Paleoclimate

source: NASA

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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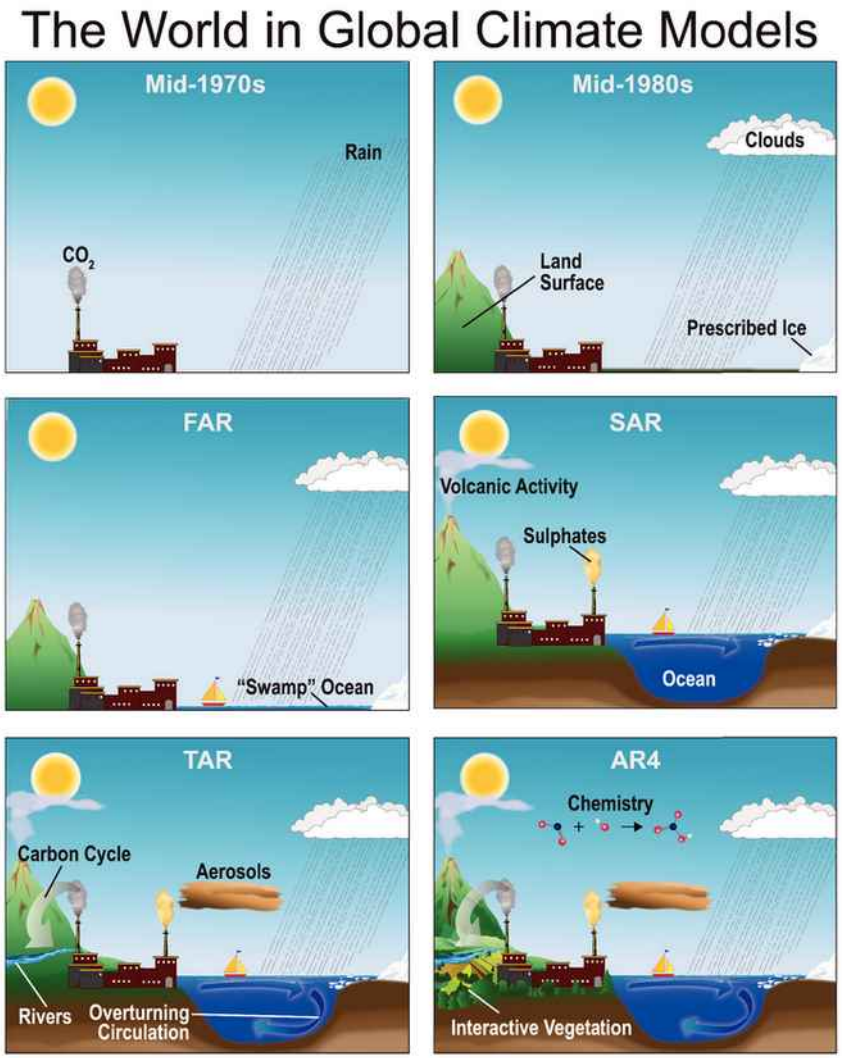
Climate Modelling

- 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

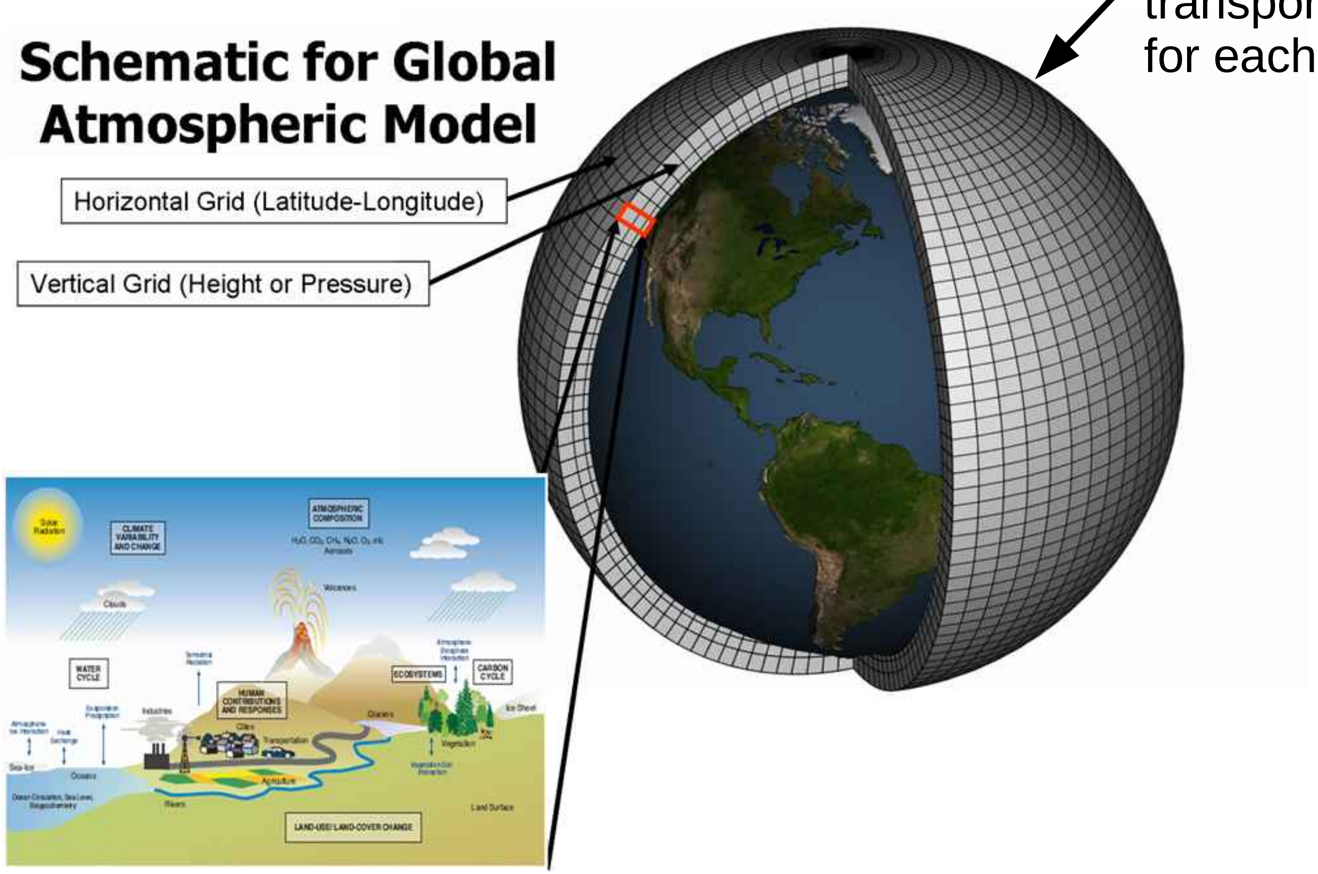
Climate Modelling



IPCC / carbonbrief.org

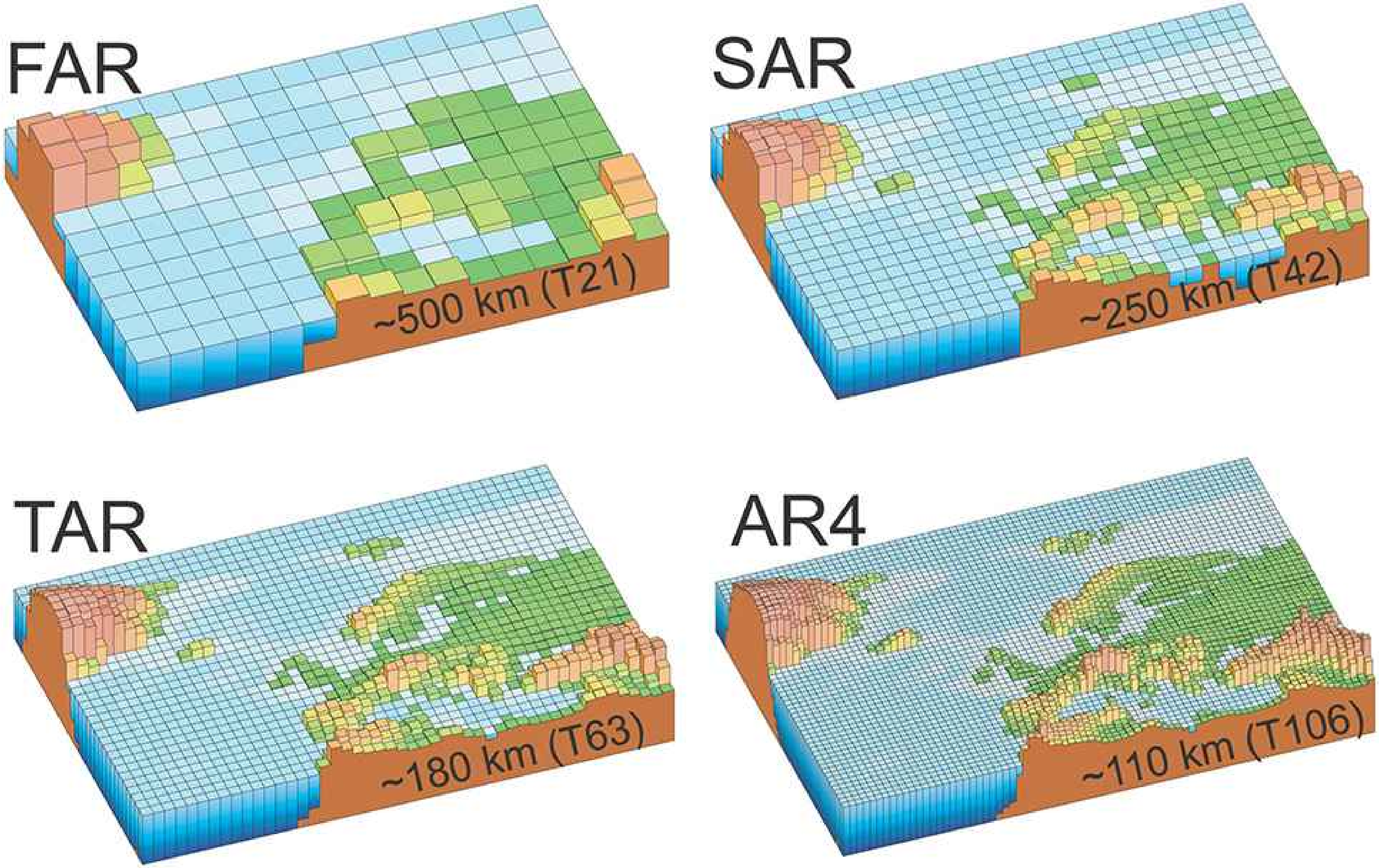
Climate Modelling

perform energy and transport equations for each time step



NOAA / carbonbrief.org

Climate Modelling



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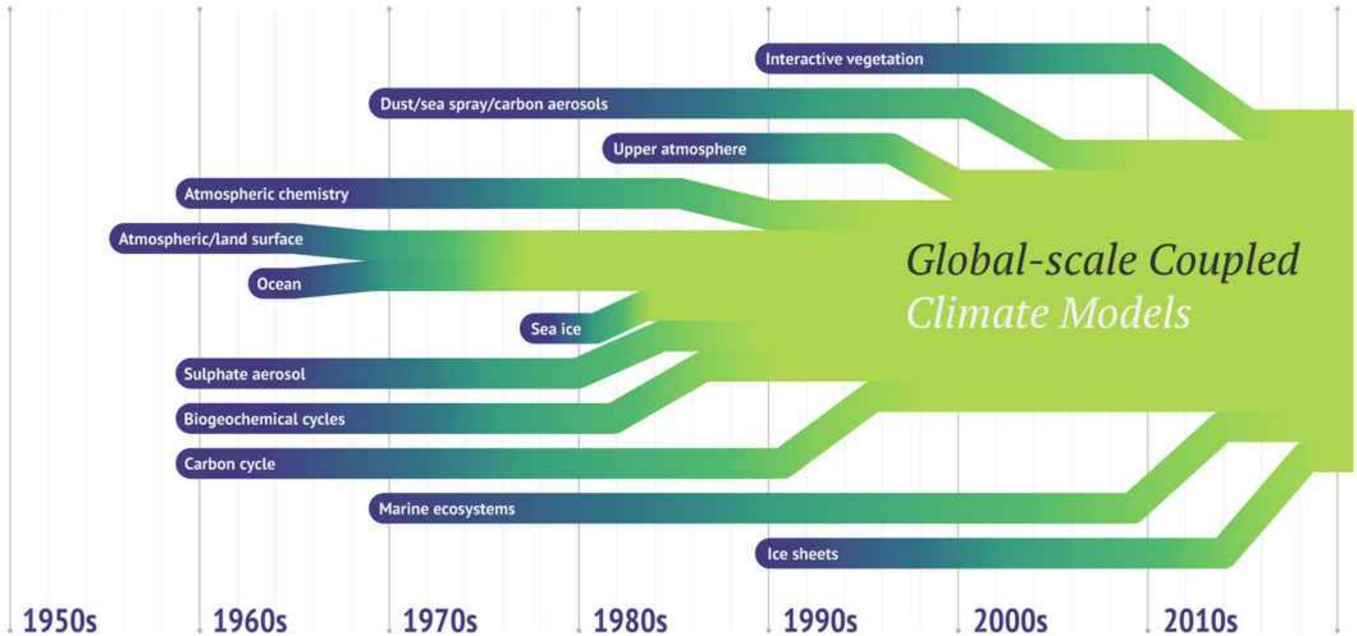
Climate Modelling

Climate models

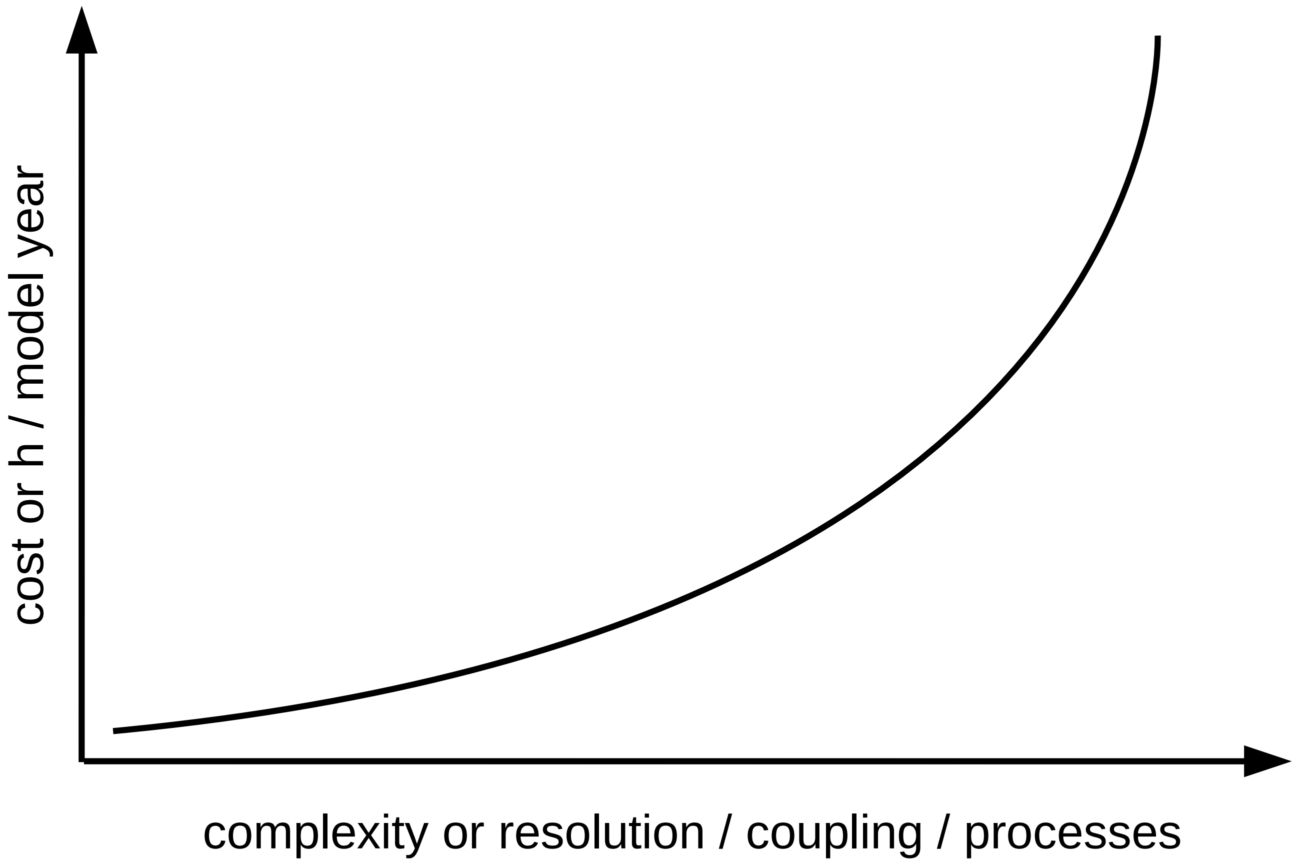
For decades scientists have been using mathematical models to help us learn more about the Earth's climate. Known as climate models, they are driven by the fundamental physics of the atmosphere and oceans, and the cycling of chemicals between living things and their environment. Over time they have increased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



Note: There were some very simplified models before the dates mentioned.

CarbonBrief

Climate Modelling



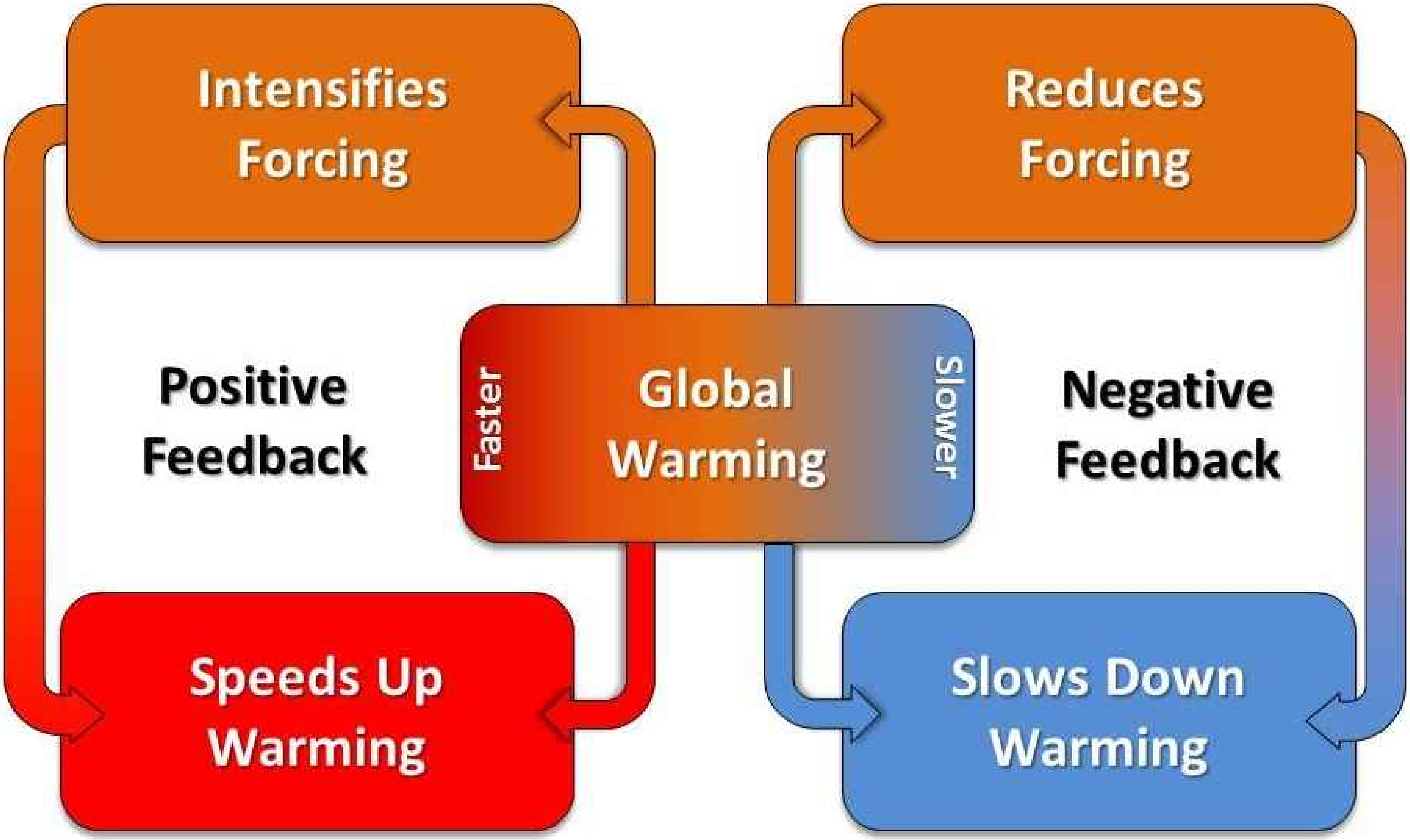
Climate Modelling

All models are wrong,
but some are useful.

