ETH zürich
Institute for Atmospheric
and Climate Sciences

MPE-CDT
Virtual Summer School
Trend Attribution 1

Sebastian Sippel

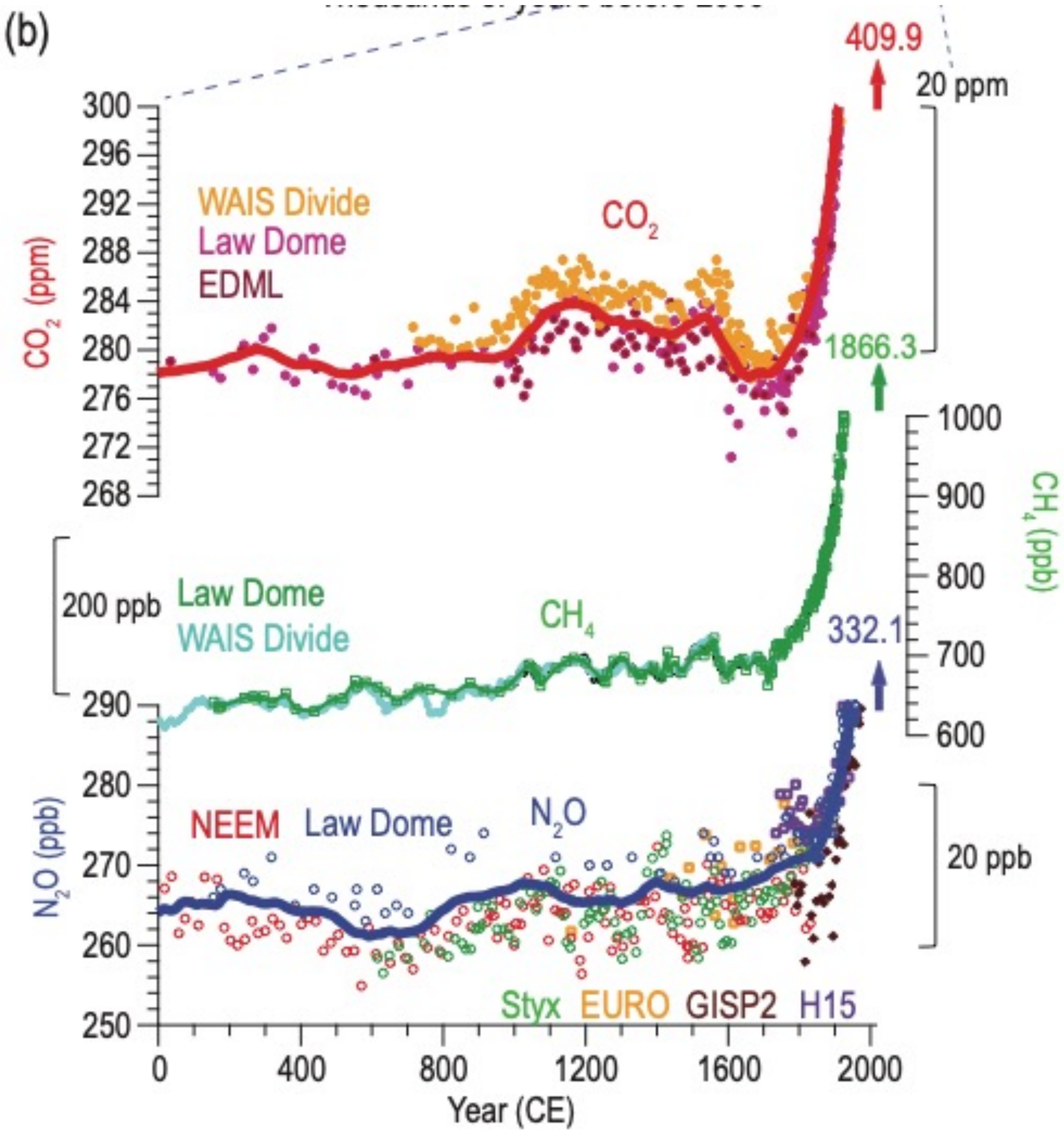
A few notes on this lecture

- Idea is to provide an introduction into key concepts of trend detection and attribution.
- Mostly based on key literature in the field (will be provided afterwards).
- Please ask questions - let's try to make this interactive!
- Caveat 1: Two hours is short – so need to see how far we get. But will also make available links to more in-depth talks related to the topics in case we can't cover everything.
- Caveat 2: As there is broad variety in background of students the focus is on concepts (and tried to strike a reasonable balance) – there will be very little actual math or statistics (so the hope is that based on these lectures you'll be able to dig deeper into specifics).

Topics:

1. Introduction [20 min]
   (1) Large-scale changes in the Earth system and IPCC statements
   (2) The issue of cause and effect (and why correlation is *not* attribution)
   (3) Earth's energy budget and imbalance
2. Forced Signal vs. internal variability [20 min]
3. Concepts and logic of detection & attribution [15 min]
4. Traditional fingerprinting [30 min]
5. Non-standard approaches [25 min]
   (1) Dynamical adjustment: Dynamical vs. thermodynamical trends
   (2) Signal/Noise maximizing pattern filtering
   (3) Statistical and machine learning to extract the forced response

The Earth system is changing…



Well-mixed GHGs
IPCC 2021, AR6 WG1
Chapter 2

"In 2019, atmospheric CO_2 concentrations were higher than at any time in at least 2 million years (high confidence), and concentrations of CH_4 and N_2O were higher than at any time in at least 800,000 years (very high confidence)." IPCC AR6 WG1 SPM

The Earth system is changing…

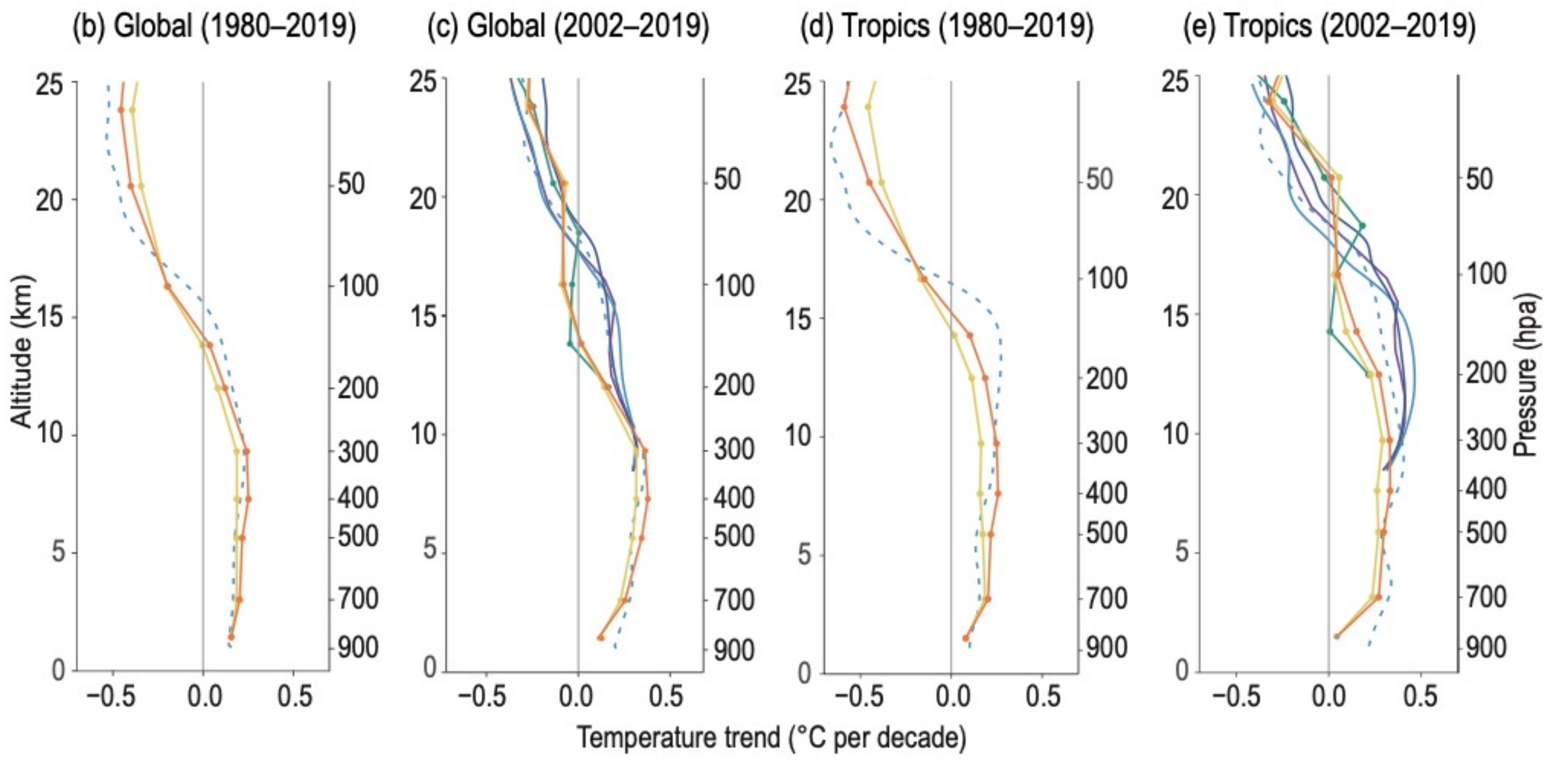
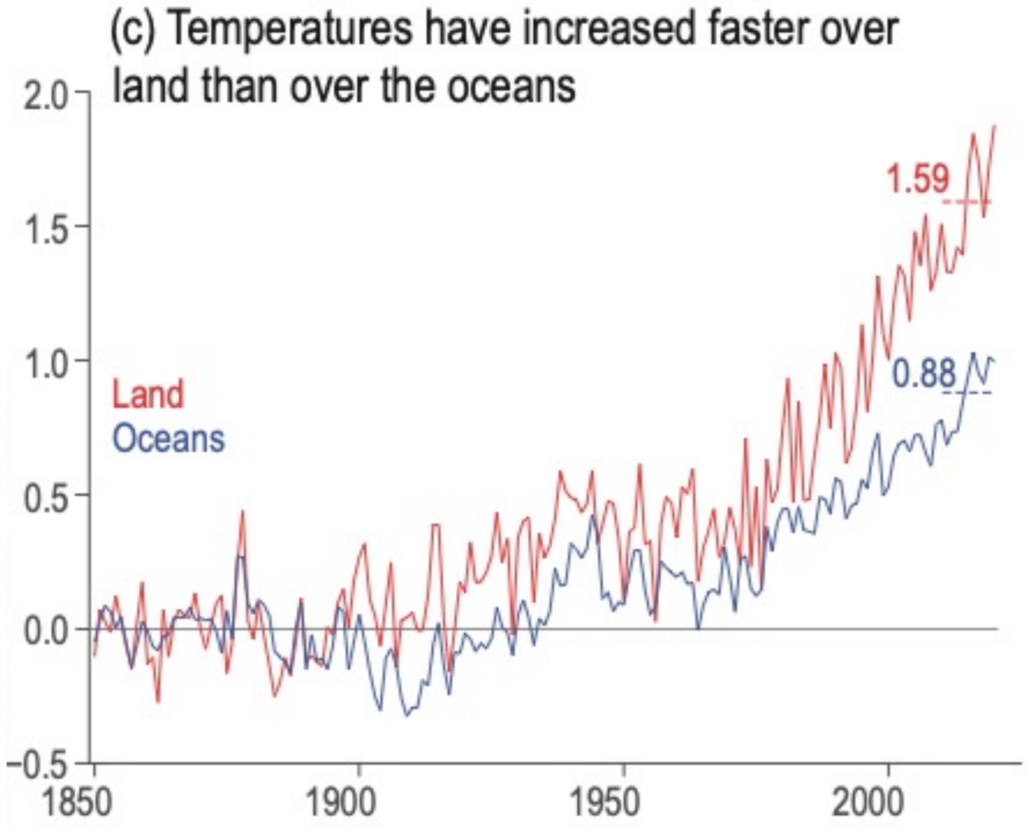


Figure 2.12 | Temperature trends in the upper air. (a) Zonal cross-section of temperature anomaly trends (2007–2016 baseline) for 2002–2019 in the upper troposphere and lower stratosphere region. The climatological tropopause altitude is marked by a grey line. Significance is not indicated due to the short period over which trends are shown, and because the assessment findings associated to this figure relate to difference between trends at different heights, not the absolute trends. **(b, c)** Trends in temperature at various atmospheric heights for 1980–2019 and 2002–2019 for the near-global (70°N–70°S) domain. **(d, e)** as for (b, c) but for the tropical (20°N–20°S) region. Further details on data sources and processing are available in the chapter data table (Table 2.SM.1).

Temperature trends: Warming at the surface and throughout the troposphere, cooling in the stratosphere

IPCC 2021, AR6 WG1 Chapter 2

The Earth system is changing…



Temperature trends:
Warming over land exceeds the warming of the ocean surface.

