Climate Change: Science, Politics, Ethics, and Hopeful Solutions

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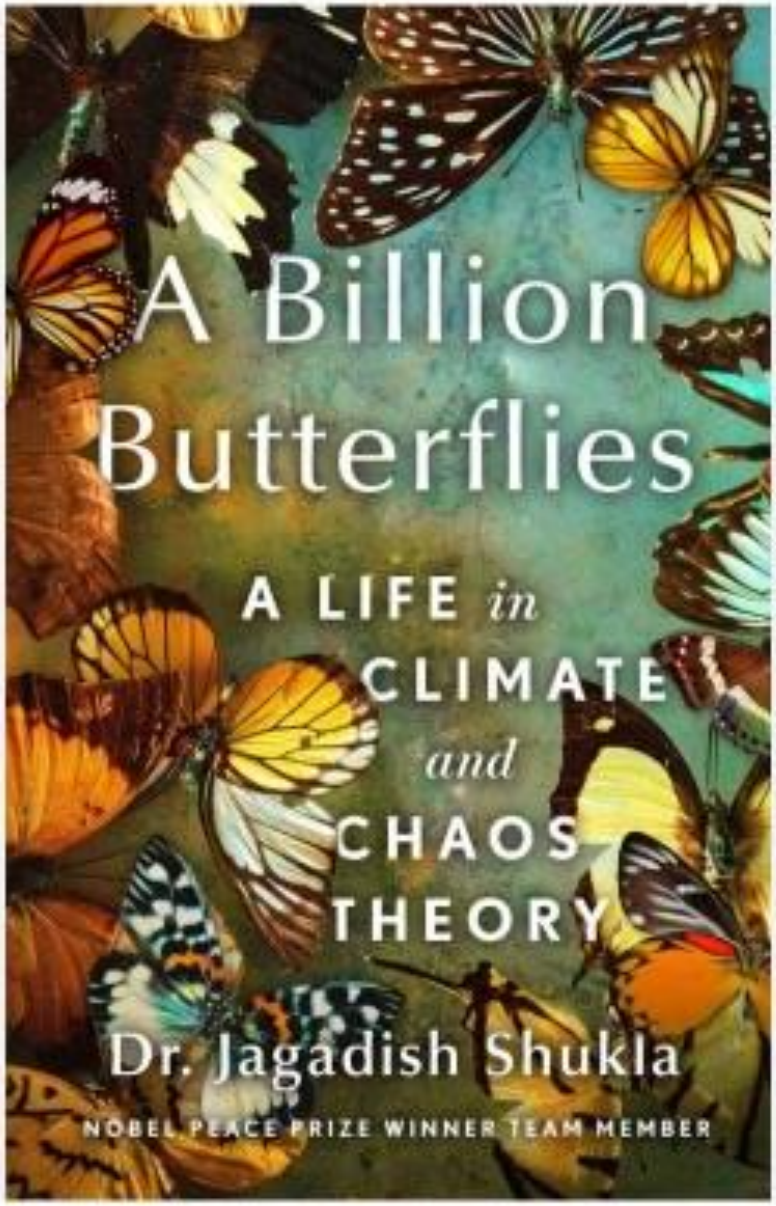
In spite of Chaos and the Butterfly Effect, Seasonal Climate should be predictable

"Predictability in the midst of chaos"

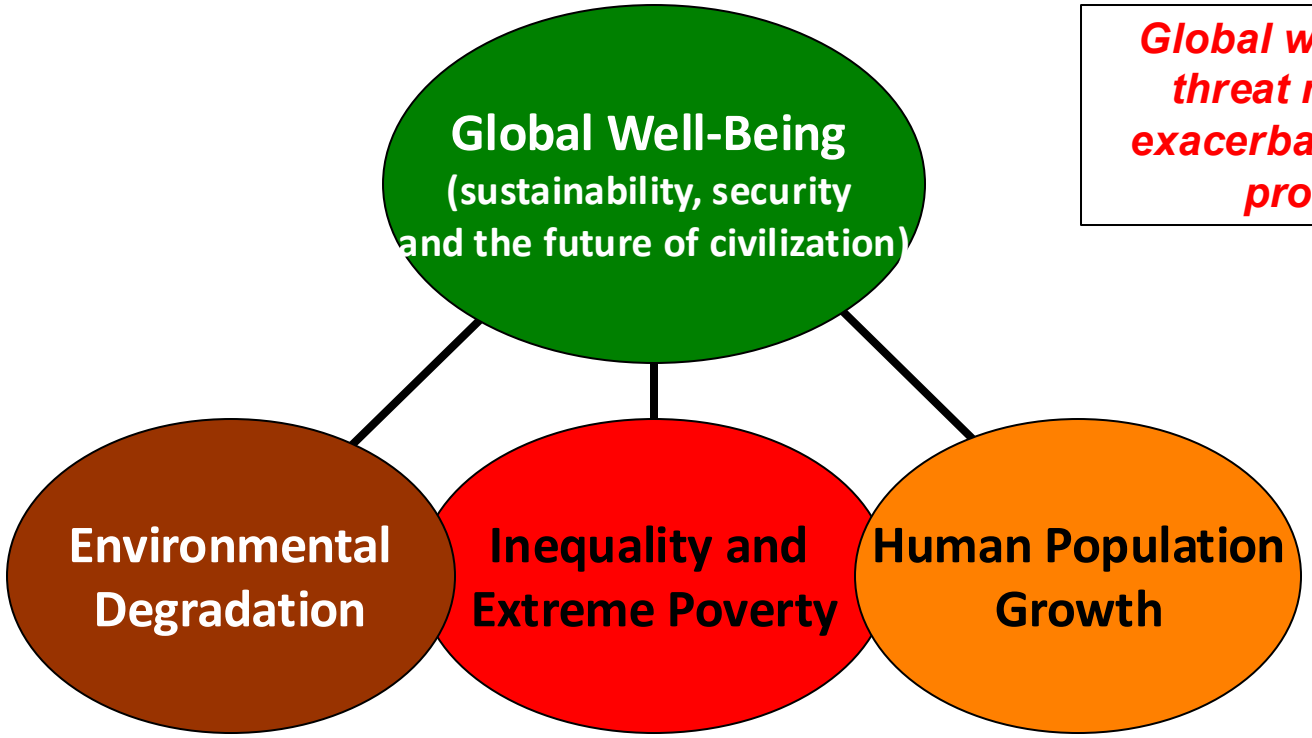


Sustainability High Energy Physics (HEP) Conference 2026, July 8-10, 2026 (CERN, IIT, Sheffield, and Oxford University)

Village: No Electricity, No Water Supply, No Library, No Roads,

Village: The Local Transportation

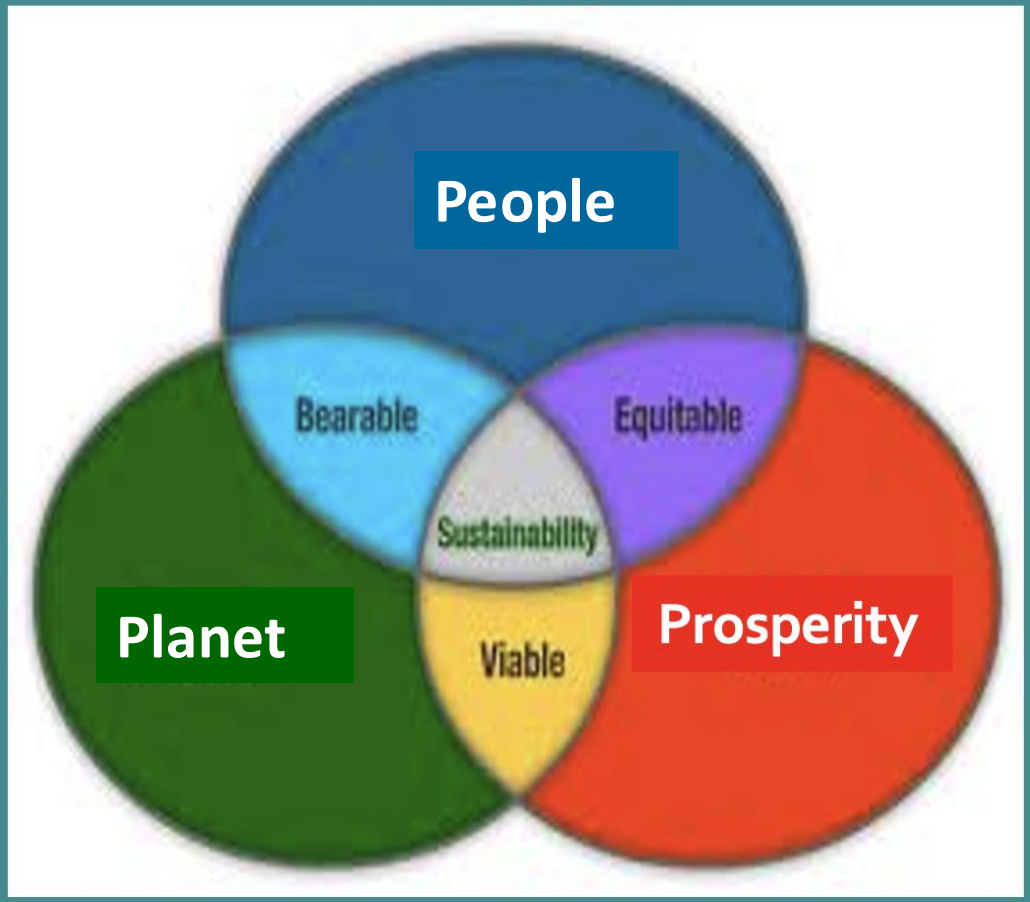
The Global Challenge



Global warming is a threat multiplier; exacerbates existing problems

Climate Change: Science, Politics, Ethics, and Hopeful Solutions

SUSTAINABLE SOCIETY



Scenes from the Anthropocene

1800: 1 billion

1927: 2 billion

1947: 4 billion

2021: 7.9 billion

2100: 10.9 billion

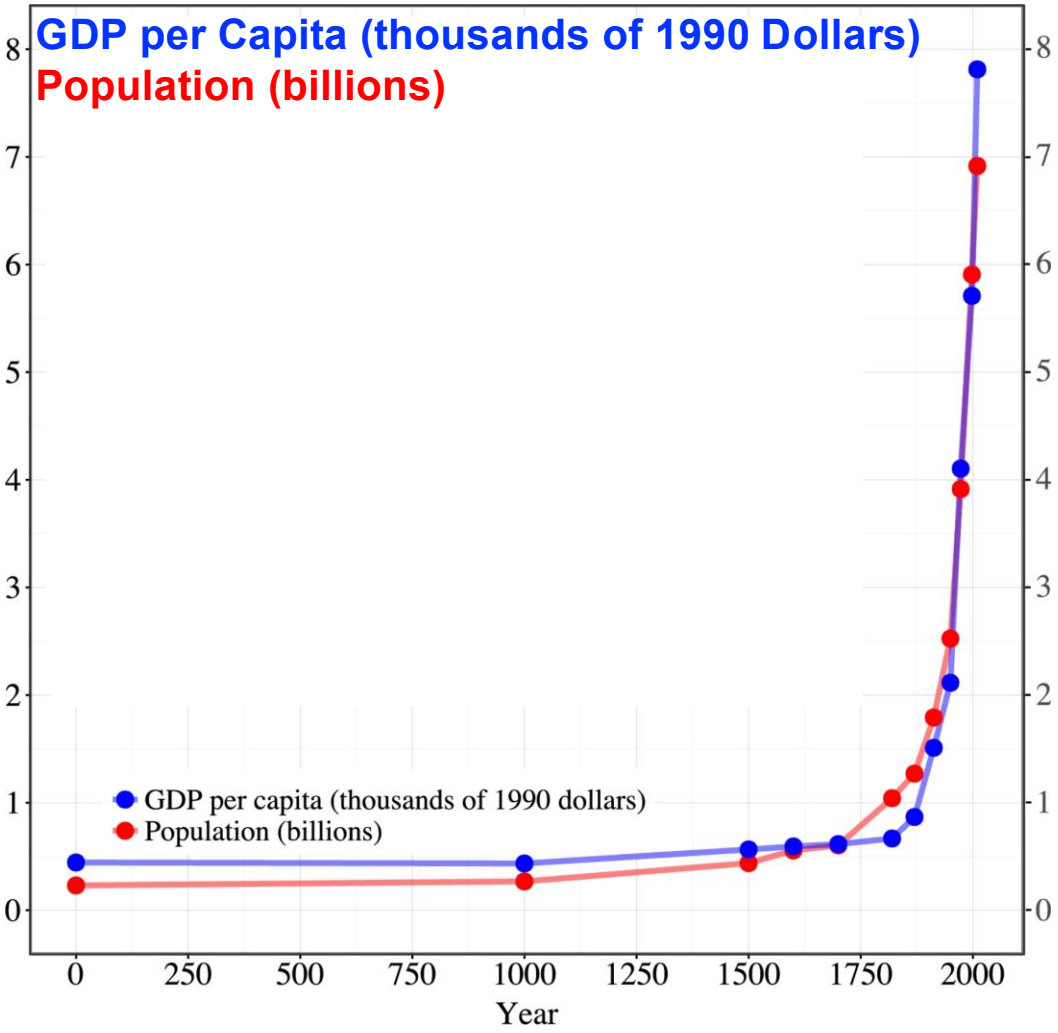
Africa

India

USA

Scenes from the Anthropocene

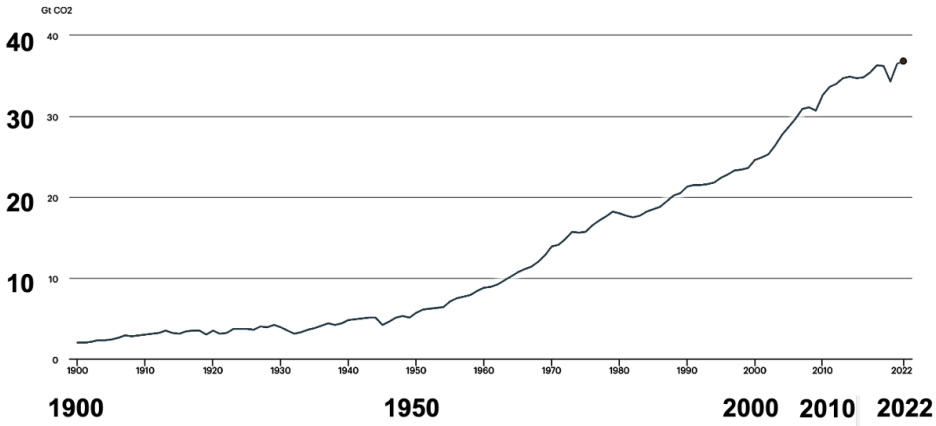
Population and GDP from Years 1-2010



Population and GDP per capita (in the main graph) from year 1 to 2010 AD. *The total human impact is their product.*

Scenes from the Anthropocene

Global Carbon Emissions



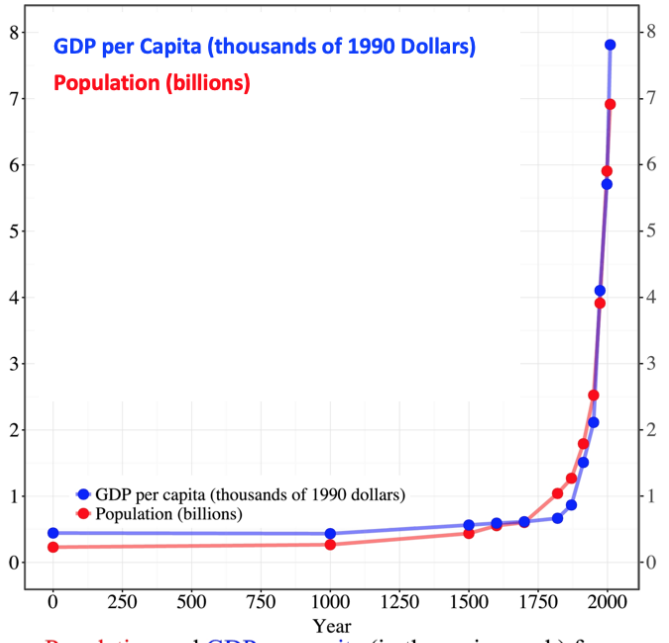
1900 1950 2000 2010 2022

2019: 36.2 GT of CO2

2019: 59 GT of CO2e

(52 GHG + 7 land)

Population and GDP from Years 1-2010



Population and GDP per capita (in the main graph) from year 1 to 2010 AD. *The total human impact is their product.*

Human impact =
Population x GDP per capita

Extraction of natural resources has increased exponentially

A Dilemma in the Anthropocene

Release of fossil fuels (coal, gas, petrol, & deforestation) have been the engines of growth of human civilization (quality of life, health, art, culture) for the past 200 years.