George Box

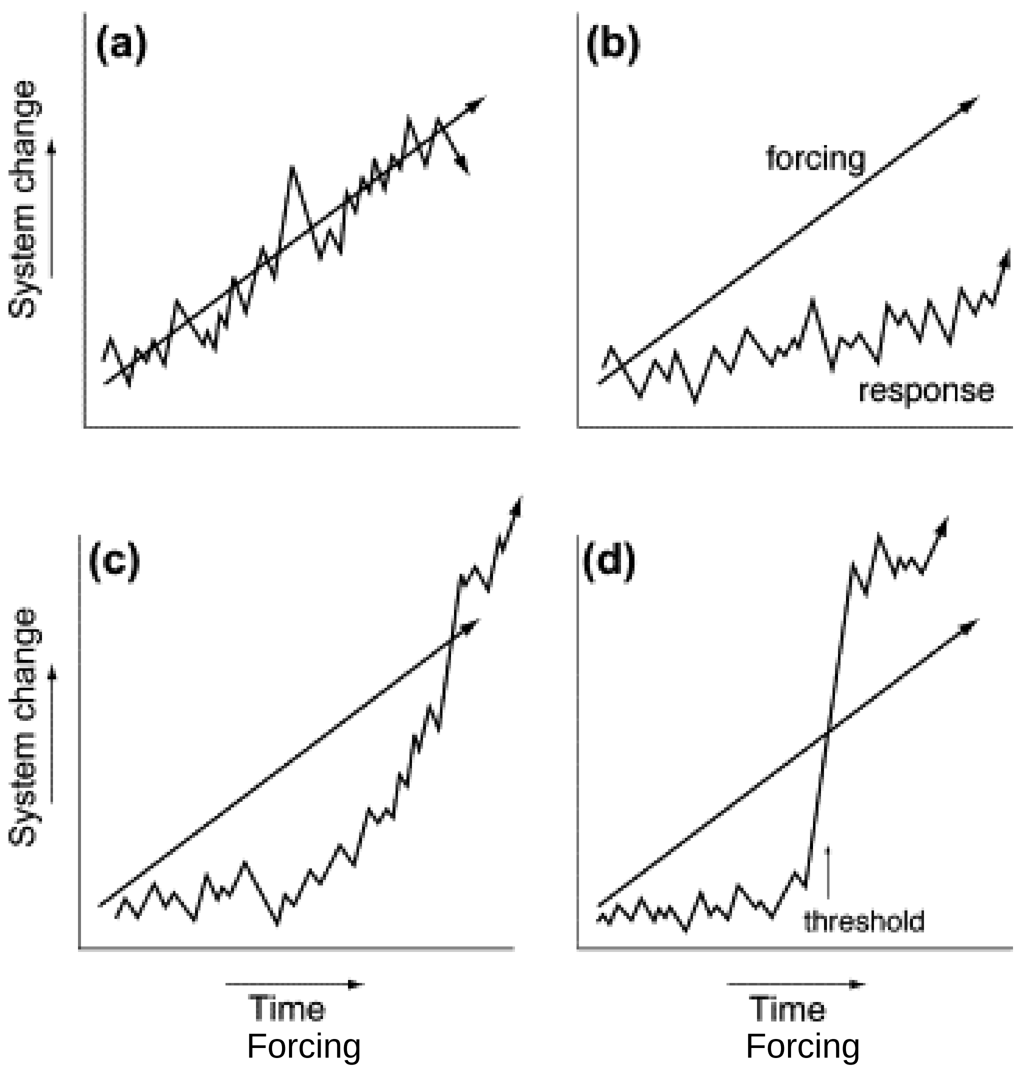
Feedbacks and Tipping Points

Feedbacks and Tipping Points



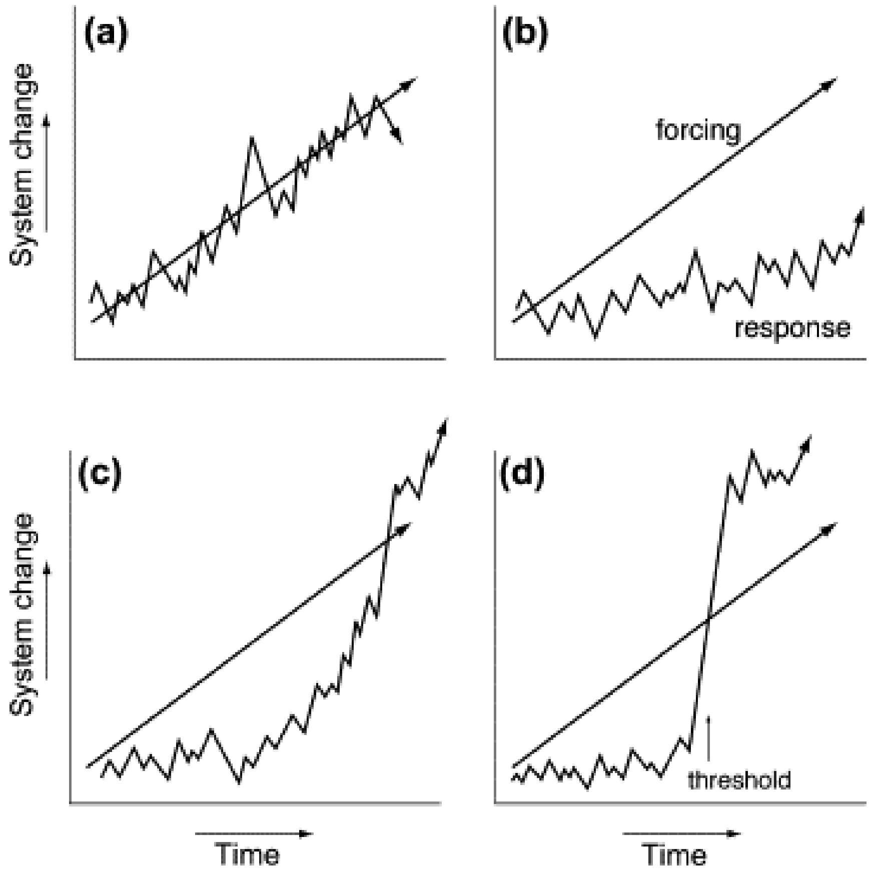
NASA Climate Science Investigations

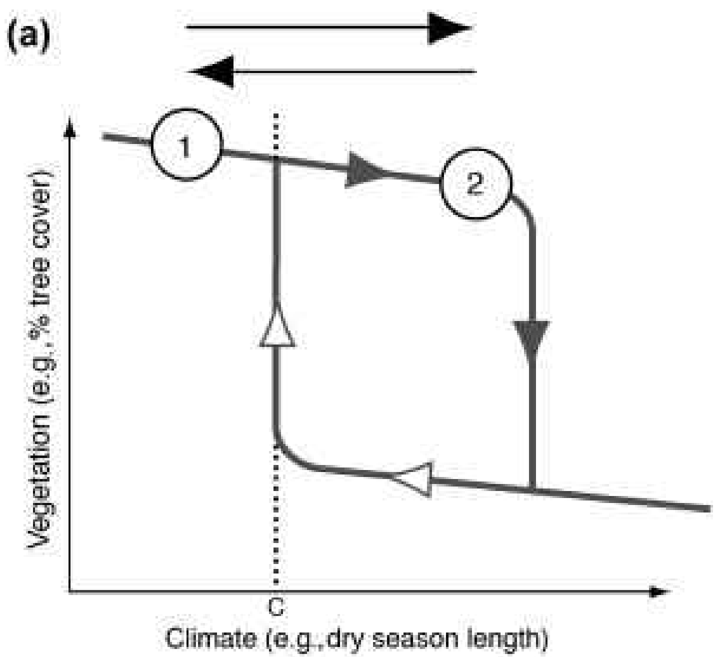
Feedbacks and Tipping Points



Maslin & Christensen (2007), Journal of Human Evolution

Feedbacks and Tipping Points





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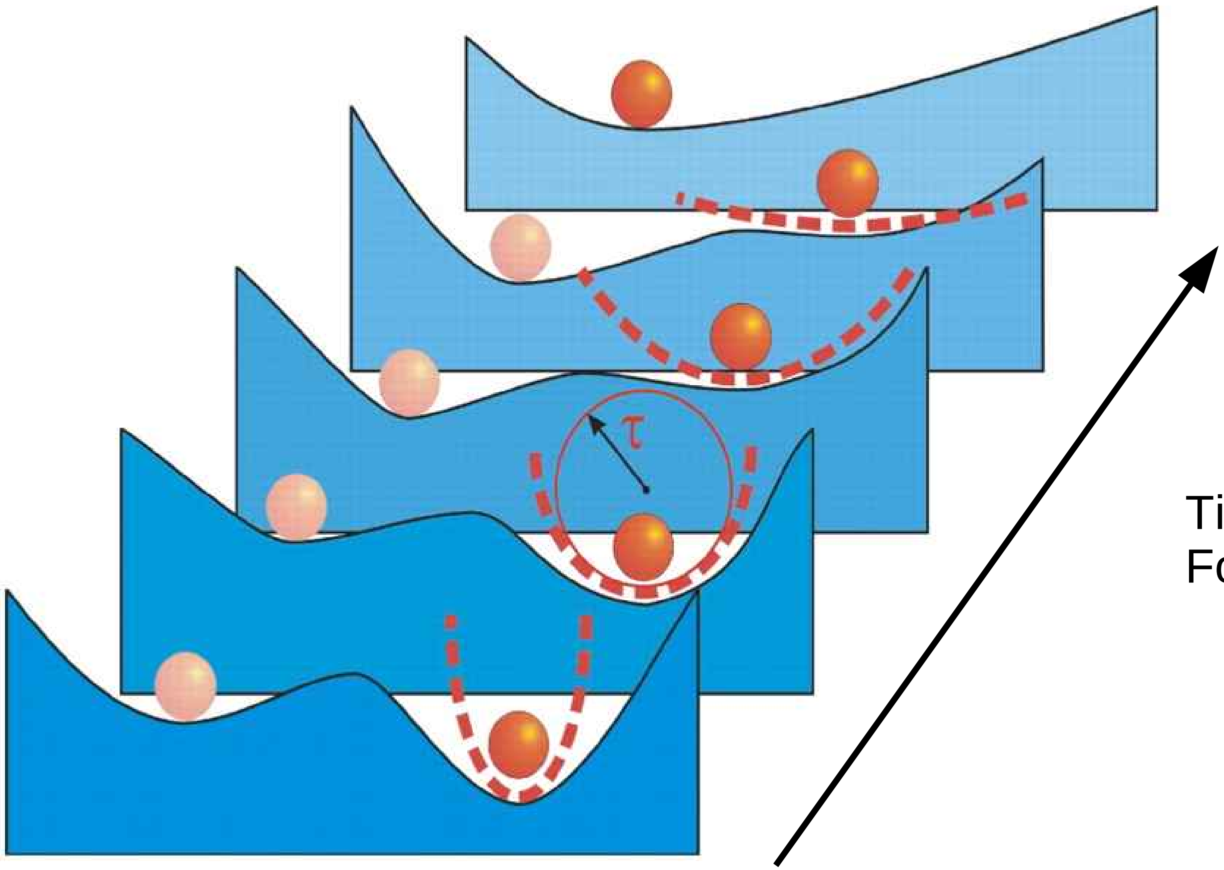
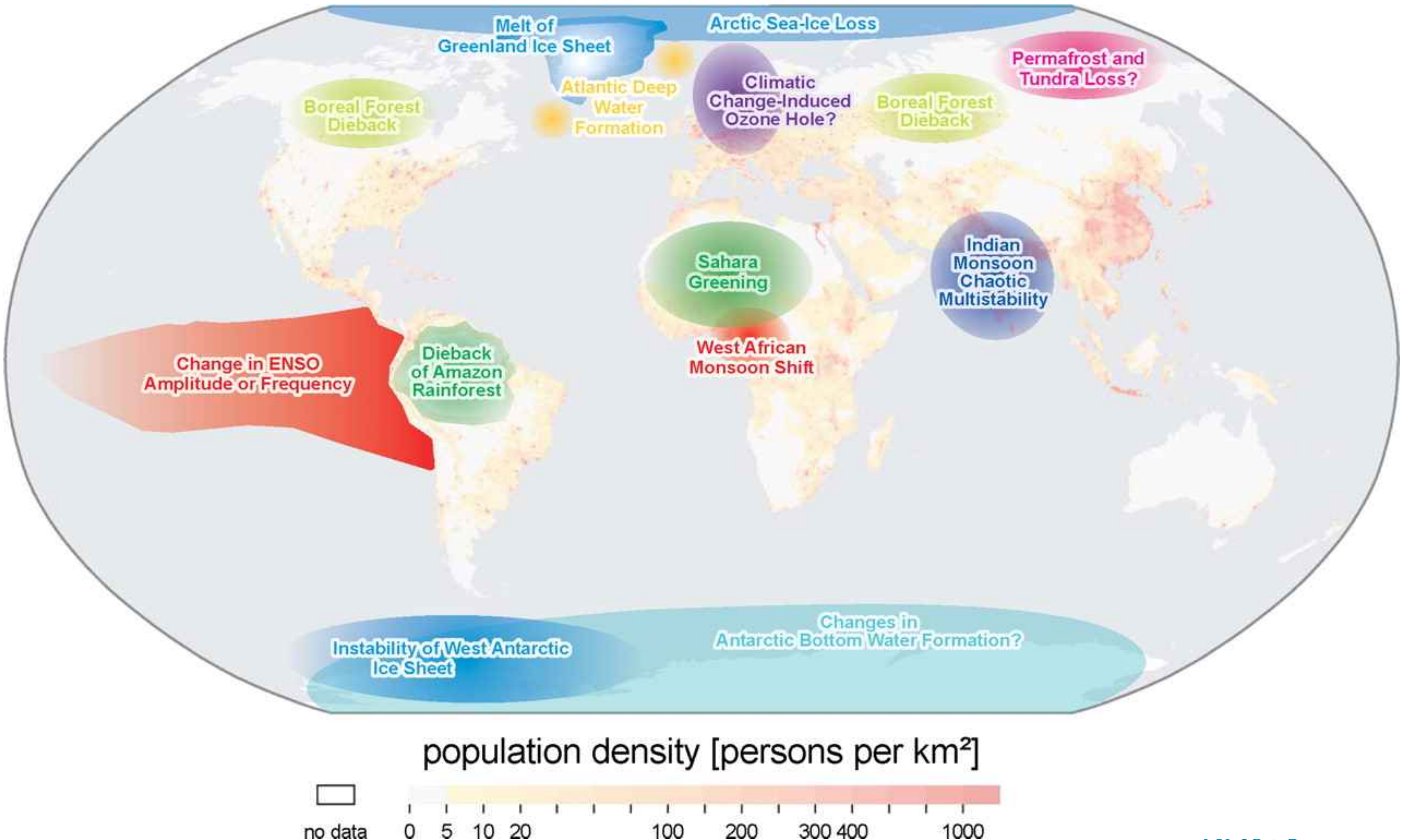
Feedbacks and Tipping Points



Lenton et al. (2008), PNAS

Feedbacks and Tipping Points



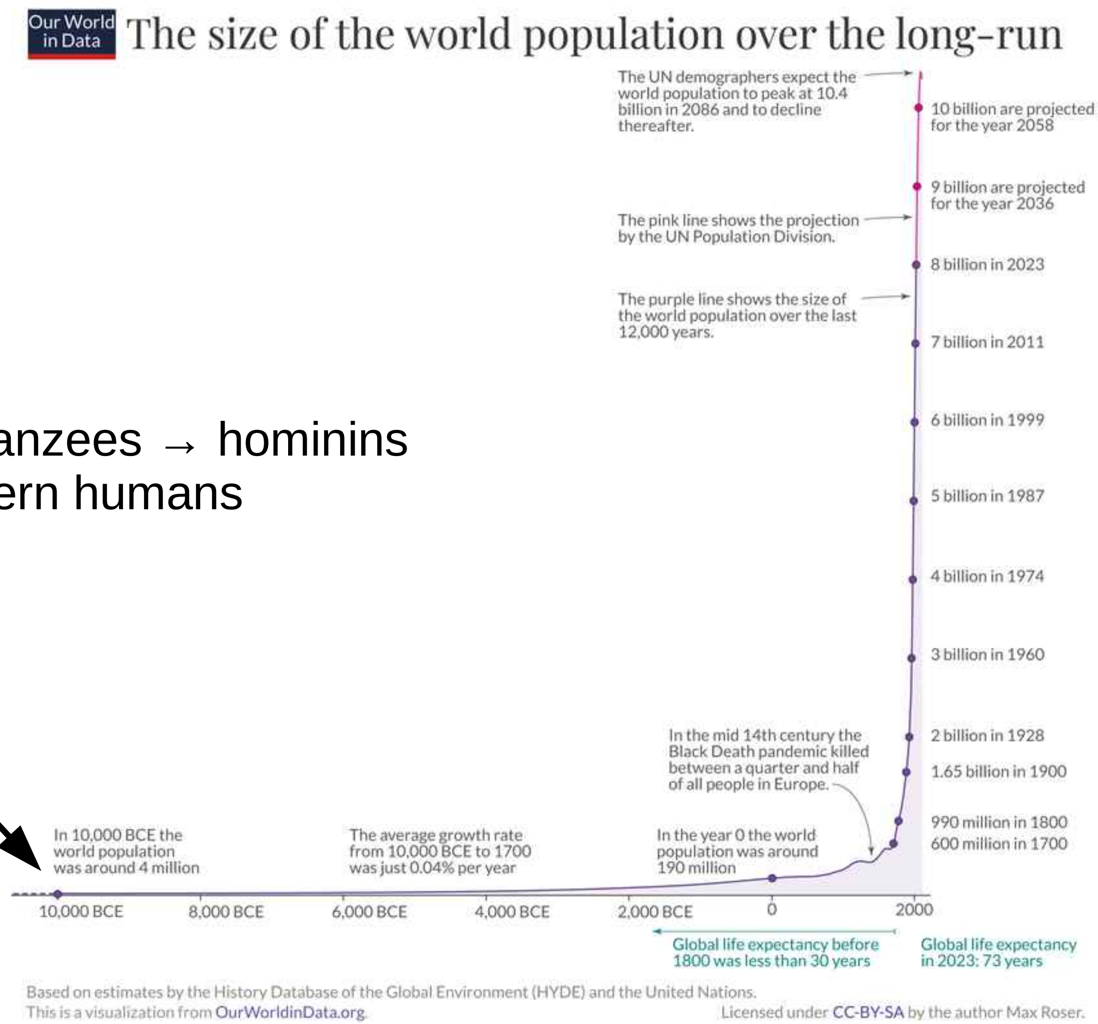
Lenton et al. (2008), PNAS

Human Influence

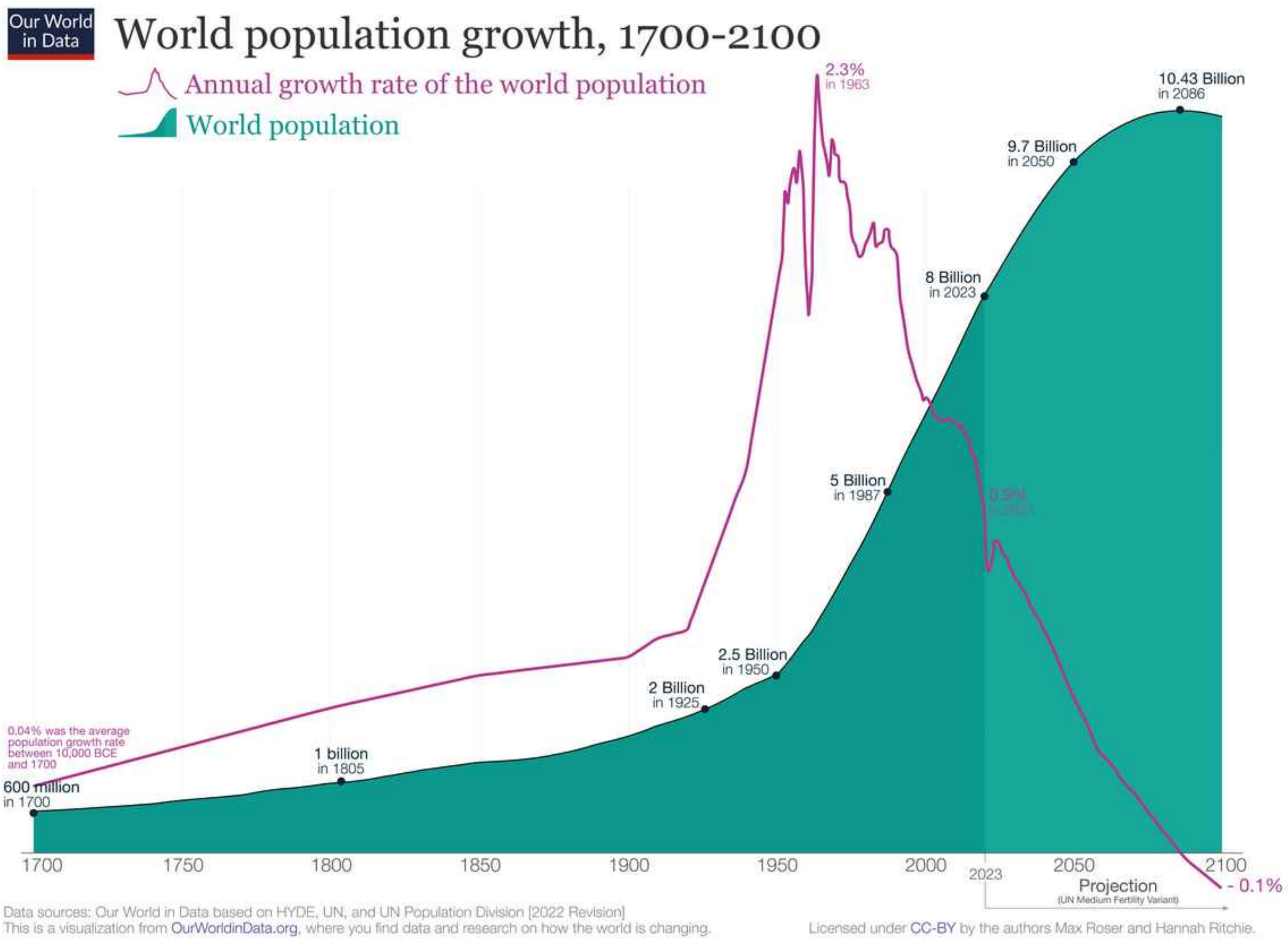
Human Influence

7 Ma chimpanzees → hominins
200 ka modern humans

agriculture



Human Influence



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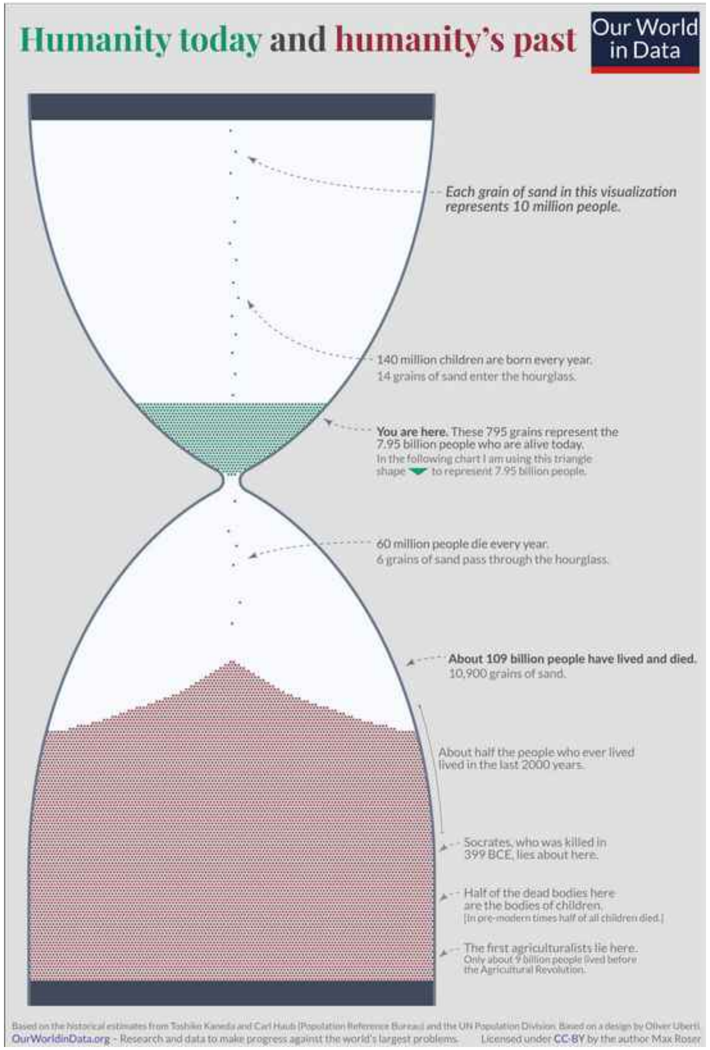

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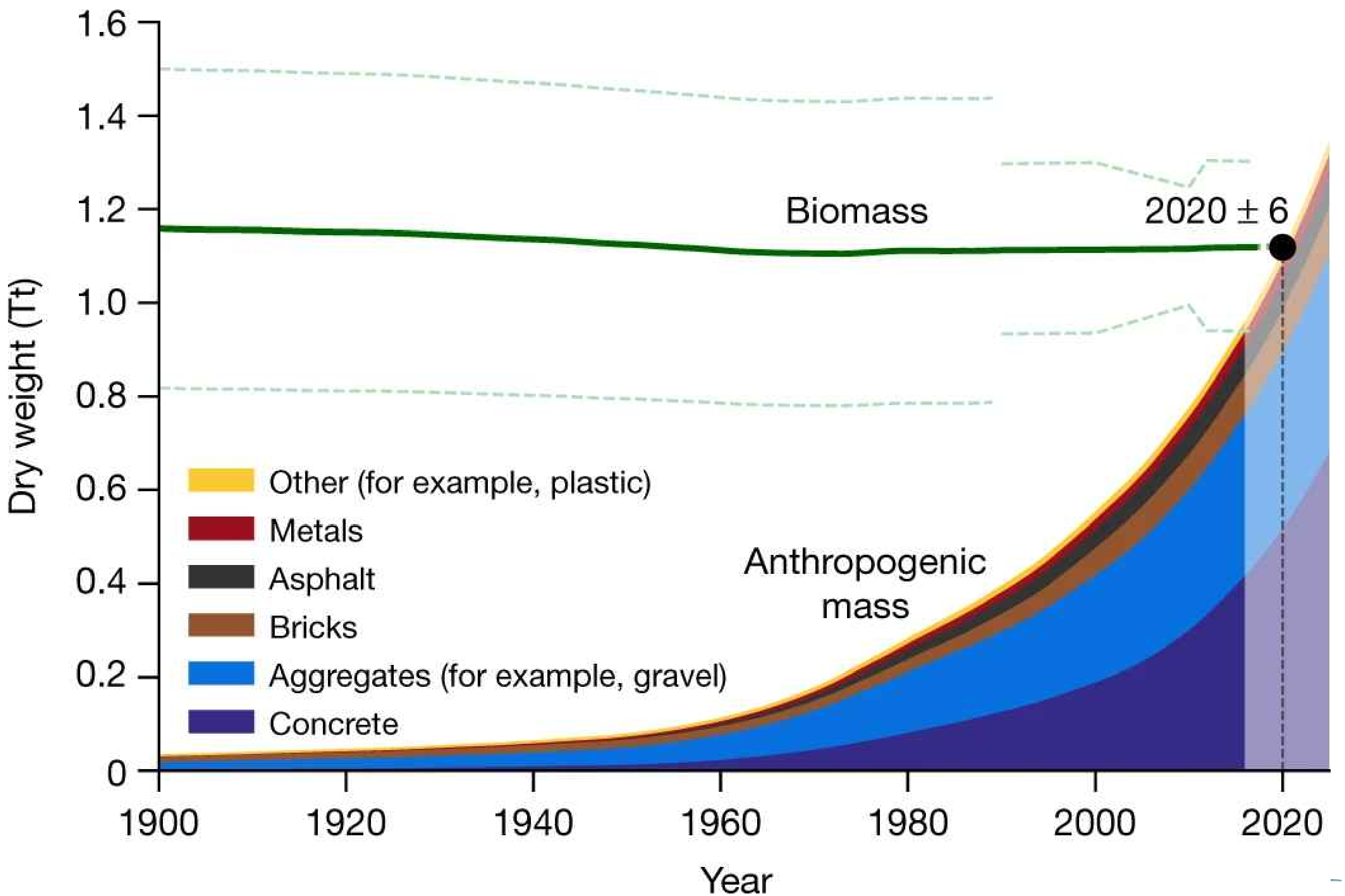


