Croll, feedback mechanisms, climate change and the future

Roy Thompson (GeoSciences, University of Edinburgh)

A 'top ten' selection of the varied subject areas that Croll tackled:

1. Causes of climate change (1864)
2. Ice-cap melt and sea-level rise (1865)
3. Predicting future climates using eccentricity (1866)
4. Combining orbital precession, eccentricity and obliquity (1867)
5. Geological time and the date of the glacial epochs (1868)
6. Geological time and denudation rates (1868)
7. Ocean currents and hemispherical temperature differences (1869)
8. Feedbacks (1875)
9. Temperature of space and its bearing on terrestrial physics (1880)
10. The causes of mild polar climates (1884)

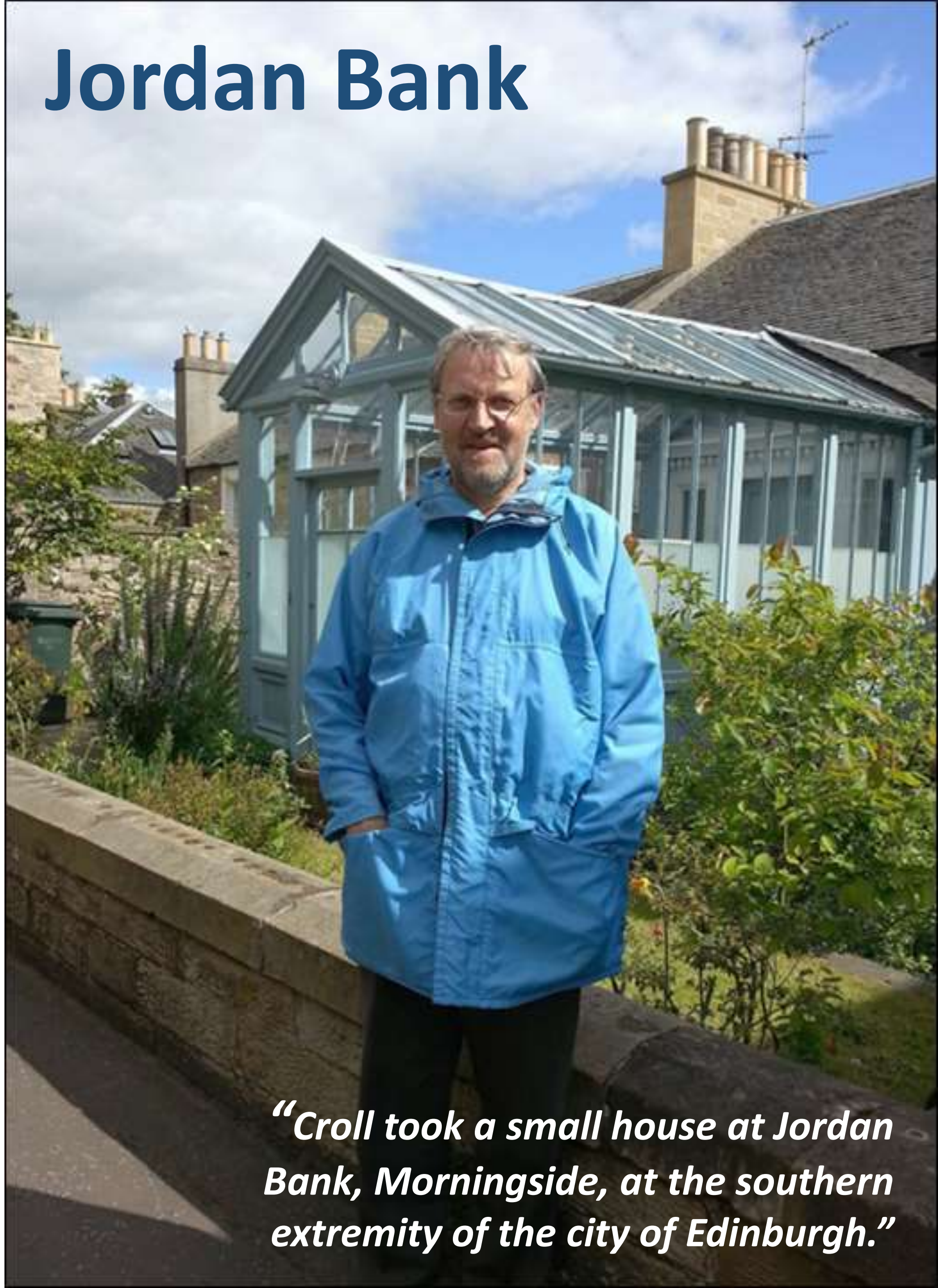
	BASIC PHYSICS AND CHEMISTRY	PHYSICS OF CLIMATE	CLIMATE AND TIME
Pre Croll	**Newton 1660** Created the science of spectroscopy by dispersing white sunlight into a continuous series of colours. **Black 1754** Discovered CO_2. Herschel 1800 Discovered infrared radiation. **Thomson 1848** Proposed the absolute temperature scale. **Clausius 1850** Stated (with Thomson) the 1st & 2nd Laws of Thermodynamics. Formulated the Clausius-Clapeyron equation.	**Fourier 1827** First to study the Earth's temperature from a mathematical and largely correct physical perspective. Recognised how dark heat and light penetrate air differently, and reasoned for a natural greenhouse effect. **Tyndall 1861** Measured the absorption of heat by a wide range of common and trace atmospheric gases, including CO_2, CH_4, N_2O & water vapour.	**Hutton 1785** Transformed our concepts of the Earth by deciphering the message carried by rocks. Recognised the immensity of geologic time. **Lyell 1830** Proposed uniformitarianism as a contrast to catastrophism. **Agassiz 1837** Proposed that glaciers had smothered much of the Northern Hemisphere in a prolonged ice age.
Post Croll	**Stefan/Boltzmann 1879** Established fourth-power radiation law.	**Arrhenius 1896** Invented the field of climate modelling. First to quantify the greenhouse effect and climate sensitivity. Explained ice ages by lowered CO_2 plus a secondary albedo effect inducing whole-Earth cooling.	**Geikie 1871** Described multiple inter-Glacial deposits in agreement with Croll's vision of oscillating glacial epochs. Chamberlin 1899 Farsighted explanation of glacials using carbon-cycle feedbacks.
Post Croll 20thC	**Planck 1900** Derived blackbody radiation formula. **Mie 1908** Established the basis of aerosol optics. **Quantum mechanics 1925** Heisenberg/Schrodinger/Dirac provided the modern theoretical framework for understanding spectroscopic observations.	**Abbe 1901** Identified the system of mathematical equations that govern the evolution of atmospheric motions. **Callendar 1938** First to demonstrate the warming of Earth's land surface. Also noted increasing atmospheric CO_2. Made the quantitative connection between global warming and greenhouse-gas emissions through human activities.	**Wegener 1912** Proposed that the horizontal movements of drifting continents gave rise to many of the climatic changes observed in the geological record. **Revelle/Suess 1957** Determined slow oceanic take-up of CO_2. Bolin/Eriksson 1958 Accurately predicted future CO_2 concentration from accelerating emissions, buffered chemistry and slow ocean mixing.
≈100 years post Croll	**Lorenz 1963** Founder of modern chaos theory. Discovered deterministic chaos, while making weather prediction calculations. Uncovered the 'Butterfly Effect' and established the theoretical basis of weather and climate predictability. **Crutzen 1970** Provided a deep understanding of the chemistry of the ozone layer.	**Manabe 1967 & 1975** Pioneered the use of computers to simulate global climate change and was the first to soundly quantify the warming expected from $2xCO_2$. **Budyko 1969** Established quantitative energy-budget modelling of the palaeoclimate system. Demonstrated the multiple equilibria of an ice-covered, ice-free and intermediate (unstable) solution.	**The Limits to Growth 1972** Provided insights into the limits of exponential growth in our resource-limited world system. Hays/Imbrie/Shackleton 1976 Used ocean cores to confirm connections between orbital motions and Ice ages. **Nordhaus 1992** Developed and optimized the first integrated assessment model.
Today	**Today** Basic climate science is well established. The world's fastest super-computers are used to validate ever-improving climate-modelling schemes against geological observations of hot-house, ice-age and historical epochs.	**Today** Croll's concept of positive climate feedbacks and their crucial role in determining climate sensitivity remain at the heart of endeavours to model and forecast future climate change.	**Today** Humankind's activities continue to raise atmospheric CO_2 concentrations. This will lead to profound effects on our future economies and societies. The resulting climate and sea-level change will persist for geological eons.