But Climate science has shown that:

The use of fossil fuels will cause global "heating" which will adversely affect global society especially the poor and vulnerable.
(Heatwaves, floods, health, agriculture, sea level rise, ocean acidification, global conflicts, loss of species, etc.)

Climate Science is Easy

It is as easy as understanding why nights are colder than days

Earth radiates about 122,400 trillion watts of energy annually to space.
Earth receives about 122,400 trillion watts of energy annually from the sun.

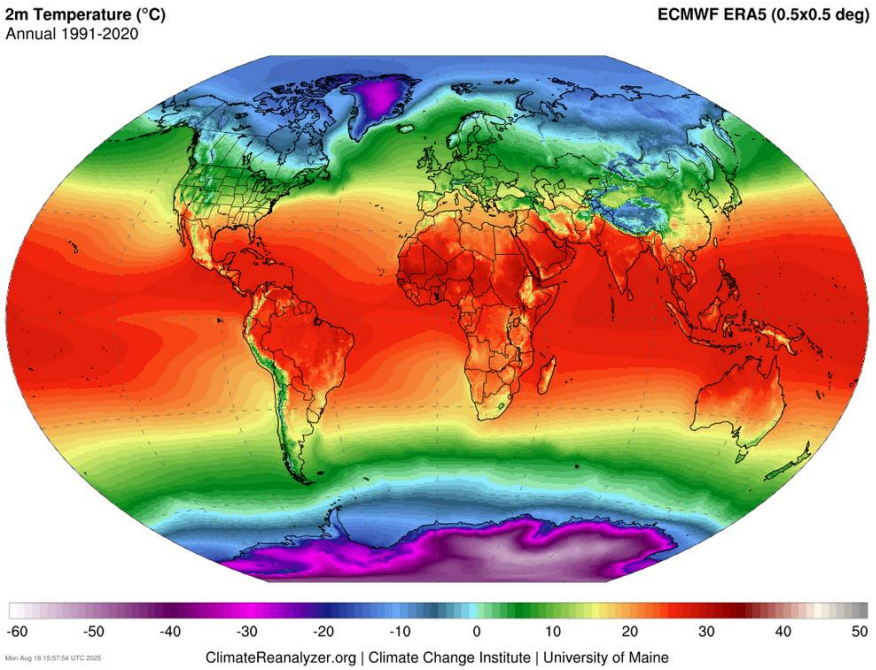
THE EARTH IS COOLING ALL THE TIME BY RADIATING ENERGY TO SPACE

Radiated Energy ~ σT^4.

122,400 trillion watts per year

WHY ARE WE NOT GETTING COLDER AND COLDER?

Global Annual Average Surface Temperature

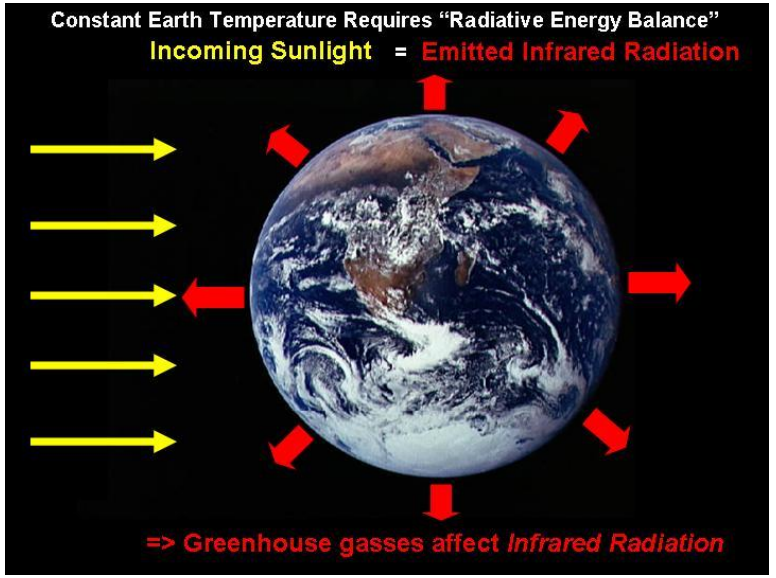


Global Mean Surface Temperate for about 10,000 years has been 14 degree C (57 degree F); For the past 100 years, it is 15 degree C.

This 1 C warming is called Global Warming

Annually Earth radiates 122,400 trillion watts to space; which is equal to the energy Earth receives from Sun

This balance creates a stable Climate



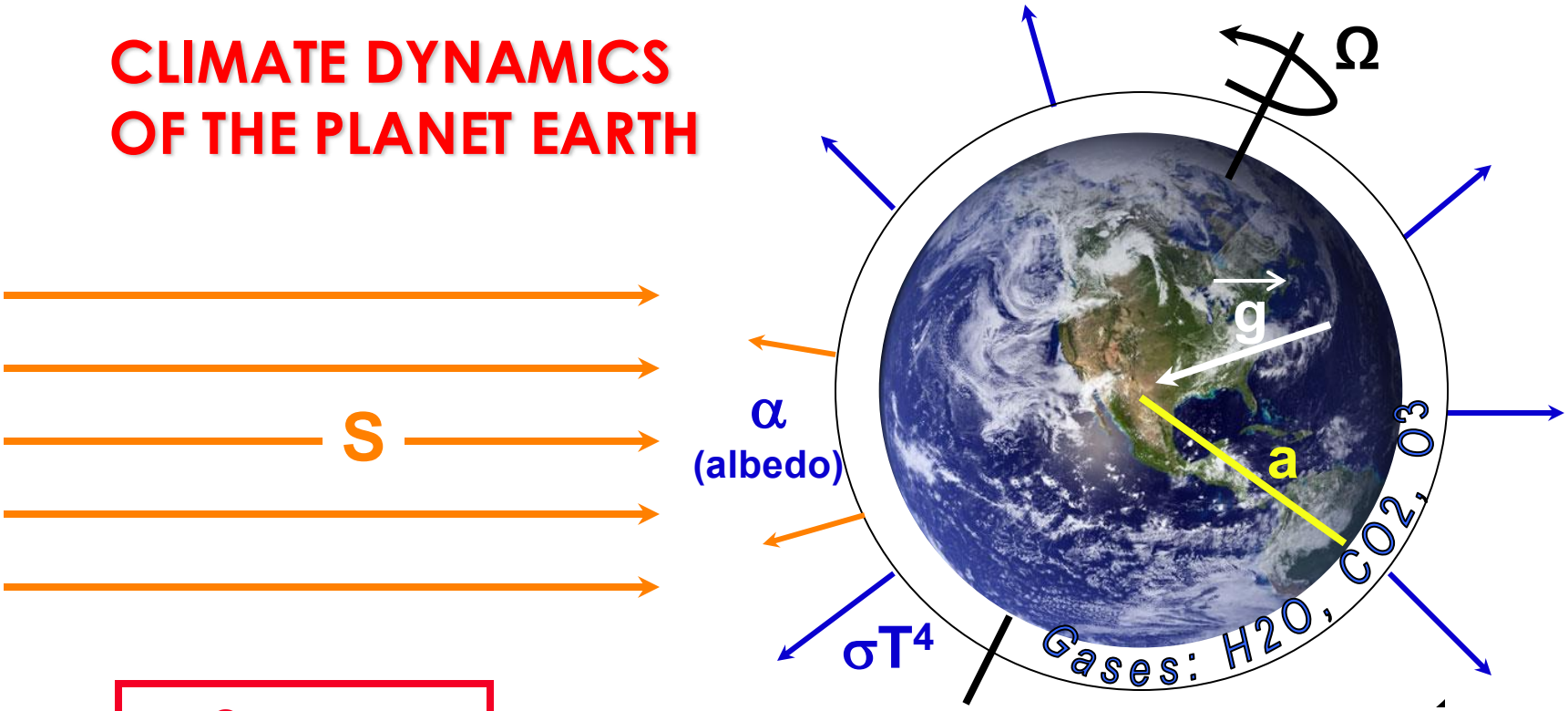
The Climate of a Planet Depends On …

1. **Energy from the Sun** — **S**

   (energy from the interior)

2. **Planetary Albedo** — **α**
3. **Speed of Planet's Rotation** — **Ω**
4. **Mass of the Planet** — **M**
5. **Radius of the Planet** — **a**
6. **Atmospheric Composition** — **H_2O, CO_2, O_3, clouds**
7. **Ocean-Land, Topography** — **h***

CLIMATE DYNAMICS OF THE PLANET EARTH



S, O_3, H_2O, CO_2, a, g, Ω

h*: mountains, oceans (SST)
w*: forest, desert (soil wetness)

$\frac{\partial \bar{T}}{\partial y}, \frac{\partial \bar{U}}{\partial y}$ $\frac{\partial \bar{T}}{\partial z}, \frac{\partial \bar{U}}{\partial z}$

stationary waves (Q, h*), monsoons

hydrodynamic instabilities of shear flows; stratification & rotation; moist thermodynamics

day-to-day weather fluctuations;
wavelike motions: wavelength, period, amplitude

WEATHER

CLIMATE

Climate is Mother of Weather

- **Mean climate of a planet is uniquely determined by: sun, volcanoes, planet's rotation, ocean, land, greenhouse gases, etc.**

- **Weather fluctuations are instabilities of, and superimposed on, mean climate.**

Therefore, all weather events (hurricanes, heat waves, etc) are influenced by climate change.

Climate and Climate Change

Climate and Seasons: Beyond Human Control

In the previous century, Earth's temperature ≈ 14 °C

Climate Change and Global Warming: Human Activities (GHG and deforestation)

In the current century, Earth's temperature ≈ 15 °C

Without greenhouse gases and the greenhouse effect, the Earth's temperature would be minus 19°C – *inhabitable Earth*

Scientific Explanations for Climate Impact

- **Warm air holds more water vapor: Heavy rainfall and Floods**
- **Warmer air dries out land: Droughts and Forest Fires**
- **Warmer ocean provides more energy: Stronger Hurricanes**
- **Warmer ocean expands: Sea Level Rise**
- **Warmer air temperature melts ice over land: Sea Level Rise**

Climate is Always Changing, What is Different Now?

The rates of warming and CO2 increase are the highest in 2 million years

In the past the global warming/cooling was:

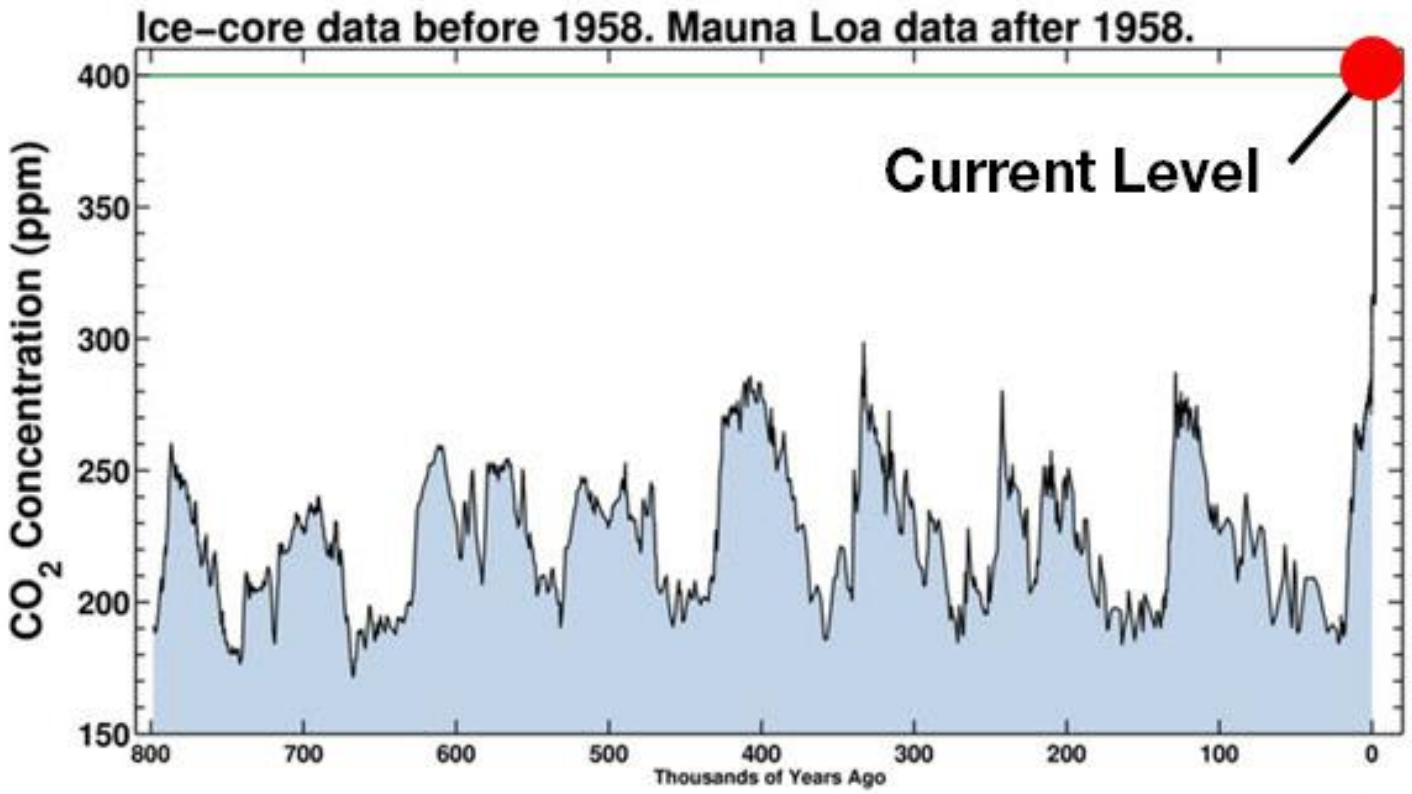
1°C in ~ 1000 - 2000 years

In the present century, global warming is:

1°C in 100 years

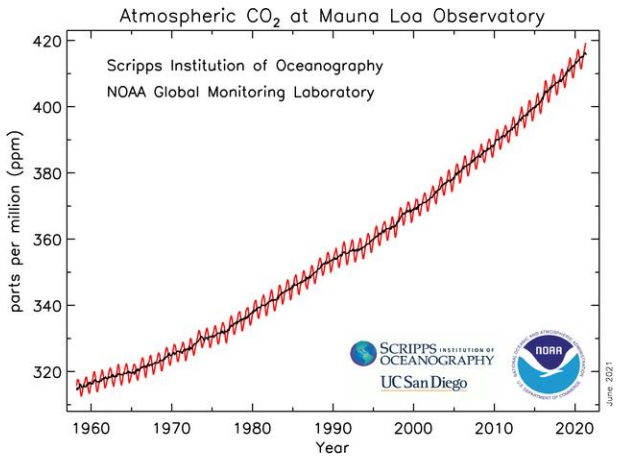
IPCC AR5, 2013, Pg. 400

The current level of CO2 highest in 2 million years (IPCC 2021)



