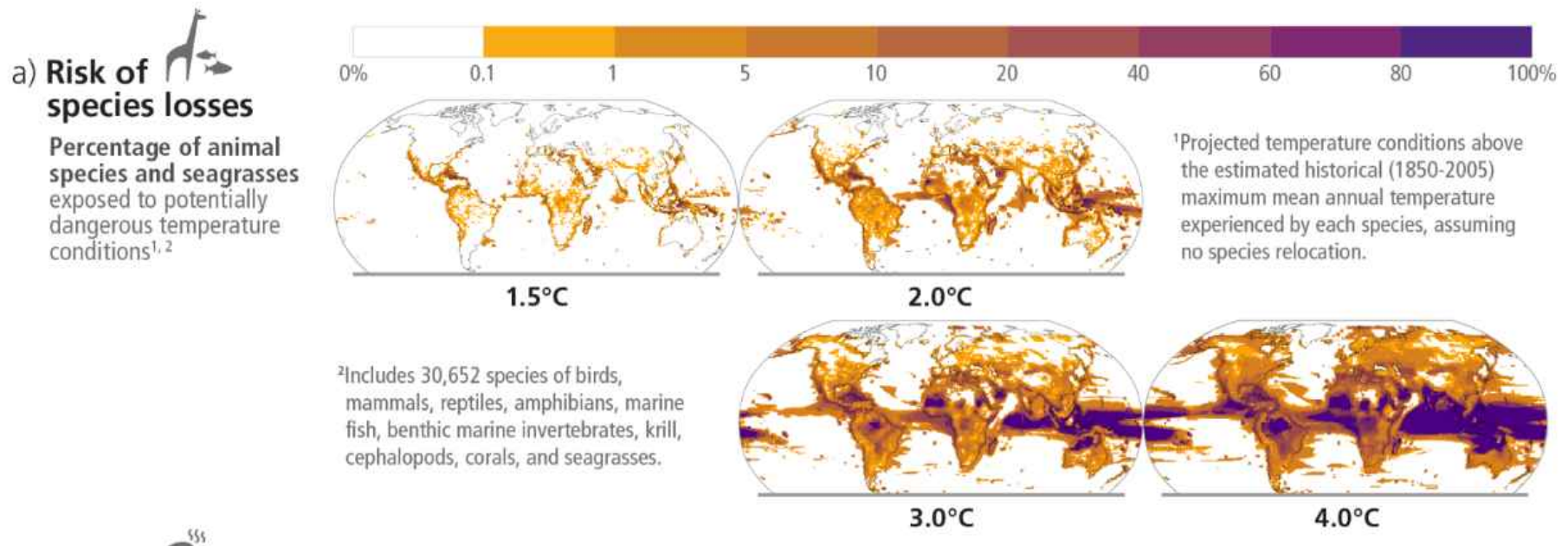


IPCC AR6



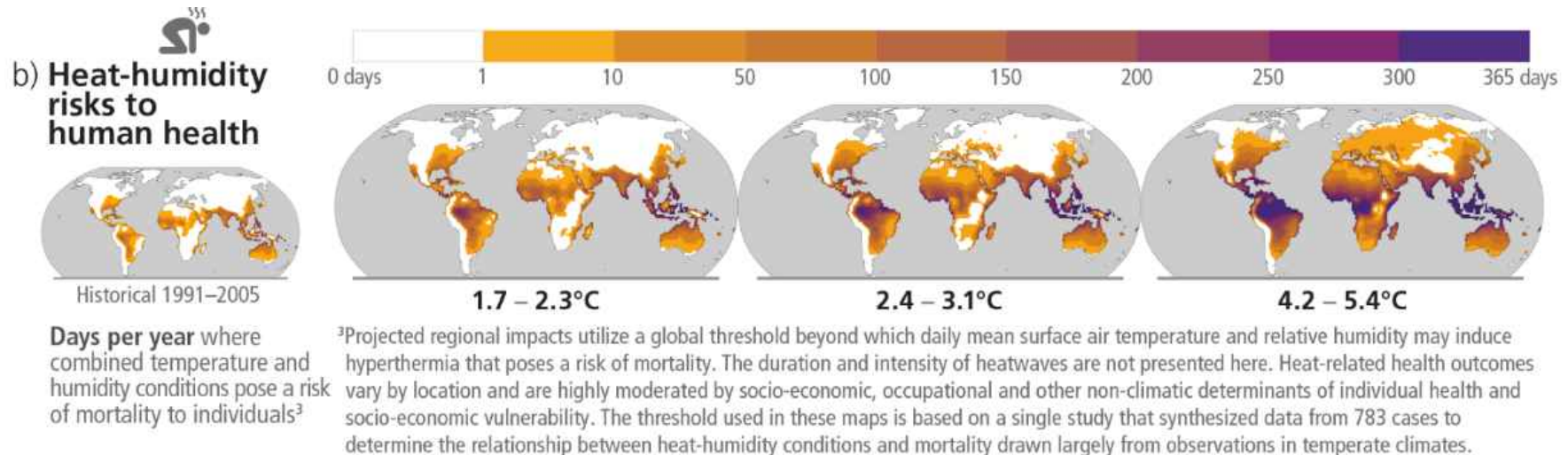
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Examples of impacts without additional adaptation