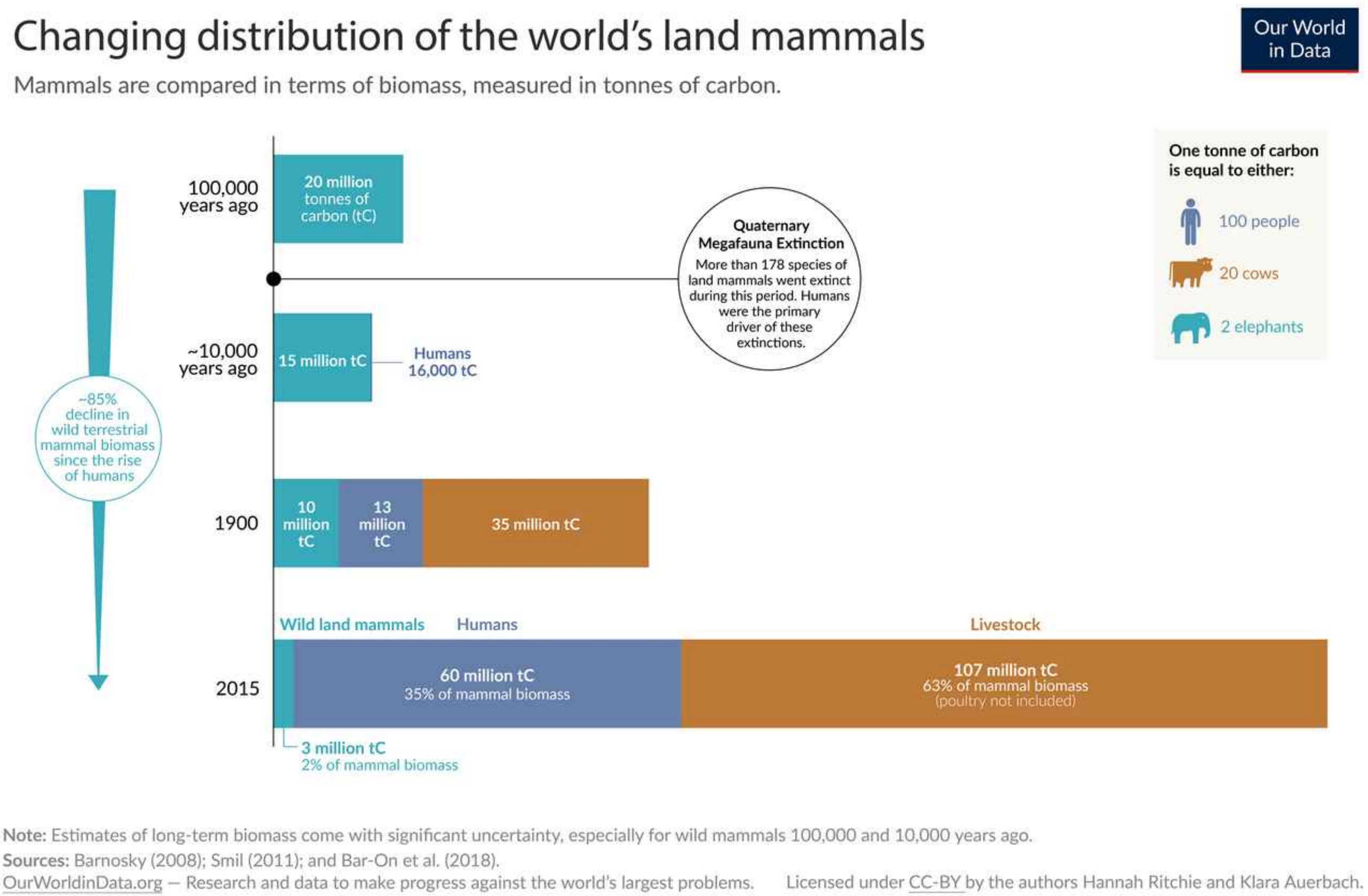
Elhacham et al. (2020), Nature

Human Influence

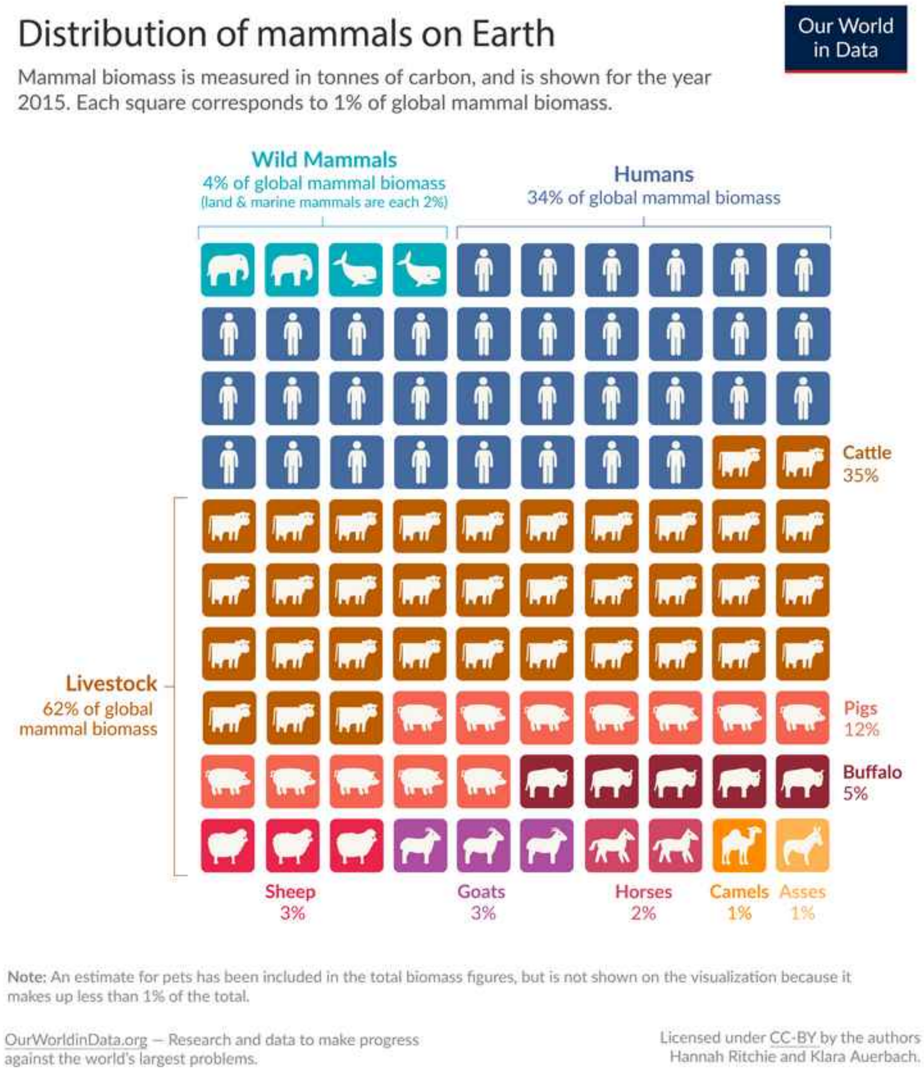
Current epoch:
The Anthropocene

Elhacham et al. (2020), Nature

Human Influence

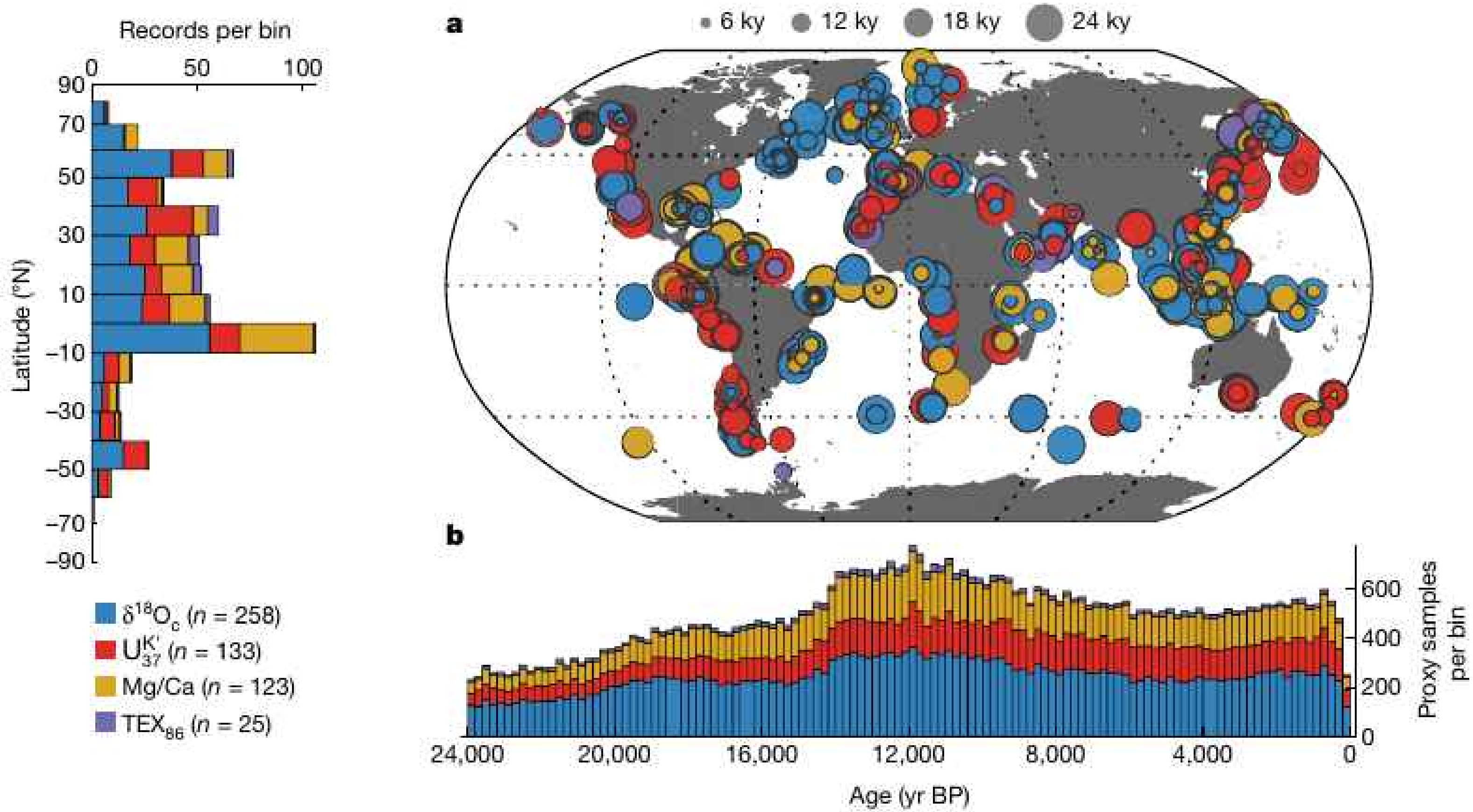


Human Influence



Human Influence

Global Climate during Human Civilization



Osman et al. (2021), Nature

Human Influence

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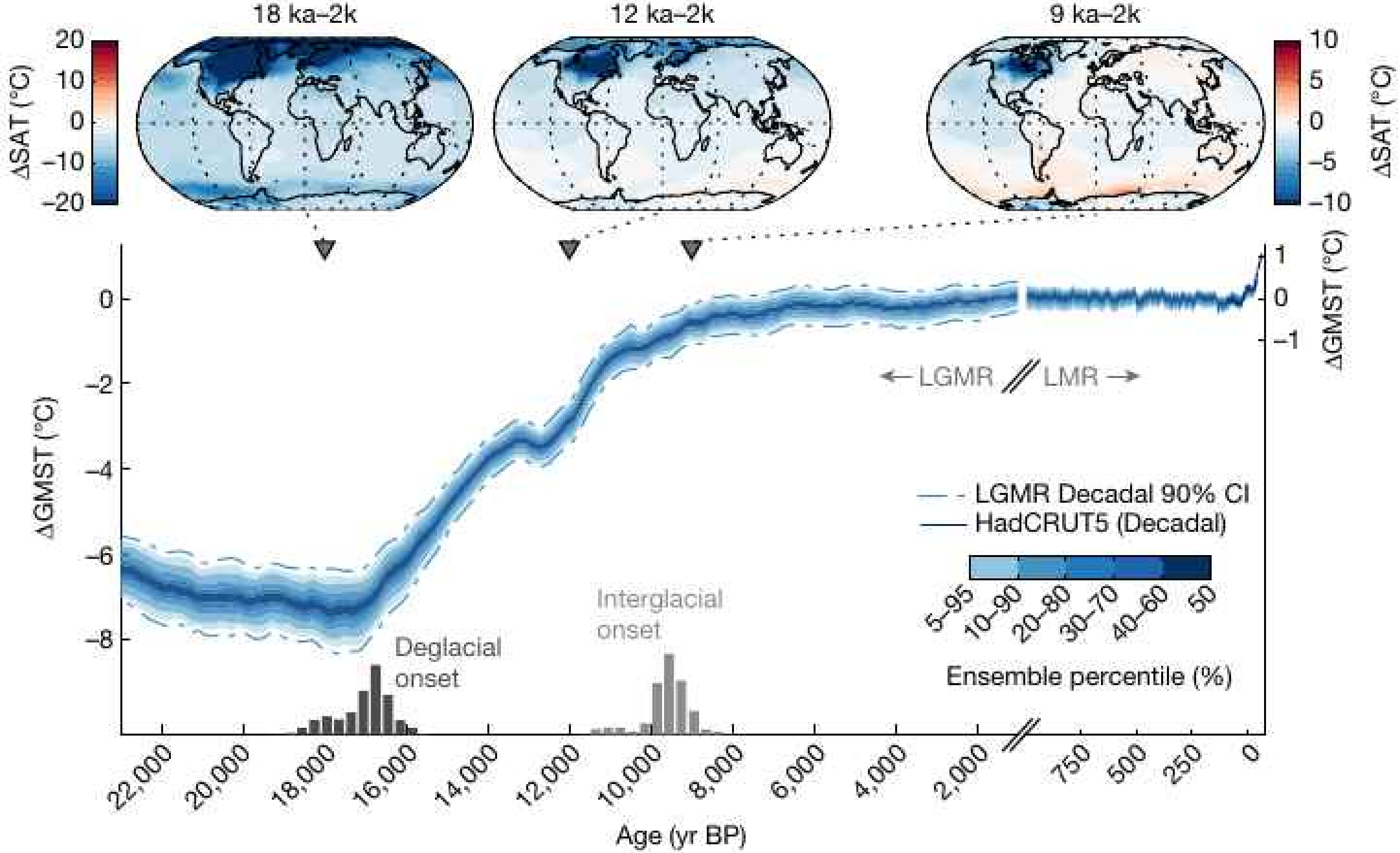

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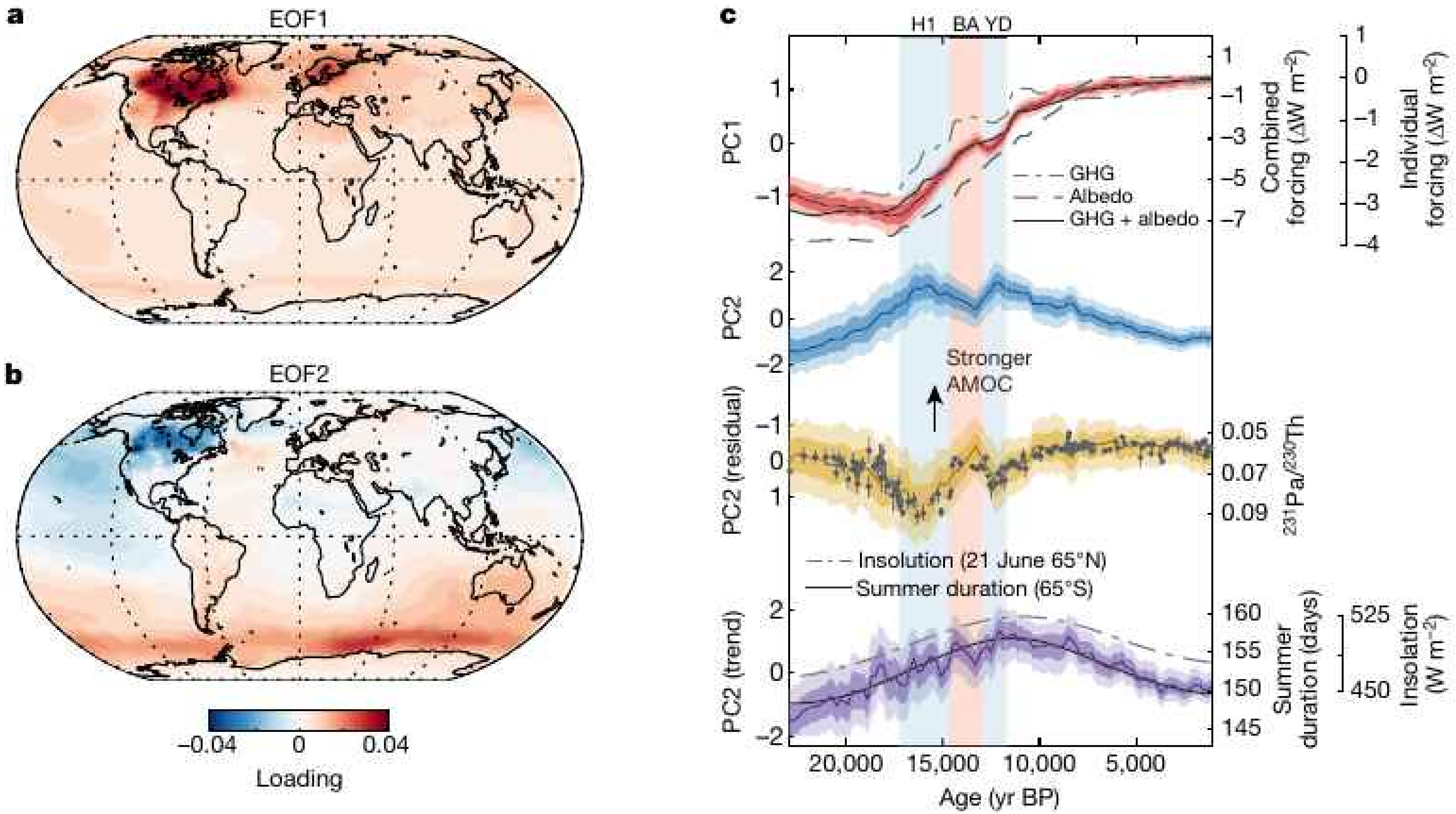

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Human Influence

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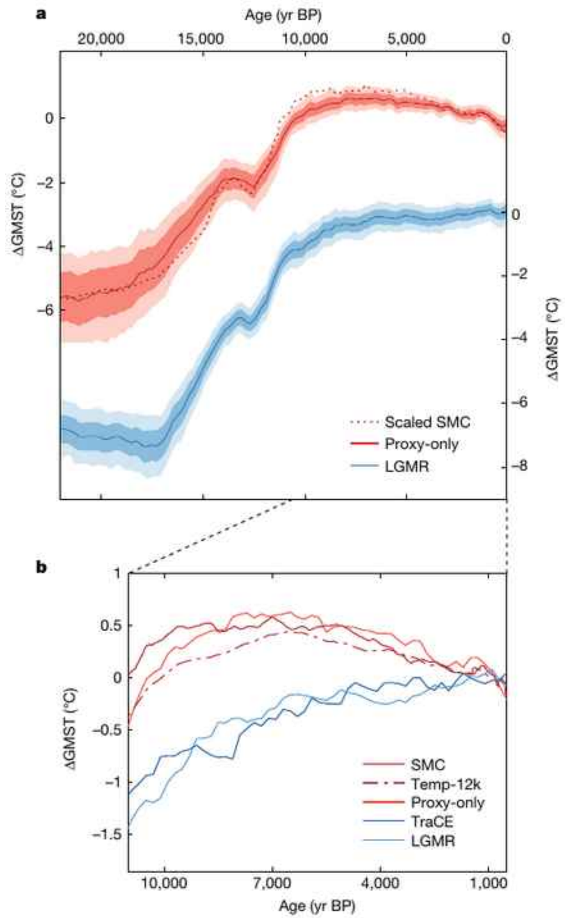


Fig. 4 | Comparison of LGM-to-present surface temperature reconstructions.

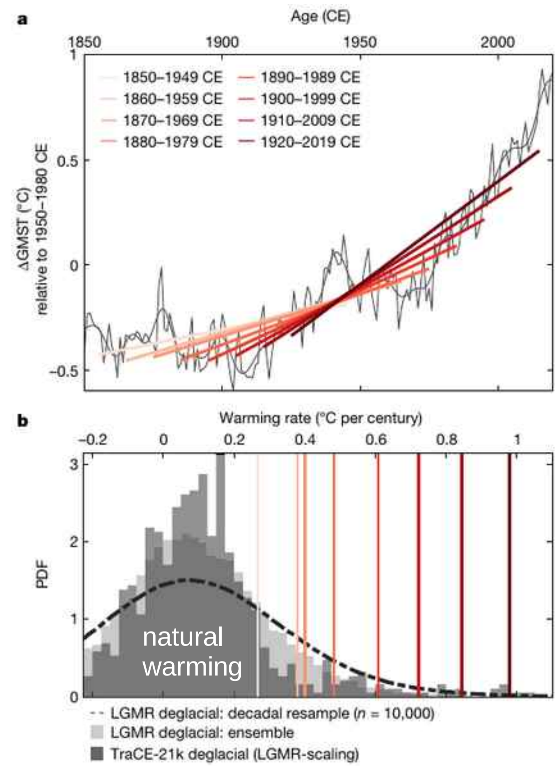
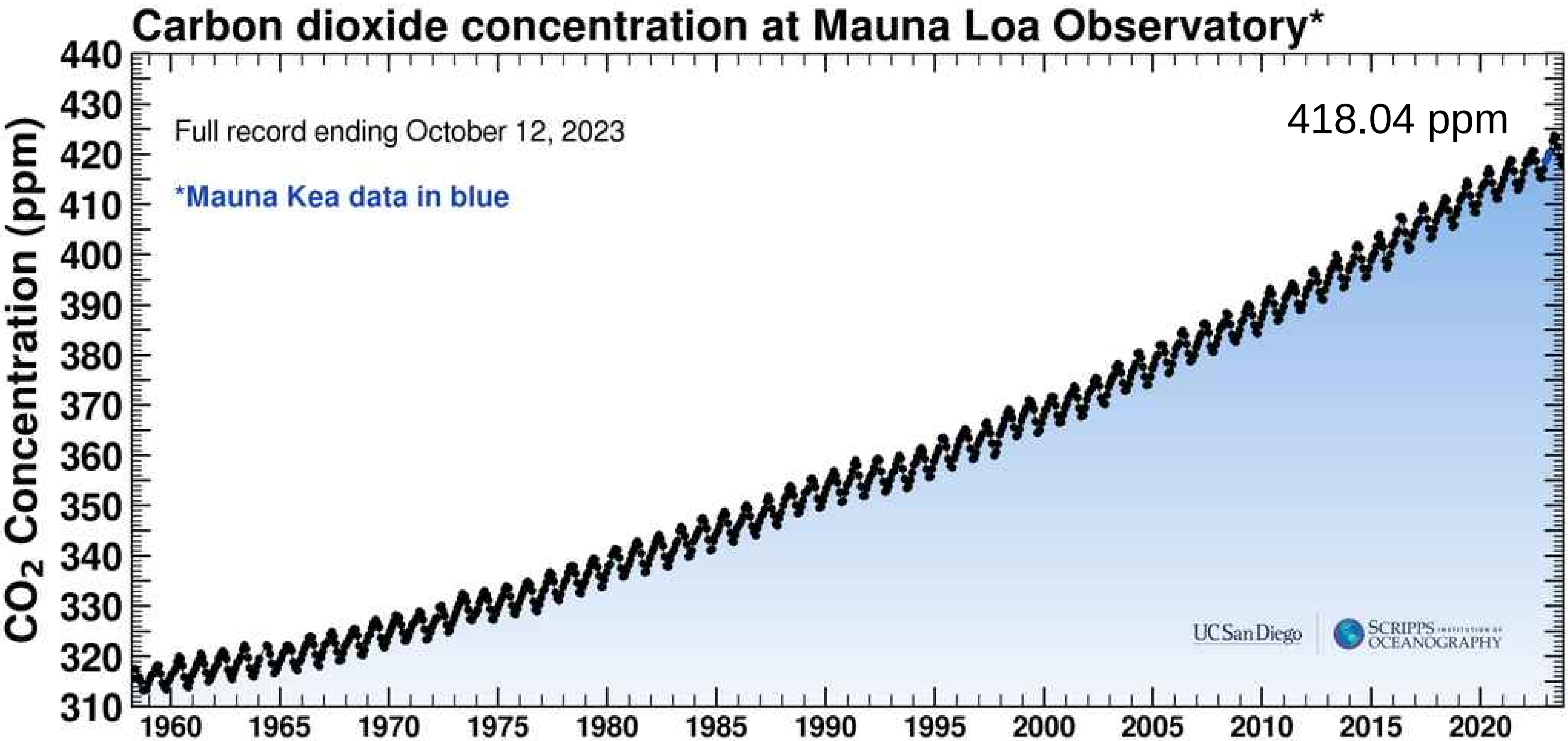


Fig. 5 | Contextualizing rates of modern warming. a, Observed rates of centennial GMST warming stepped decade-wise to present based on HadCRUT5 observations[11]. **b**, Comparison of HadCRUT5 warming rates (vertical red lines) to the distribution of deglacial warming rates from (1) the LGMR ensemble ($n = 500$ 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 simulation[1] scaled to reflect the magnitude of LGMR deglacial warming (Supplementary Information). Observed centennial warming rates after 1910 CE exceed the

recent warming

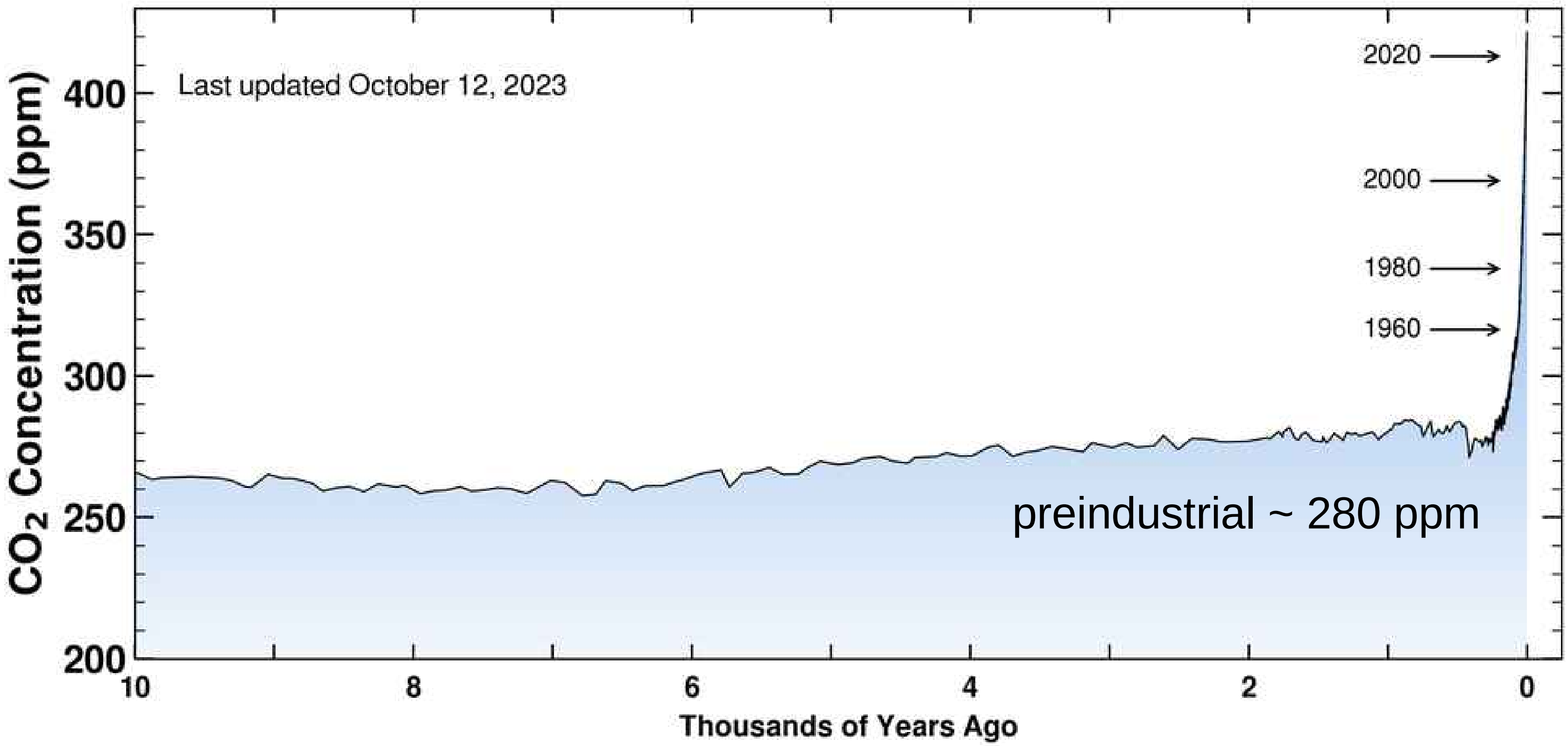
Osman et al. (2021), Nature

Human Influence



keelingcurve.ucsd.edu

Human Influence



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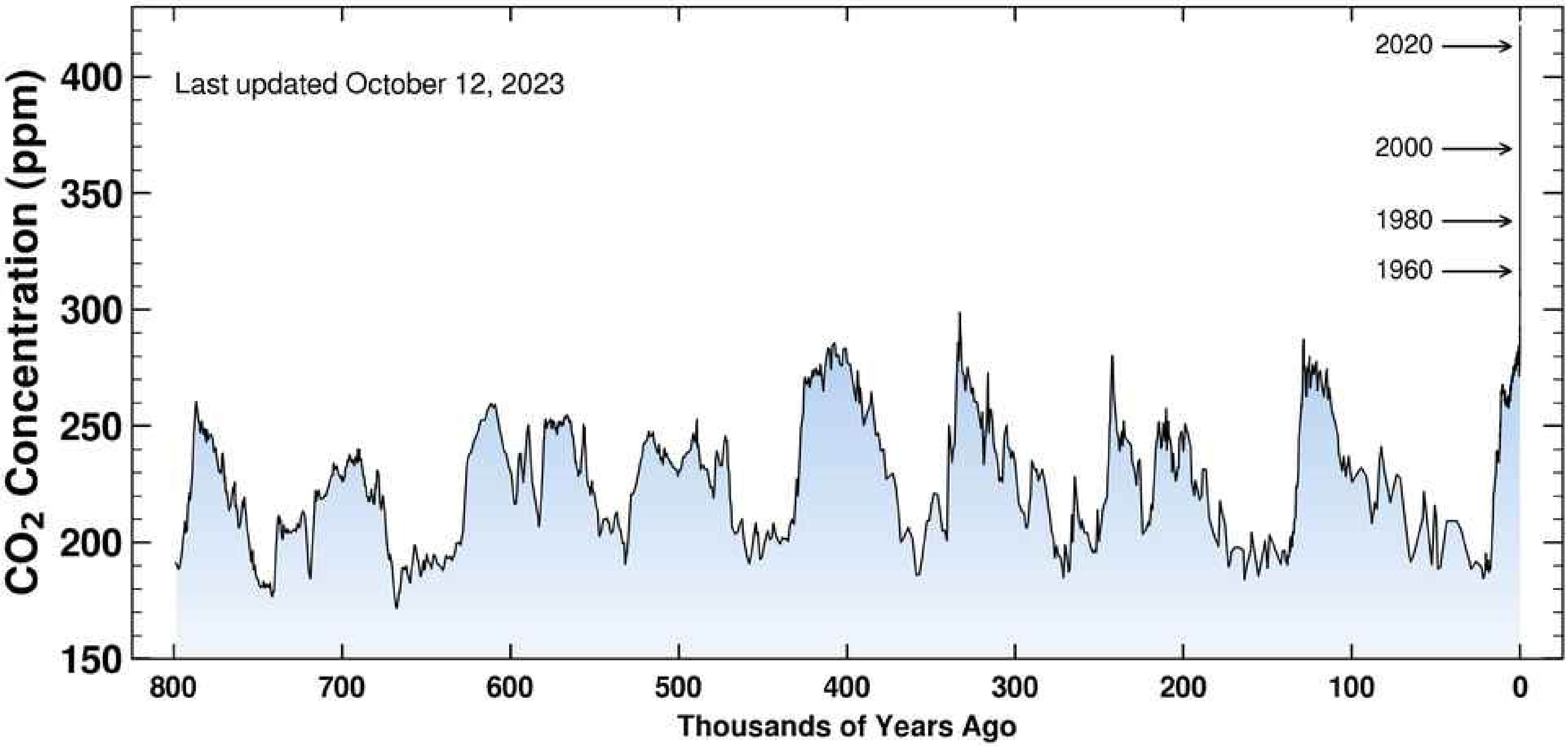

