EXHIBIT 5

Understanding how carbon dioxide emissions from human activity contribute to global climate change

MYLES ALLEN Environmental Change Institute, School of Geography and the Environment & Department of Physics

University of Oxford

myles.allen@ouce.ox.ac.uk

The impact of carbon dioxide emissions on global climate

- How rising atmospheric CO_2 causes global warming
- How industrial emissions are increasing atmospheric CO_2
- Modeling the impact of increasing CO_2 concentrations
- Quantifying human and natural influences on global climate
  - A digression on ice-ages
- How rising temperatures are affecting global sea level
- The permanent, cumulative impact of CO_2 emissions
  - Implications for the impact of delay in emission reductions

eci

UNIVERSITY OF OXFORD

The impact of carbon dioxide emissions on global climate

- How rising atmospheric CO_2 causes global warming
- How industrial emissions are increasing atmospheric CO_2
- Modeling the impact of increasing CO_2 concentrations
- Quantifying human and natural influences on global climate
  - A digression on ice-ages
- How rising temperatures are affecting global sea level
- The permanent, cumulative impact of CO_2 emissions
  - Implications for the impact of delay in emission reductions

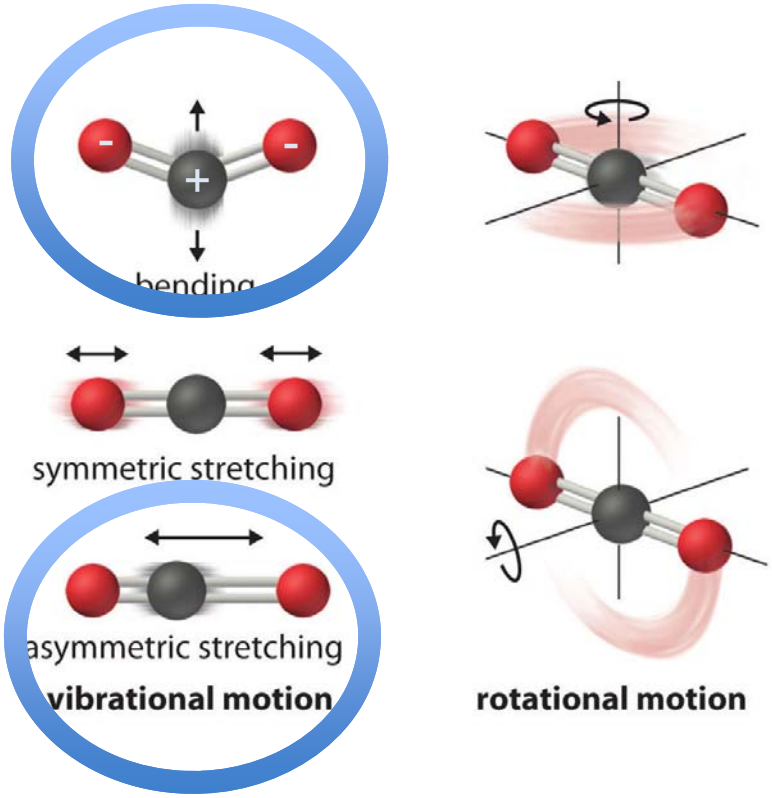
eci

UNIVERSITY OF OXFORD

1824-1860s: Fourier and Tyndall

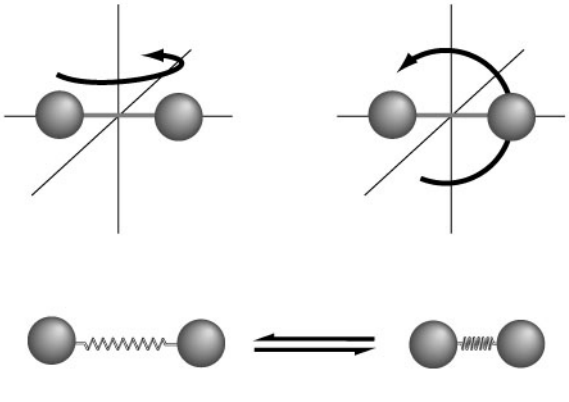
- Identified CO_2 as one of the trace gases responsible for the blanketing effect of the atmosphere, absorbing and emitting infra-red radiation, keeping Earth's surface warm.

How air molecules interact with electromagnetic radiation



Some of these modes create asymmetrically-charged “dipoles” which interact with electromagnetic radiation, particularly in the infra-red part of the spectrum.

Some of the many modes of motion of a CO_2 molecule



The fewer modes of motion of an O_2 or N_2 molecule

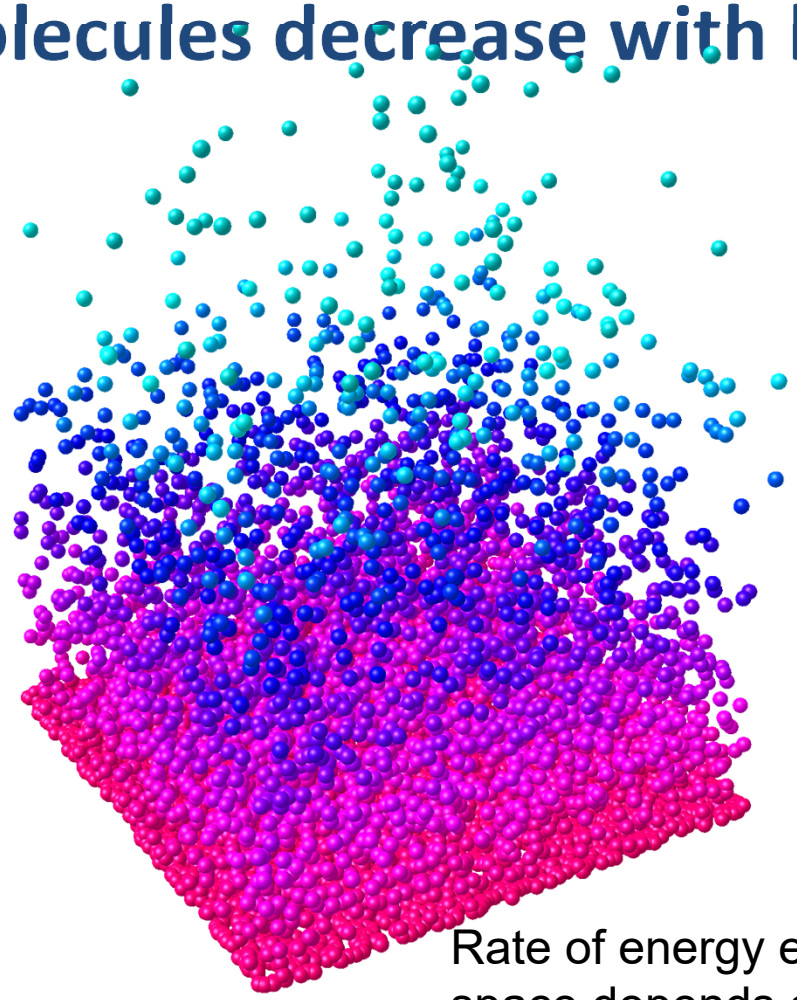
The first quantitative account of the impact of rising CO_2 on temperature: Svante Arrhenius

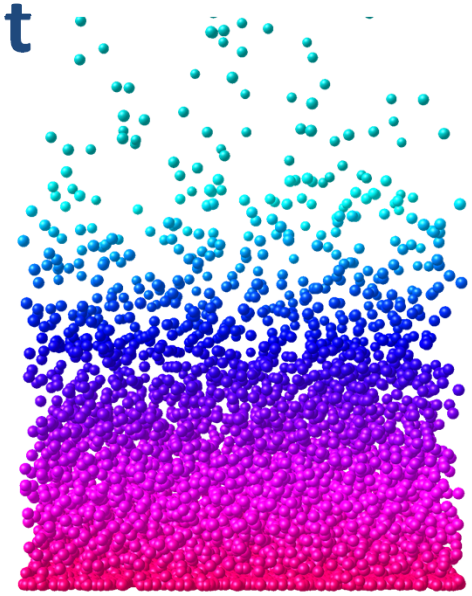
- "Any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4° C; and if the carbon dioxide were increased fourfold, the temperature would rise by 8° C."

eci

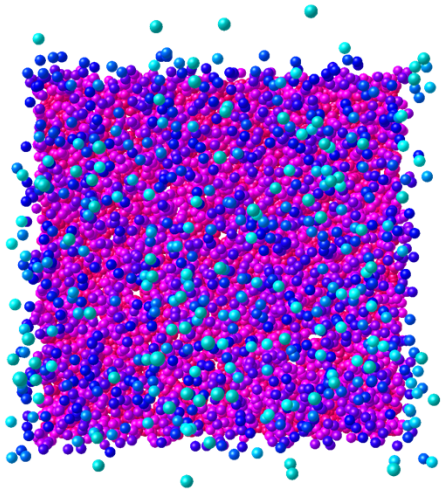
UNIVERSITY OF OXFORD

Both temperature and density of absorbing CO_2 molecules decrease with height





View from side



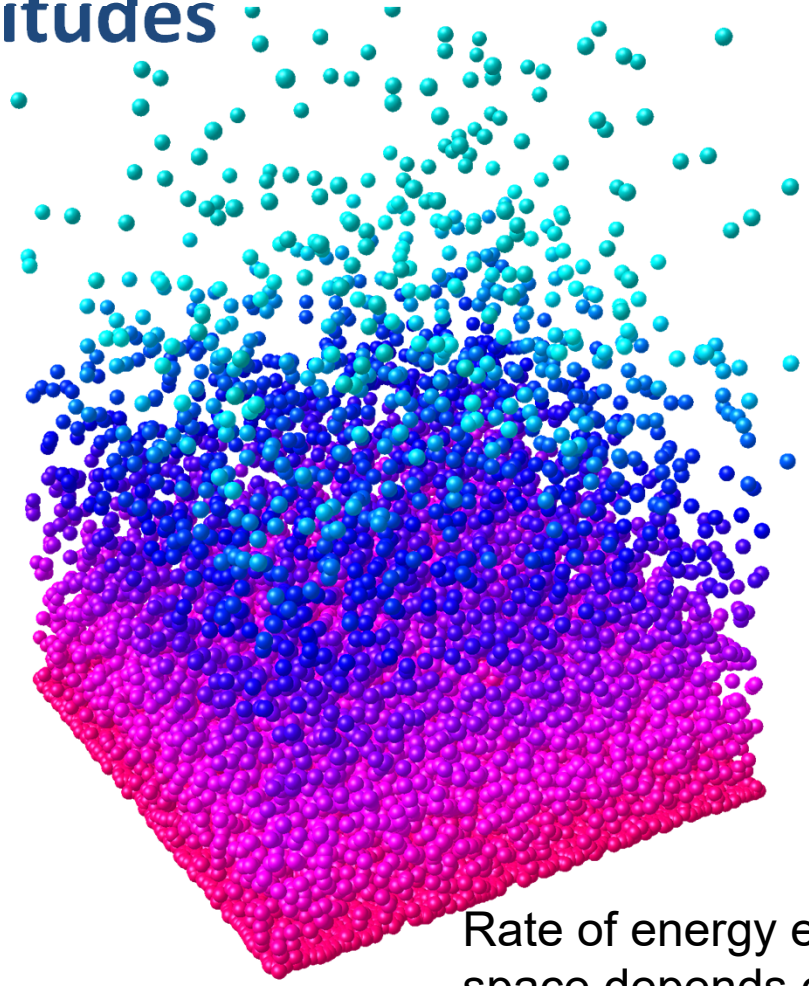
View from above

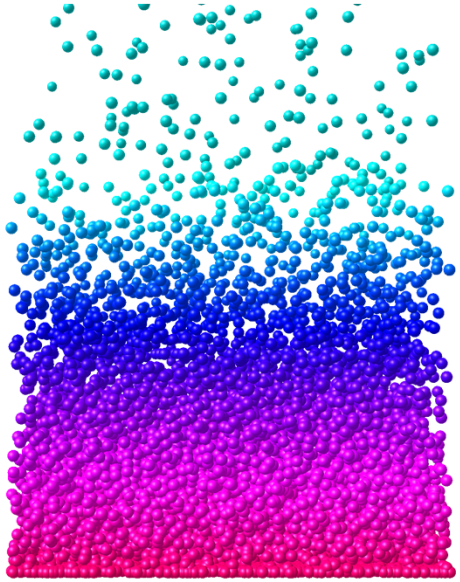
Rate of energy emitted to space depends on the average temperature of molecules as seen from above

eci

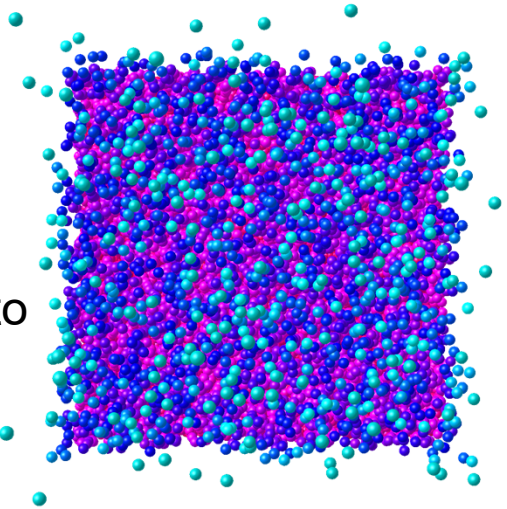
UNIVERSITY OF OXFORD

Increasing CO_2 forces energy to escape from higher altitudes





View from side



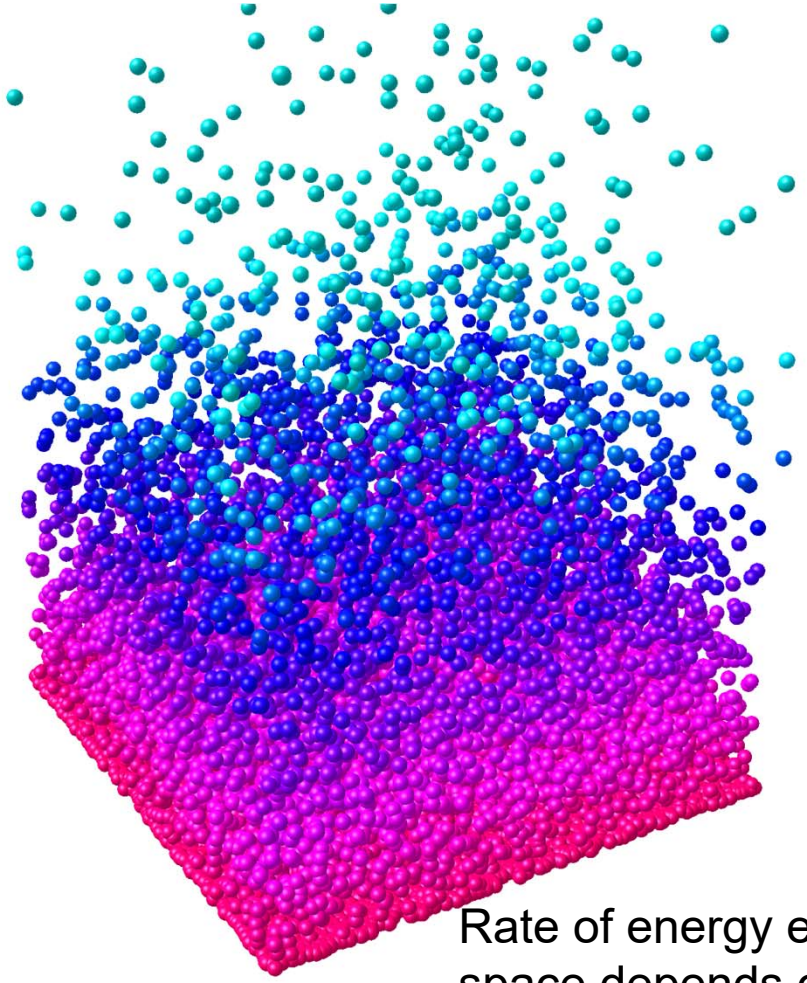
View from above

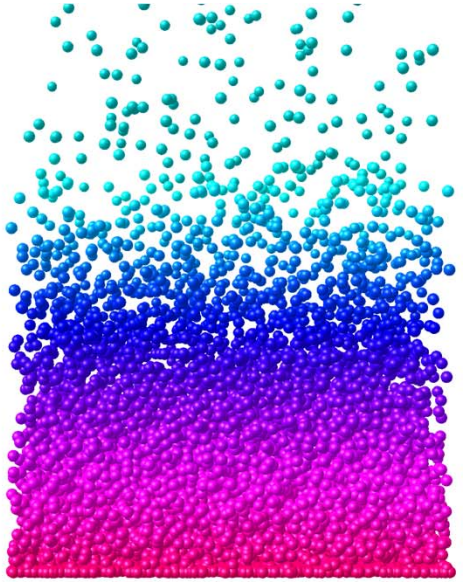
Rate of energy emitted to space depends on the average temperature of molecules as seen from above

eci

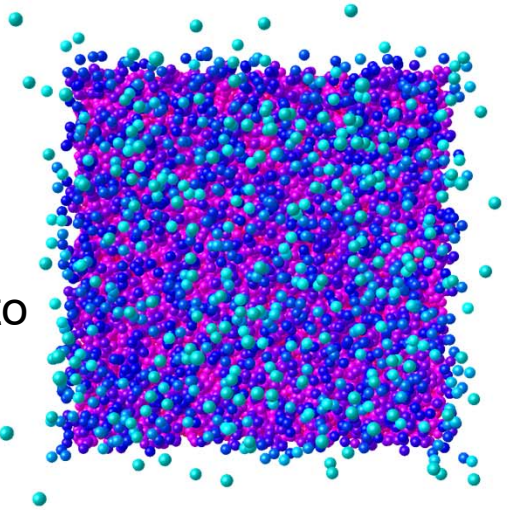
UNIVERSITY OF OXFORD

Higher air is colder, and so radiates less energy





View from side



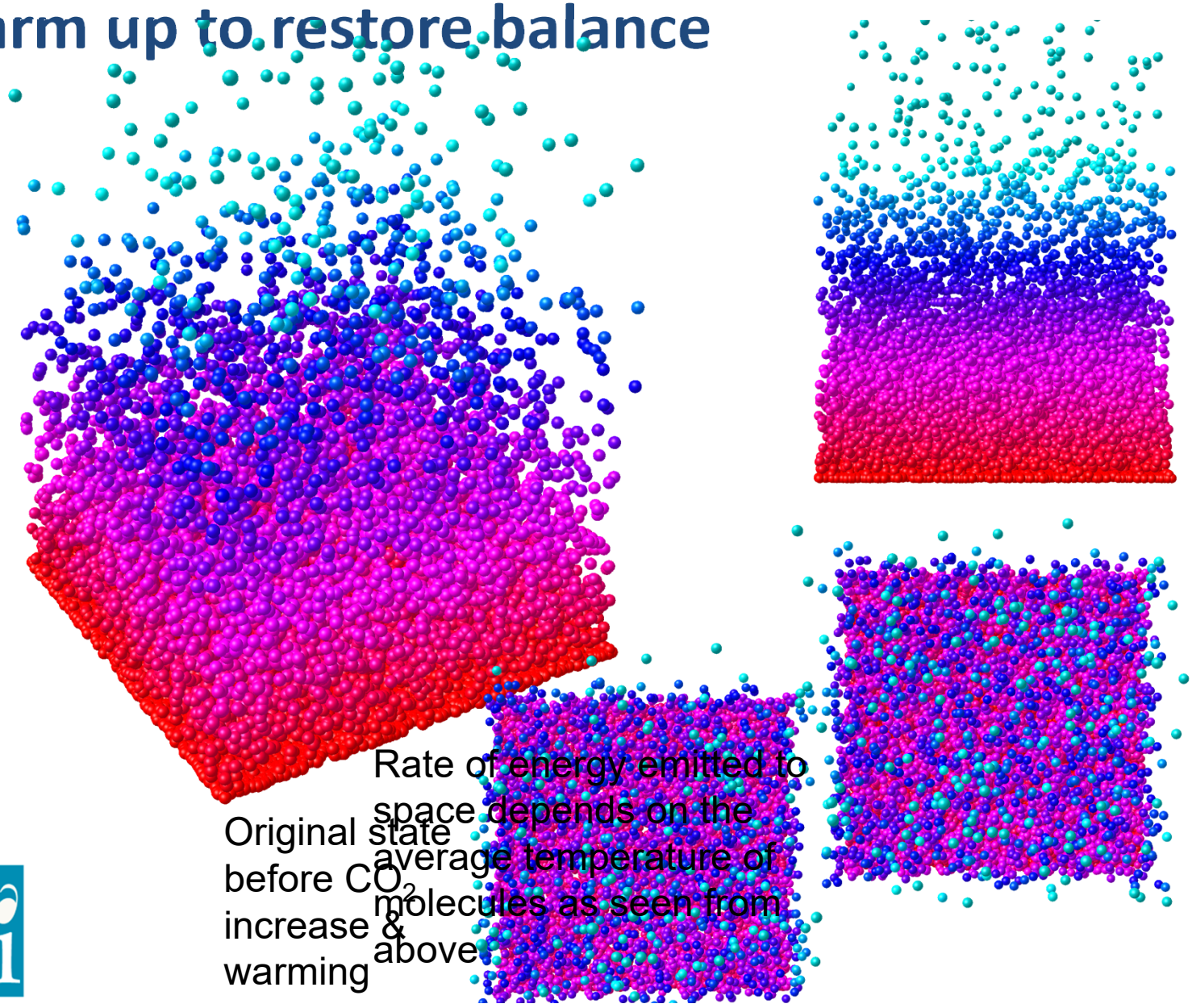
View from above

Rate of energy emitted to space depends on the average temperature of molecules as seen from above

eci

UNIVERSITY OF OXFORD

So the surface and lower atmosphere have to warm up to restore balance



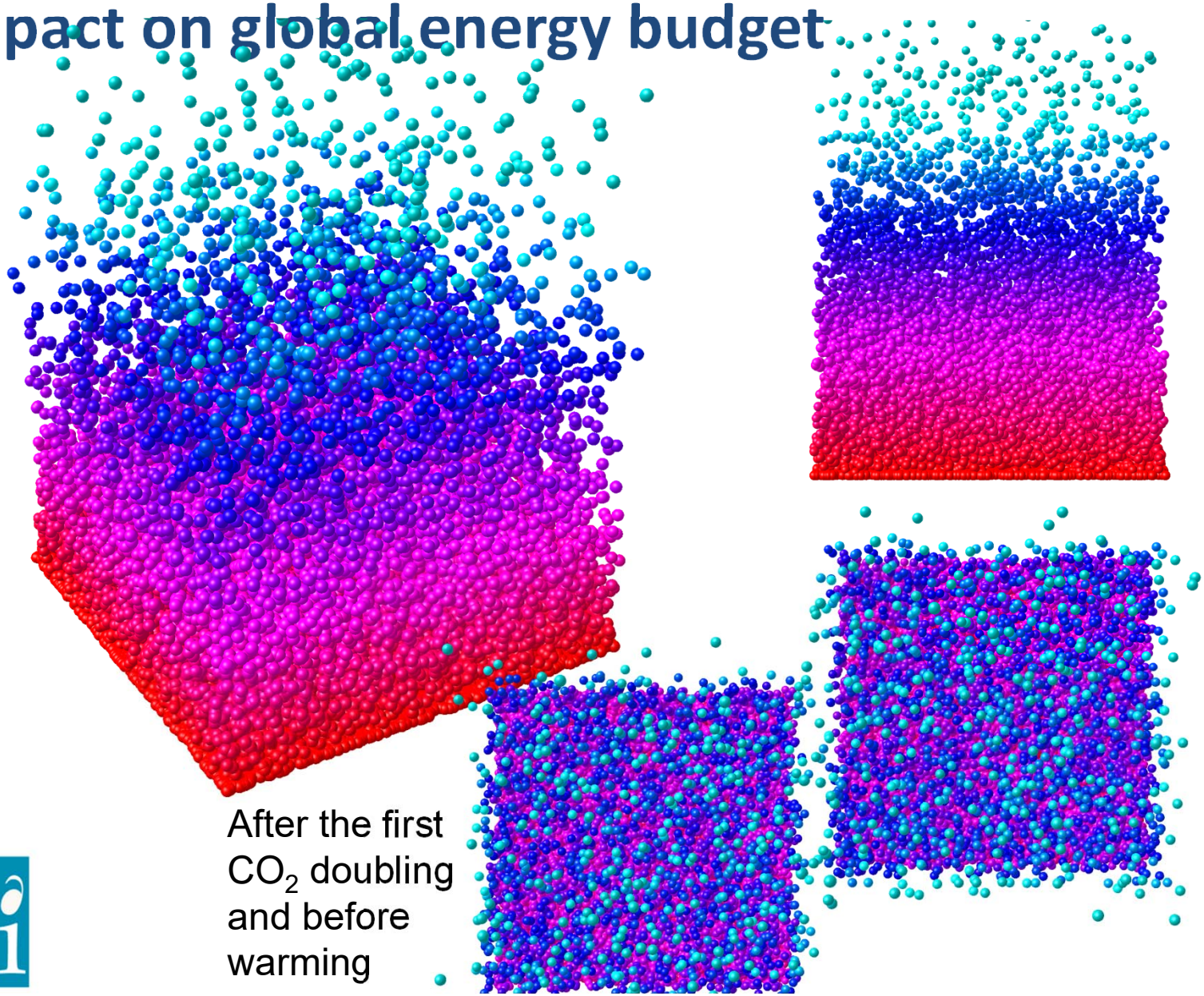
View from side

View from above

Original state before CO_2 increase & warming

Rate of energy emitted to space depends on the average temperature of molecules as seen from above