SSS

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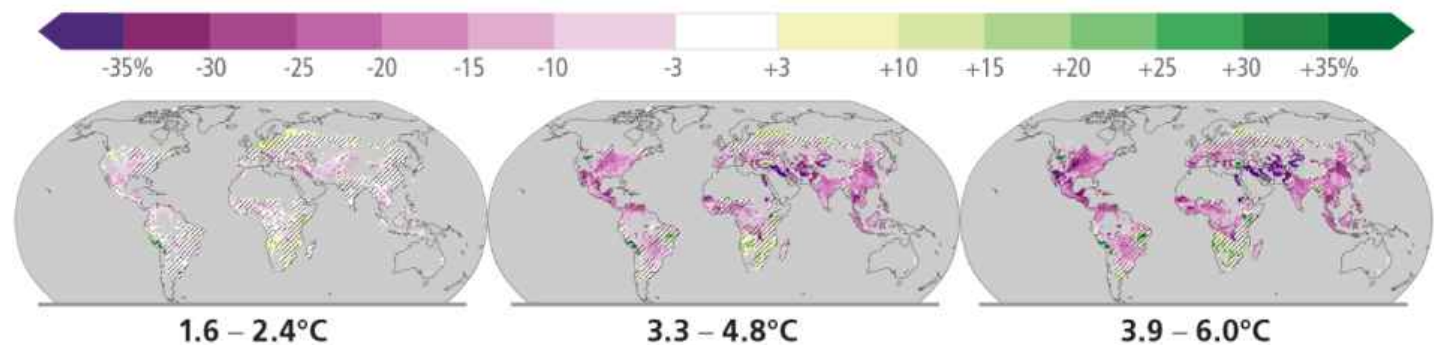
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c) Food production impacts



c1) Maize yield⁴

Changes (%) in yield

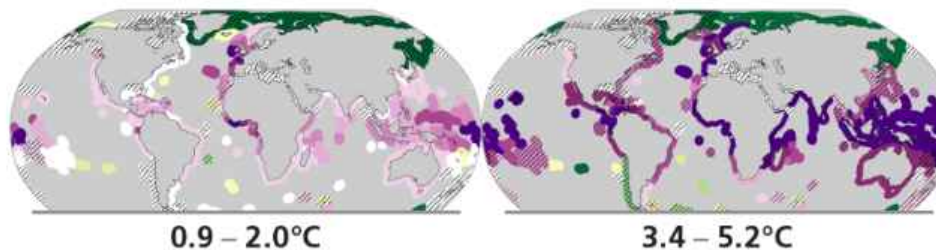


⁴Projected regional impacts reflect biophysical responses to changing temperature, precipitation, solar radiation, humidity, wind, and CO₂ enhancement of growth and water retention in currently cultivated areas. Models assume that irrigated areas are not water-limited. Models do not represent pests, diseases, future agro-technological changes and some extreme climate responses.