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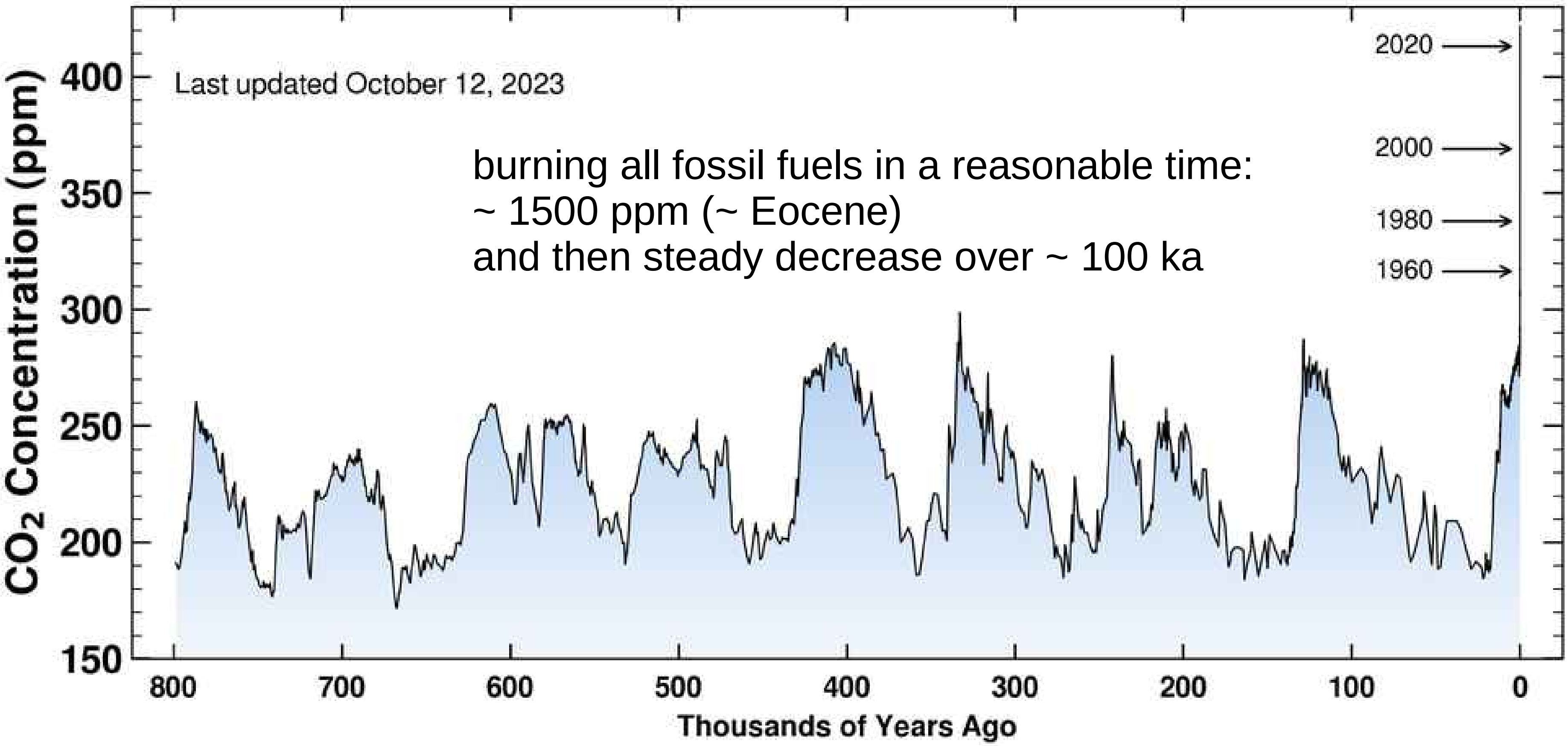
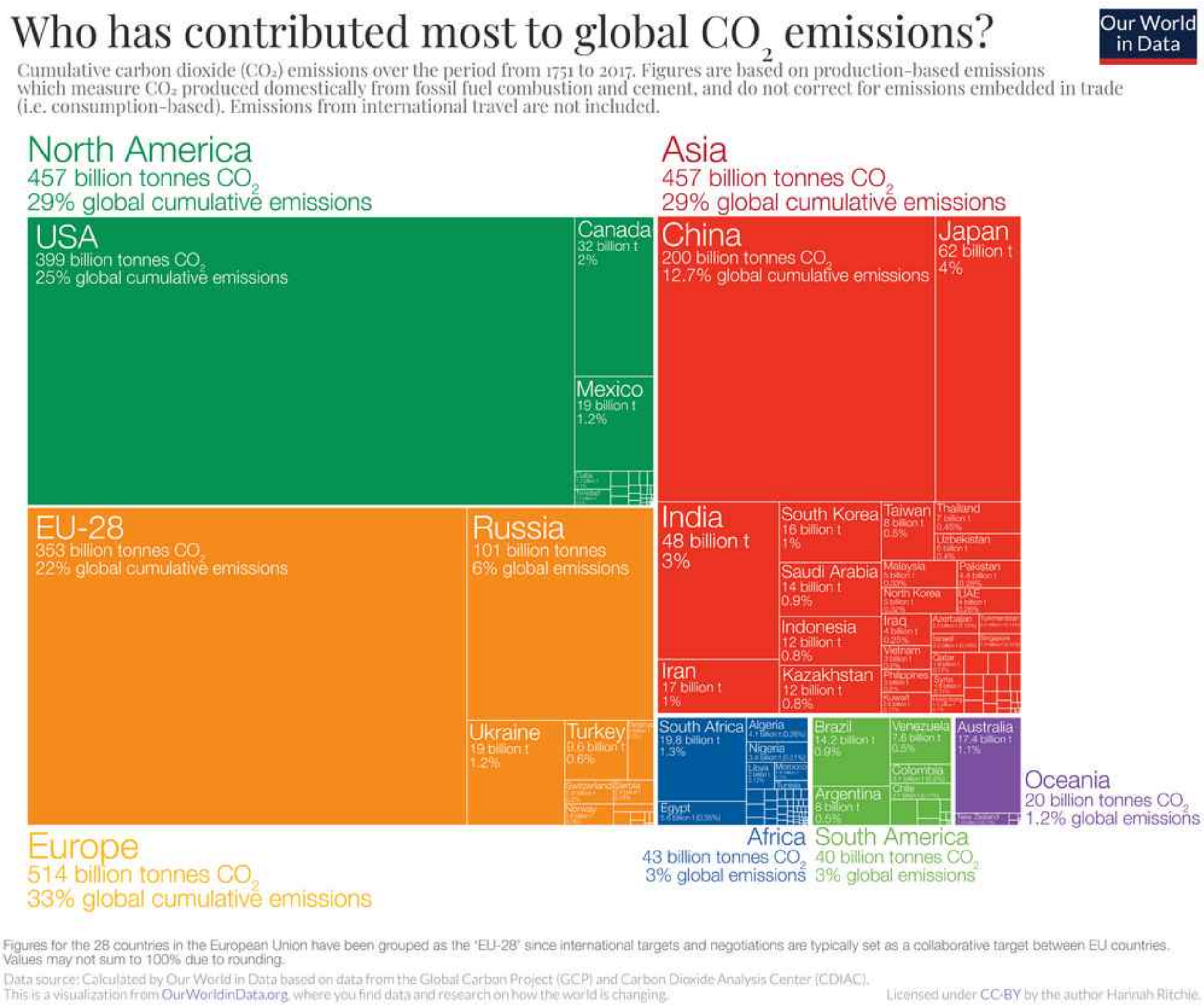
Human Influence

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 19^{th} C.	end 19^{th} C.	1950s	1970s	1990s	2020s

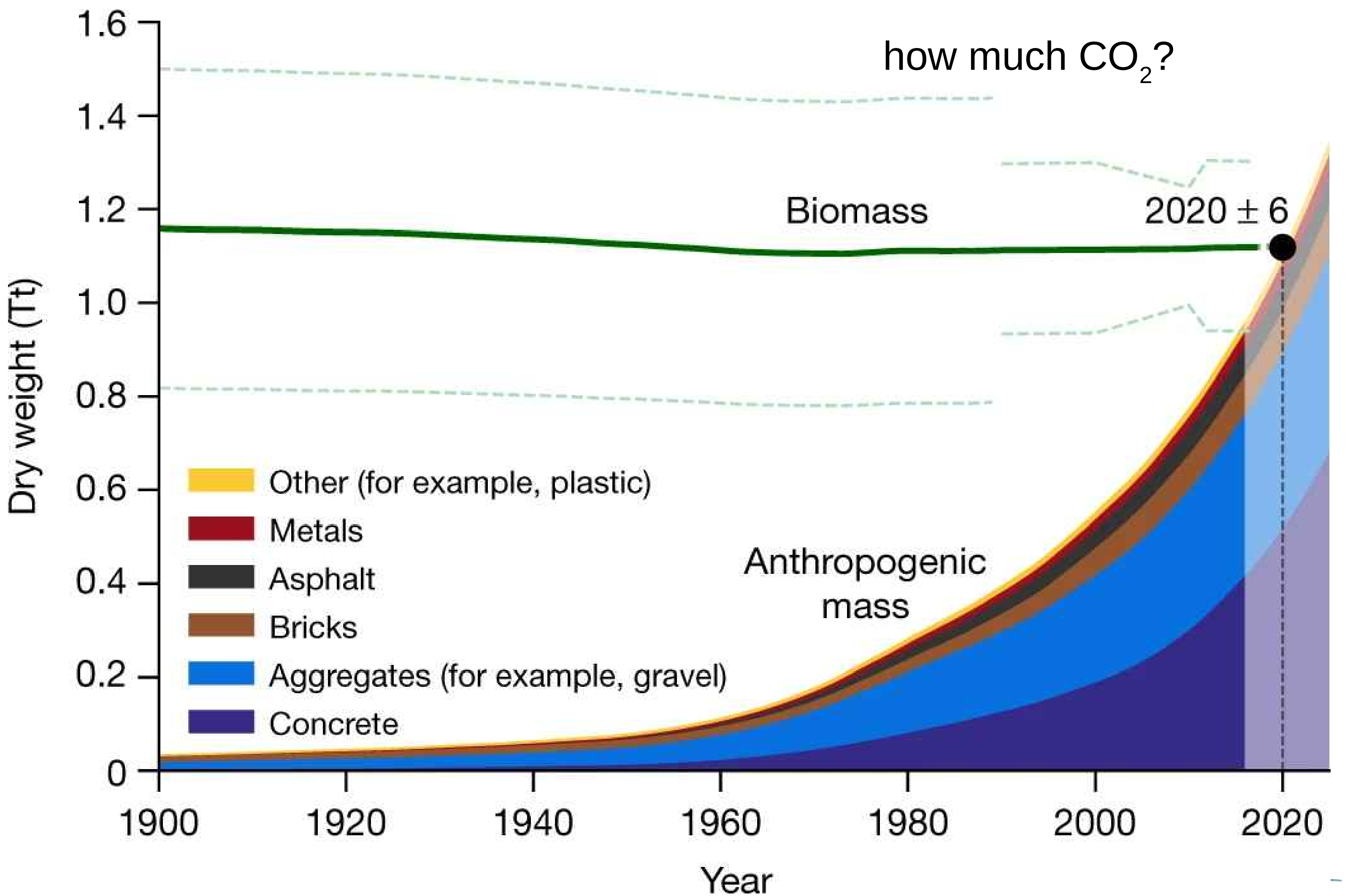
Human Influence



Human Influence



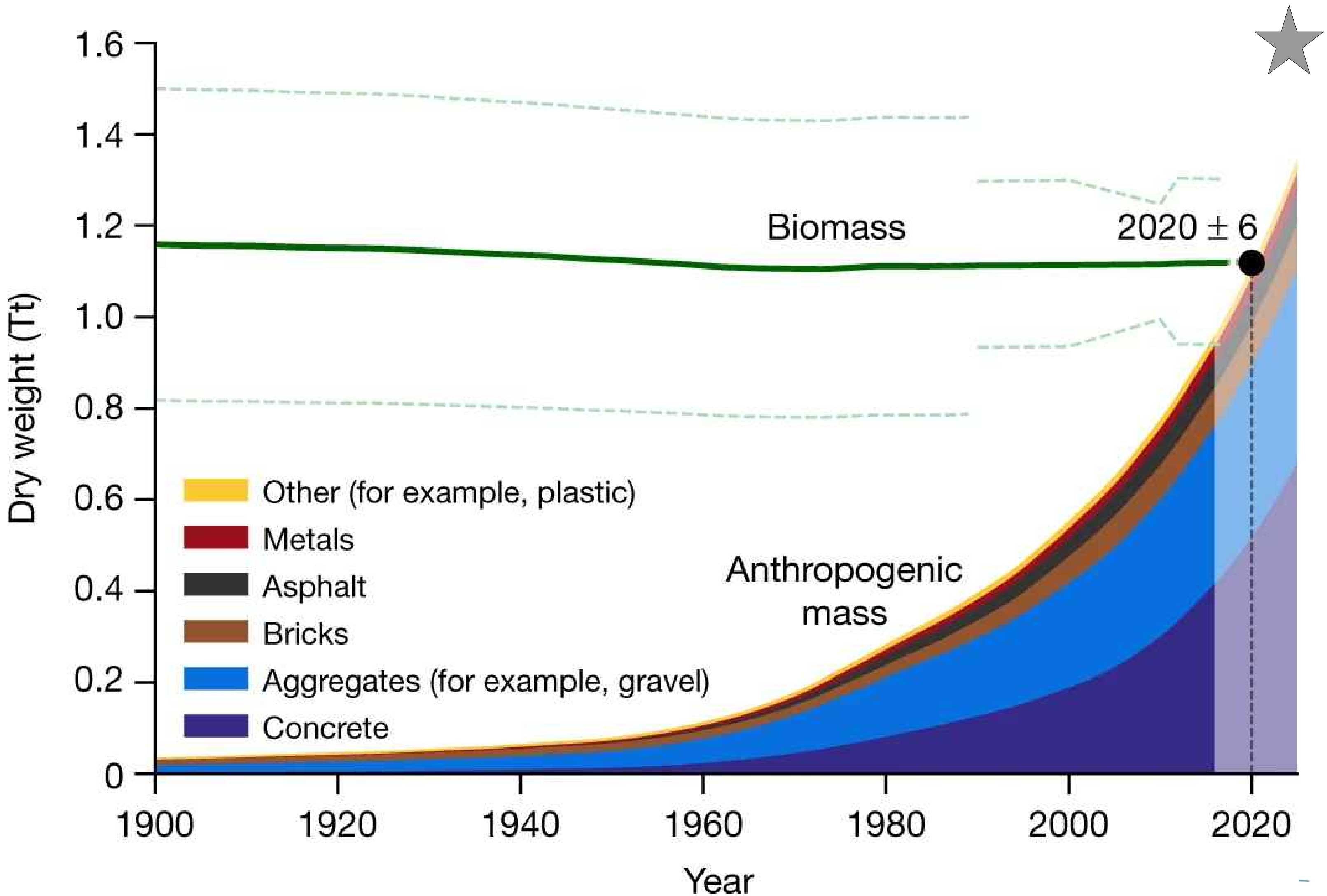
Human Influence



Elhacham et al. (2020), Nature

Human Influence

CO_2:
1.7 Tt



Elhacham et al. (2020), Nature

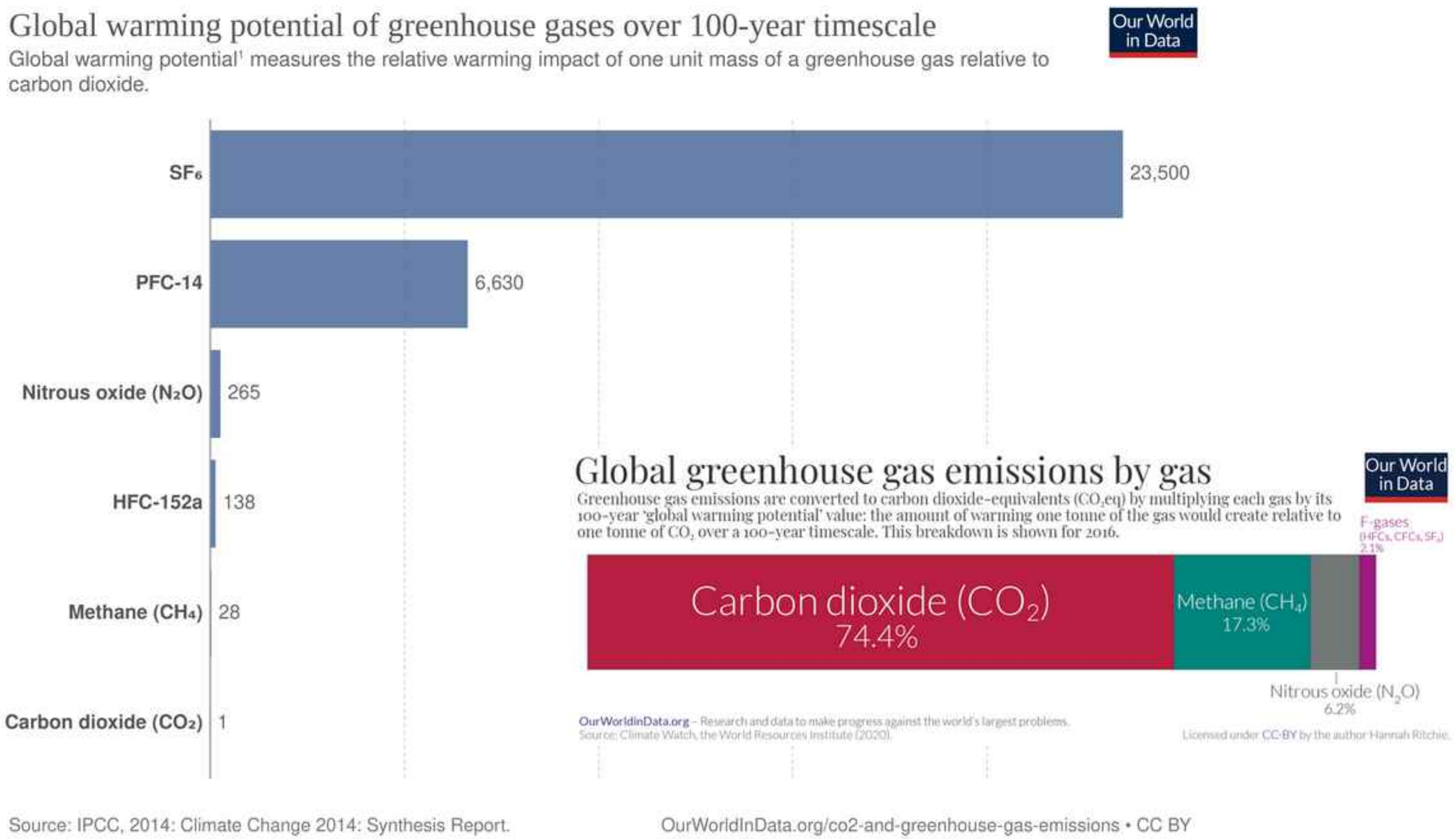
Human Influence

where did all the CO_2 go?

Human Influence

where did all the CO_2 go?
https://youtube.com/watch?v=dwVsD9CiokY

Human Influence



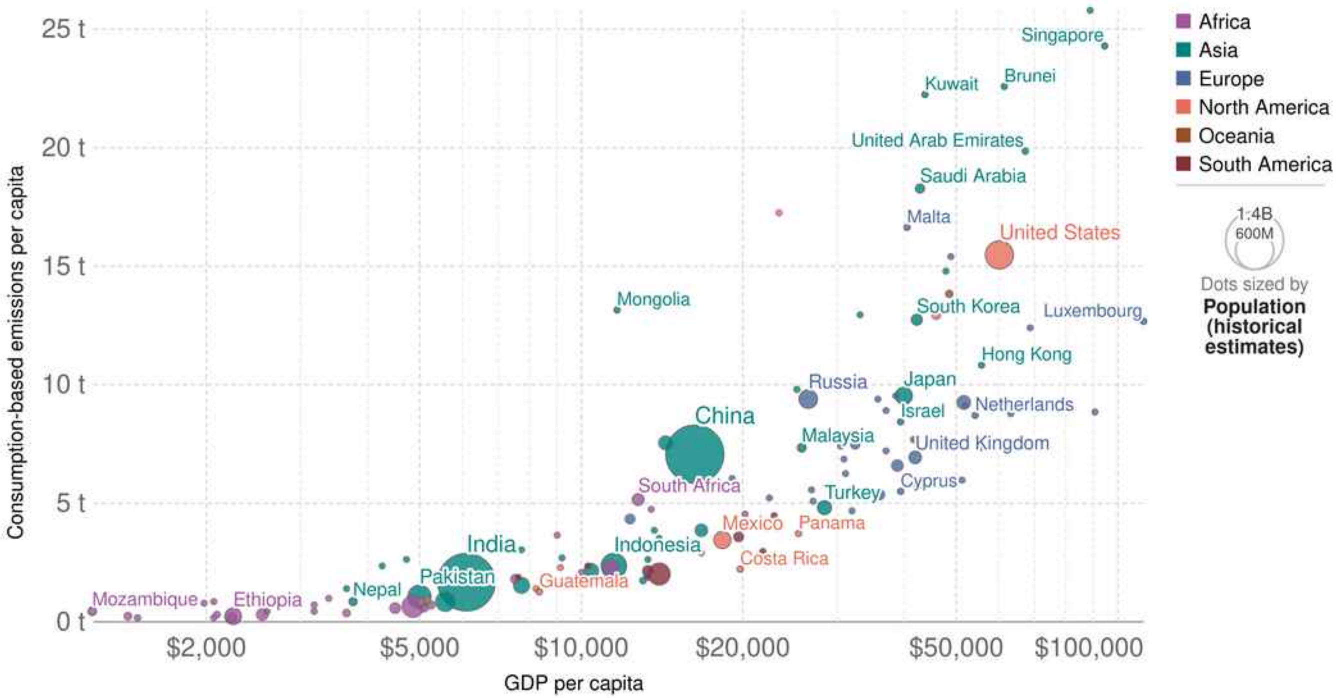
1. **Global warming potential**: Global warming potential (GWP) measures the amount of heat absorbed by a greenhouse gas relative to the same mass of carbon dioxide (CO_2). It measures the amount of warming a gas creates compared to CO_2. Carbon dioxide is given a GWP value of one. If a gas had a GWP of 10 then one kilogram of that gas would generate ten times the warming effect as one kilogram of CO_2. 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 CO_2.