Successive CO_2 doublings have about the same impact on global energy budget



View from side

View from above

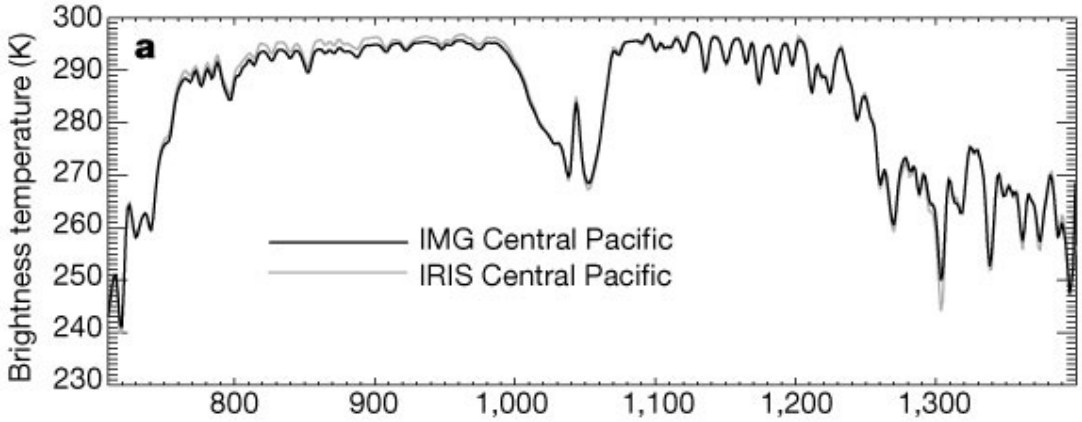
After the first CO_2 doubling and before warming

eci

UNIVERSITY OF OXFORD

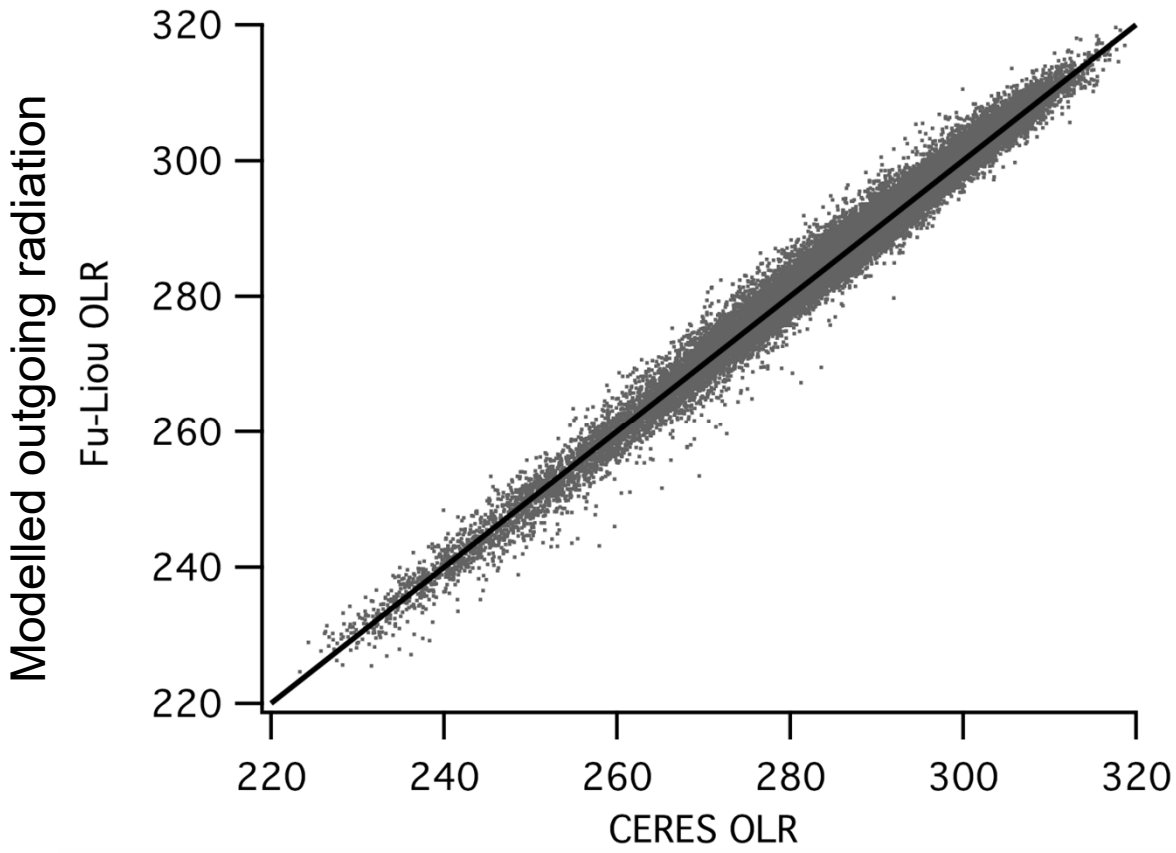
Impact of rising GHGs on the spectrum of outgoing energy has been directly observed from space

Nimbus 4, 1970



Comparison of outgoing spectra, 1997 versus 1970. Harries et al (2001)

And is tested in the models used for weather forecasting millions of times per day



Dessler et al, JGR, 2008

Gilbert Plass (1955) and the role of water vapour

- Noted "the CO_2 theory" had been criticized because of strong absorption of infra-red radiation by water vapor.
- Correctly observed that at the altitudes from which radiation escapes to space, above the humid lower atmosphere, CO_2 is the dominant greenhouse gas.
- Emphasized urgency of measuring CO_2.

eci

UNIVERSITY OF OXFORD

The impact of carbon dioxide emissions on global climate

- How rising atmospheric CO_2 causes global warming
- How industrial emissions are increasing atmospheric CO_2
- Modeling the impact of increasing CO_2 concentrations
- Quantifying human and natural influences on global climate
  - A digression on ice-ages
- How rising temperatures are affecting global sea level
- The permanent, cumulative impact of CO_2 emissions
  - Implications for the impact of delay in emission reductions

eci

UNIVERSITY OF OXFORD

Roger Revelle, 1957

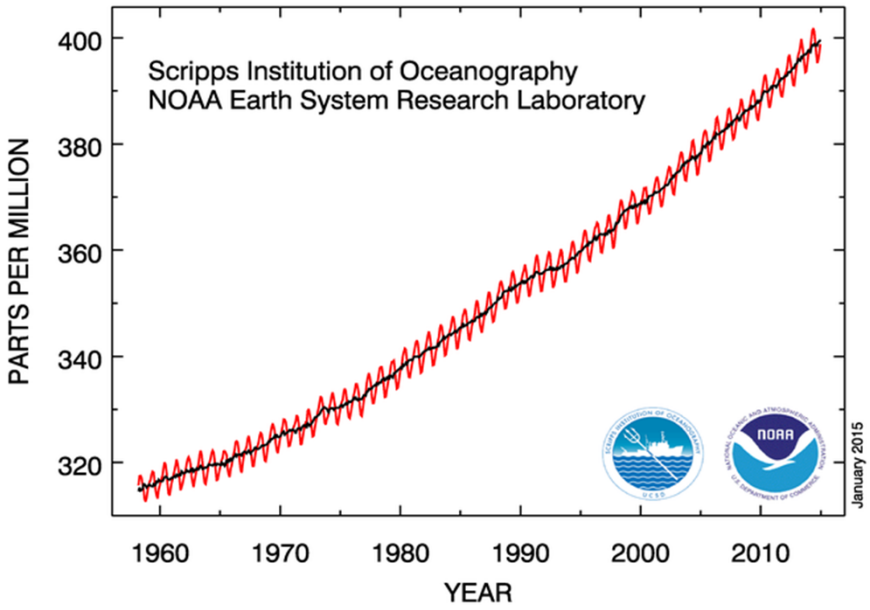
- Explained how ocean buffer chemistry limits the amount of CO_2 taken up by the oceans, even in equilibrium.
- Hence CO_2 emissions have a permanent impact on climate: we can't rely on the oceans to dilute them away.

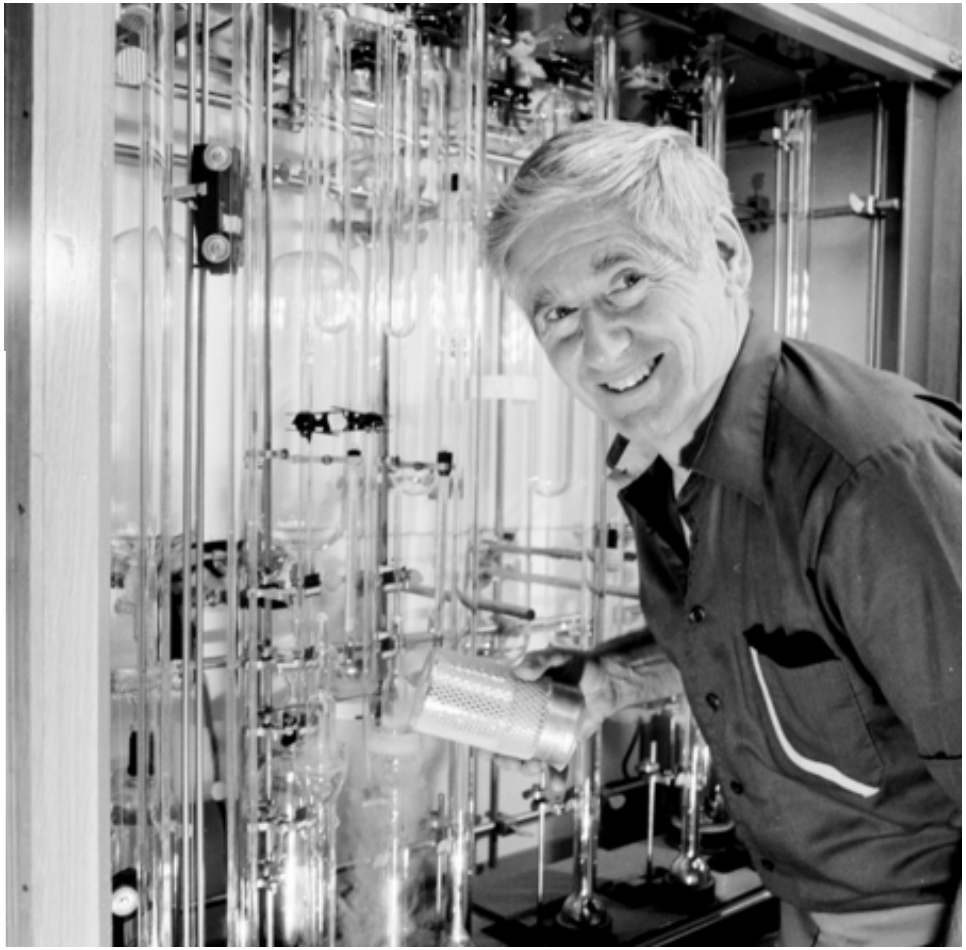
eci

UNIVERSITY OF OXFORD

Charles David Keeling's observations, 1958-60

- Unequivocal evidence that CO_2 concentrations are rising steadily

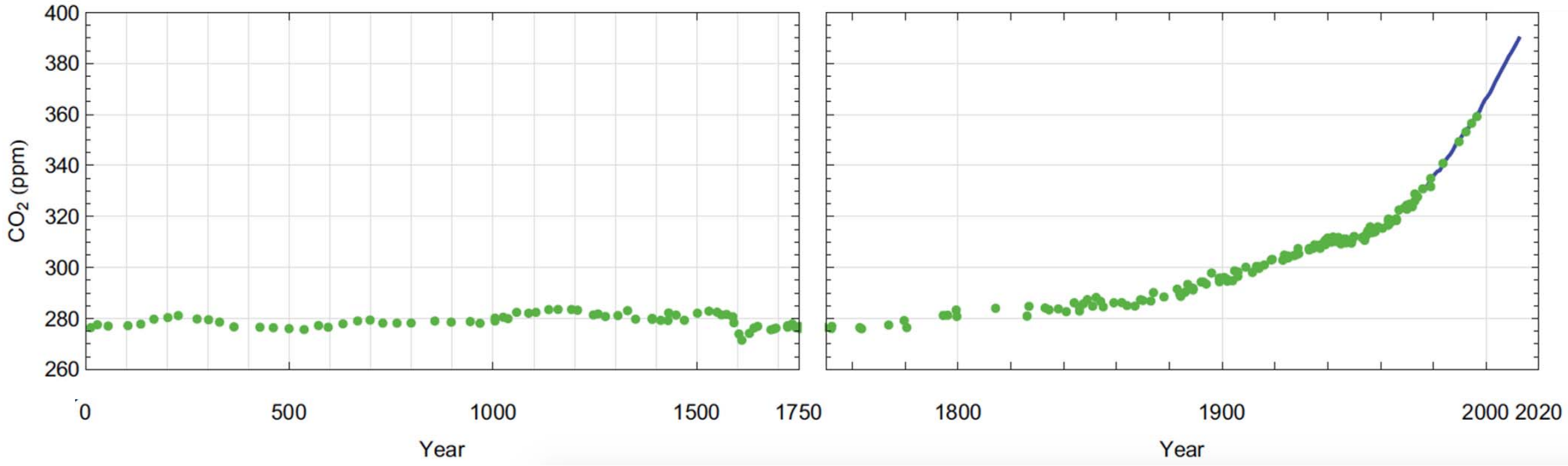




eci

UNIVERSITY OF OXFORD

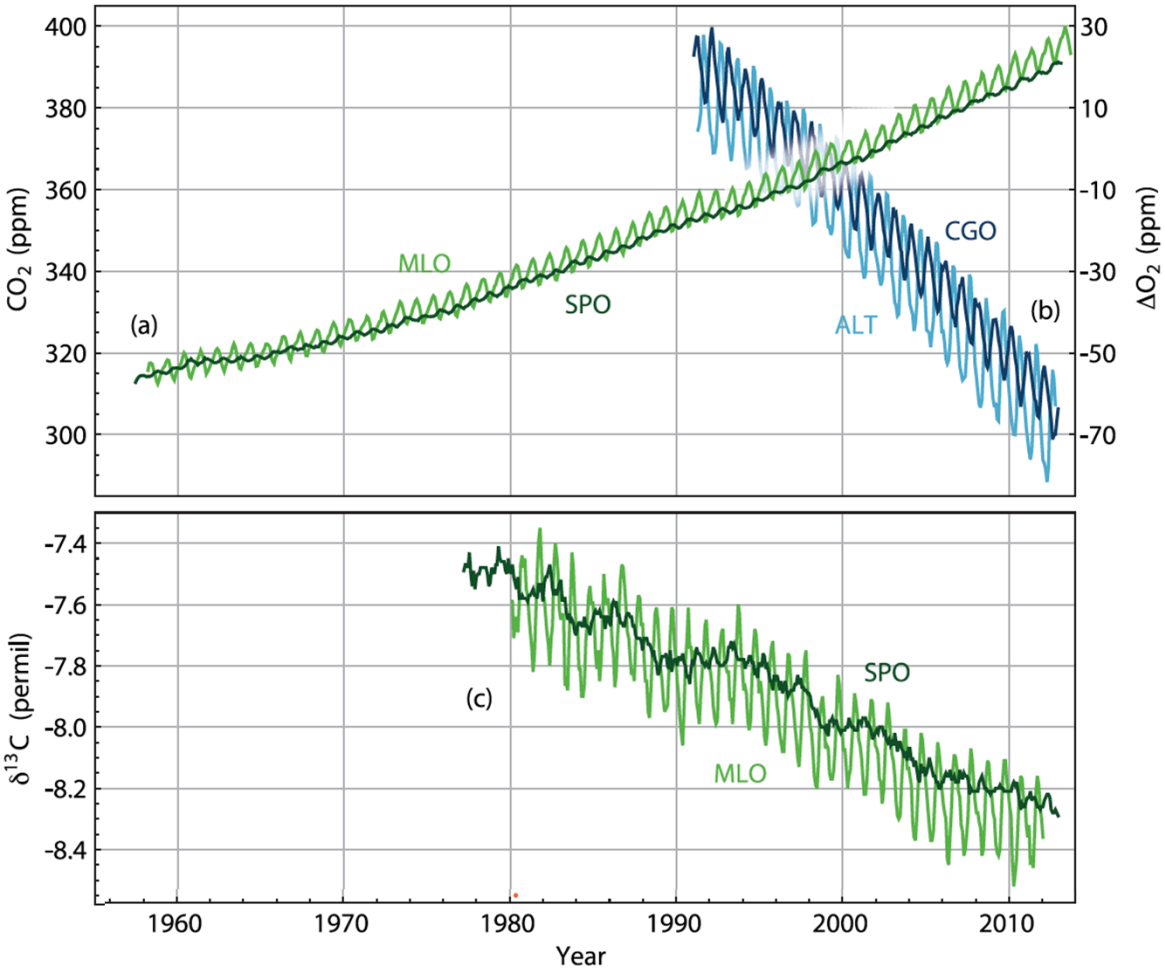
Carbon dioxide levels are rising to levels not seen in over 20 million years



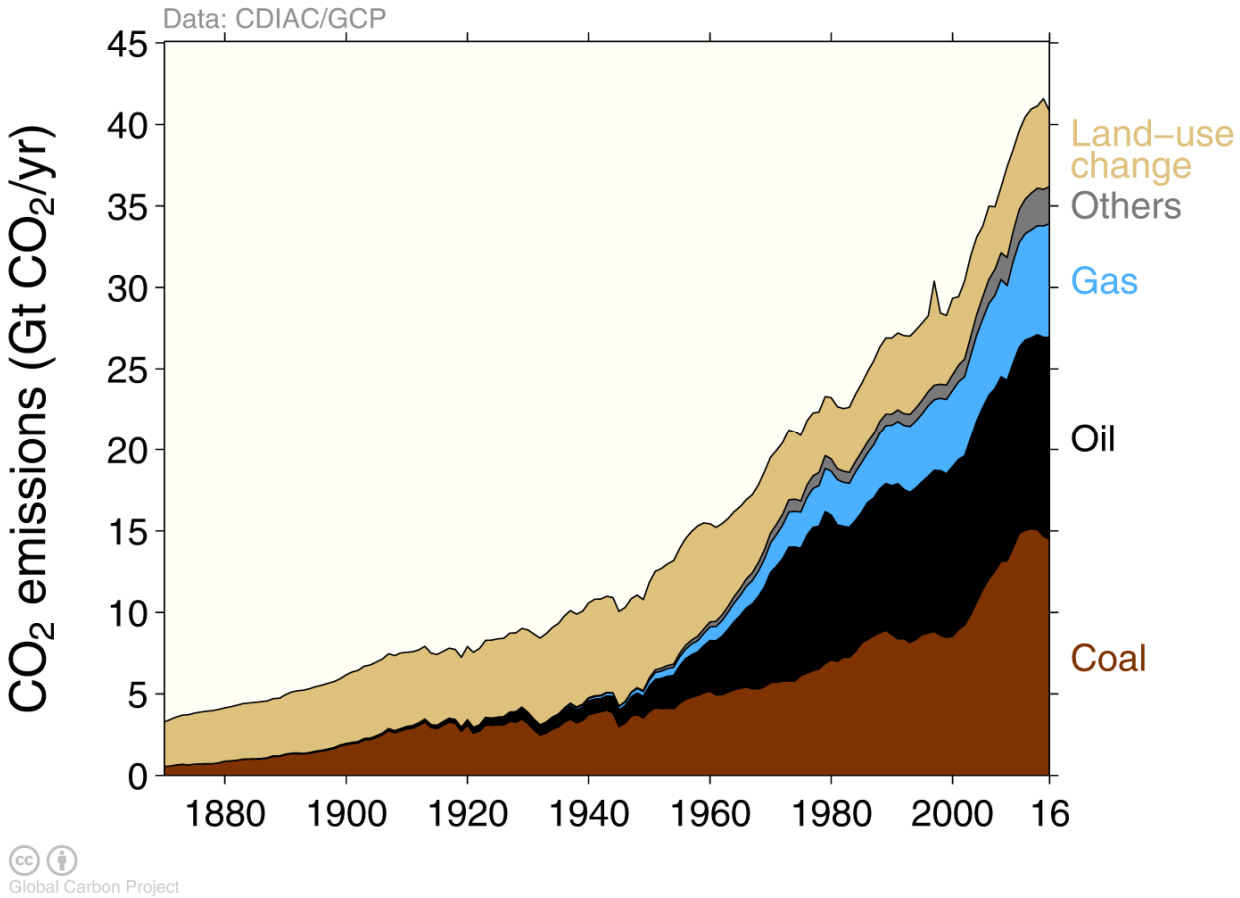
eci

UNIVERSITY OF OXFORD

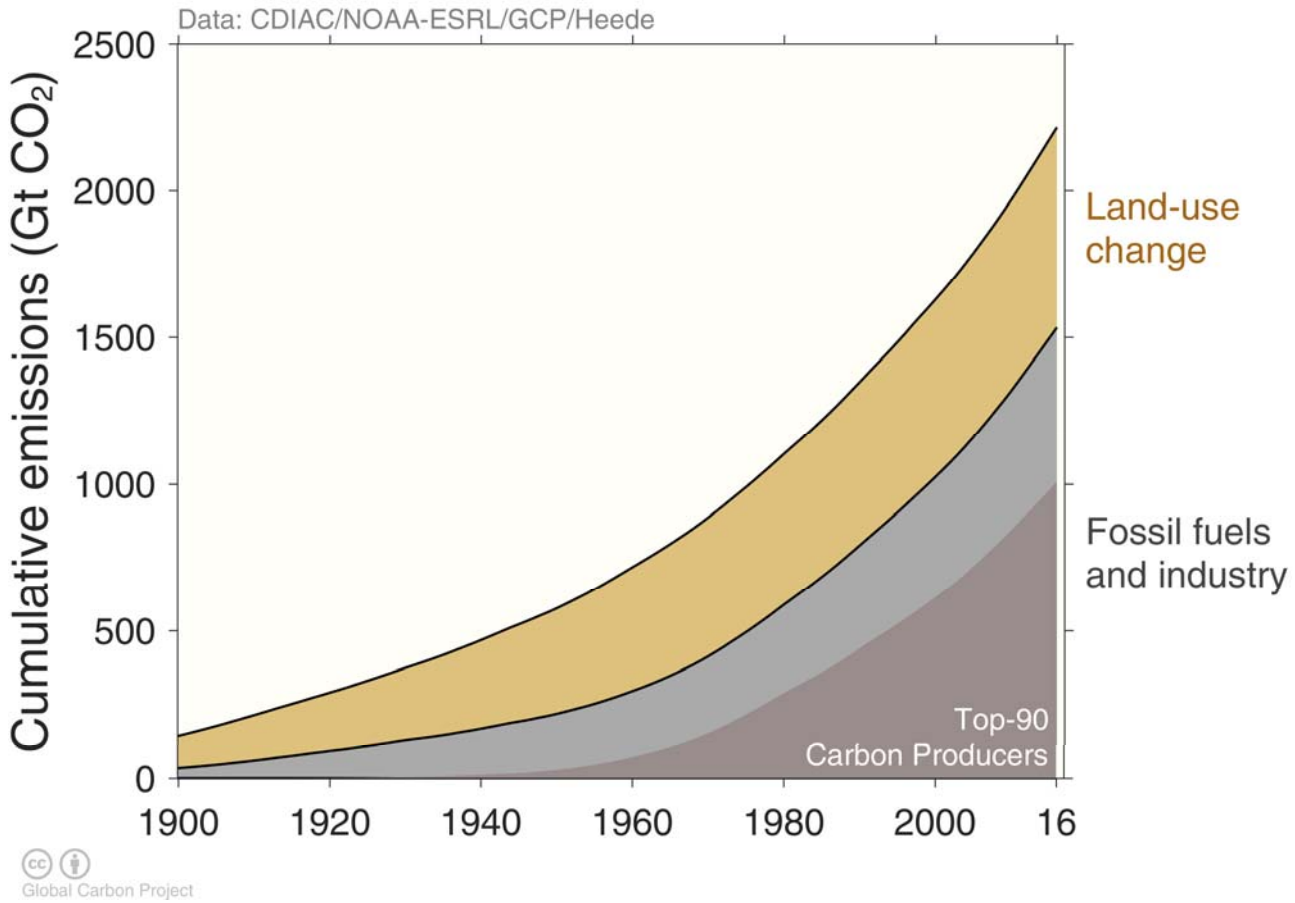
Atmospheric oxygen and carbon isotopes indicate recent CO_2 increase is created by combustion, not simply released from the oceans