IPCC 2021, AR6 WG1 Chapter 2

The Earth system is changing…

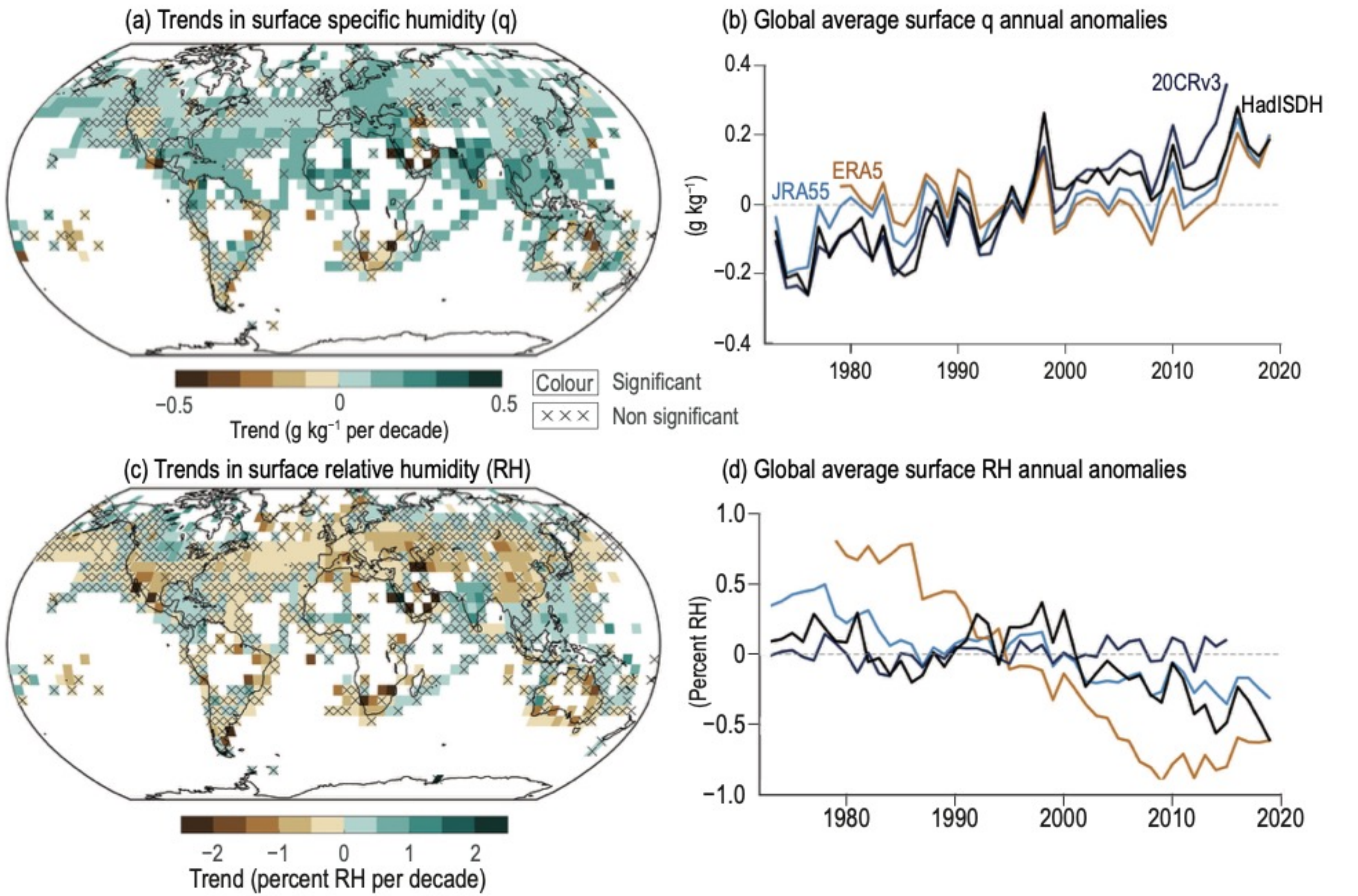
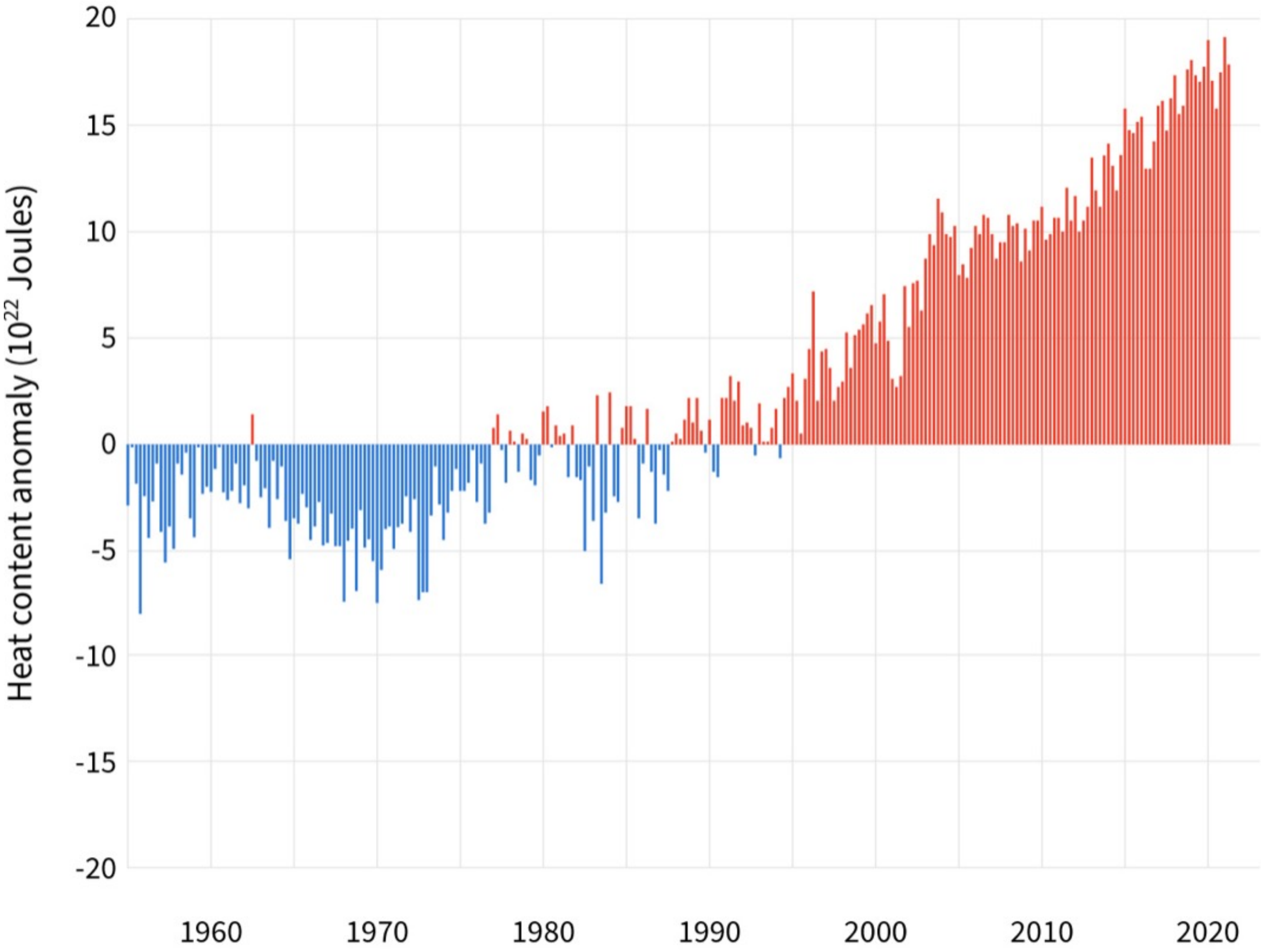


Figure 2.13 | Changes in surface humidity. (a) Trends in surface specific humidity over 1973–2019. Trends are calculated using OLS regression with significance assessed following AR(1) adjustment after Santer et al. (2008); '×' marks denote non-significant trends). **(b)** Global average surface specific humidity annual anomalies (1981–2010 base period). **(c)** as (a) but for the relative humidity. **(d)** as (b) but for the global average surface relative humidity annual anomalies. Further details on data sources and processing are available in the chapter data table (Table 2.SM.1).

Humidity:
Increases in specific humidity, but decreases or relatively weak changes of relative humidity.

IPCC 2021, AR6 WG1 Chapter 2

The Earth system is changing…



Ocean heat content: Increases with very little variability.

NOAA climate.gov
https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content

The Earth system is changing… But what are the causes?

Some key IPCC AR6 WG1 (Chapter 3) Statements:

- “It is unequivocal that human influence has warmed the atmosphere, ocean and land since pre-industrial times.”
- “It is *likely* that human influence has contributed to observed large-scale precipitation changes since the mid-20th century."
- “Human-induced greenhouse gas forcing is the main driver of the observed changes in hot and cold extremes on the global scale (*virtually certain*) and on most continents (*very likely*).“

But how do we know *with confidence* about the causes?

Topics:

1. Introduction
   (1) Example of large-scale changes in the Earth system and IPCC statements
   (2) The issue of cause and effect (and why correlation is *not* attribution)
   (3) Earth's energy budget and imbalance
2. Forced Signal vs. internal variability
3. Concepts and logic of detection & attribution
4. Traditional fingerprinting
5. Non-standard approaches

(2) The issue of cause and effect

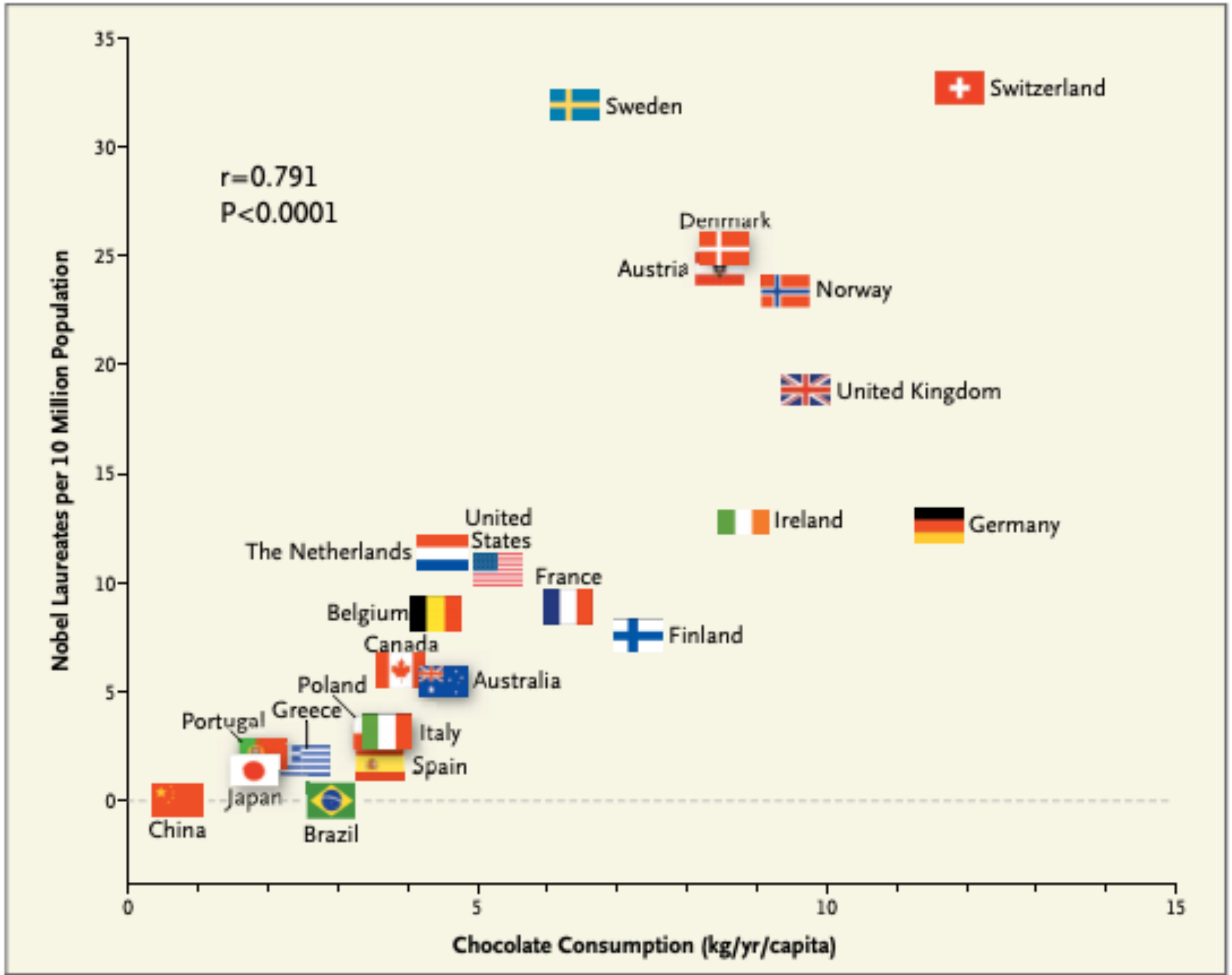


Figure 1. Correlation between Countries' Annual Per Capita Chocolate Consumption and the Number of Nobel Laureates per 10 Million Population.

The New England Journal of Medicine
DOI: 10.1056/NEJMon1211064
'Chocolate Consumption, Cognitive Function and Nobel Laureates'
Author: Franz H. Messerli, M.D.

(2) The issue of cause and effect

“it seems most likely that in a dose-dependent way, chocolate intake provides the abundant fertile ground needed for the sprouting of Nobel laureates. […]

A second hypothesis, reverse causation — that is, that enhanced cognitive performance could stimulate countrywide chocolate consumption — must also be considered.”

