Arthur H. Compton Lecture Series:
An Intro to Climate Systems Engineering

Climate Models

Lecturer: Tiffany Shaw

October 18, 2025

	Speakers	Topics
Oct 4	Keith	Introductions. Climate in 4 Dimensions. Emissions are peaking. Adaptation. Climate in Context.
Oct 11	Archer	Carbon cycle and natural geochemical processes as basis to understand carbon removal.
Oct 18	Shaw	Scientific basis for predicting climate changes in response to emissions of greenhouse gases and aerosol pollution.
Oct 25	Cael	Carbon removal, including ocean alkalinity enhancement, land-based methods, bioenergy with carbon capture, and direct air capture with storage.
Nov 1	Keith	Sunlight Reflection Methods (SRM) Part 1: How to Reflect Sunlight, the history of SRM, and why stratospheric sulfur aerosols are most plausible now.
Nov 8	MacAyeal & Keith	MacAyeal on science of glaciers and interventions to prevent glacial melt. Keith on developing DAC technologies at Carbon Engineering, and lessons for cleantech.
Nov 15	Shaw & Keith	The climate responses to SRM, potential side effects, and what can be learned from past aerosol pollution, highlighting the limits and uncertainties of experiments.
Nov 22	Keith	The future of climate systems engineering, and climate engineering in context.

Tiffany Shaw

Professor, Geophysical Sciences

Physicist and climate scientist interested in understanding the physical mechanisms controlling the planetary and regional response to climate changes so that we can have greater confidence in climate predictions.

Undergraduate: Math and Earth Science,

U. British Columbia 2004

PhD: Physics,

U. Toronto 2009

Coordinating Lead Author for Chapter 2 of the 7th Assessment Report of the IPCC

Some recent work:

NATURE 2025 The other climate crisis, Tiffany Shaw, Bjorn Stevens

SCIENCE ADVANCES 2025 Confronting Earth System Model Trends with Observations, Isla Simpson, Tiffany Shaw et al.

AGU ADVANCES 2024 Anthropogenic aerosols have significantly weakened the regional summertime circulation in the Northern Hemisphere during the satellite era, Joonsuk Kang, Tiffany Shaw, Lantao Sun

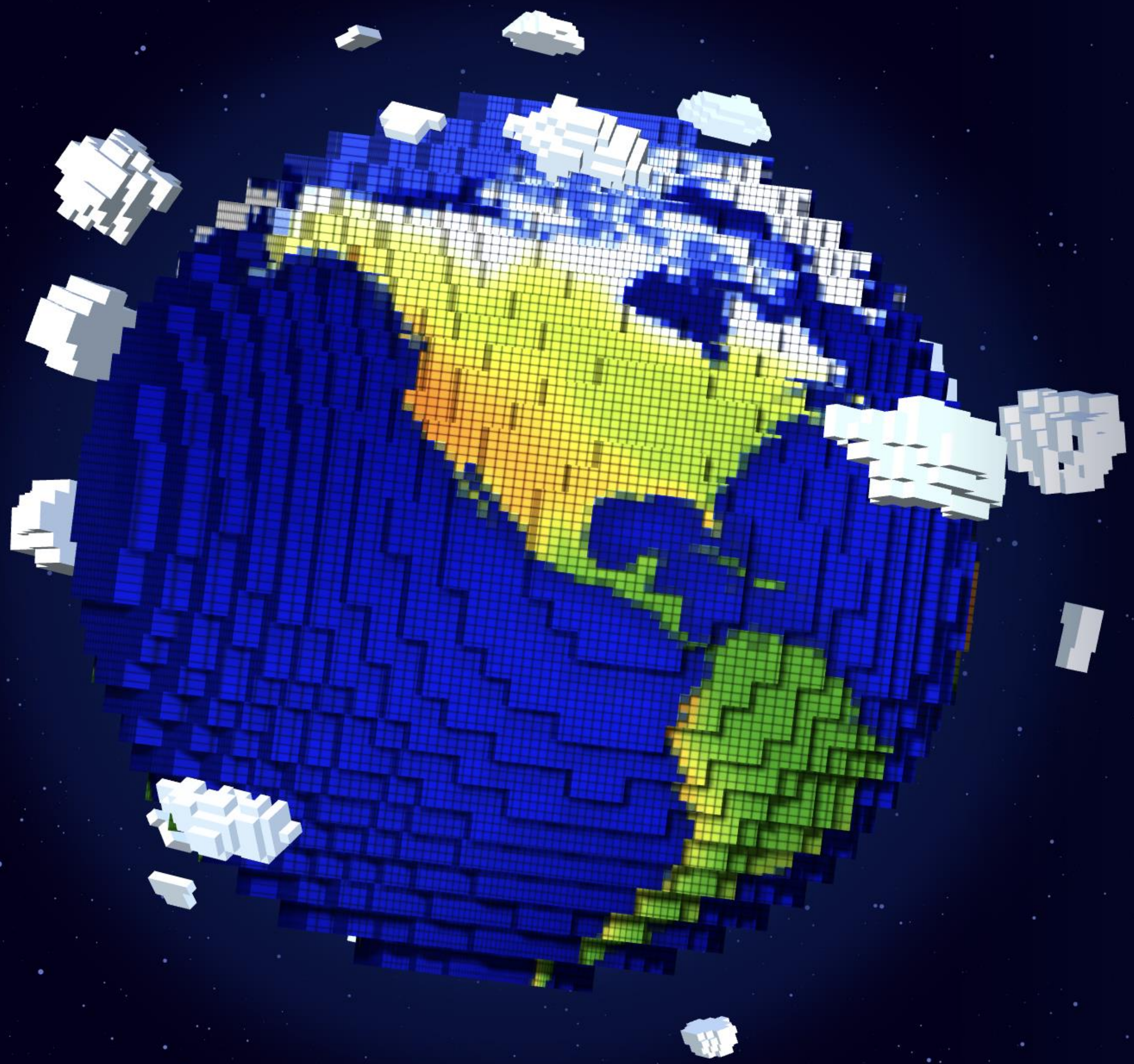
FEATURE

How Climate Scientists Saw the Future Before It Arrived

30 MINUTE READ →

By Zack Savitsky

Over the past 60 years, climate scientists have largely succeeded in building a computer model of the planet, capturing the most relevant processes of an impossibly complex system to see what the future holds. Now many of their predictions are being borne out and the impacts of climate change are becoming inescapable. At the same time, climate modeling faces threats from those who don't like the answers it provides.



How We Came To Know Earth

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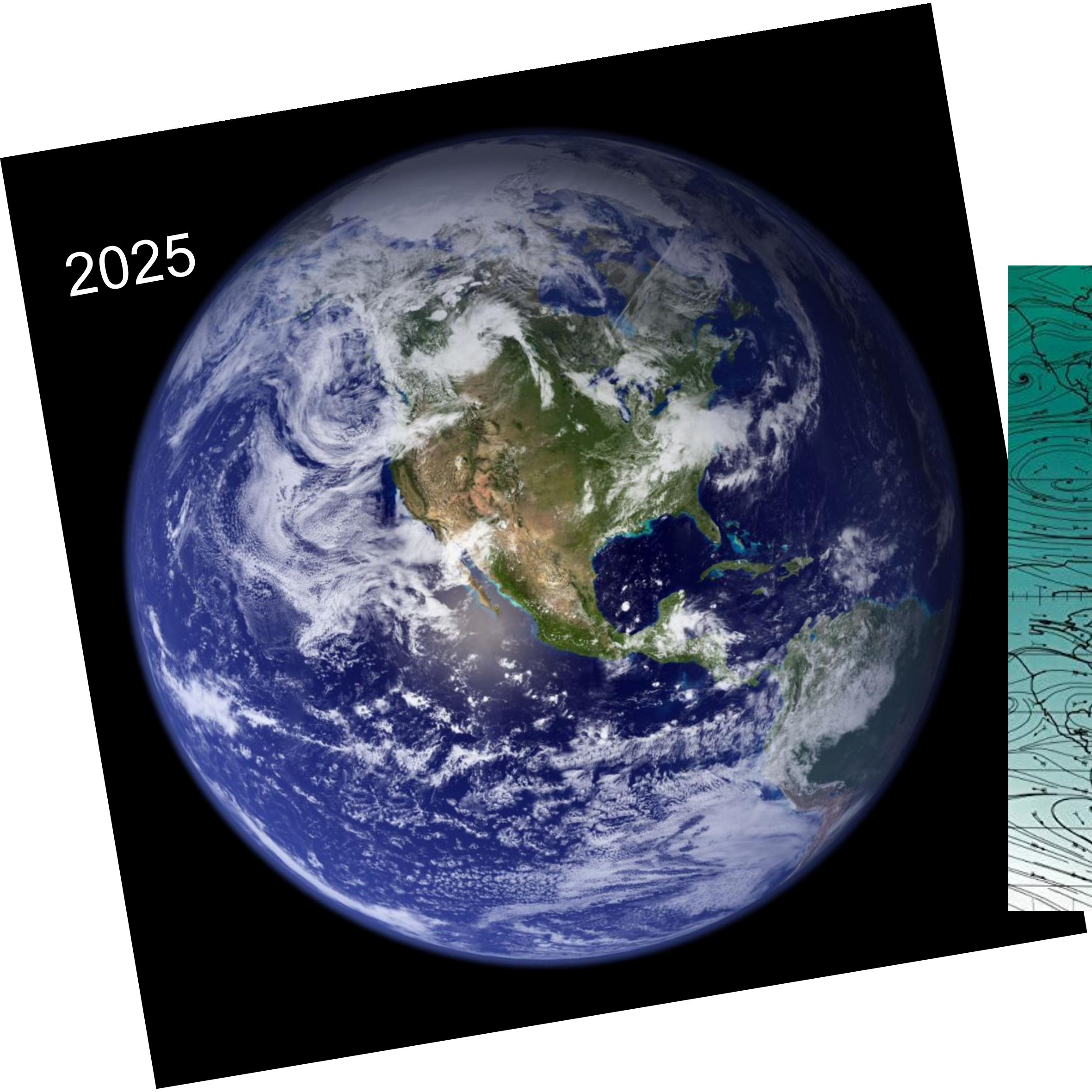
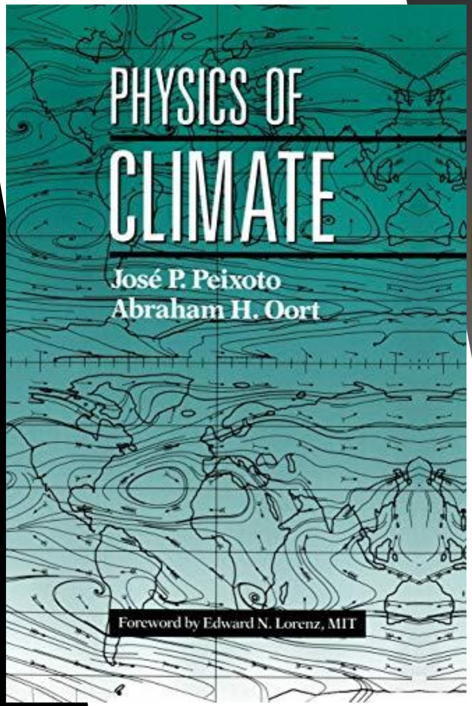
VIEW ALL STORIES

Predicting the future requires physics





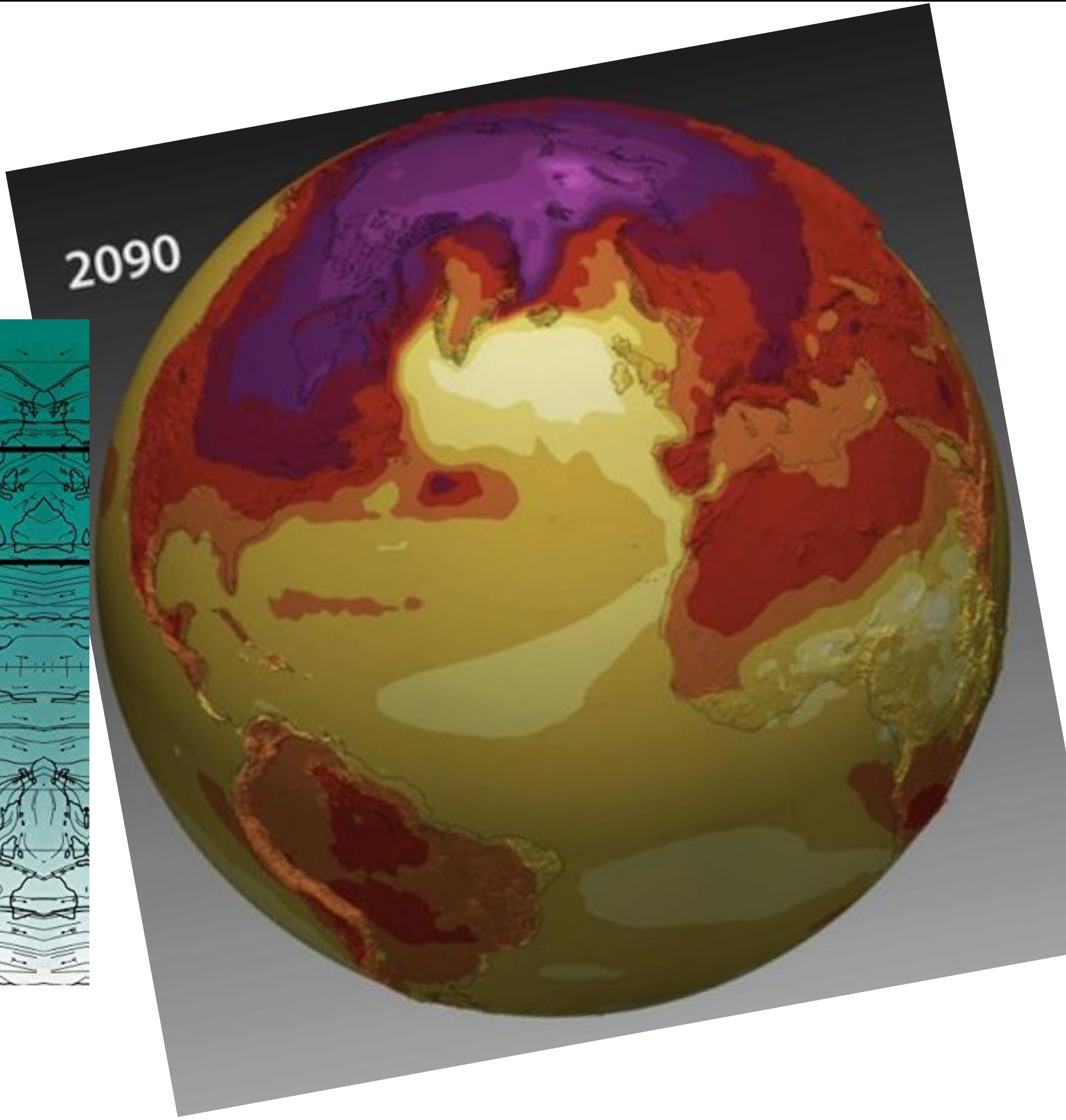
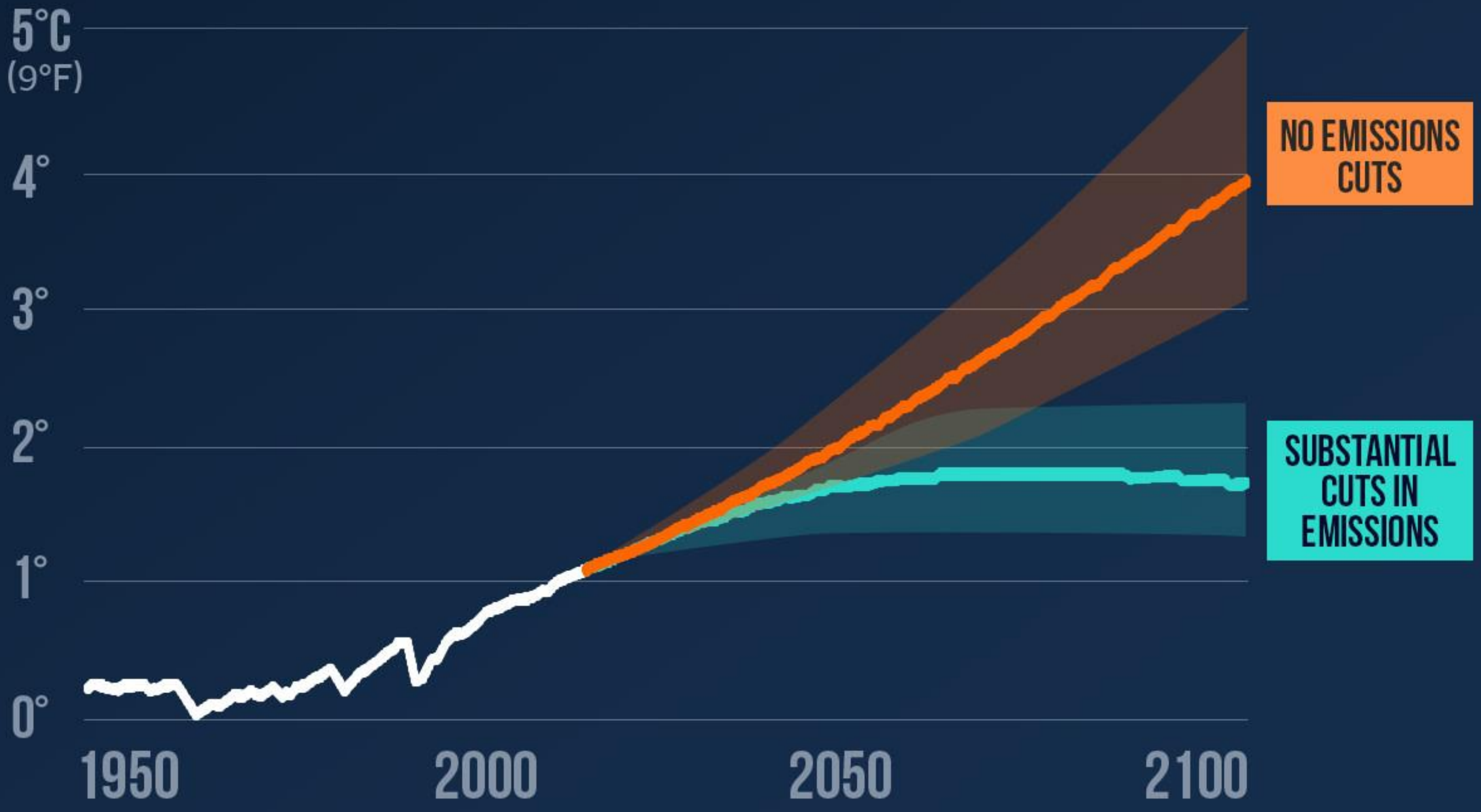