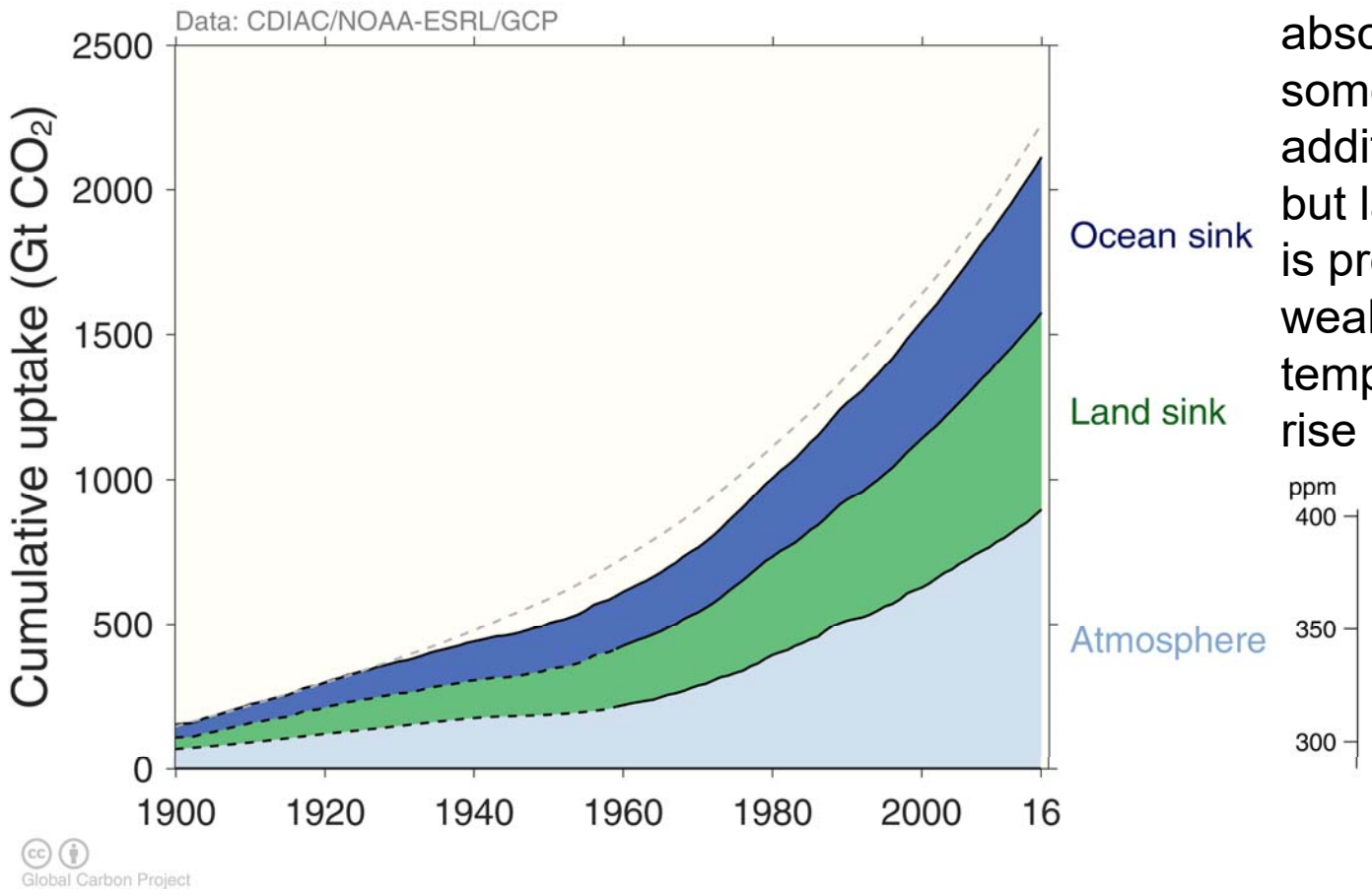
Where is this carbon dioxide coming from?



Cumulative CO_2 emissions added up over time



And cumulative sinks: atmospheric accumulation is more than half cumulative fossil fuel emissions



Plants and soils are absorbing some additional CO_2 but land sink is predicted to weaken as temperatures rise

The impact of carbon dioxide emissions on global climate

- How rising atmospheric CO_2 causes global warming
- How industrial emissions are increasing atmospheric CO_2
- Modeling the impact of increasing CO_2 concentrations
- Quantifying human and natural influences on global climate
  - A digression on ice-ages
- How rising temperatures are affecting global sea level
- The permanent, cumulative impact of CO_2 emissions
  - Implications for the impact of delay in emission reductions

eci

UNIVERSITY OF OXFORD

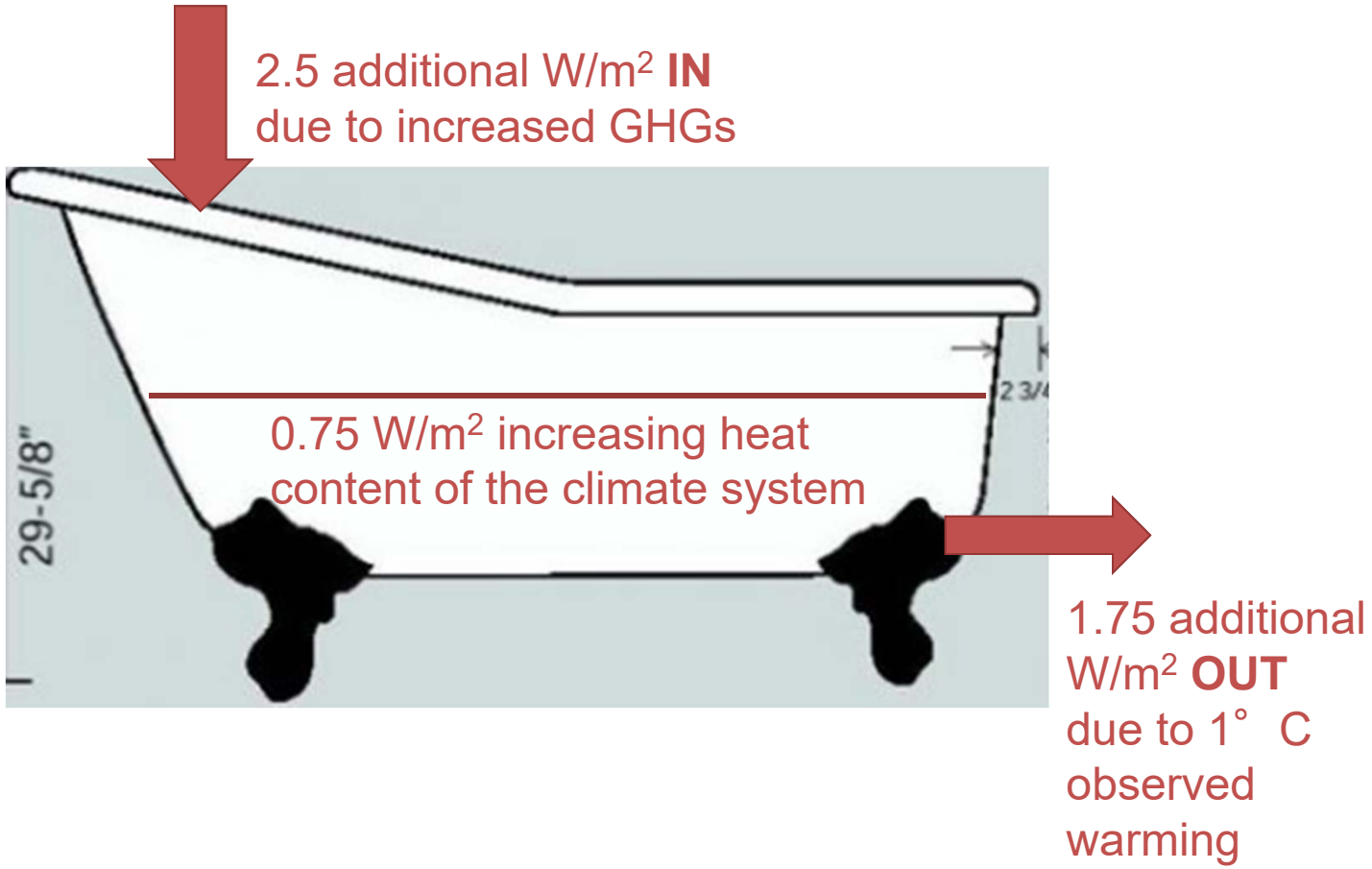
Modeling the impact of rising CO_2 concentrations: the global energy budget

- Increased CO_2 and other forms of pollution are already reducing outgoing radiation by about 2.5 W/m^2
  - Equals 12.5 million TWh per year
  - World primary energy consumption is ~175,000 TWh per year
- The planet as a whole has to warm up to restore the balance between incoming and outgoing energy.

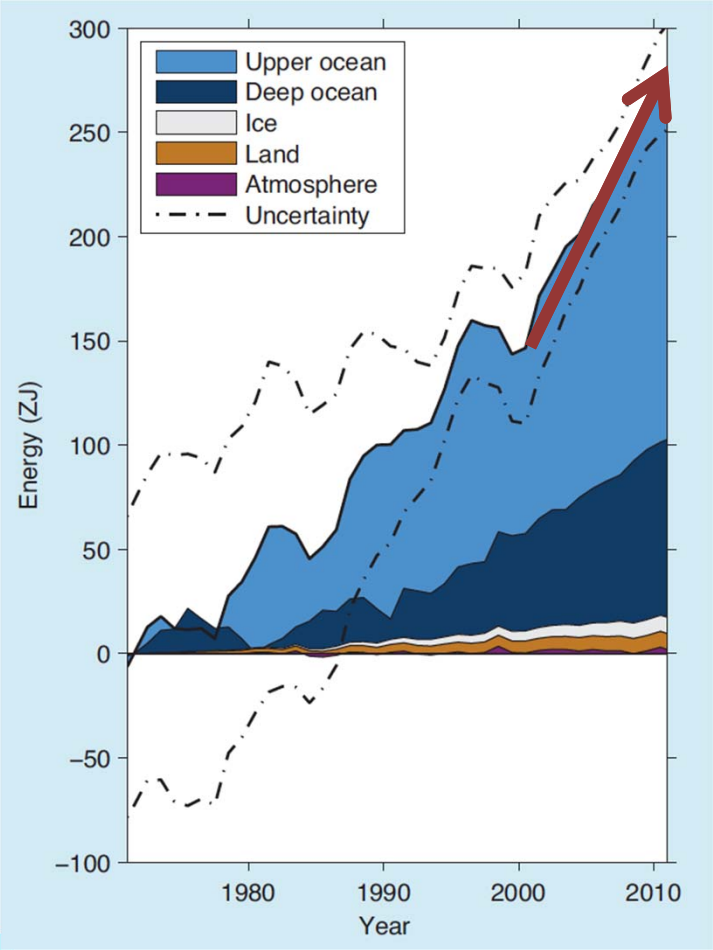
eci

UNIVERSITY OF OXFORD

Disturbing the global energy balance



Most of that energy imbalance is being trapped in the oceans



- 0.75W/m^2 = 135 ZJ/decade
- First documented by Sydney Levitus et al (2000)

eci

UNIVERSITY OF OXFORD

The global energy budget, now and in equilibrium

Net energy imbalance due to external drivers = c. 2.5 W/m^2

Additional energy emitted to space per degree of warming due to disequilibrium

Warming relative to pre-industrial = c. 1° C

Rate of energy accumulation in climate system = c. 0.75 W/m^2

Now: $$\Delta F_{\text{external}} = (\lambda + \mu)\Delta T + \Delta Q_{\text{ocean}}$$

Equilibrium: $$\Delta F_{2\text{xCO2}} = \lambda \Delta T_{2\text{xCO2}}$$

Energy imbalance due to doubling CO_2 = 3.7 W/m^2

Additional energy emitted to space per degree of warming in equilibrium

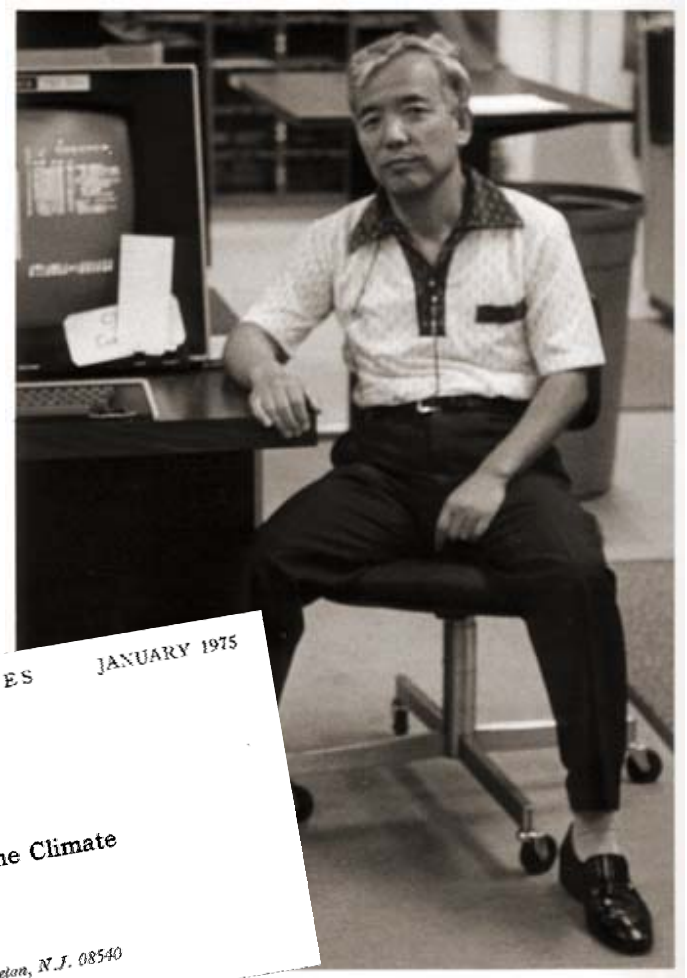
Equilibrium warming due to doubling CO_2 ("Climate Sensitivity")

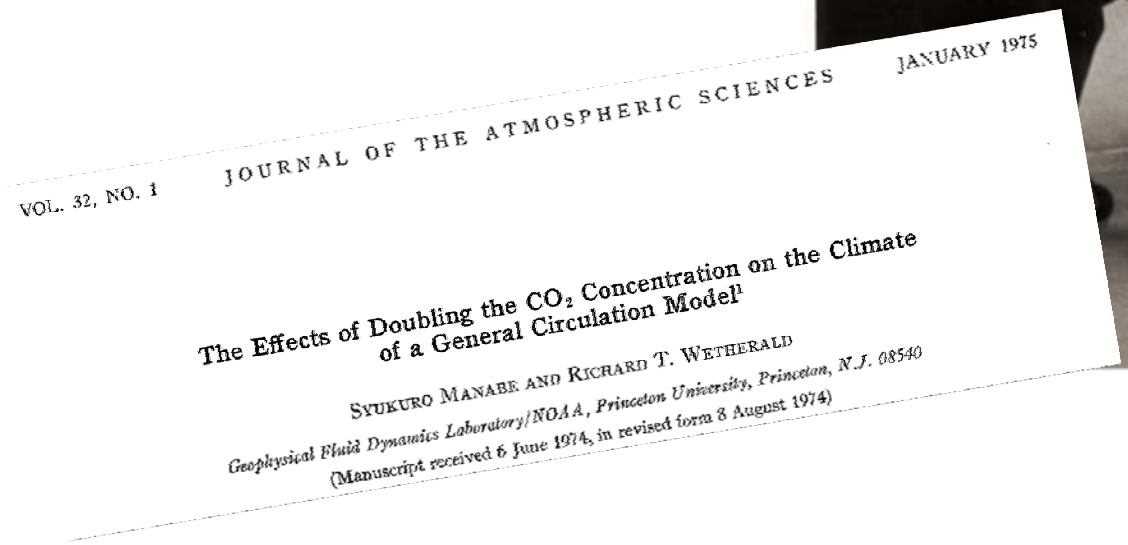
eci

UNIVERSITY OF OXFORD

"Bottom-up" estimates of warming due to doubling of CO_2

- Manabe and Wetherald, 1967: single-column radiative convective model, 2.3° C
- Manabe and Wetherald, 1975: three-dimensional general circulation model, 3.5° C





VOL. 32, NO. 1 JOURNAL OF THE ATMOSPHERIC SCIENCES JANUARY 1975

The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model[1]

SYUKURO MANABE AND RICHARD T. WETHERALD

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, N.J. 08540

(Manuscript received 6 June 1974, in revised form 8 August 1974)

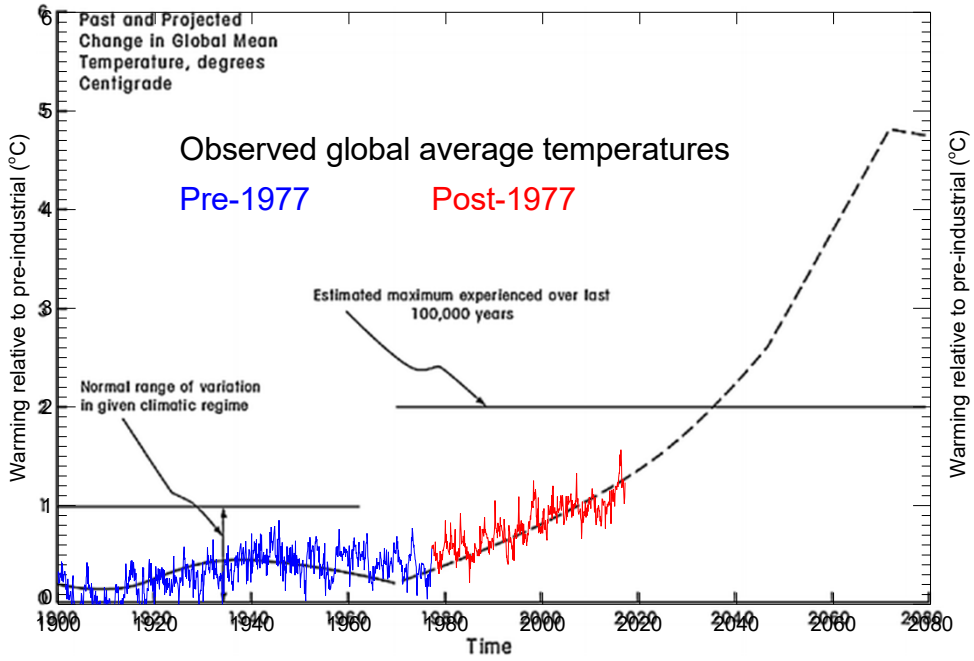
The 1979 National Academy of Sciences Report

- Gave a range of 1.5-4.5° C for equilibrium warming on doubling CO_2, emphasizing:
  - Oceans "could delay the estimated warming for several decades"
  - "We may not be given a warning until the CO_2 loading is such that an appreciable climate change is inevitable."