c2) Fisheries yield⁵

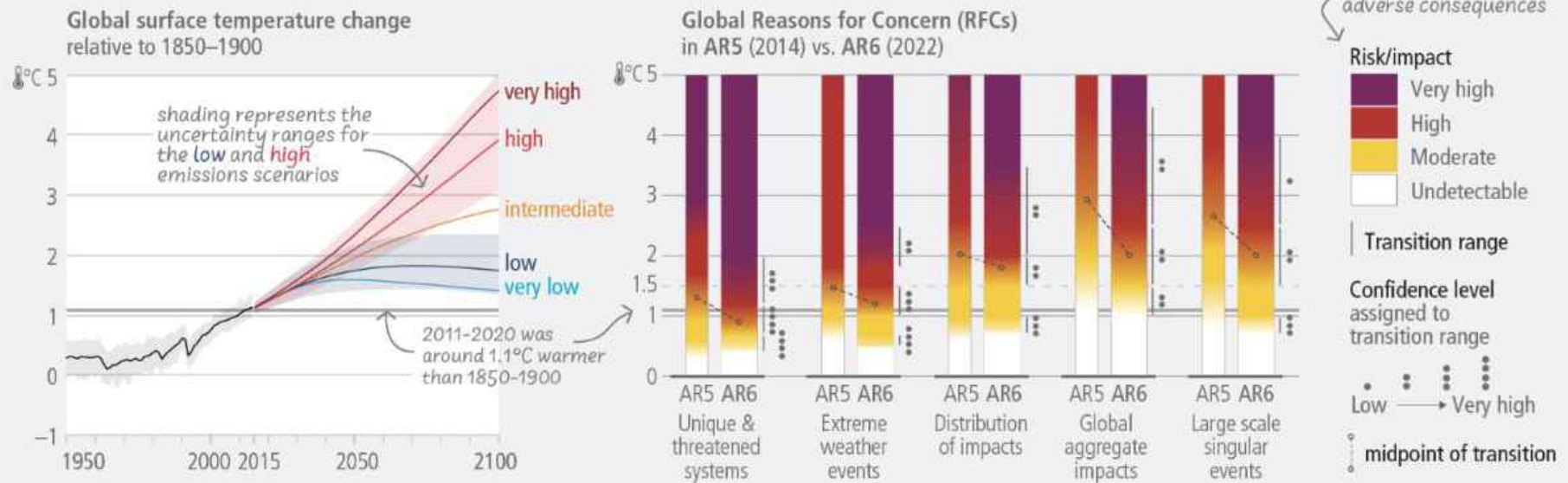
Changes (%) in maximum catch potential



Areas with little or no production, or not assessed
Areas with model disagreement

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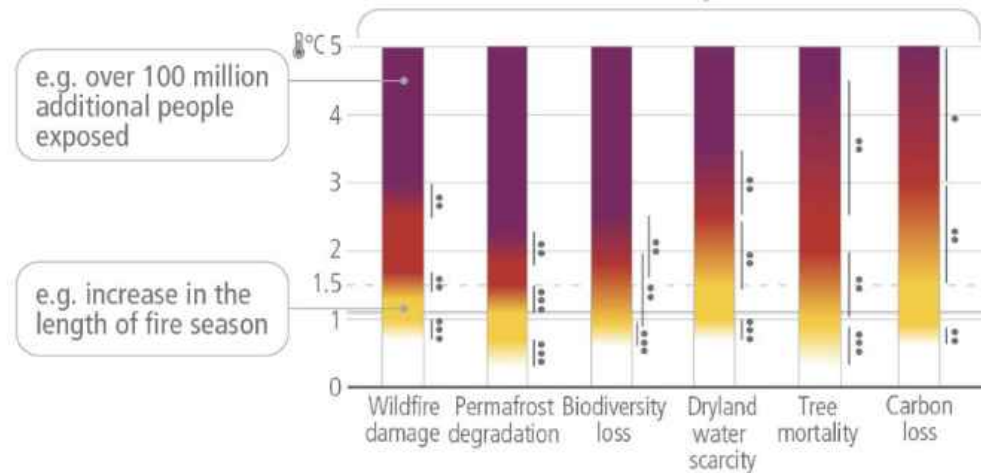
a) High risks are now assessed to occur at lower global warming levels



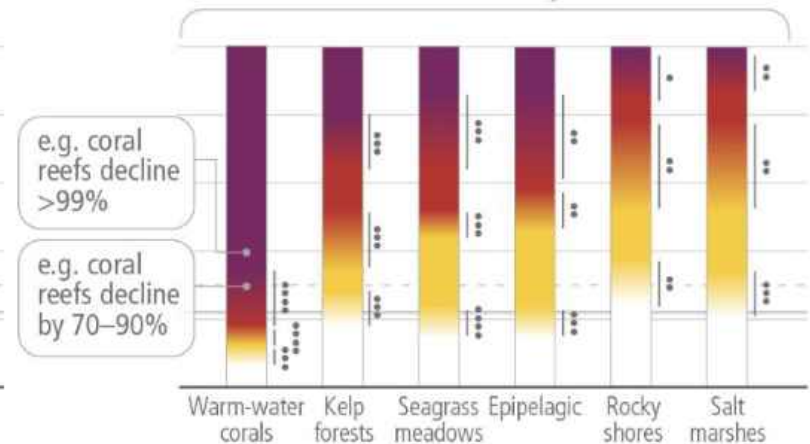
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b) Risks differ by system