Herdwick sheep in Cumbria

POSITIVE FEEDBACK **Once a phenomenon has started it augments its own state in a 'runaway' fashion. In this example, once panic causes some sheep to start running, others will find this frightening and also start to run, thereby increasing the general level of panic.**

Outline

1. The next generation of climate models is running hot
2. Croll's feedback mechanisms and climate sensitivity
3. Greenhouse gas emissions: *quo vadis*?
4. The climate-change crossroads
5. James Croll's most enduring legacy



1. The next generation of climate models is running hot

UK Met Office ploughs £1.2bn into record-breaking weather and climate supercomputer 17 Feb 2020


CMIP6/ESGF contributors
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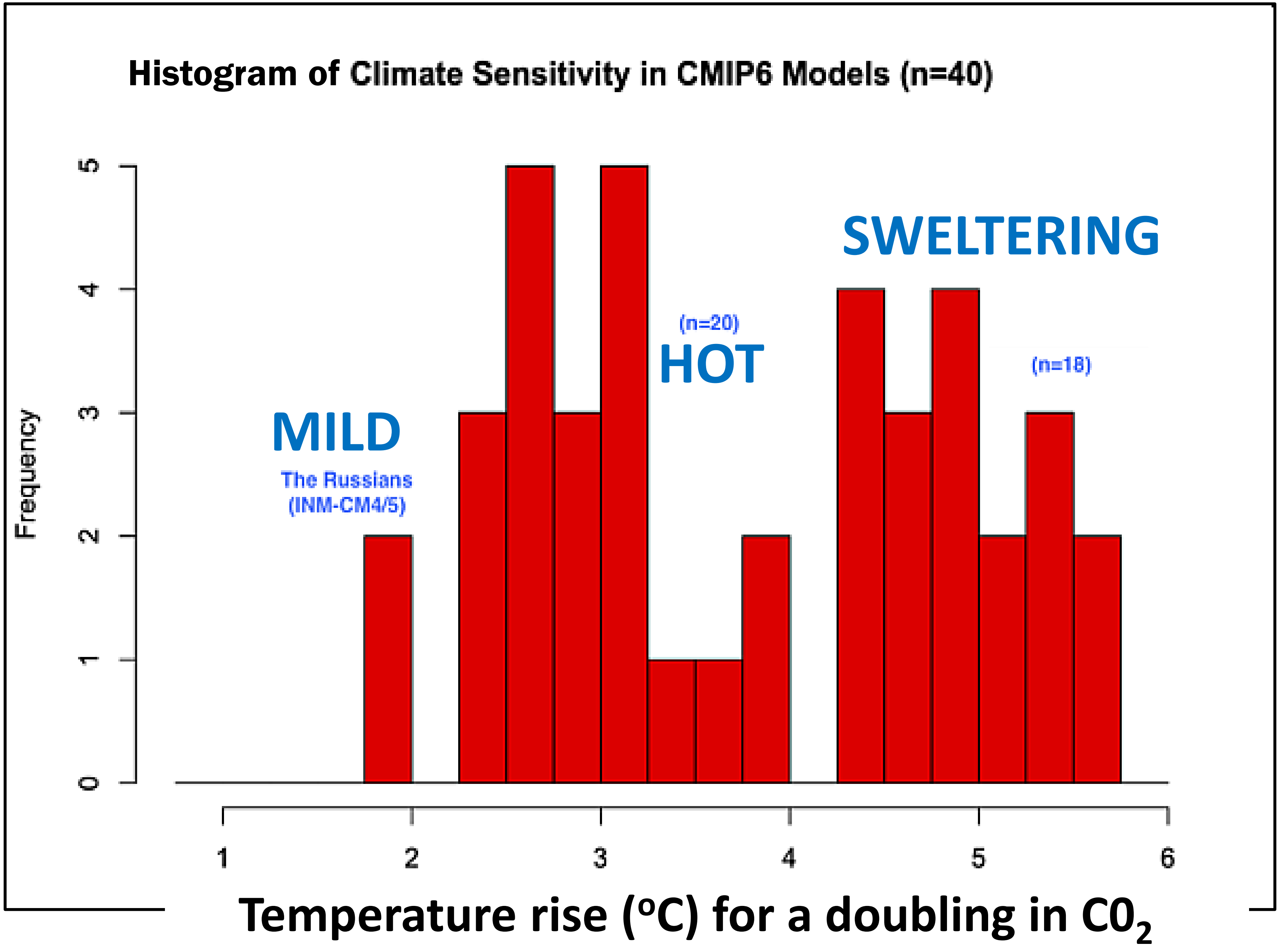
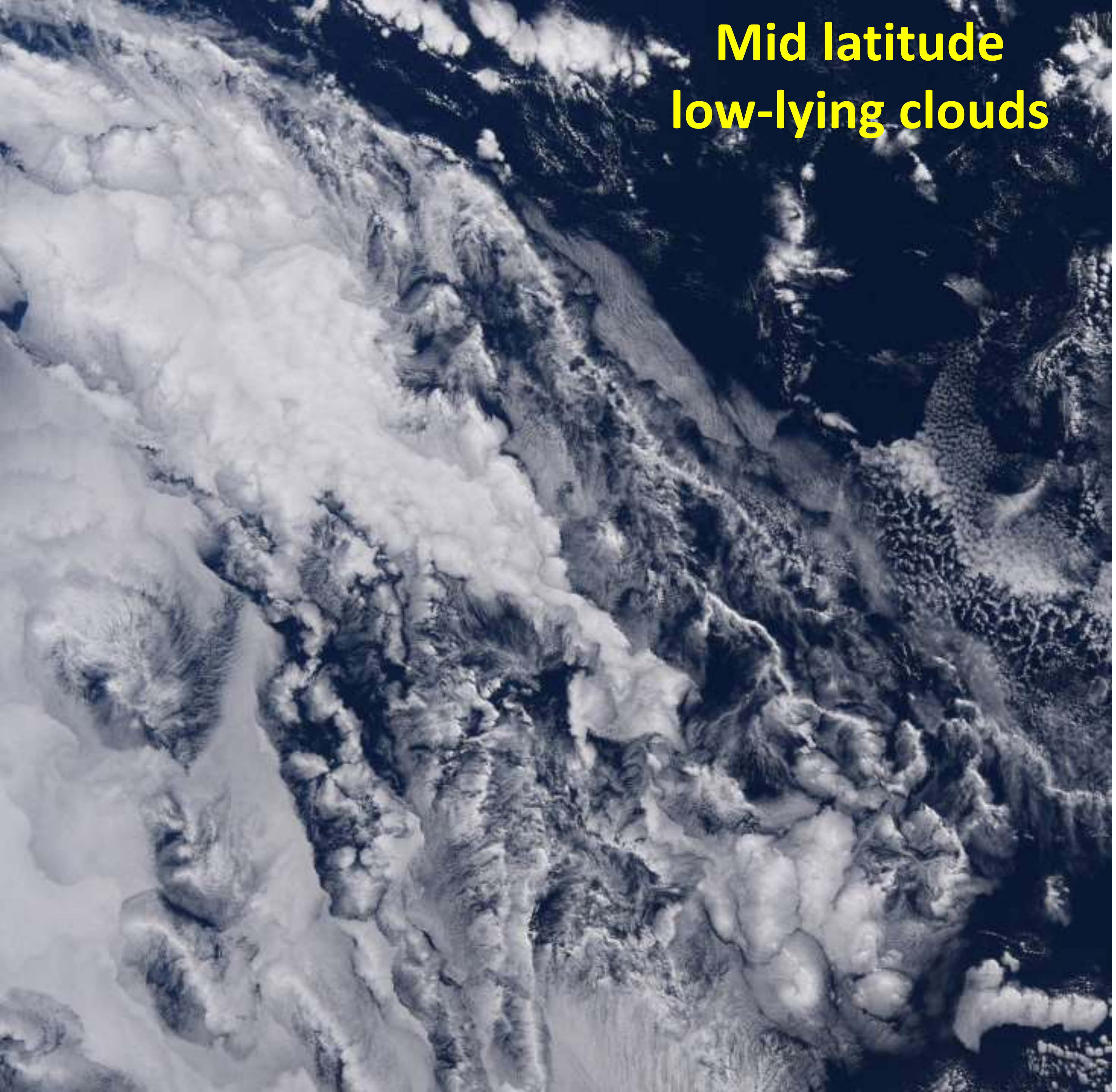
Finland
Iceland
Russia
Canada