Image: NASA, MPI

FUTURE TEMPERATURES

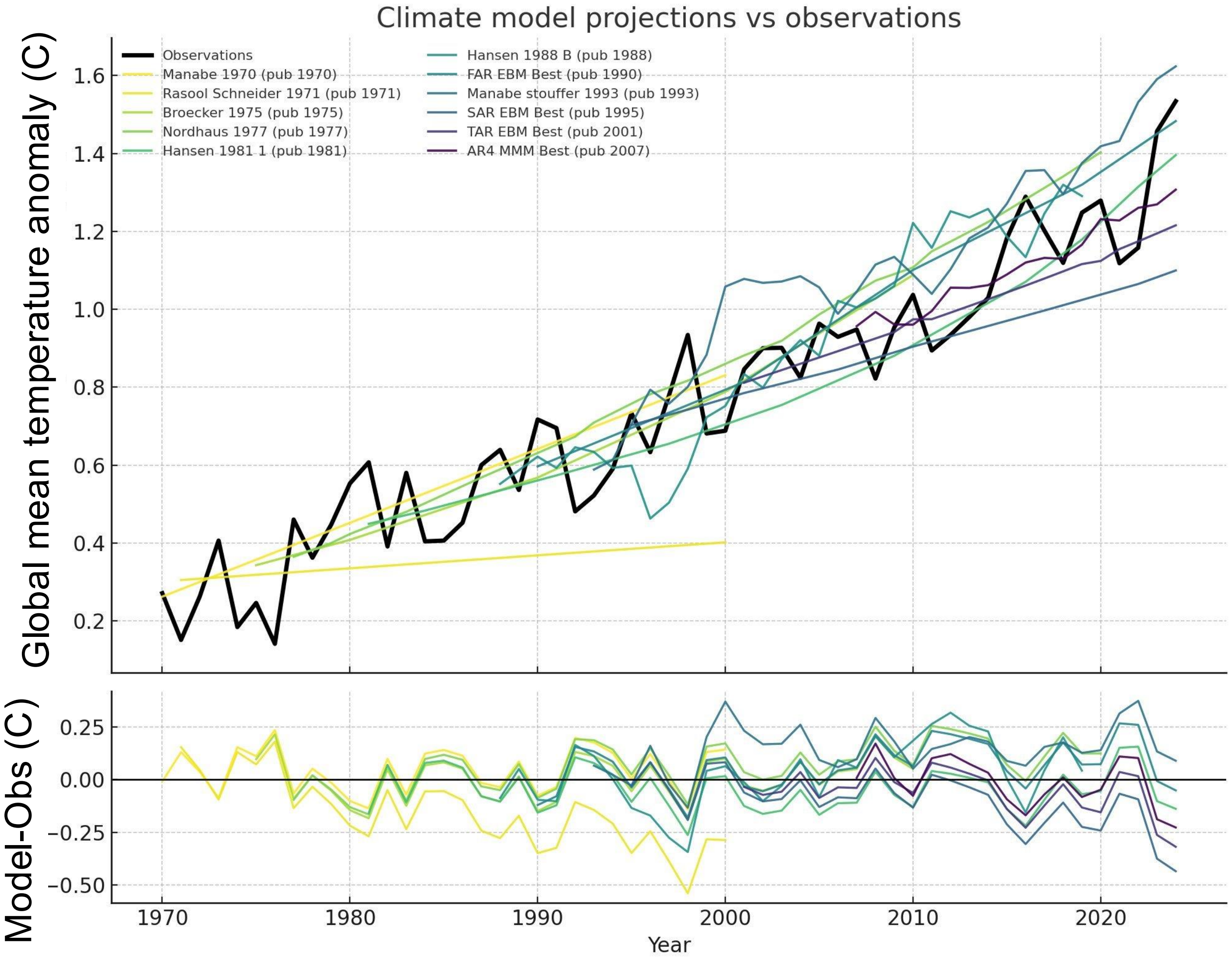
WARMING DEPENDS ON CHOICES TODAY



Global surface temperature (°C) anomaly relative to 1850-1900
High warming scenario: SSP3-7, Low warming scenario from SSP1-2.6.
Source: IPCC AR6 WG1

CLIMATE CENTRAL

Predicting the global warming today back in the 1960s requires physics



Hausfather et al. (2019)

THE NOBEL PRIZE IN PHYSICS 2021

Illustrations: Niklas Elmehed

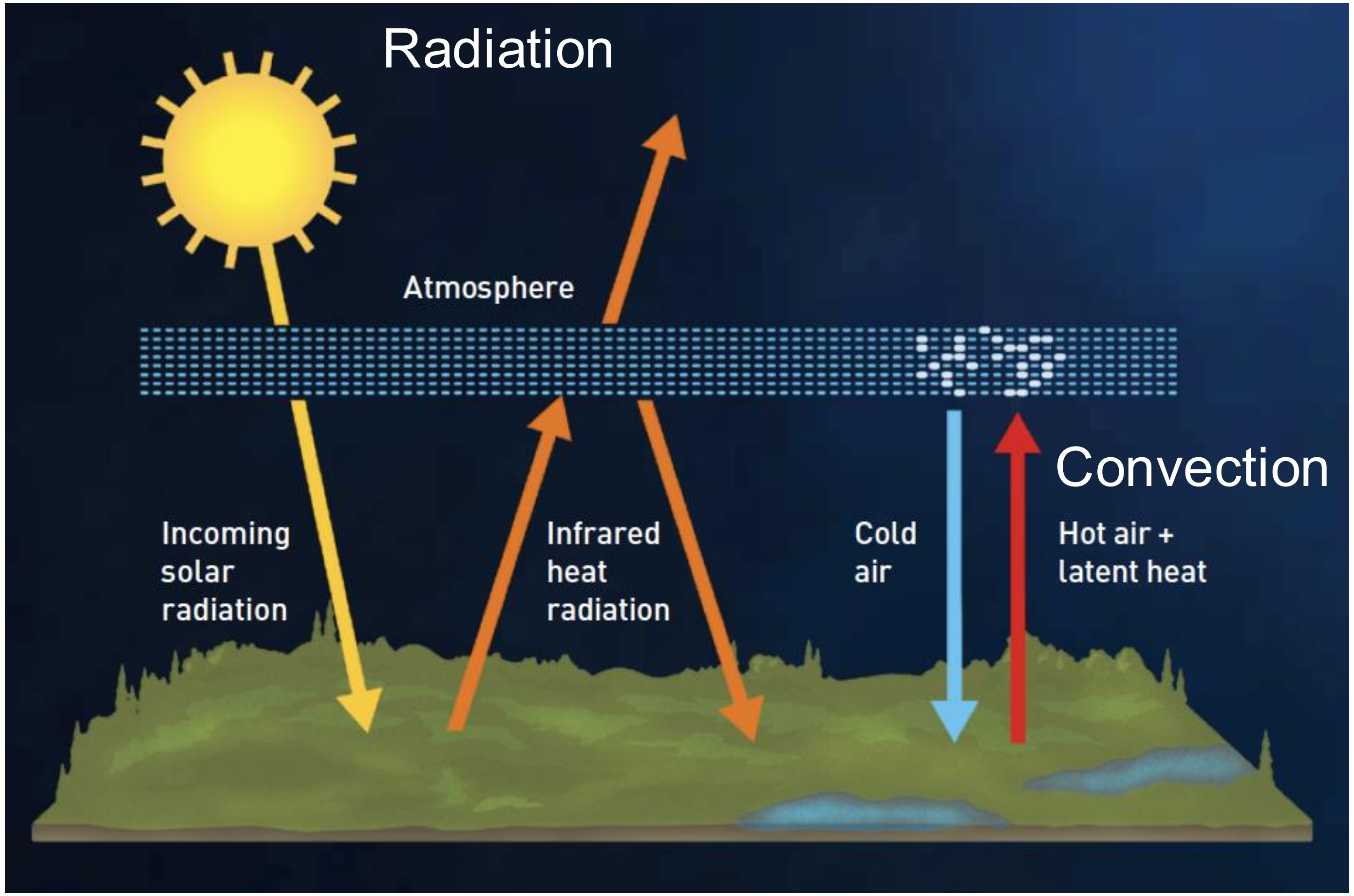
Syukuro Manabe | **Klaus Hasselmann** | **Giorgio Parisi**

"for the physical modelling of Earth's climate, quantifying variability and reliably predicting global warming"

"for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales"

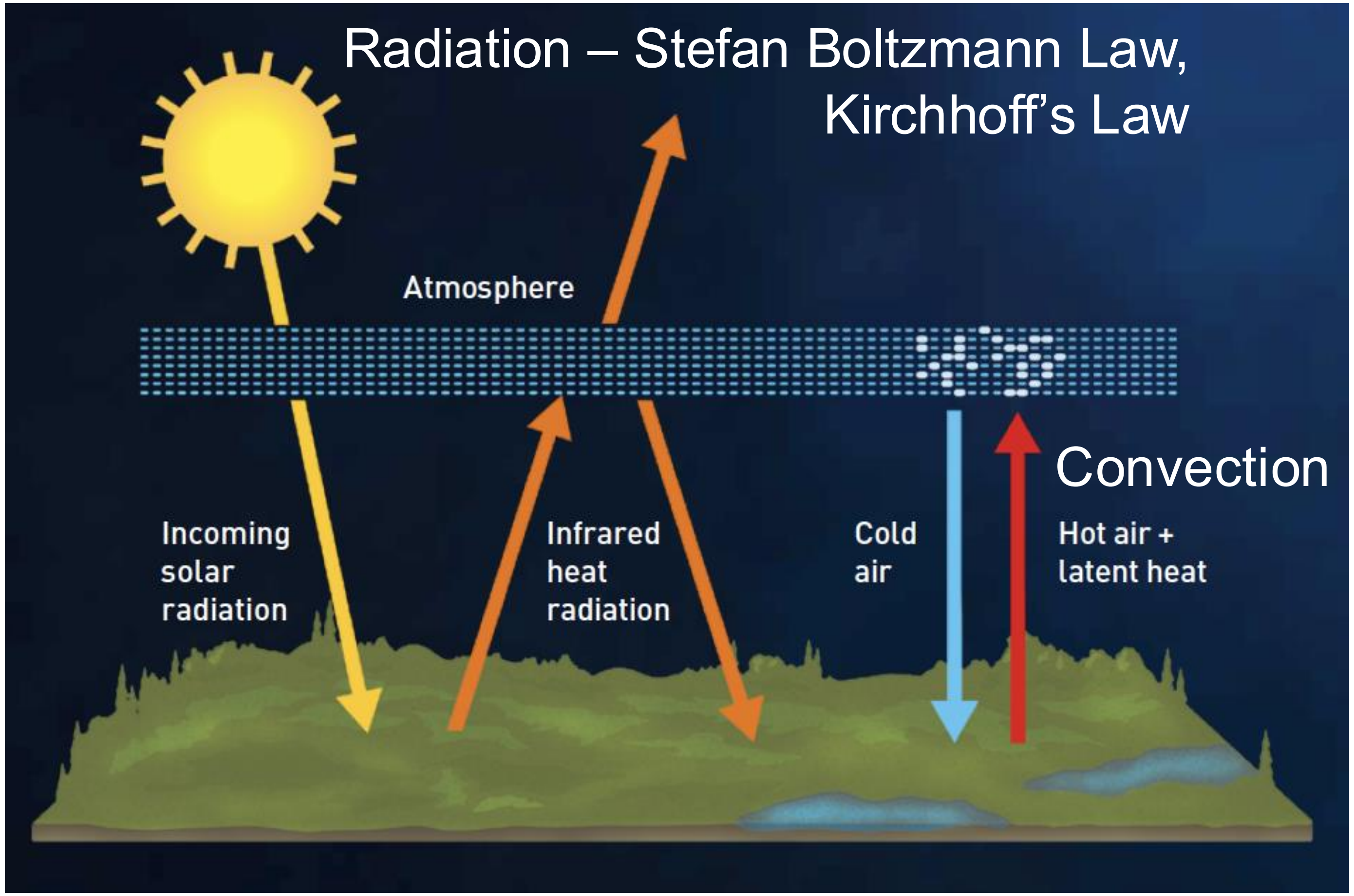
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Manabe's climate models relied on applying energy conservation to large-scales



Nobel committee

Manabe's climate models relied on applying energy conservation to large-scales



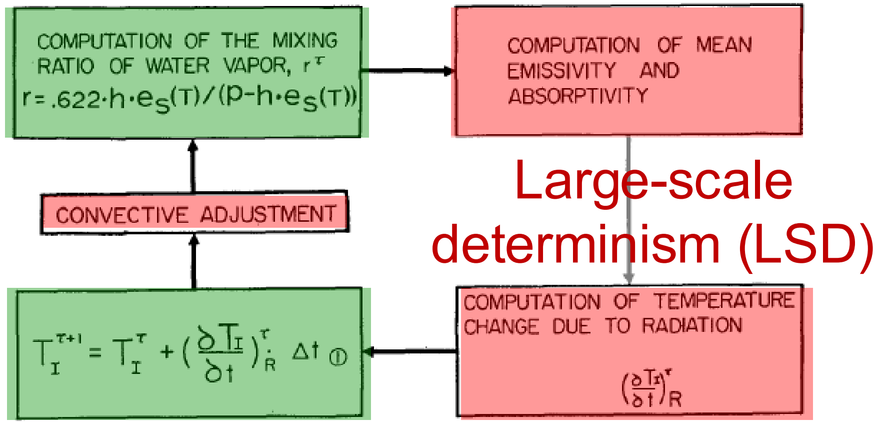
determined by temperature adjustment to moist adiabat

Nobel committee

Climate models involve the application of physical laws to large-scales

$$\underbrace{\frac{\partial T}{\partial t}}_{\text{large-scales}} = \underbrace{Q_{\mathrm{R}} + Q_{\mathrm{C}} + \ldots}_{\text{LSD closures}}$$

Atmospheric energy balance

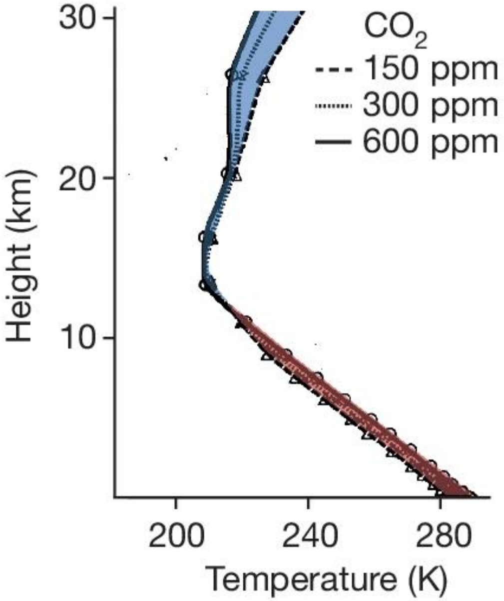


Manabe & Weatherald (1967)

Physical Complexity

Climate model predicts increased CO2 leads to global-mean surface warming, cooling aloft

Atmospheric energy balance



Manabe & Wetherald (1967)

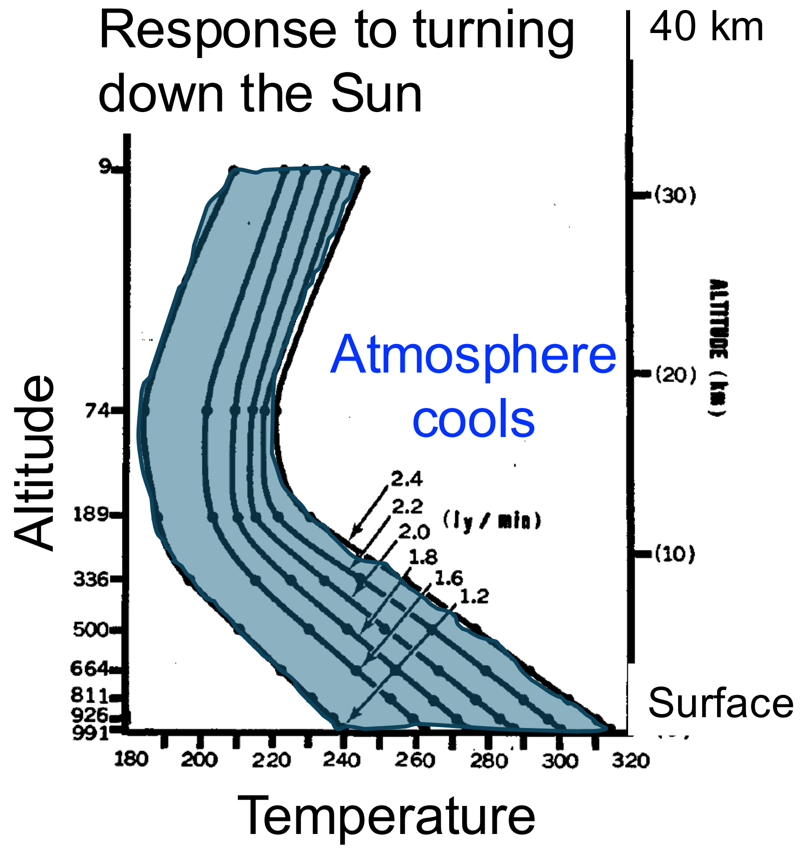
Physical Complexity

Surface warming sensitive to assumptions about moisture and clouds

Change of CO_2 content (ppm)	Fixed relative humidity		Fixed absolute humidity	
	Average cloudiness	Clear	Average cloudiness	Clear
300 → 600	+2.36	2.92	+1.33	+1.36

Manabe & Weatherald (1967)

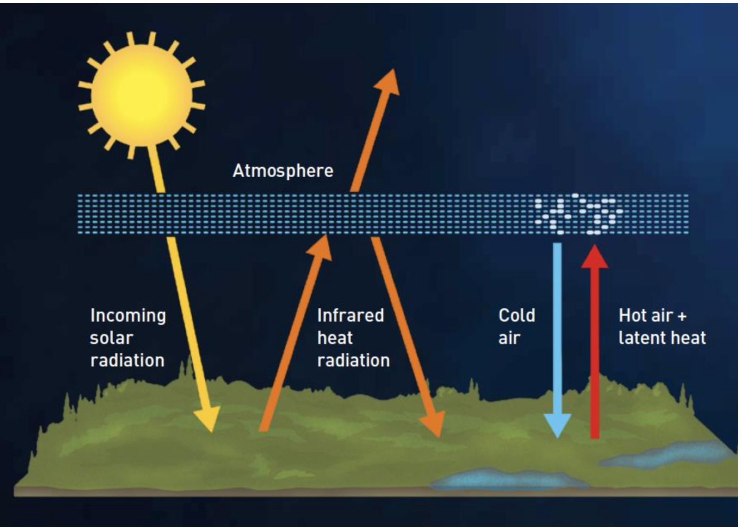
Climate model predicts turning down the sun leads to global-mean cooling at all altitudes