CO_2 concentration for [illegible] years (ice core data)

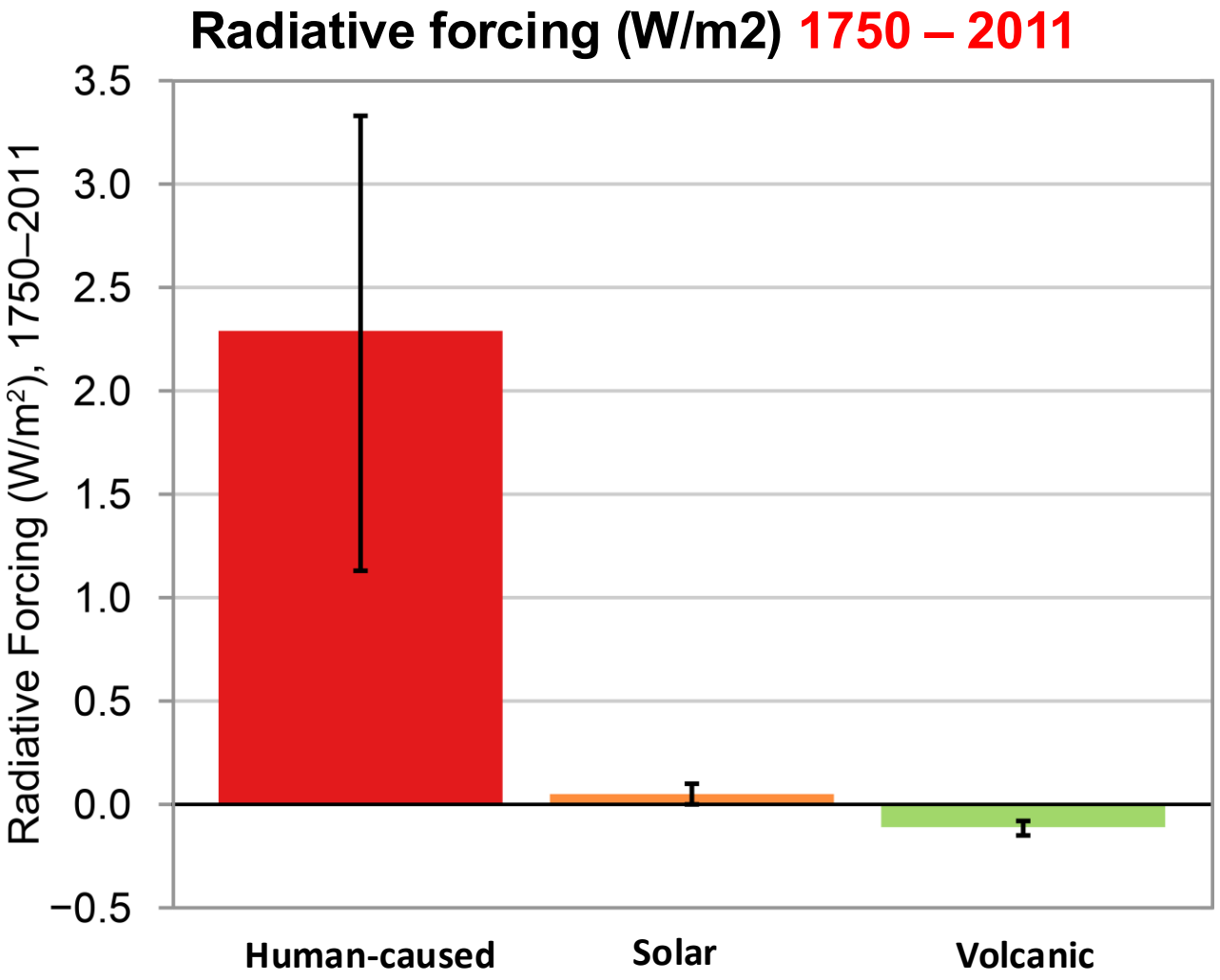
Mauna Loa Observatory 1958 to present



Climate is Always Changing, What is Different Now?

In the past, the dominant causes of climate change were solar and volcanic.

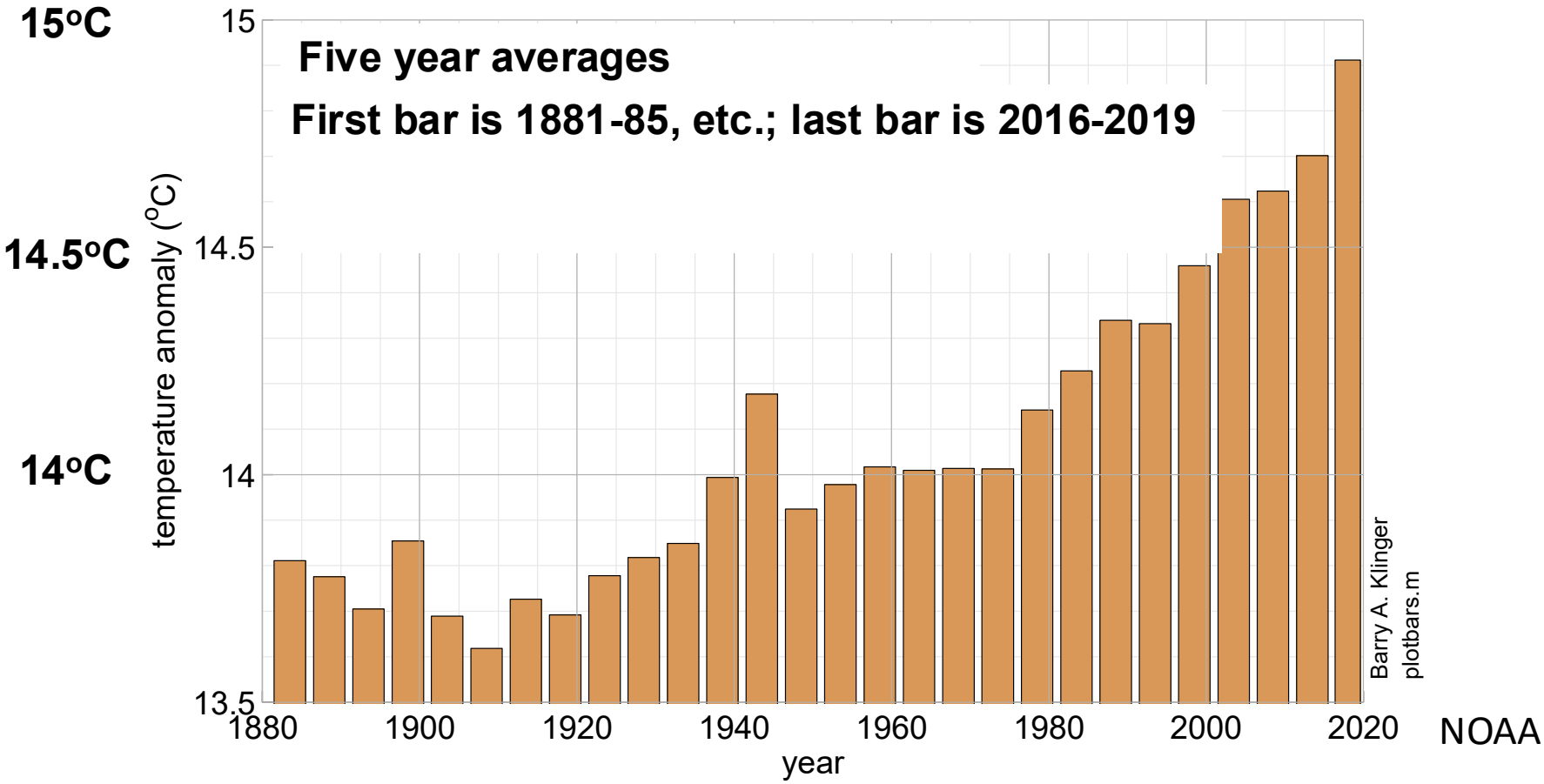
In the present, the dominant causes of climate change are human activities (CO2, Methane, deforestation, etc.)



Global Warming

Increase in the average temperature of the Earth's near surface air and oceans

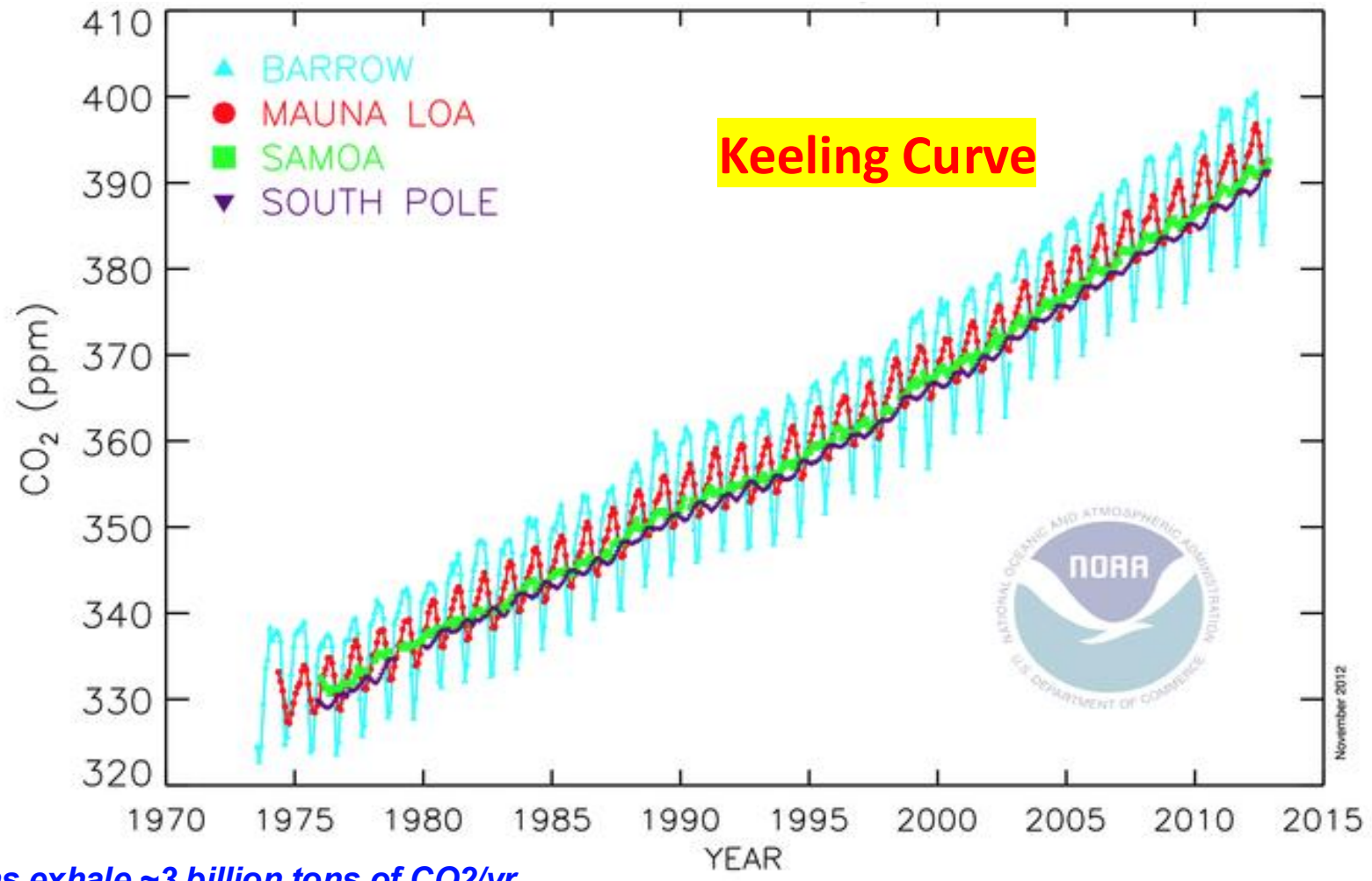
Rate of increase of T and CO2 is unprecedented



100 year (1901-2000) average global mean temp. = 14 °C (57.18 °F)

Monthly Mean Carbon Dioxide

Plants grow, they take CO2 from the atmosphere



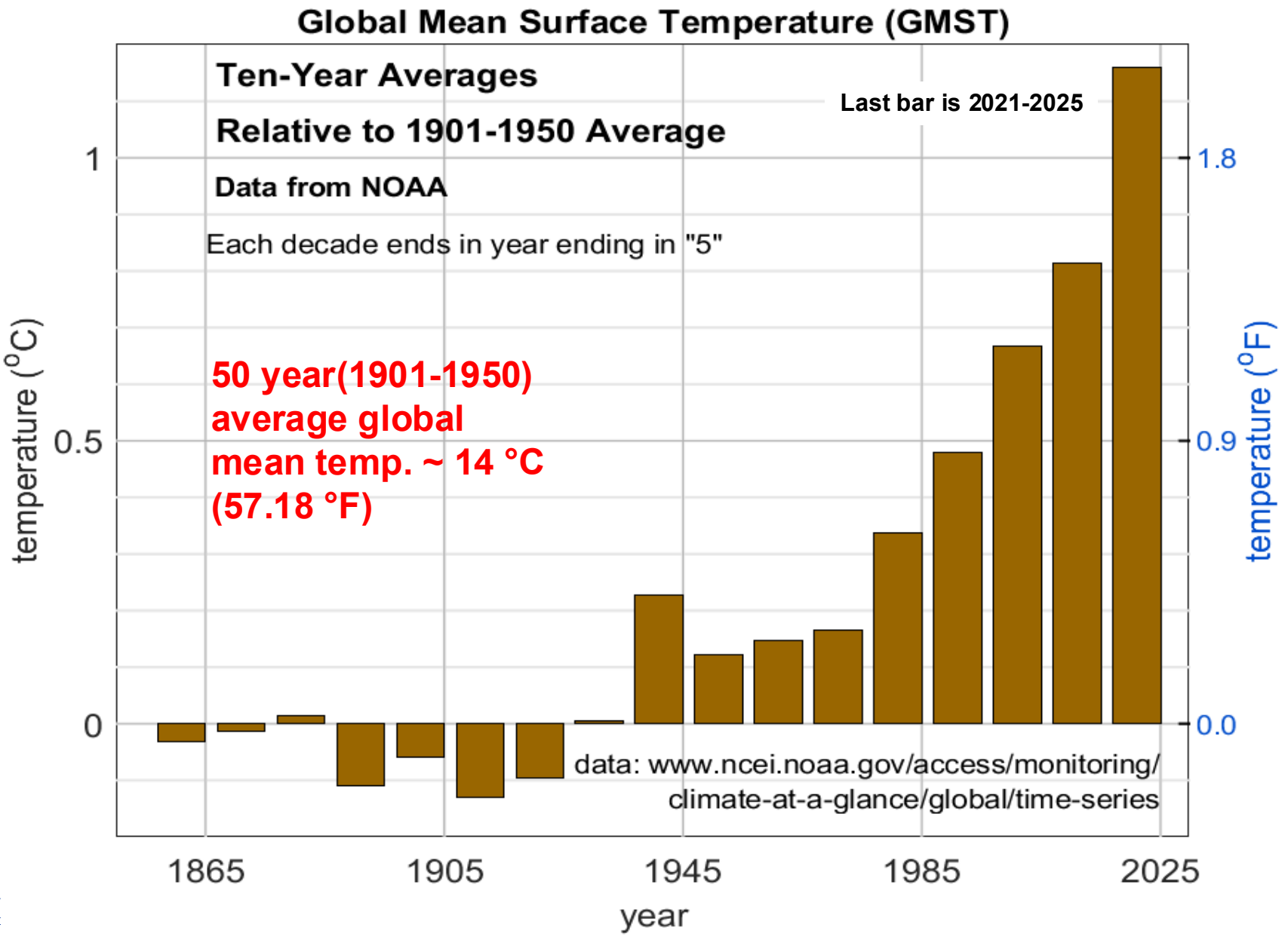
Humans exhale ~3 billion tons of CO2/yr

Atmospheric carbon dioxide mixing ratios determined from the continuous monitoring programs at the 4 NOAA CMDL baseline observations. Principal investigator: Dr. Pieter Tans. NOAA CMDL Carbon Cycle Greenhouse Gases. Boulder, Colorado. (303) 497-6678

During the warm months when plants grow, they take CO2 from the atmosphere because photosynthesis outweighs respiration, which offers all the time but dominates during colder months.