eci

UNIVERSITY OF OXFORD

Evidence that a detectable signal was not needed to make predictions



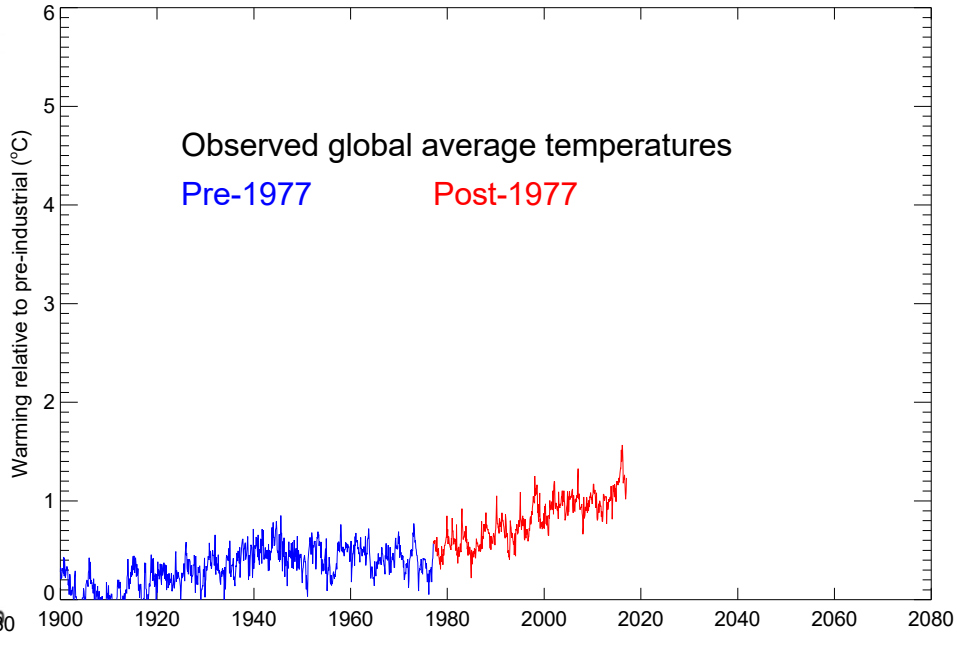


Figure 1 from William D. Nordhaus, “Strategies for Control of Carbon Dioxide”, Cowles Discussion Paper 477, January 6, 1977

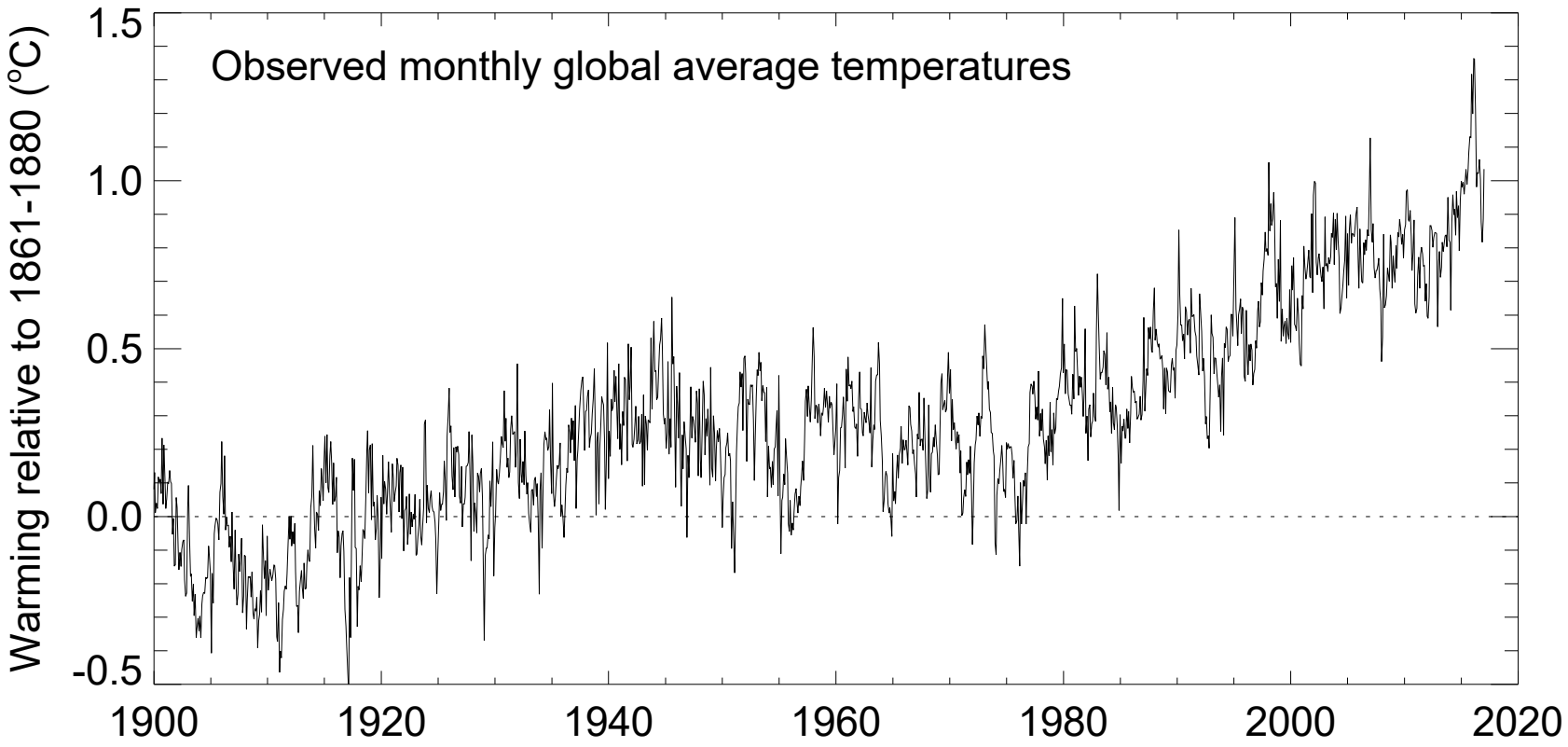
The impact of carbon dioxide emissions on global climate

- How rising atmospheric CO_2 causes global warming
- How industrial emissions are increasing atmospheric CO_2
- Modeling the impact of increasing CO_2 concentrations
- Quantifying human and natural influences on global climate
  - A digression on ice-ages
- How rising temperatures are affecting global sea level
- The permanent, cumulative impact of CO_2 emissions
  - Implications for the impact of delay in emission reductions

eci

UNIVERSITY OF OXFORD

Warming itself is unequivocal

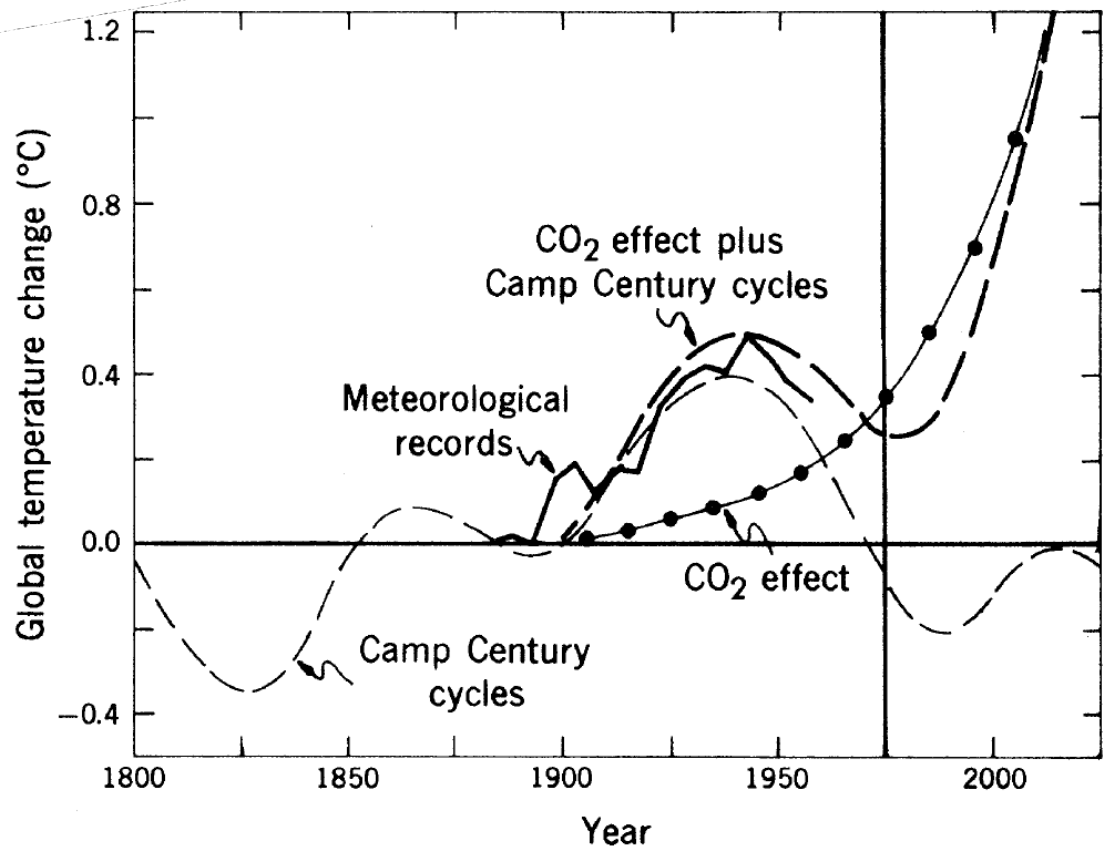


eci

UNIVERSITY OF OXFORD

Observed changes are a consequence of human and natural influences: Wallace Broeker, 1974

Climatic Change: Are We on the Brink of a Pronounced Global Warming?



The impact of carbon dioxide emissions on global climate

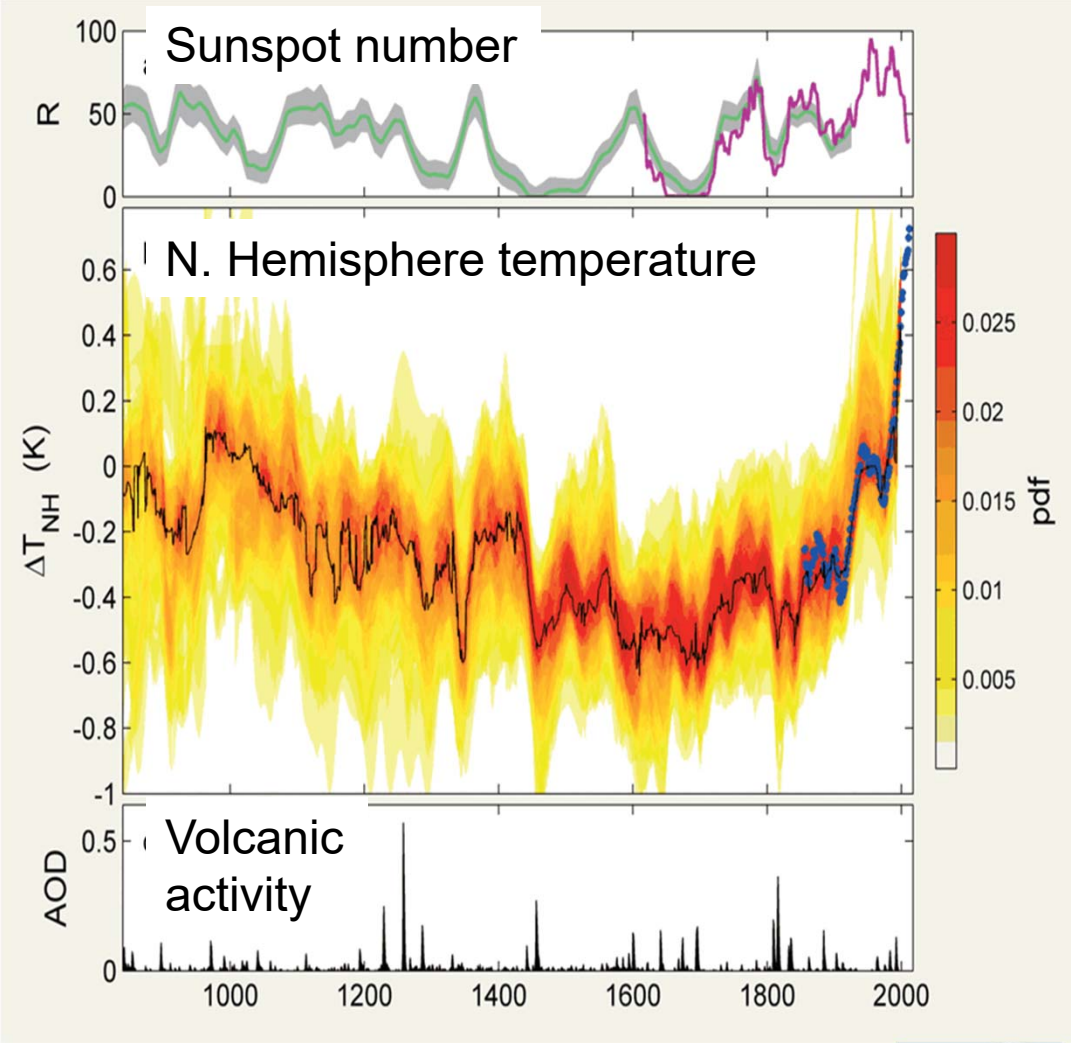
- How rising atmospheric CO_2 causes global warming
- How industrial emissions are increasing atmospheric CO_2
- Modeling the impact of increasing CO_2 concentrations
- Quantifying human and natural influences on global climate
  - A digression on ice-ages
- How rising temperatures are affecting global sea level
- The permanent, cumulative impact of CO_2 emissions
  - Implications for the impact of delay in emission reductions

eci

UNIVERSITY OF OXFORD

The origins of the Little Ice Age, 1400-1900

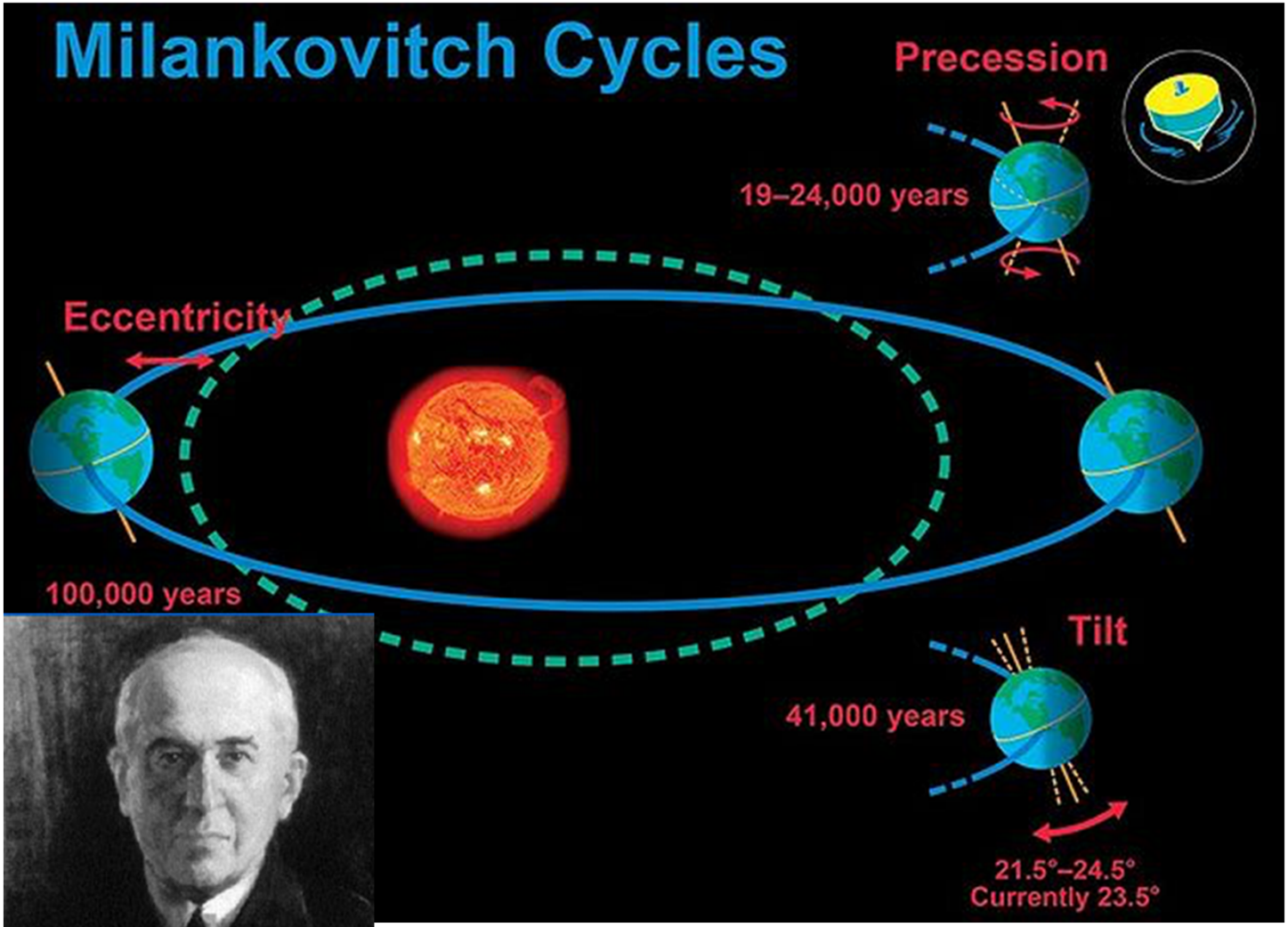
- Gradual 0.5° C cooling over the millennium.
- Onset can be explained as a response to higher volcanic activity and low solar activity.



eci

UNIVERSITY OF OXFORD

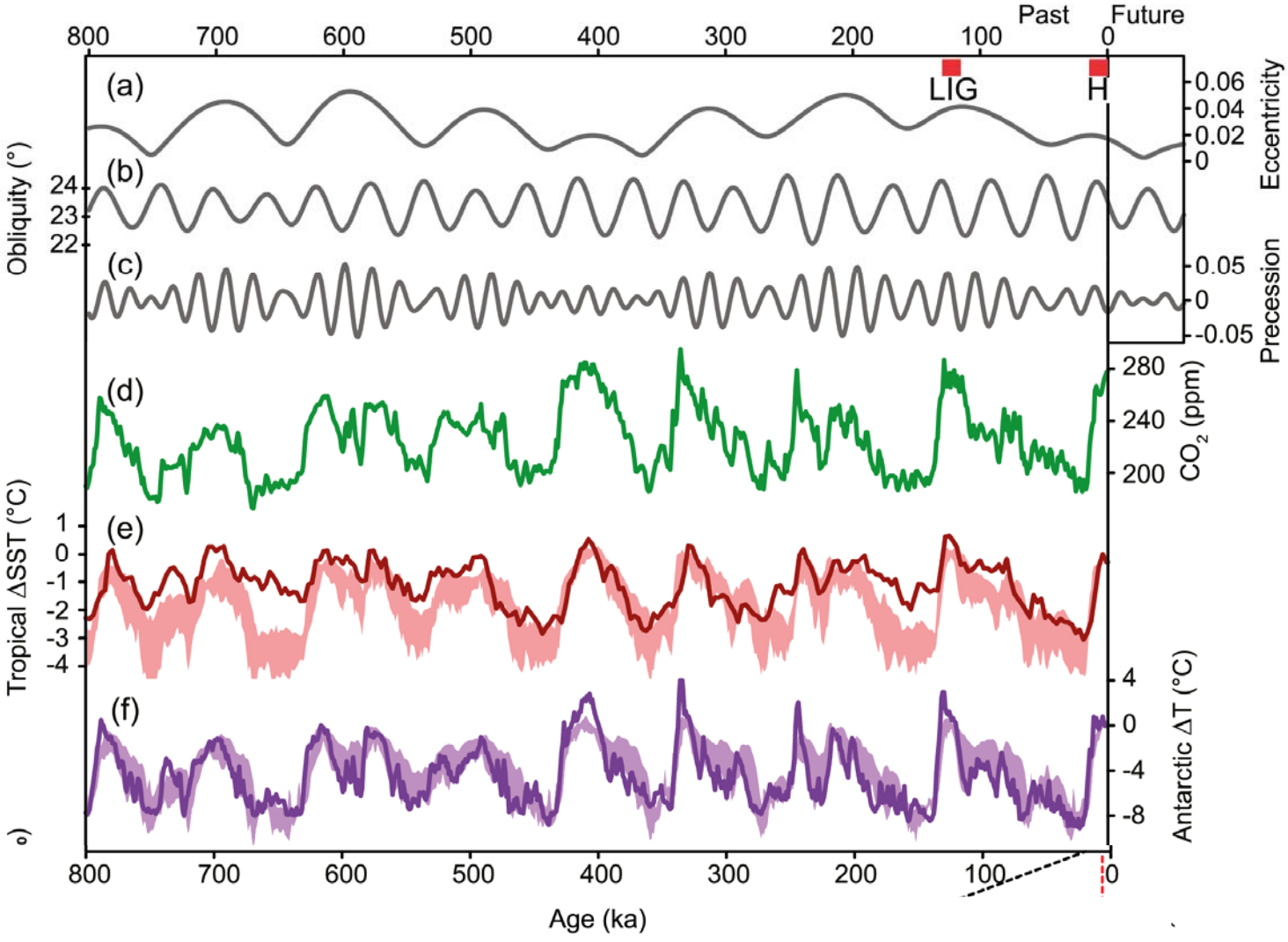
Milutin Milankovitch and the origins of the ice ages