Land-based systems

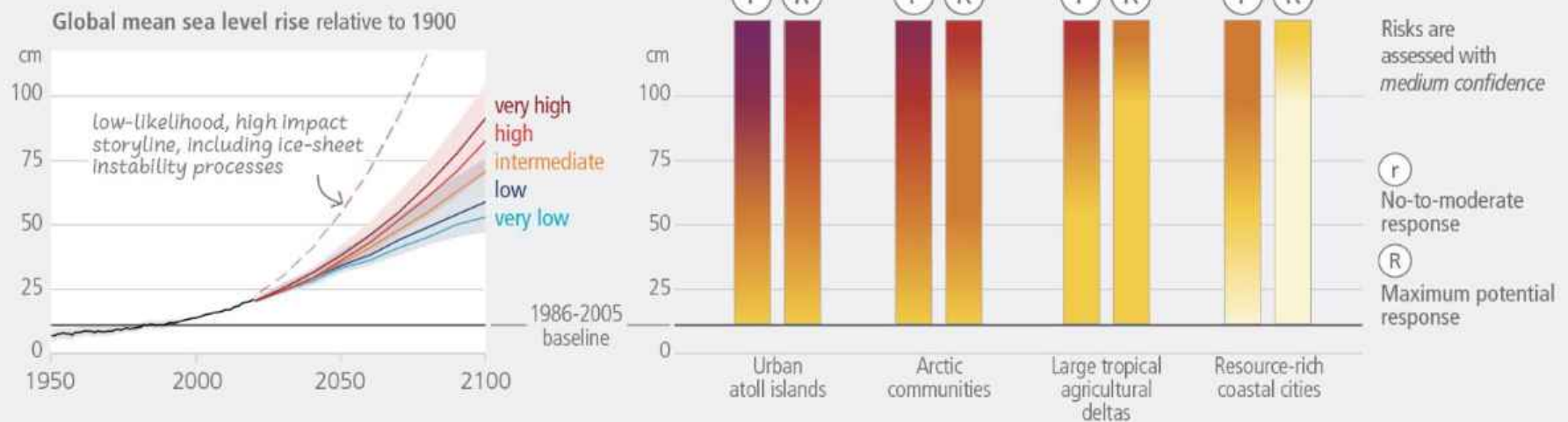


Ocean/coastal ecosystems



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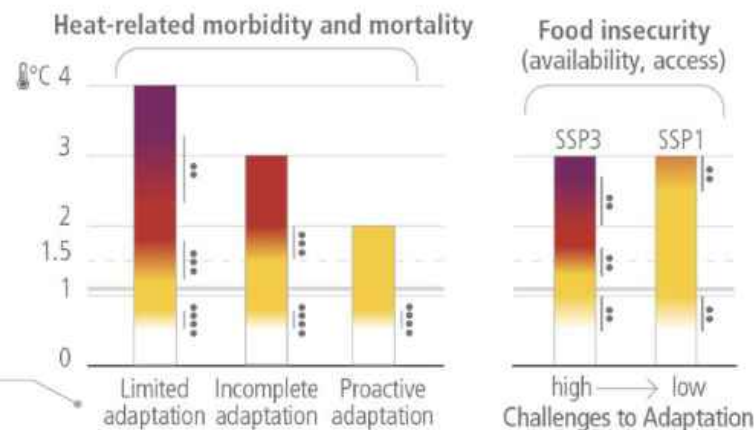
c) Risks to coastal geographies increase with sea level rise and depend on responses



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d) Adaptation and socio-economic pathways affect levels of climate related risks

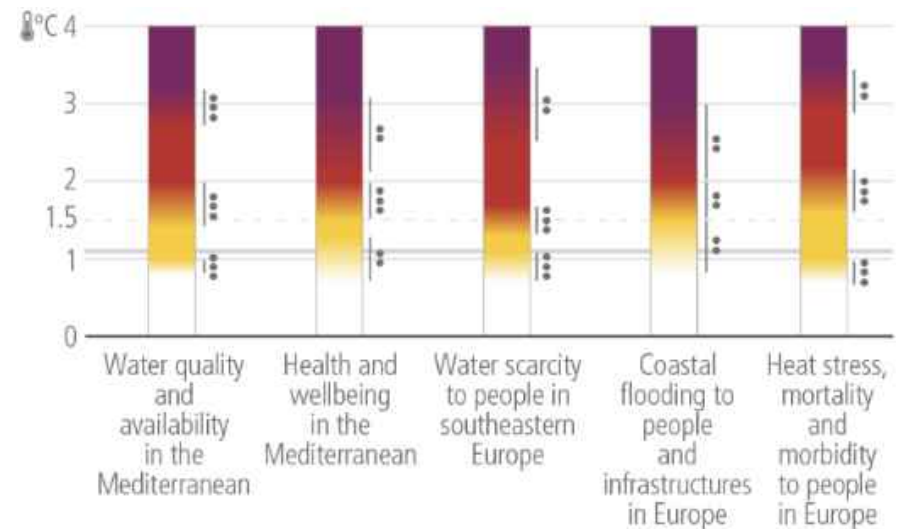
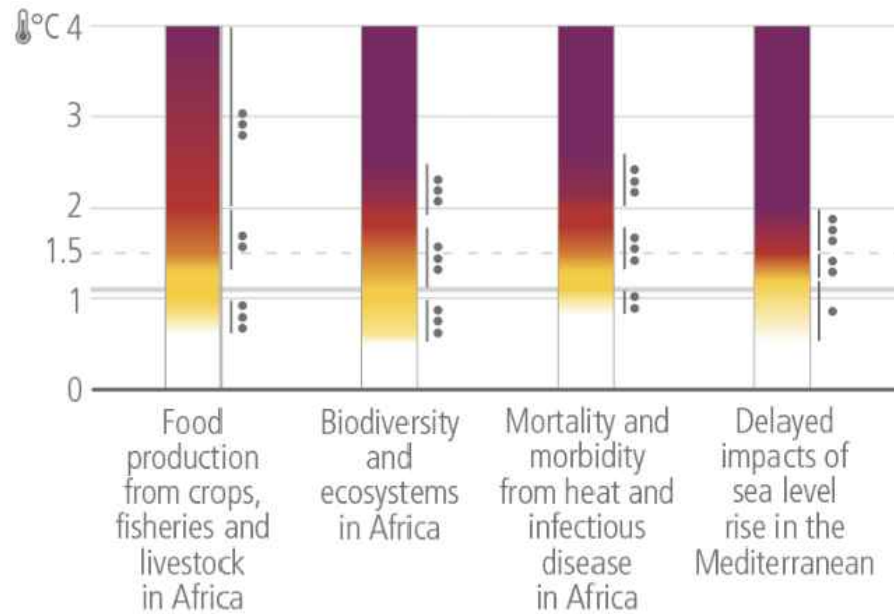
Limited adaptation (failure to proactively adapt; low investment in health systems); incomplete adaptation (incomplete adaptation planning; moderate investment in health systems); proactive adaptation (proactive adaptation management; higher investment in health systems)