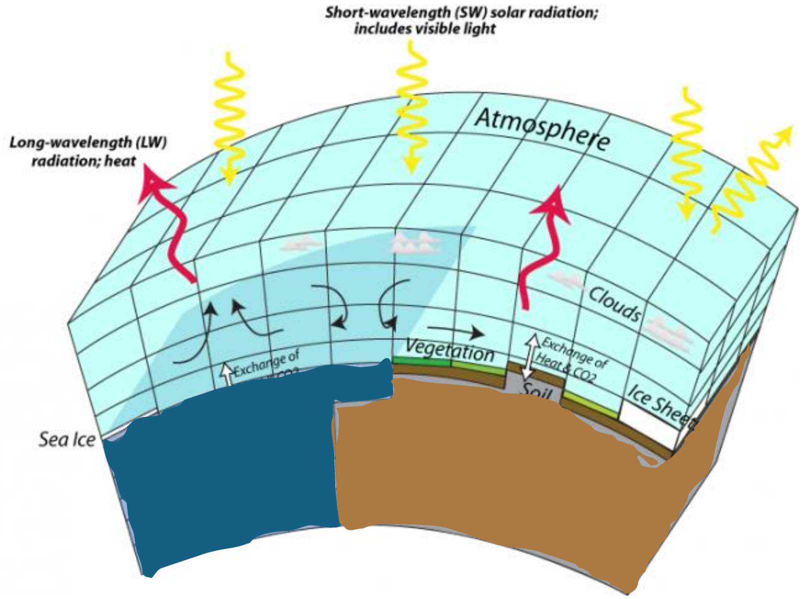
Physical Complexity

Climate models involve the application of physical laws to large-scales

Global-mean (altitude)
Atmospheric energy balance



Latitude-altitude
Atmospheric energy and momentum balance



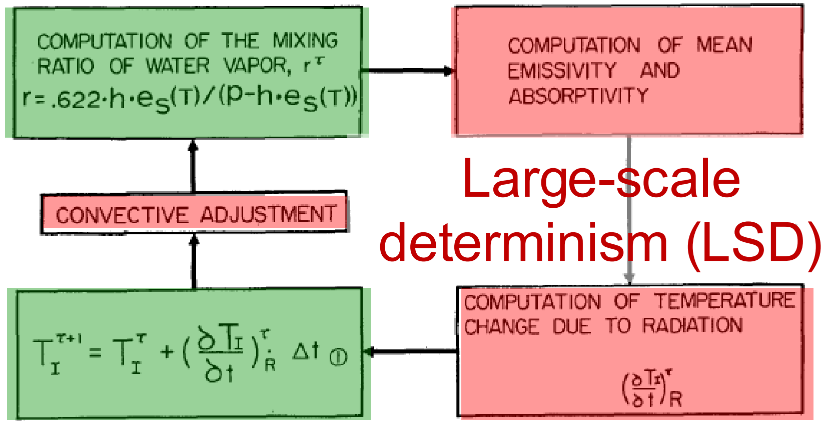
$$\underbrace{\frac{\partial T}{\partial t} + \mathbf{v}\cdot\nabla T}_{\text{large-scales}} = \underbrace{Q_{\mathrm{R}} + Q_{\mathrm{C}} + ...}_{\text{LSD closures}}$$

$$\underbrace{\frac{\partial u}{\partial t} + \mathbf{v}\cdot\nabla u - fv + \frac{\partial p}{\partial x}}_{\text{large-scales}} = \underbrace{F_{\mathrm{W}} + F_{\mathrm{F}} + ...}_{\text{LSD closures}}$$

Physical Complexity

Climate models involve the application of physical laws to large-scales

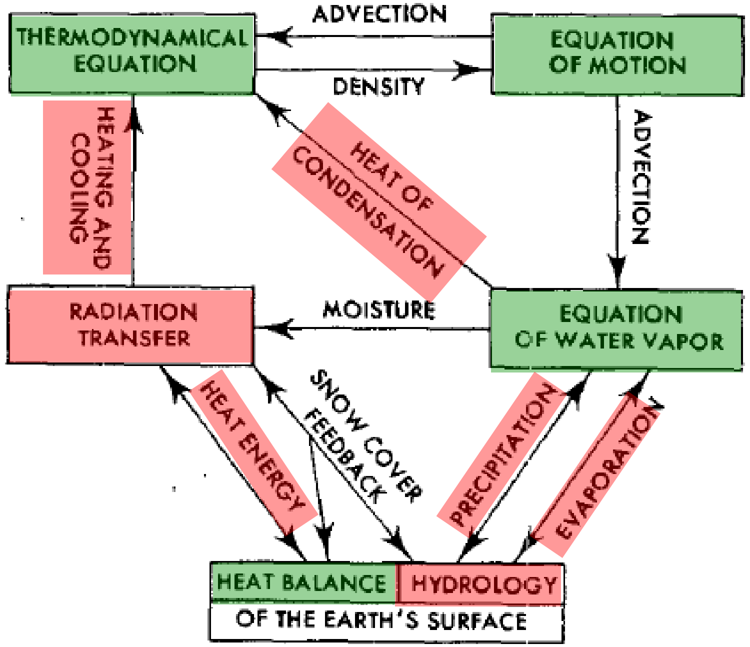
Atmospheric energy balance



Physical laws

Manabe & Wetherald (1967)

Atmospheric energy (1st law) and momentum (2nd law) balance

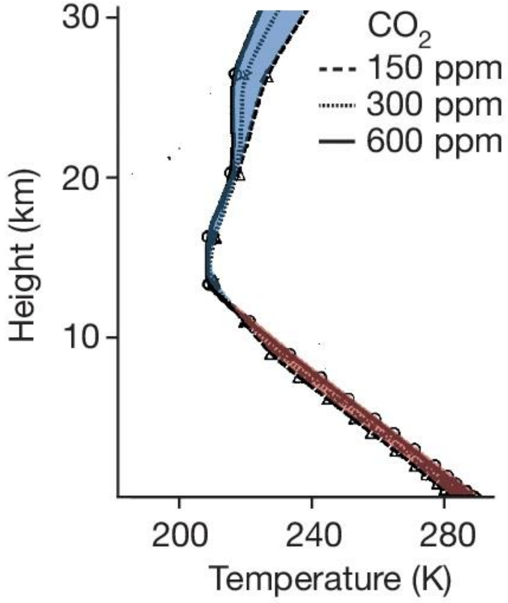


Manabe & Wetherald (1975)

Physical Complexity

Climate model predict increased CO2 leads to polar amplified surface warming

Atmospheric energy balance



Manabe & Wetherald (1967)

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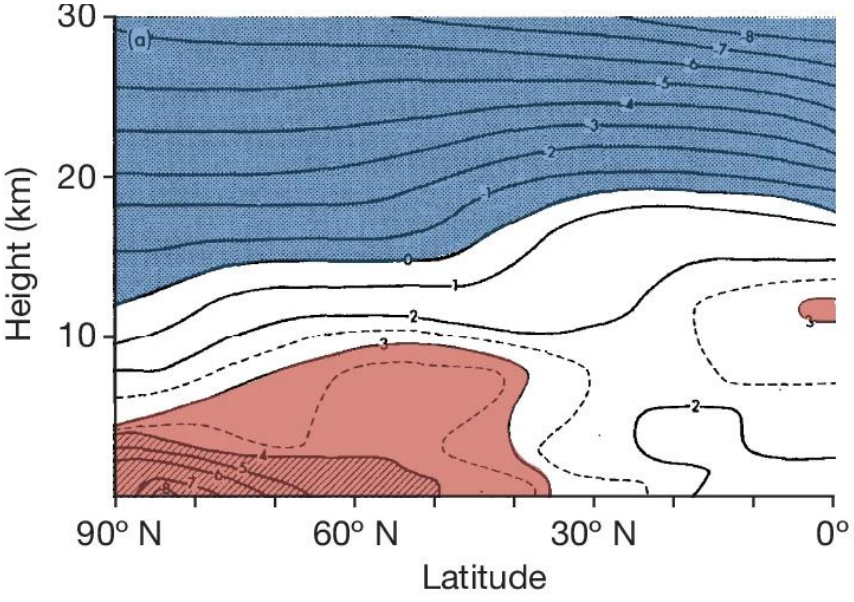
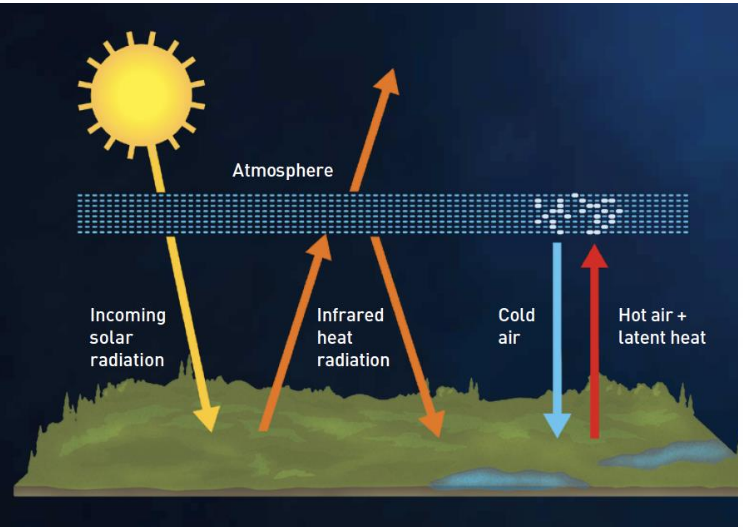


Manabe & Wetherald (1980)

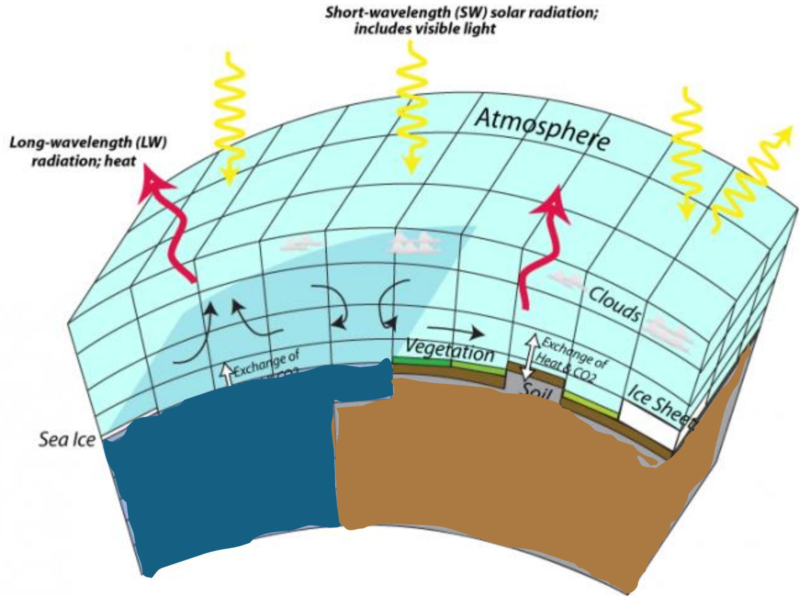
Physical Complexity

Climate models involve the application of physical laws to large-scales

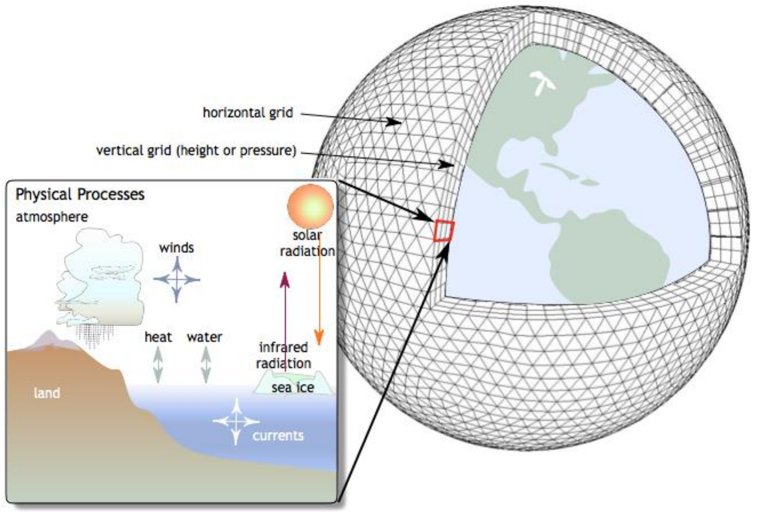
Global-mean (altitude)
Atmospheric energy balance



Latitude-altitude
Atmospheric energy and momentum balance



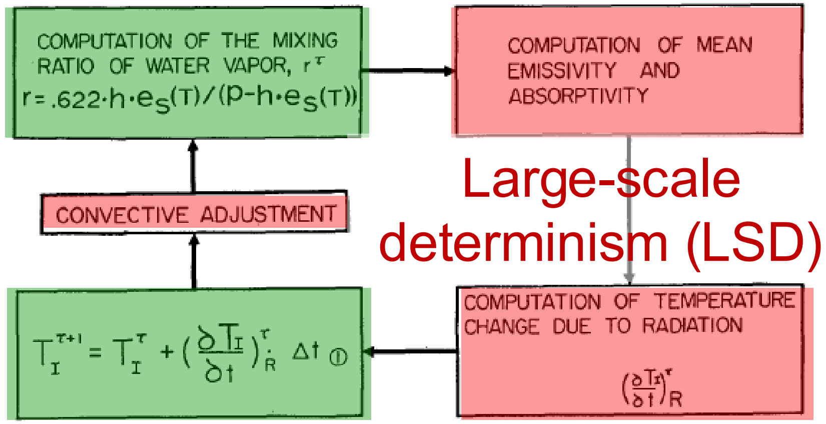
Latitude-longitude-altitude
Atmosphere & Ocean
energy and momentum balance



Physical Complexity

Climate models involve the application of physical laws to large-scales

Atmospheric energy balance



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Manabe & Wetherald (1967)

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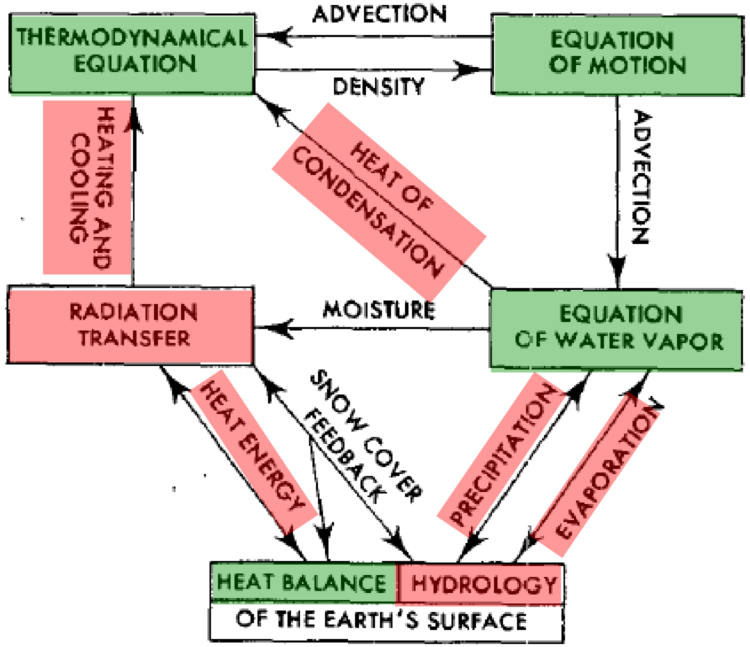
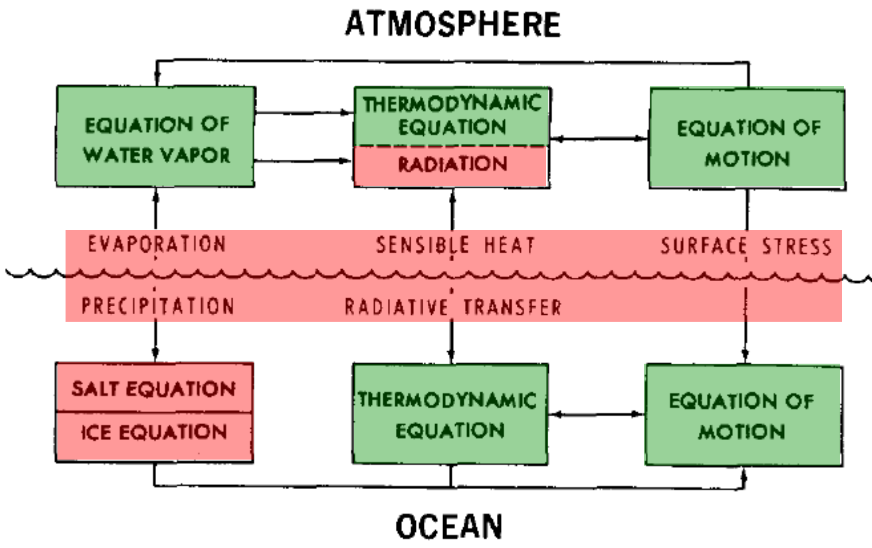


Manabe & Wetherald (1975)

Atmosphere & Ocean energy and momentum balance

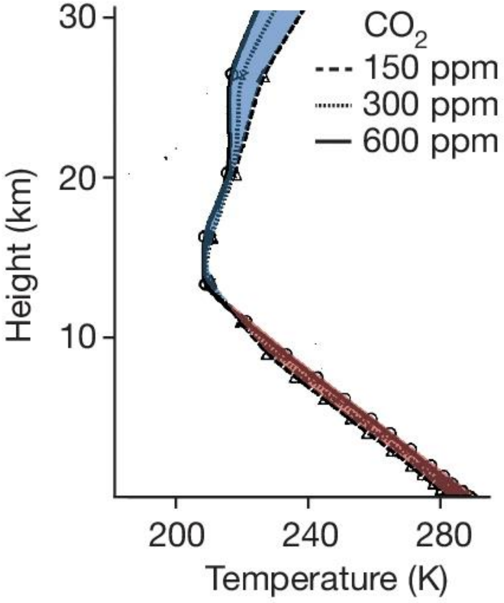


Stouffer et al. (1989)