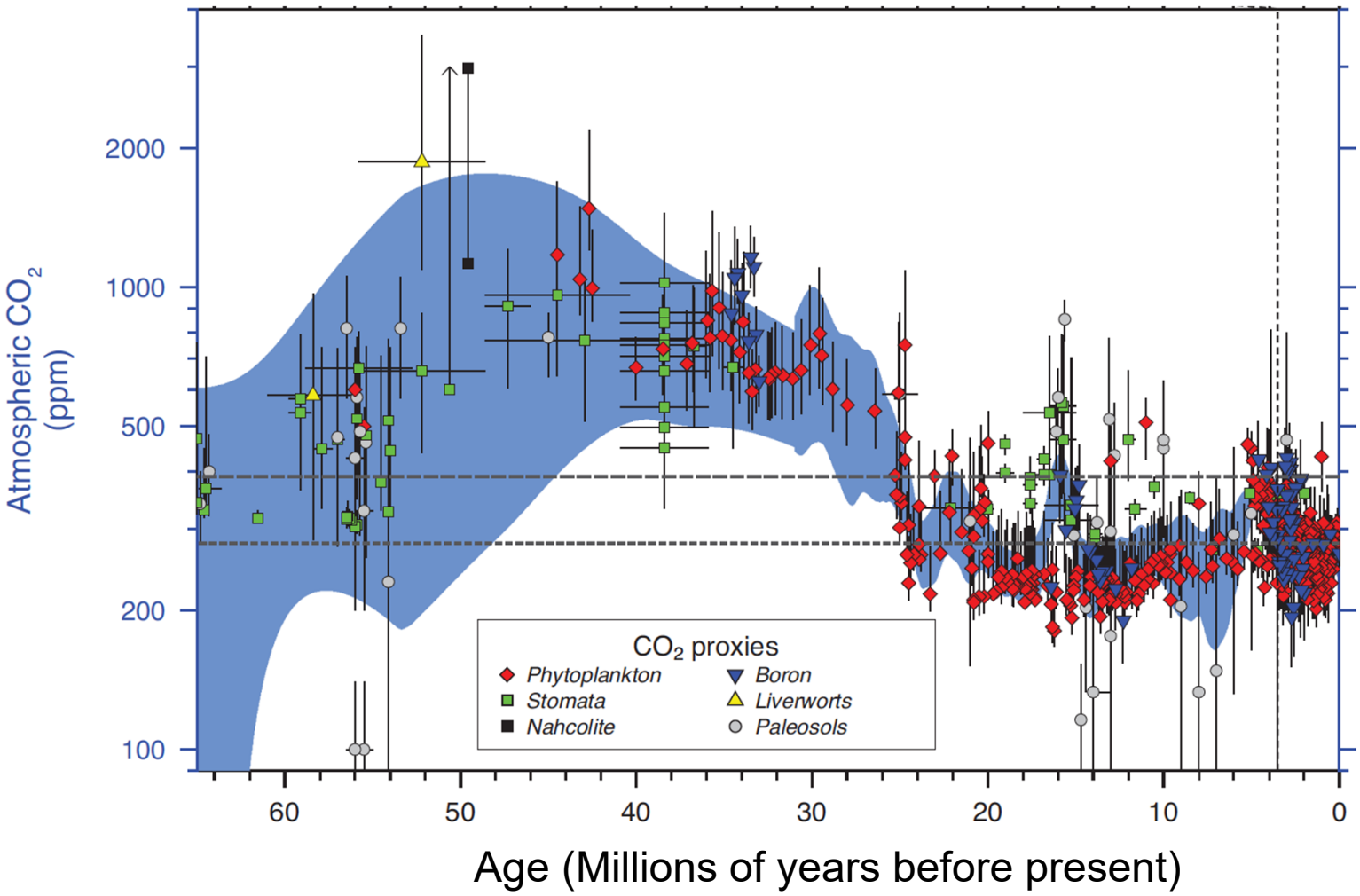
eci

UNIVERSITY OF OXFORD

Milankovitch cycles and ice-core records over the past 800,000 years



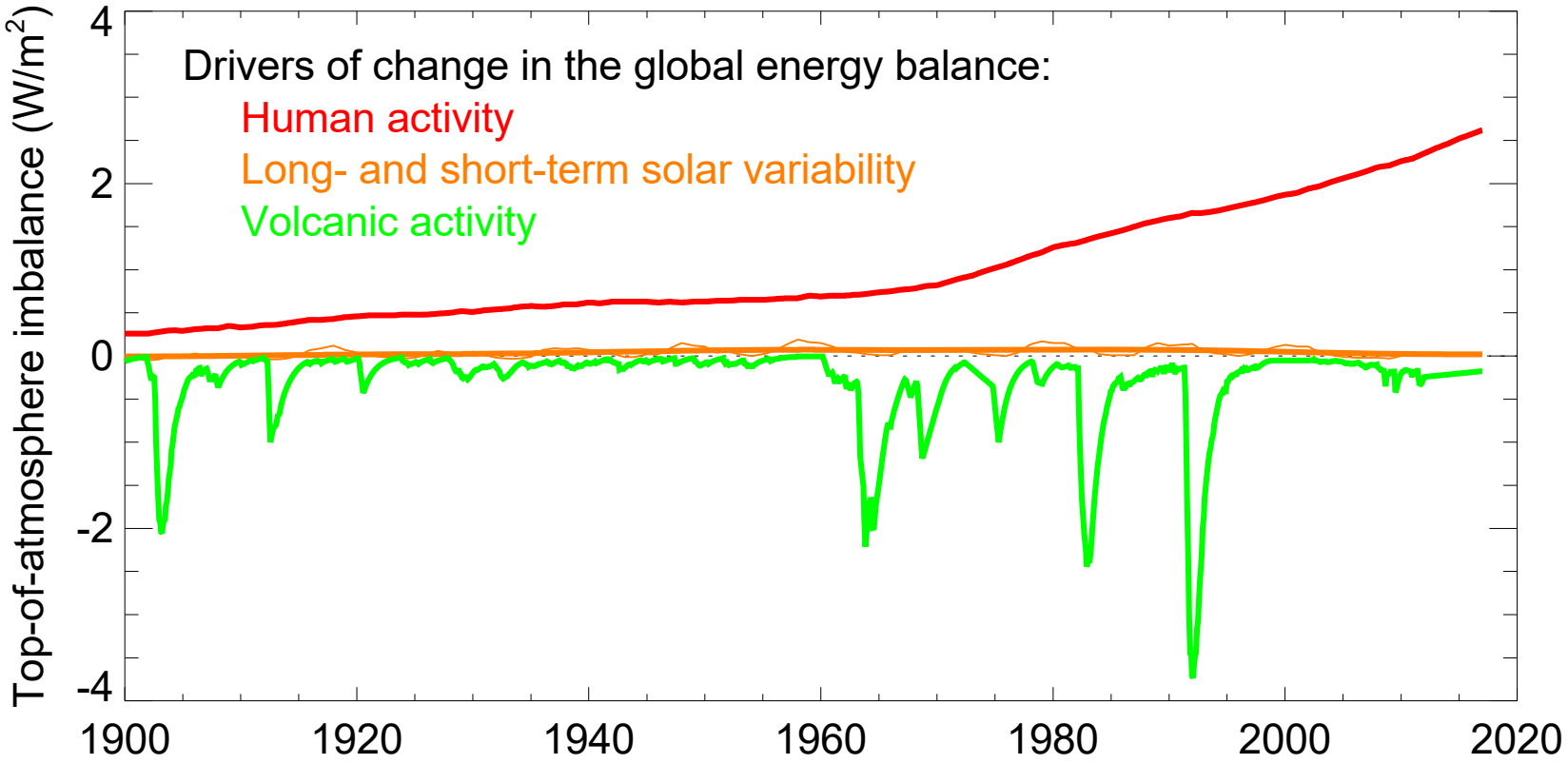
Permanent ice observed (even in Antarctica) only appeared after CO_2 dropped below 400ppm



eci

UNIVERSITY OF OXFORD

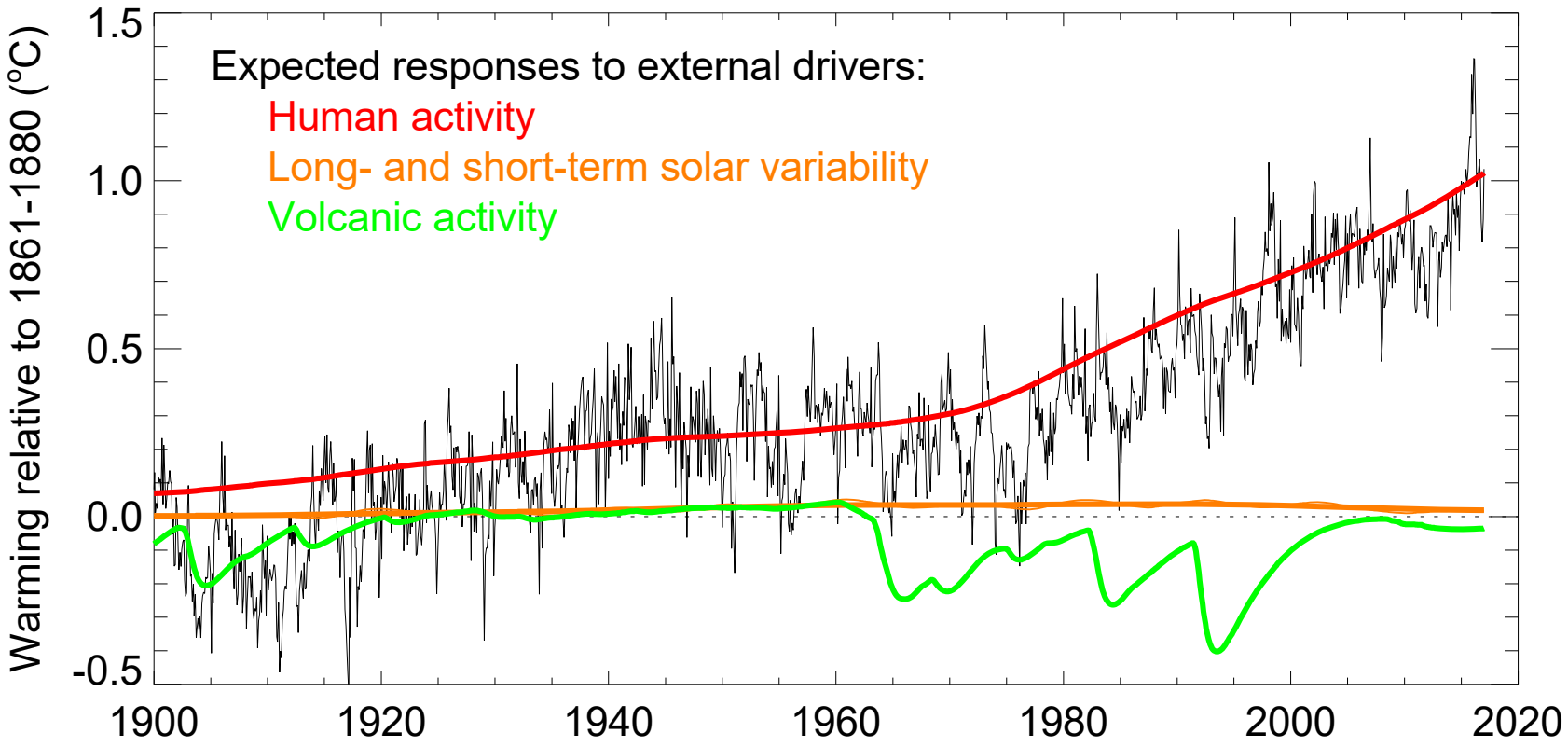
More recent drivers of change in global temperature



eci

UNIVERSITY OF OXFORD

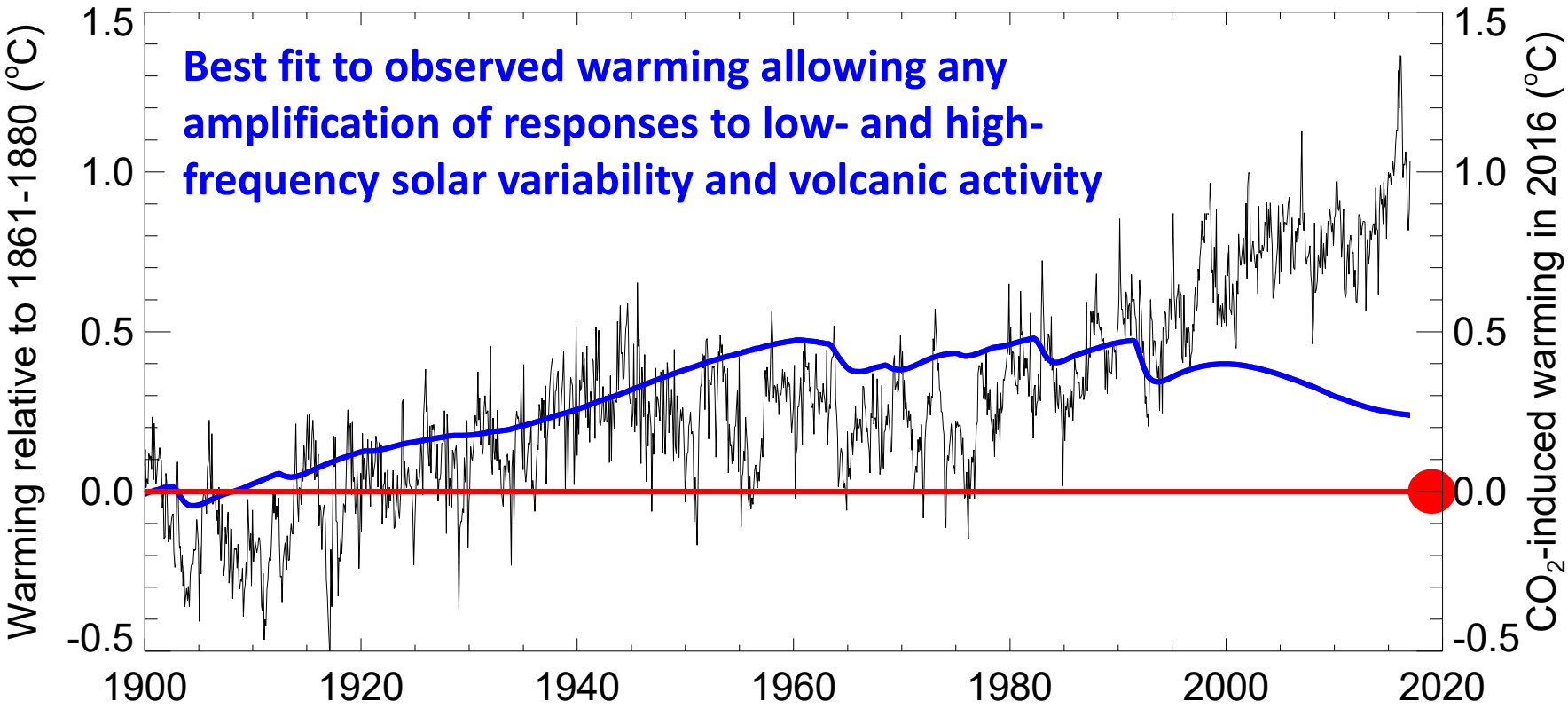
The shape of the responses to these drivers is determined by simple energy conservation



eci

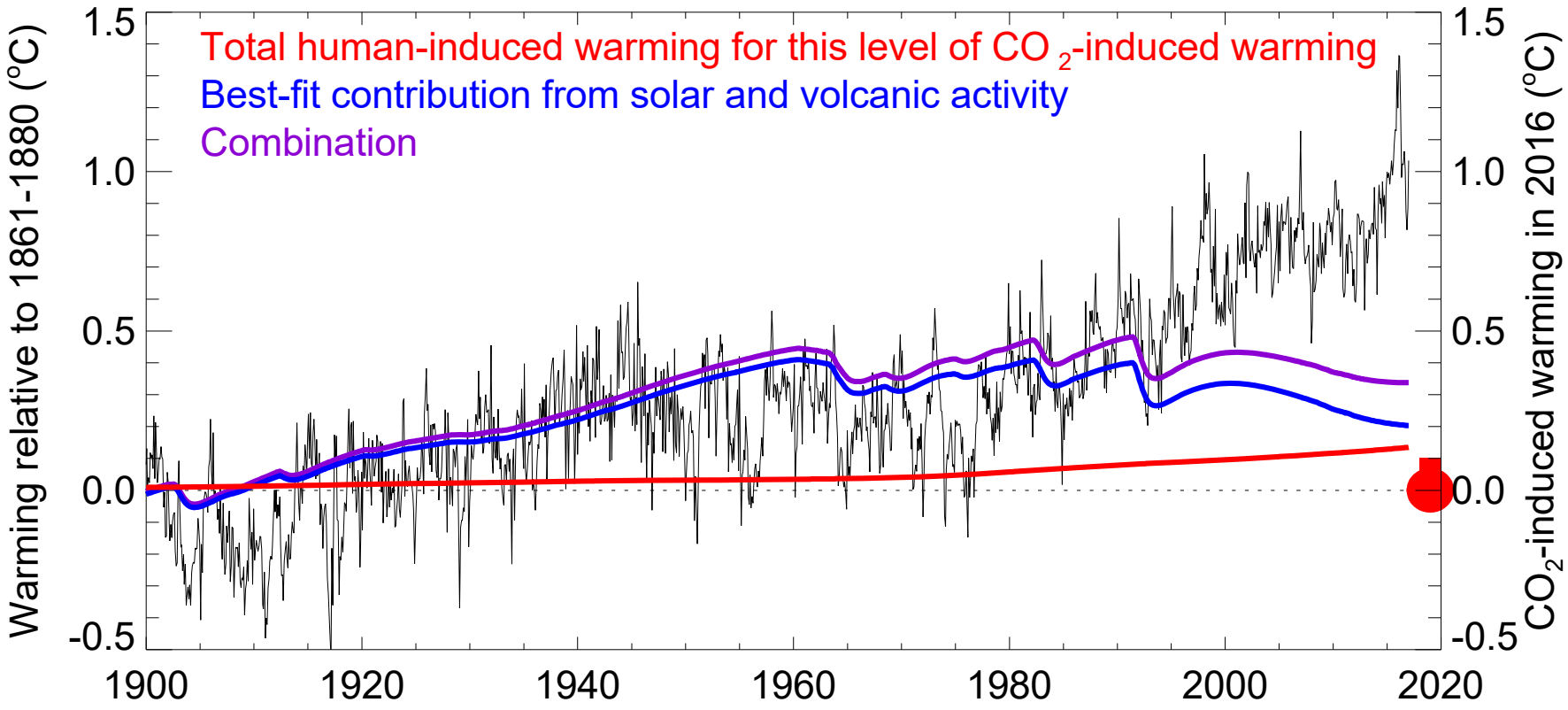
UNIVERSITY OF OXFORD

We use these "fingerprints" to test the null-hypothesis that CO_2 has no warming effect



"What if" exercise: what if CO2 has no impact on global temperature? Observed changes would then be extremely unlikely, even if we allow for unknown processes amplifying the response to very small changes in solar activity.

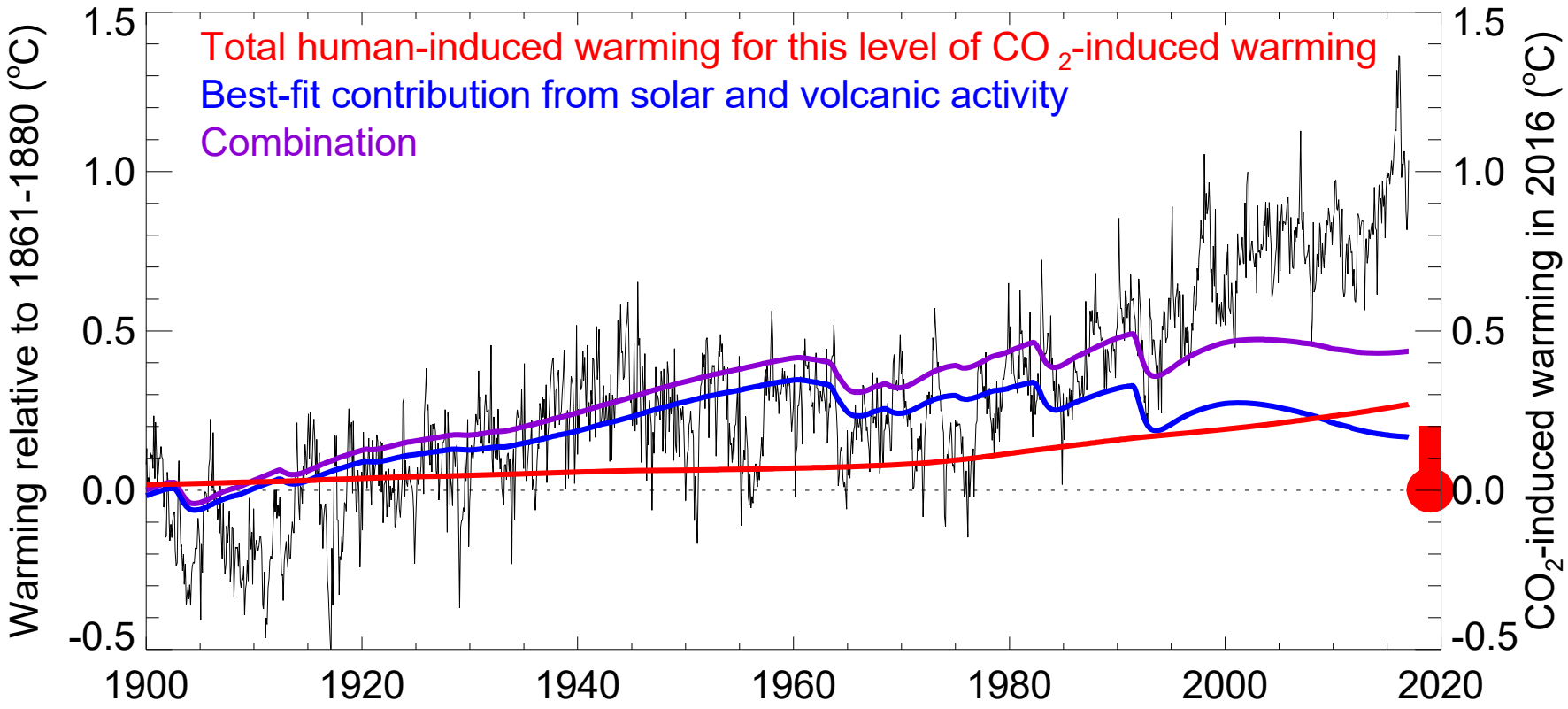
Explaining global temperature change, varying the level of CO_2-induced warming to date



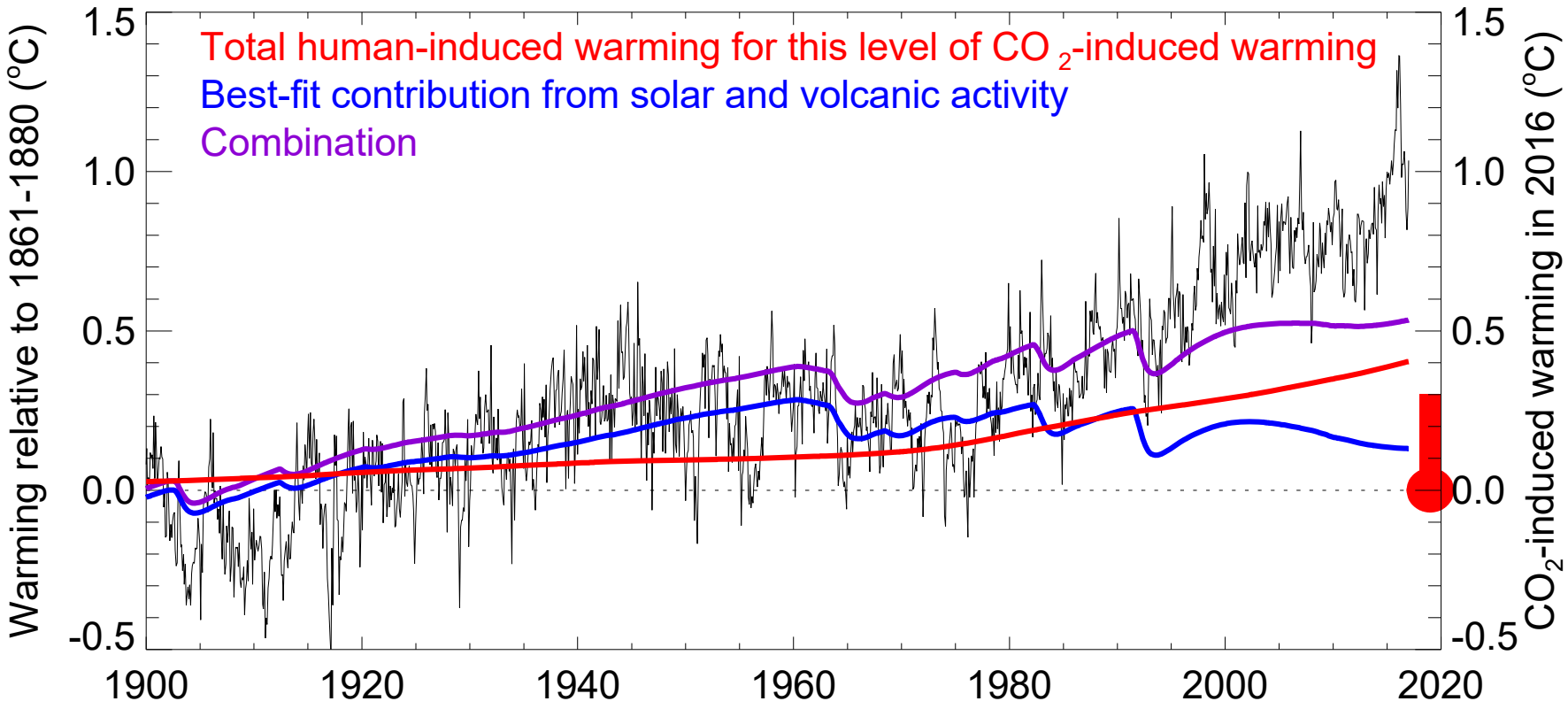
eci

UNIVERSITY OF OXFORD

Explaining global temperature change, varying the level of CO_2-induced warming to date