Human Influence

Consumption-based CO_2 emissions per capita vs. GDP per capita, 2020

Our World in Data

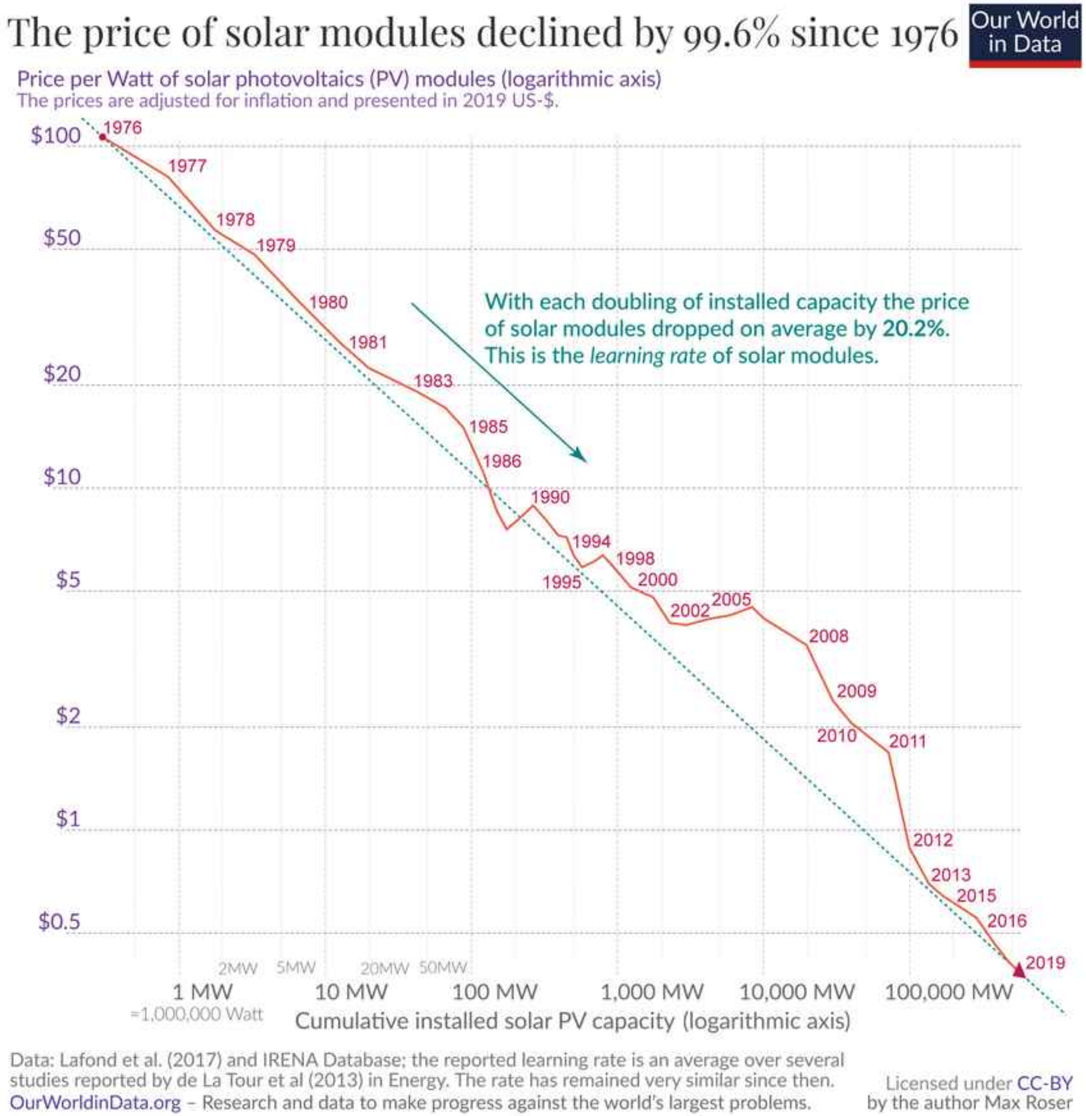
– Consumption-based emissions[1] are national emissions that have been adjusted for trade. It's production-based emissions minus emissions embedded in exports, plus emissions embedded in imports.
– GDP per capita is adjusted for price differences between countries (PPP) and over time (inflation).



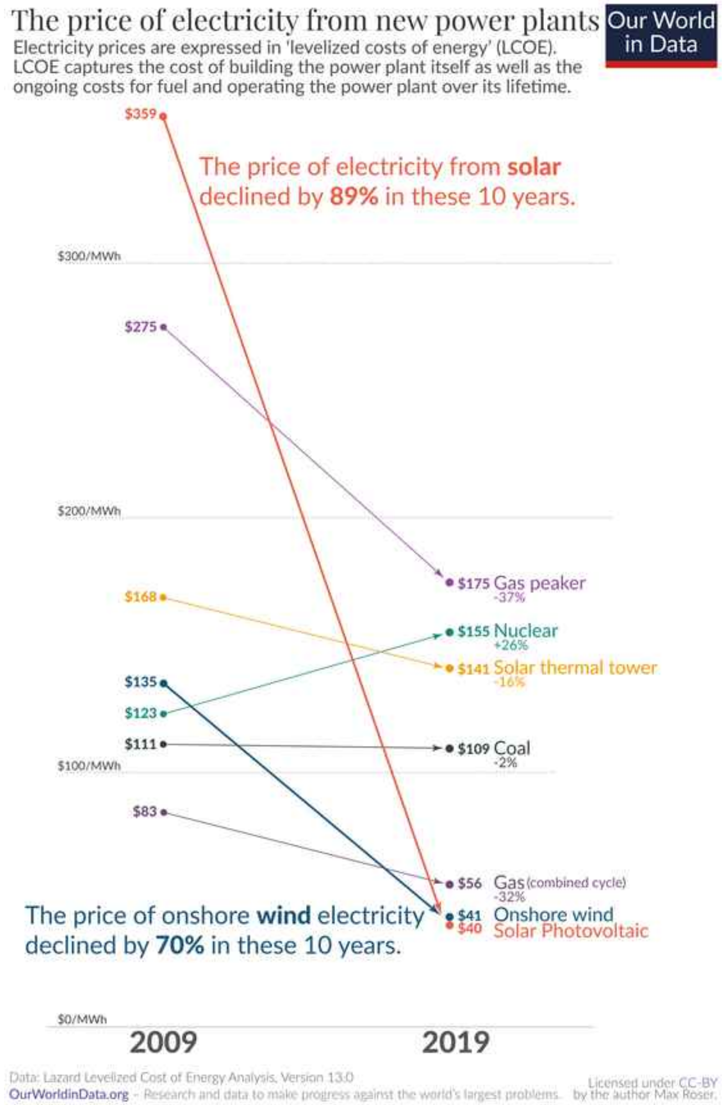
Source: Global Carbon Project (2022); Population based on various sources (2023); Data compiled from multiple sources by World Bank
OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

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

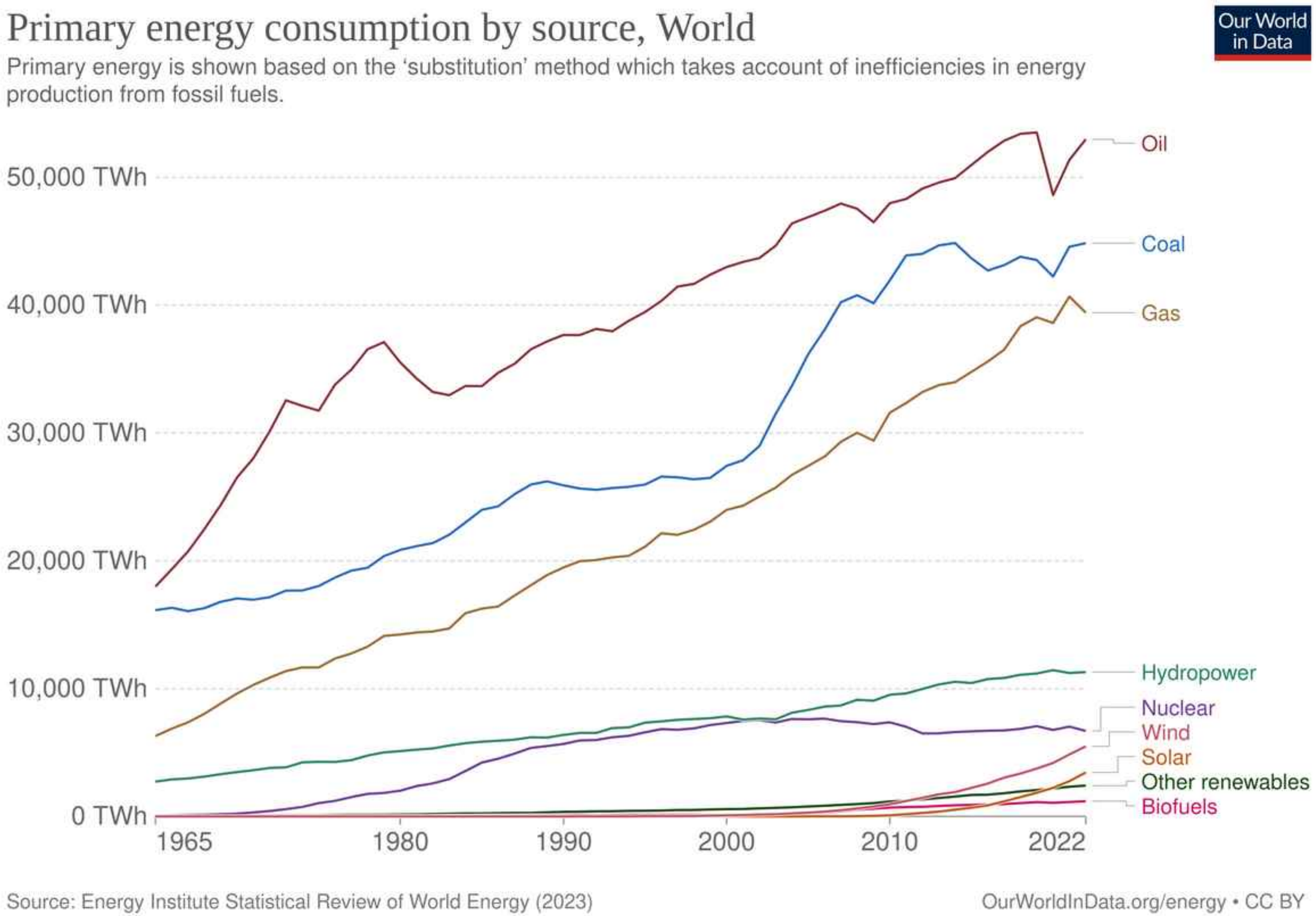
Human Influence



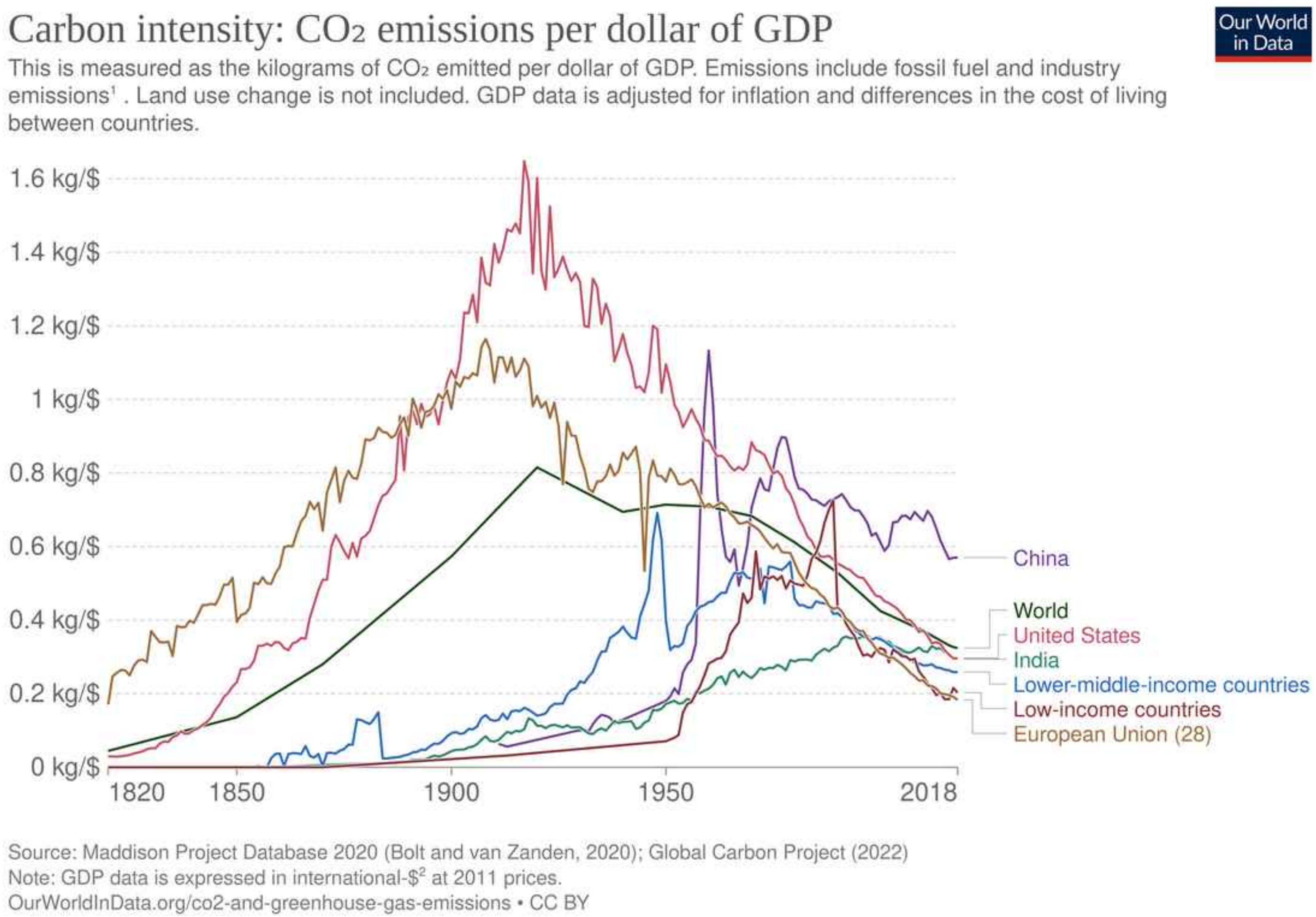
Human Influence



Human Influence



Human Influence



Human Influence

examples on fossil fuels

Human Influence

- average energy intensity EU ~ 0.2 kg CO_2 per € spent
- how much is 0.2 kg CO_2?

- @ 20°C ideal gas ~ 24 litres / mole
- 0.2 kg CO_2 ~ 4.5 moles

→ ~ 100 litres CO_2 gas

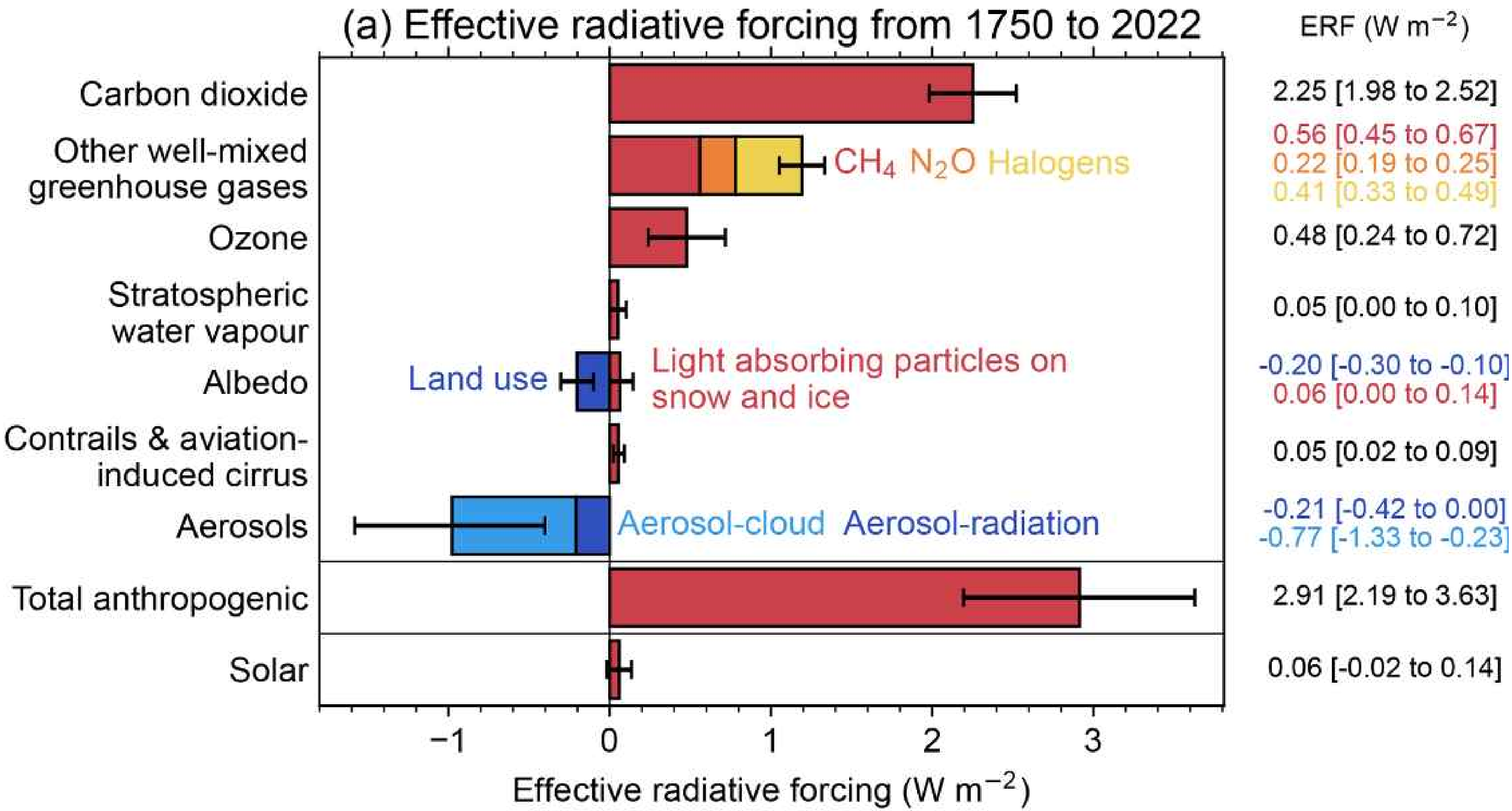
(that's a nice bath in a small tub)

Human Influence

same as spending average 16 €!

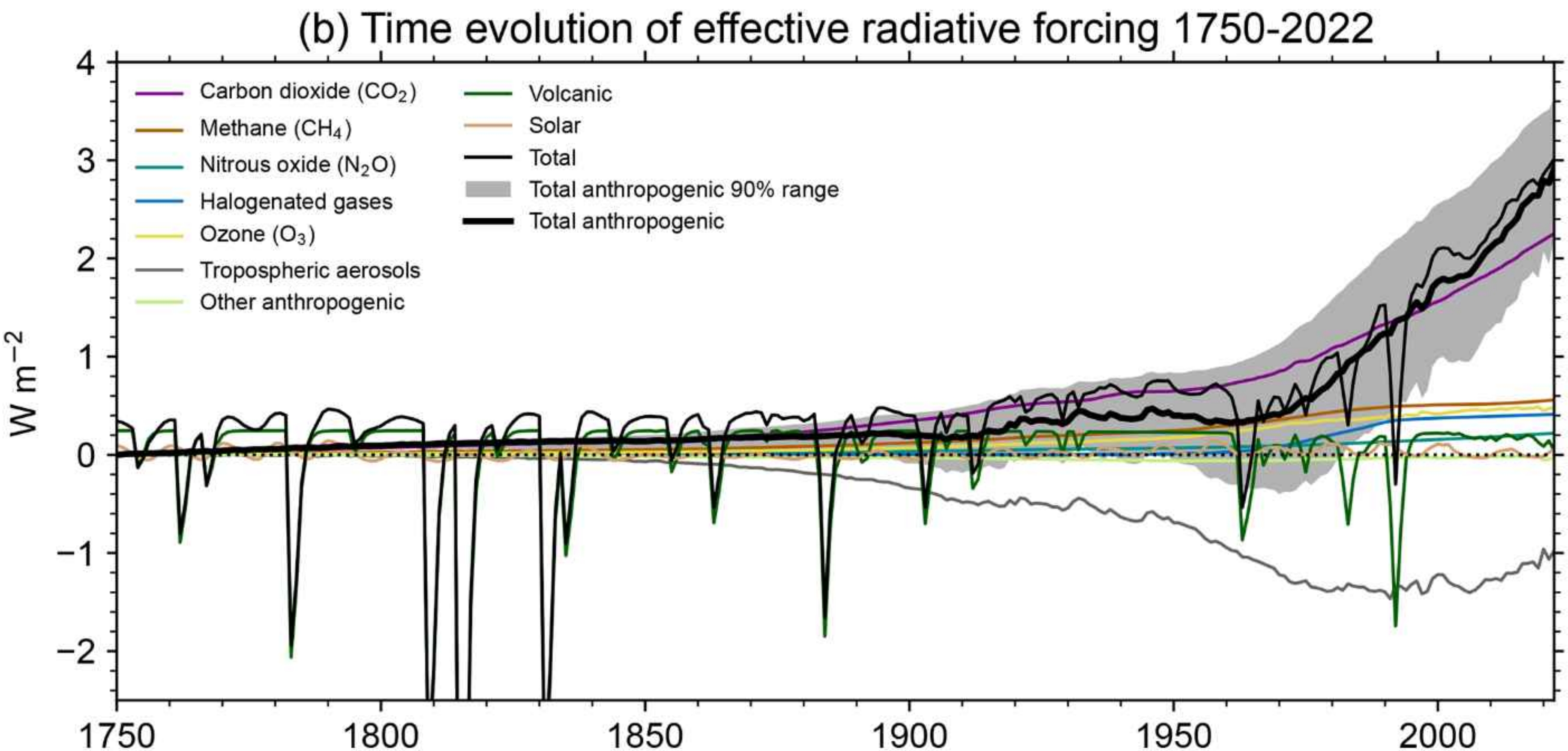
- how much does burning coal heat the planet vs. e.g. your house?
- 1 kg coal: 30 MJ heating value (8 kWh), 3.2 kg CO_2
- 70 ppm CO_2 increase ~ climate forcing of 2.5 W/m²
- Earth surface ~ 510.000.000 km² → 1.3 * 10^{15} W
- ~ 800 Gt C in atmosphere (3000 Gt CO_2)
- 3.2 kg CO_2 from coal ~ 10^{-15} of atm. CO_2 ~ 1W
- 8000 h ~ 333 d ~ 1 year
- over 100 years ~ 100 x more heating in atmosphere

Human Influence



Forster et al. (2023),
Earth System Science Data

Human Influence



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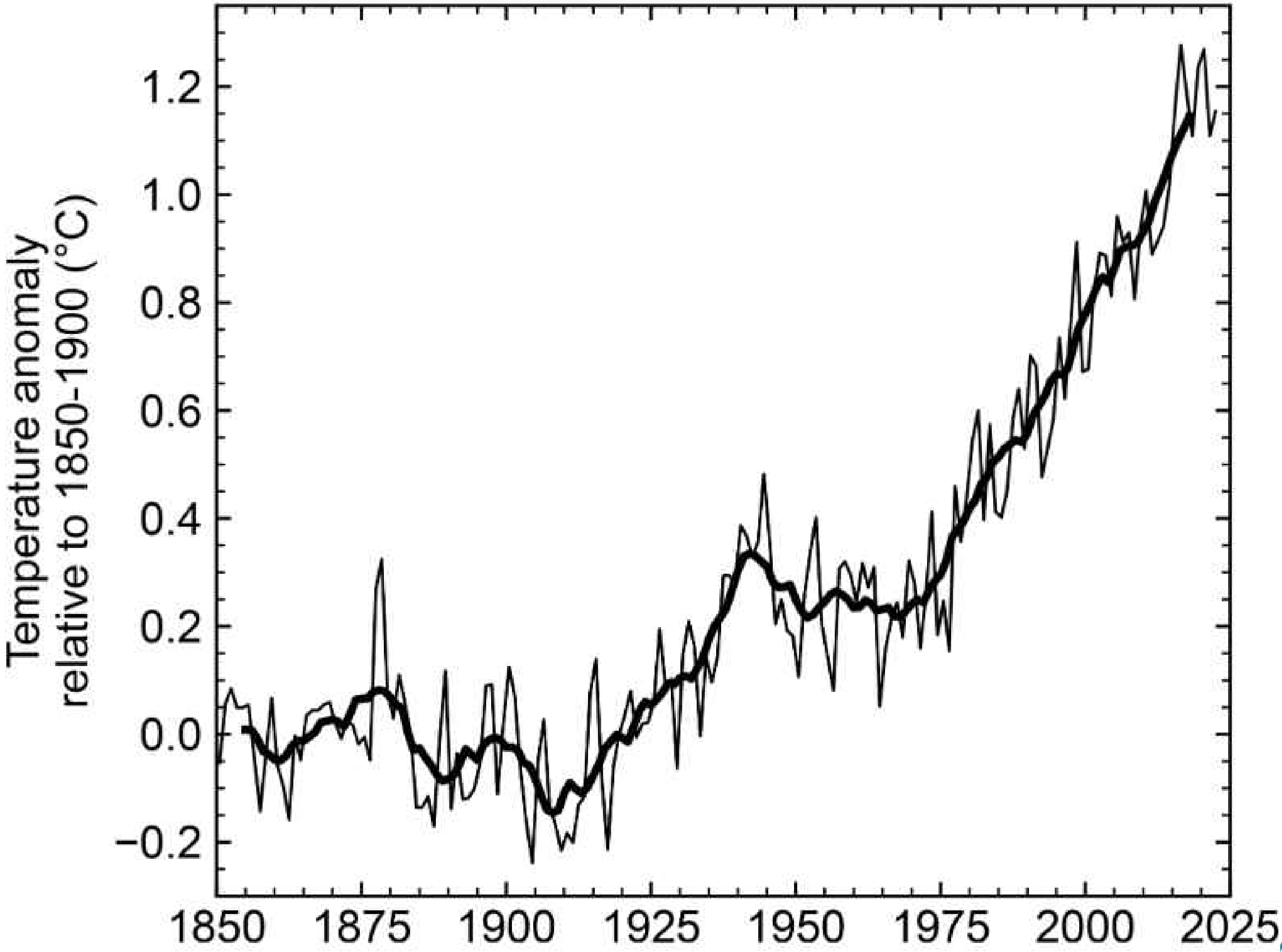