Ukraine
Kazakhstan
Mongolia
North Atlantic Ocean
China
Iraq
Iran
Afghanistan
Algeria
Libya
Egypt
Pakistan
Mexico
Arabia
Thailand
Mali
Niger
Sudan
Chad
Nigeria
Ethiopia
Venezuela
Colombia
Kenya
DRC
Indonesia
Papua New Guinea
Tanzania
Brazil
Peru
Angola
Bolivia
Namibia
Madagascar
Indian Ocean
South Pacific Ocean
Chile
South Atlantic Ocean
Australia
South Africa
Argentina
New Zealand
Google My Maps
Map data ©2021
Terms
2,000 km

2. Climate Sensitivity

The central question that remains in climate science is exactly how much warming can we expect (both in the near-term and the long-term) for a given increase in carbon dioxide? Essentially we are asking how sensitive our climate is to increases in CO_2, hence the term – 'climate sensitivity'.



Calculations by Mark Zelinka



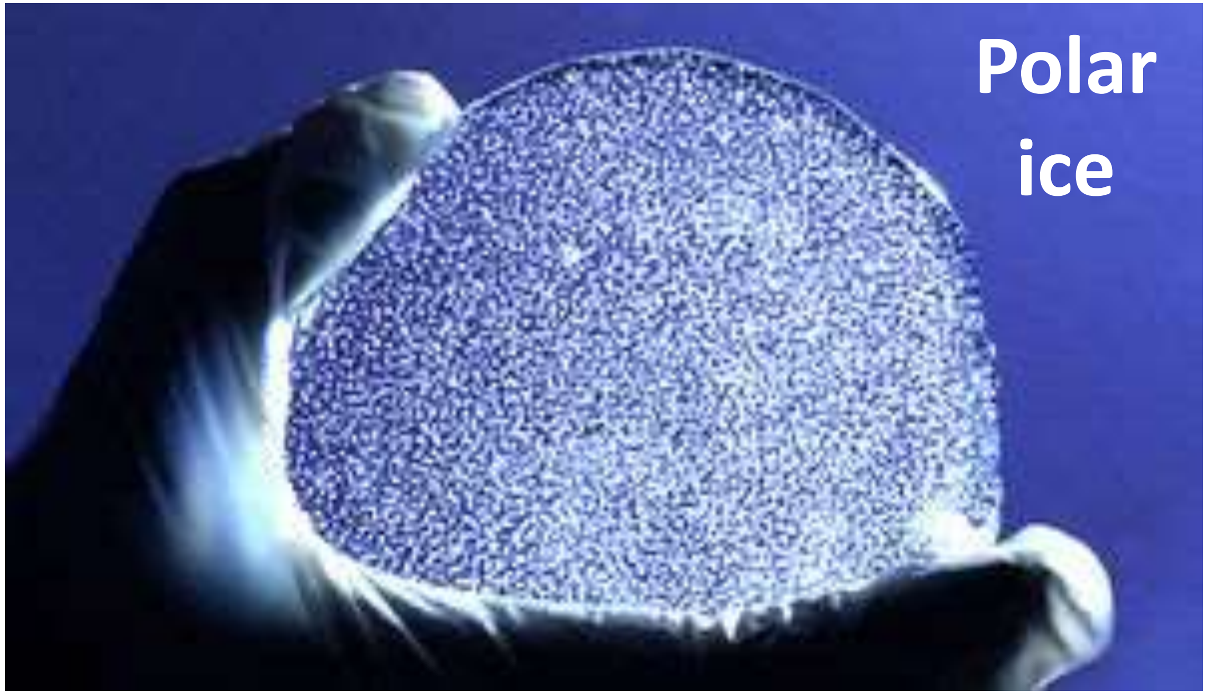
Why are the new generation of models running so hot?