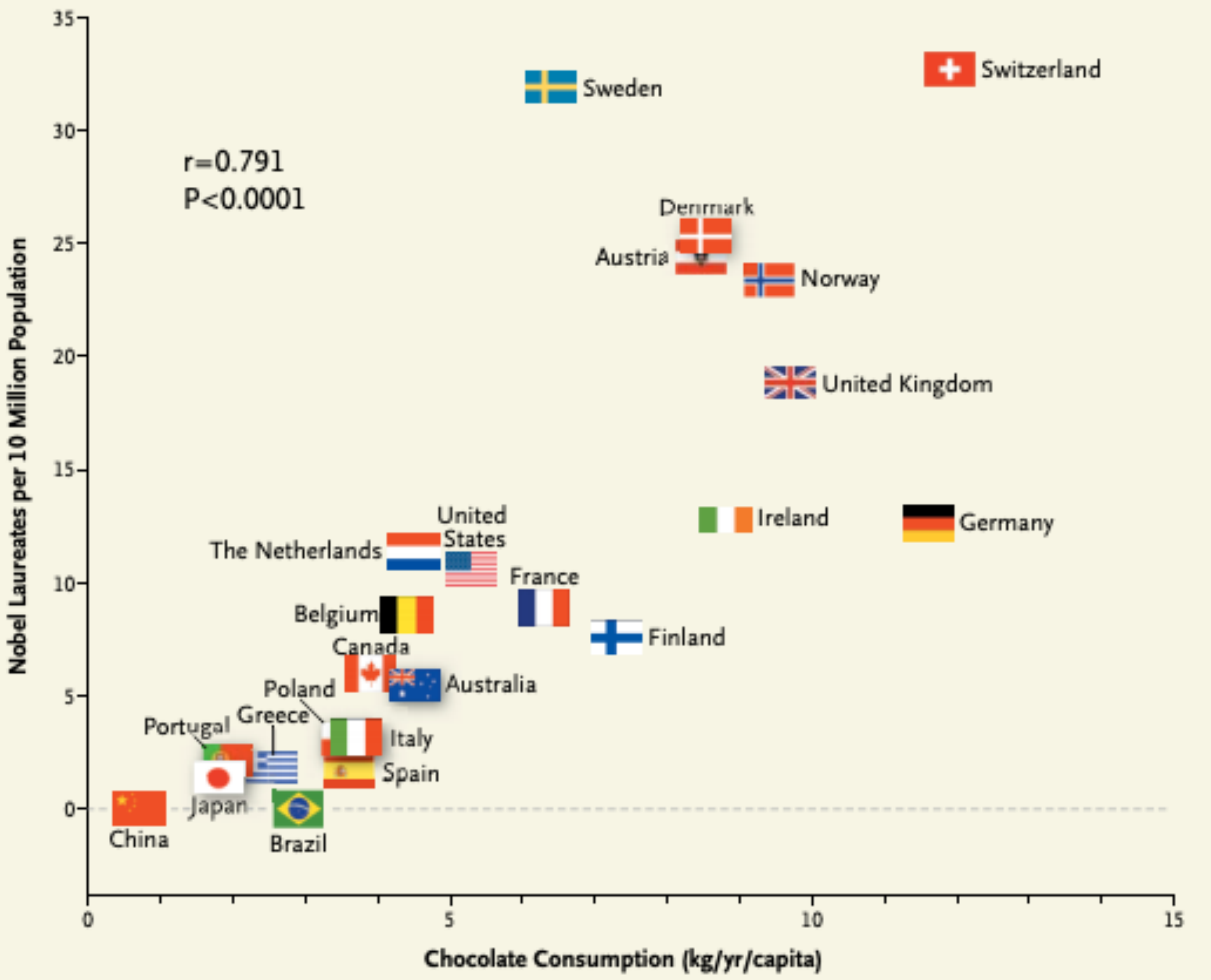
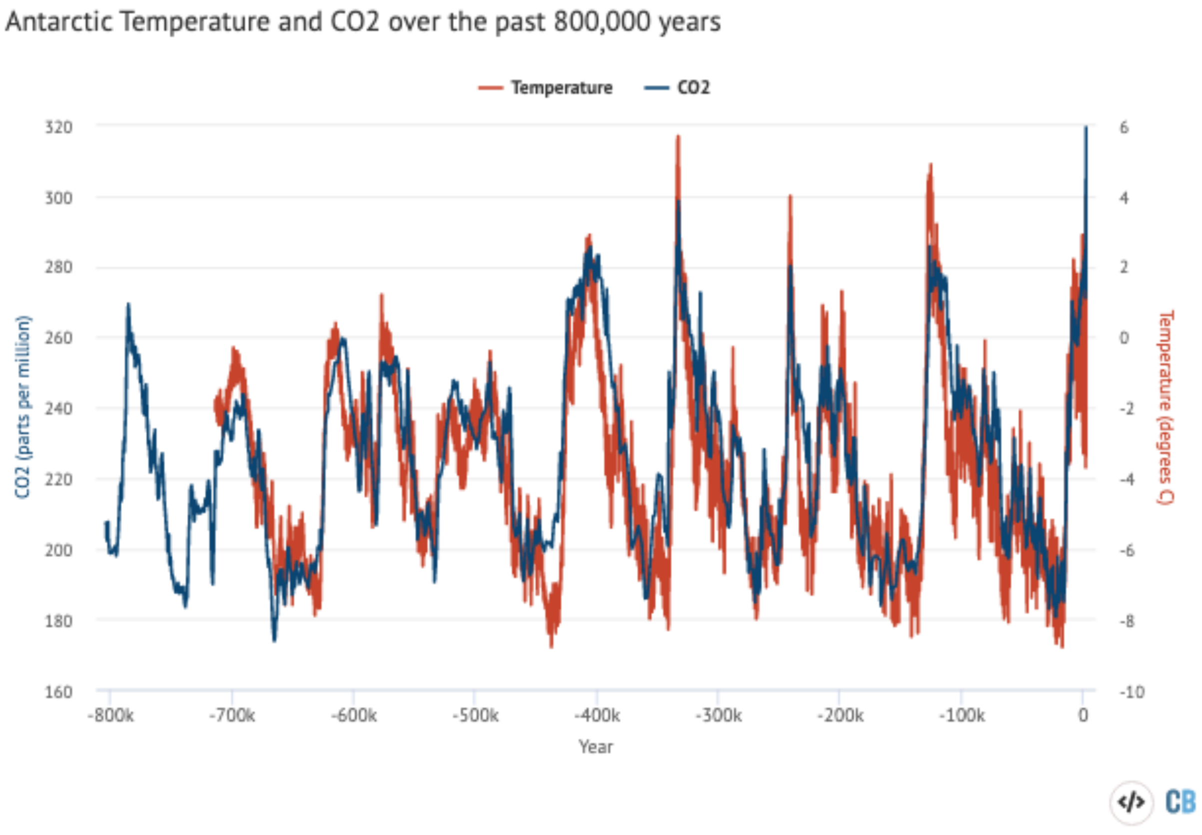


Figure 1. Correlation between Countries’ Annual Per Capita Chocolate Consumption and the Number of Nobel Laureates per 10 Million Population.

The New England Journal of Medicine
DOI: 10.1056/NEJMon1211064
‘Chocolate Consumption, Cognitive Function and Nobel Laureates’
Author: Franz H. Messerli, M.D.

ETH zürich

(2) The issue of cause and effect

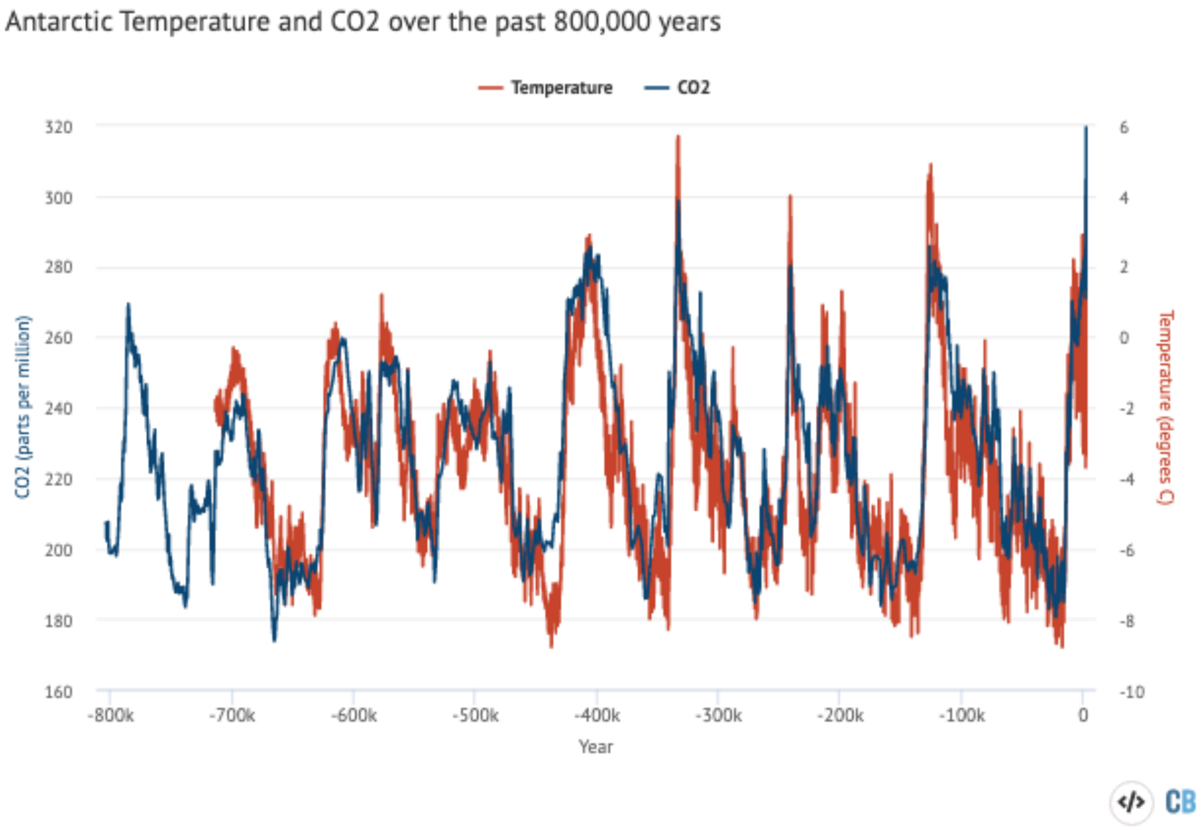


Antarctic reconstructed air temperature (red line) at Dome Fuji site Antarctica using isotope modelling from Uemura et al (2018) and Antarctic composite ice core atmospheric CO2 data (blue line) from Bereiter et al (2014). Data spans the period from 800,000 BCE to 1980 CE. Chart by Carbon Brief using Highcharts.

https://www.carbonbrief.org/explainer-how-the-rise-and-fall-of-co2-levels-influenced-the-ice-ages

- CO_2 and temperature are tightly connected across glacial cycles over the past 800.000 years
- CO_2 may lag temperatures by a few hundreds up to 1000 years, or may be synchronous (recent studies)

(2) The issue of cause and effect

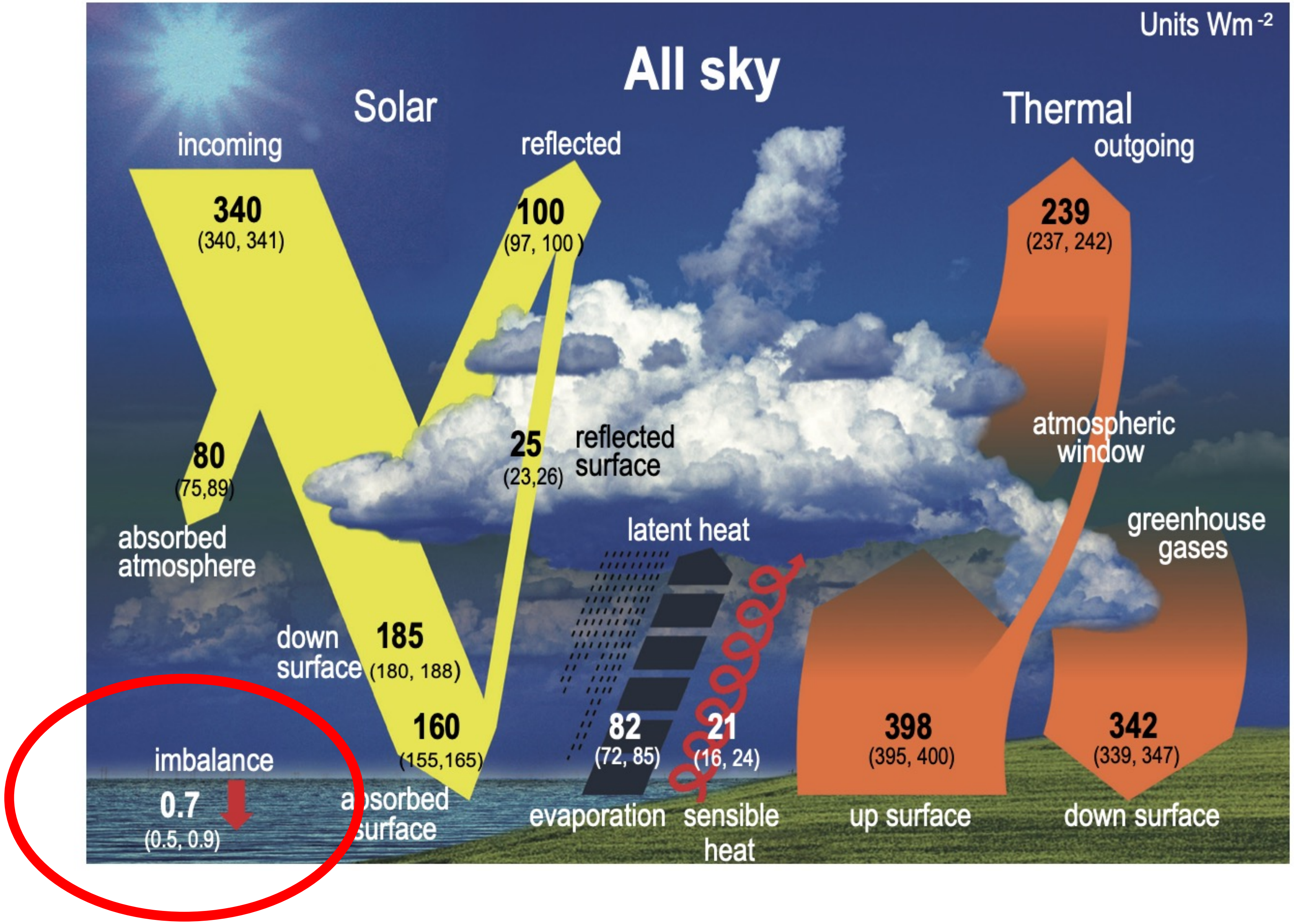


Antarctic reconstructed air temperature (red line) at Dome Fuji site Antarctica using isotope modelling from Uemura et al (2018) and Antarctic composite ice core atmospheric CO2 data (blue line) from Bereiter et al (2014). Data spans the period from 800,000 BCE to 1980 CE. Chart by Carbon Brief using Highcharts.

https://www.carbonbrief.org/explainer-how-the-rise-and-fall-of-co2-levels-influenced-the-ice-ages