The SSP1 pathway illustrates a world with low population growth, high income, and reduced inequalities, food produced in low GHG emission systems, effective land use regulation and high adaptive capacity (i.e., low challenges to adaptation). The SSP3 pathway has the opposite trends.

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example risks



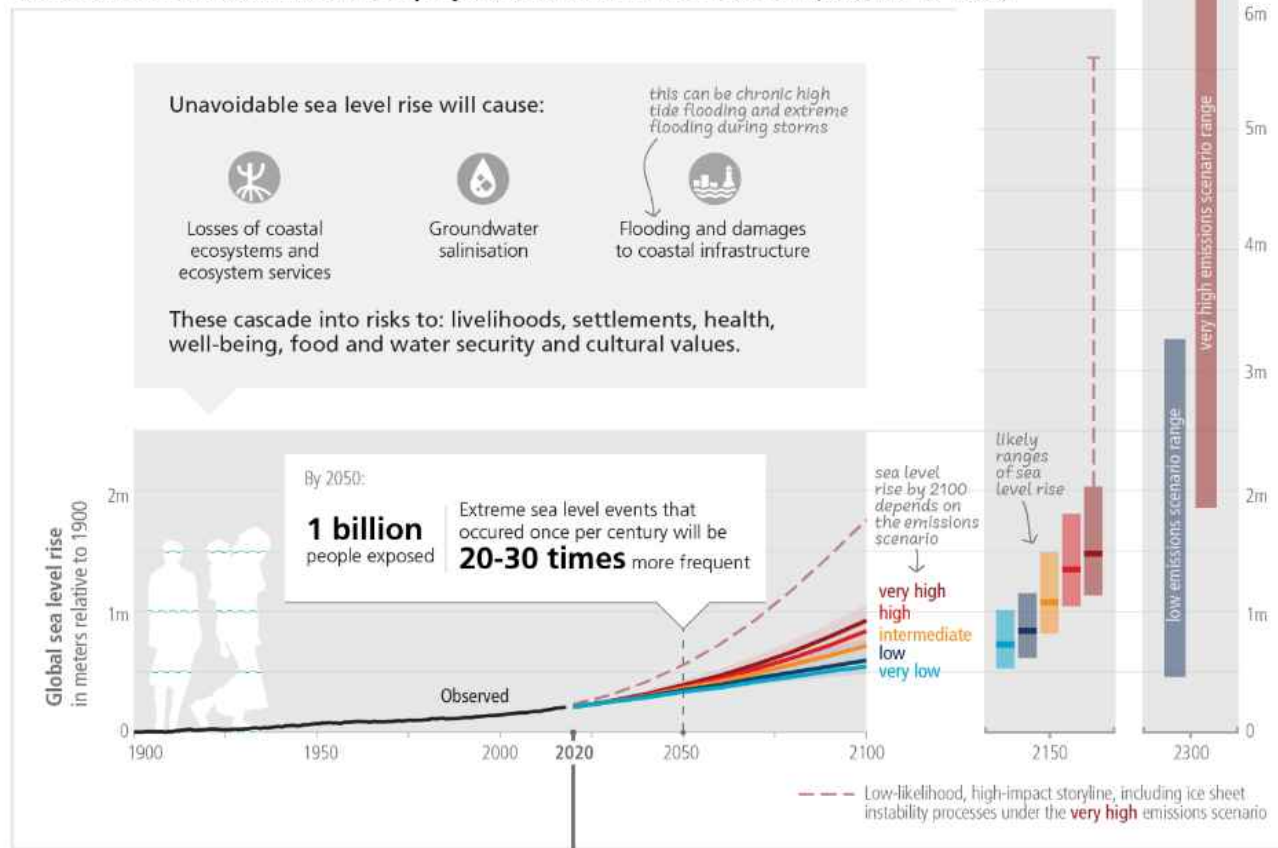
Unil

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Sea level rise will continue for millennia, but how fast and how much depends on future emissions

a) Sea level rise: observations and projections 2020-2100, 2150, 2300 (relative to 1900)