The low cloud feedbacks have changed particularly in the mid-latitude Southern Hemisphere. Correction of the previous underestimation of supercooled liquid water in low-level mixed-phase clouds, leads to the average feedback being a little more positive. Consequently, as the Earth warms, the low-lying cloud cover decreases and reflects less sunlight back to space and so amplifies warming.

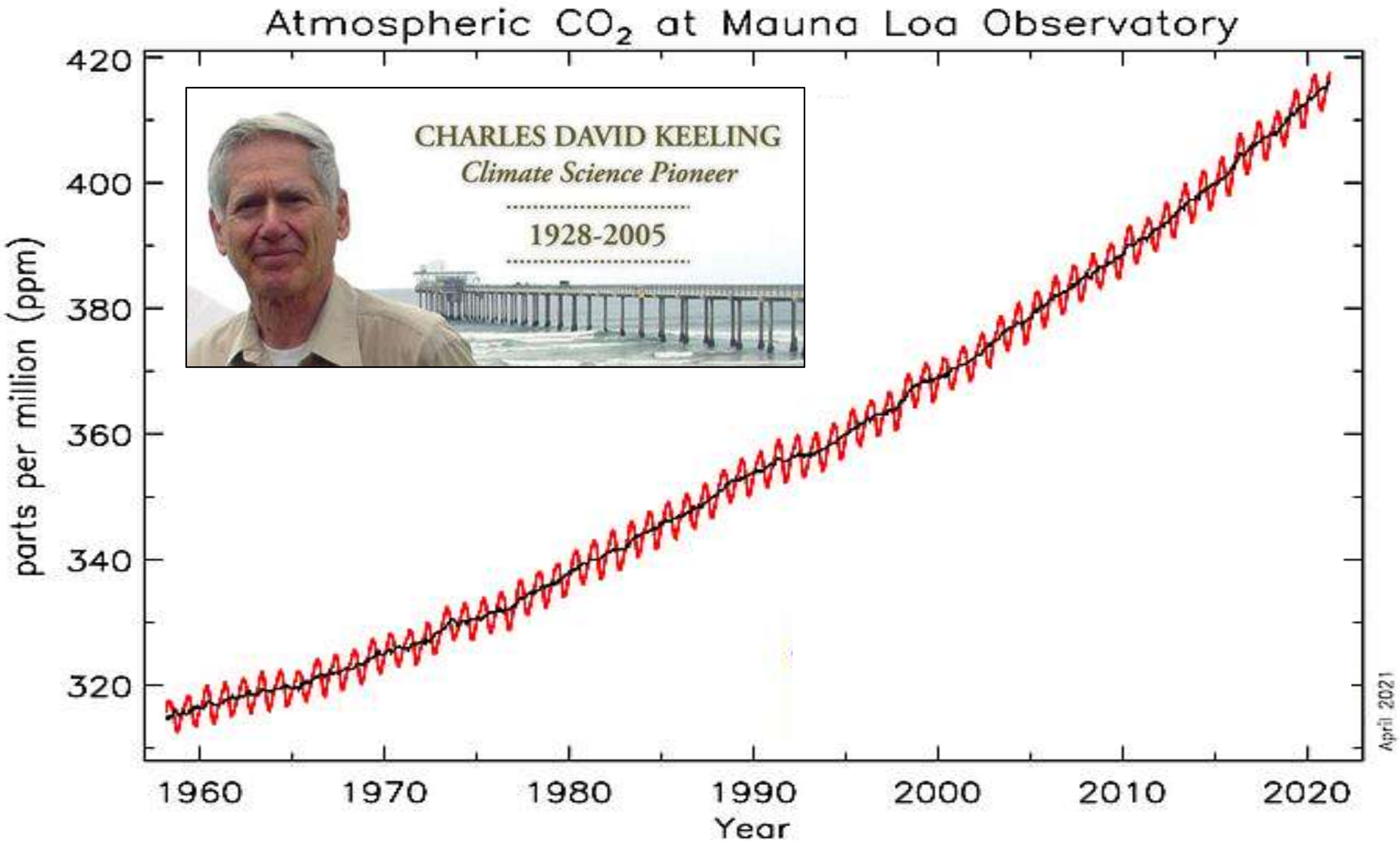
NB. The CMIP6 models were updated because the CALIPSO satellite lidar showed how common supercooled liquid droplets (as opposed to ice) are in low cloud tops, even at -35 C.