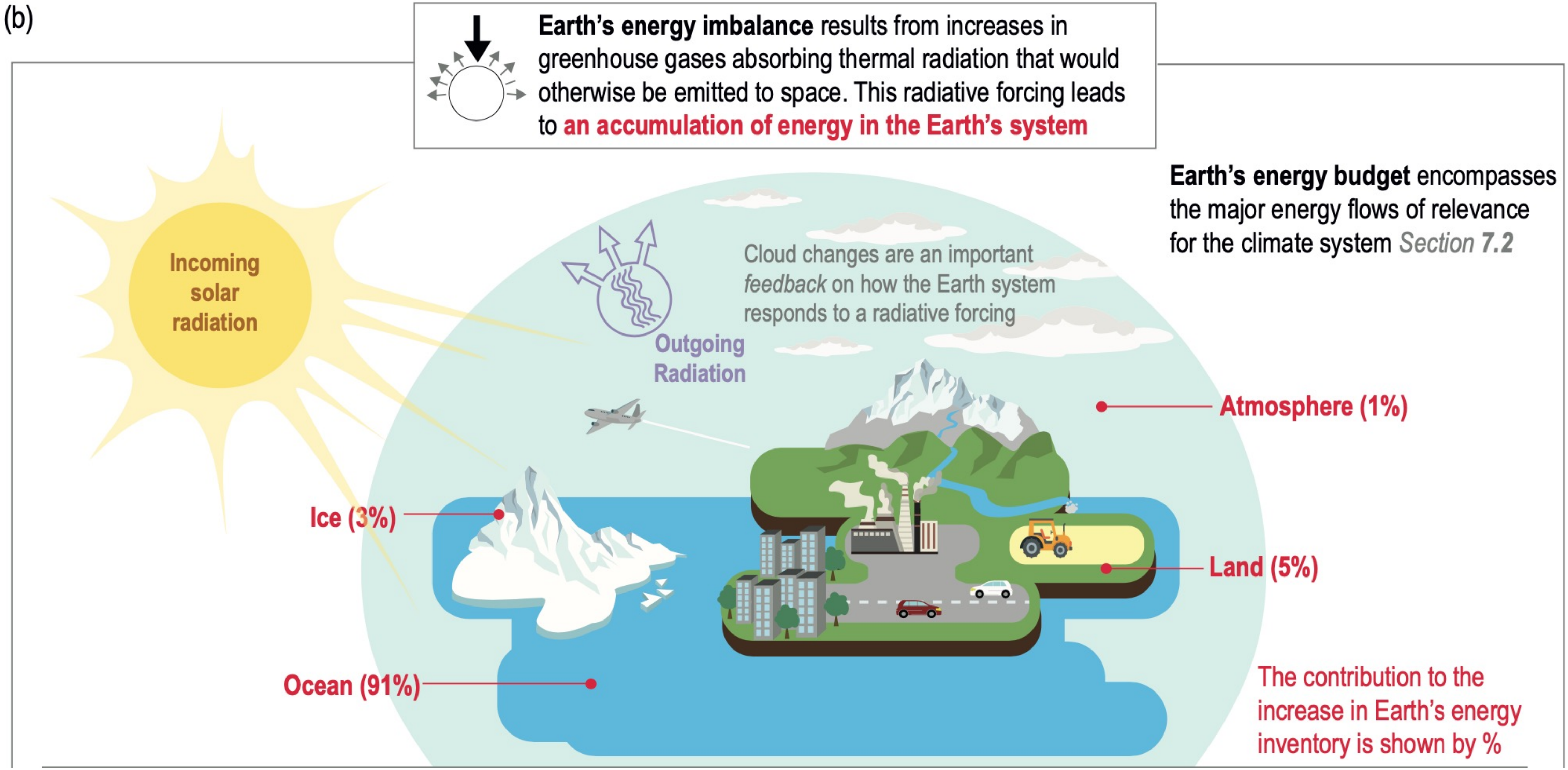
- CO_2 and temperature are tightly connected across glacial cycles over the past 800.000 years
- CO_2 may lag temperatures by a few hundreds up to 1000 years, or may be synchronous (recent studies)
- BUT: Lead-lag analysis cannot reveal the direction of causality as (for well understood physical reasons) CO_2 is both a cause and effect of increased temperatures during glacial cycles.

(3) Earth's energy budget and imbalance

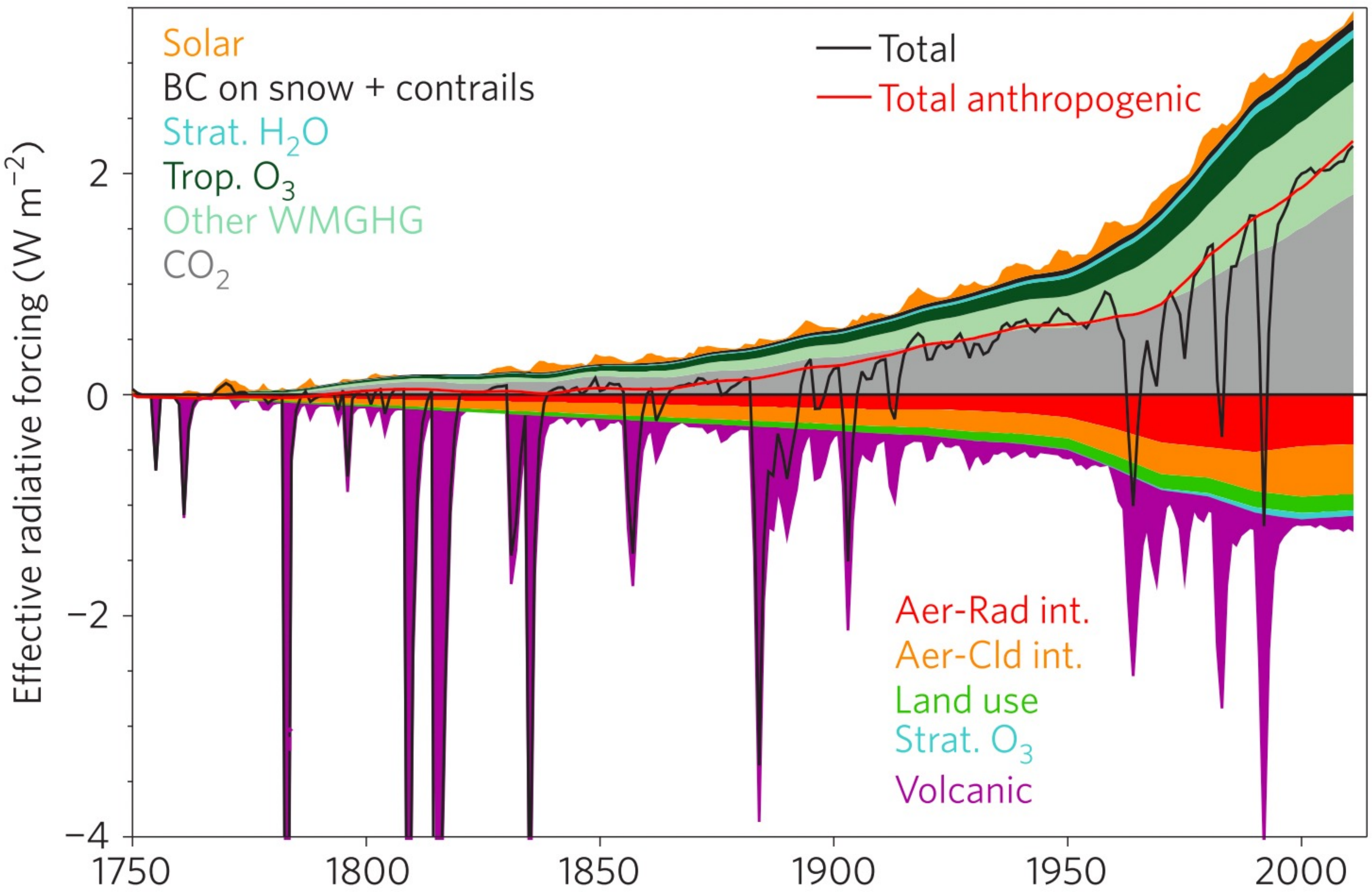


IPCC 2021, AR6 WG1
Chapter 6

(3) Earth's energy budget and imbalance



(3) Earth’s energy imbalance is sustained by increased radiative forcing



Schuckmann et al. 2016
Nat Clim. Change

Summary: Large-scale changes in the Earth system

- Observations show large-scale changes in the Earth system, with very distinct trend signals (in most cases physically understood)

- (Lead-lag) Correlation analysis (or other statistical or exploratory analysis) are useful but cannot (alone) reveal the causal directions and are *not* attribution

- Earth's energy imbalance is a key indicator to track the energy flows through the Earth system, and radiative forcing estimates give a sense of the importance of individual forcing agents over time

Summary: Large-scale changes in the Earth system

- Observations show large-scale changes in the Earth system, with very distinct trend signals (in most cases physically understood)

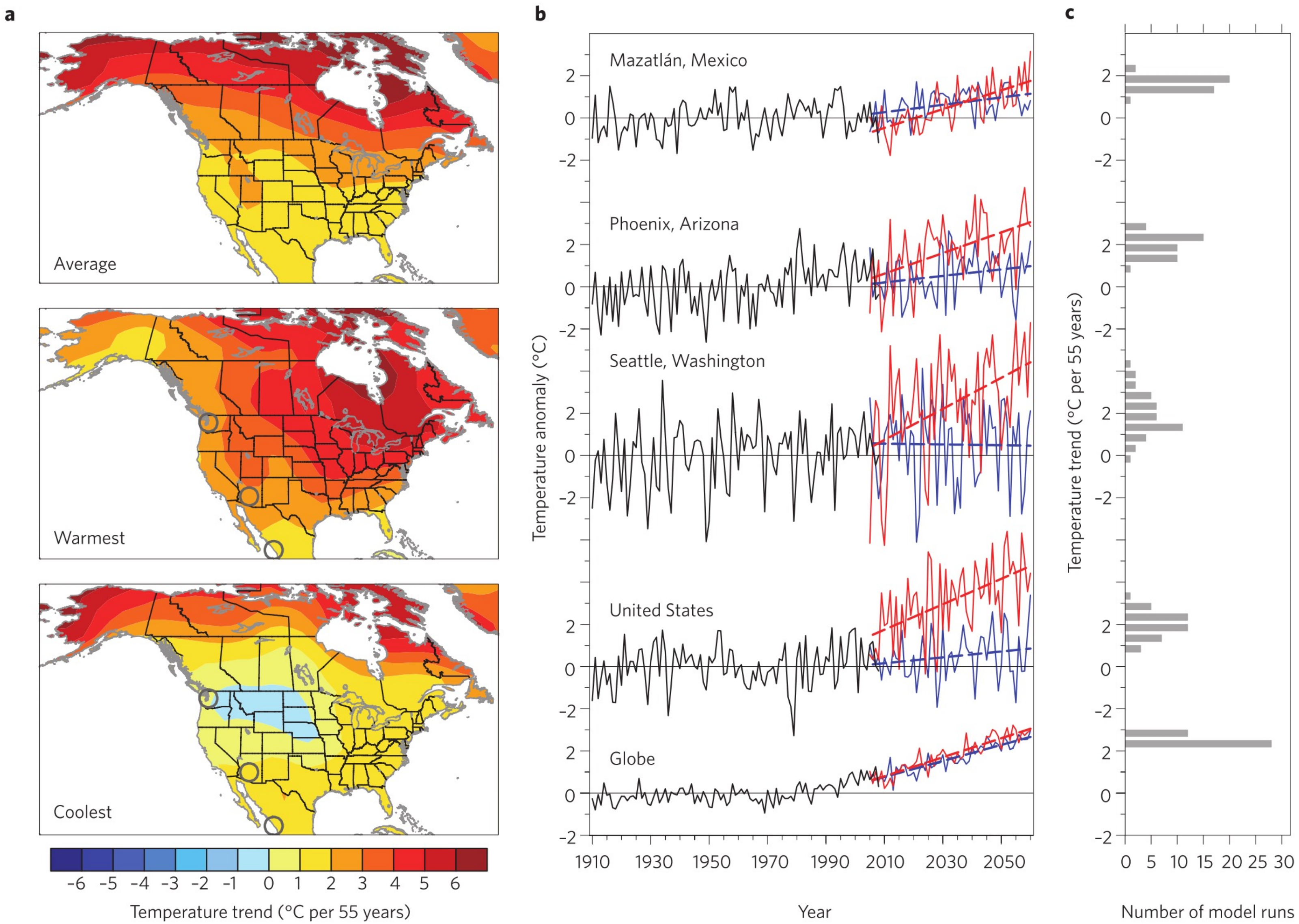
- (Lead-lag) Correlation analysis (or other statistical or exploratory analysis) are useful but cannot (alone) reveal the causal directions and are *not* attribution

- Earth's energy imbalance is a key indicator to track the energy flows through the Earth system, and radiative forcing estimates give a sense of the importance of individual forcing agents over time. BUT: Just because we know the forcing has changed, does *not* mean we have detected or attributed changes in the response.