Physical Complexity

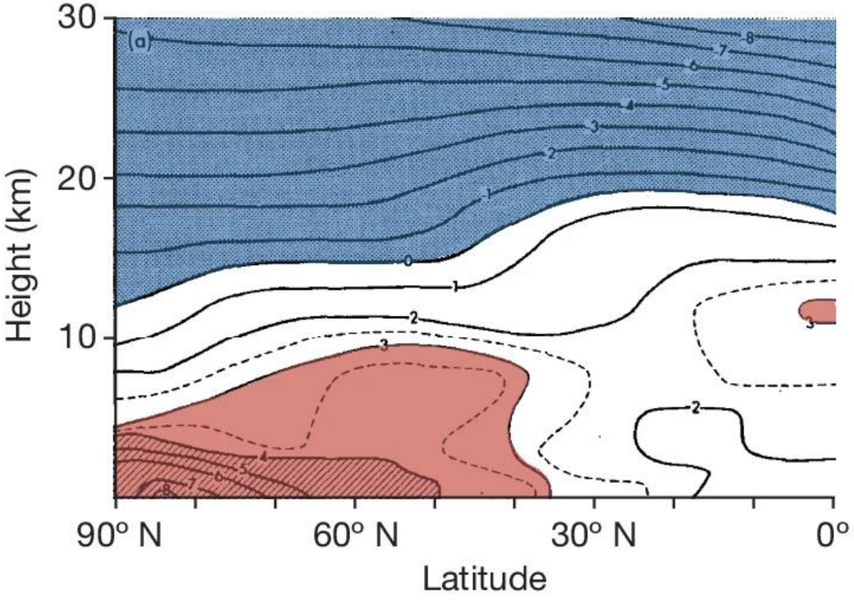
Climate models predict increased CO2 leads to delayed surface warming over the Southern Ocean

Atmospheric energy balance



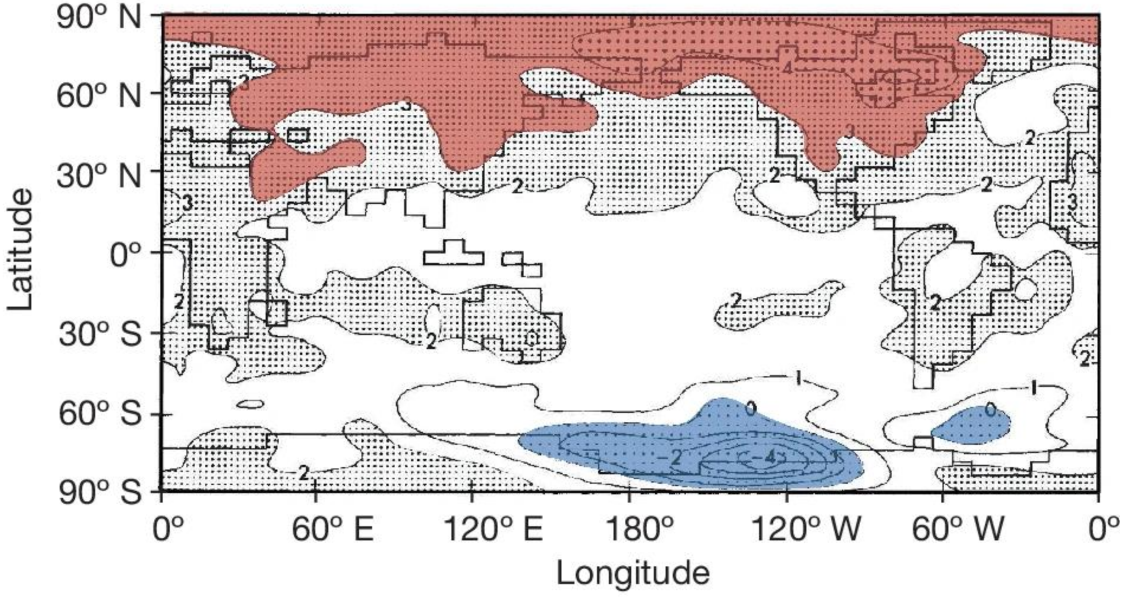
Manabe & Wetherald (1967)

Atmospheric energy (1st law) and momentum (2nd law) balance



Manabe & Wetherald (1980)

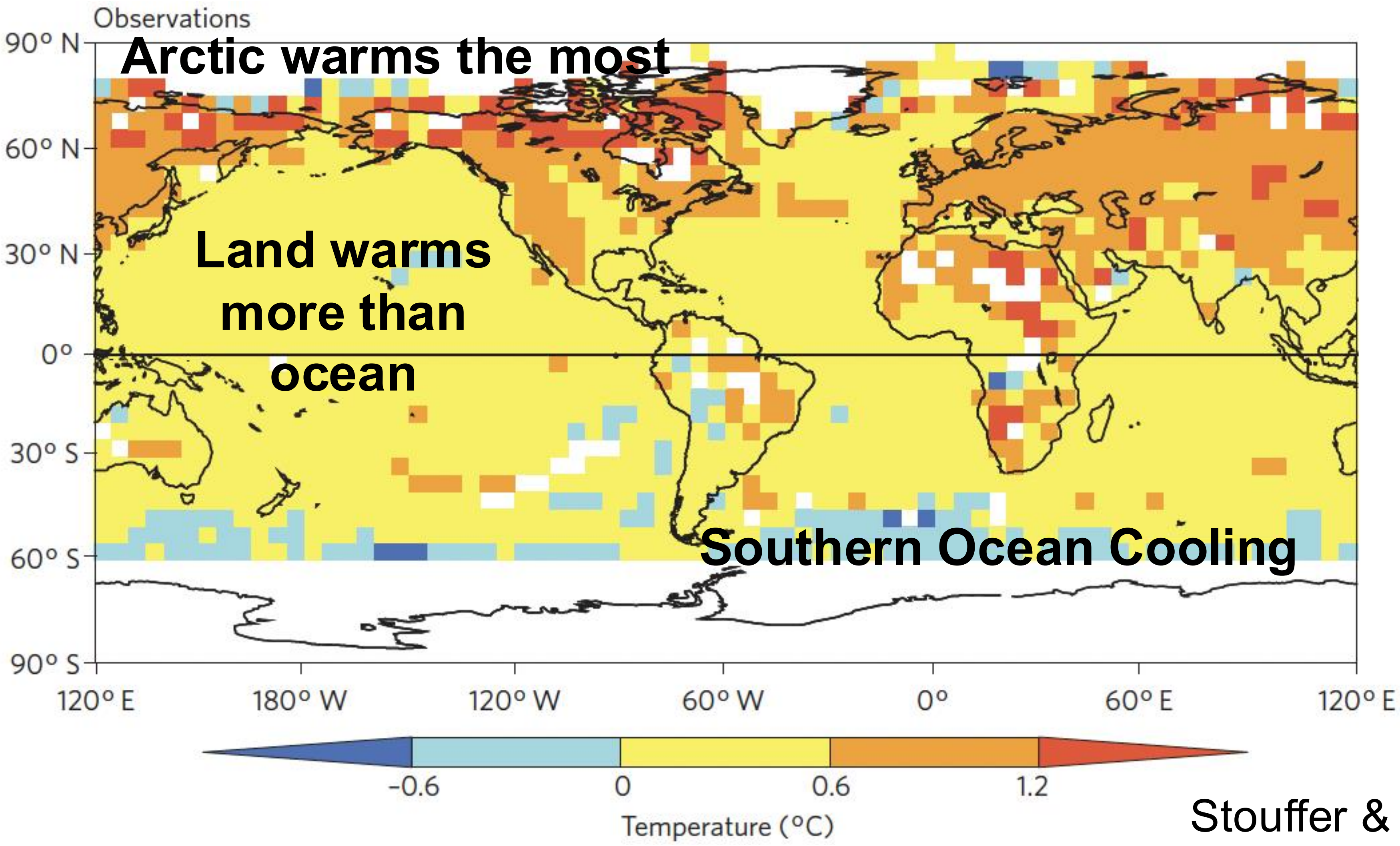
Atmosphere & Ocean energy and momentum balance



Stouffer et al. (1989)

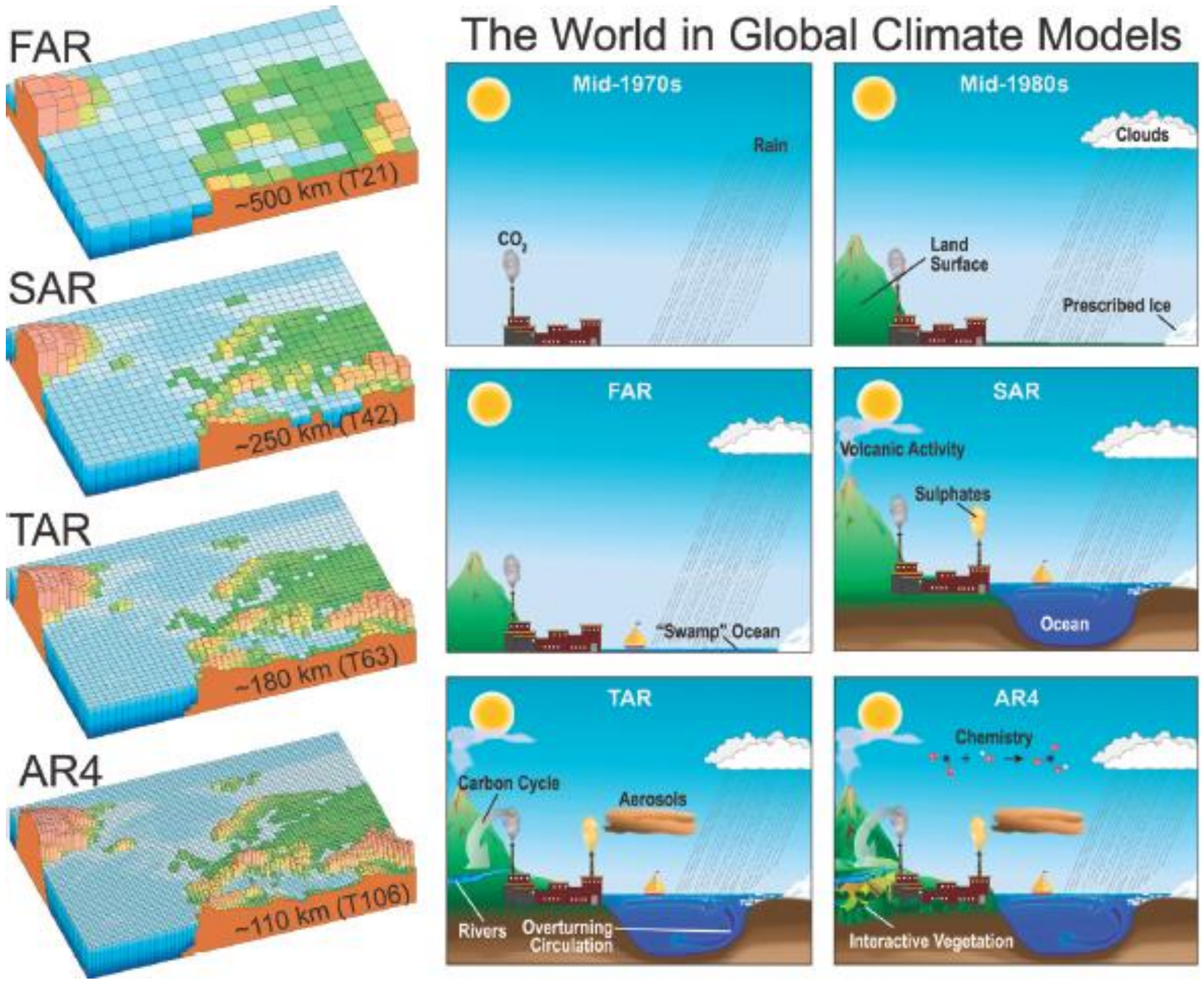
Physical Complexity

Predicted temperature signals have emerged across many regions



Stouffer & Manabe (2017)

60 years later…"We've gotten better at doing pretty much the same thing" D. Randall

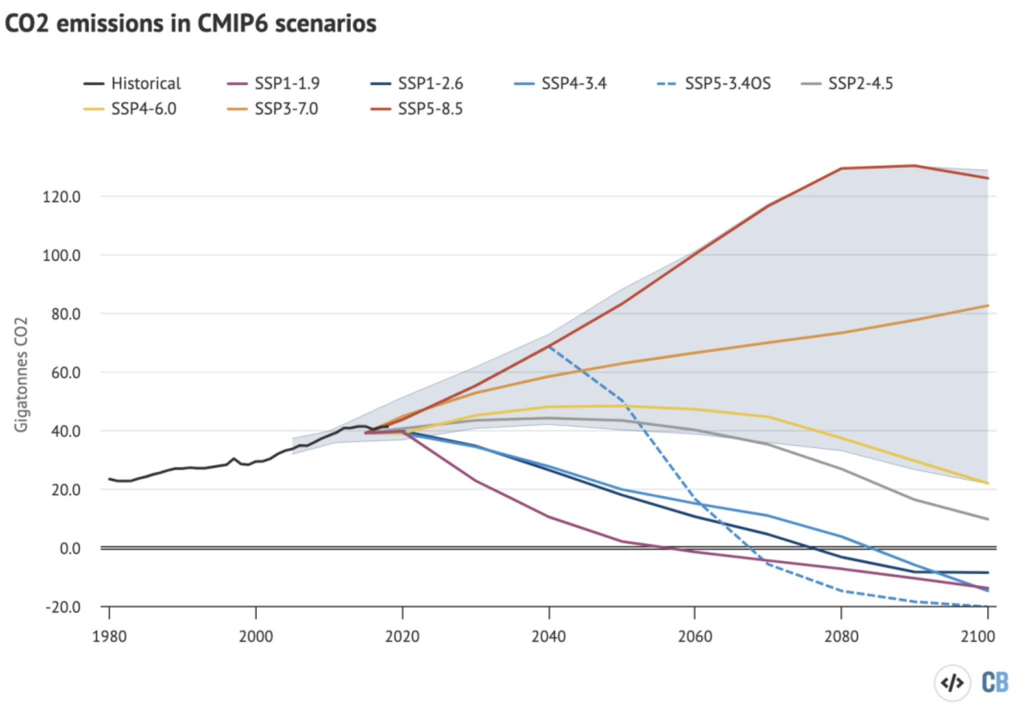


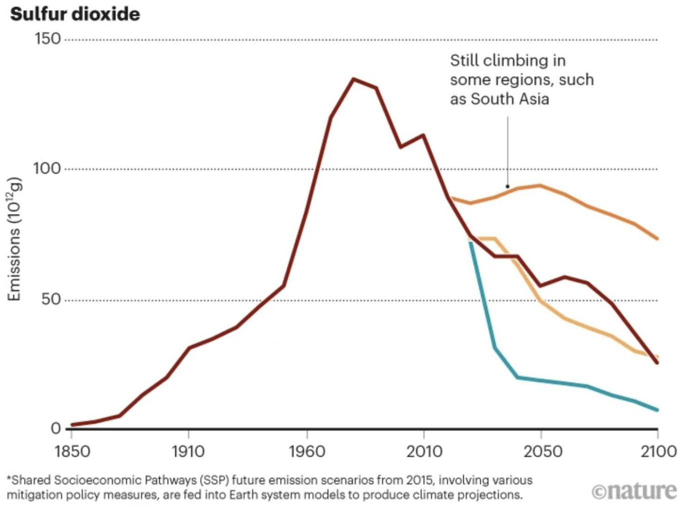
National Academy of Sciences

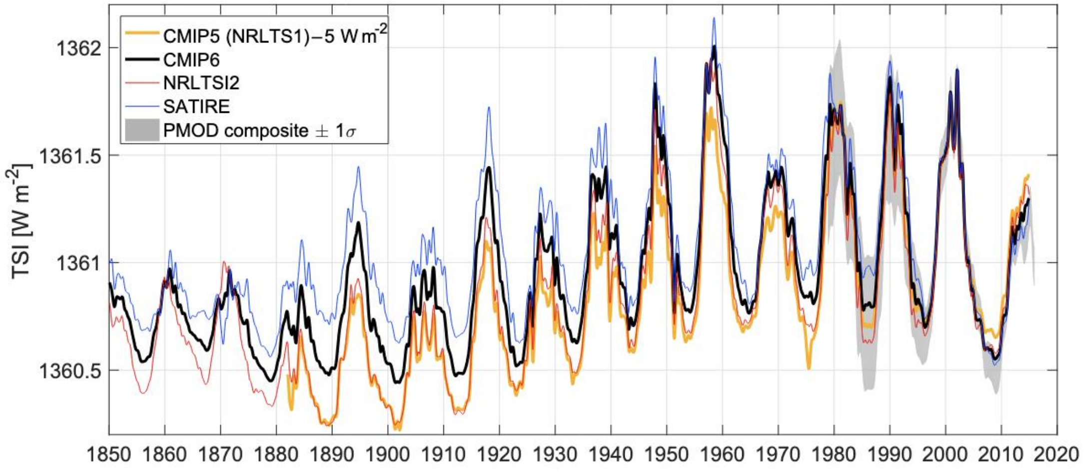
Dozens of climate model centers around the world