Global Warming

Increase in the average temperature of the Earth's near surface air and oceans



A

Weather and Climate Prediction Equations (ECMWF model)

Conservation of mass, momentum and energy

$$\frac{\partial U}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial U}{\partial \lambda} + v\cos\theta\frac{\partial U}{\partial \theta}\right\} + \dot{\eta}\frac{\partial U}{\partial \eta}$$

$$(-fv) + \frac{1}{a}\left\{\frac{\partial \phi}{\partial \lambda} + R_{dry}T_v\frac{\partial}{\partial \lambda}(\ln p)\right\} = P_U + K_U$$

East-west wind (momentum equation)

$$\frac{\partial V}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial V}{\partial \lambda} + V\cos\theta\frac{\partial V}{\partial \theta} + \sin\theta(U^2 + V^2)\right\} + \dot{\eta}\frac{\partial V}{\partial \eta}$$

$$+ fU + \frac{\cos\theta}{a}\left\{\frac{\partial \phi}{\partial \theta} + R_{dry}T_v\frac{\partial}{\partial \theta}(\ln p)\right\} = P_V + K_V$$

North-south wind (momentum equation)

$$\frac{\partial T}{\partial t} + \frac{1}{a\cos^2\theta}\left\{U\frac{\partial T}{\partial \theta} + V\cos\theta\frac{\partial T}{\partial \theta}\right\} + \dot{\eta}\frac{\partial T}{\partial \eta} - \frac{\kappa T_v \omega}{(1 + (\delta - 1)q)p} = P_T + K_T$$

Temperature (1st Law of Thermodynamics)

$$\frac{\partial q}{\partial t} = \frac{1}{a\cos^2\theta}\left\{U\frac{\partial q}{\partial \lambda} + V\cos\theta\frac{\partial q}{\partial \theta}\right\} = \eta\frac{\partial q}{\partial \eta} = P_q + K_q$$

Humidity (conservation of water mass)

$$\frac{\partial}{\partial t}\left(\frac{\partial p}{\partial \eta}\right) + \nabla.\left(\mathbf{v}_H\frac{\partial p}{\partial \eta}\right) + \frac{\partial}{\partial \eta}\left(\dot{\eta}\frac{\partial p}{\partial \eta}\right) = 0$$

Continuity (conservation of dry air mass)

$$\frac{\partial p_{surf}}{\partial t} = -\int_0^1 \nabla.\left(\mathbf{v}_H\frac{\partial p}{\partial \eta}\right)d\eta$$

Surface pressure (hydrostatic approximation)

Weather and Climate Prediction Models

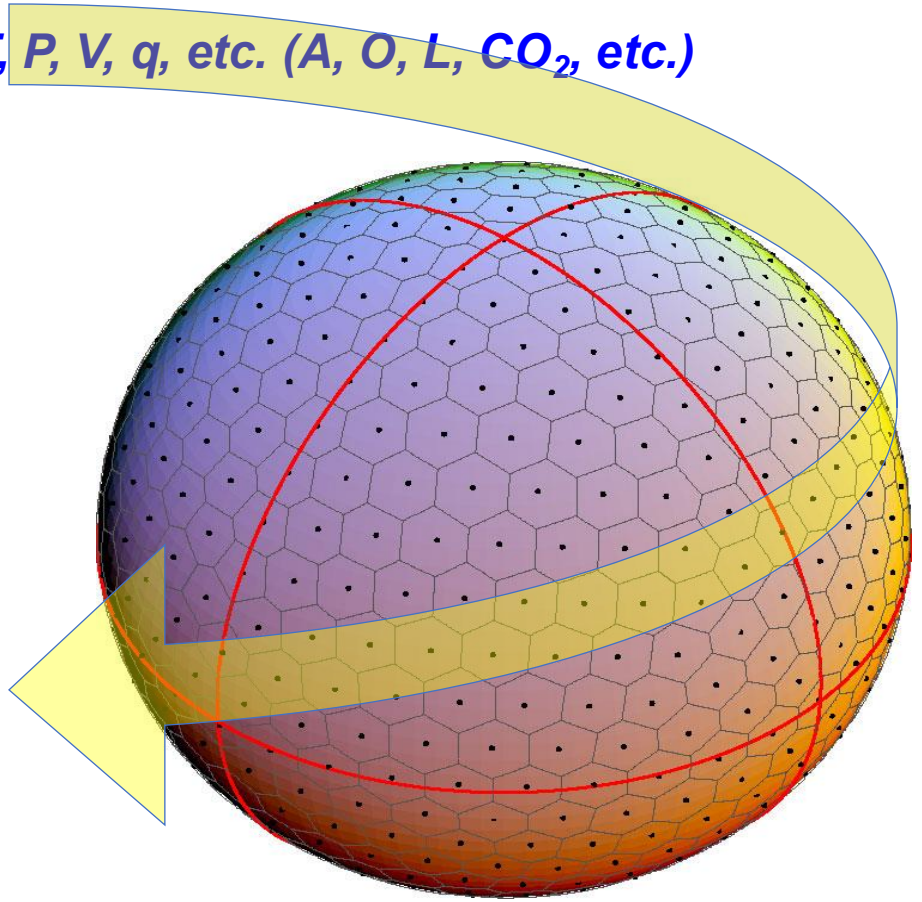
Use of laws of physics and supercomputers to predict future weather and climate is one of the major scientific advances of the 20th century.

100 Million Equations:
10 million "grids" × 10 Variables
With Time Steps of: ~ 1-5 Minutes
Use of Supercomputers

- **Long-term climate projection for mitigation**
- **Short-term climate prediction for adaptation**

Equations of motions and laws of thermodynamics to predict rate of change of:

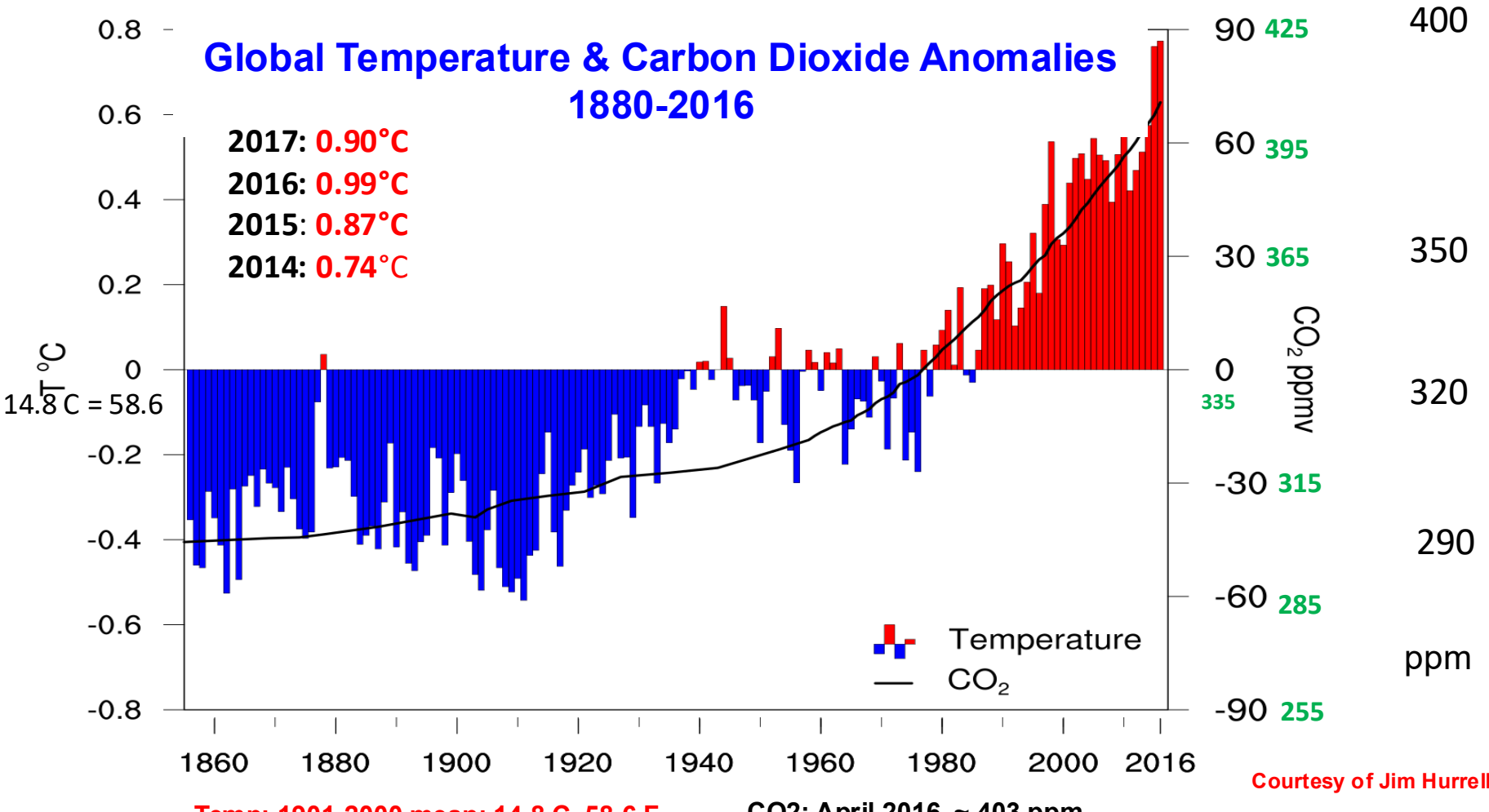
T, P, V, q, etc. (A, O, L, CO_2, etc.)



An Elegant Science Question:

Are increases in greenhouse gases responsible for increase in global mean temperature (global warming)?

Climate models are tools for answering this question



(Net) Global Warming

Warming

1. Greenhouse gases (CO_2, CH_4, N_2O)

- **CO_2: Carbon Dioxide : Emission from fossil fuel**
- **CH_4: Methane : Agriculture**
- **N_2O: Nitrous Oxide**