3. Greenhouse gas emissions: *quo vadis*?

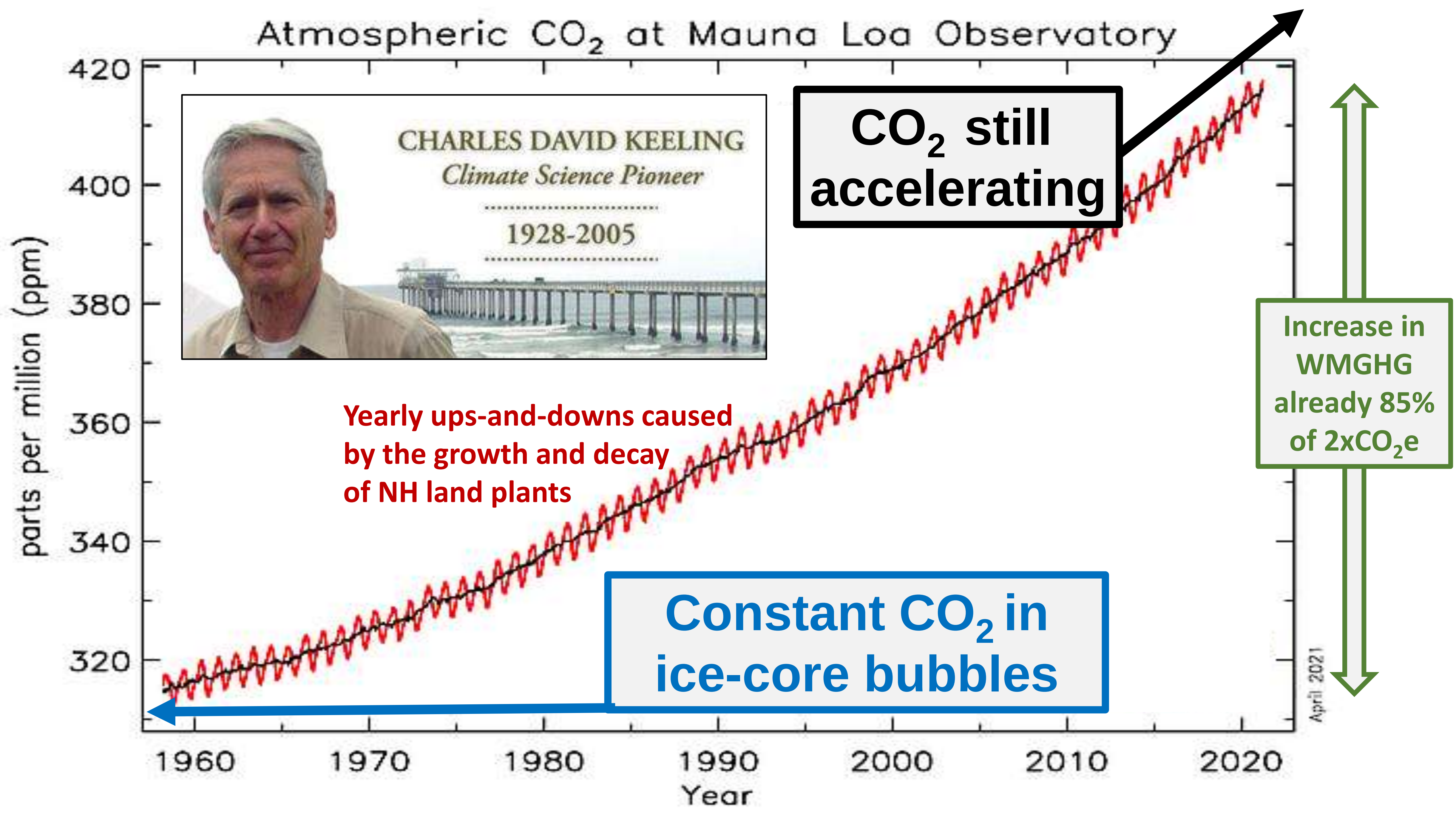
Atmospheric concentrations of CO_2 are still rising

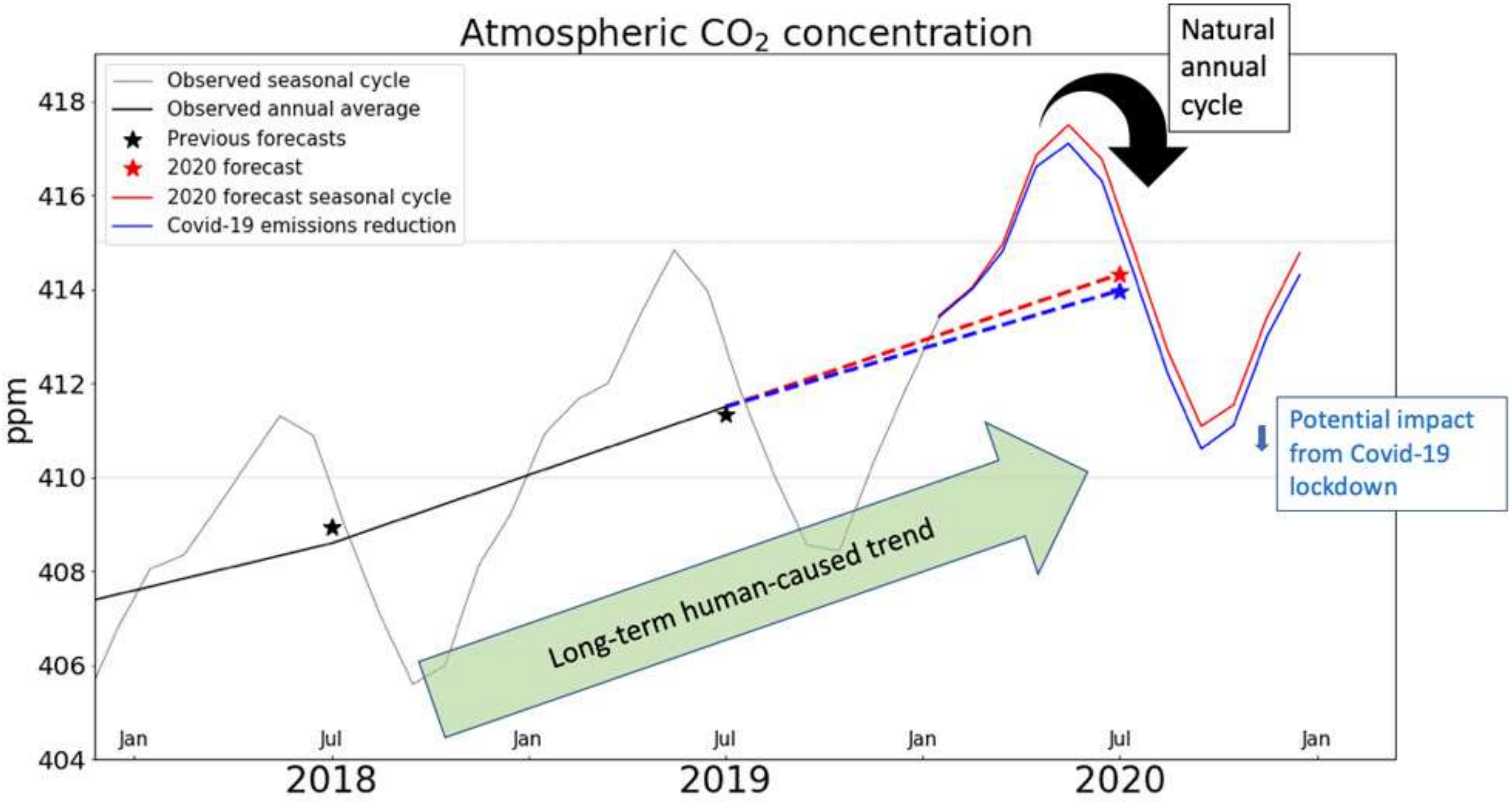


Fossil fuel CO_2 emissions are the main driver of human-induced climate change. Historically, they have increased over many decades in all countries.