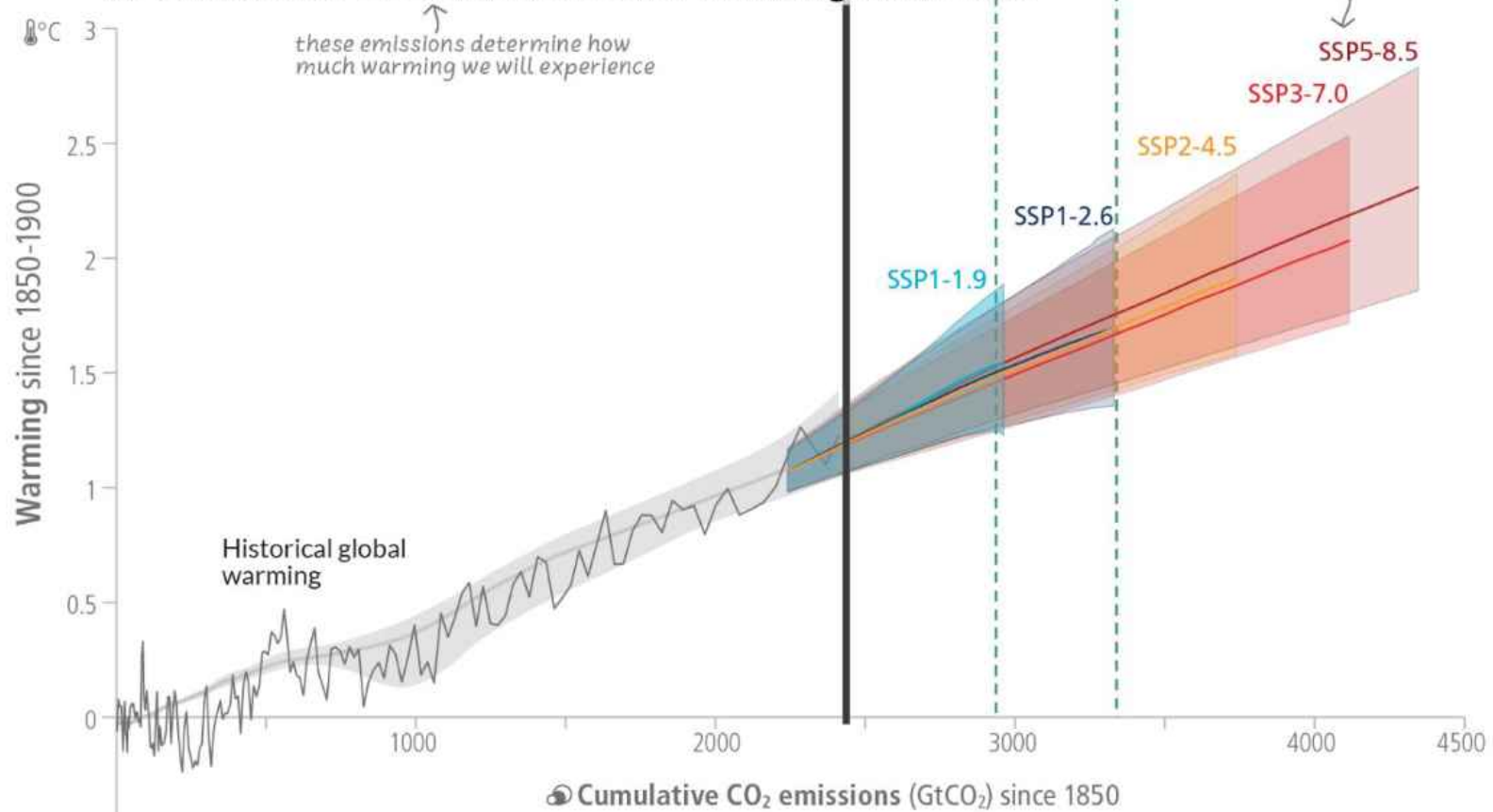
nil

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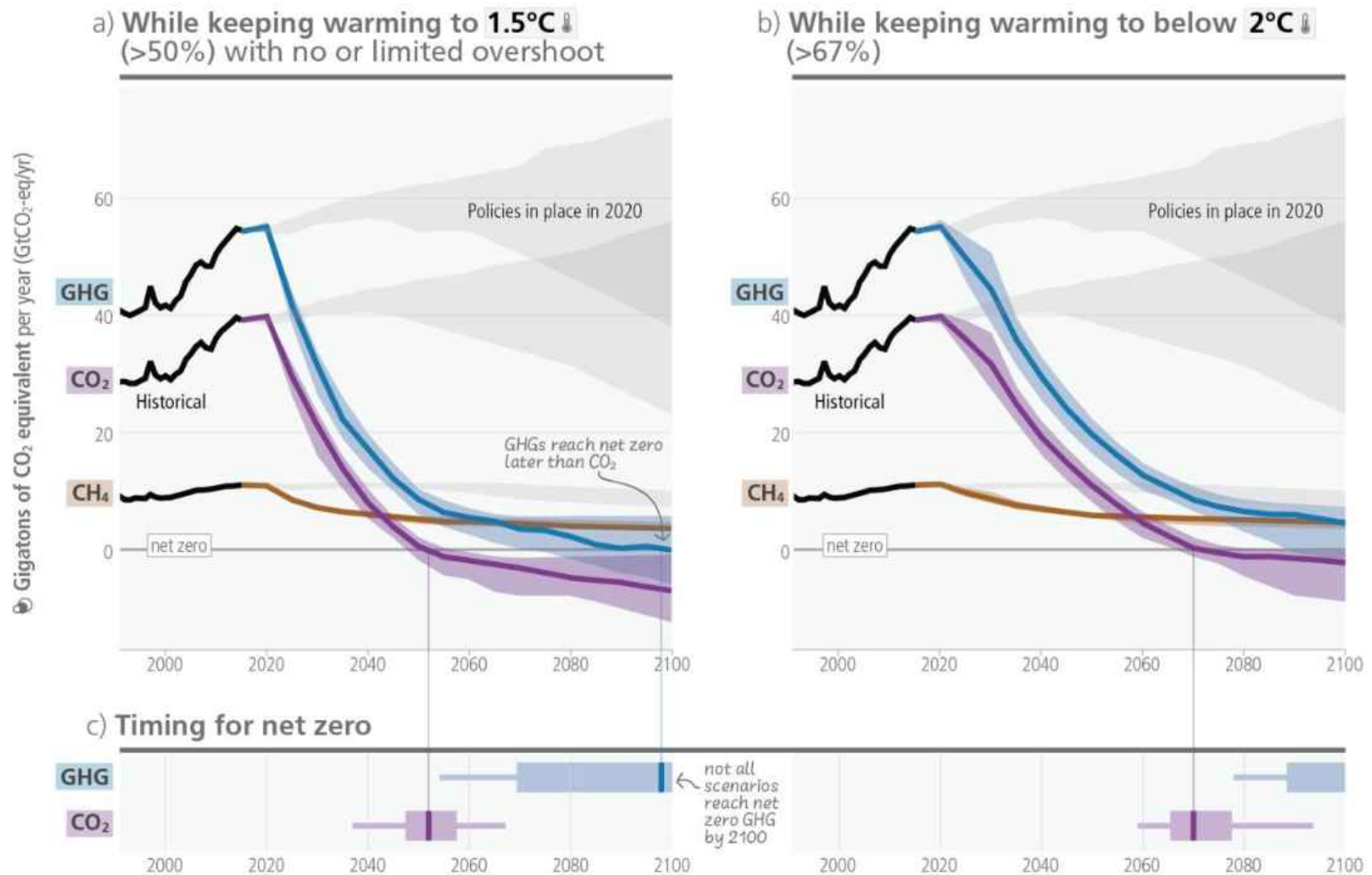
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Every ton of CO₂ adds to global warming

b) Cumulative CO₂ emissions and warming until 2050