Probablefutures.org

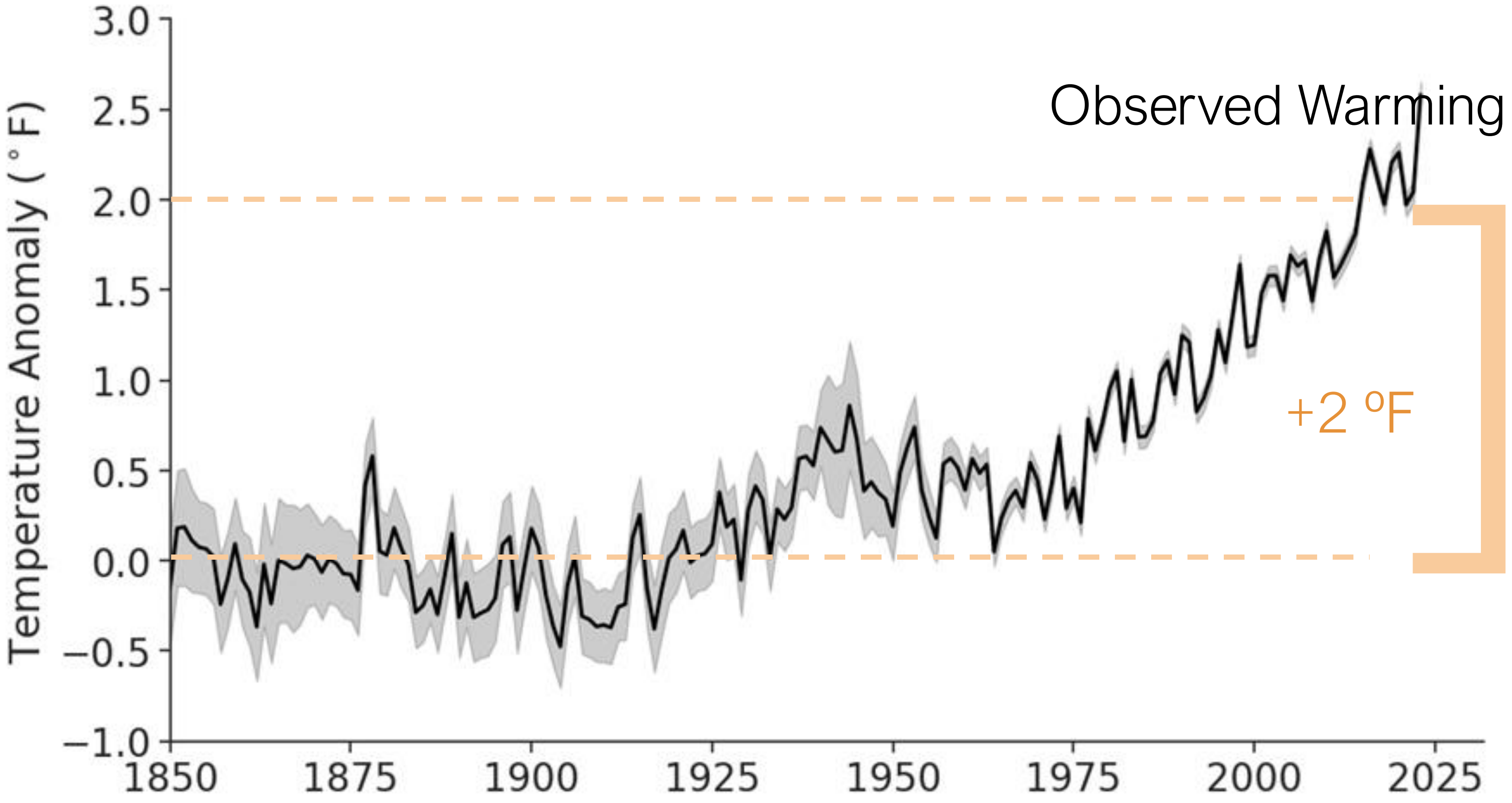
Climate models given boundary conditions from natural sources and human influence





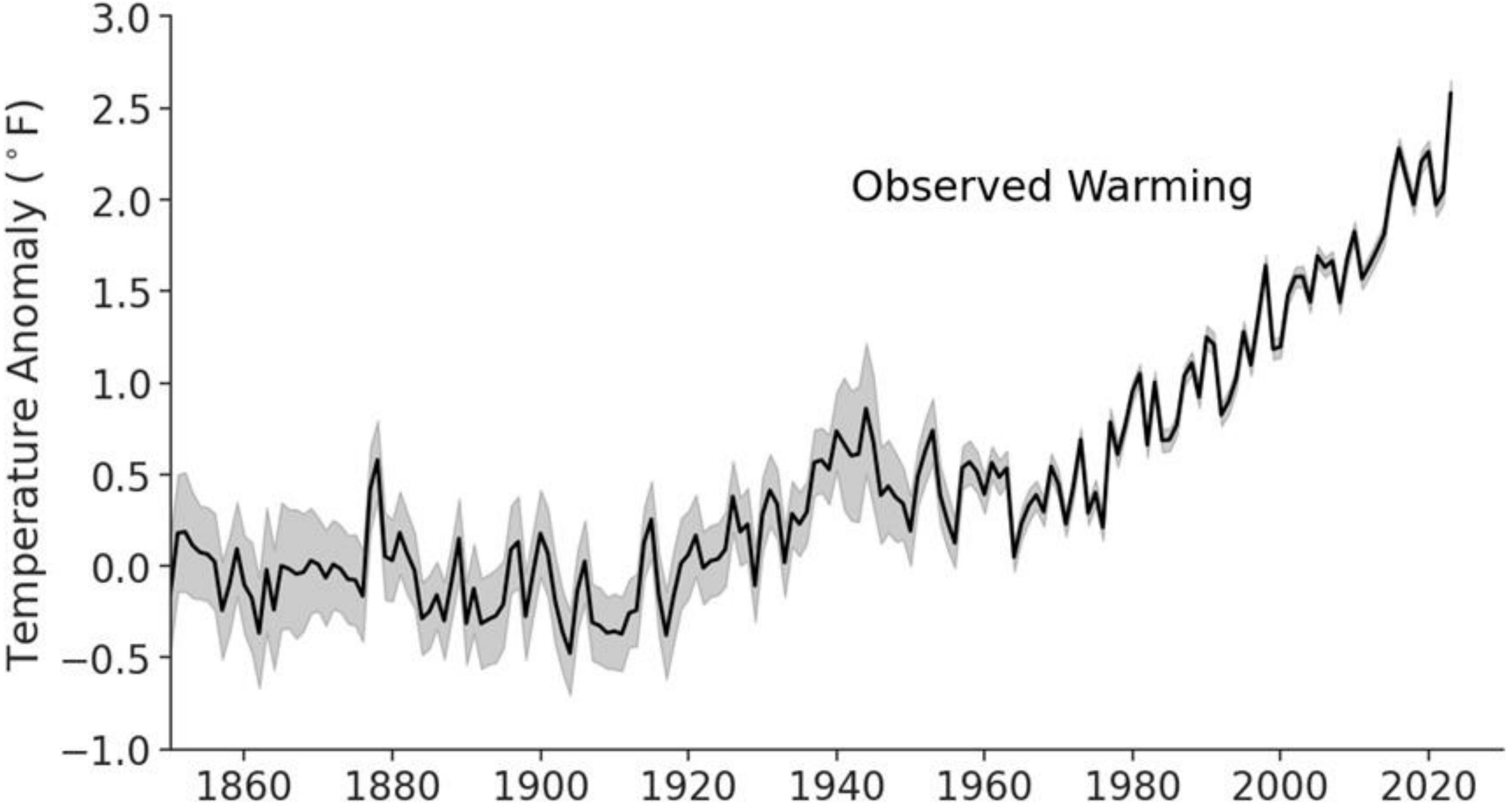


Observed global warming is around 2F



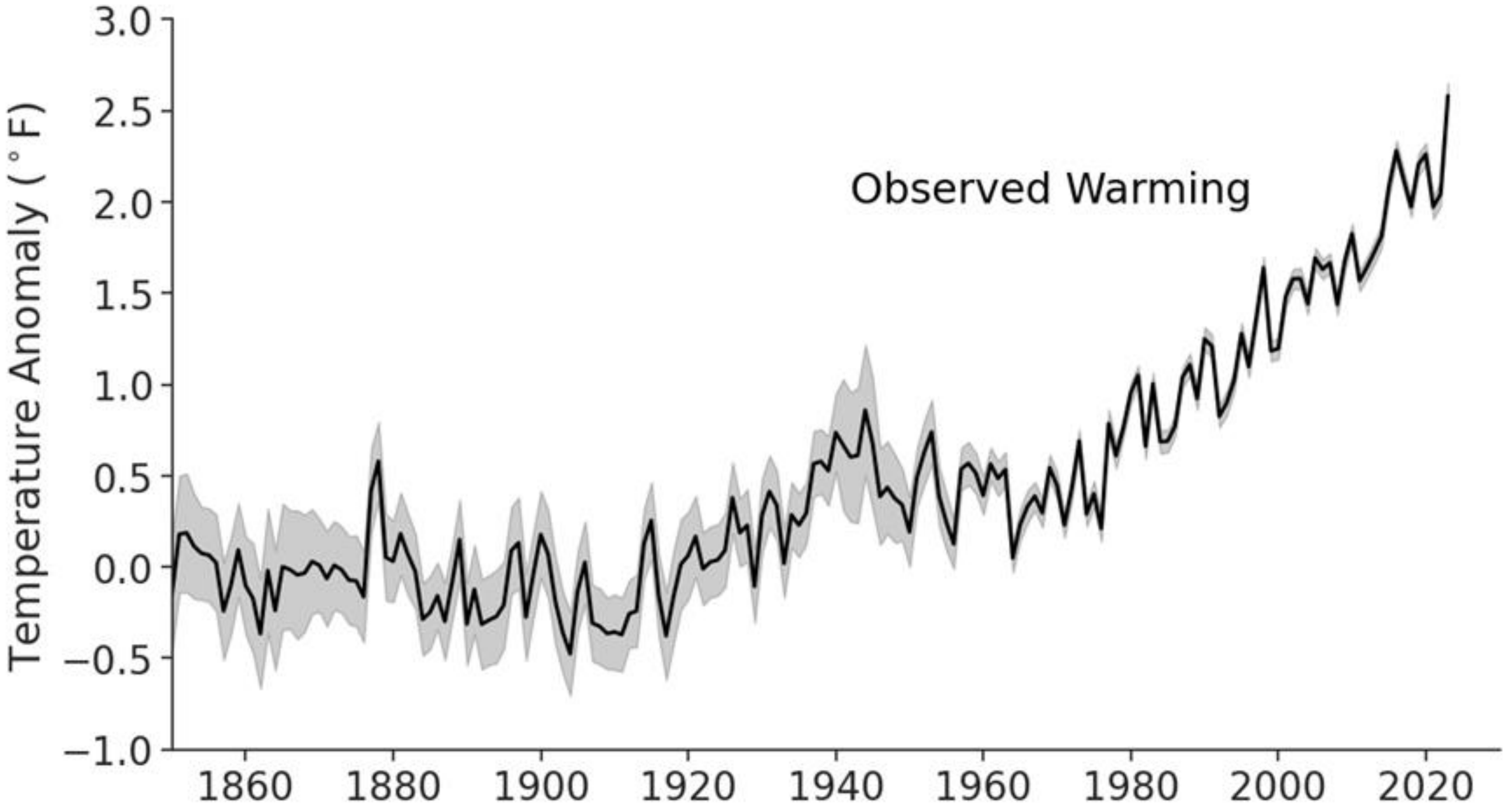
Source: HADCRUT5 (Met Office).

Physics-based climate models show global mean warming does not occur due to natural changes

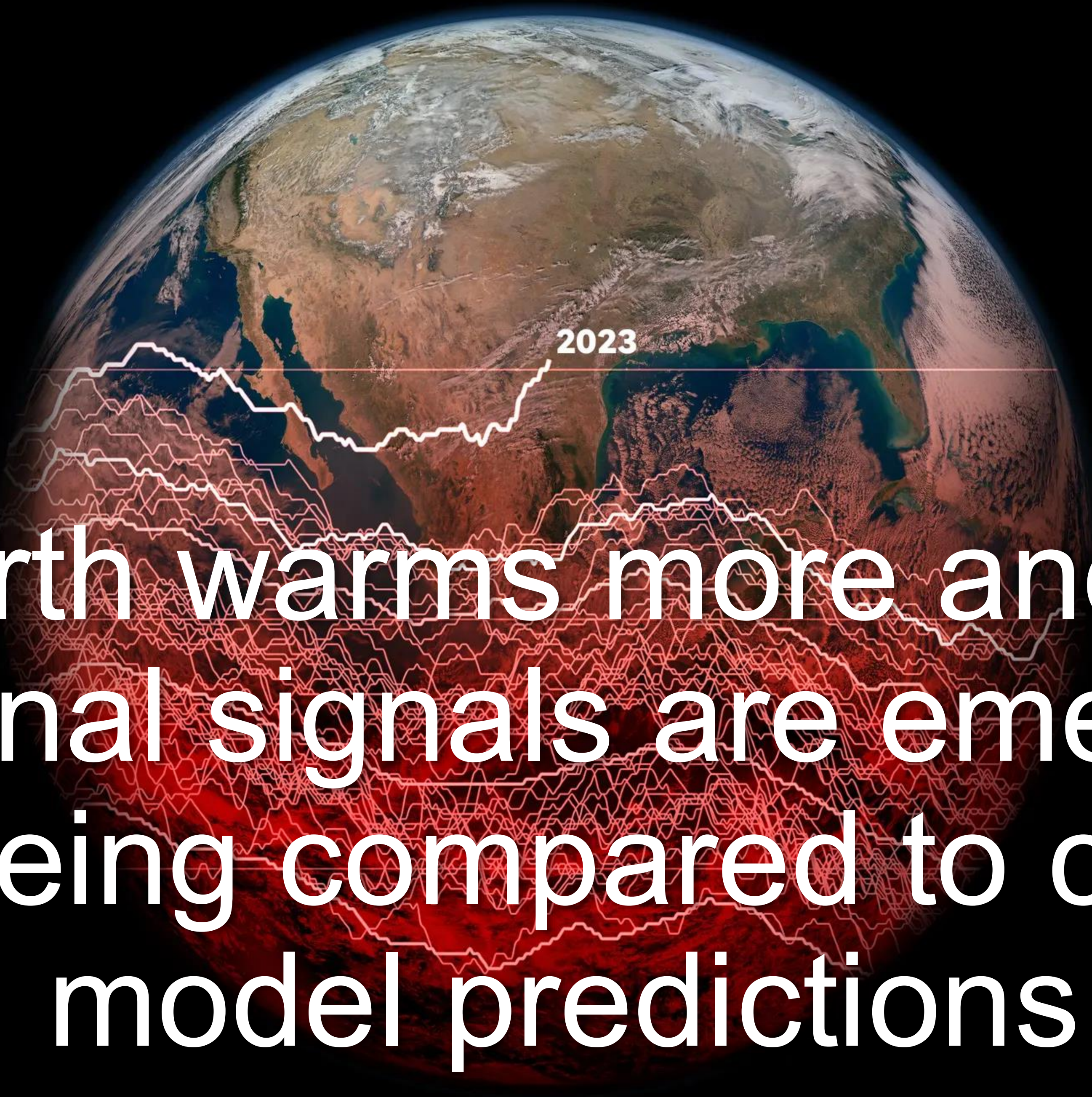


Source: Modeled natural changes from FAQ 3.1, Figure 1 in IPCC, 2021: Chapter 3. The Physical Science Basis. Observed warming is HADCRUT5.

Physics-based climate models show observed warming only occurs with human influence

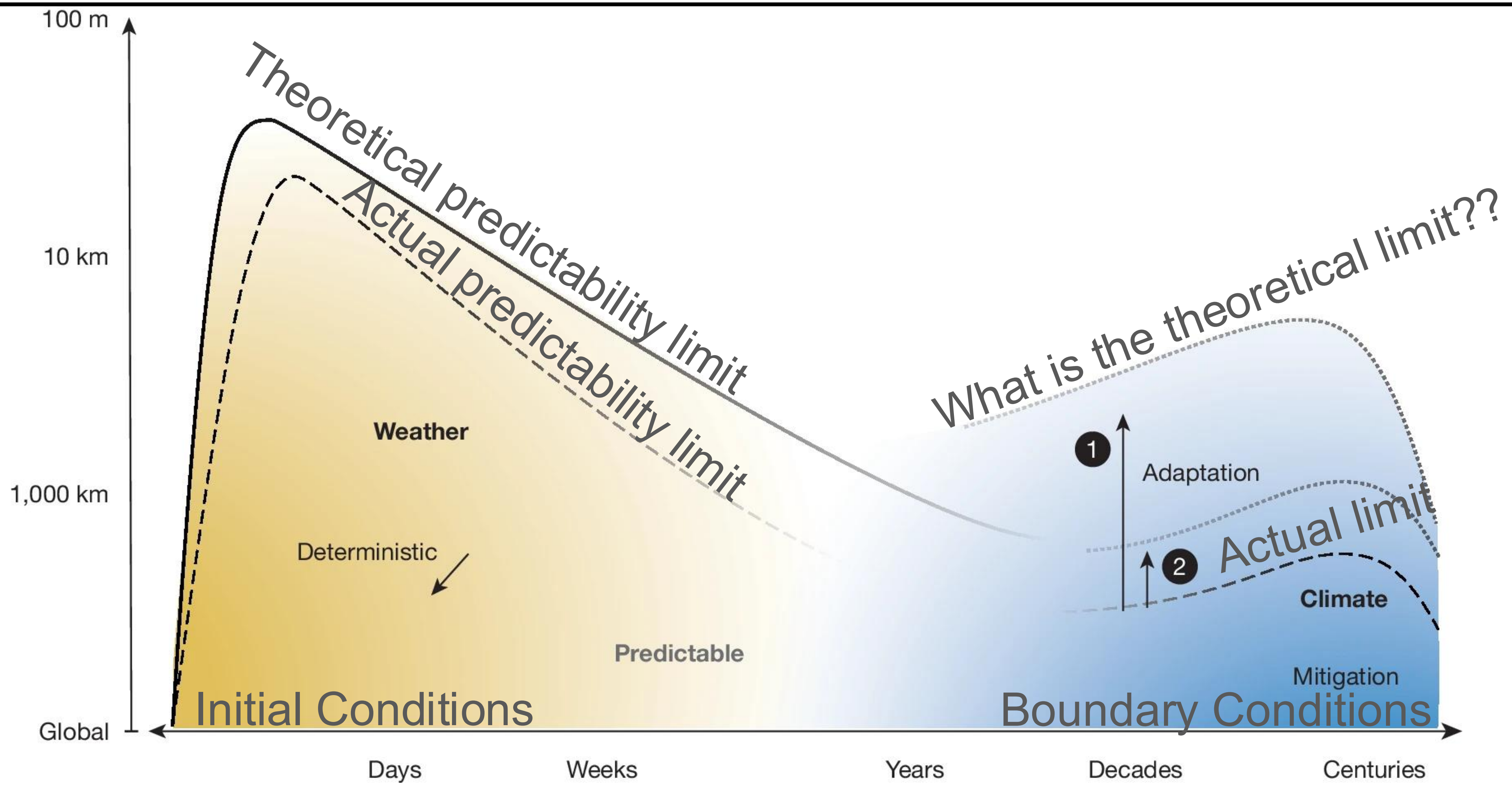


Source: Modeled human + natural changes from FAQ 3.1, Figure 1 in IPCC, 2021: Chapter 3. The Physical Science Basis. Observations are HADCRUT5.