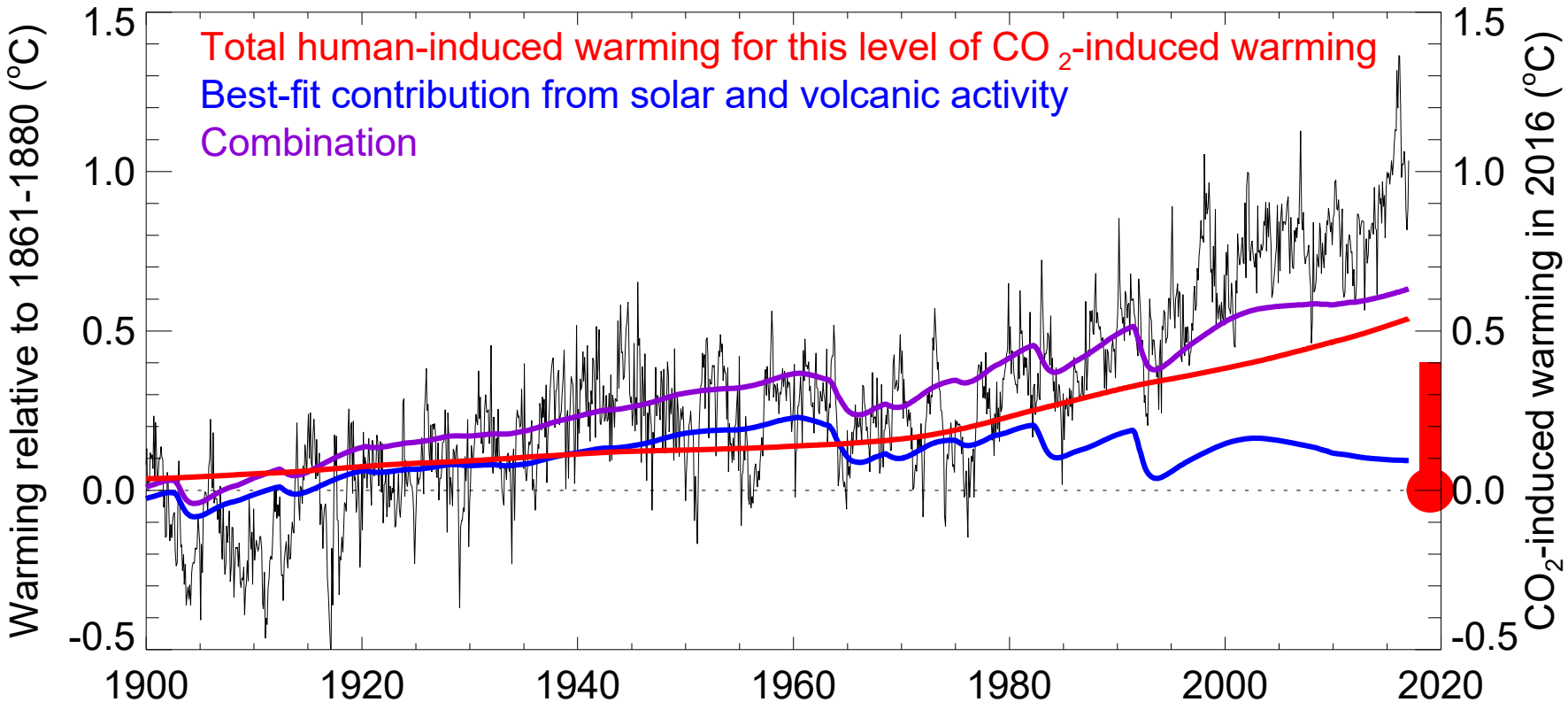
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

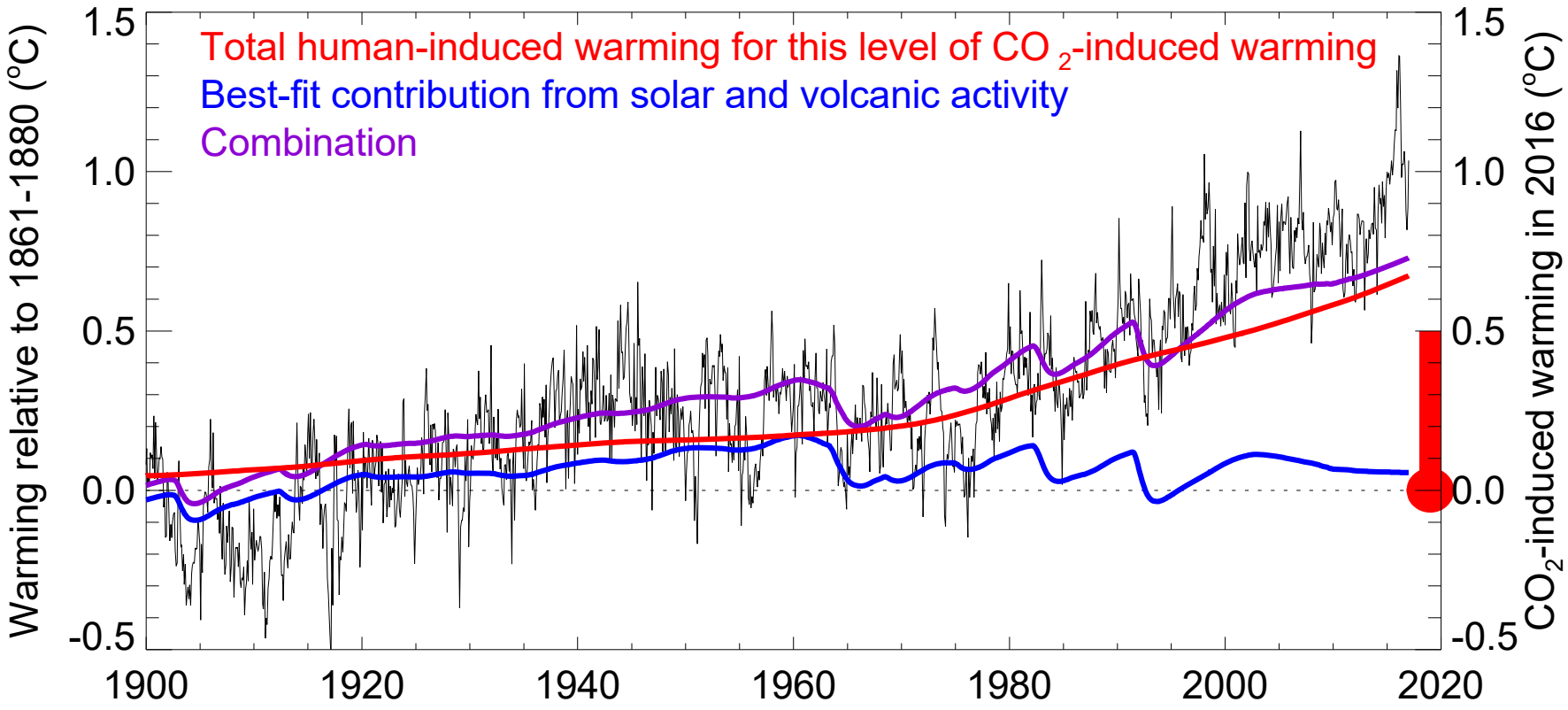
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

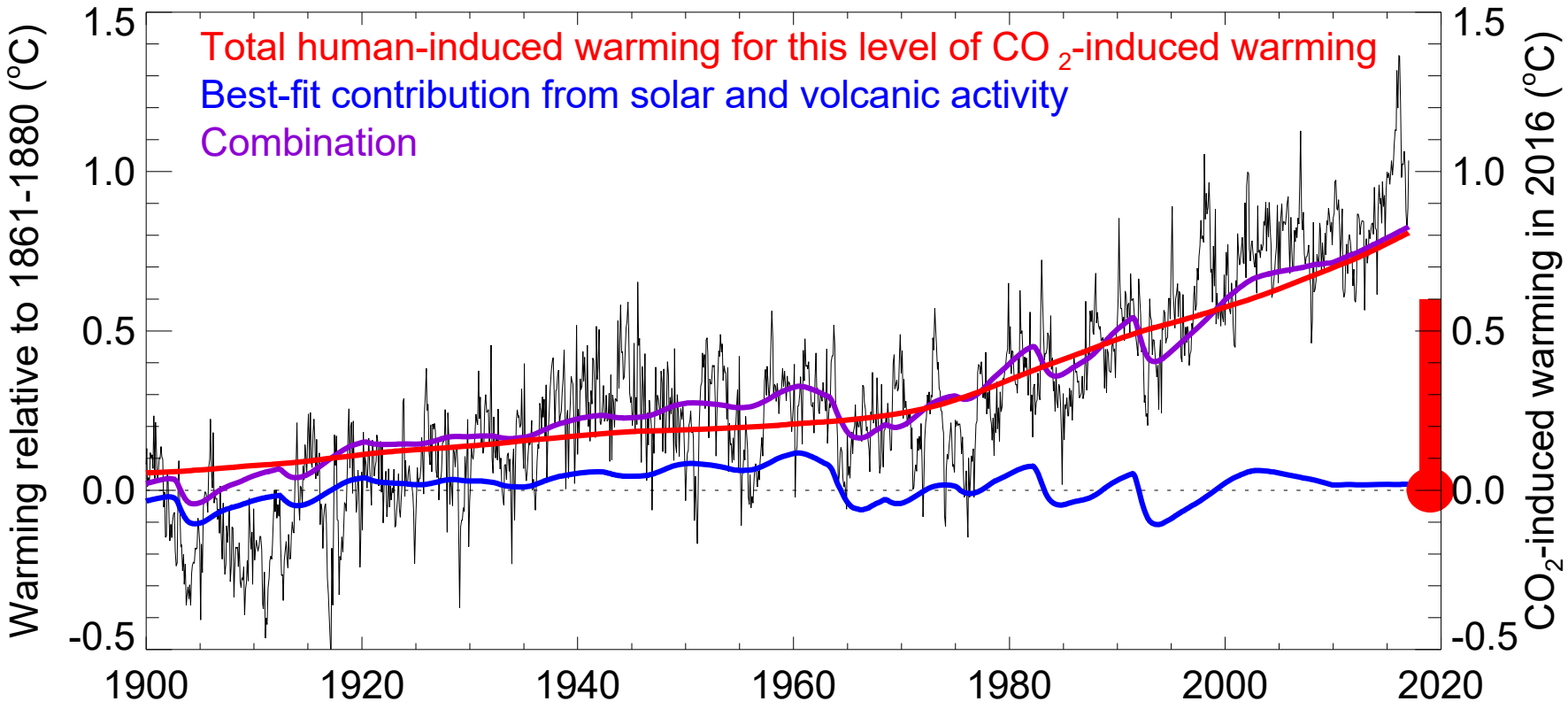
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

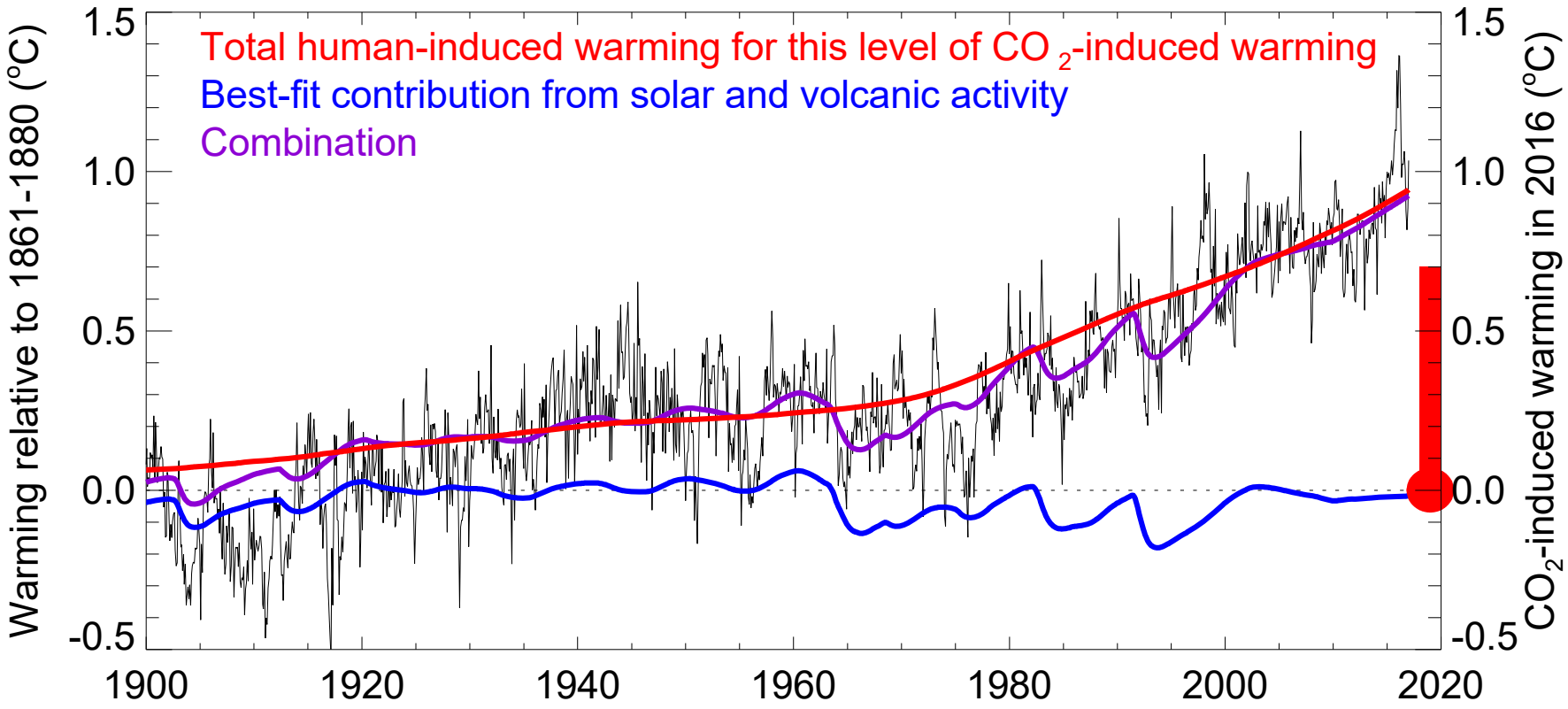
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

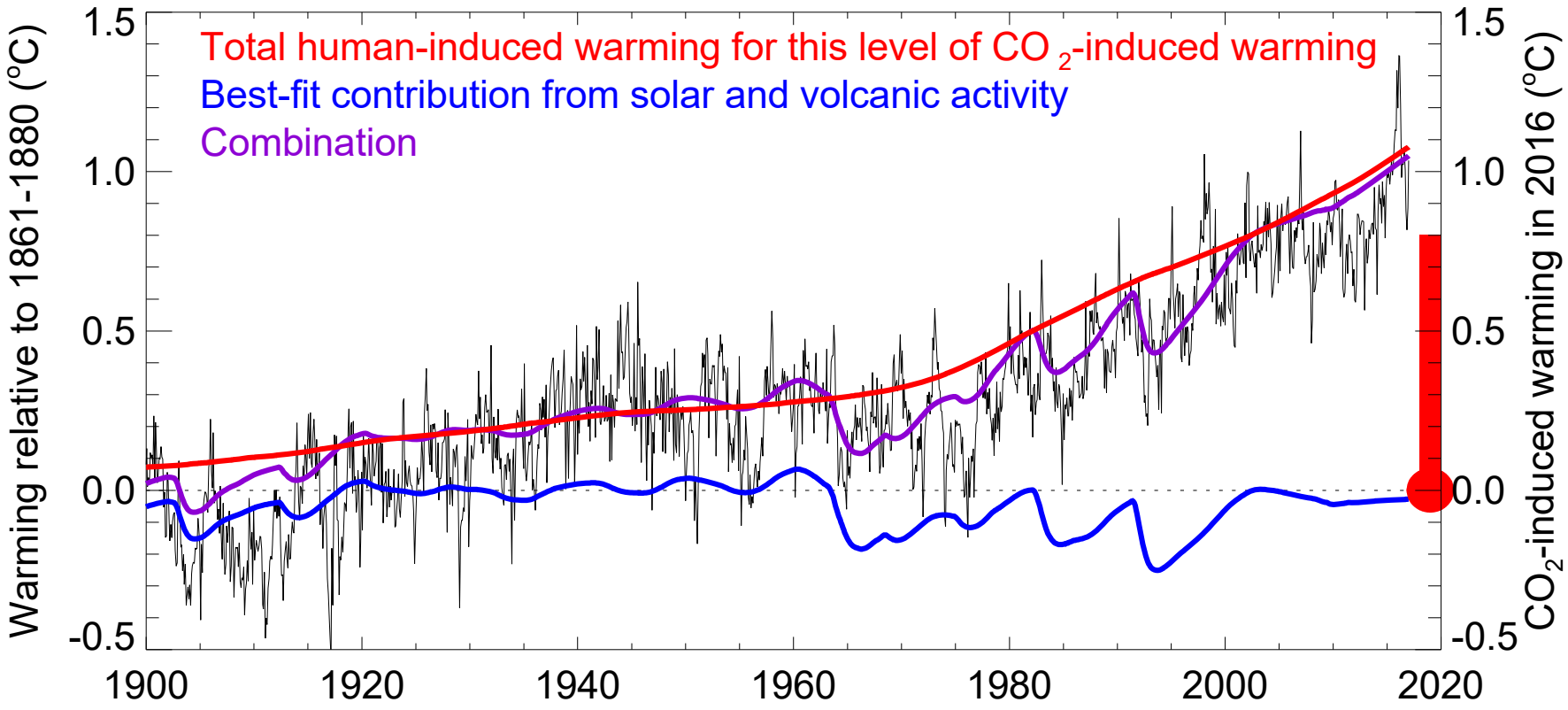
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

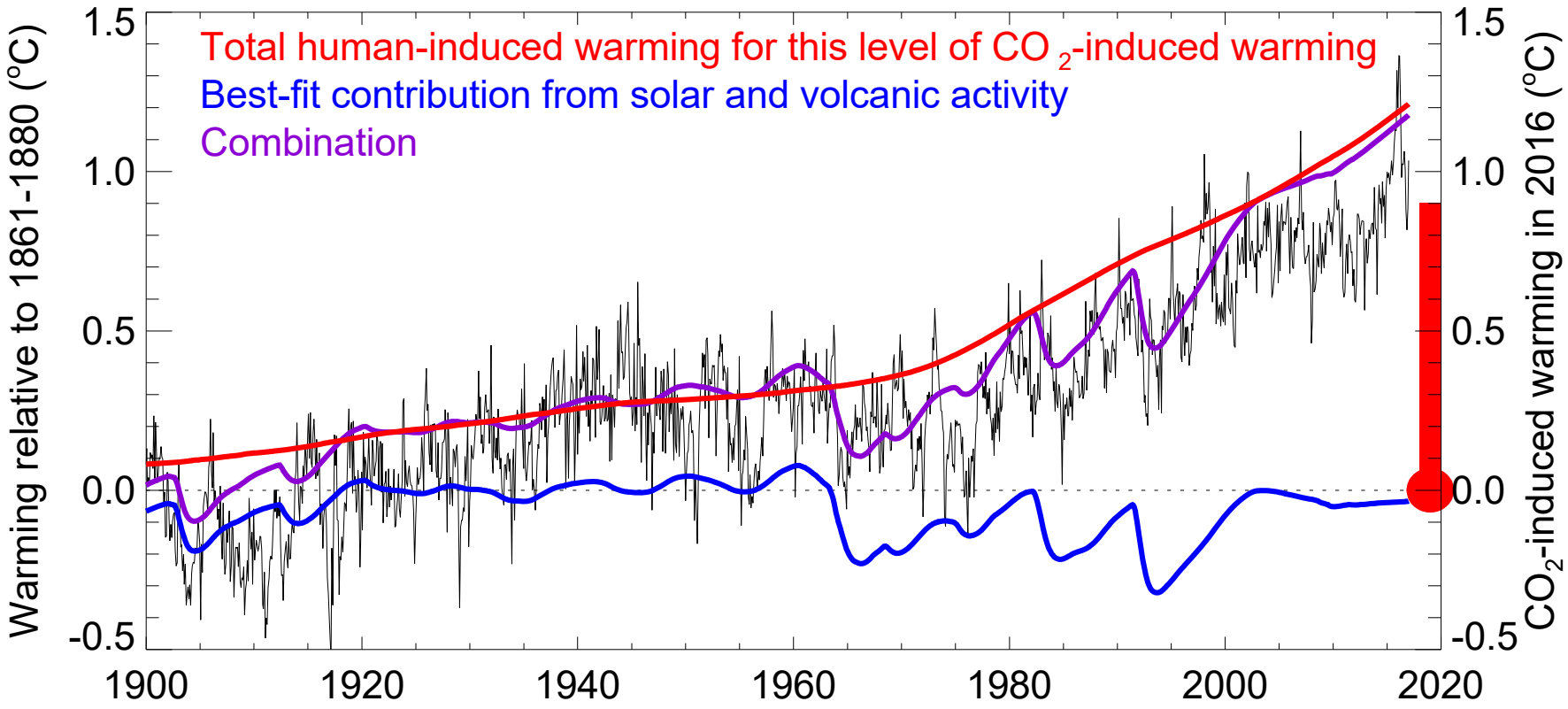
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

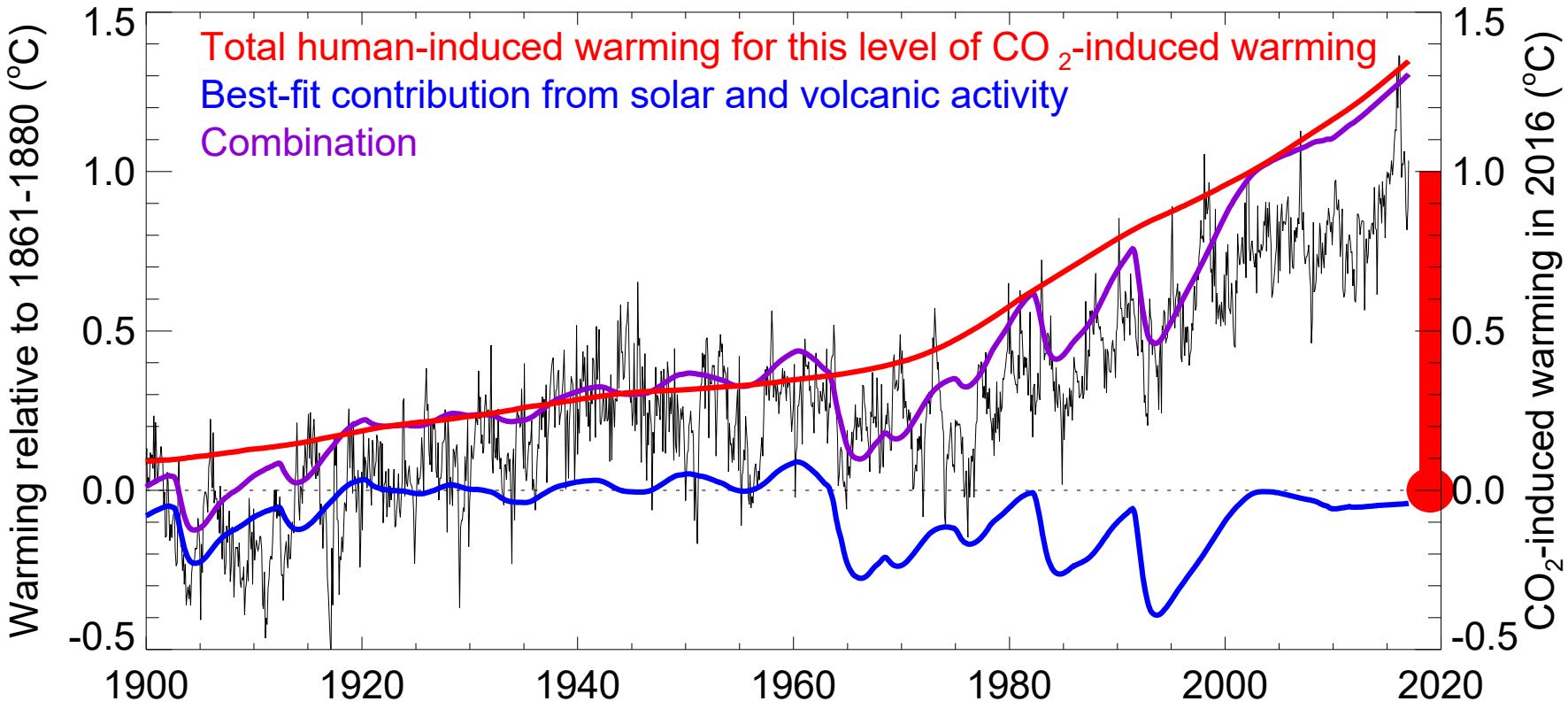
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