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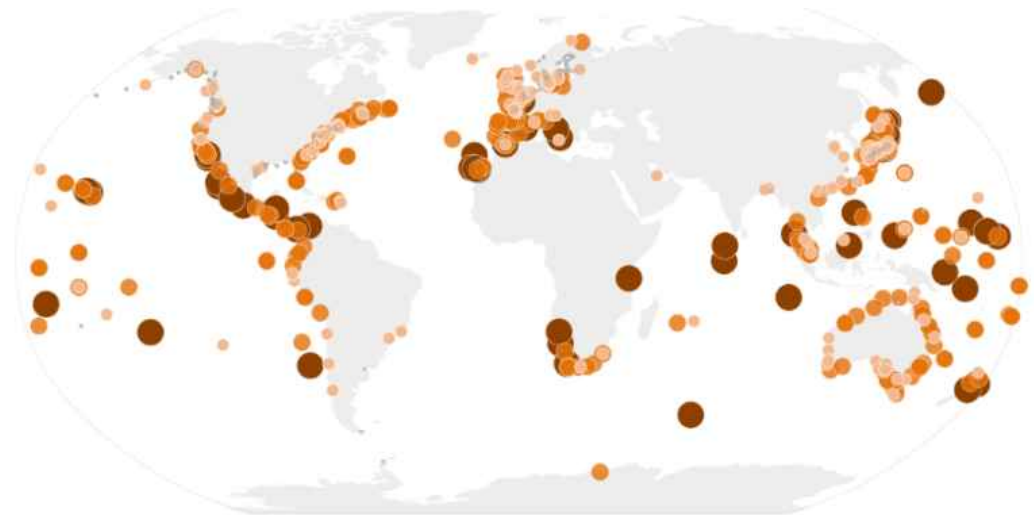
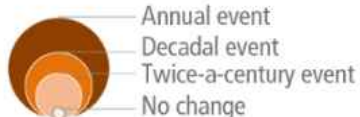
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b) Increased frequency of extreme sea level events by 2040