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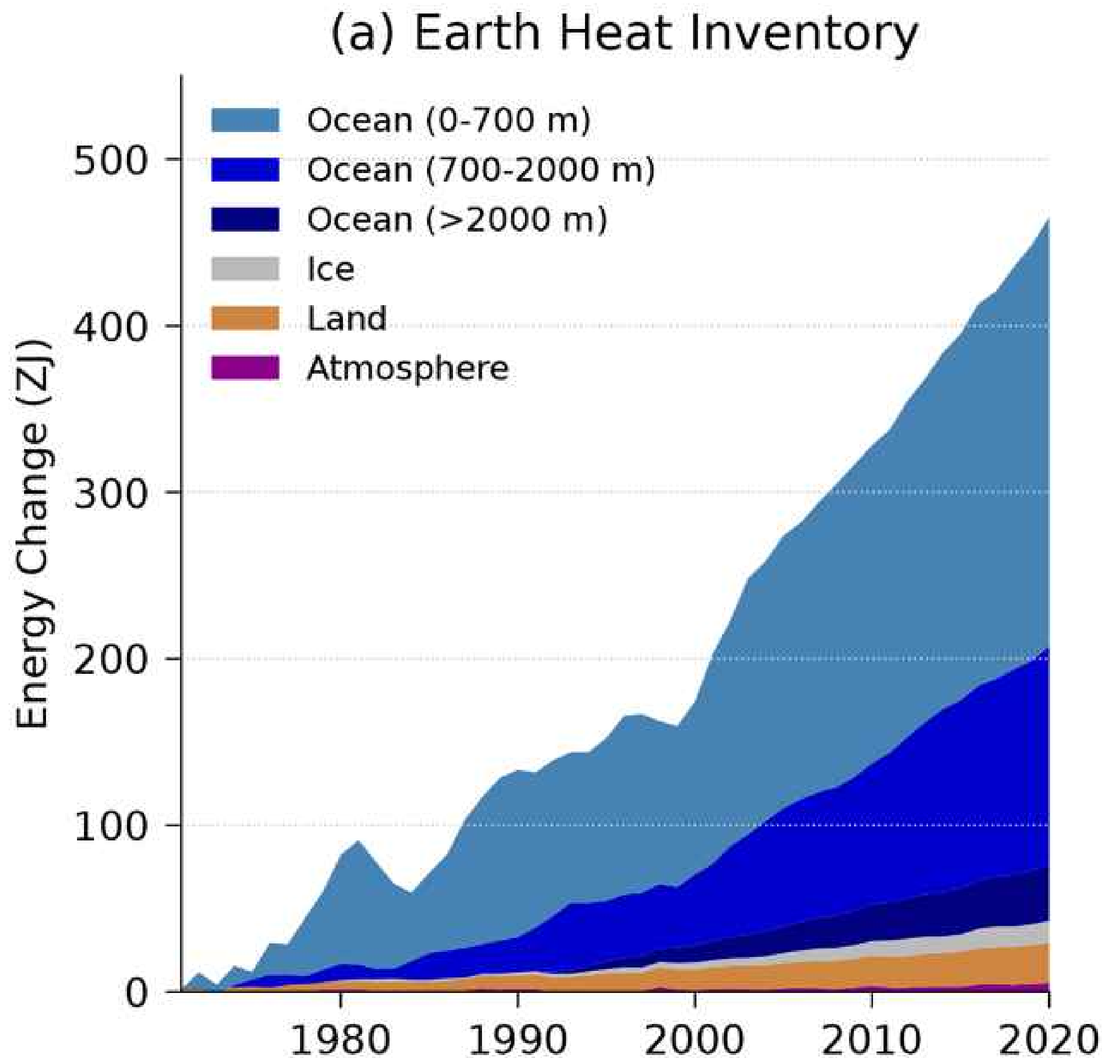
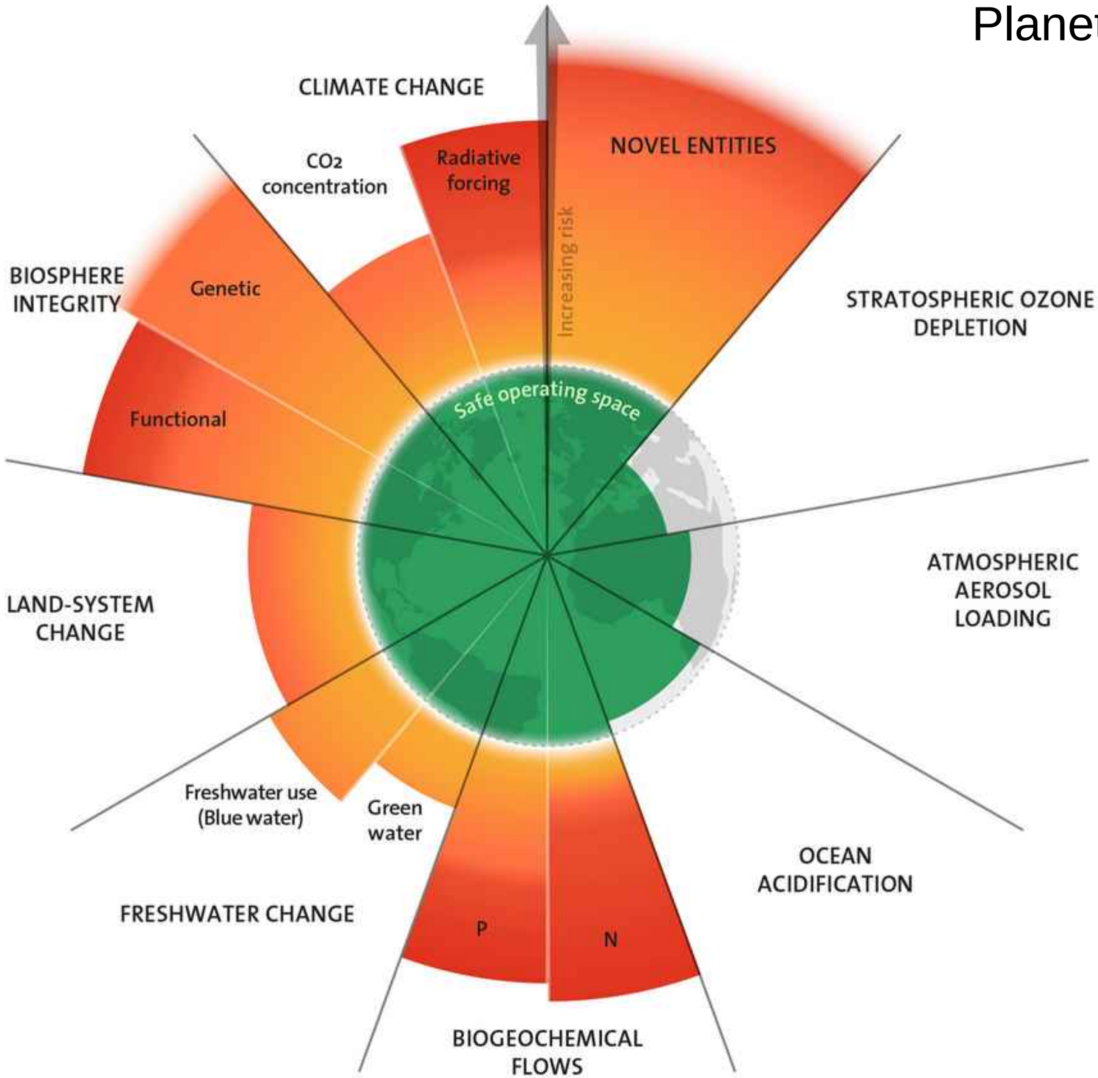


Forster et al. (2023),
Earth System Science Data

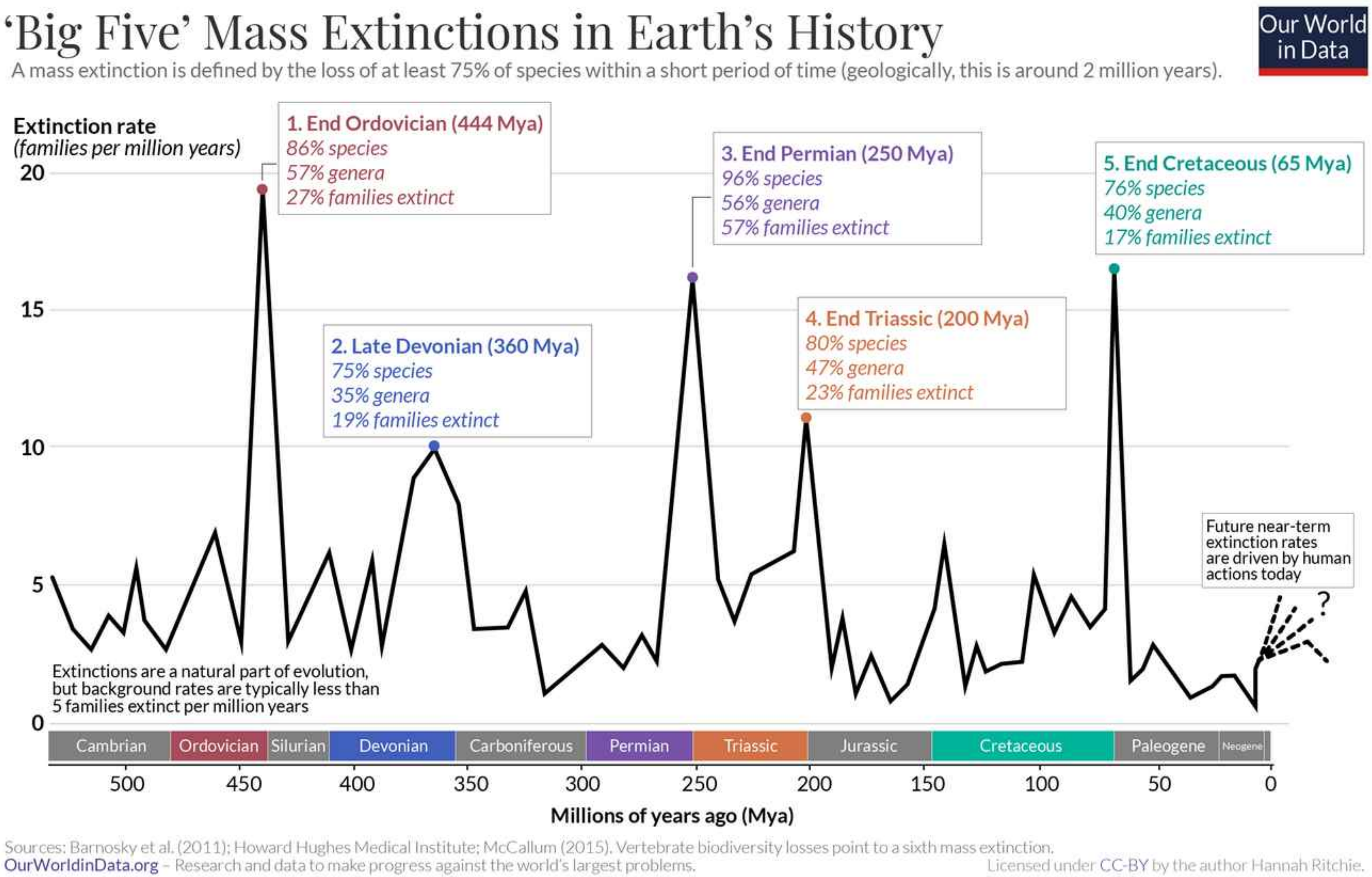
Human Influence

Planetary Boundaries



Helene Karlsson, Stockholm University

Human Influence



IPCC

Intergovernmental Panel on Climate Change

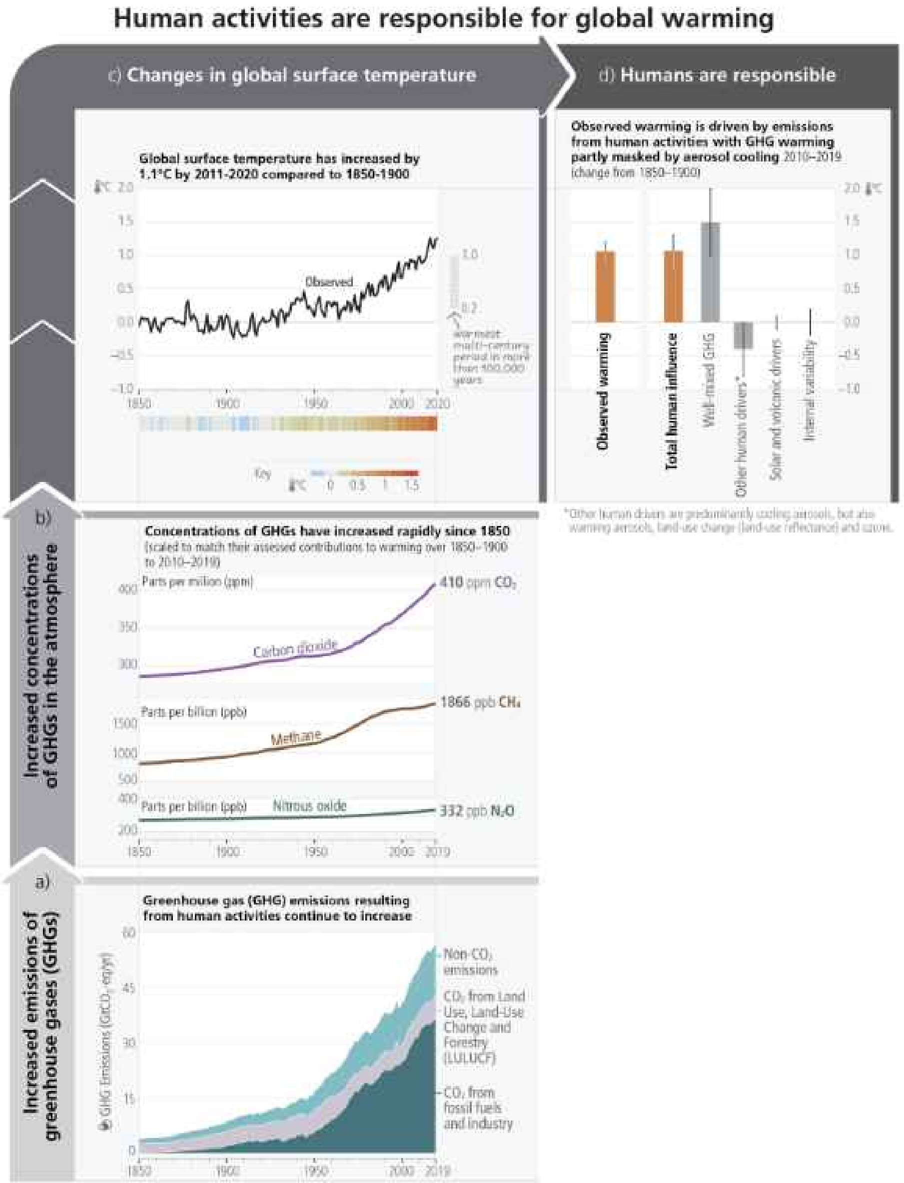
IPCC

Projections based on
Representative Concentration Pathways (RCP)

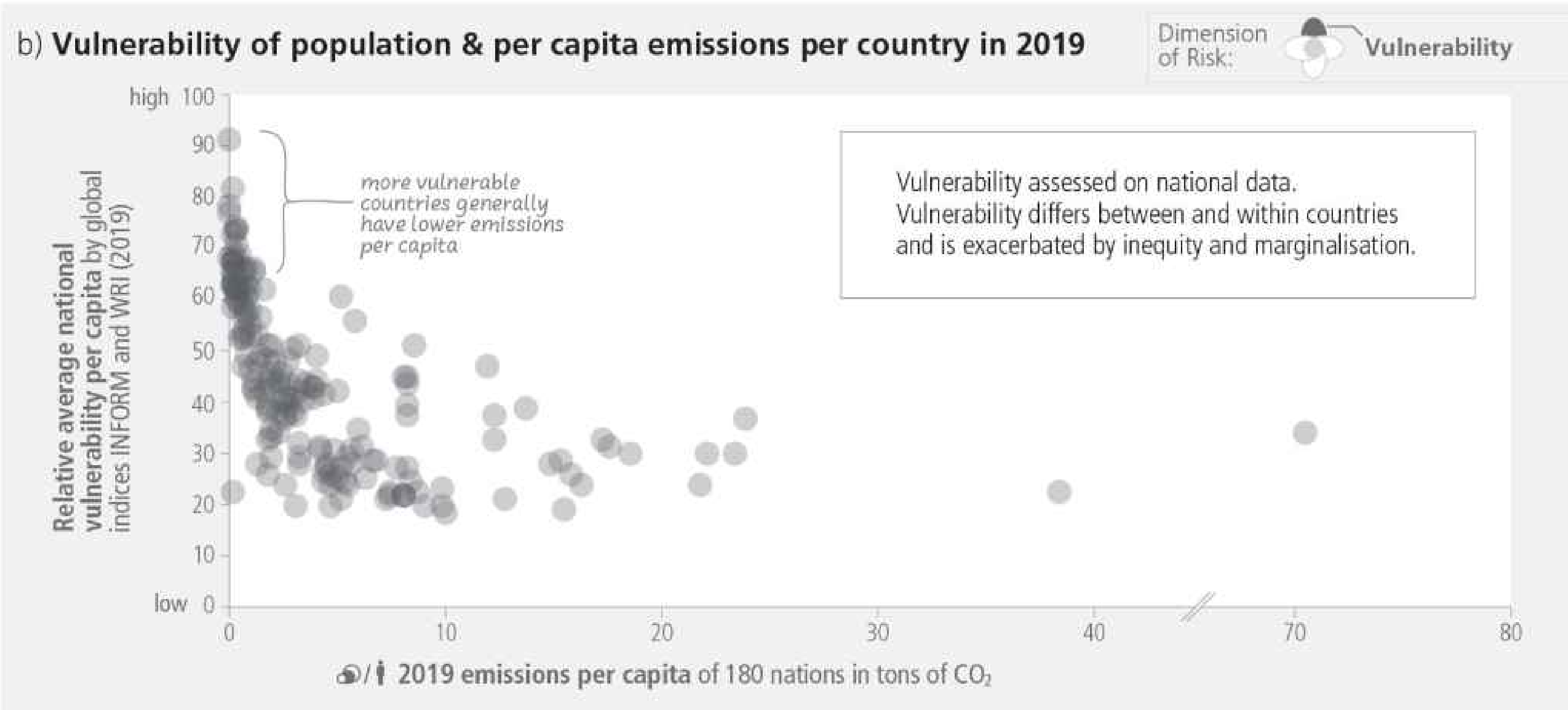
- RCPX has climate forcing of X W/m^2 in 2100
- does not consider feedbacks on emissions

- 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

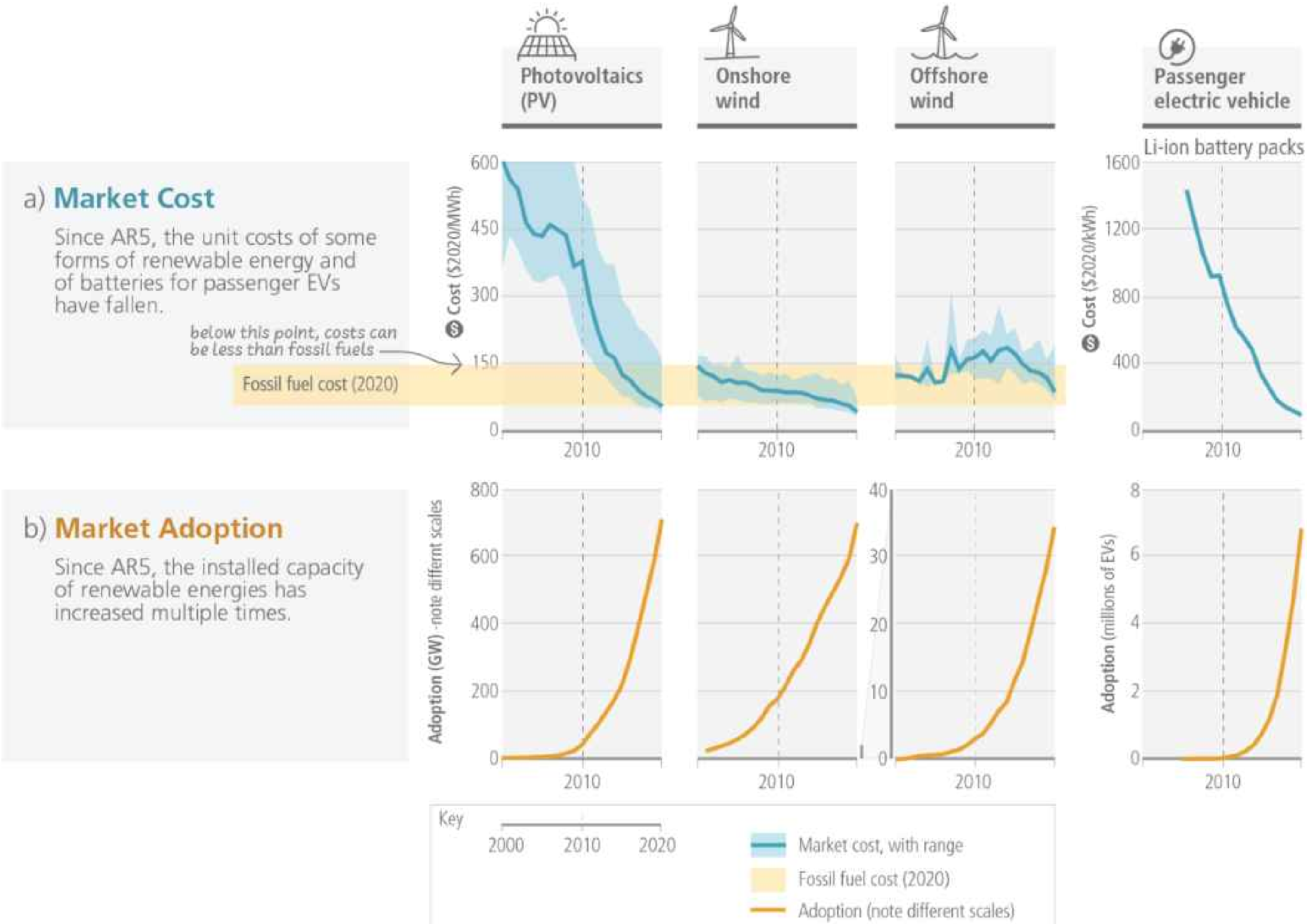

Human activities are responsible for global warming
c) Changes in global surface temperature
d) Humans are responsible
Global surface temperature has increased by 1.1°C by 2011-2020 compared to 1850-1900
Observed
Observed warming is driven by emissions from human activities with GHG warming partly masked by aerosol cooling 2010–2019 (change from 1850–1900)
Observed warming
Total human influence
Well-mixed GHG
Other human drivers*
Solar and volcanic drivers
Internal variability
*Other human drivers are predominantly cooling aerosols, but also warming aerosols, land-use change (land-use reflectance) and ozone.
b)
Increased concentrations of GHGs in the atmosphere
Concentrations of GHGs have increased rapidly since 1850
Parts per million (ppm)
Carbon dioxide
410 ppm CO2
Parts per billion (ppb)
Methane
1866 ppb CH4
Nitrous oxide
332 ppb N2O
a)
Increased emissions of greenhouse gases (GHGs)
Greenhouse gas (GHG) emissions resulting from human activities continue to increase
Non-CO2 emissions
CO2 from Land Use, Land-Use Change and Forestry (LULUCF)
CO2 from fossil fuels and industry

IPCC AR6



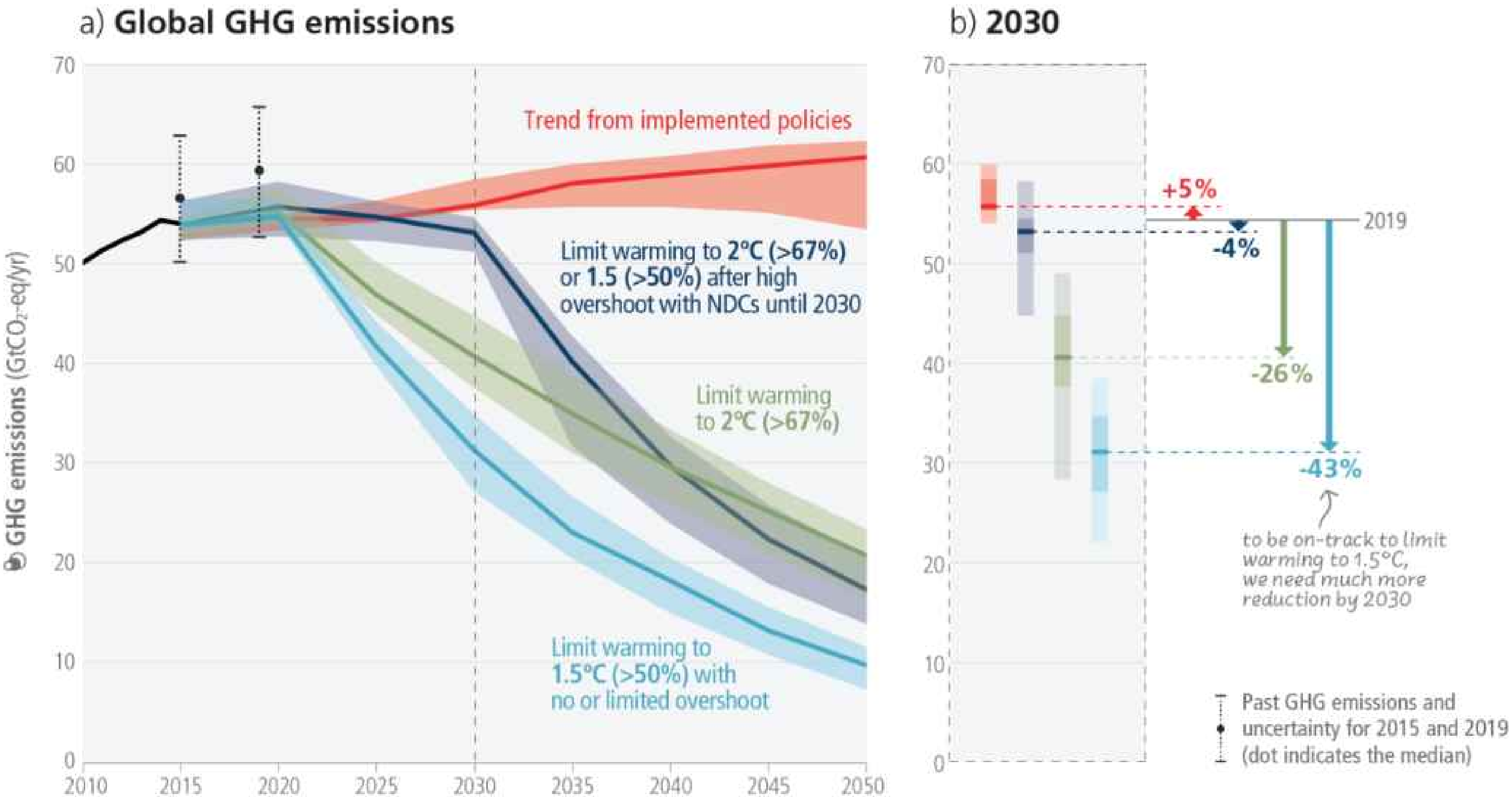
b) Vulnerability of population & per capita emissions per country in 2019
Dimension of Risk:
Vulnerability
high
low
100
90
80
70
60
50
40
30
20
10
0
Relative average national vulnerability per capita by global indices INFORM and WRI (2019)
more vulnerable countries generally have lower emissions per capita
Vulnerability assessed on national data.
Vulnerability differs between and within countries and is exacerbated by inequity and marginalisation.
0
10
20
30
40
70
80
2019 emissions per capita of 180 nations in tons of CO_2