Topics:

1. Introduction
2. Forced Signal vs. internal variability
3. Concepts and logic of detection & attribution
4. Traditional fingerprinting
5. Non-standard approaches

Internal variability and the forced response



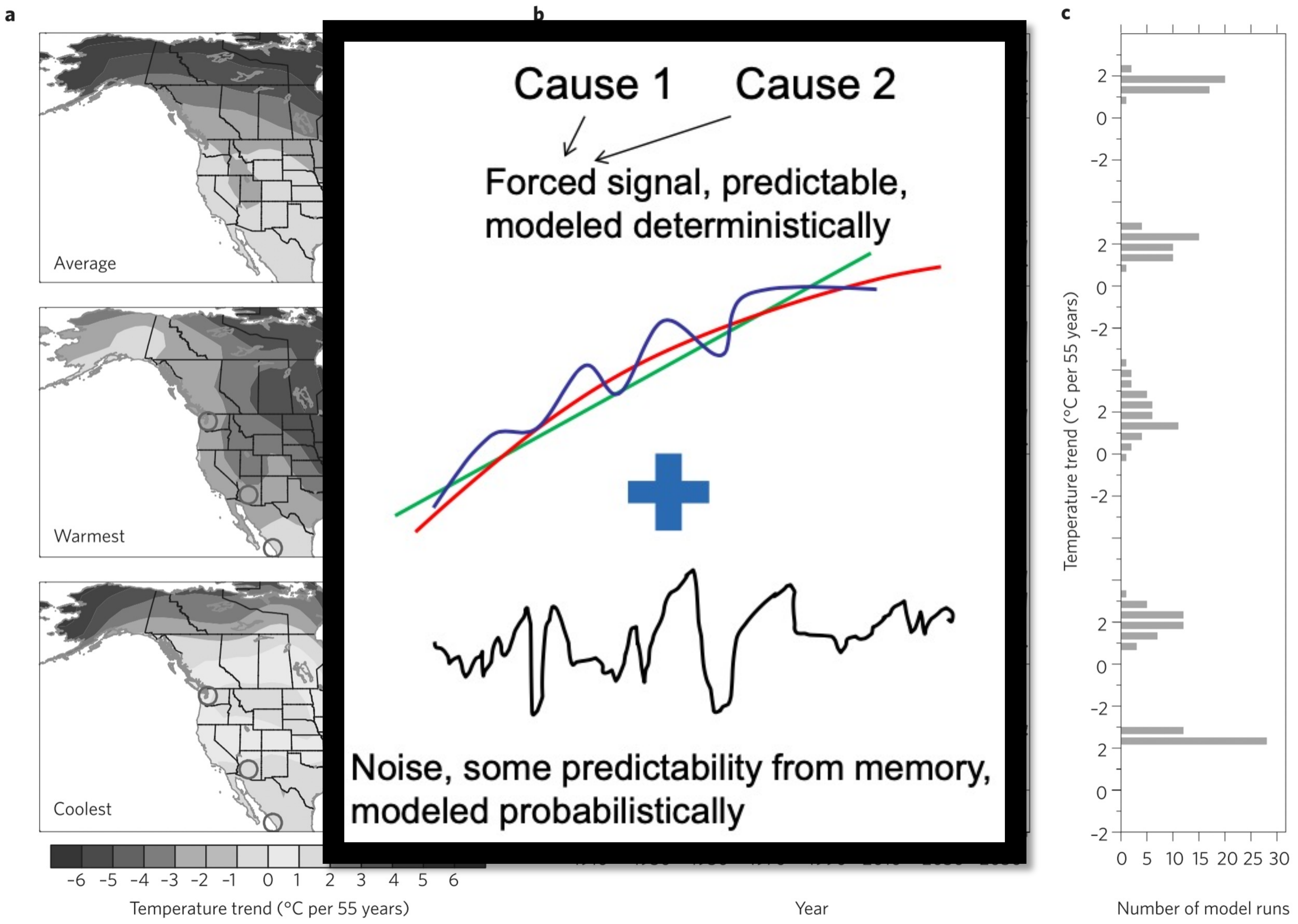
Internal variability: internal climate variation over time and space

Forced response: Component that is externally forced (e.g. Solar forcing, Aerosols, GHGs)

- 45 model simulations with one **climate model** (=same physics)
- 55 year temperature trend maps, starting 2006

Deser et al., 2012, *Nat. Clim. Change*

Internal variability and the forced response



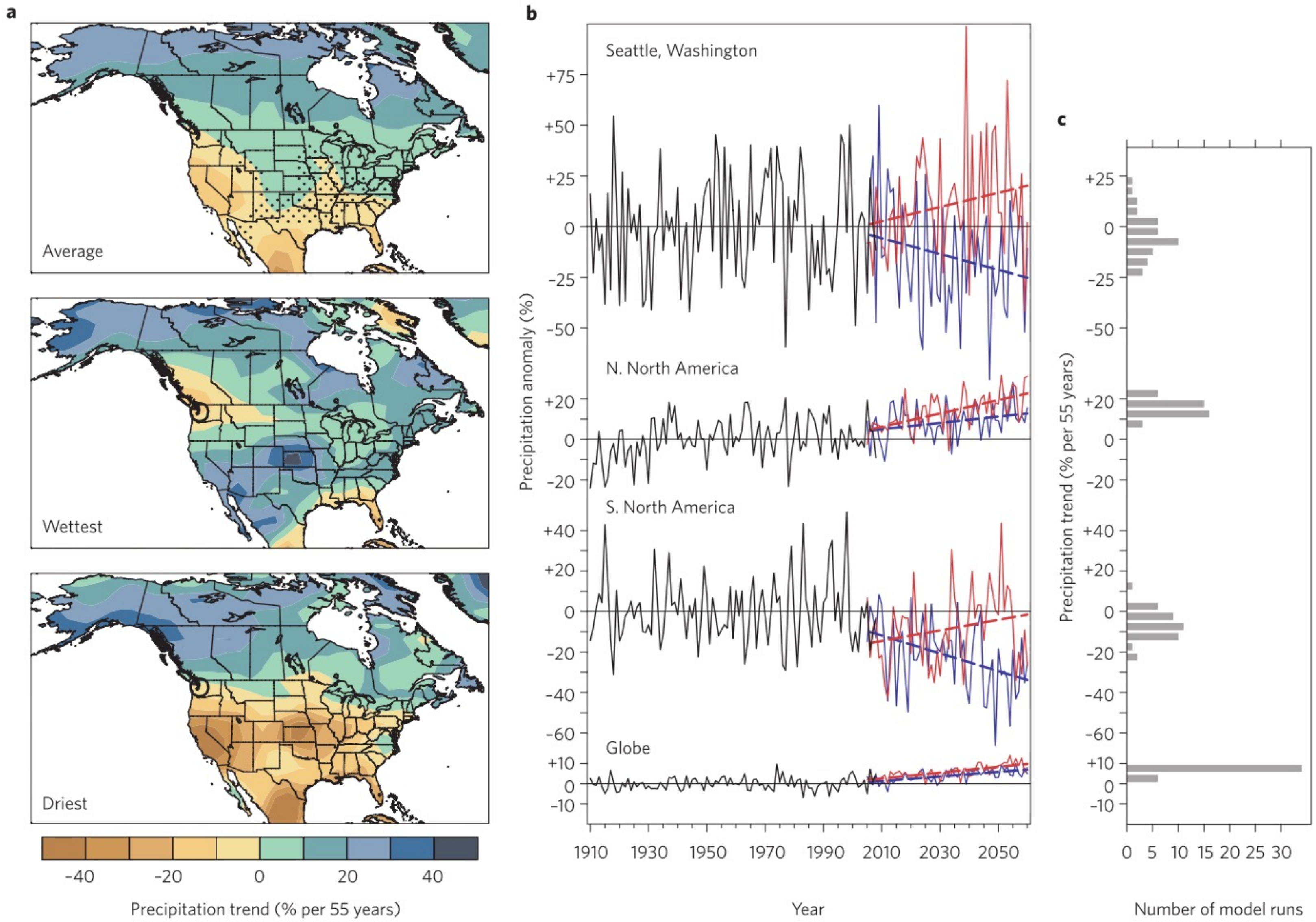
Deser et al., 2012, *Nat. Clim. Change*

Internal variability: internal climate variation over time and space

Forced response: Component that is externally forced (e.g. Solar forcing, Aerosols, GHGs)

- 45 model simulations with one **climate model** (=same physics)
- 55 year temperature trend maps, starting 2006

Internal variability and the forced response

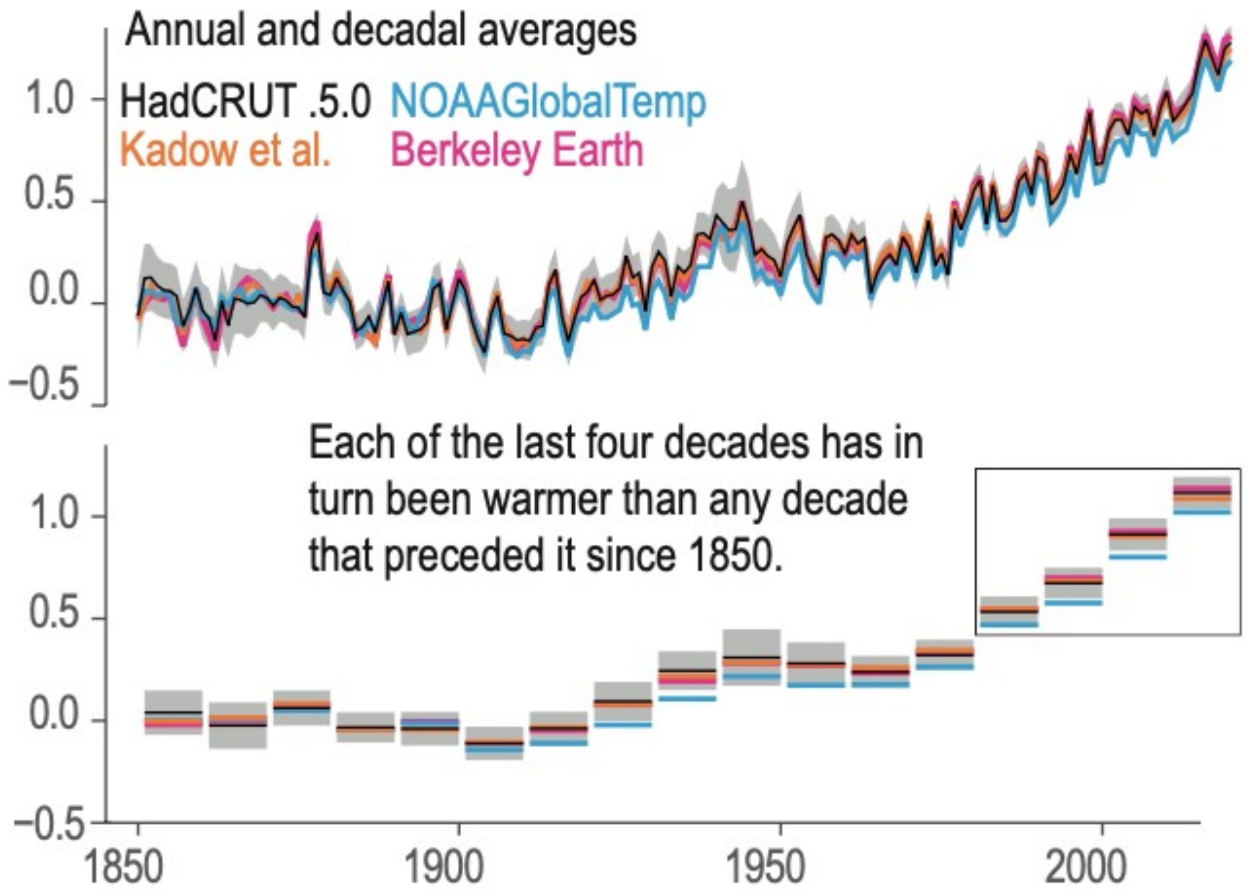


- Internal variability fundamentally limits climate projections
- Strong implications for interpretation of regional climate trends

- 45 model simulations with one **climate model** (=same physics)
- 55 year temperature trend maps, starting 2006

Deser et al., 2012, *Nat. Clim. Change*

Internal variability and the forced response

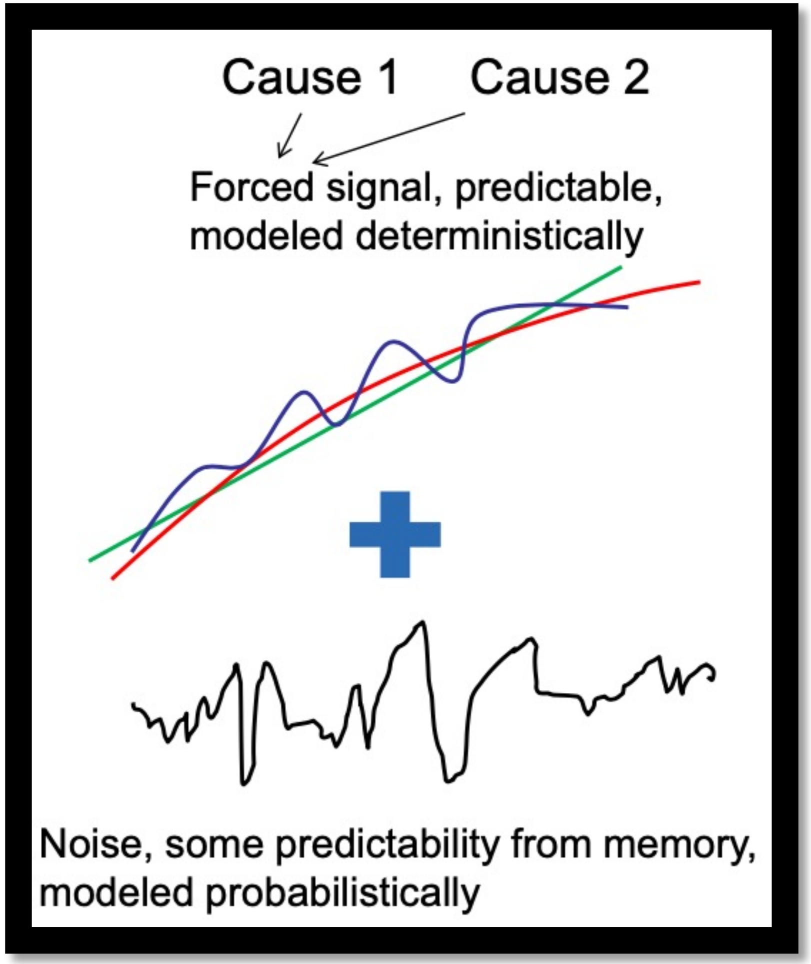


- What is the signal?
- What is (internal) variability?
- Other problems of instruments, interpolation, coverage?

