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
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
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 the many modes of motion of a CO₂ molecule create asymmetrically-charged “dipoles” which interact with electromagnetic radiation, particularly in the infra-red part of the spectrum.

The fewer modes of motion of an O₂ or N₂ molecule
The first quantitative account of the impact of rising CO\textsubscript{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.”
Both temperature and density of absorbing CO$_2$ molecules decrease with height.

Rate of energy emitted to space depends on the average temperature of molecules as seen from above.
Increasing CO$_2$ forces energy to escape from higher altitudes.

Rate of energy emitted to space depends on the average temperature of molecules as seen from above.
Higher air is colder, and so radiates less energy.

Rate of energy emitted to space depends on the average temperature of molecules as seen from above.
So the surface and lower atmosphere have to warm up to restore balance.
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
Impact of rising GHGs on the spectrum of outgoing energy has been directly observed from space.

Nimbus 4, 1970

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

![Graph showing modeled outgoing radiation vs. satellite observed outgoing radiation. The graph includes data points and a trend line. The x-axis represents CERES OLR, and the y-axis represents modeled outgoing radiation. The source is Dessler et al., JGR, 2008.](image-url)
Gilbert Plass (1955) and the role of water vapour

- Noted “the CO₂ 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, CO₂ is the dominant greenhouse gas.
- Emphasized urgency of measuring CO₂.
The impact of carbon dioxide emissions on global climate

• How rising atmospheric CO₂ causes global warming
• How industrial emissions are increasing atmospheric CO₂
• Modeling the impact of increasing CO₂ 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 CO₂ emissions
  – Implications for the impact of delay in emission reductions
Roger Revelle, 1957

- Explained how ocean buffer chemistry limits the amount of CO₂ taken up by the oceans, even in equilibrium.
- Hence CO₂ emissions have a permanent impact on climate: we can’t rely on the oceans to dilute them away.
Charles David Keeling’s observations, 1958-60

- Unequivocal evidence that CO₂ concentrations are rising steadily
Carbon dioxide levels are rising to levels not seen in over 20 million years.
Atmospheric oxygen and carbon isotopes indicate recent CO₂ 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

Data: CDIAC/NOAA-ESRL/GCP/Heede

Cumulative emissions (Gt CO$_2$)

Land-use change

Fossil fuels and industry

Top-90 Carbon Producers

Global Carbon Project

UNIVERSITY OF OXFORD
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
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.
Disturbing the global energy balance

2.5 additional W/m² IN due to increased GHGs

0.75 W/m² increasing heat content of the climate system

1.75 additional W/m² OUT due to 1°C observed warming
Most of that energy imbalance is being trapped in the oceans

- $0.75 \text{W/m}^2 = 135 \text{ZJ/decade}$
The global energy budget, now and in equilibrium

Now:

\[ \Delta F_{\text{external}} = (\lambda + \mu) \Delta T + \Delta Q_{\text{ocean}} \]

Net energy imbalance due to external drivers = c. 2.5 W/m²

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

Equilibrium:

\[ \Delta F_{2xCO_2} = \lambda \Delta T_{2xCO_2} \]

Energy imbalance due to doubling CO₂ = 3.7 W/m²

Rate of energy accumulation in climate system = c. 0.75 W/m²

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

Additional energy emitted to space per degree of warming in equilibrium

Equilibrium warming due to doubling CO₂ ("Climate Sensitivity")
“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
The 1979 National Academy of Sciences Report

• Gave a range of 1.5-4.5°C for equilibrium warming on doubling CO₂, emphasizing:
  – Oceans “could delay the estimated warming for several decades”
  – “We may not be given a warning until the CO₂ loading is such that an appreciable climate change is inevitable.”
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 CO₂ causes global warming
• How industrial emissions are increasing atmospheric CO₂
• Modeling the impact of increasing CO₂ 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 CO₂ emissions
  – Implications for the impact of delay in emission reductions
Warming itself is unequivocal