2. Land use change

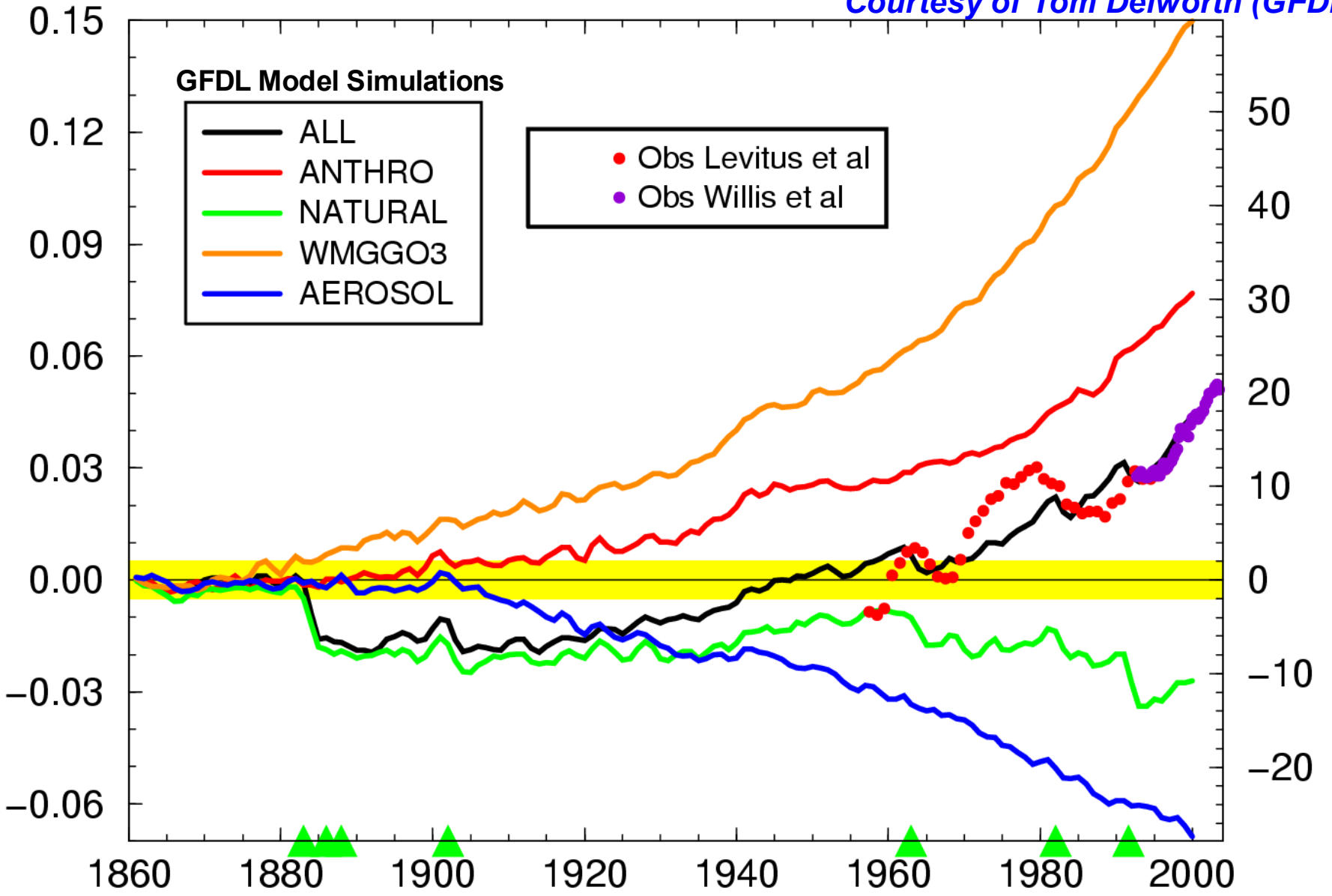
Cooling

1. **Aerosols**
   - **Man made/Natural**
   - **Volcanoes**

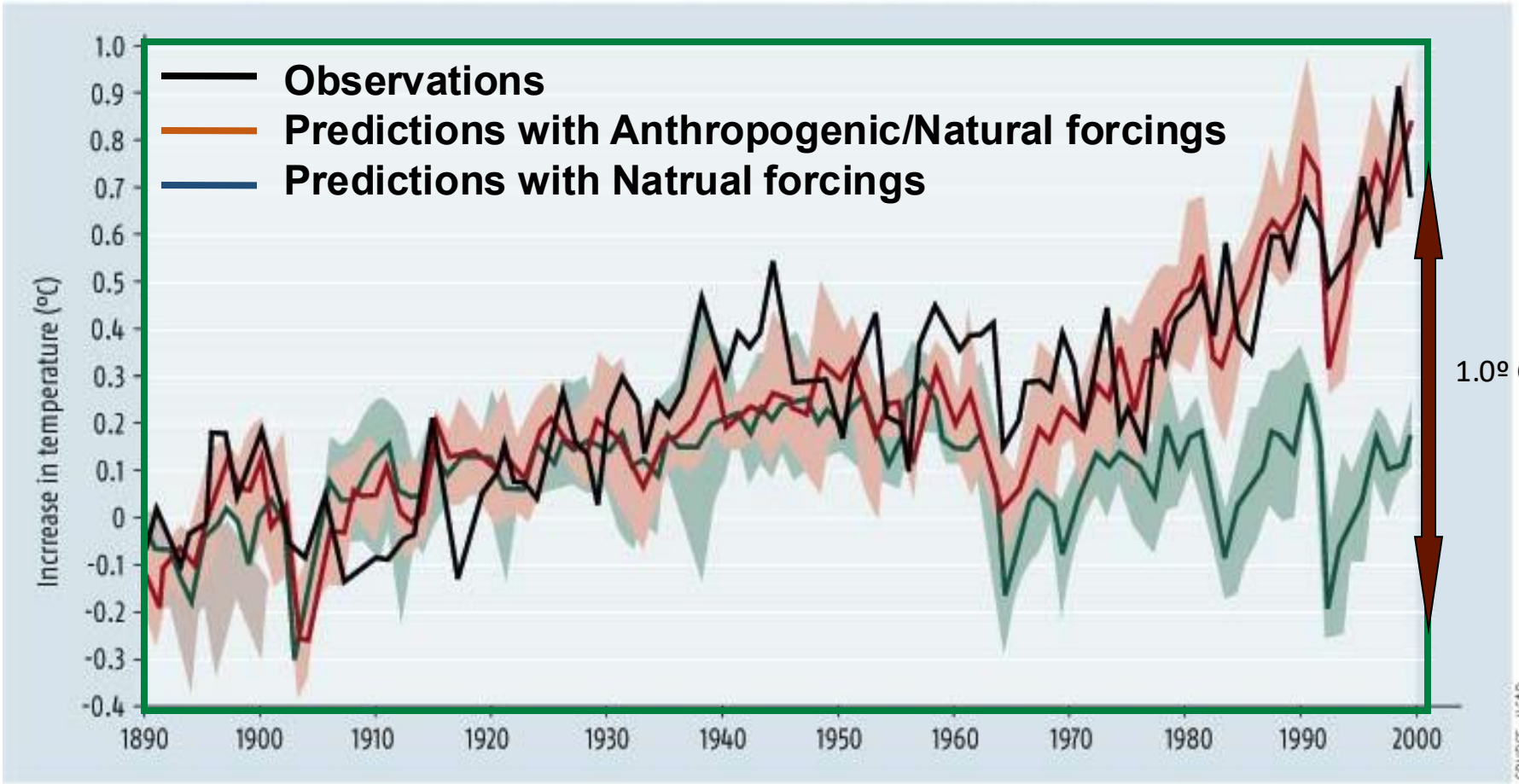
※Rate of increase of GHG is largest in 10,000 years

Global mean, volume mean ocean temperature

Courtesy of Tom Delworth (GFDL)

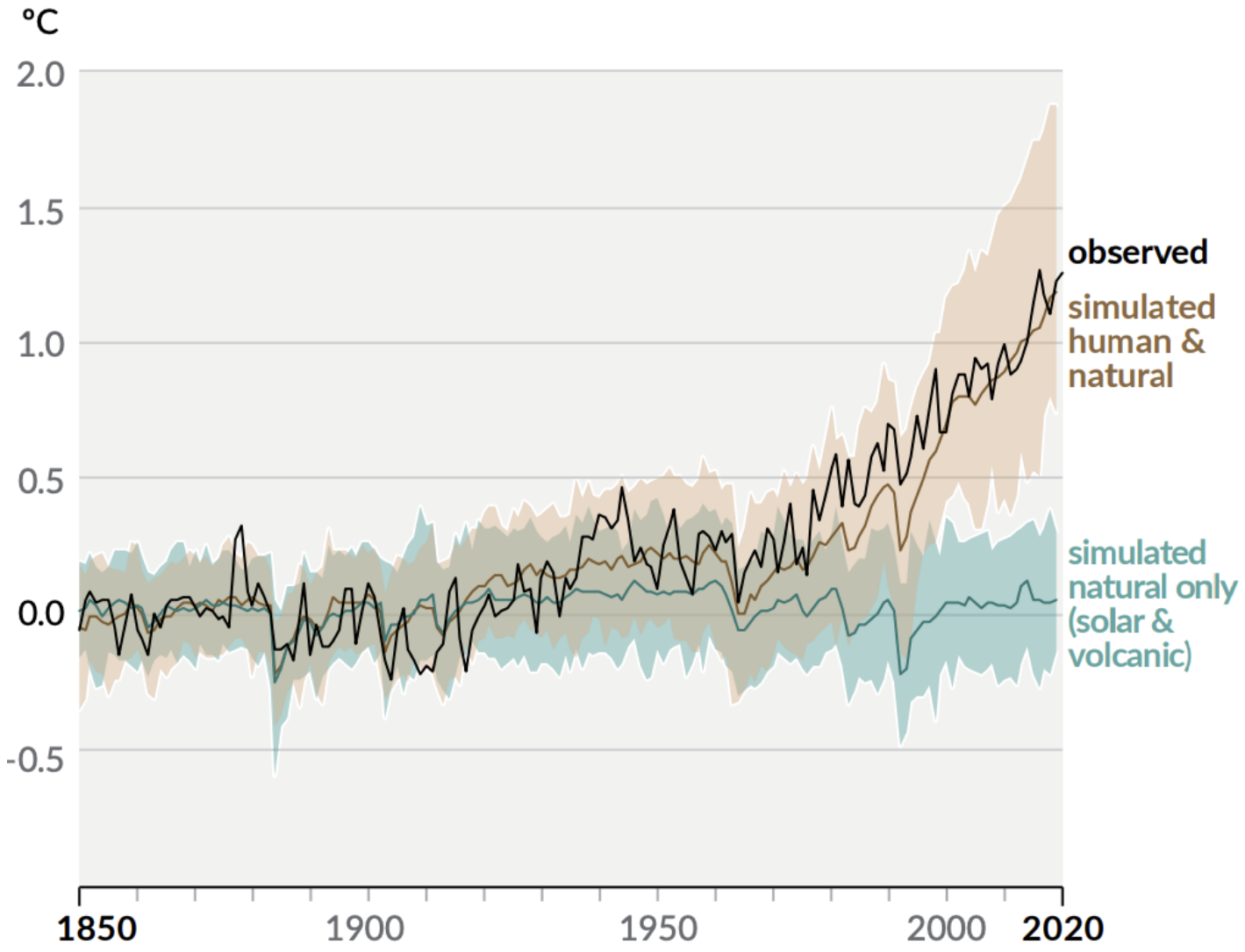


Natural Forcing cannot explain observations



IPCC 2007

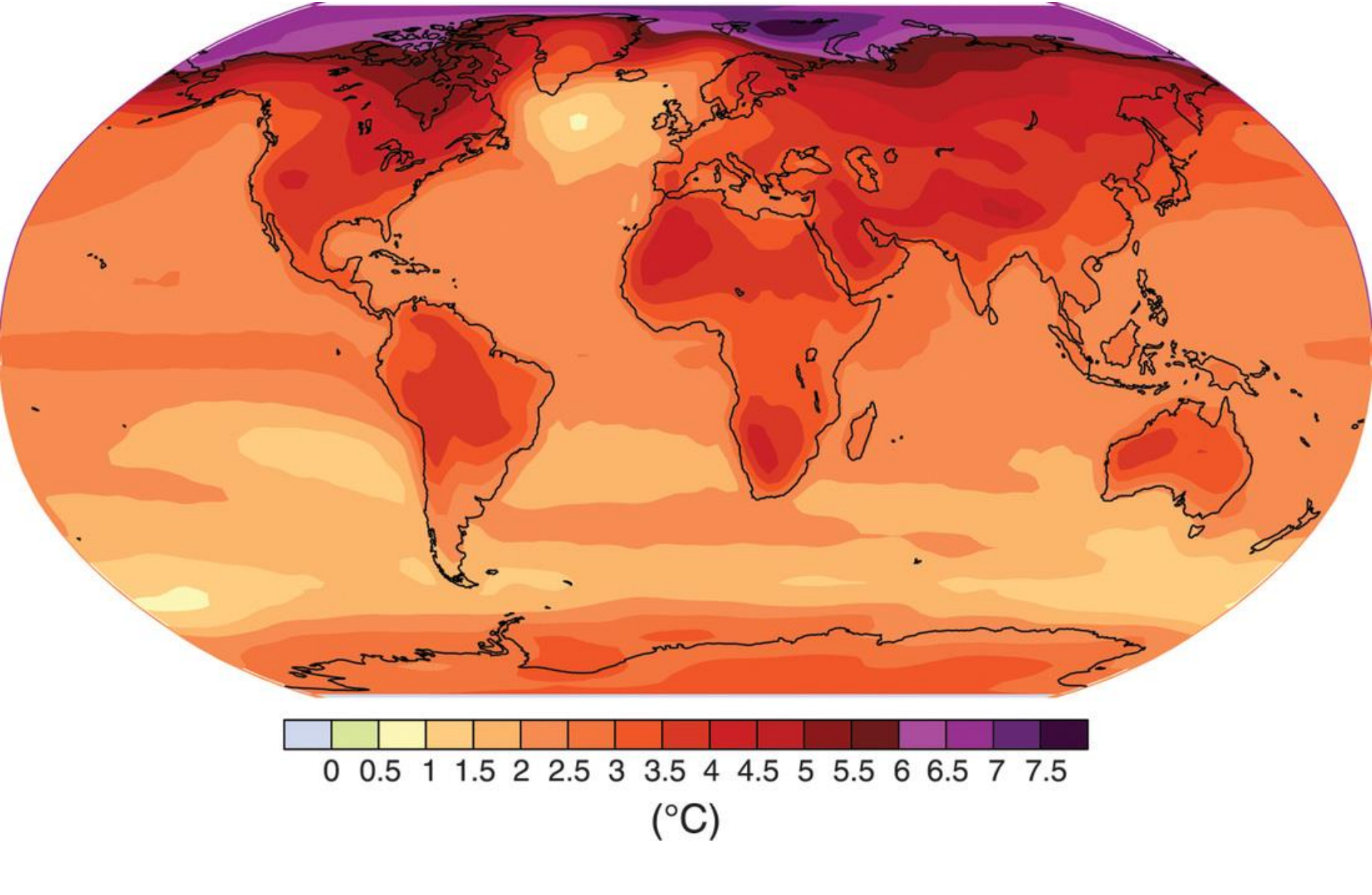
Change in global annual surface temperature relative to 1850 - 1900 as observed and simulated using human & natural and only natural factors for 1850 - 2020