IPCC 2021, AR6 WG1 Chapter 3

Separation of signal and noise

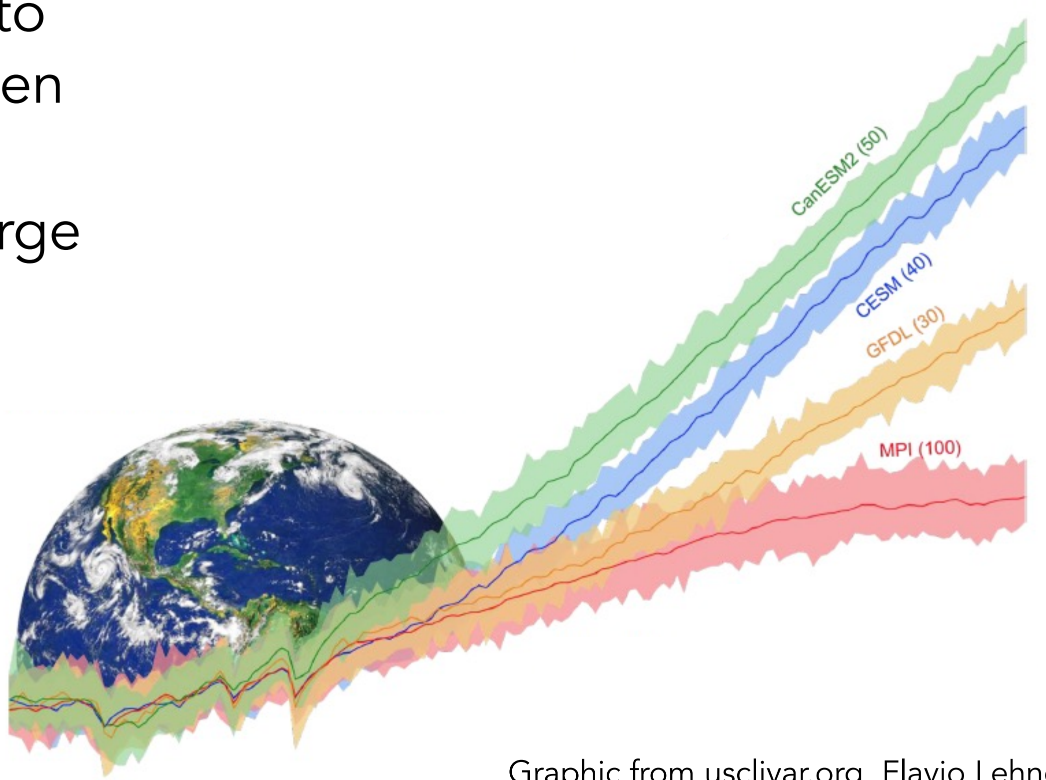
- **Smoothing** (e.g. Hawkins and Sutton, 2009 *BAMS*)



Separation of signal and noise

- Smoothing (e.g. Hawkins and Sutton, 2009 *BAMS*)

- Ensemble averaging:
  - Average over multiple ensemble members to remove internal variability that varies between realizations
  - Multi-model (e.g., CMIP) or single-model large ensembles



Graphic from usclivar.org, Flavio Lehner

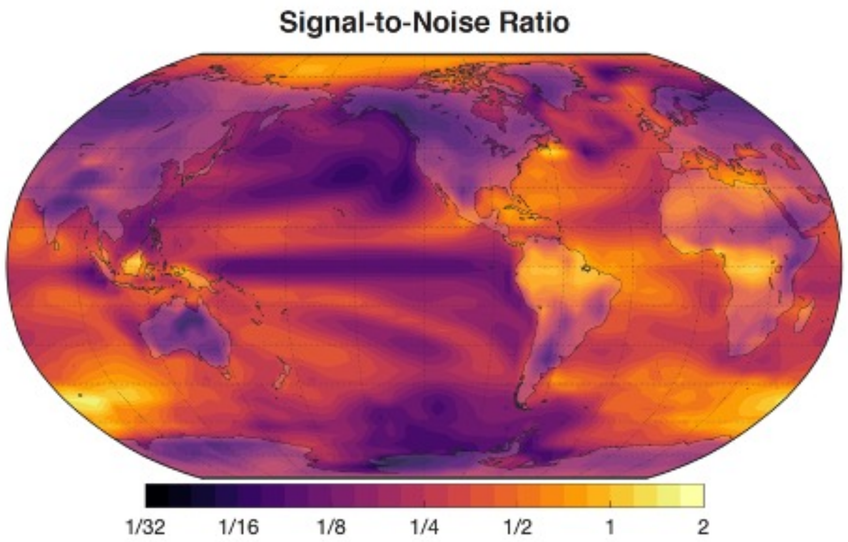
See also: Deser et al., 2020 *Nat Clim Change*

Separation of signal and noise

- **Smoothing** (e.g. Hawkins and Sutton, 2009 *BAMS*)

- **Ensemble averaging:**
  - Average over multiple ensemble members to remove internal variability that varies between realizations
  - Multi-model (e.g., CMIP) or single-model large ensembles

- **Advanced pattern filtering techniques** (e.g., Wills et al., 2020, *Journal of Climate*)



Wills, Sippel, Barnes (2020, US CLIVAR Variations)

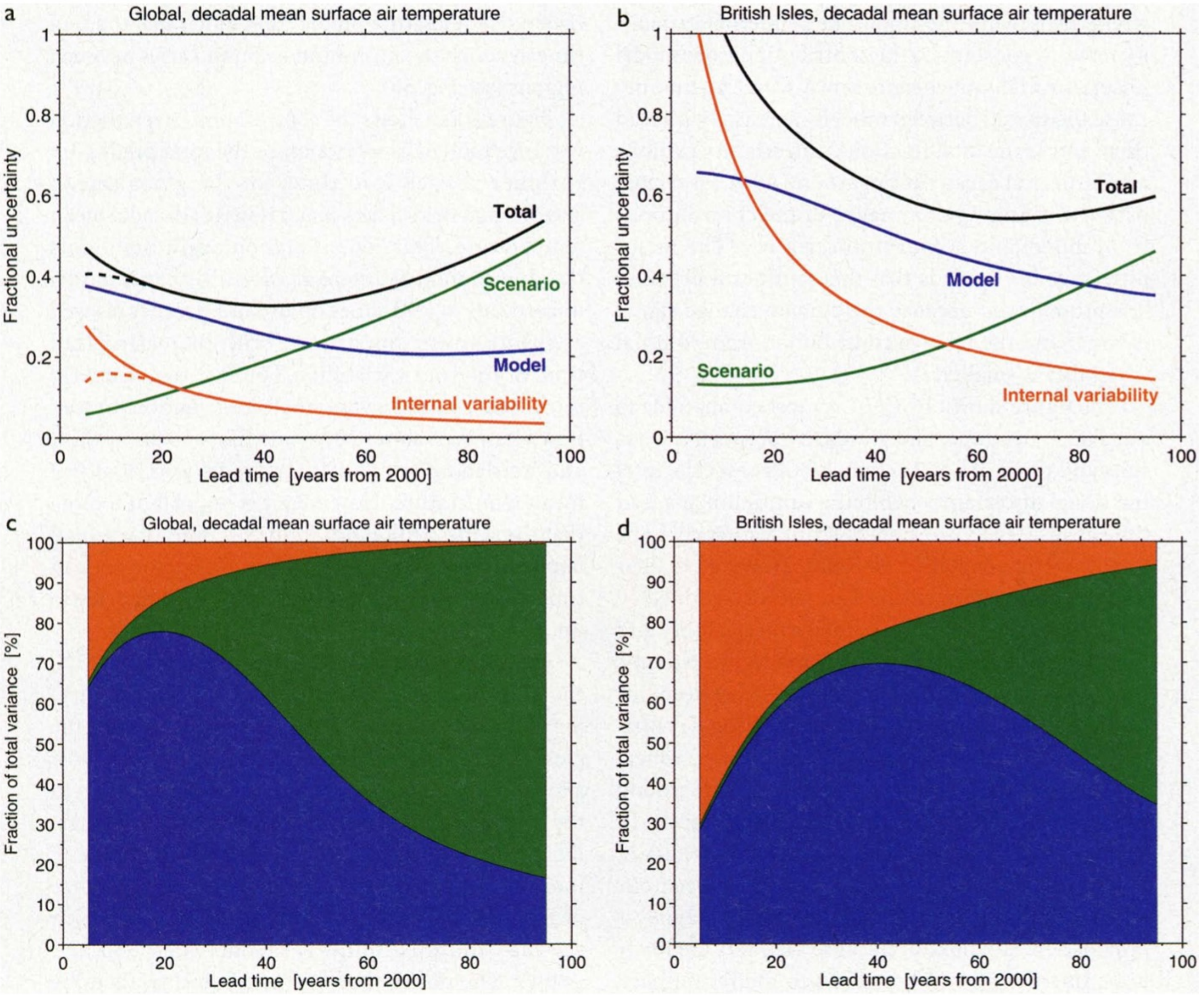
See, for instance:
CLIVAR Webinar by Robb Wills, 2020:
https://www.youtube.com/watch?v=K0kzgLg4CzQ&t=322s

Separation of signal and noise

- **Smoothing** (e.g. Hawkins and Sutton, 2009 *BAMS*)
- **Ensemble averaging:**
  - Average over multiple ensemble members to remove internal variability that varies between realizations
  - Multi-model (e.g., CMIP) or single-model large ensembles
- **Advanced pattern filtering techniques** (e.g., Wills et al., 2020, *Journal of Climate*)
- **Detection and attribution** used to identify a known forced response pattern from observations

Sources of uncertainty

- Internal variability
- Scenario uncertainty
- Model uncertainty



Hawkins and Sutton (2009) *BAMS*

Summary: Internal variability and the forced response

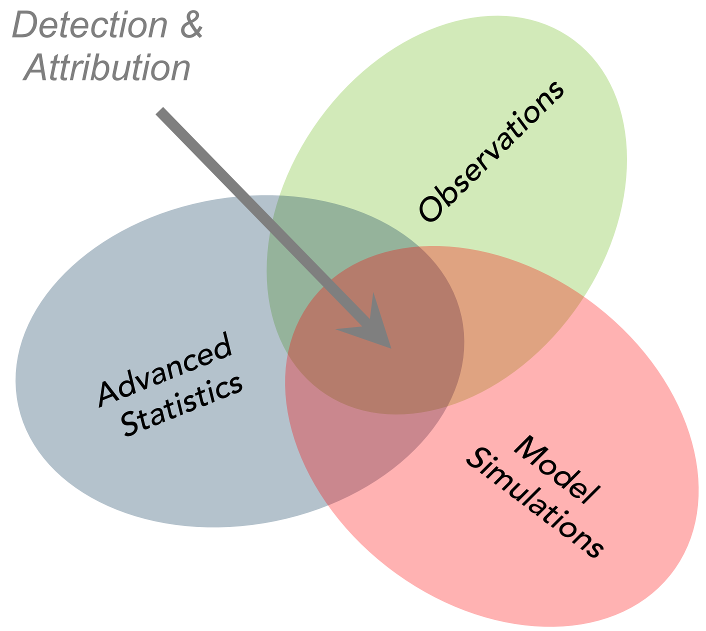
- What we observe is a combination of forced change and internal (largely unpredictable) variability. Separation is crucially important but not easy
- Signal to noise depends on variable, spatial scale, temporal scale, quantity, …
- Various statistical techniques exist to separate forced response from internal variability. Possible to do in models, but generally difficult in observations (will come back later)

Topics:

1. Introduction
2. Forced Signal vs. internal variability
3. Concepts and logic of detection & attribution
4. Traditional fingerprinting
5. Non-standard approaches

Detection and attribution: What is it?

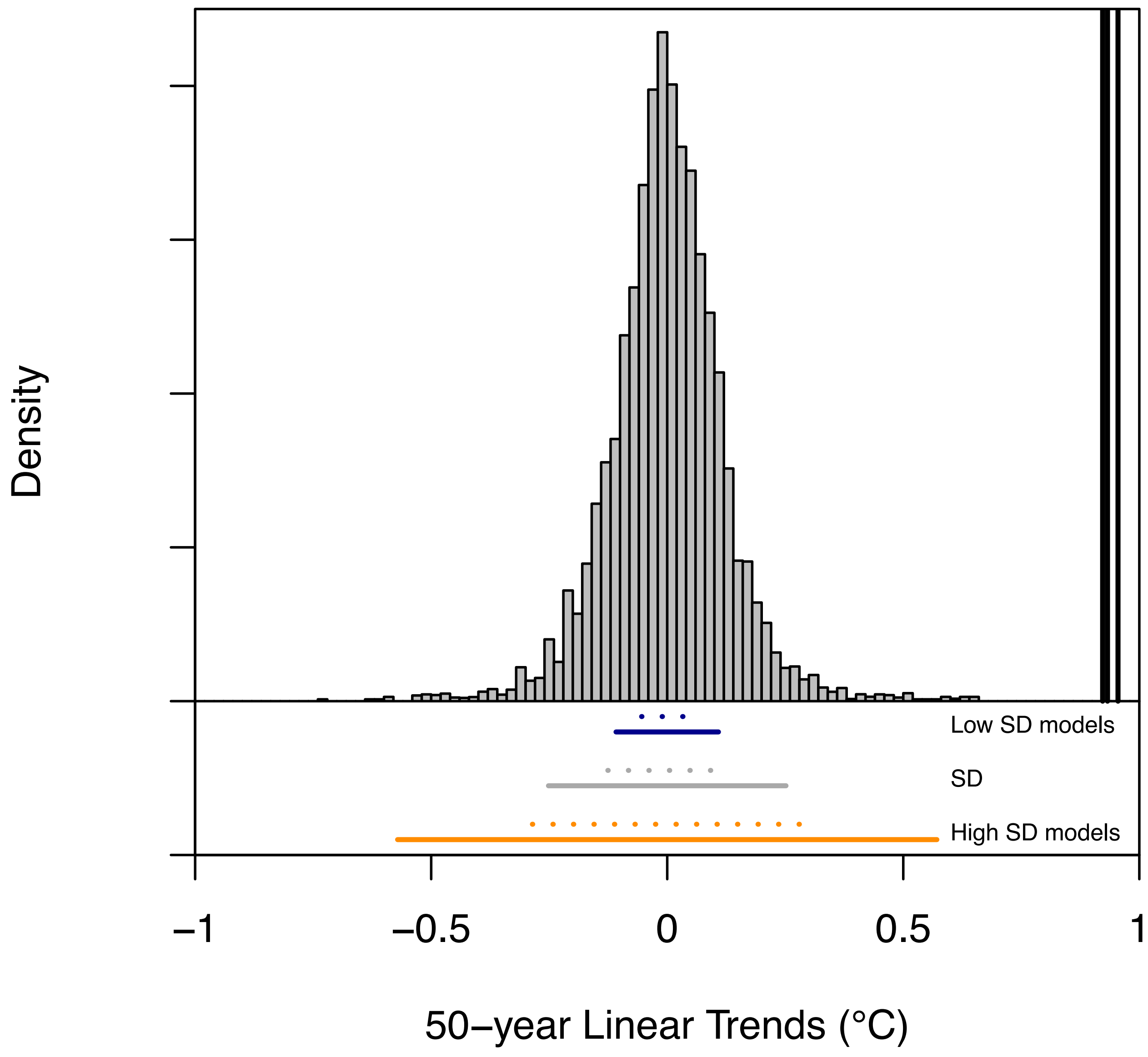
Detection and attribution of climate change involves **assessing the causes of observed changes in the climate system through systematic comparison of climate models and observations using various statistical methods**. (4th National Climate Assessment, USA, 2017)



Detection and attribution: Why do we need it?