IPCC AR6



Photovoltaics (PV)
Onshore wind
Offshore wind
Passenger electric vehicle
Li-ion battery packs
a) Market Cost
Since AR5, the unit costs of some forms of renewable energy and of batteries for passenger EVs have fallen.
below this point, costs can be less than fossil fuels
Fossil fuel cost (2020)
Cost ($2020/MWh)
Cost ($2020/kWh)
600
450
300
150
0
1600
1200
800
400
2010
b) Market Adoption
Since AR5, the installed capacity of renewable energies has increased multiple times.
Adoption (GW) -note different scales
Adoption (millions of EVs)
800
600
400
200
40
30
20
10
8
6
4
2
Key
2000
2010
2020
Market cost, with range
Fossil fuel cost (2020)
Adoption (note different scales)

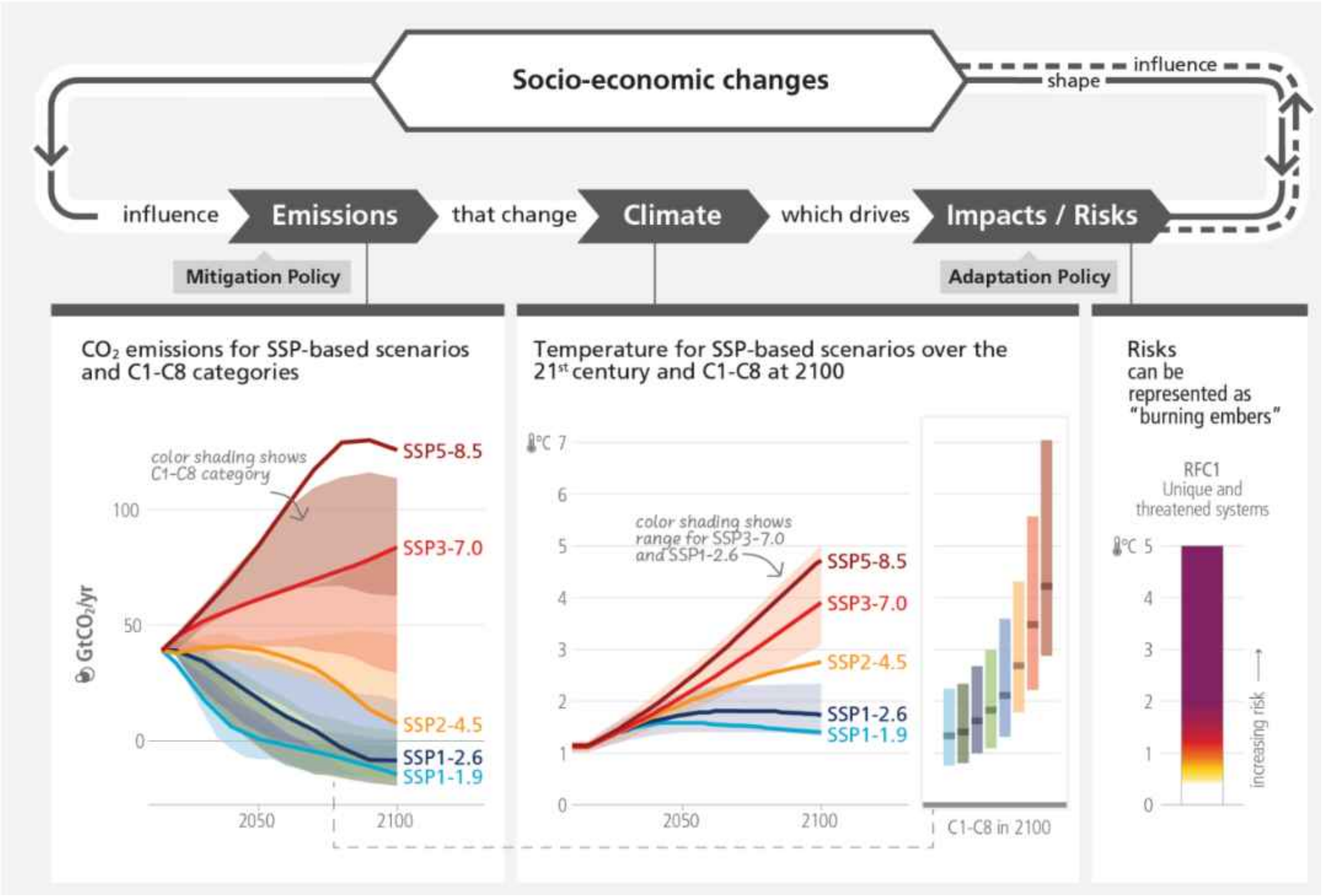
IPCC AR6



a) Global GHG emissions
b) 2030
GHG emissions ($GtCO_2$-eq/yr)
70
60
50
40
30
20
10
0
2010
2015
2020
2025
2030
2035
2040
2045
2050
Trend from implemented policies
Limit warming to 2°C (>67%) or 1.5 (>50%) after high overshoot with NDCs until 2030
Limit warming to 2°C (>67%)
Limit warming to 1.5°C (>50%) with no or limited overshoot
+5%
2019
-4%
-26%
-43%
to be on-track to limit warming to 1.5°C, we need much more reduction by 2030
Past GHG emissions and uncertainty for 2015 and 2019 (dot indicates the median)

IPCC AR6

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



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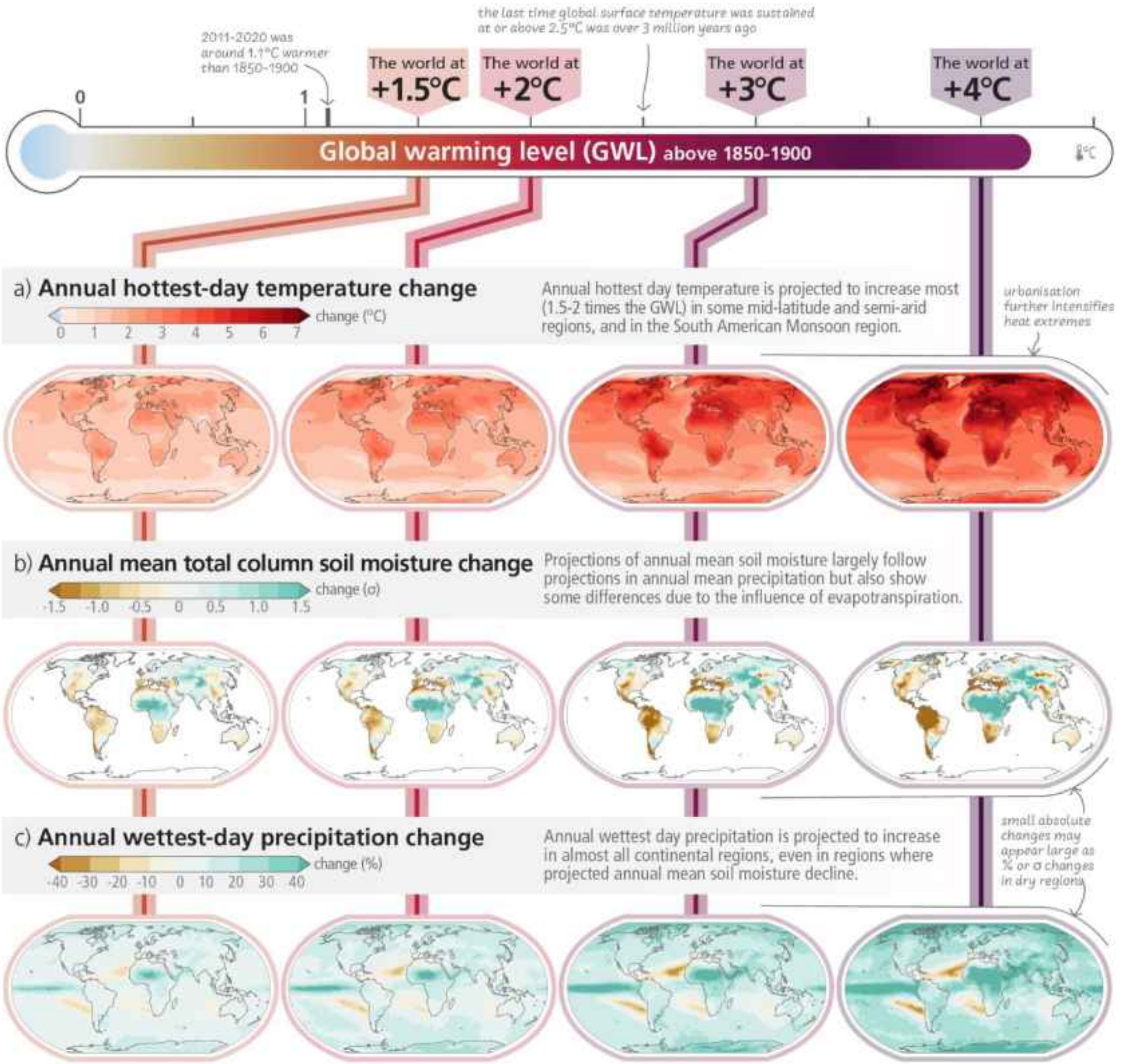

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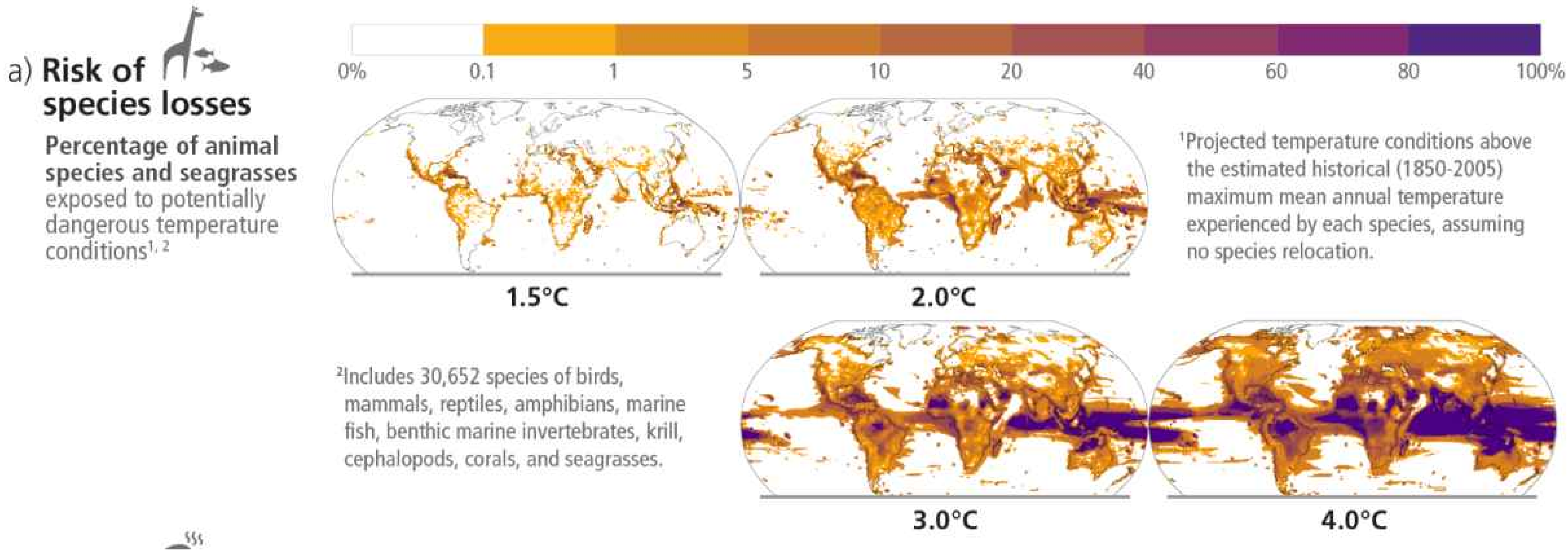
Examples of impacts without additional adaptation



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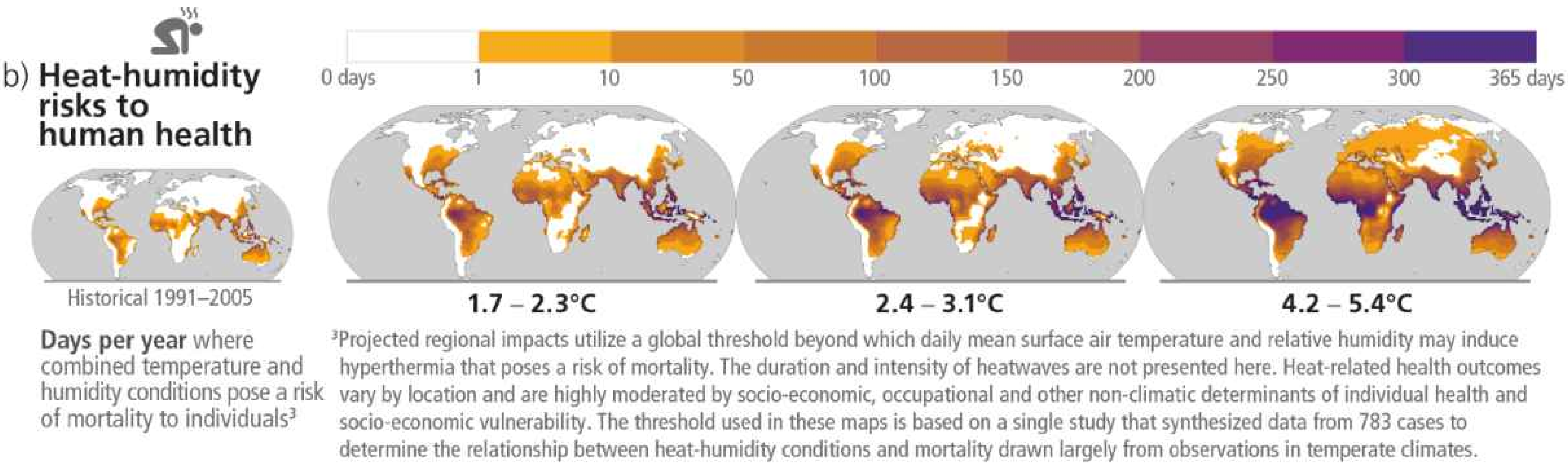
b) Heat-humidity risks to human health
0 days
1
10
50
100
150
200
250
300
365 days
Historical 1991–2005
1.7 – 2.3°C
2.4 – 3.1°C
4.2 – 5.4°C
Days per year where combined temperature and humidity conditions pose a risk of mortality to individuals[3]
[3]Projected regional impacts utilize a global threshold beyond which daily mean surface air temperature and relative humidity may induce hyperthermia that poses a risk of mortality. The duration and intensity of heatwaves are not presented here. Heat-related health outcomes vary by location and are highly moderated by socio-economic, occupational and other non-climatic determinants of individual health and socio-economic vulnerability. The threshold used in these maps is based on a single study that synthesized data from 783 cases to determine the relationship between heat-humidity conditions and mortality drawn largely from observations in temperate climates.

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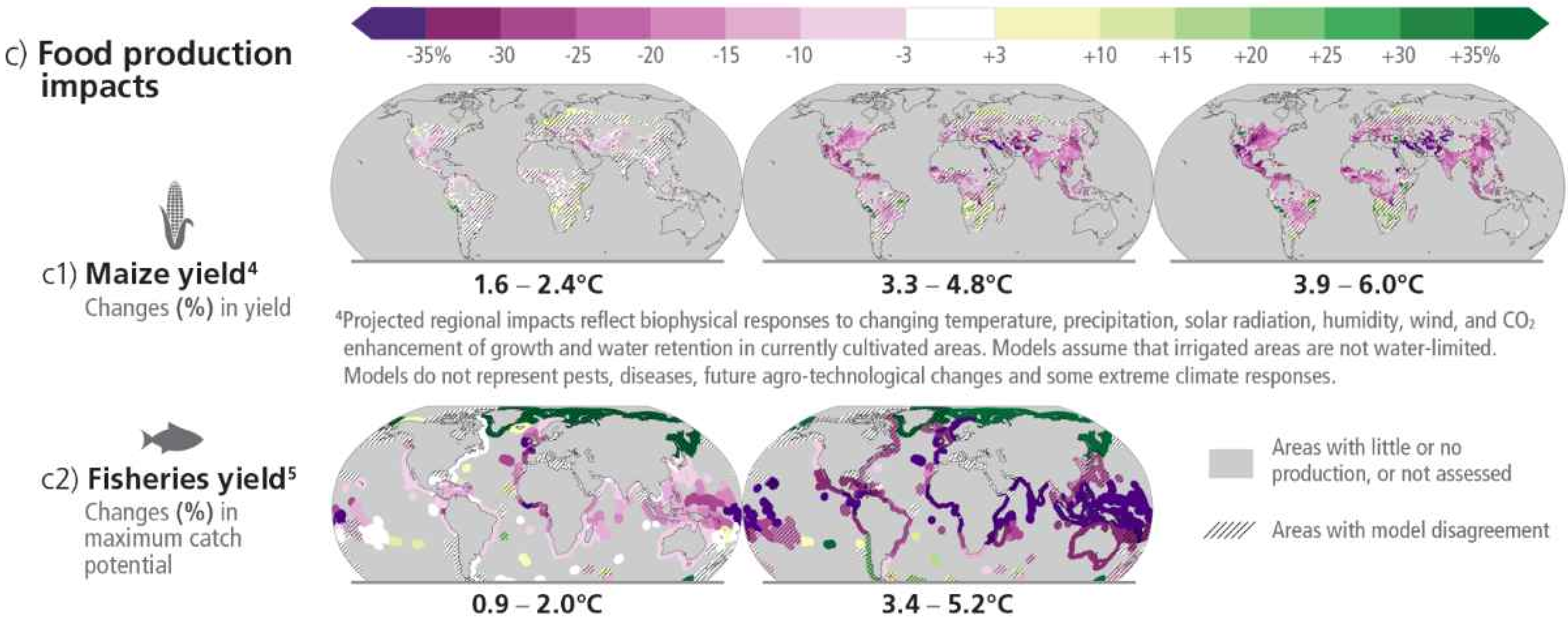

c) Food production impacts
-35%
-30
-25
-20
-15
-10
-3
+3
+10
+15
+20
+25
+30
+35%
c1) Maize yield[4]
Changes (%) in yield
1.6 – 2.4°C
3.3 – 4.8°C
3.9 – 6.0°C
[4]Projected regional impacts reflect biophysical responses to changing temperature, precipitation, solar radiation, humidity, wind, and CO_2 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 yield[5]
Changes (%) in maximum catch potential
0.9 – 2.0°C
3.4 – 5.2°C
Areas with little or no production, or not assessed
Areas with model disagreement

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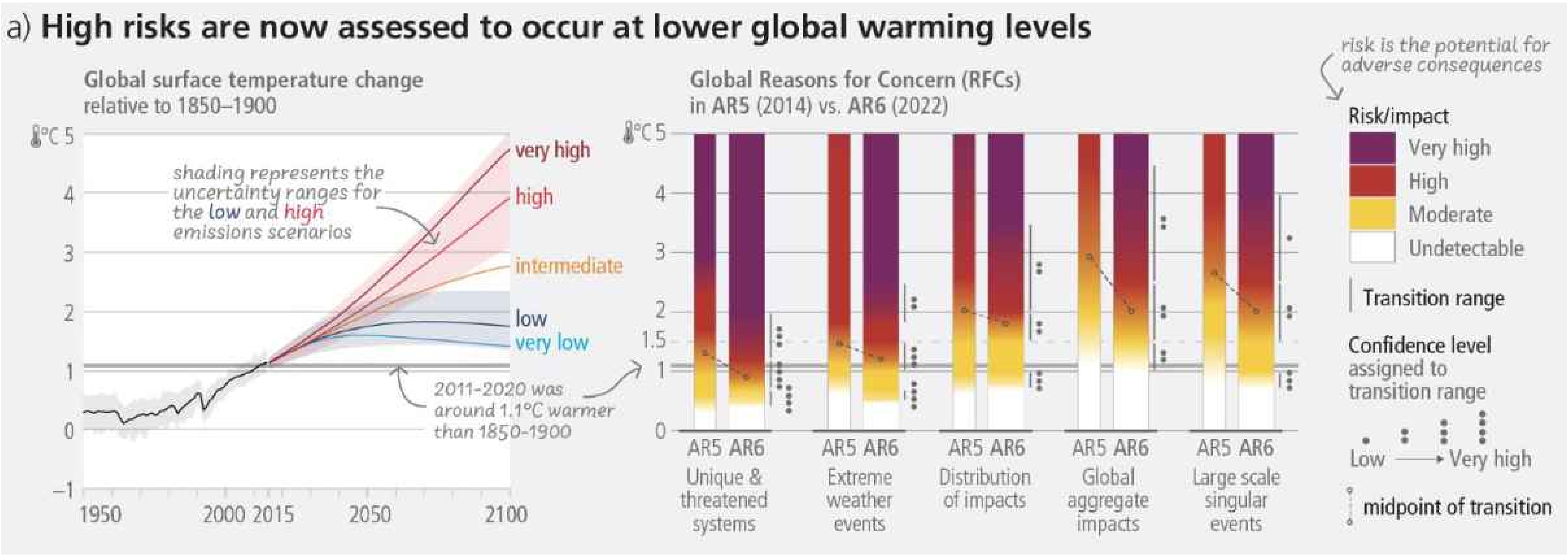
a) High risks are now assessed to occur at lower global warming levels
Global surface temperature change relative to 1850–1900
°C 5
4
3
2
1
0
−1
1950
2000 2015
2050
2100
shading represents the uncertainty ranges for the low and high emissions scenarios
very high
high
intermediate
low
very low
2011-2020 was around 1.1°C warmer than 1850-1900
Global Reasons for Concern (RFCs) in AR5 (2014) vs. AR6 (2022)
1.5
AR5 AR6
Unique & threatened systems
Extreme weather events
Distribution of impacts
Global aggregate impacts
Large scale singular events
risk is the potential for adverse consequences
Risk/impact
Very high
High
Moderate
Undetectable
Transition range
Confidence level assigned to transition range
Low
Very high
midpoint of transition

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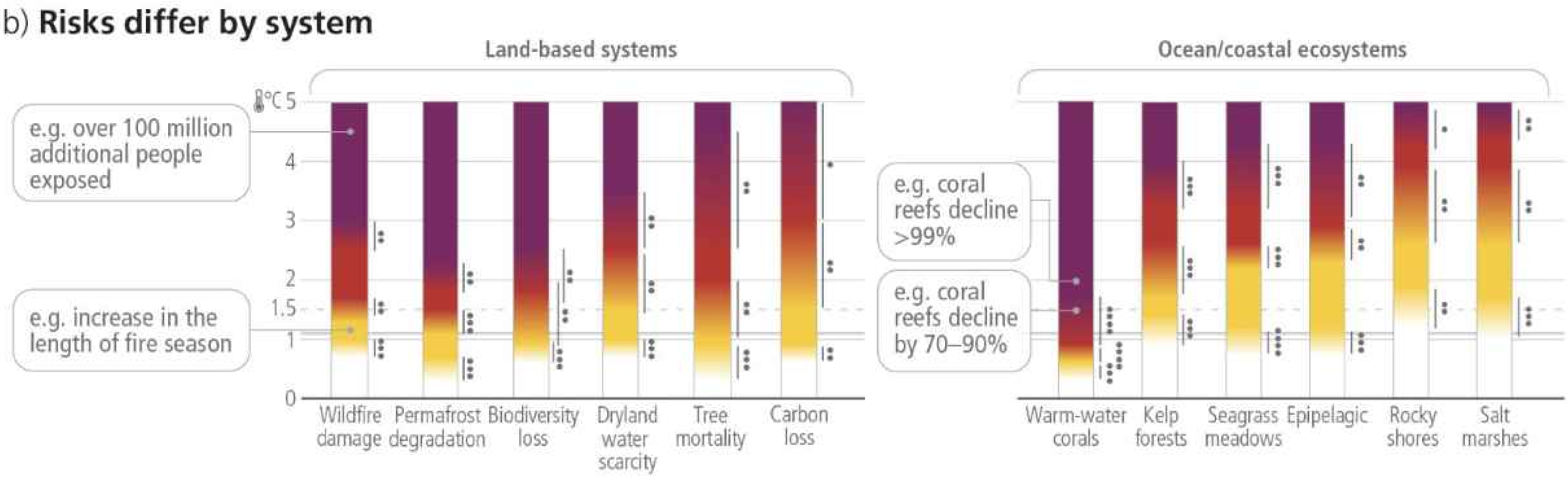
b) Risks differ by system
Land-based systems
Ocean/coastal ecosystems
°C 5
4
3
2
1.5
1
0
e.g. over 100 million additional people exposed
e.g. increase in the length of fire season
e.g. coral reefs decline >99%
e.g. coral reefs decline by 70–90%
Wildfire damage
Permafrost degradation
Biodiversity loss
Dryland water scarcity
Tree mortality
Carbon loss
Warm-water corals
Kelp forests
Seagrass meadows
Epipelagic
Rocky shores
Salt marshes

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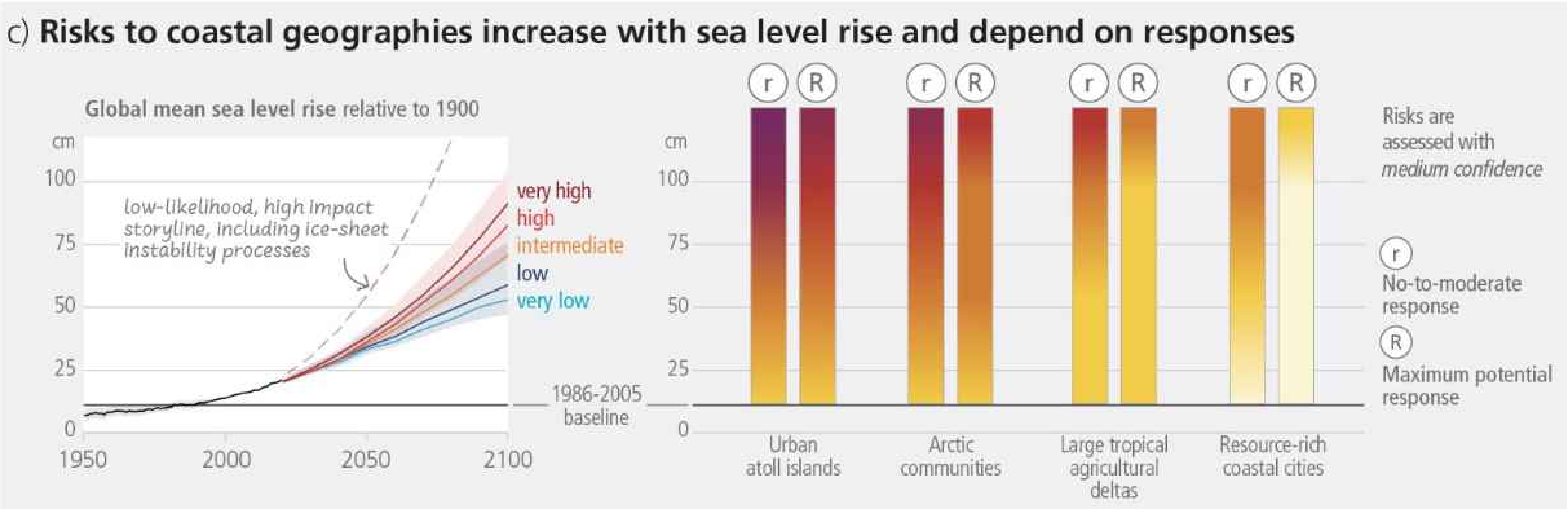
c) Risks to coastal geographies increase with sea level rise and depend on responses
Global mean sea level rise relative to 1900
cm
100
75
50
25
0
1950
2000
2050
2100
low-likelihood, high impact storyline, including ice-sheet instability processes
very high
high
intermediate
low
very low
1986-2005 baseline
r
R
Urban atoll islands
Arctic communities
Large tropical agricultural deltas
Resource-rich coastal cities
Risks are assessed with *medium confidence*
r No-to-moderate response
R Maximum potential response