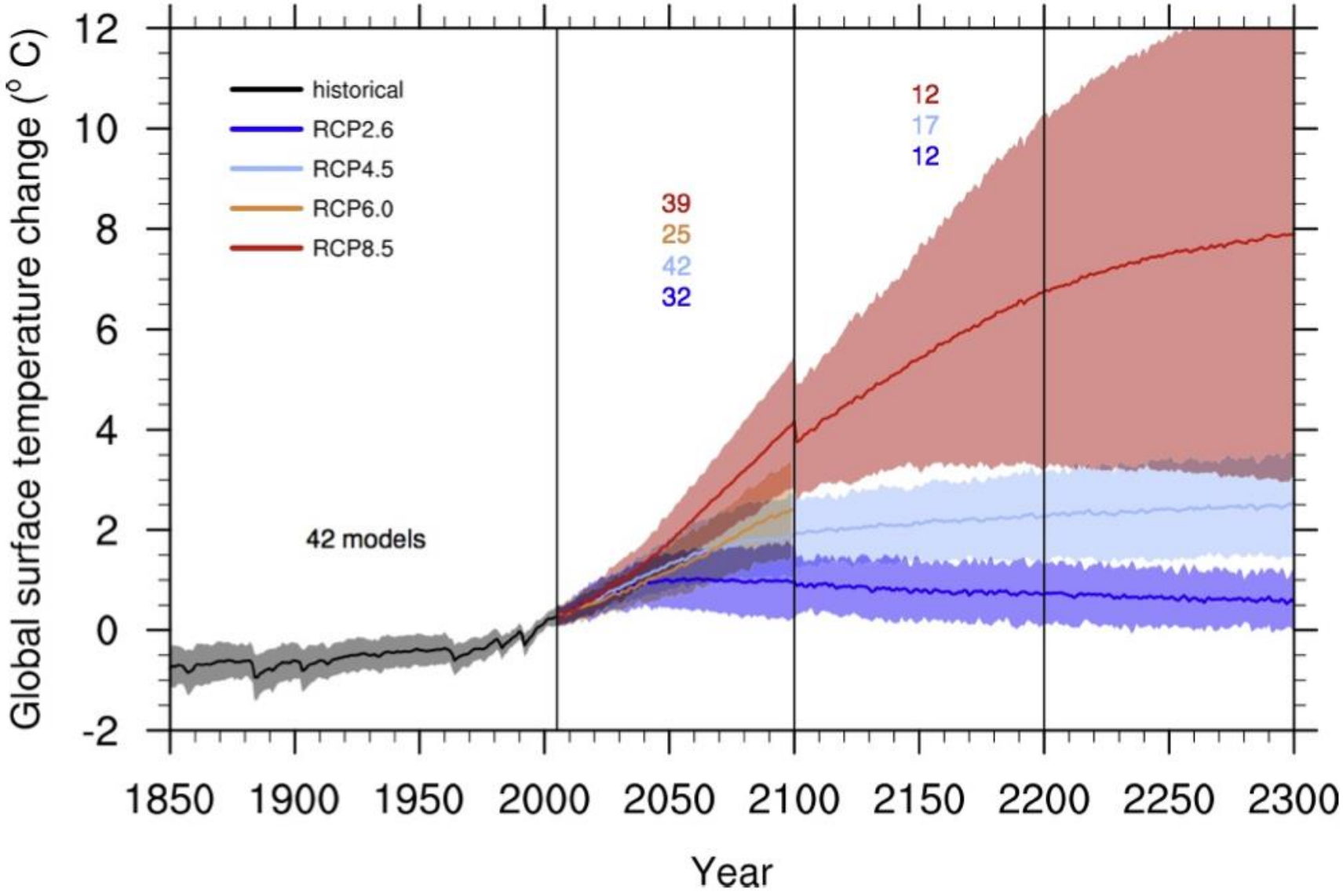
IPCC AR6 2022 Figure SPM.1

AR6

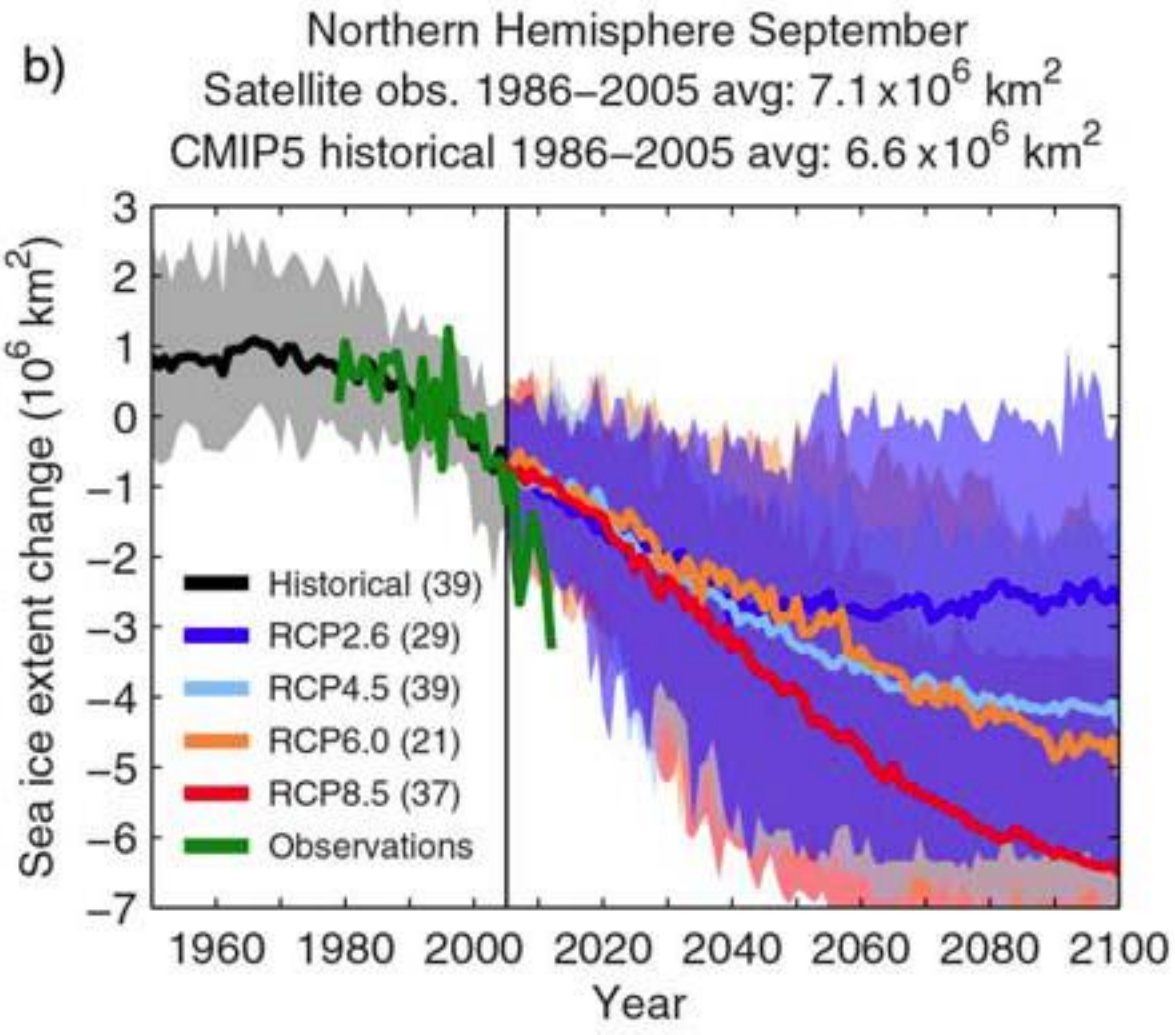
Projected Global Temperatures in 2090-99, relative to 1990-99



Change in Global Surface Temperature



Change in Sea Ice Extent

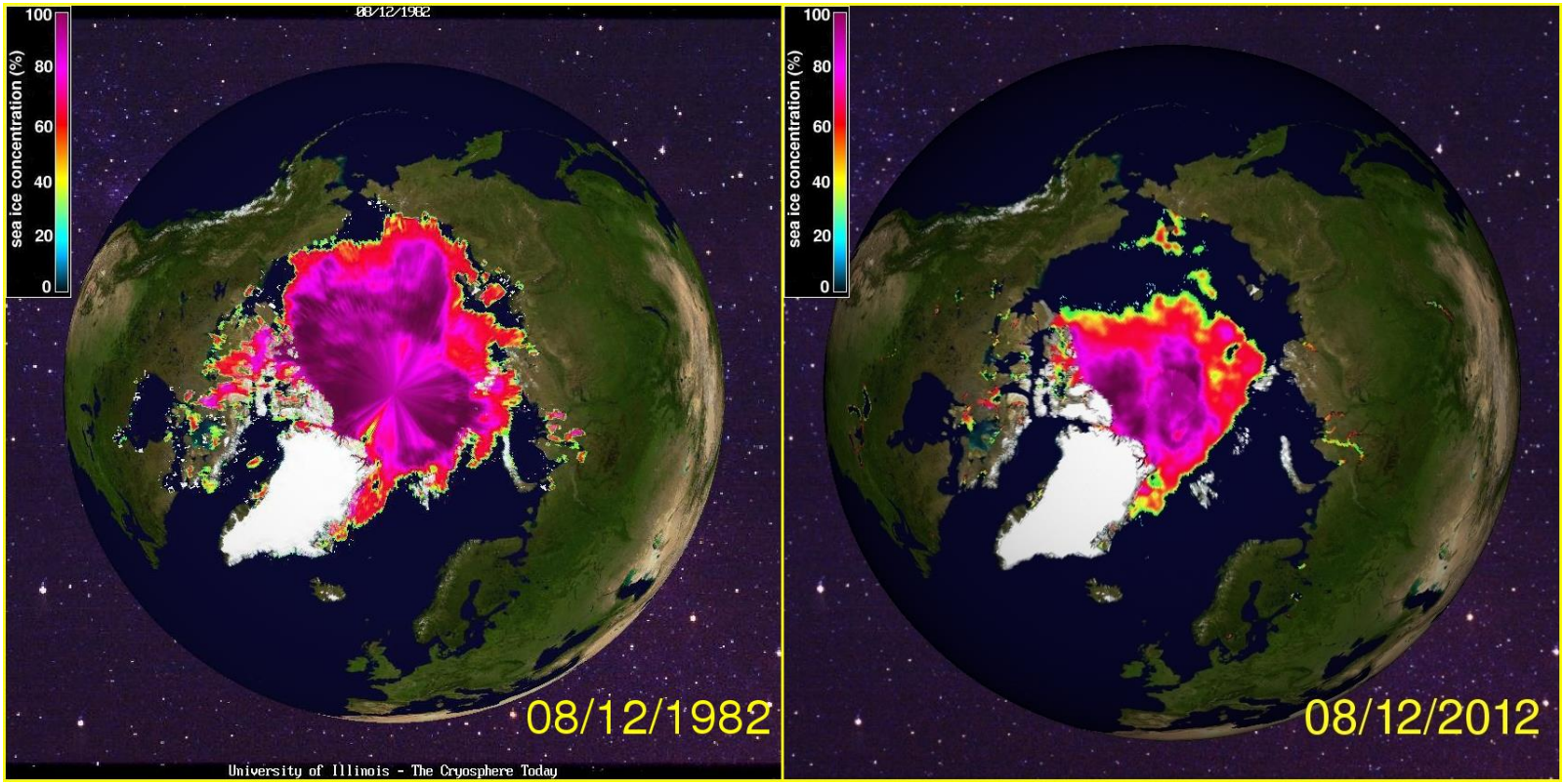


AR5

Arctic Sea Ice is Disappearing

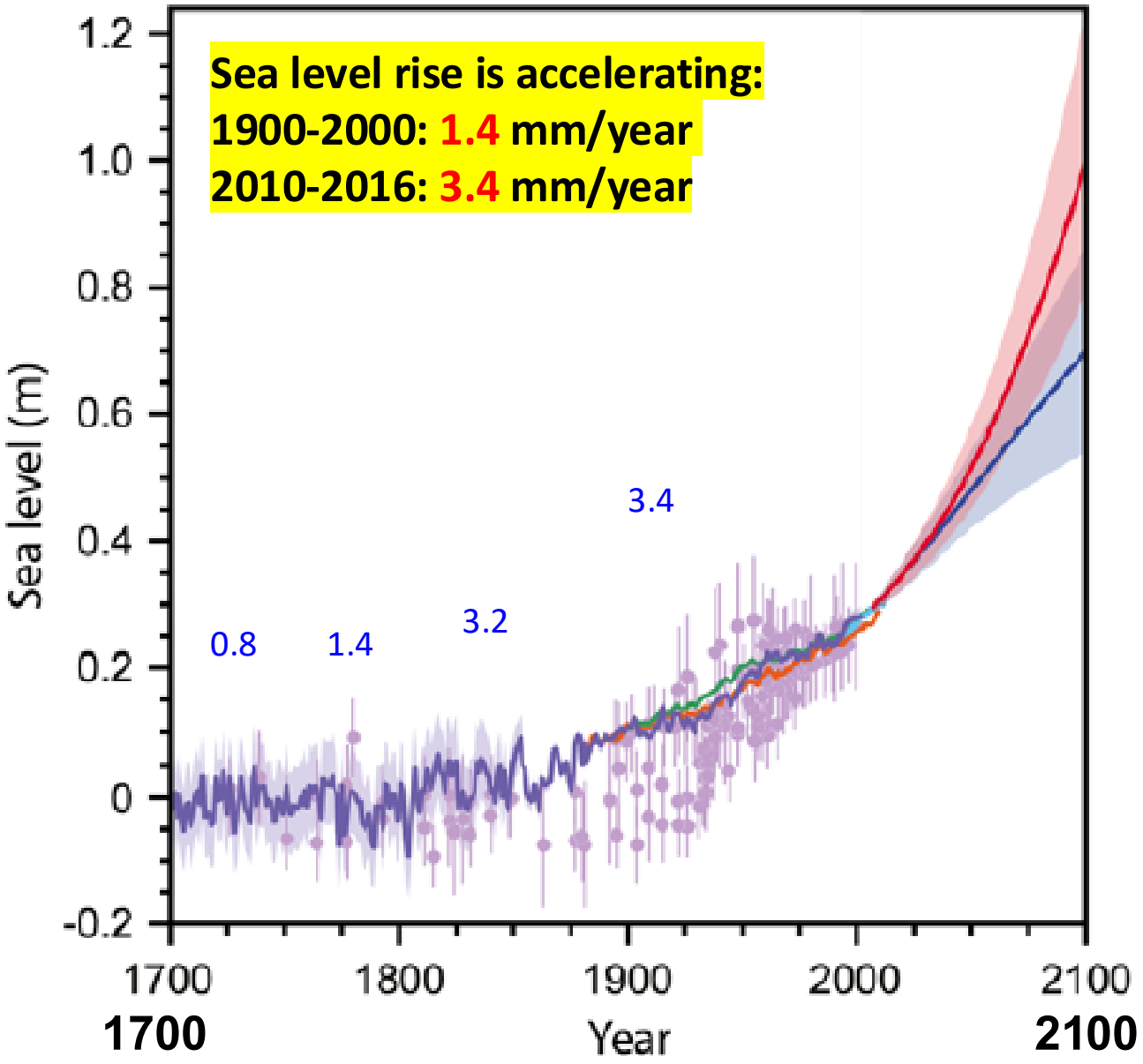
Sea Ice Extent Aug 1982

Sea Ice Extent Aug 2012



Arctic ice loss (2005-2015) = 447 billion tons of ice per year
Antarctic ice loss (2012-2017) = 219 billion tons per year
Both Arctic and Antarctic loss rate have tripled during the recent period

Change in Sea level (Meters)



Eemian period: 114 - 130,000 years ago; 2°C ; sea level 4 - 6 meters higher

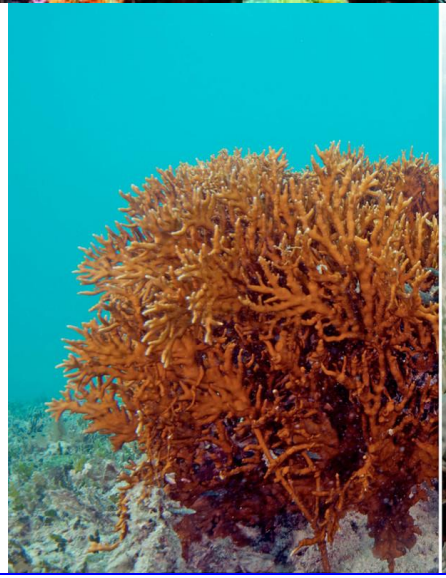
Pliocene period: 2.6 - 5.3 million years ago

Biodiversity Loss Accelerates

Healthy Coral

Bleached Coral

Species loss is accelerating at a rate 10-100 times faster than in the past 10 million years



1 million species at risk of extinction in coming decades (~1.5m currently identified)

Ethics of Climate Change:
Global Inequality in Income and Carbon Emissions

The richest top 10% emit 27.5 tons of CO2e per capita (40% of total emissions) (yellow bar)

The poorest bottom 90% emit 3.6 tons of CO2e per capita (blue bar)

Top 10% own 88% of wealth (top 1% own 50%)

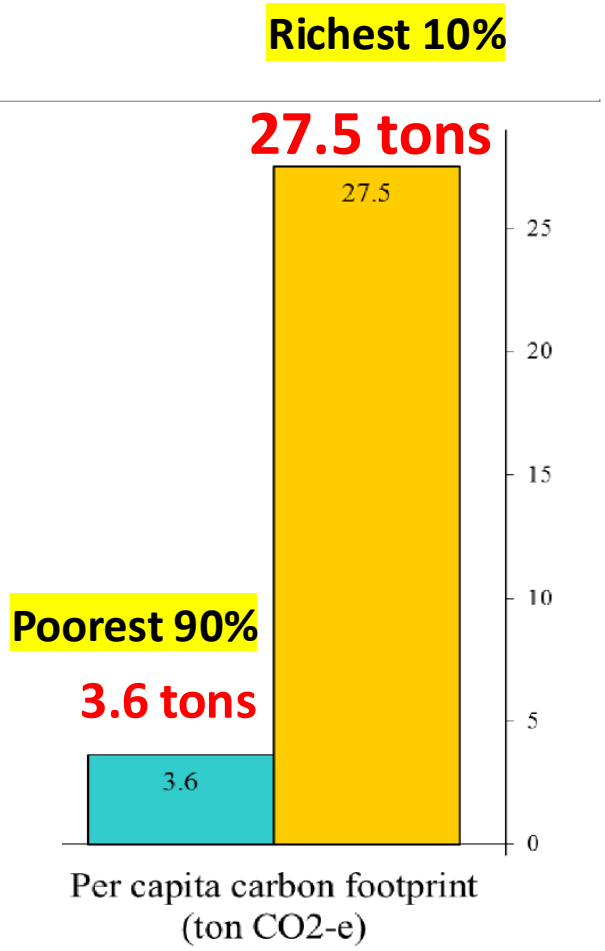


Figure 2: Global inequality in carbon emissions.

Safa et. al. 2016

Ethics of Global Warming

- **"Polluter must pay"**

  (We (US) are the biggest polluters but we also have the biggest guns.)

- **Those who have contributed the least to global warming will suffer the most and the earliest.**

- **Poor countries would like to improve the quality of life of their people (consume more energy).**

- **Sustainable developement in a changing climate is challenged by population growth and extreme poverty.**

GEORGE MASON UNIVERSITY

Ethics

(Those who contributed the least will suffer the most)

Who is causing global warming?

Rich vs. Poor

Developed vs. Developing Countries

Who should pay?