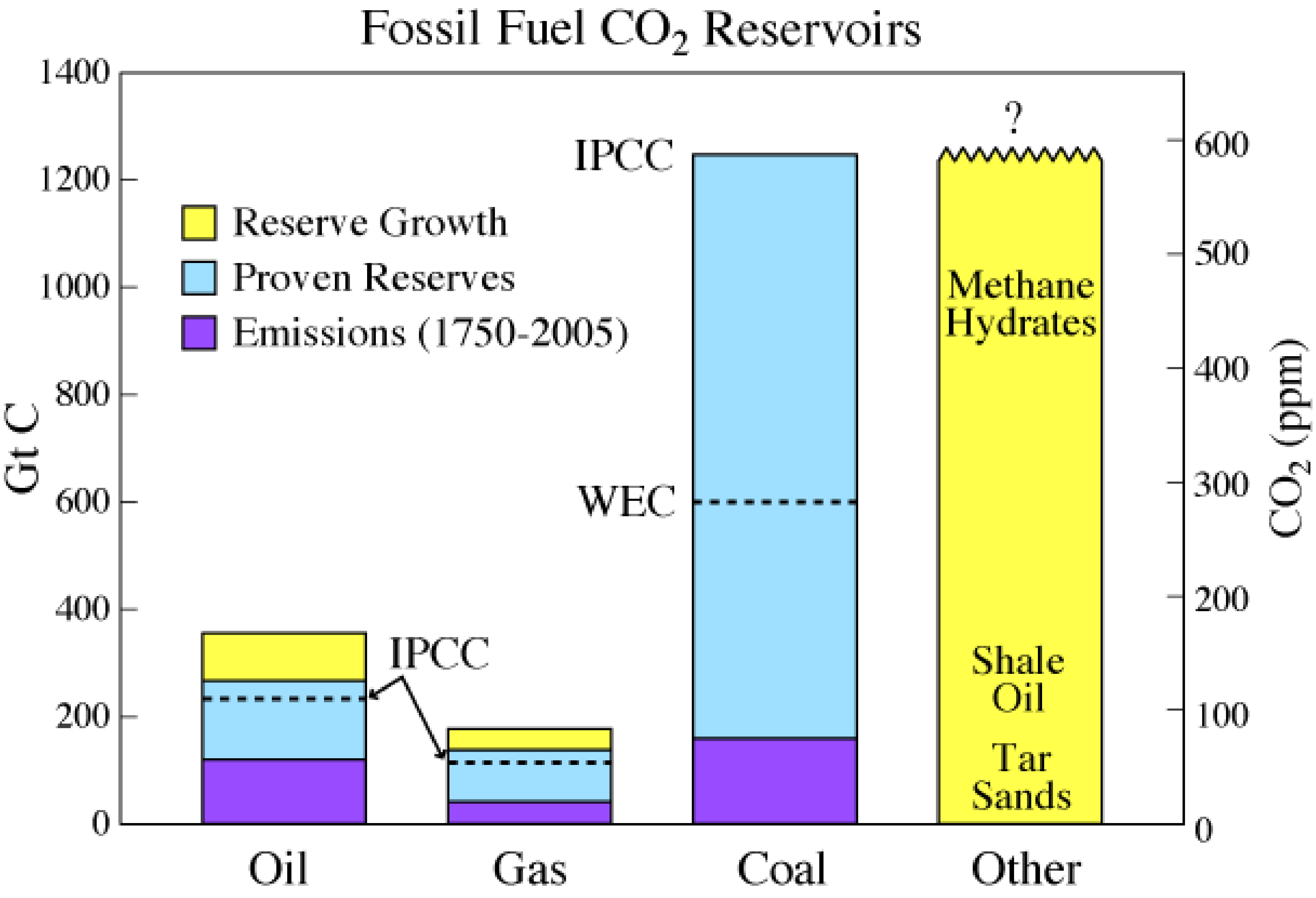
Atmospheric CO_2 at Mauna Loa Observatory
CHARLES DAVID KEELING
Climate Science Pioneer
1928-2005
parts per million (ppm)
420
400
380
360
340
320
1960
1970
1980
1990
2000
2010
2020
Year
April 2021


Atmospheric CO_2 at Mauna Loa Observatory
CHARLES DAVID KEELING
Climate Science Pioneer
1928-2005
CO_2 still accelerating
Yearly ups-and-downs caused by the growth and decay of NH land plants
Constant CO_2 in ice-core bubbles
Increase in WMGHG already 85% of $2xCO_2e$
parts per million (ppm)
Year
420
400
380
360
340
320
1960
1970
1980
1990
2000
2010
2020
April 2021