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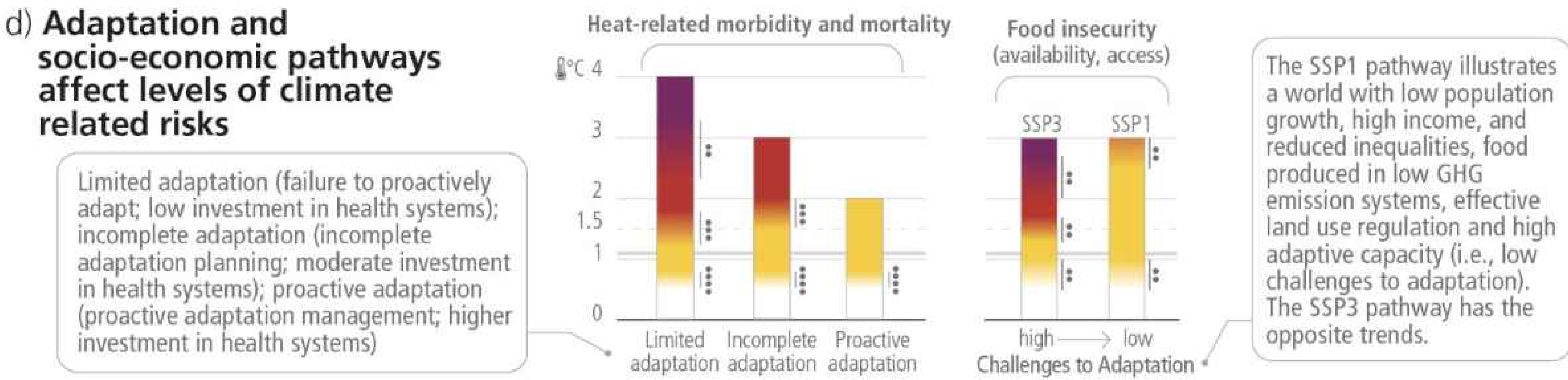

d) Adaptation and socio-economic pathways affect levels of climate related risks
Limited adaptation (failure to proactively adapt; low investment in health systems); incomplete adaptation (incomplete adaptation planning; moderate investment in health systems); proactive adaptation (proactive adaptation management; higher investment in health systems)
Heat-related morbidity and mortality
°C 4
3
2
1.5
1
0
Limited adaptation
Incomplete adaptation
Proactive adaptation
Food insecurity (availability, access)
SSP3
SSP1
high → low
Challenges to Adaptation
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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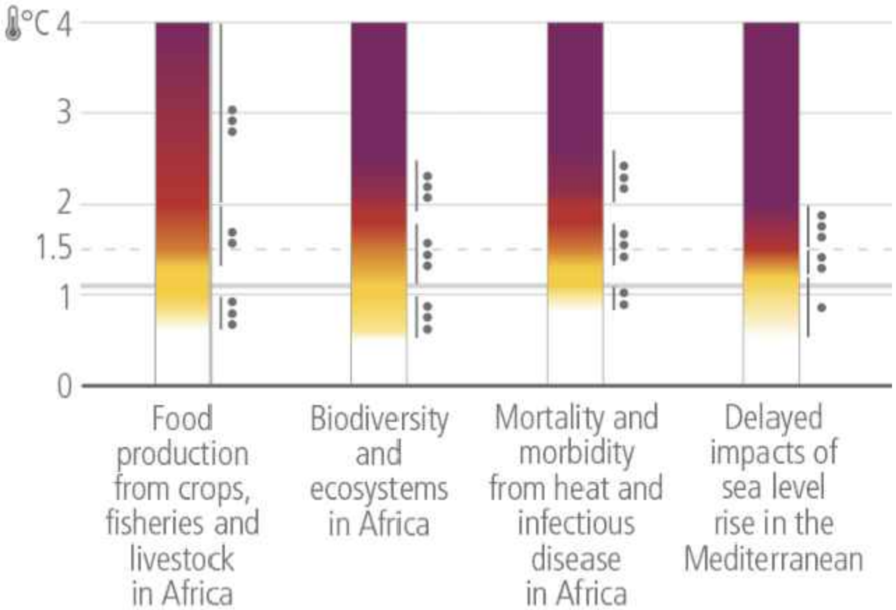
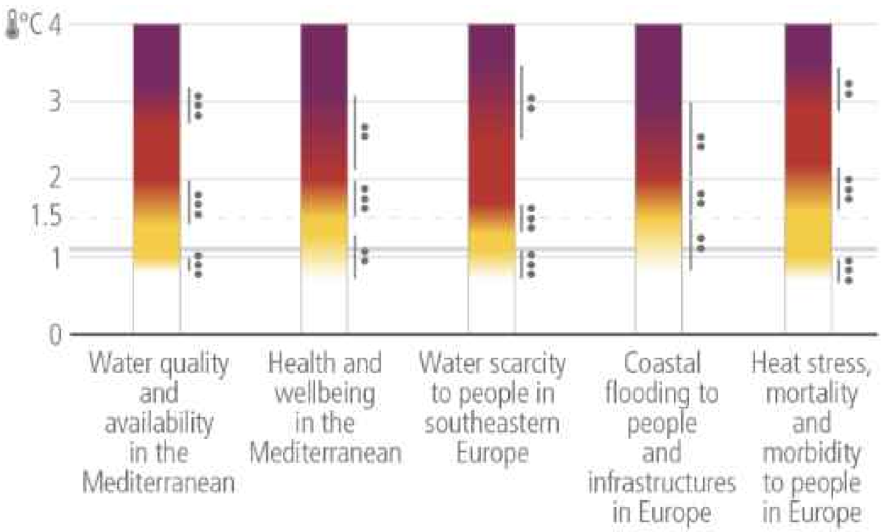
example risks





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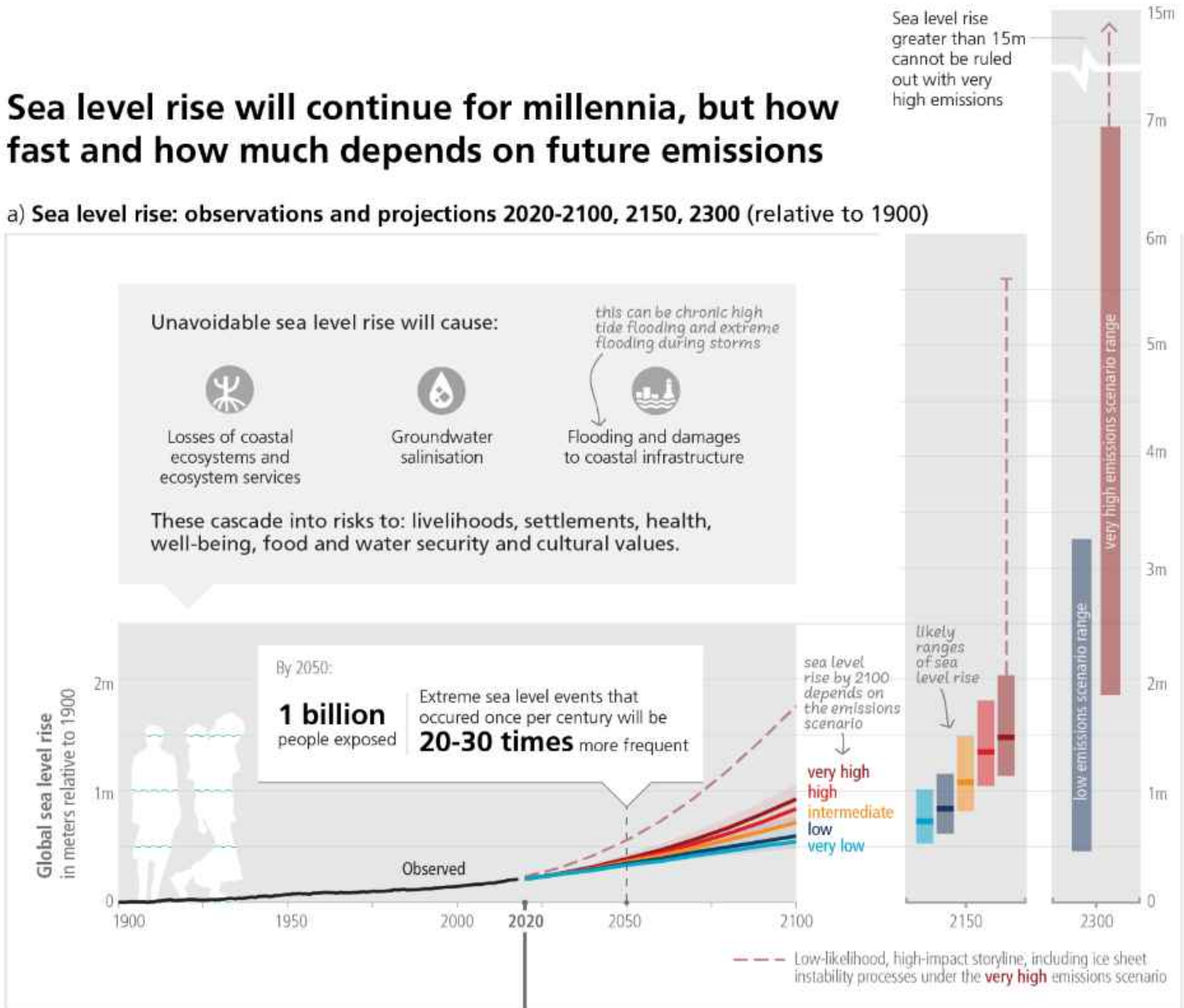

Sea level rise will continue for millennia, but how fast and how much depends on future emissions
a) Sea level rise: observations and projections 2020-2100, 2150, 2300 (relative to 1900)
Unavoidable sea level rise will cause:
this can be chronic high tide flooding and extreme flooding during storms
Losses of coastal ecosystems and ecosystem services
Groundwater salinisation
Flooding and damages to coastal infrastructure
These cascade into risks to: livelihoods, settlements, health, well-being, food and water security and cultural values.
By 2050:
1 billion people exposed
Extreme sea level events that occured once per century will be 20-30 times more frequent
Observed
sea level rise by 2100 depends on the emissions scenario
very high
high
intermediate
low
very low
likely ranges of sea level rise
Sea level rise greater than 15m cannot be ruled out with very high emissions
very high emissions scenario range
low emissions scenario range
Global sea level rise in meters relative to 1900
Low-likelihood, high-impact storyline, including ice sheet instability processes under the very high emissions scenario

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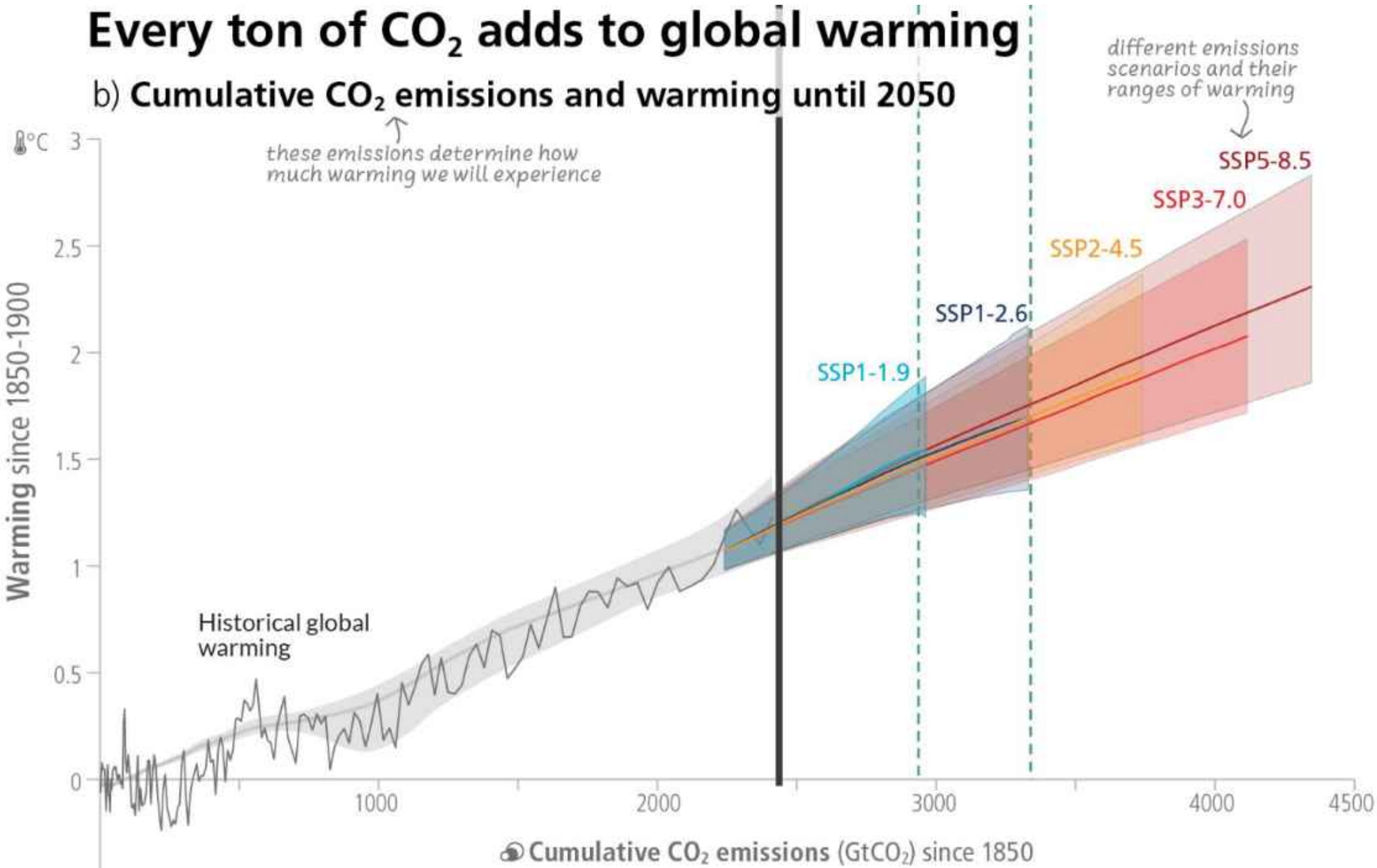

Every ton of CO_2 adds to global warming
b) Cumulative CO_2 emissions and warming until 2050
these emissions determine how much warming we will experience
different emissions scenarios and their ranges of warming
°C
Warming since 1850-1900
3
2.5
2
1.5
1
0.5
0
1000
2000
3000
4000
4500
SSP5-8.5
SSP3-7.0
SSP2-4.5
SSP1-2.6
SSP1-1.9
Historical global warming
Cumulative CO_2 emissions ($GtCO_2$) since 1850

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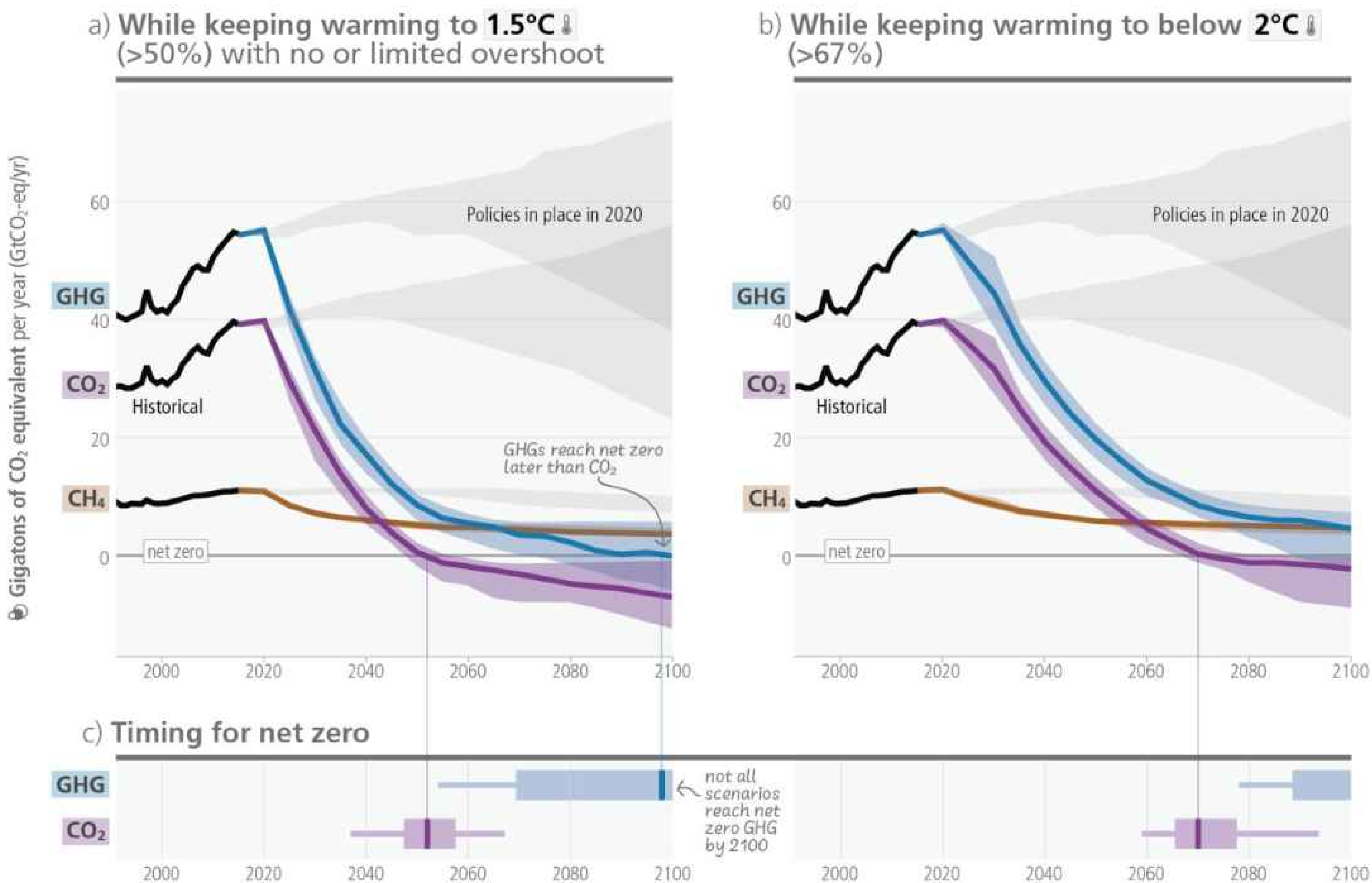

a) While keeping warming to 1.5°C (>50%) with no or limited overshoot
b) While keeping warming to below 2°C (>67%)
Gigatons of CO_2 equivalent per year ($GtCO_2$-eq/yr)
60
40
20
0
GHG
CO_2
CH_4
Historical
Policies in place in 2020
net zero
GHGs reach net zero later than CO_2
2000
2020
2040
2060
2080
2100
c) Timing for net zero
not all scenarios reach net zero GHG by 2100

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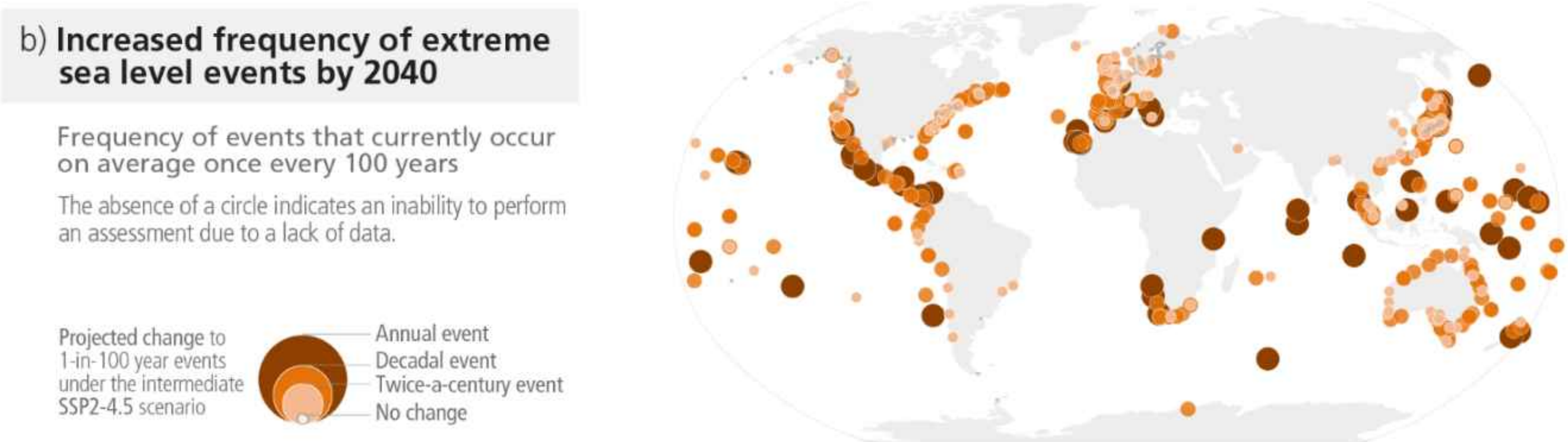
b) Increased frequency of extreme sea level events by 2040
Frequency of events that currently occur on average once every 100 years
The absence of a circle indicates an inability to perform an assessment due to a lack of data.
Projected change to 1-in-100 year events under the intermediate SSP2-4.5 scenario
Annual event
Decadal event
Twice-a-century event
No change

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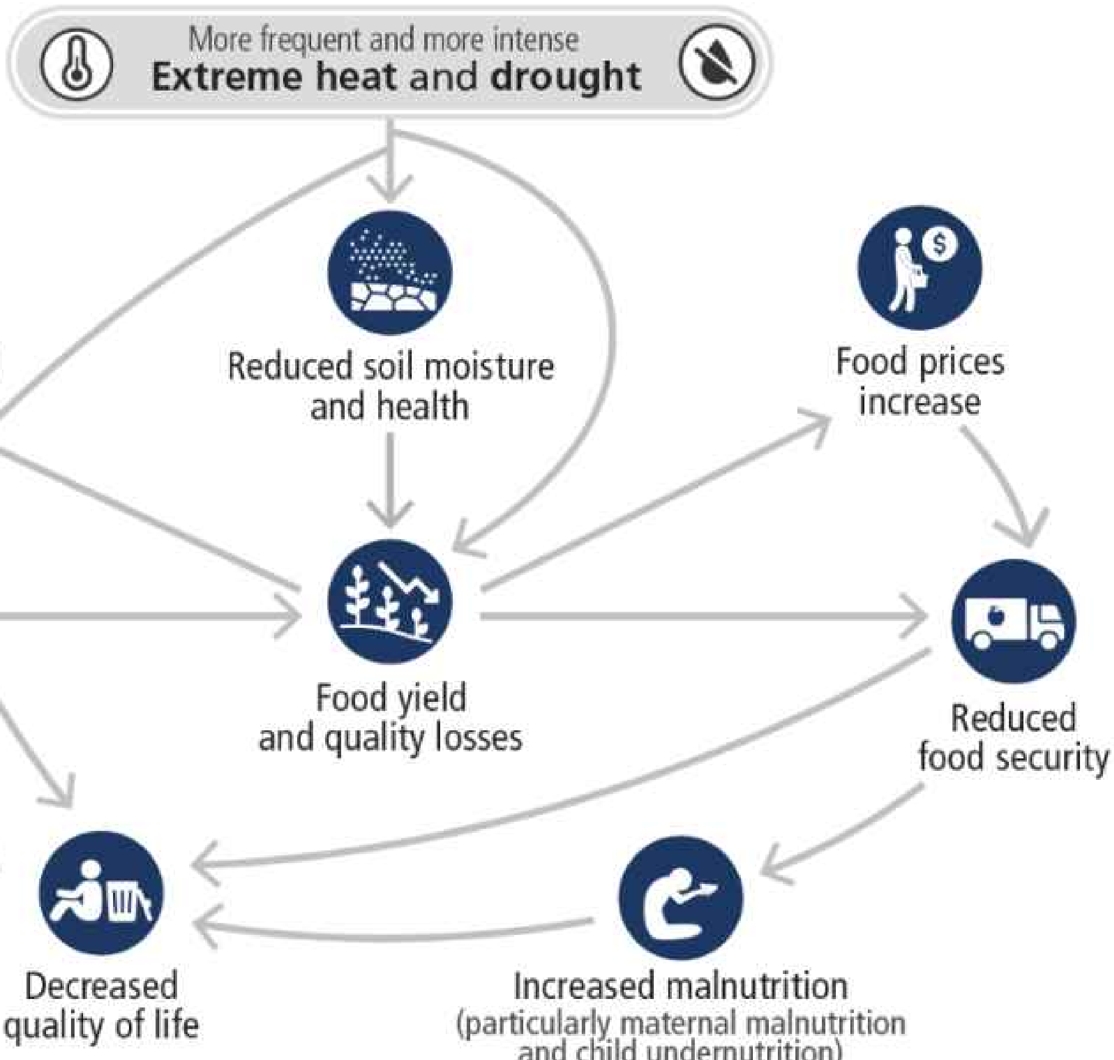
example for
complex risk



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

Further Literature

- Princeton Primers in Climate series
  - Paleoclimate (Michael L. Bender, 2013)
    Princeton University Press

- Introduction to Climate Science
  Open Textbook by Andreas Schmittner, 2019
  (https://open.oregonstate.education/climatechange)

- IPCC (Sixth Assessment Report, 2021)
  (https://www.ipcc.ch)

- ourworldindata.org
- carbonbrief.org
- PC game “Fate of the World”

Conclusions?