Ethical Challenges

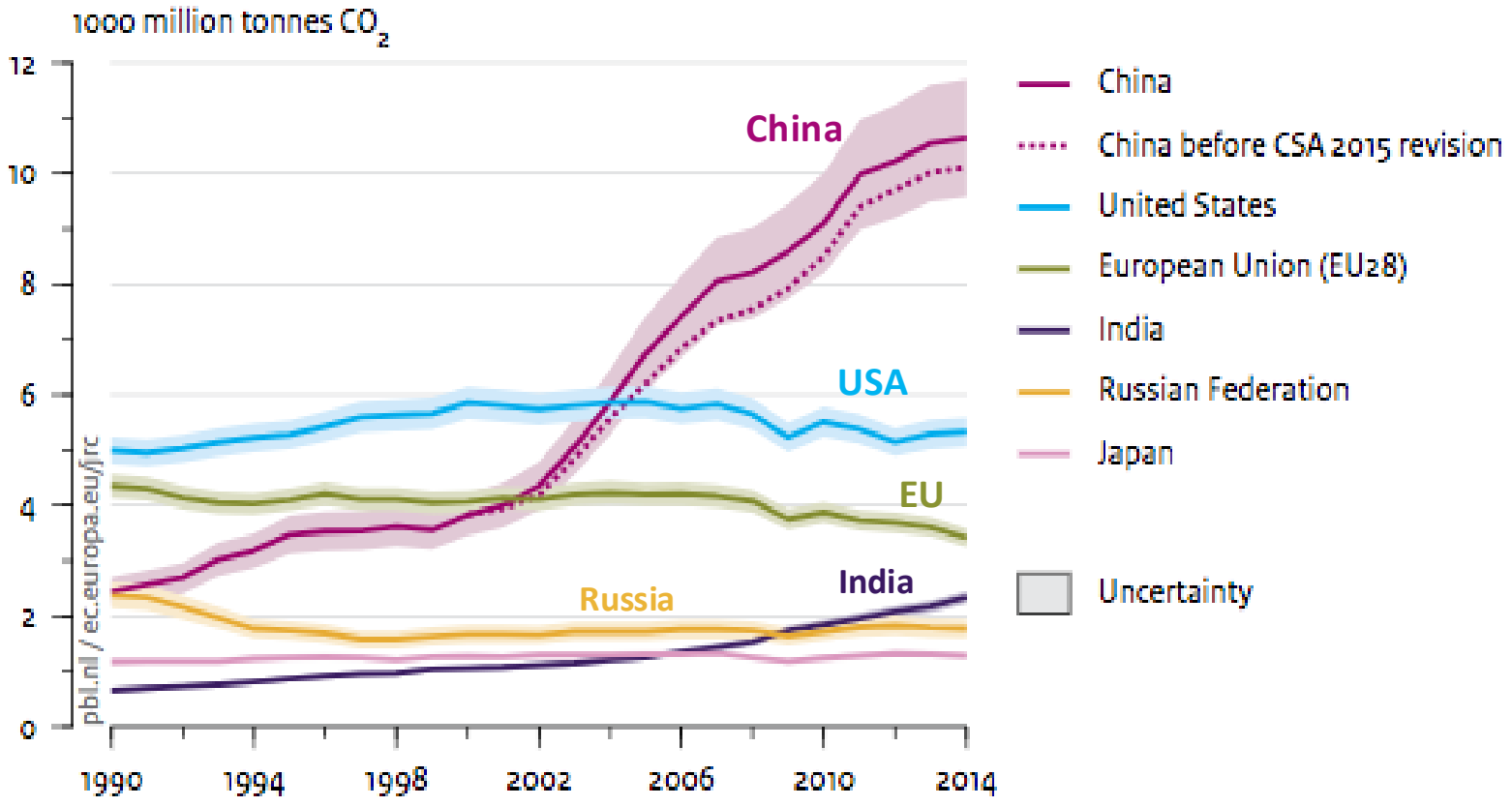
- **Those who have contributed the least to global warming will suffer the most and the earliest.**

- **Developing countries would like to improve the quality of life of their people; how can the requirements of human development be balanced with sustainable energy consumption?**

Emissions for Top 5 Emitting Countries and the EU

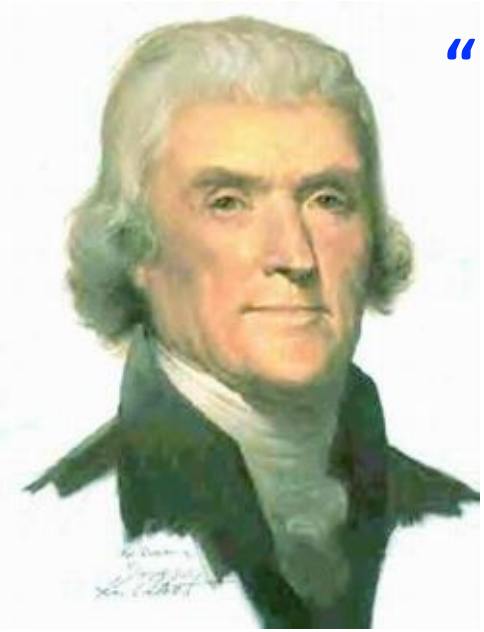
Figure 2.2

CO_2 emissions from fossil-fuel use and cement production in the top 5 emitting countries and the EU



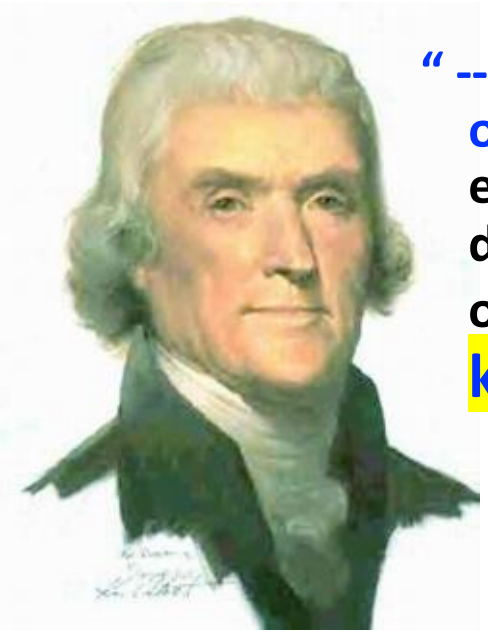
Source: EDGAR 4.3 (JRC/PBL, 2015) (1970-2012; notably IEA 2014 and NBS 2015); EDGAR 4.3FT2014 (2013-2014): BP 2015; GGFR 2015; USGS 2015; WSA 2015

Netherlands Env. Assessment Agency



“--- laws and institutions must go hand in hand with the progress of the human mind. As that becomes more developed, more enlightened, as new discoveries are made, new truths discovered and manners and opinions change, with the change of circumstances, institutions must advance also to keep pace with the times.”

Thomas Jefferson: Letter to George Wythe, August 13, 1790



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Letter from More than 200 members of the U.S. National Academy of Sciences

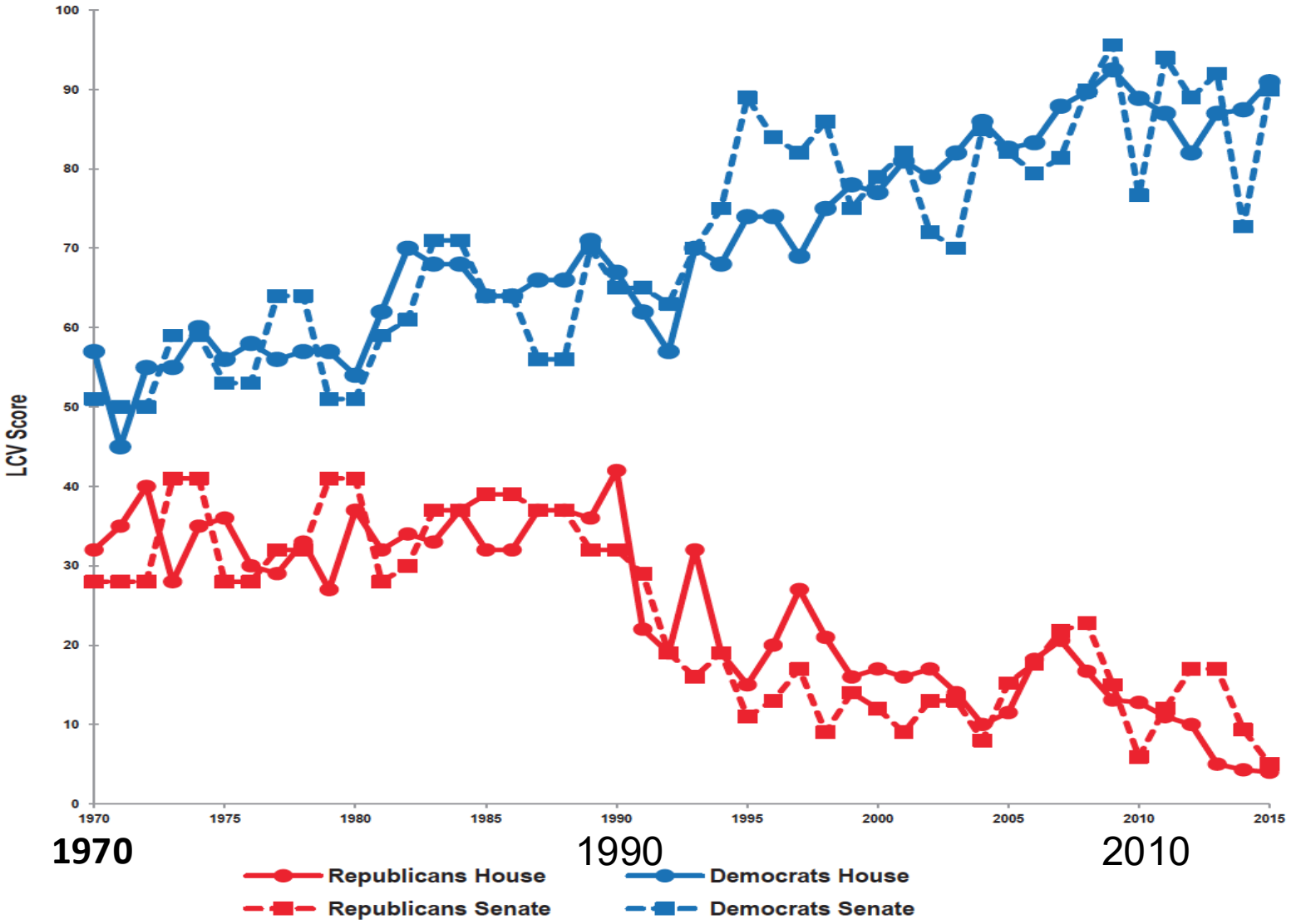
There is compelling, comprehensive, and consistent objective evidence that humans are changing the climate in ways that threaten our societies and ecosystems on which we depend.

US Politics

2015

US Congress Environmental Voting Scores

Figure 1. League of Conservation Voters' environmental voting scores
U.S. Congress – by chamber and party



2015
Democrats

Republicans
2015

Elections Matter for Climate Policy

Paris Climate Agreement:
A Triumph for International Cooperation
A Triumph for Science

November 30 – December 12, 2015

US goes in and out of Paris Climate Agreement

Obama: US joins Paris Agreement

Trump: US withdraws from Paris Agreement

Biden: US again joins Paris Agreement

Trump: *US again withdraws from Paris Agreement;*
*Trump **obliterates** climate research in US*

Auto Emission Policy: Obama; Trump ; Biden

- Obama (2012): *50 mpg in test condition*
- Trump (2018): *37 mpg in test condition .*
- Biden (2021): 52 mpg by 2026

Social Cost of Carbon SC-CO_2

- Obama Administration: $42 per ton
- Trump Administration: $1 - $6 per ton

Hopeful Signs for Climate Solutions

- National and International Policies and Negotiations
- Technological Advances
- Plans and Policies of Institutions and Corporations
- Individual and Collective Action

Hopeful Signs for Climate Solutions

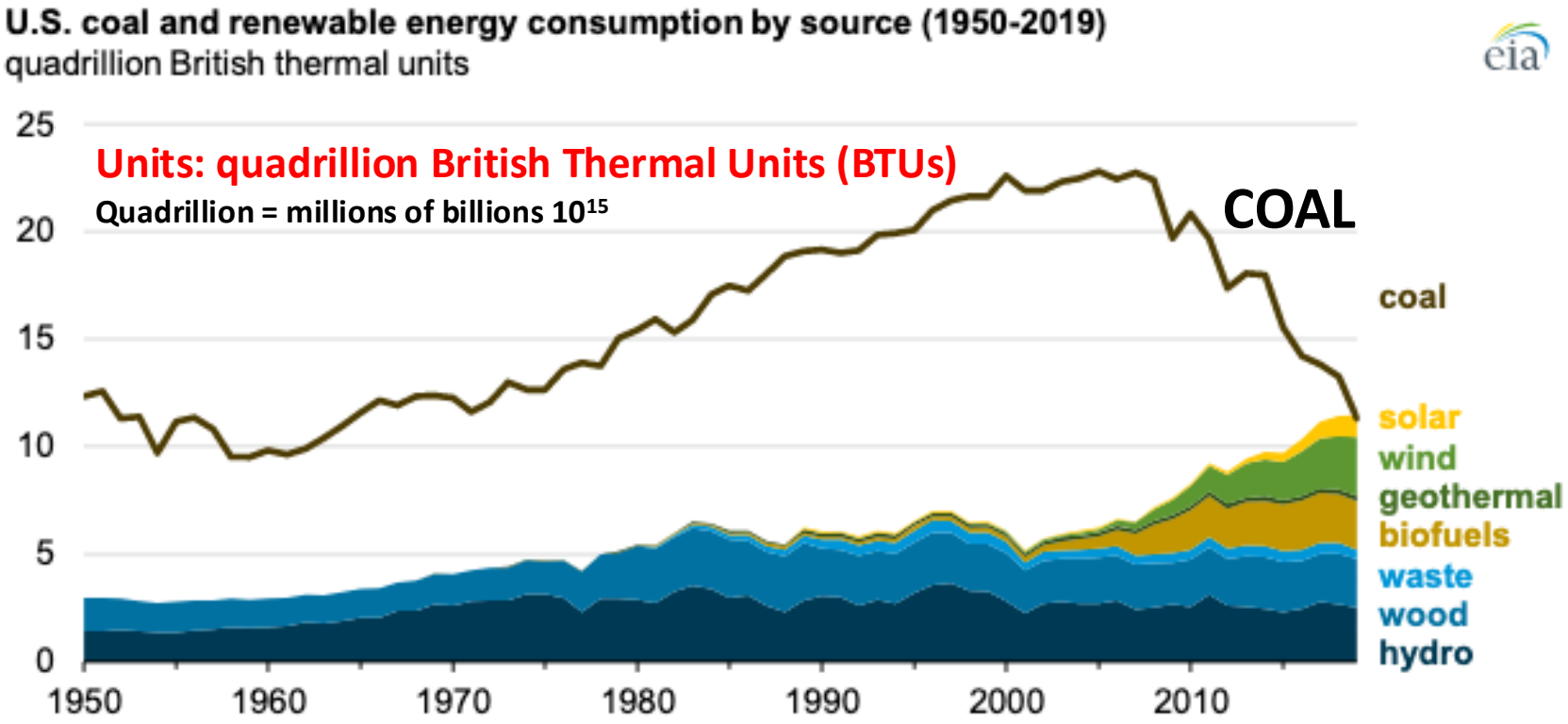
Technological Advances

- **Massive growth of solar and wind energy**
  (solar annual growth 42%)
- **Promising advances in battery technology**
  (price decline by 97% since ‘91)

- **Electric vehicles likely cost-competitive with gas cars**
- **Carbon capture & sequestration**
- **Ecosystem restoration and protection**

U.S. renewable energy consumption surpasses coal for the first time in over 130 years

US produced 50% of electricity from coal in 2000 and 20% in 2020



Role of Institutions: Corporations, NGOs, Universities

Hopeful Signs for Climate Solutions

Plans and Policies of Institutions and Corporations

- Universities and NGOs are developing climate action plans
  (over 700 universities have pledged to reach net-zero emissions)
- 350 major corporations pledged to net-zero
  (50 in US pledged by 2040)
- Major airlines commit to carbon neutrality by 2050
- Worldwide, 450 cities have committed to net-zero by 2050
- Major financial institutions are phasing out fossil fuel investments
- Worldwide Auto Industry is Shifting to Electric Vehicles

Hopeful Signs for Climate Solutions
International Policies and Negotiations

- **China:** peak emissions before 2030 and to achieve carbon neutrality before 2060 *(China pledged not to fund coal globally)*
- **US:** 50-52% emissions reduction over 2005 levels by 2030, 100% clean electricity by 2035, net-zero by 2050
- **India:** 40% clean power generation by 2030; 450 GW of all renewable energy by 2030 *(but India has made no commitment to reduce emissions and timeline for net-zero).*
- **European Union:** 55% net emissions reductions by 2030 and carbon neutral by 2050 *(The first climate neutral continent)*
- **US and EU (2021):** Global Methane Pledge (30% by 2030)