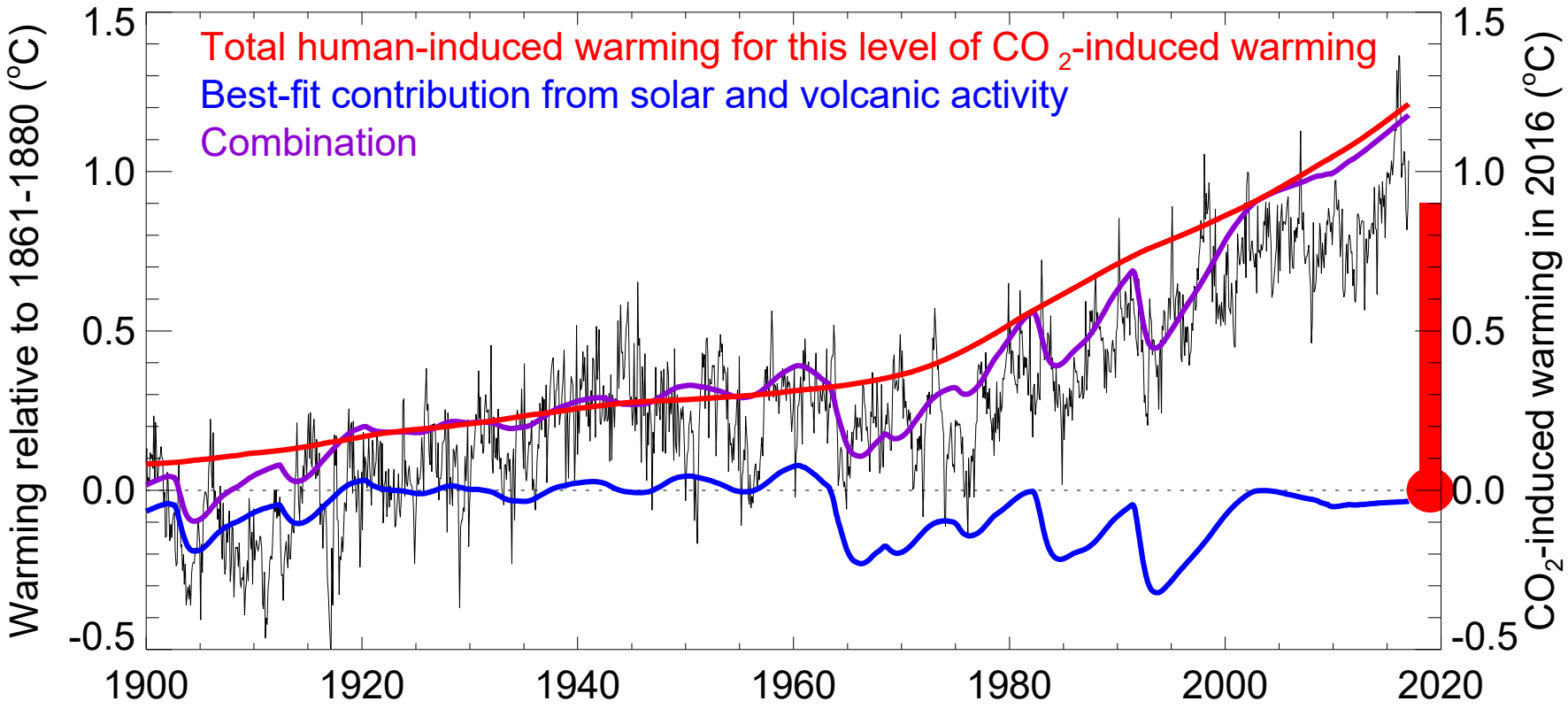
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

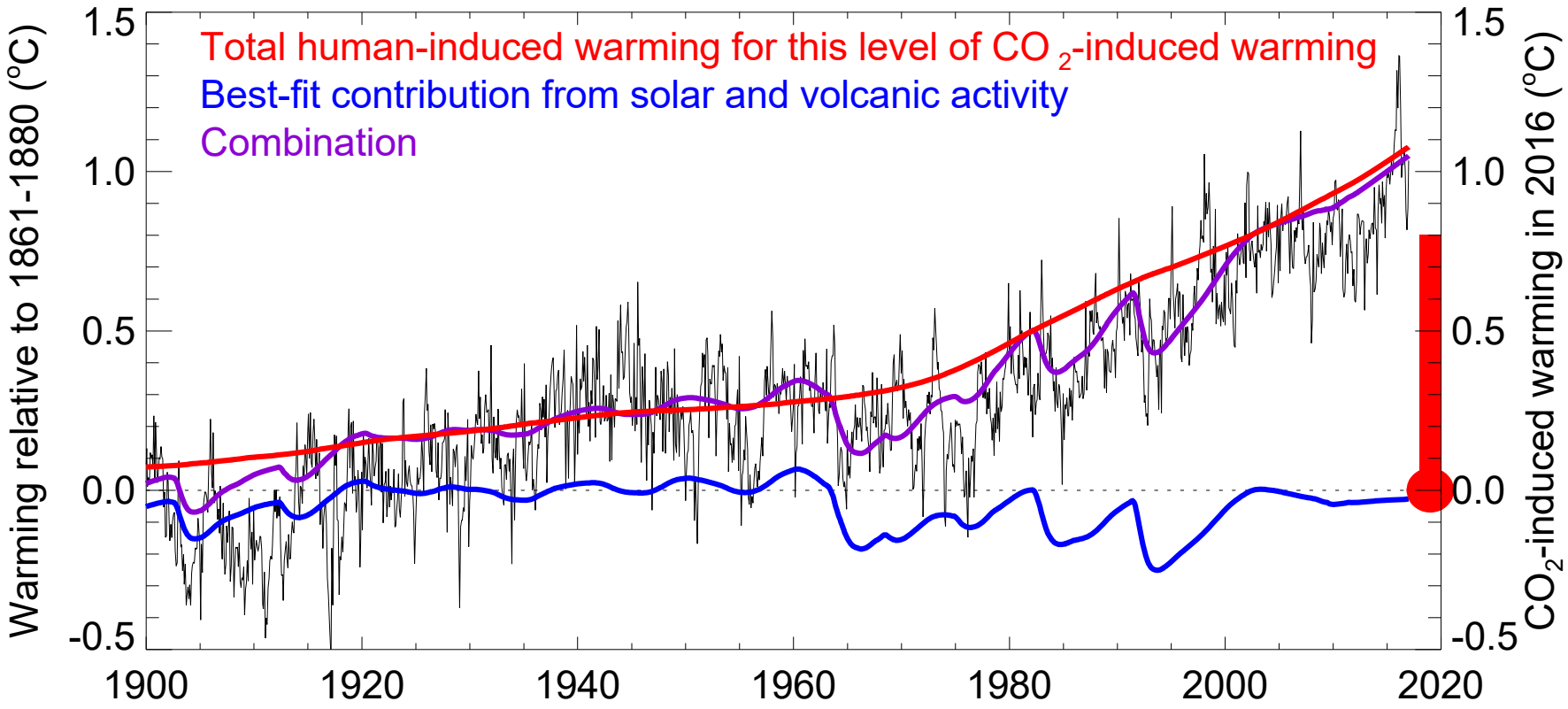
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

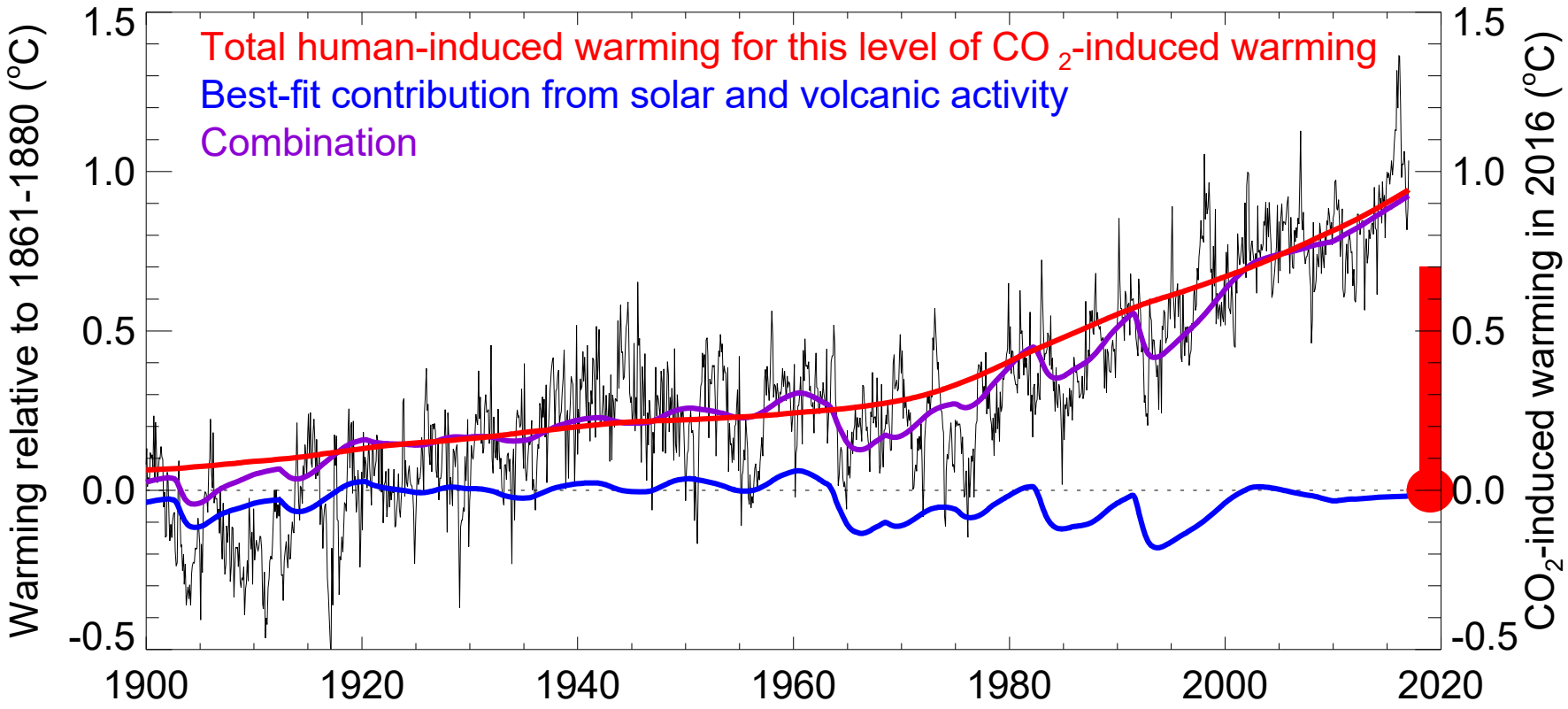
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

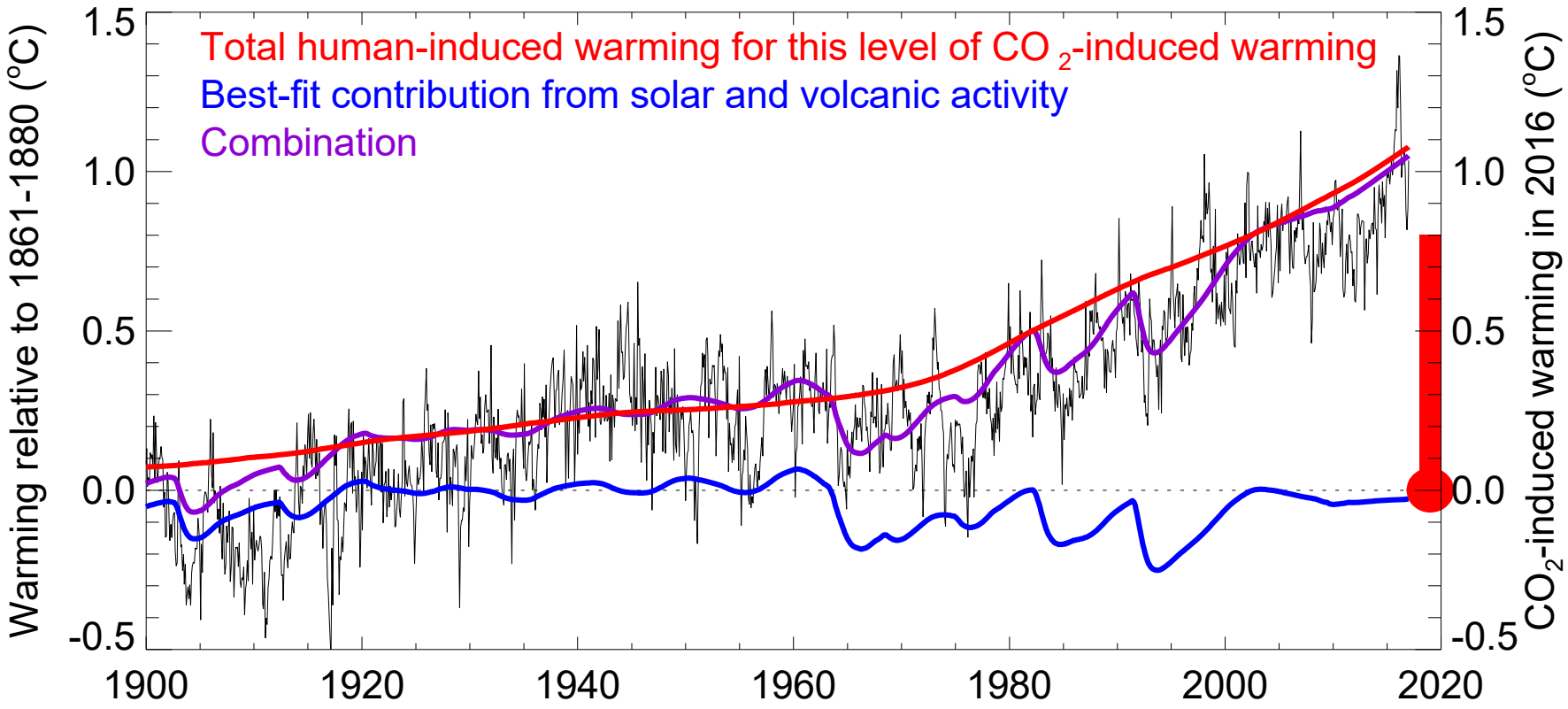
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

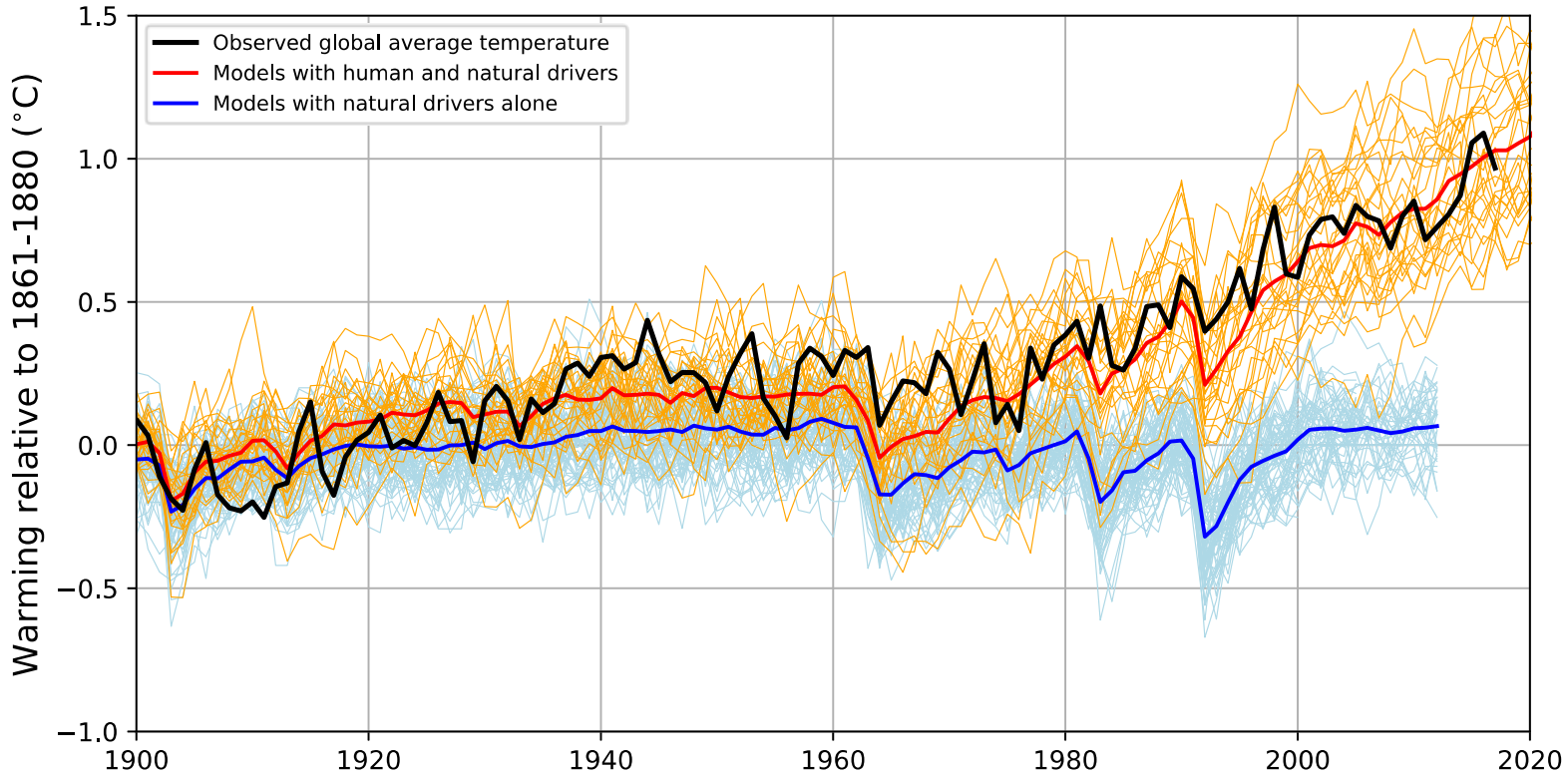
Explaining global temperature change, varying the level of CO_2-induced warming to date



eci

UNIVERSITY OF OXFORD

Similar conclusions from multi-dimensional fingerprints based on complex climate models



eci

UNIVERSITY OF OXFORD

The evidence that human influence is the dominant cause of the observed warming

- Agreement with global climate models provides one line of evidence, but not the only one.
- Physics understood in the 19th century predicted current warming of at least 0.2° C per decade, as observed.
- Formal comparison of expected responses to known drivers ("fingerprints") allowed the null-hypothesis of negligible human influence to be rejected at the 95% confidence level ($P<0.05$) back in the 1990s.
- Human-induced warming is now 1° C ± 0.15° C, about 80% due to CO_2.

eci

UNIVERSITY OF OXFORD

The impact of carbon dioxide emissions on global climate

- How rising atmospheric CO_2 causes global warming
- How industrial emissions are increasing atmospheric CO_2
- Modeling the impact of increasing CO_2 concentrations
- Quantifying human and natural influences on global climate
  - A digression on ice-ages
- How rising temperatures are affecting global sea level
- The permanent, cumulative impact of CO_2 emissions
  - Implications for the impact of delay in emission reductions

eci

UNIVERSITY OF OXFORD

Sea-level rise has long been known to be one of the key impacts of climate change

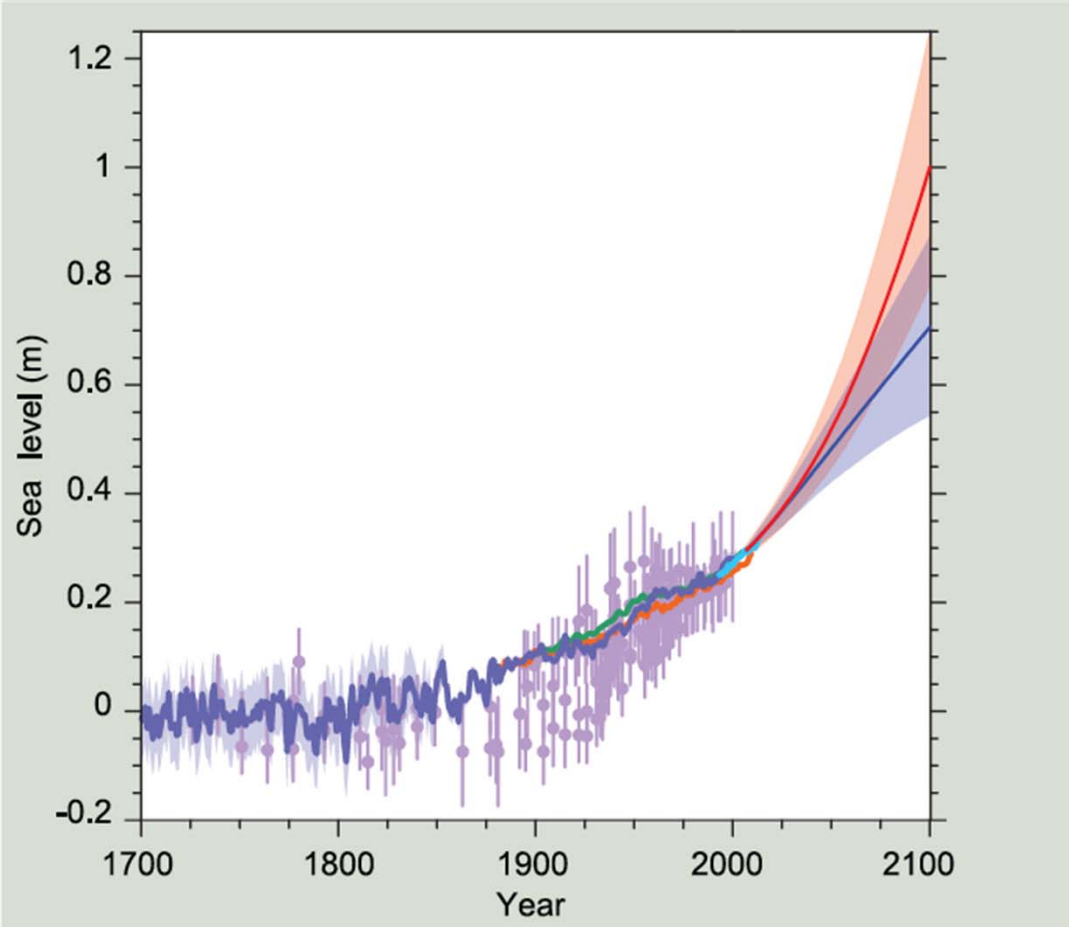
RESTORING THE QUALITY
OF
OUR ENVIRONMENT

Report of The
Environmental Pollution Panel
President's Science Advisory Committee

THE WHITE HOUSE
NOVEMBER 1965

Rise of sea level.—The melting of the Antarctic ice cap would raise sea level by 400 feet. If 1,000 years were required to melt the ice cap, the sea level would rise about 4 feet every 10 years, 40 feet per century. This is a hundred times greater than present worldwide rates of sea level change.