As Earth warms more and more regional signals are emerging and being compared to climate model predictions

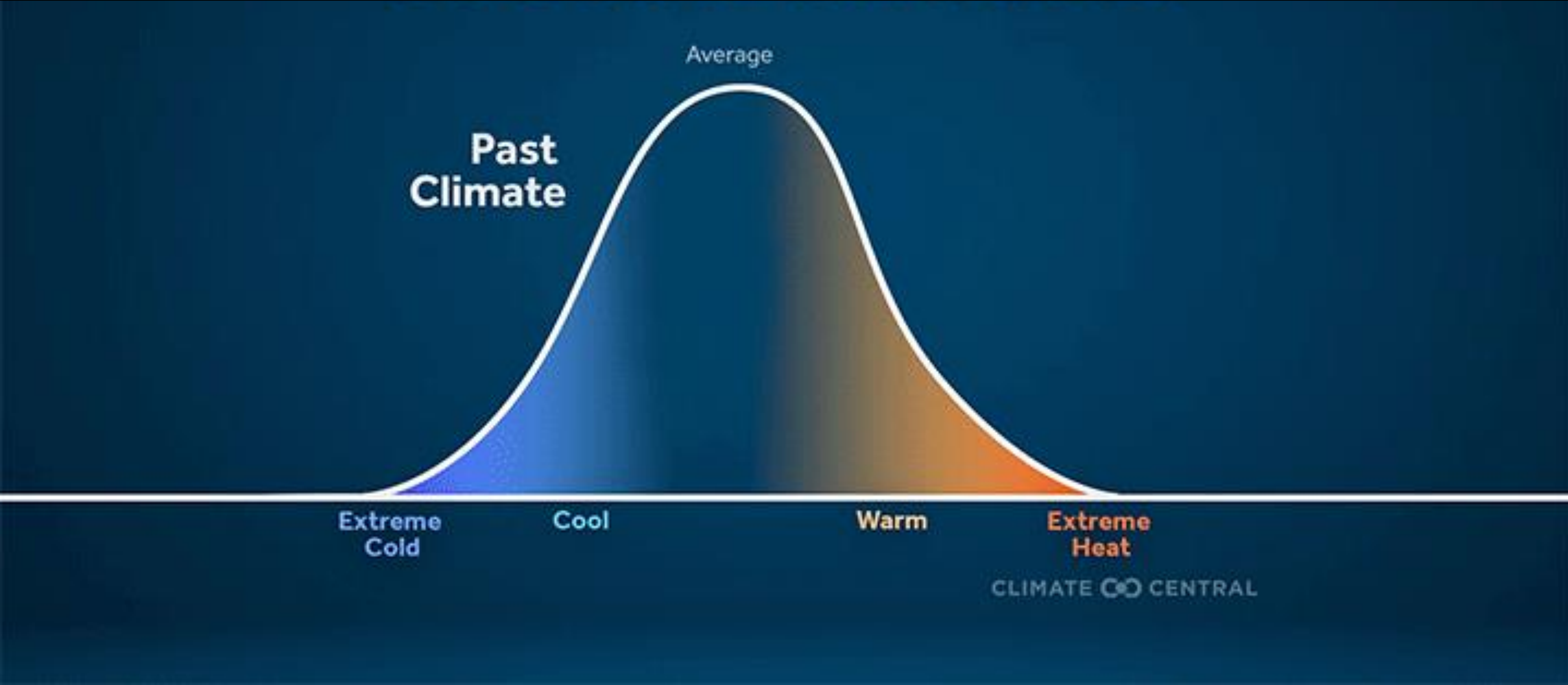
We are testing the limits of climate prediction in real time



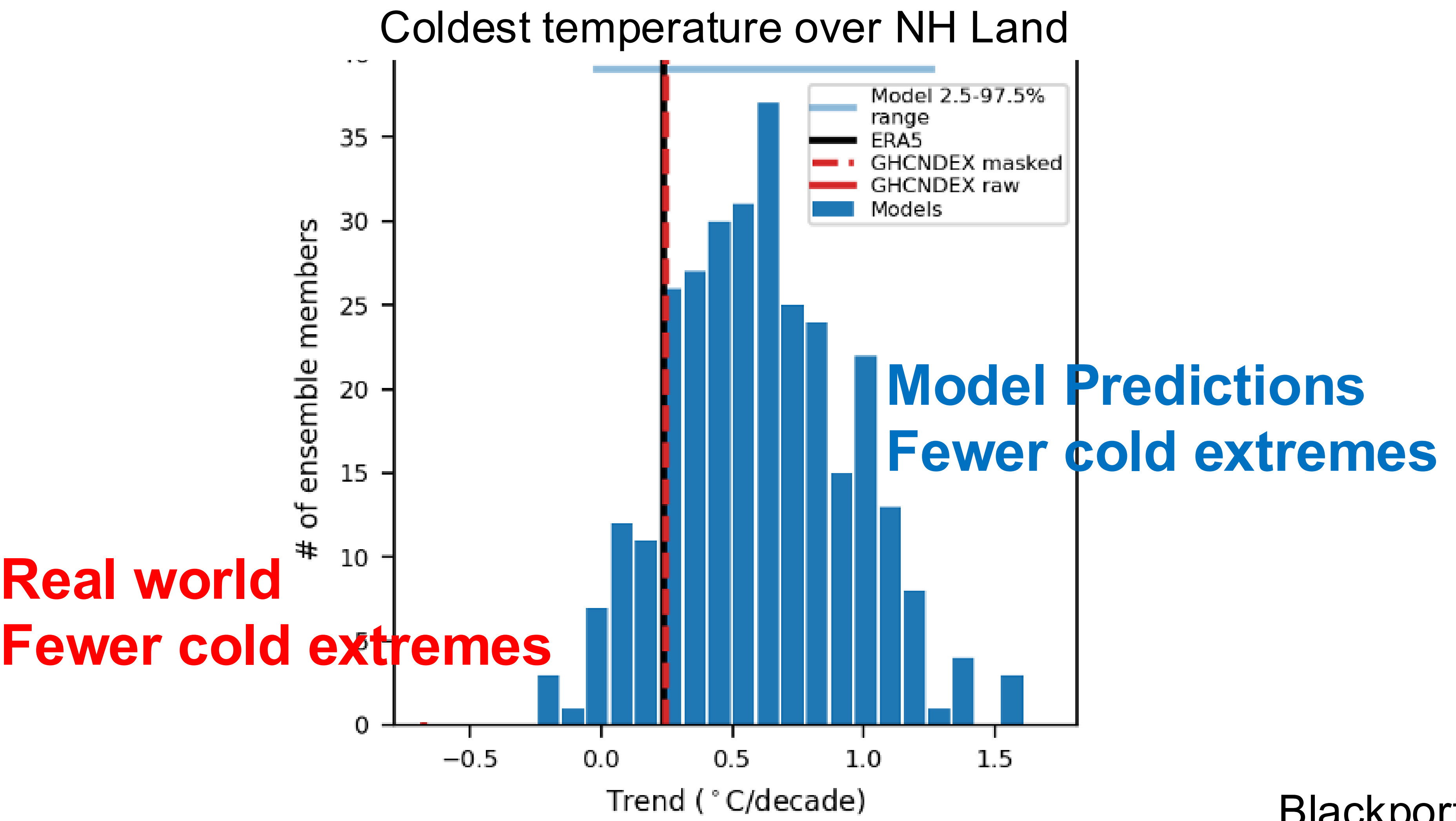
Shaw & Stevens (2025, Nature)


Cold waves
have become
less cold.

Extreme cold gets less cold following an increase of the average

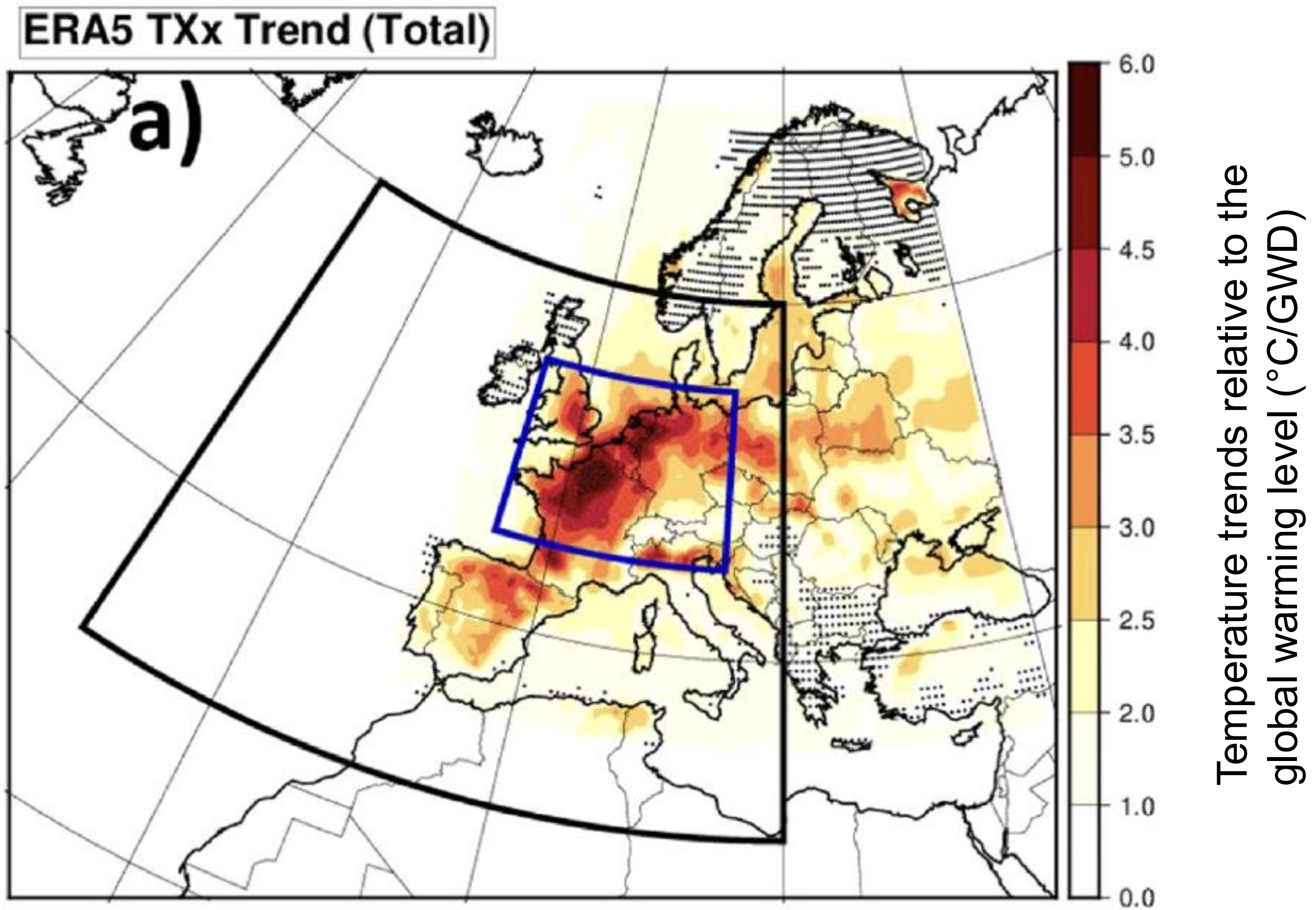


Climate predictions with human influence capture increase of coldest land temperature



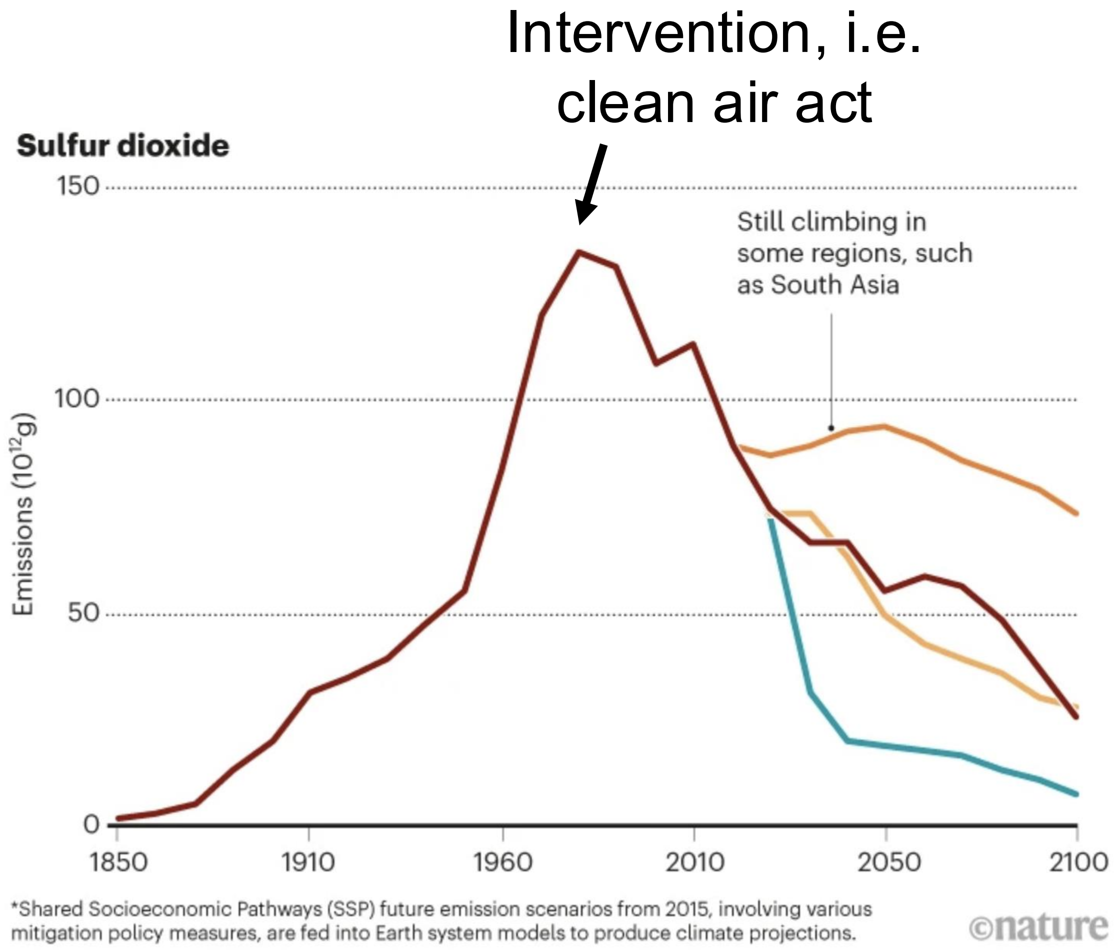
Blackport et al. (2024)

Heatwave hotspots have also emerged



Vautard et al. (2023)

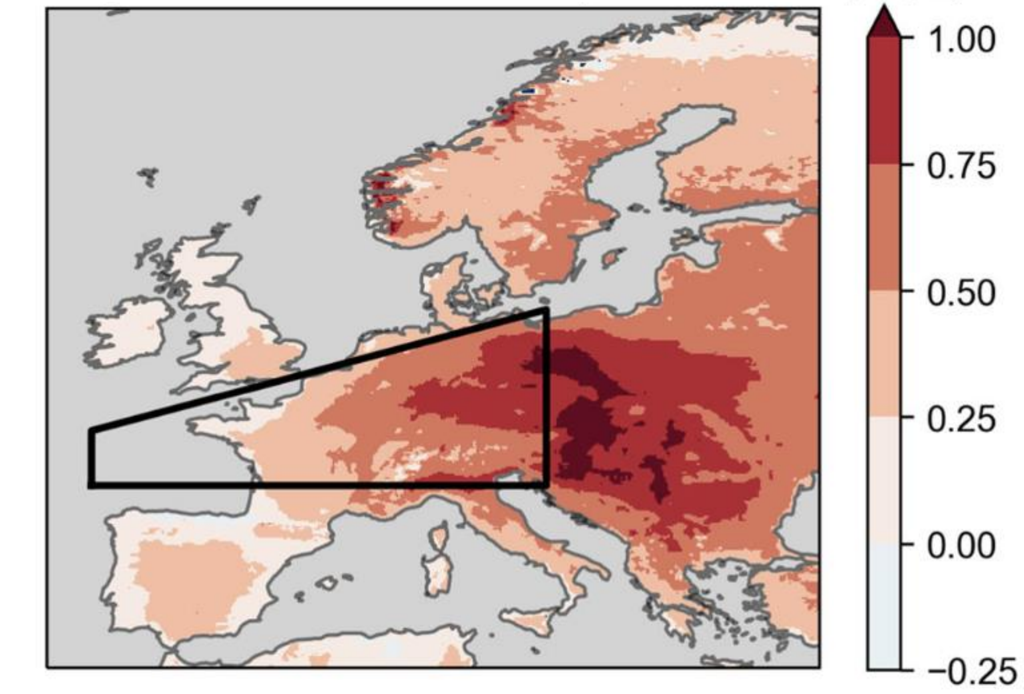
Aerosol clean up the air since the 1970s is an intended human intervention



Persad et al. (2022)

Heat wave hot spots have been connected to cleaning up the air since the 1980s

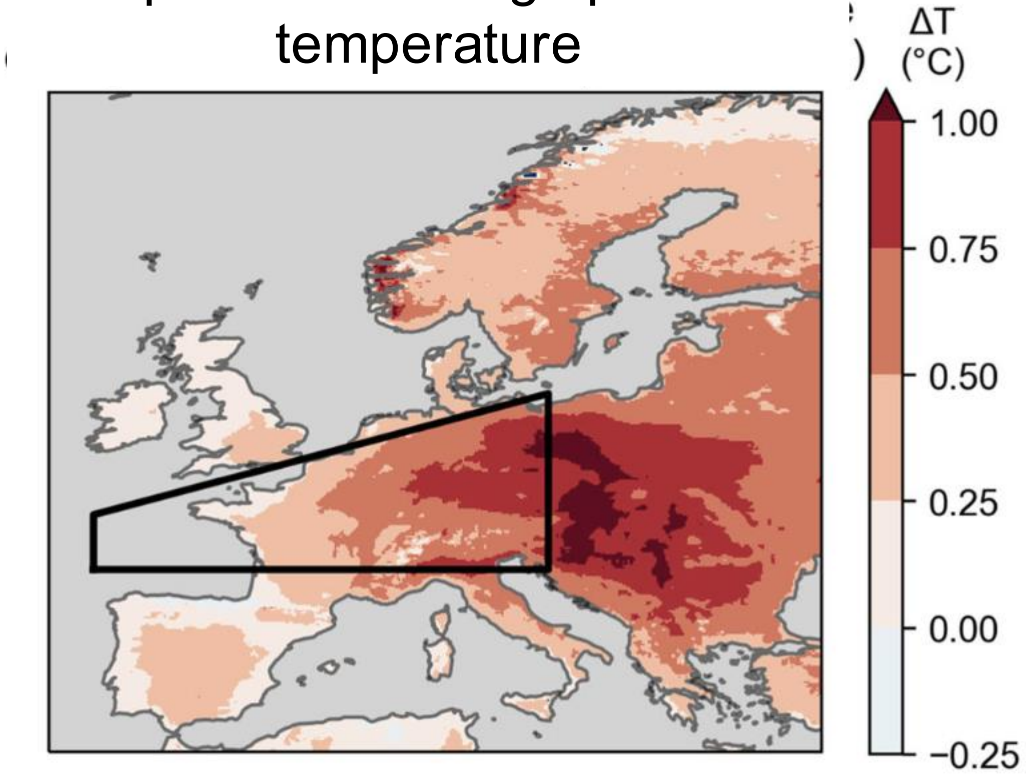
Impact of cleaning up air on temperature