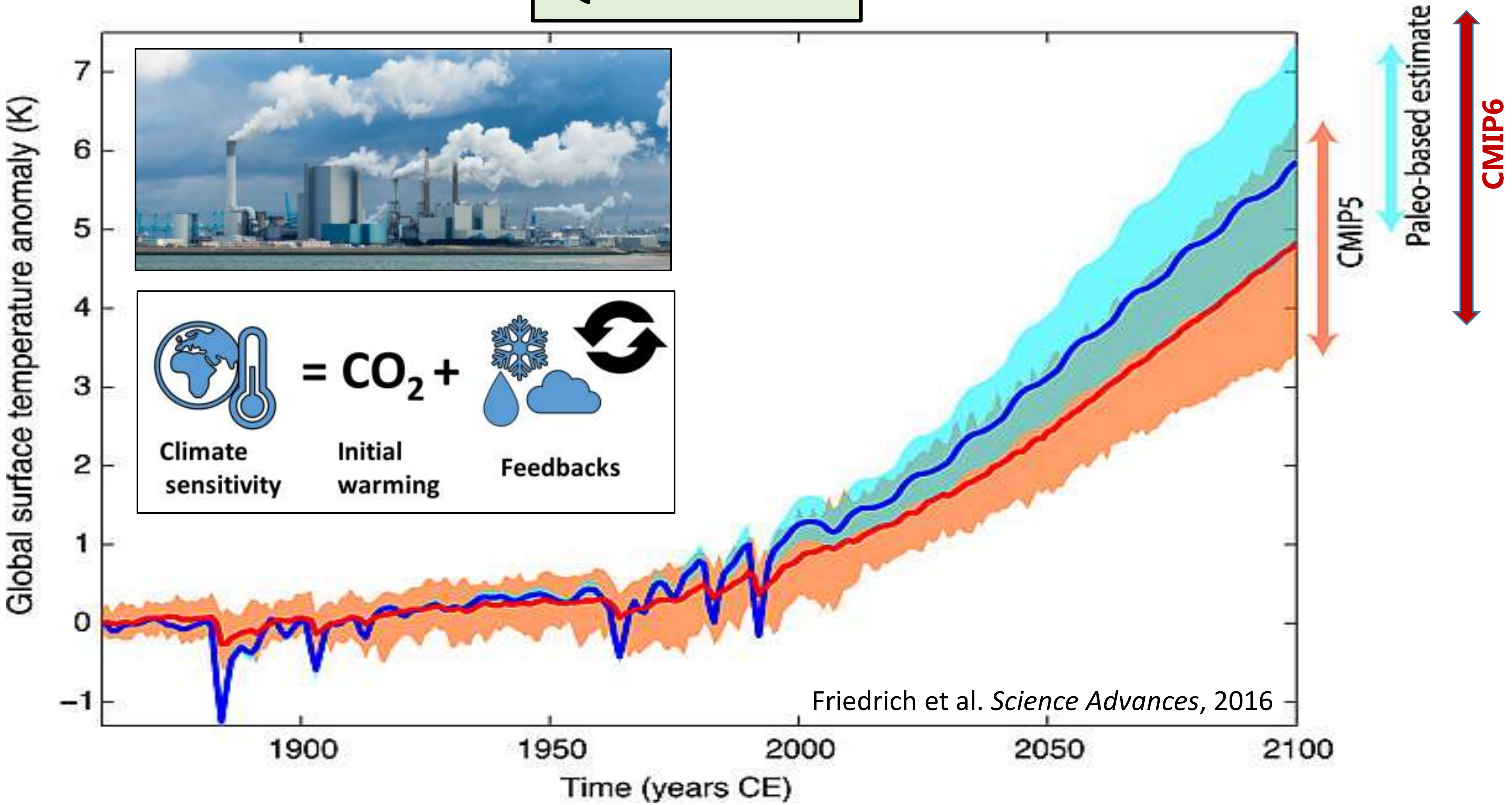


Observed and forecast CO_2 concentrations at Mauna Loa, showing both annual and monthly values, illustrating the impact of a potential 8% reduction (from Covid-19) in global CO_2 emissions on the predicted rise in concentrations.
Credit: Met Office

What about future CO_2 emissions?



Quo vadis?



Climate sensitivity
= CO_2 +
Initial warming
Feedbacks
Global surface temperature anomaly (K)
Time (years CE)
CMIP5
Paleo-based estimate
CMIP6
Friedrich et al. *Science Advances*, 2016

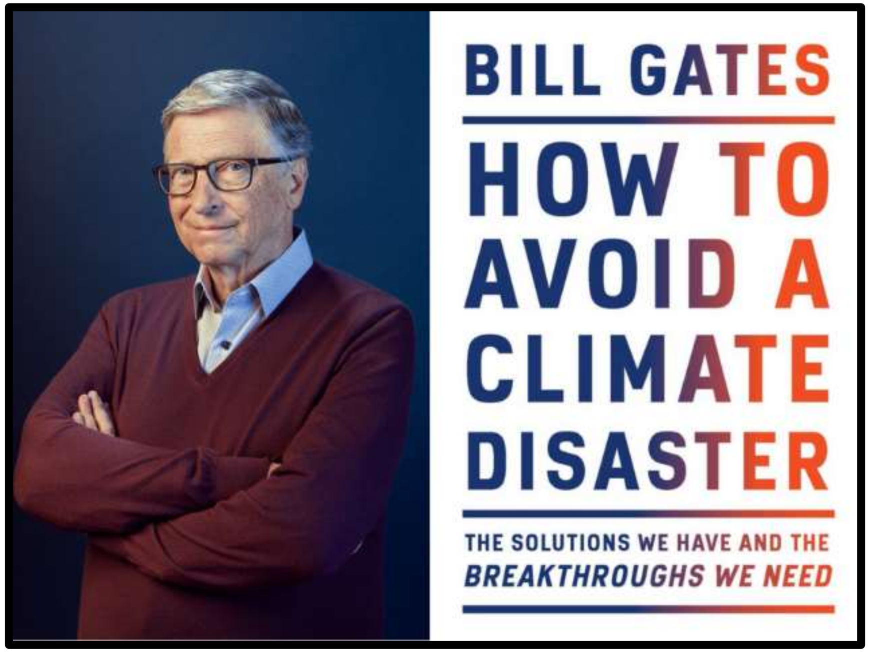
4. The climate-change crossroads

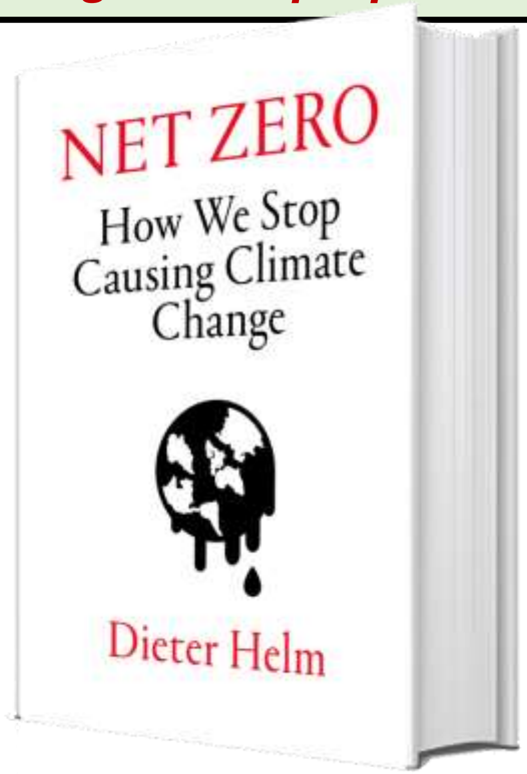
Books released during just the past few months.