Many lines of evidence point to a sustained rise in sea level

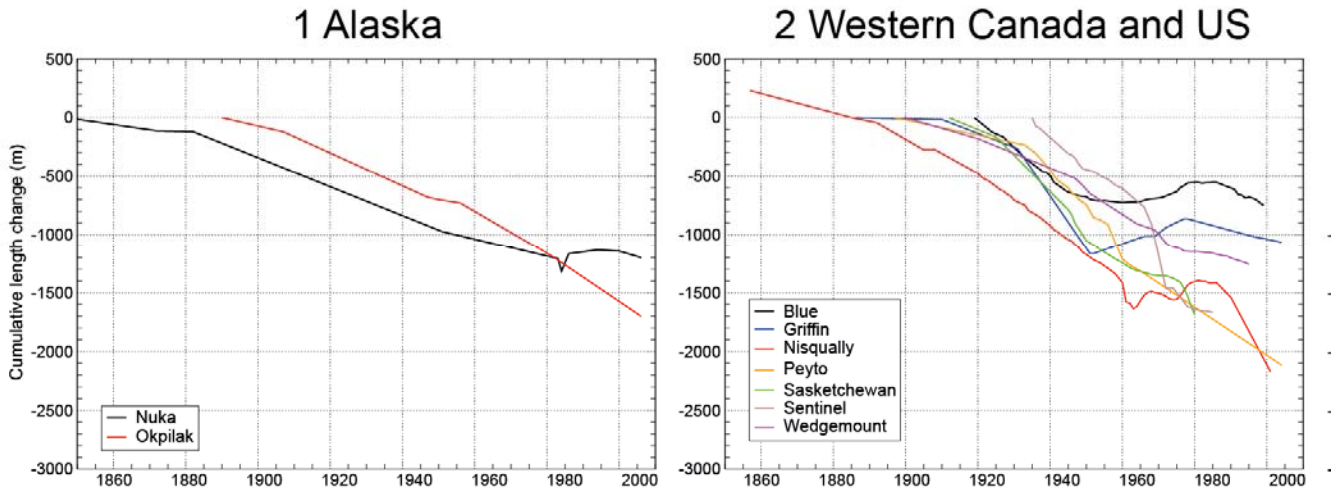


eci

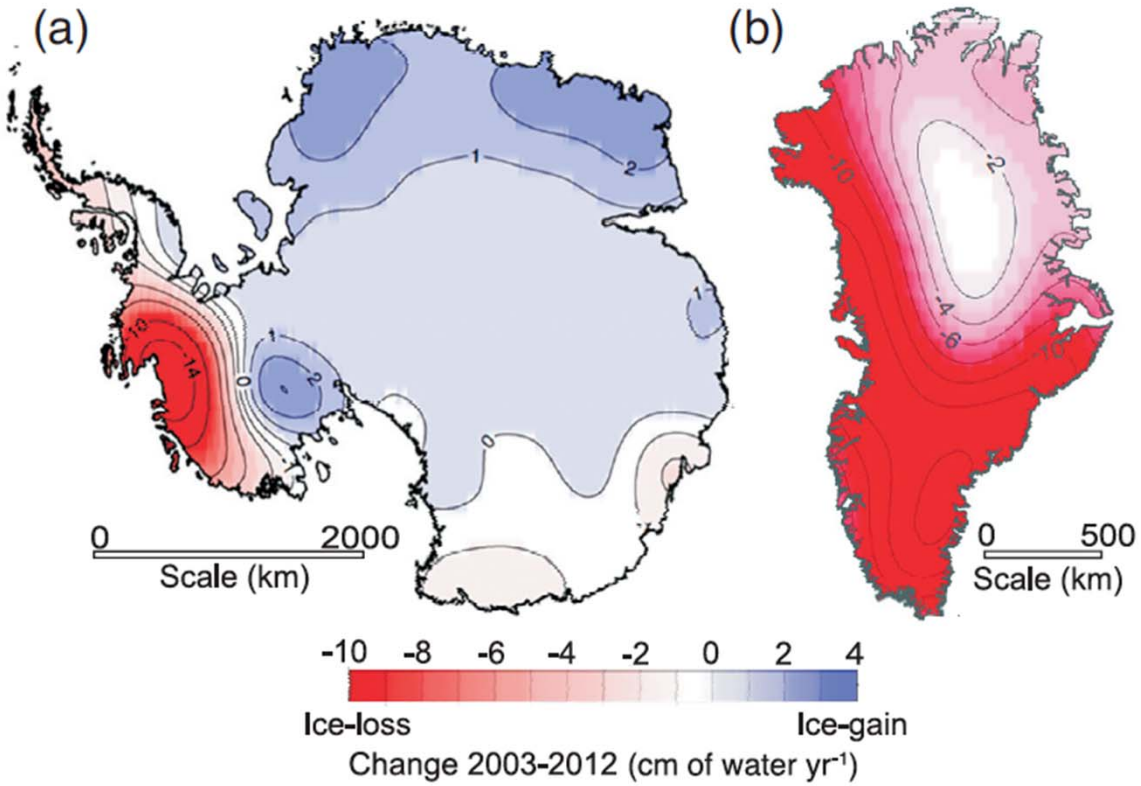
UNIVERSITY OF OXFORD

Mountain glaciers are melting faster due to human-induced warming

- Worldwide retreat of mountain glaciers, likely exacerbated by human-induced warming since 1960s.



And Greenland and Antarctica are losing ice

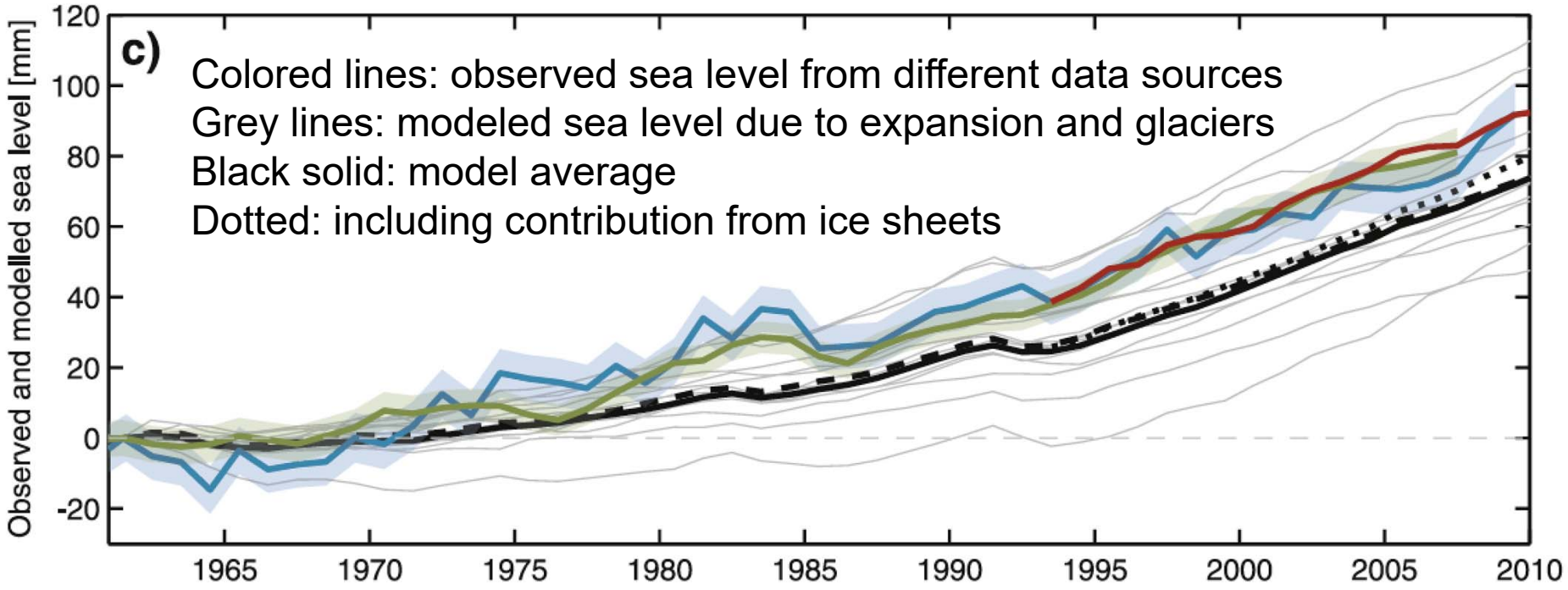


- Mass loss in Greenland and in Antarctic peripheral glaciers

eci

UNIVERSITY OF OXFORD

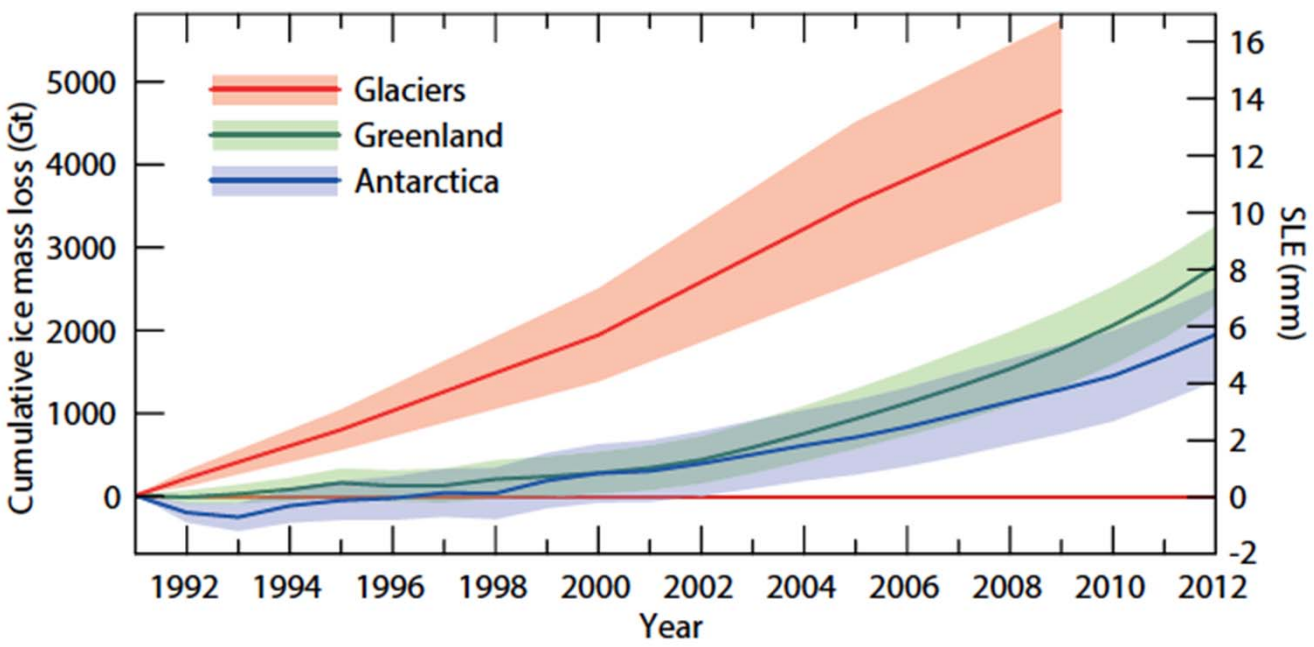
Most sea level change so far is due to thermal expansion and melting glaciers



eci

UNIVERSITY OF OXFORD

But contribution from Greenland and Antarctica is accelerating



Potential sea-level rise if entirely melted:

Glaciers: 0.4m

Greenland: 7m

Antarctica: 60m

- Glaciers have contributed more than ice-sheets to sea level rise since 1991, but ice-sheets have more potential

eci

UNIVERSITY OF OXFORD

The impact of carbon dioxide emissions on global climate

- How rising atmospheric CO_2 causes global warming
- How industrial emissions are increasing atmospheric CO_2
- Modeling the impact of increasing CO_2 concentrations
- Quantifying human and natural influences on global climate
  - A digression on ice-ages
- How rising temperatures are affecting global sea level
- The permanent, cumulative impact of CO_2 emissions
  - Implications for the impact of delay in emission reductions

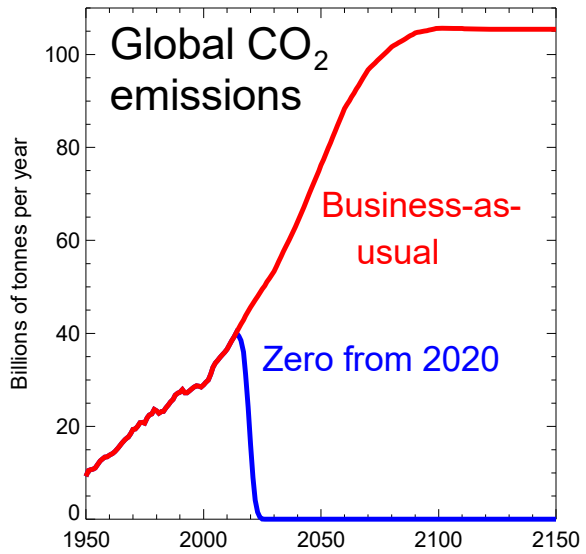
eci

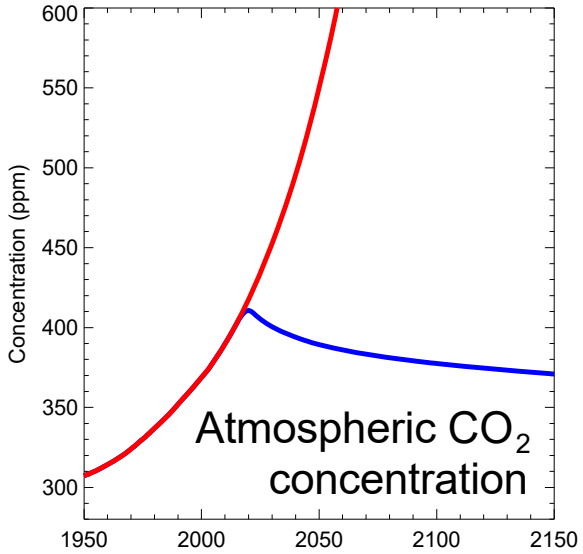
UNIVERSITY OF OXFORD

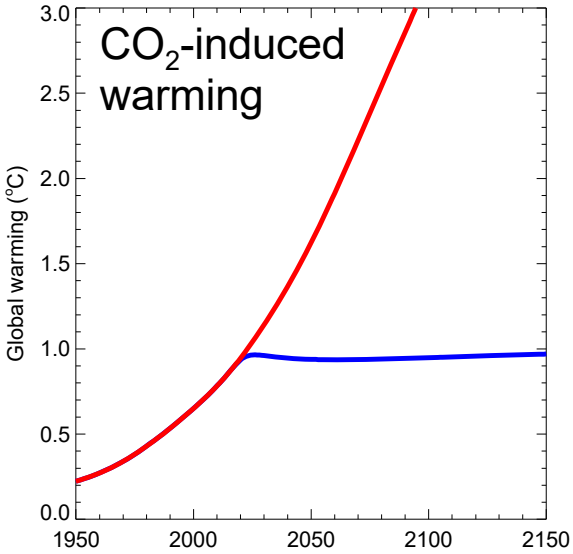
Permanent, cumulative impact of CO2 emissions on climate

- Roger Revelle, picked up by David Archer in the 2000s.
- Susan Solomon and others in 2009: net CO_2 emissions need to be reduced to zero to stabilize temperatures, at any level.

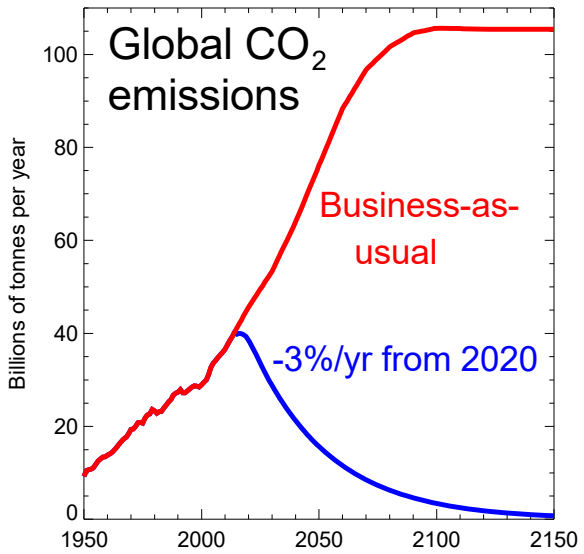
CO_2 emissions have a permanent, cumulative impact of on global temperatures

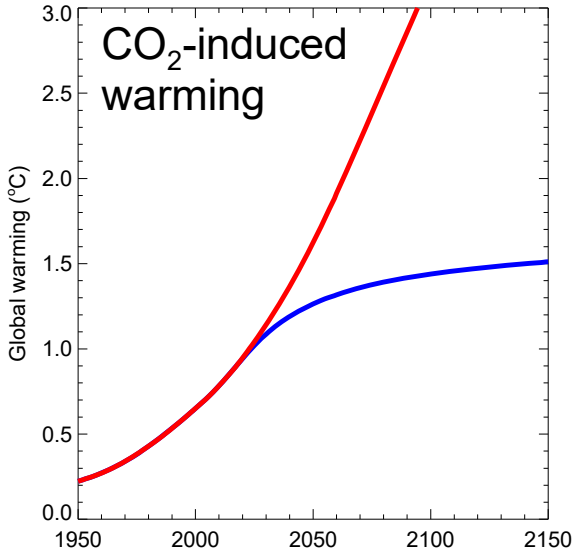


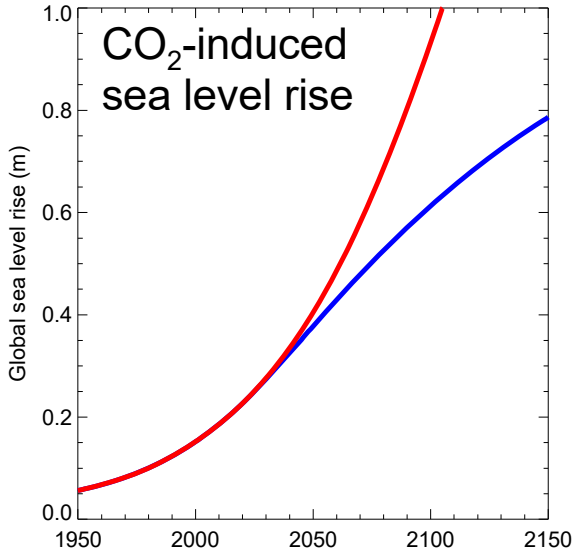




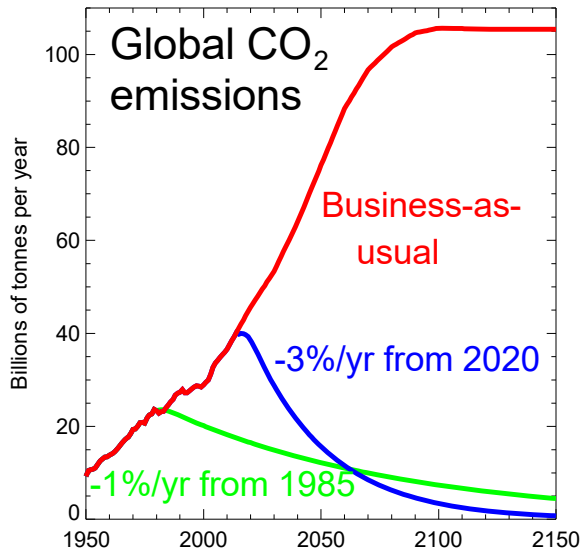
So net CO_2 emissions need to be reduced to zero to stabilize global temperatures at any level

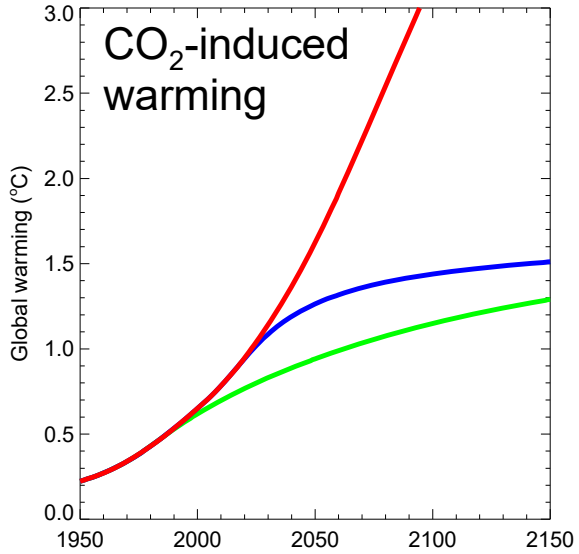


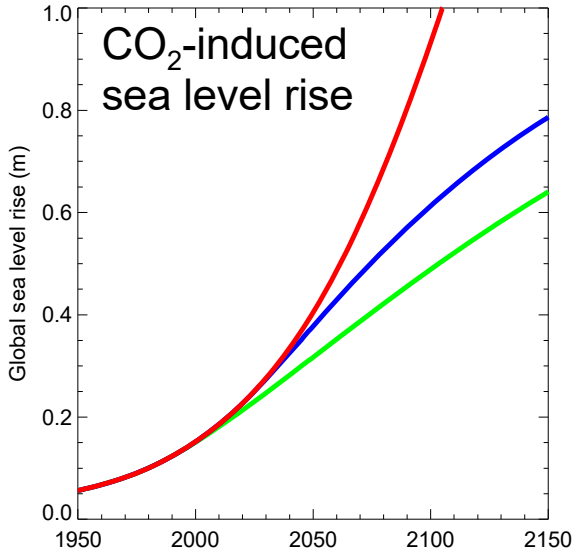




And delay increases the rate of emission reduction required for the same peak warming







Key points

- The essential physics linking CO_2, global temperatures and global sea level have been known for over 100 years.
- The contribution of fossil fuel emissions to rising atmospheric CO_2 largely understood since the 1960s.
- The expectation of a substantial warming due to increasing CO_2 was established in the 1970s.
- Evidence for an observable human-induced warming emerged in the 1990s.
- The need for net zero CO_2 emissions emerged post-2000.

eci

UNIVERSITY OF OXFORD