Frequency of events that currently occur on average once every 100 years

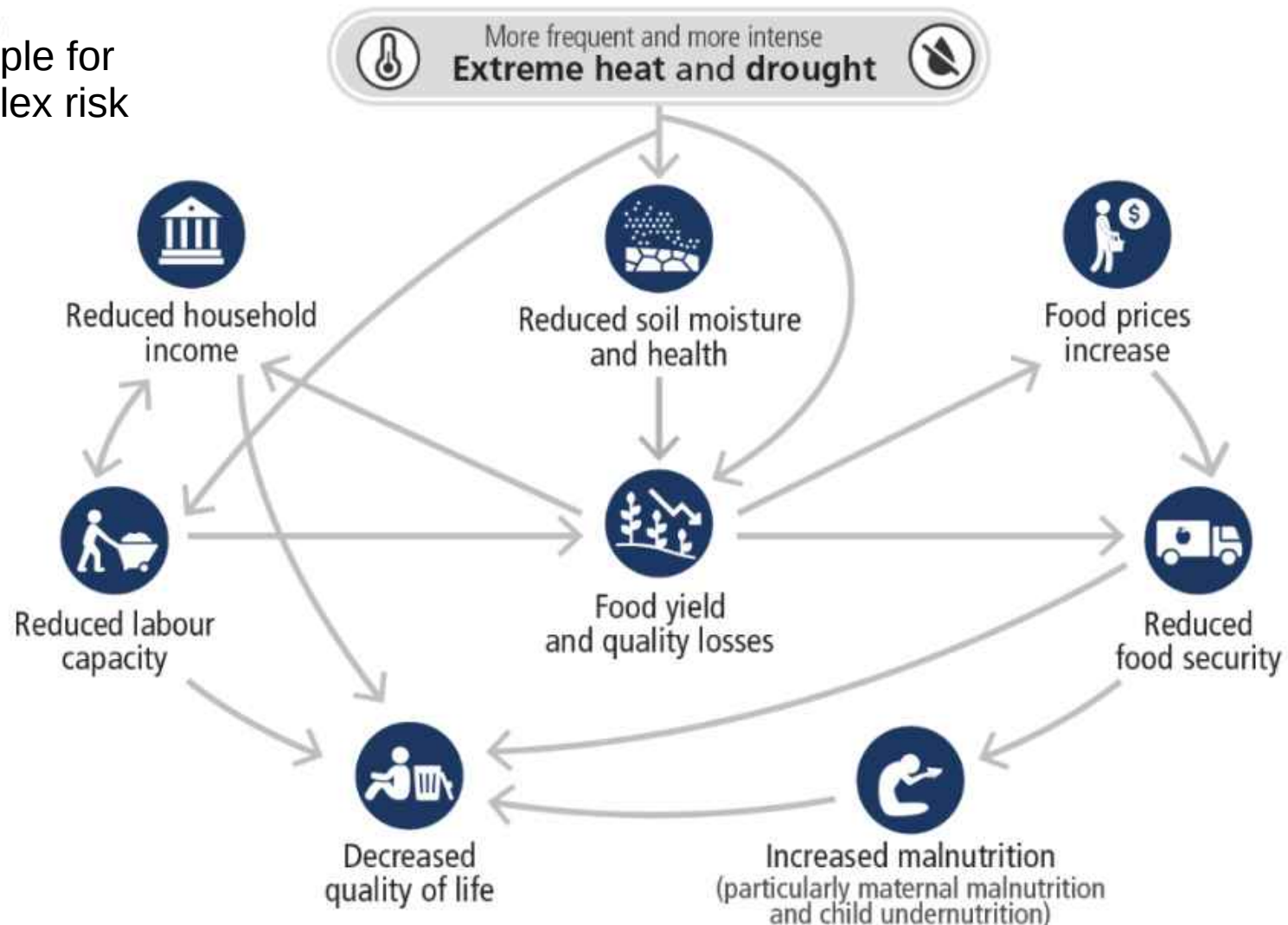
The absence of a circle indicates an inability to perform an assessment due to a lack of data.

Projected change to 1-in-100 year events under the intermediate SSP2-4.5 scenario



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example for
complex risk



Today's Overview

- Climate Modelling
- Climate Feedbacks and Tipping Points
- The Human Influence
 - human civilisation
 - human emissions
 - other influences
- IPCC AR6 projections

Outlook

Monday	Introduction	Earth History
Tuesday	Proxies I	Cenozoic Hot & Warm House
Wednesday	Specific Climate System components	Pleistocene G-IG climate
Thursday	Proxies II & Climate System Interactions	Abrupt Climate Change
Friday	Current Climate Change	Future & Synthesis

Conclusions?