- Understanding historical climate change and it’s most likely causes at the global and regional scale
- Constraints on future projections (based on understanding of the past)
- Counterfactual questions (what if we would have changed XYZ in the climate system?)

What is Detection?

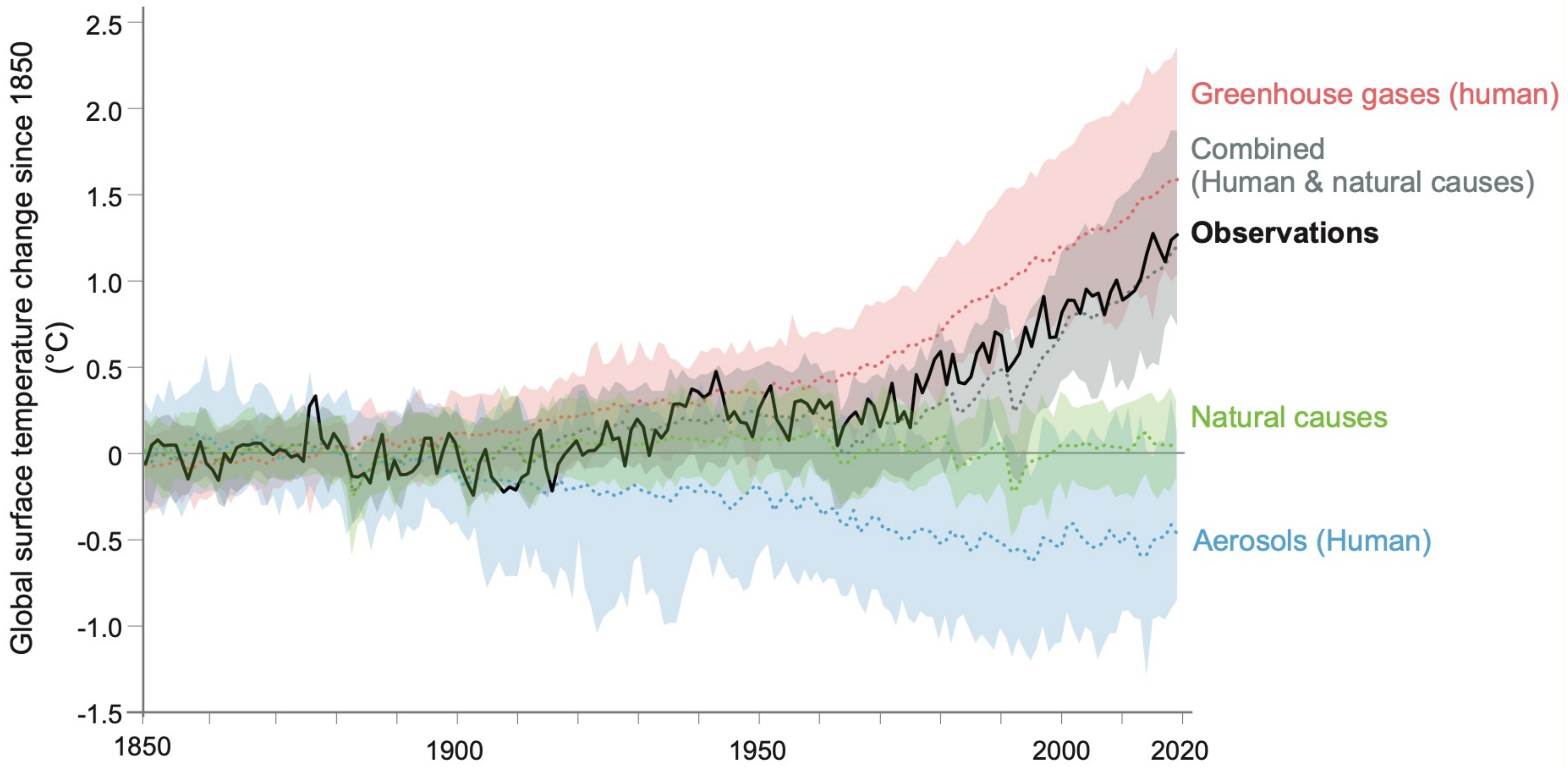


Sippel et al. (2021), *Science Advances*

Detection is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense without providing a reason for that change (IPCC Good Practice Guidance Paper on D&A 2010).

What is Attribution?

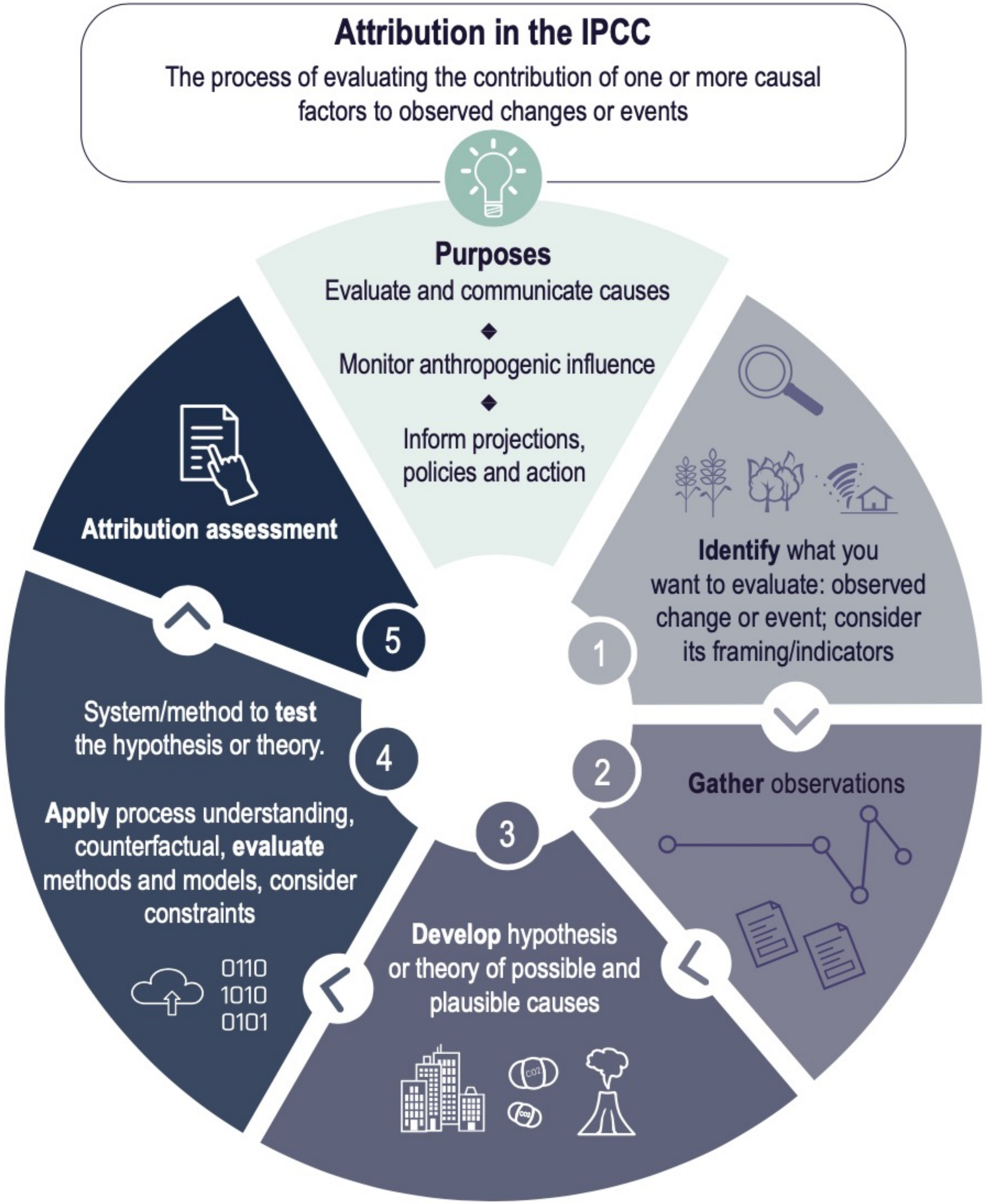
Observed warming (1850-2019) is only reproduced in simulations including human influence.



Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence. (IPCC Good Practice Guidance Paper on D&A 2010).

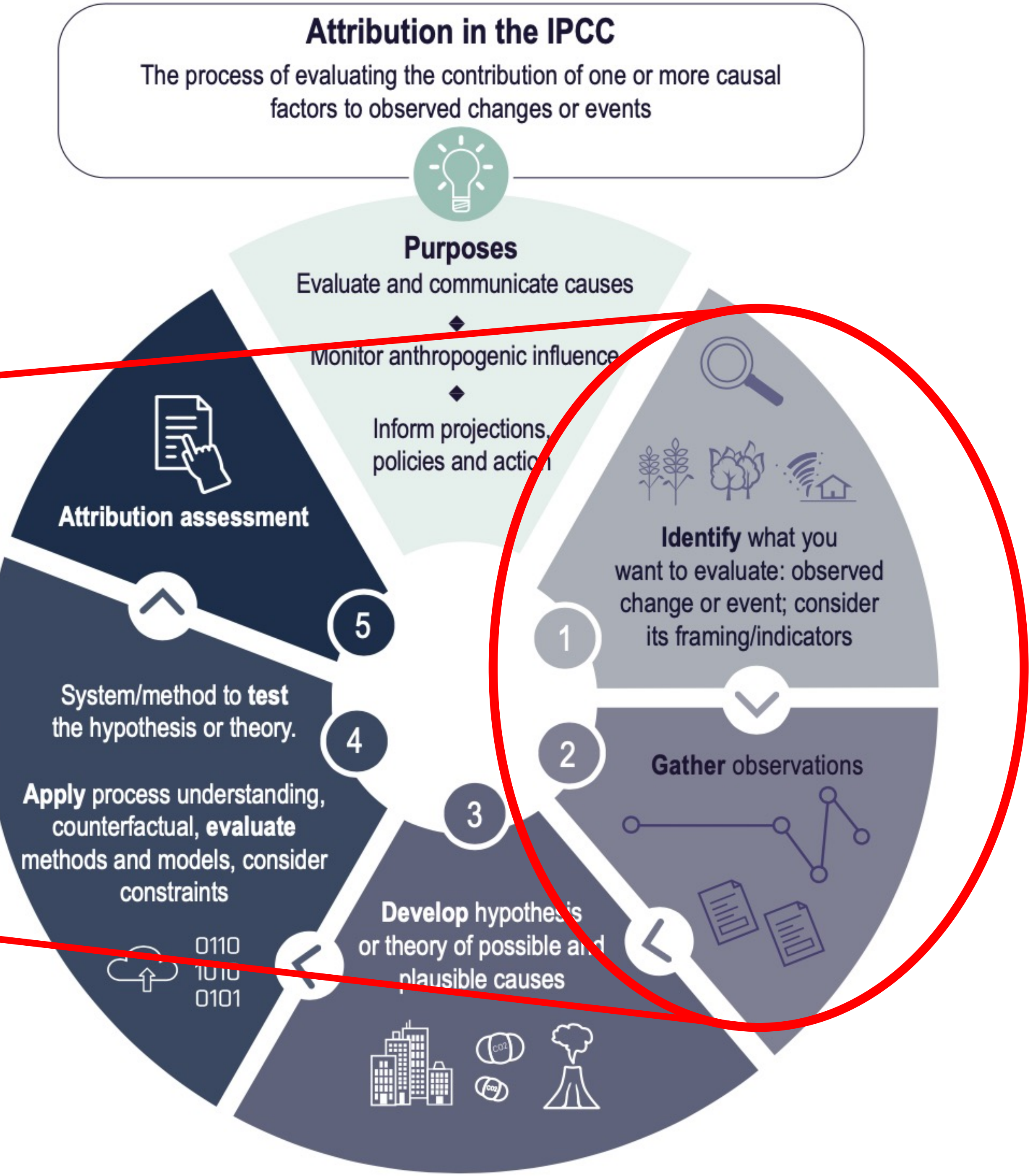
IPCC 2021, AR6 WG1 Chapter 3

D&A: From the "what" to "why" is it happening?



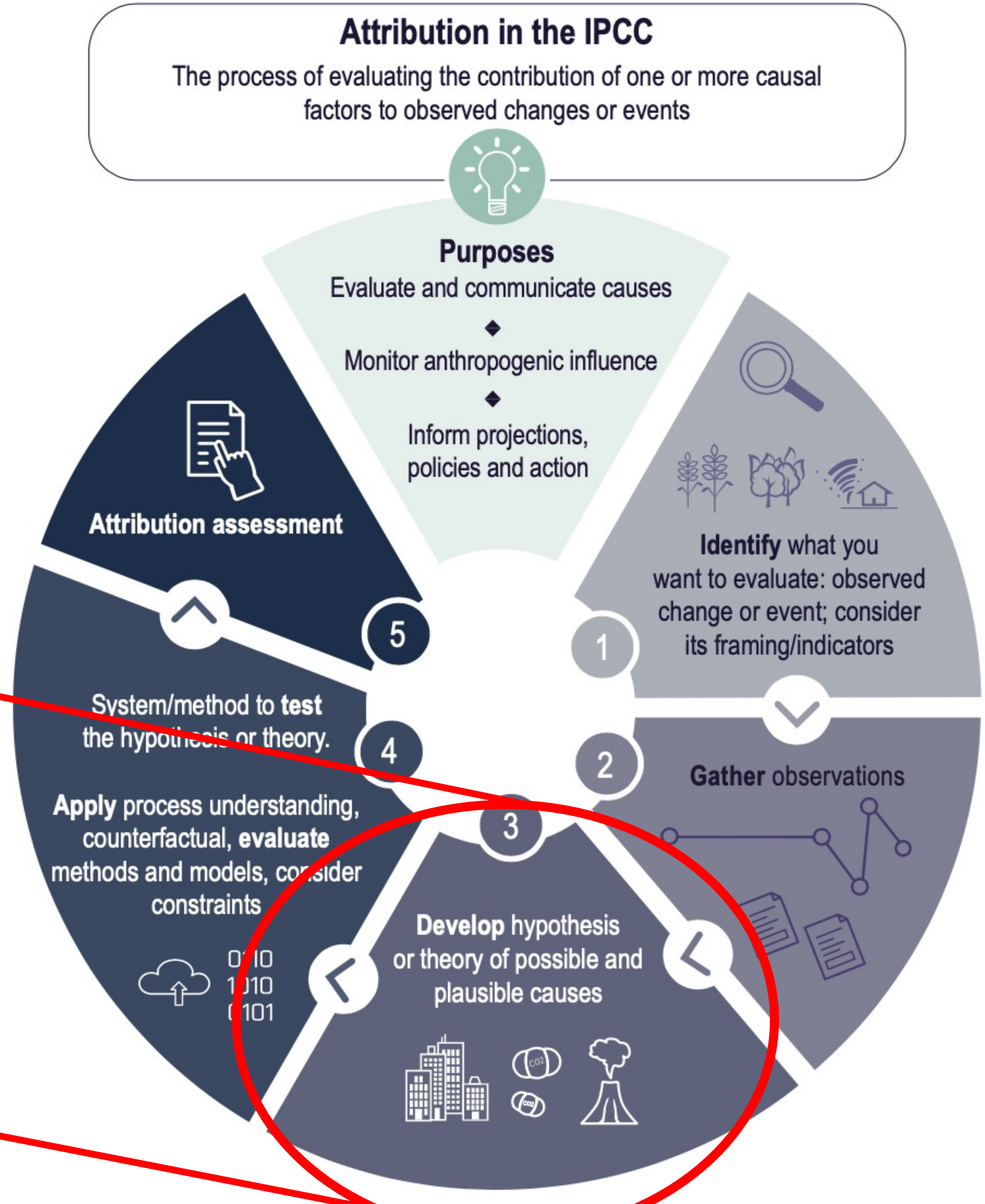
D&A: From the "what" to "why" is it happening?