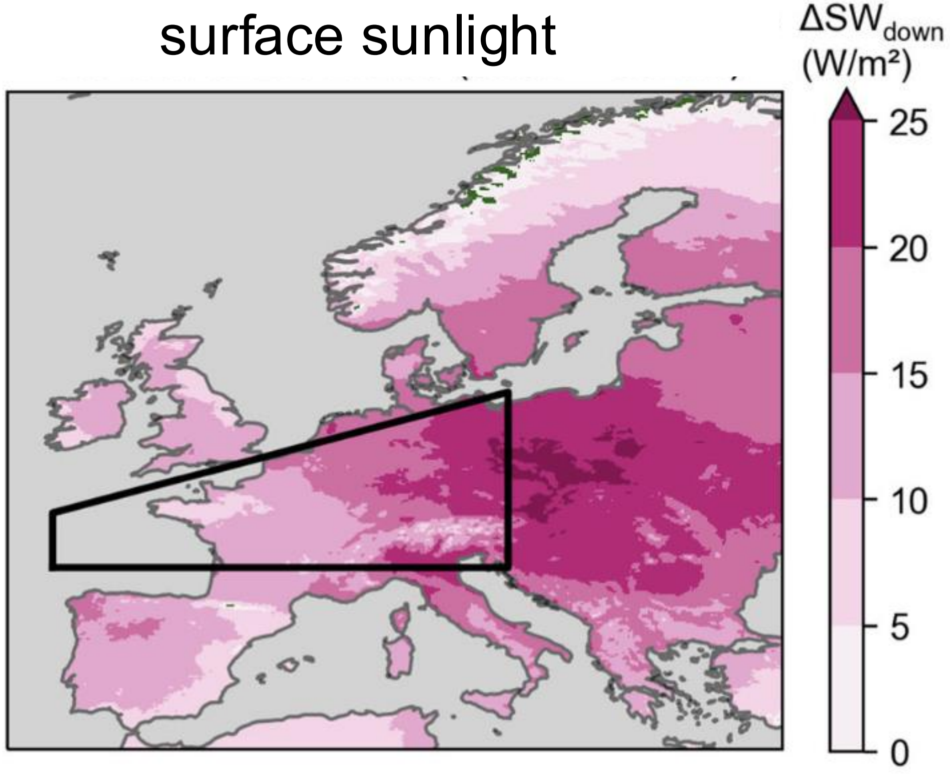
Schumacher et al. (2024)

Heat wave hot spots have been connected to cleaning up the air and increased solar radiation

Impact of cleaning up air on temperature



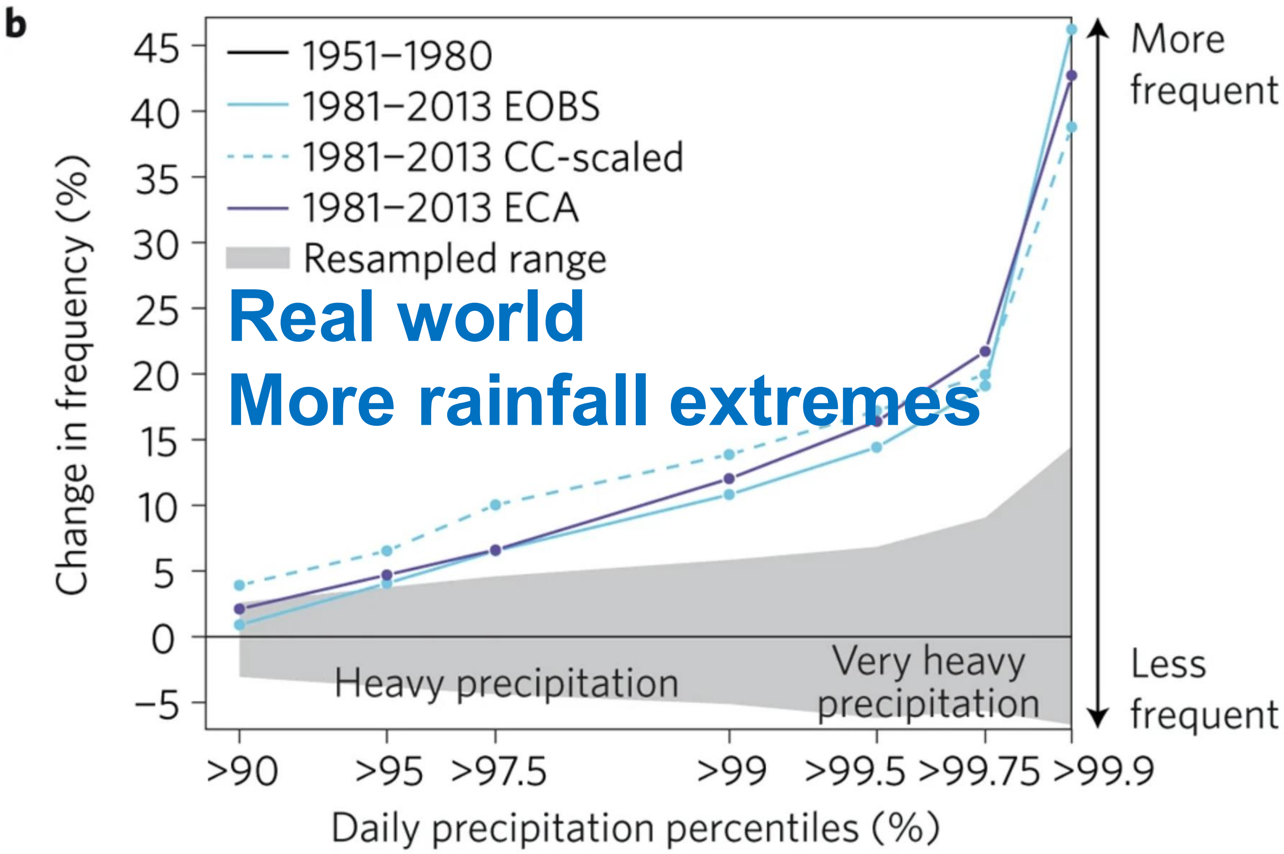
Impact of cleaning up air on surface sunlight



Schumacher et al. (2024)

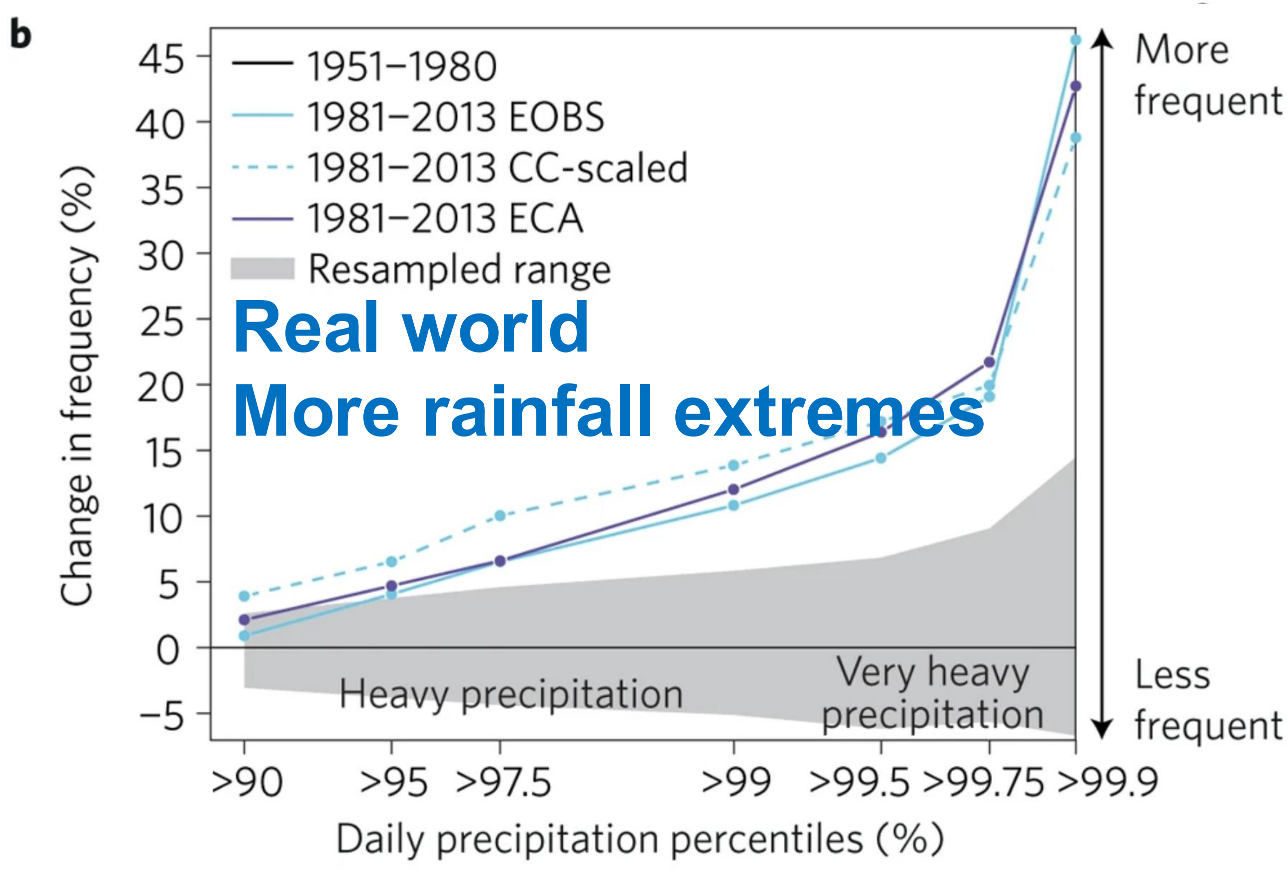

Extreme rainfall has *increased.*
MENTOR
Photo by Kristopher Radder/Brattleboro Refo

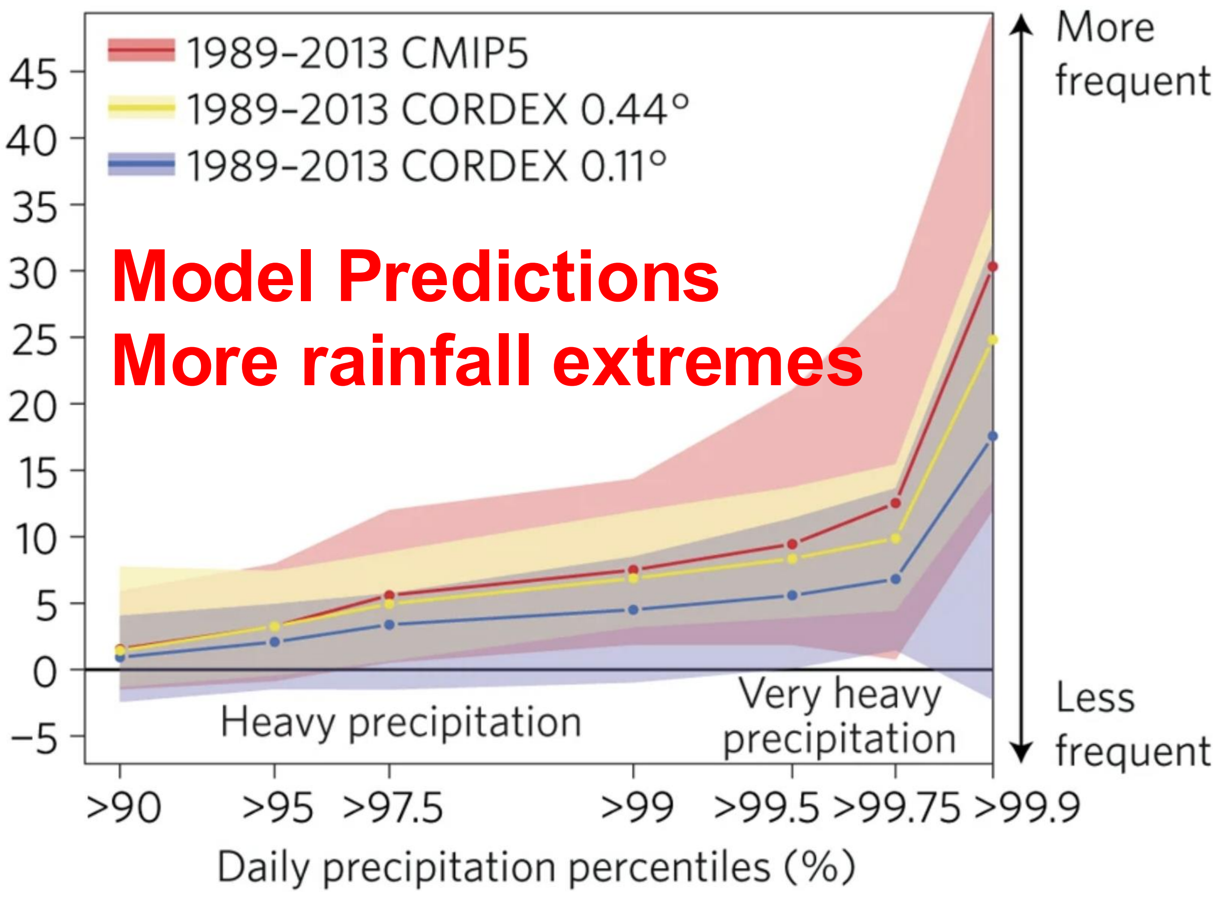
Climate predictions capture increase of European rainfall extremes



Fischer & Knutti (2016)

Climate predictions capture increase of European rainfall extremes

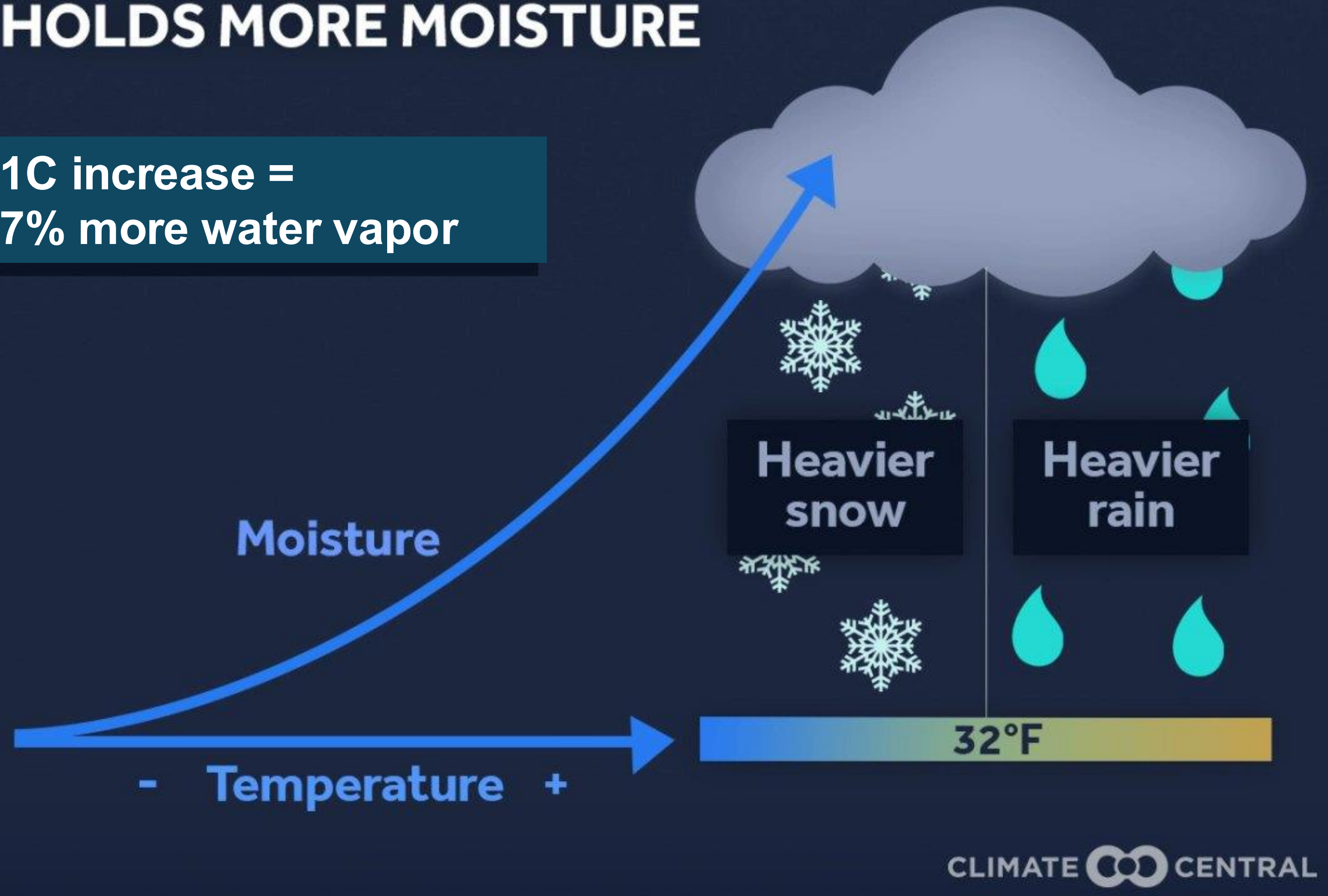




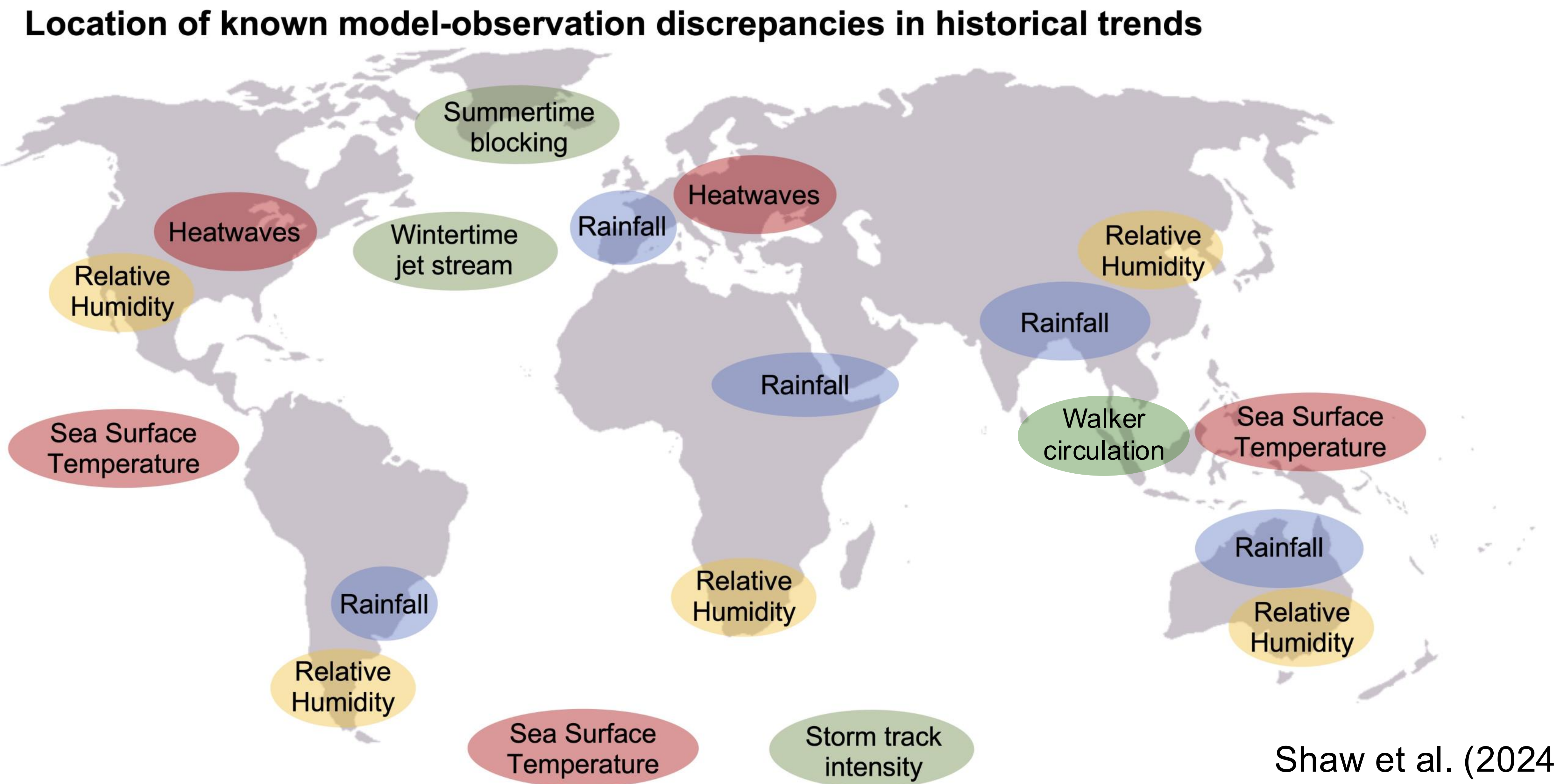
Fischer & Knutti (2016)