Observed monthly global average temperatures
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 CO₂ causes global warming
• How industrial emissions are increasing atmospheric CO₂
• Modeling the impact of increasing CO₂ 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 CO₂ emissions
  – Implications for the impact of delay in emission reductions
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.
Milutin Milankovitch and the origins of the ice ages
Milankovitch cycles and ice-core records over the past 800,000 years
Permanent ice observed (even in Antarctica) only appeared after CO₂ dropped below 400ppm
More recent drivers of change in global temperature

Drivers of change in the global energy balance:
- Human activity
- Long- and short-term solar variability
- Volcanic activity
The shape of the responses to these drivers is determined by simple energy conservation.
We use these “fingerprints” to test the null-hypothesis that CO$_2$ has no warming effect

"What if" exercise: what if CO$_2$ 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 CO₂-induced warming to date

![Graph showing temperature change over time](image)

- Total human-induced warming for this level of CO₂-induced warming
- Best-fit contribution from solar and volcanic activity
- Combination

---

Case 3:17-cv-06011-WHA   Document 183-5   Filed 03/23/18   Page 43 of 71
Explaining global temperature change, varying the level of CO₂-induced warming to date

![Graph showing temperature changes from 1900 to 2020, with markers for total human-induced warming, best-fit contribution from solar and volcanic activity, and combination.]
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
Explaining global temperature change, varying the level of CO$_2$-induced warming to date
Explaining global temperature change, varying the level of $\text{CO}_2$-induced warming to date

Total human-induced warming for this level of $\text{CO}_2$-induced warming
Best-fit contribution from solar and volcanic activity
Combination
Explaining global temperature change, varying the level of CO$_2$-induced warming to date

![Graph showing temperature change over time, with labels for total human-induced warming, best-fit contribution from solar and volcanic activity, and CO$_2$-induced warming in 2016.](image)
Explaining global temperature change, varying the level of CO₂-induced warming to date
Explaining global temperature change, varying the level of \( \text{CO}_2 \)-induced warming to date
Explaining global temperature change, varying the level of CO$_2$-induced warming to date
Explaining global temperature change, varying the level of CO₂-induced warming to date

![Graph showing warming relative to 1861-1880 (°C) from 1900 to 2020. The graph includes lines for total human-induced warming, best-fit contribution from solar and volcanic activity, and combination. The x-axis represents years from 1900 to 2020, and the y-axis represents warming relative to 1861-1880 (°C).]
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
Explaining global temperature change, varying the level of CO\textsubscript{2}-induced warming to date
Similar conclusions from multi-dimensional fingerprints based on complex climate models
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 CO₂.
The impact of carbon dioxide emissions on global climate

• How rising atmospheric CO₂ causes global warming
• How industrial emissions are increasing atmospheric CO₂
• Modeling the impact of increasing CO₂ 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 CO₂ emissions
  – Implications for the impact of delay in emission reductions
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
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
Most sea level change so far is due to thermal expansion and melting glaciers

Colored lines: observed sea level from different data sources
Grey lines: modeled sea level due to expansion and glaciers
Black solid: model average
Dotted: including contribution from ice sheets
But contribution from Greenland and Antarctica is accelerating

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

Potential sea-level rise if entirely melted:
- Glaciers: 0.4m
- Greenland: 7m
- Antarctica: 60m
The impact of carbon dioxide emissions on global climate

• How rising atmospheric CO₂ causes global warming
• How industrial emissions are increasing atmospheric CO₂
• Modeling the impact of increasing CO₂ 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 CO₂ emissions
  – Implications for the impact of delay in emission reductions
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.
CO₂ emissions have a permanent, cumulative impact on global temperatures.

- **Global CO₂ emissions**
  - Blue line: Business-as-usual
  - Red line: Zero from 2020

- **Atmospheric CO₂ concentration**

- **CO₂-induced warming**
So net CO₂ 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.