"What":
- Identification of interesting/relevant questions
- Exploratory analysis: what are changes, trends? Other statistical properties?
- How reliable are observations? Outliers, biases? Missing values?
- Time scales, spatial scales of observations?



D&A: From the "what" to "why" is it happening?

"Why":
- Understand the process
- Understand the time scales, spatial scales of the signal, and the noise
- Build a quantitative model (in most cases this is where existing climate models are invoked)



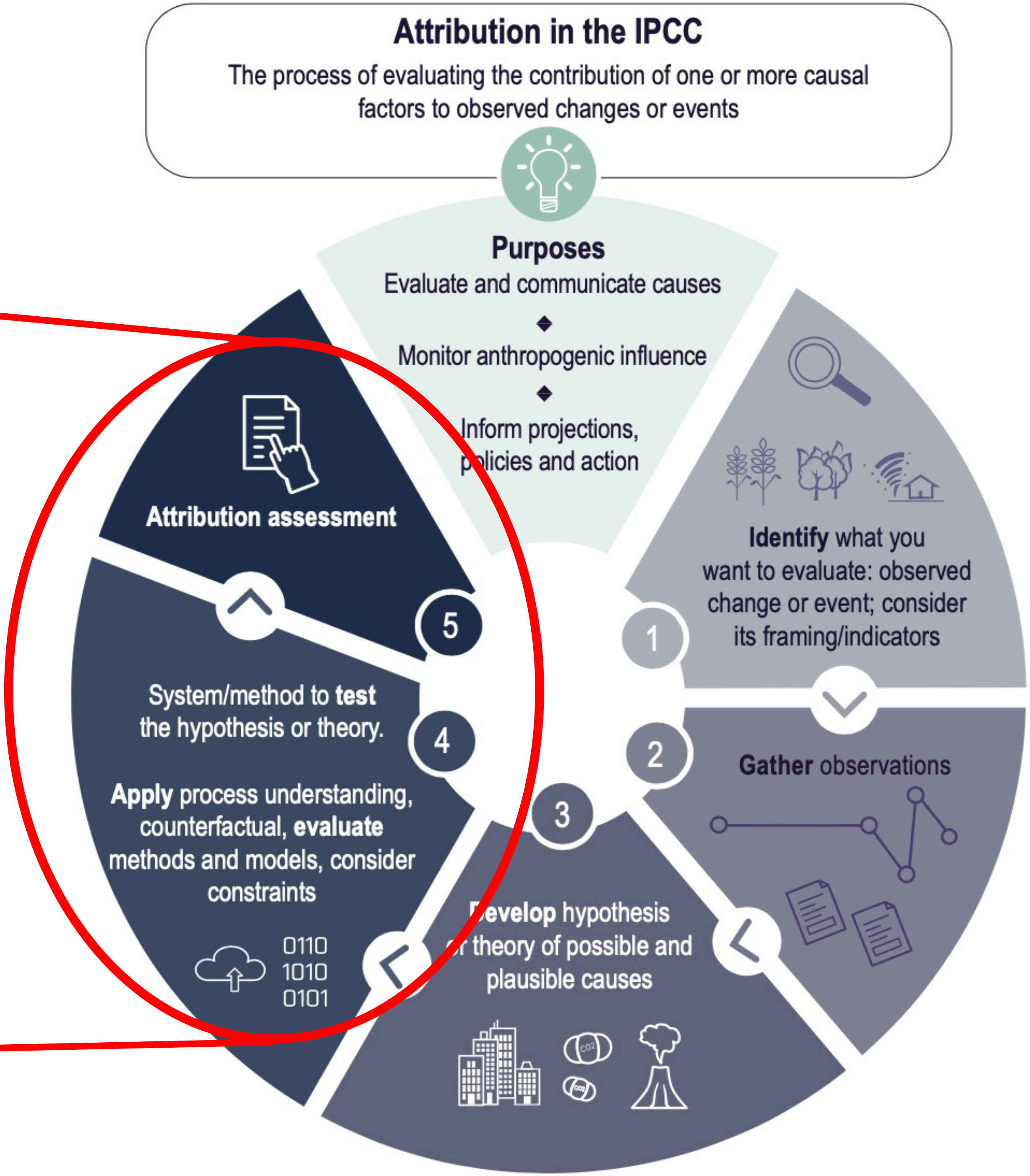
D&A: From the "what" to "why" is it happening?

Apply a D&A technique/argumentation:

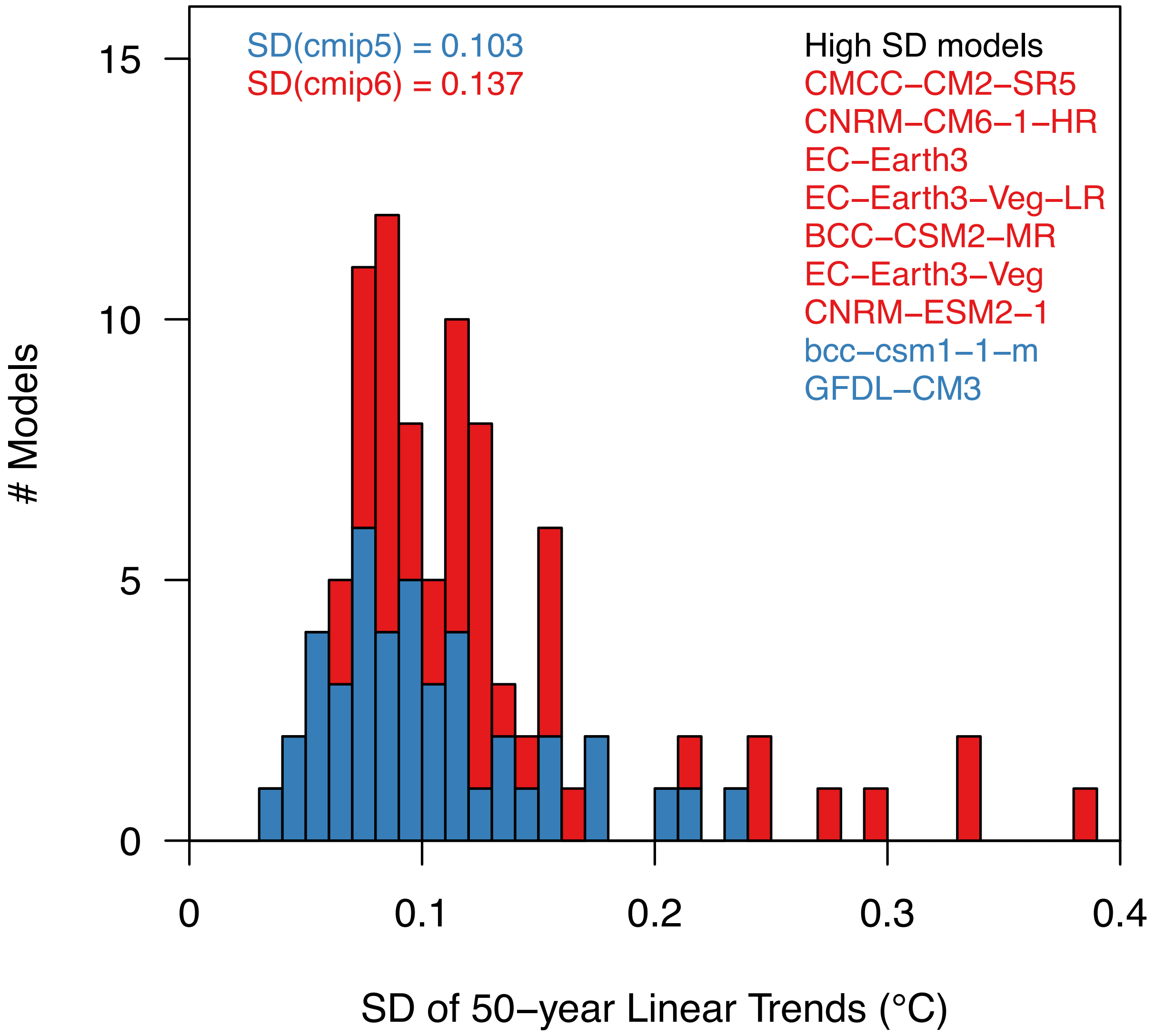
- Observed changes are unlikely to be due to internal variability ("detection")
- Observed changes are consistent with the calculated responses from best-guess estimates of anthropogenic and natural forcing (attribution)
- Observed changes are not consistent with alternative explanations of recent climate
- Difference between observations and attribution patterns must be consistent with internal variability

Evaluation:

- What are the limitations of the theoretical (climate) model in simulating the signal or variability?
- What are data limitations?

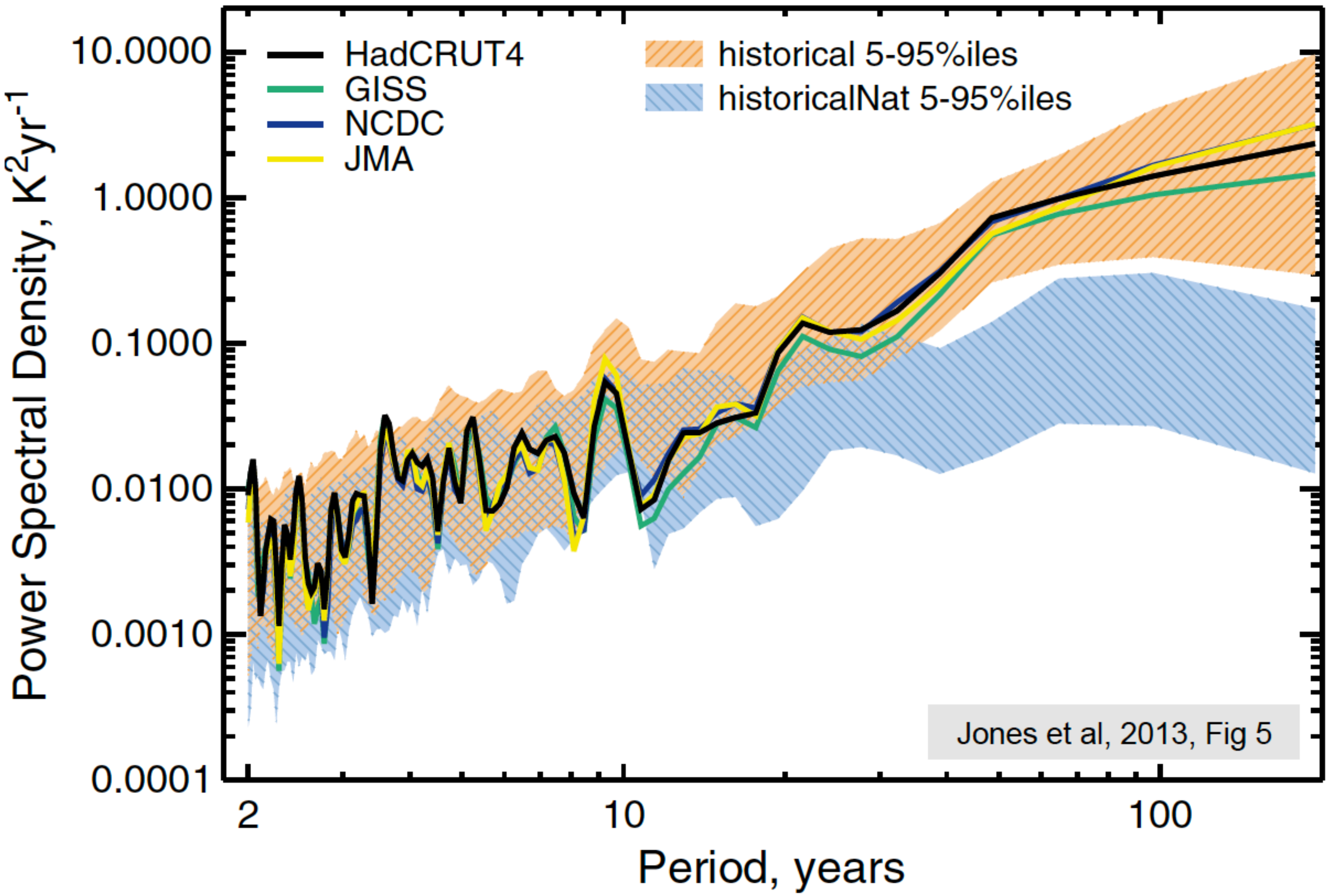


Model evaluation is critical



Multidecadal variability is uncertain and highly variable across climate models.

Model evaluation is critical



Models tend to capture variability of the observations. But the observed record is short, and a combination of forced and internal variability, so comparisons are difficult

Sebastian Sippel
sebastian.sippel@env.ethz.ch

ETH Zurich
Institute for Atmospheric and Climate Sciences
CHN N18 / N16.1
Universitätstrasse 16
8006 Zürich