WARMER AIR
HOLDS MORE MOISTURE

1C increase =
7% more water vapor

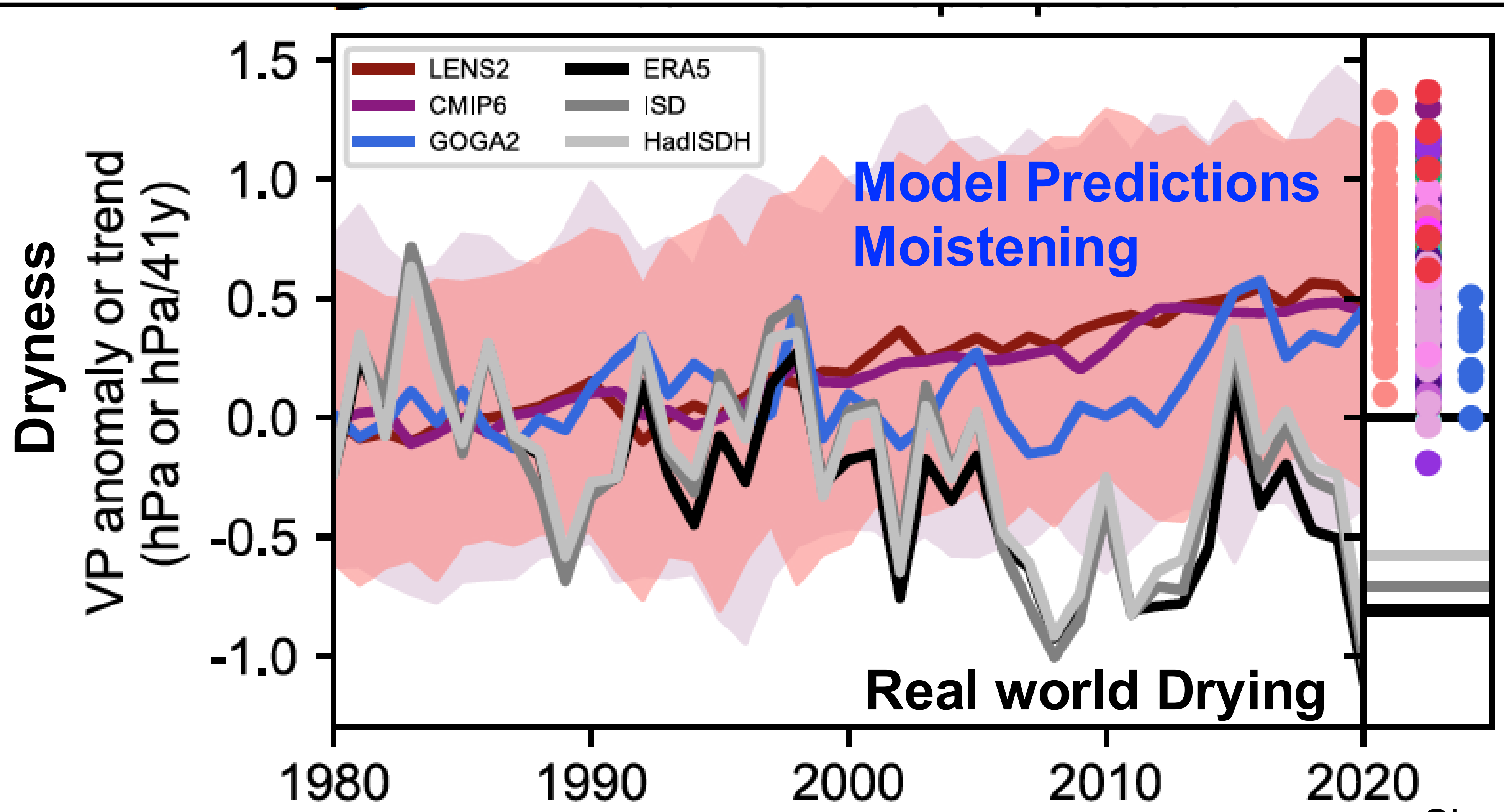


Regional discrepancies have also emerged



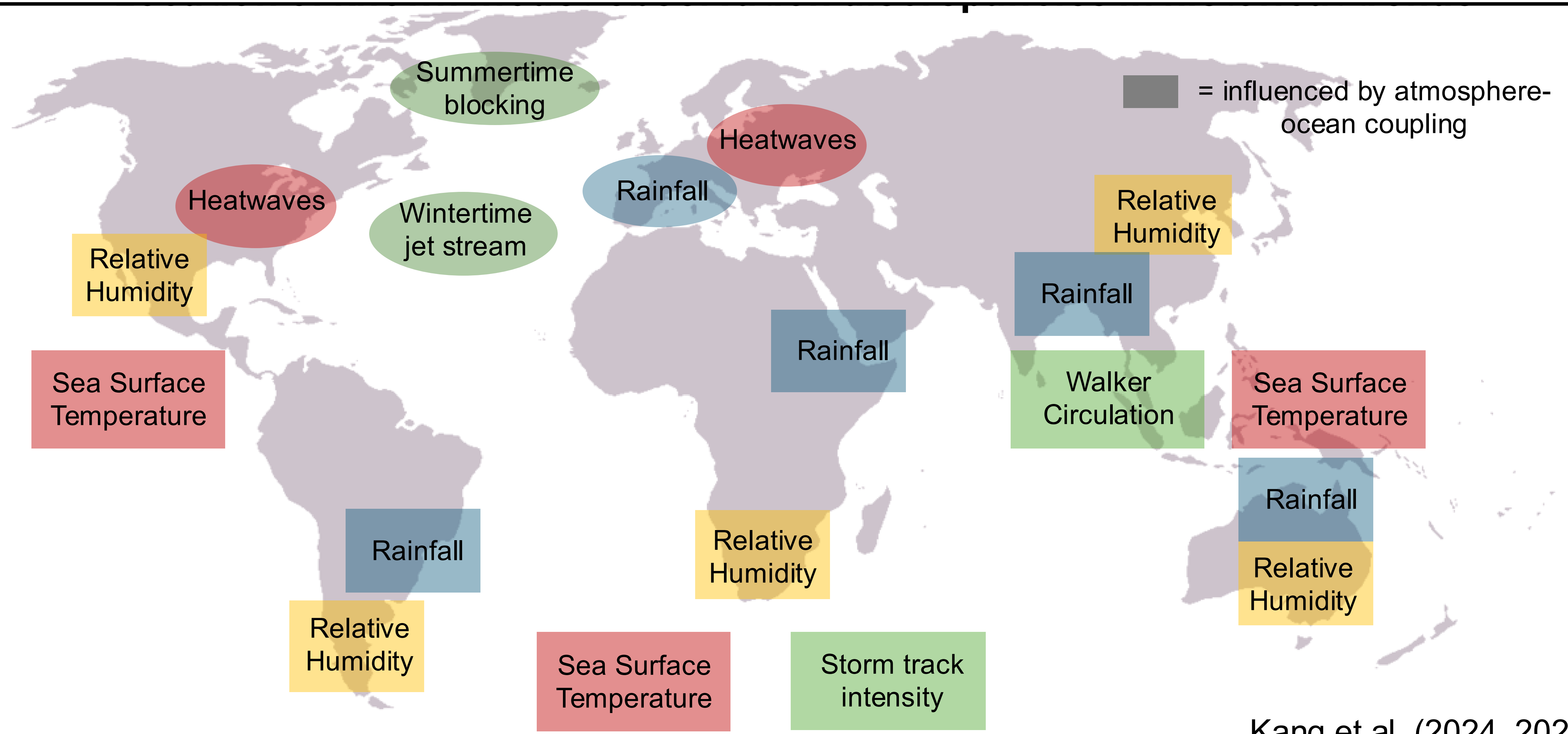
Shaw et al. (2024)

Discrepancy in drying trends over US Southwest



Simpson et al (2024)

Many regional discrepancies linked to atmosphere-ocean coupling



Kang et al. (2024, 2025)

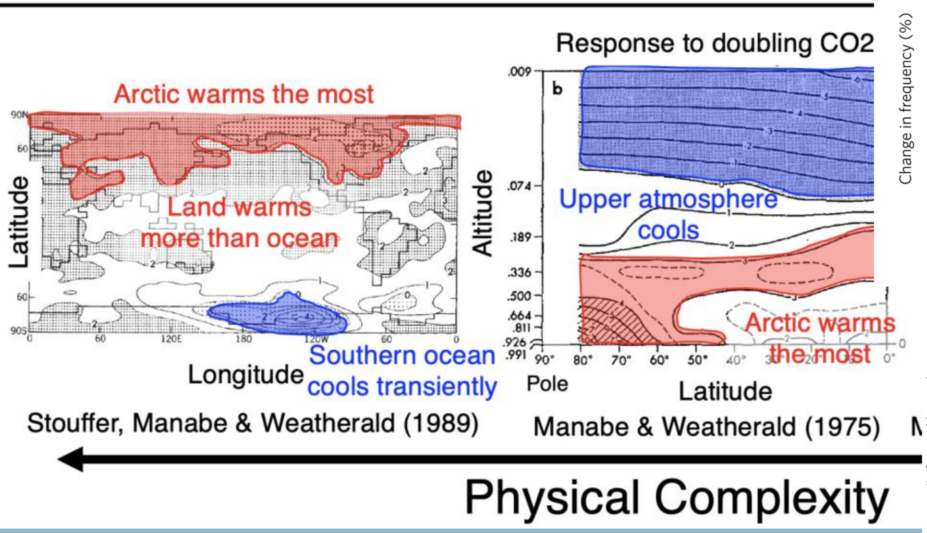
Landscape of regional climate information

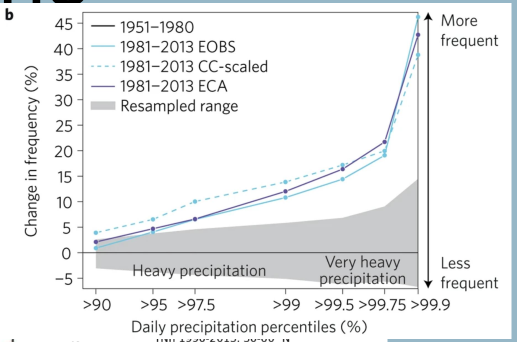
Knowledge

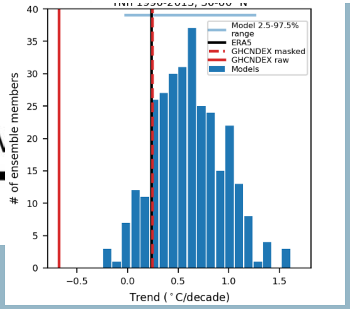
Tied to a chain of reasoning

Multiple lines of evidence

Successful predictions







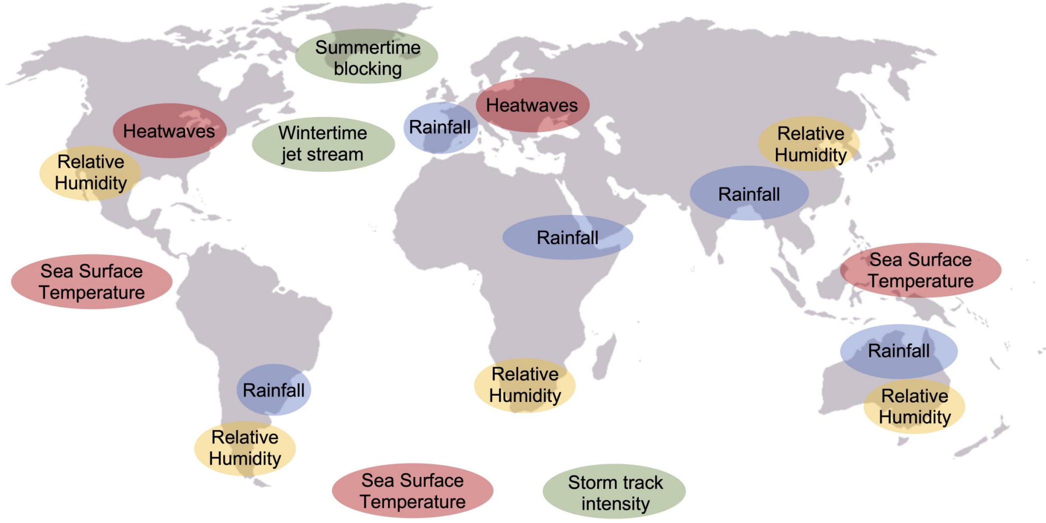
Knowledge gap

Discrepancies

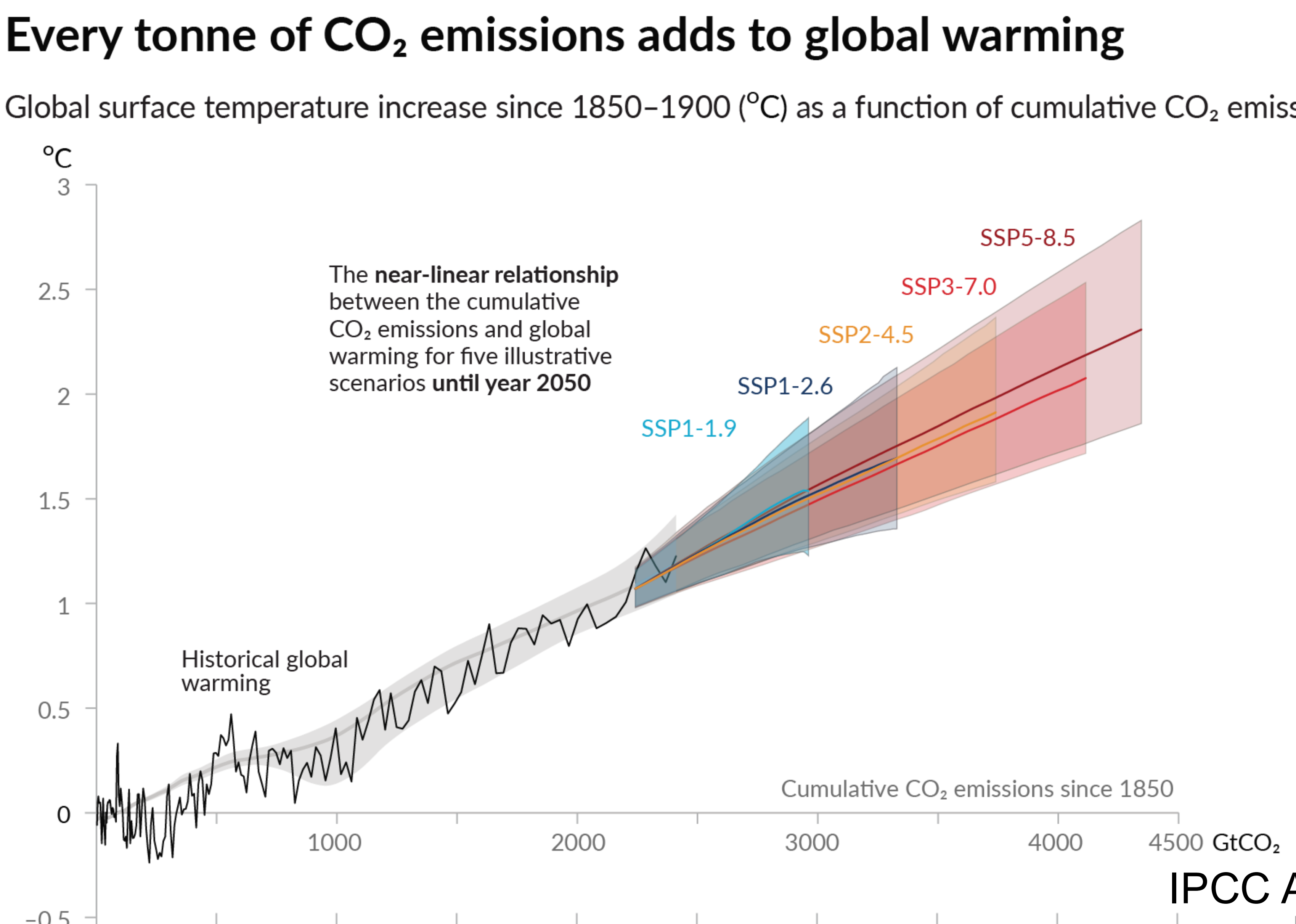
Failed predictions?

Risk assessment

Location of known model-observation discrepancies in historical trends



Knowledge gaps do not justify inaction



IPCC AR6 WG1 Fig. SPM10