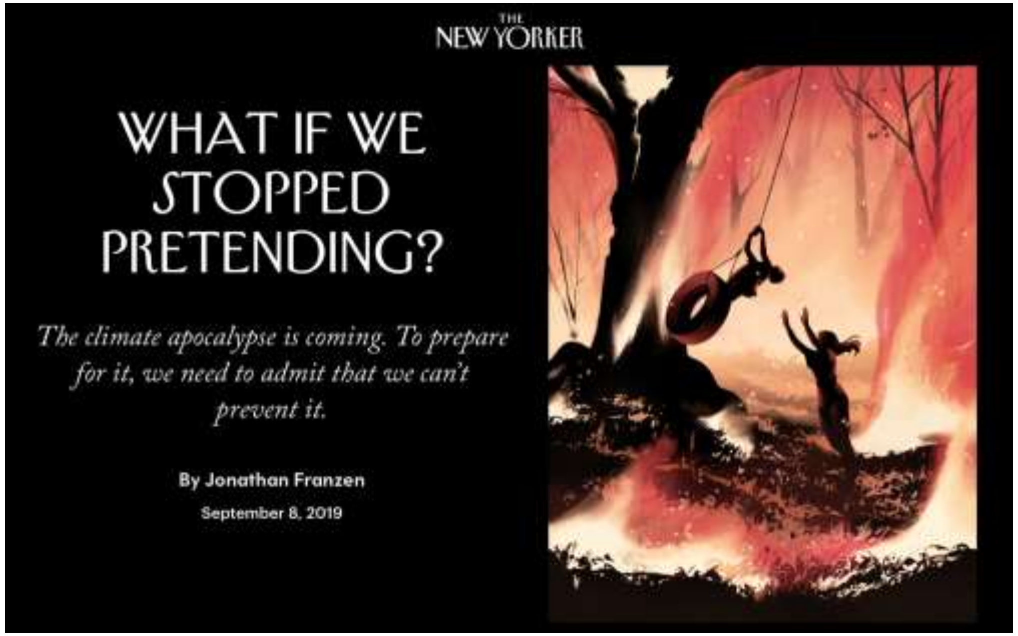
Authors, in 2020, included leading scientists, entrepreneurs, engineers, journalists, the sibling of the inventor of the World Wide Web and the world's 4th richest man.

A billionaire, a novelist and an economist all wrote a book about climate change…

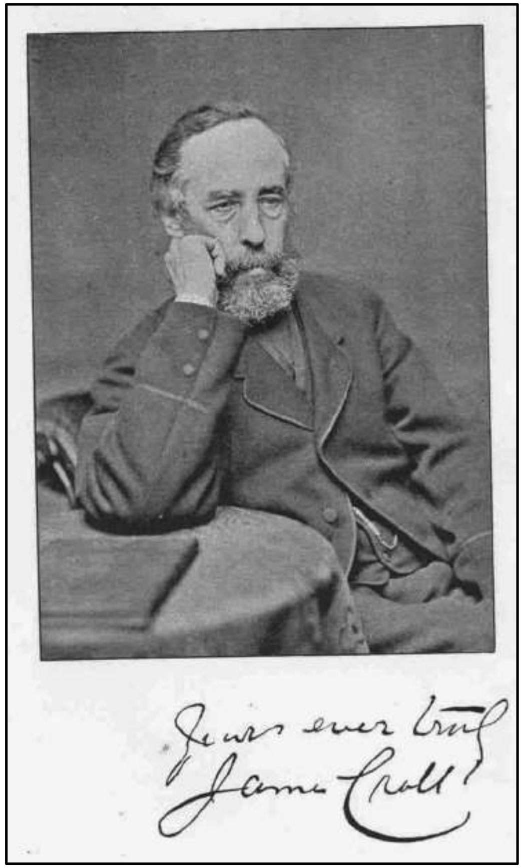
- <u>Billionaire Gates</u>: ***"We don't have … a serious climate plan … we need more innovation … I call on governments to quintuple clean energy and climate-related R&D over the next decade."***
- <u>Economist Helm</u>: ***"We all need to tackle the climate emergency. We need a carbon price, and one that applies to everything and everywhere: from flights, to food and farming. [Carbon pricing] is fundamentally about incentivising the right sort of behaviour and penalising what is wrong."***
- <u>Novelist Franzen</u>: ***"If you're younger than sixty, you have a good chance of witnessing massive crop failures, apocalyptic fires, imploding economies, epic flooding, hundreds of millions of refugees fleeing regions made uninhabitable by extreme heat or permanent drought. We need to accept that [climate change] is coming and to prepare for it."***





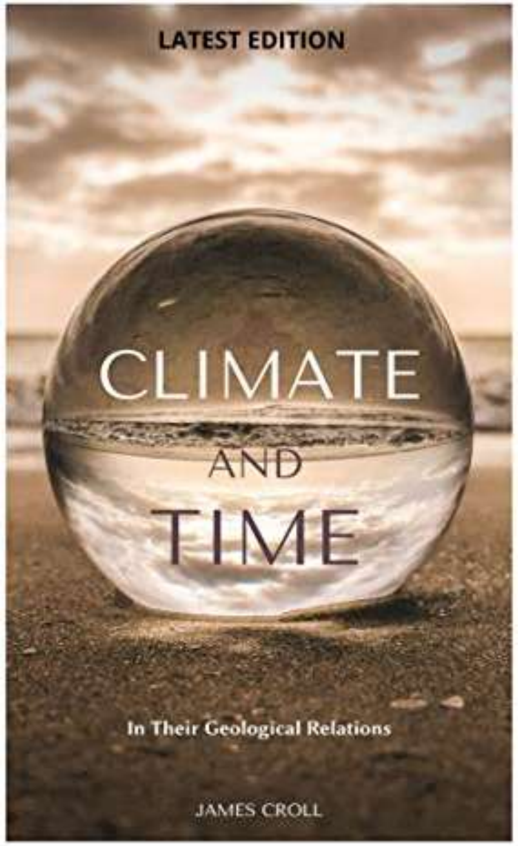


5. James Croll's most enduring legacy



Croll 1875,
Climate and Time,
Ch IV

Croll single-handedly launched the crucial topic of feedbacks in the climate system. In 1875 he perceptively wrote that in connection with *"those causes which lead to … changes of climate— **there is one remarkable circumstance … which deserves special notice … It is quite a common thing in physics for the effect to react on the cause … But it is usually, if not universally, the case that the reaction of the effect tends to weaken the cause.** The weakening influences of this reaction tend to impose a limit on the efficiency of the cause. **But, strange to say, in regard to the physical causes concerned in the bringing about of the glacial condition of climate, cause and effect mutually reacted so as to strengthen each other**"*



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