Hopeful Signs for Climate Solutions
Individual and Collective Action

- **Reduction in personal carbon footprint**
  (car, diet, food waste, travel, energy efficient appliances, compost)
- **Expanding social movements, protests, rallies, and demonstrations:**

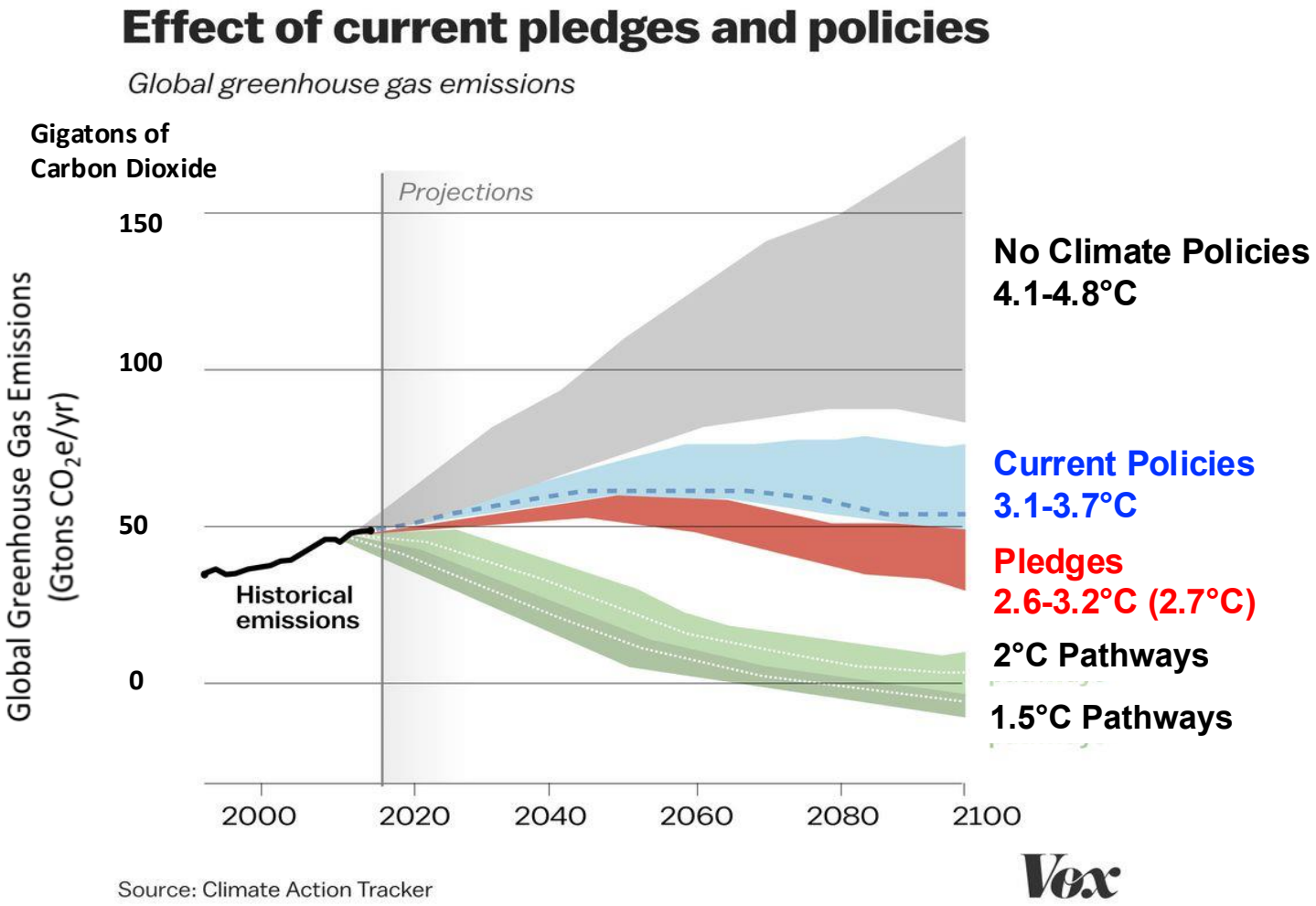
7 million people across 185 countries joined the world's largest climate strike in 2019

- **Election of climate-literate policymakers**
- **US Congress Bipartisan Climate Solutions Caucus**
  - **24 Republicans and 41 Democrats, drafted carbon tax bill in 2019**
- **Advocate for net-zero emissions and divestment – work and home**
- **GMU Climate Action Plan for net-zero emissions:**

  how to get there?

Projected Climate Change

A Solvable Problem



120,000 years ago, + 2°C ; sea level 4 - 6 meters higher

2.6 - 5.3 million years ago, + 3-4 °C ; sea level 15 – 20m higher

People Ask: "What Can I Do?"

- **Reduce personal carbon footprint**
  (car, house, diet, travel); Conserve energy and water

- **Vote to elect climate-literate leaders**

- **Join protests and rallies**

- **Solution to climate anxiety is climate action**

highest impact action: educate girls (Project Drawdown)

Greta Thunberg at Youth4Climate in Milan

https://www.youtube.com/watch?v=UryIL4kUcx8

Climate Change is a Solvable Problem

Science & technology + ambitious and enlightened policy

- **Montreal Protocol: global agreement to phase out CFC's to protect ozone layer and save humanity**

- **COVID-19: vaccine development and distribution and public health policies and precautions**

- **Climate change: we understand the science, we have the technology, we need an engaged public and the political will to advance ambitious policies**

THANK YOU!

ANY QUESTIONS?

For any additional questions, please contact me at jshukla@gmu.edu

The Washington Post

Terrifying Floods in China – July 2021

European Floods of July 2021

Outline

1. **Memoir - A Billion Butterflies: A Life in Climate and Chaos Theory**

   Journey from Village to MIT to NASA to UMD to COLA to GMU

2. **Evolution of Scientific Ideas**

   (Reanalysis; Land-Atmosphere Interaction; Predictability in the Midst of Chaos, Dynamical Seasonal Prediction)

3. **Climate Change: Science, Politics and Solutions**

Village: The Elementary School Now Has A Building

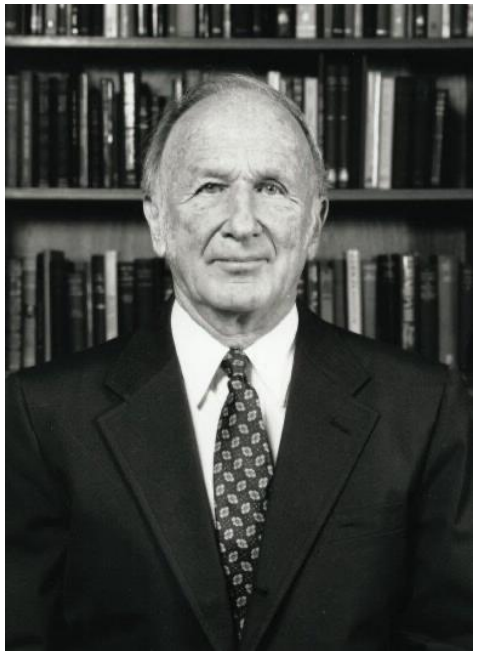
Middle School: walk barefoot each way 3 miles
High School: walk with sandals each way 2 miles
B.Sc., M.Sc., Ph.D. (Geophysics): Banaras Hindu University

“I will give you a talisman.
Whenever you are in doubt, or when the self becomes too much with you, apply the following test.
Recall the face of the poorest and the weakest man whom you may have seen,
and ask yourself if the step you contemplate is going to be of any use to him.
Will he gain anything by it?
Will it restore him to a control over his own life and destiny?”

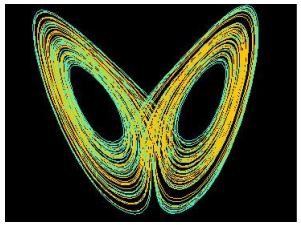
(Mahatma Gandhi, 1948)

MIT Green Building (1971-76)

Sc.D. (Meteorology, 1976)



Lorenz (1963)



Butterfly Effect

Charney et al (1950)

Birth of Numerical Weather prediction:
Origin of Weather Prediction using mathematical equations and digital computer
(by Von Neumann)

Ed Lorenz visiting COLA

Nobel Prize Award Ceremony (2021) at National Academy of Sciences

Manabe received Nobel Prize in Physics

The first US supercomputer (Cray XMP-14) purchased by India for weather forecasting, in the lobby of the National Centre for Medium Range Weather Forecasting (NCMRWF) in New Delhi, February 2024.

Billion Butterflies Experiment

- ***Tropical Atmosphere:***

Make predictions from two initial conditions of the atmosphere which are much larger than the flaps of the billions or trillions of butterflies

- ***Tropical Ocean:***

Make predictions from two initial conditions of the atmosphere which are much larger than the flaps of the billions or trillions of butterflies

This helped communicate the feasibility of DSP not based on case studies but in the language of predictability (a la Lorenz)

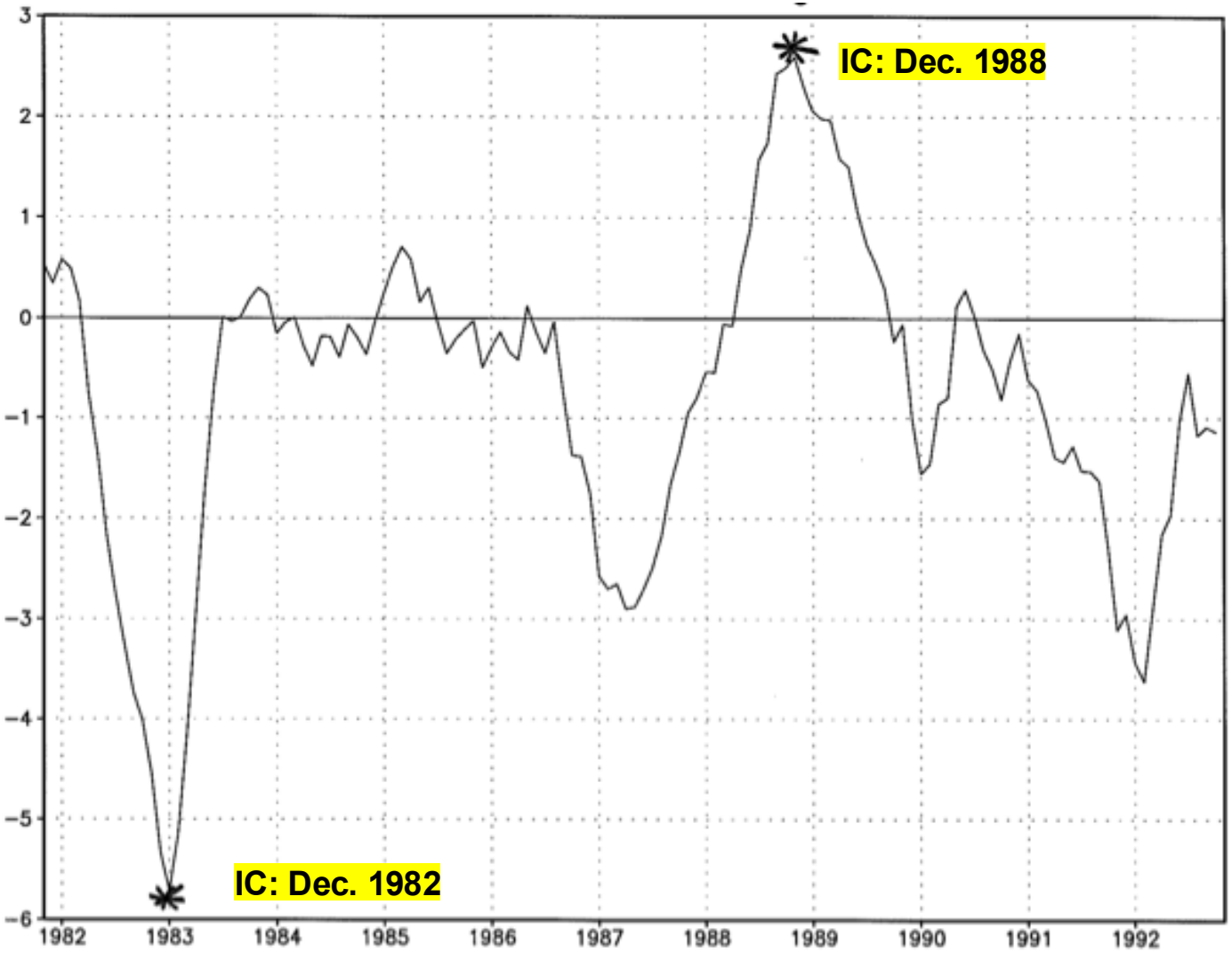
Billion Butterflies Experiment (Atmosphere)

IC were very different in 1982 and 1988

Sea Level Pressure Difference

Southern Oscillation Index (SOI)

SOI = Tahiti – Darwin SLP



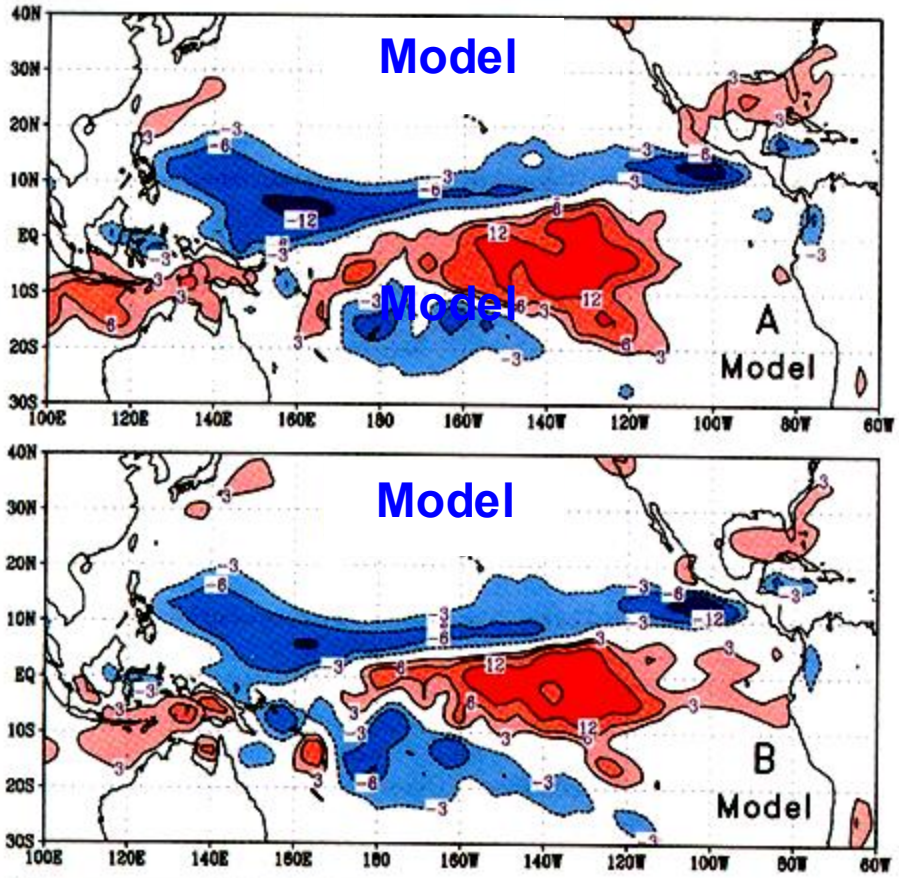
Observed 5-month running mean SOI

JFM Mean Rainfall Anomalies

Seasonal Mean Rainfall is Not Sensitive to Atmospheric Initial Conditions

IC: Dec. 1988

IC: Dec. 1982



"Predictability in the Midst of Chaos"