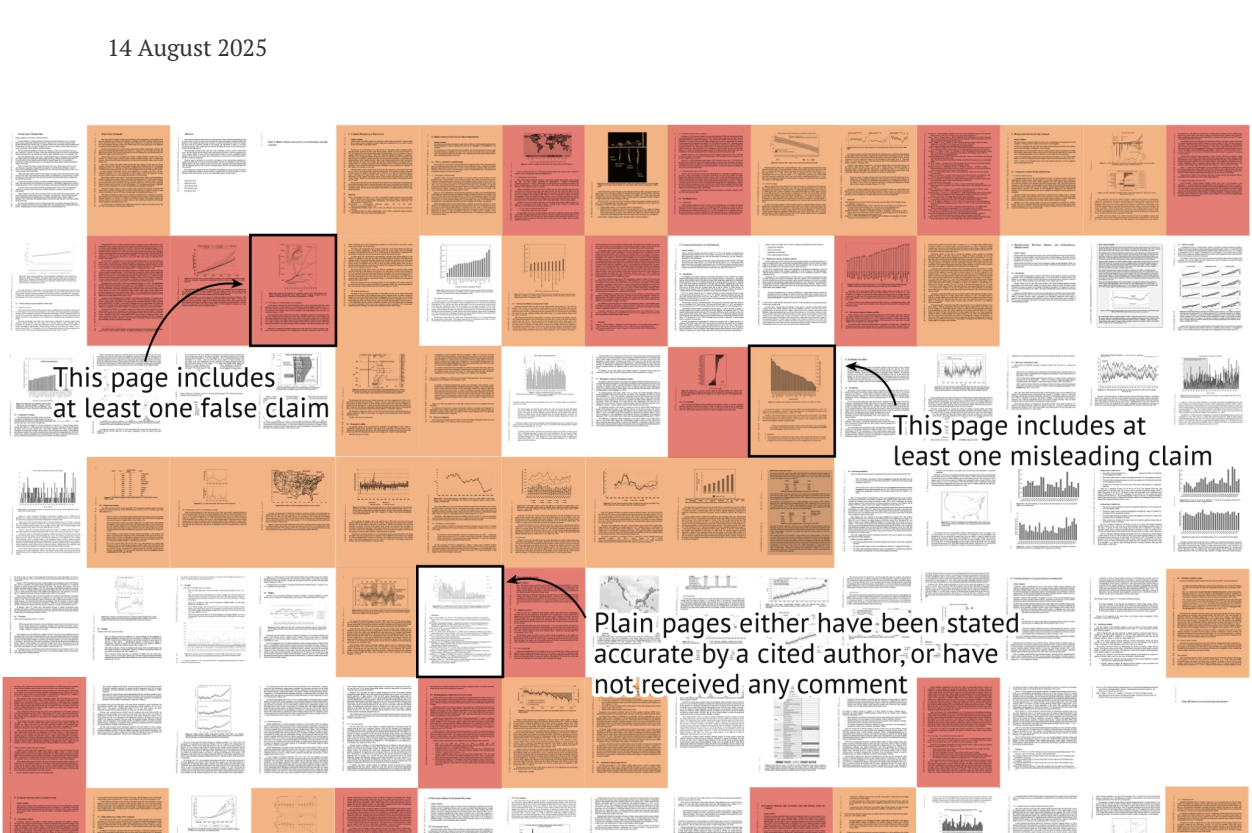
CarbonBrief
CLEAR ON CLIMATE

Factcheck: Trump’s climate report includes more than 100 false or misleading claims

By Ayesha Tandon, Leo Hickman, Cecilia Keating and Robert McSweeney
Design by Tom Prater

14 August 2025



Pages highlighted red contain false statements, whilst pages highlighted orange contain misleading statements. Pages can contain more than one false or misleading statement. Pages that remain uncoloured represent parts of the report that either have been stated as accurate by the cited author, or have not received any comment from invited experts. Front pages, reference and glossary pages omitted.

Executive summary

Page 0

MISLEADING

Elevated concentrations of CO_2 directly enhance plant growth, globally contributing to “greening” the planet and increasing agricultural productivity.

Dr David Lobell, associate professor, Stanford University.

I see two main problems with this (very old) argument. The direct benefits of CO_2 are widely acknowledged and nothing new. But we know that elevated CO_2 leads to climate changes and so the question is whether the CO_2 benefits are big enough to offset the climate losses. Their report does not address the net effects, which many studies have shown are negative, even for the US. The numbers they cite for direct effects of CO_2 are mainly from co2science.org, which is not a reputable source. Their summaries are not peer reviewed and include many studies of pots in greenhouses which are known to be biased. The numbers cited in the report are more than 2x what the best literature shows, such as in Ainsworth & Long (2021).

Quote from external source

Supporting evidence

1. Global Change Biology | Environmental Change Journal | Wiley Online Library

Page 0

FALSE

The world’s several dozen global climate models offer little guidance on how much the climate responds to elevated CO_2...The combination of overly sensitive models and implausible extreme scenarios for future emissions yields exaggerated projections of future warming.

Prof Veronika Eyring, professor of climate modelling, German Aerospace Center & University of Bremen.

In IPCC AR6, inconsistencies between models and observations and potential biases in model climate sensitivity values are taken into account in assessments of future climate change. IPCC AR6 clearly notes that some CMIP6 models simulate warming that is either above or below the assessed very likely range of observed warming. However, this information about how well models simulate past warming, as well as other insights from observations and theory, are used to assess projections of global warming (see cross-section Box TS.1 in Arias et al. (2021)).

Quote given to Carbon Brief

Supporting evidence

1. IPCC AR6 Working Group 1: Technical Summary | Climate Change 2021: The Physical Science Basis

Part I: Direct human influence on ecosystems and the climate

1 Carbon dioxide as a pollutant

Page 2

MISLEADING

The growing amount of CO_2 in the atmosphere directly influences the Earth system by promoting plant growth (global greening), thereby enhancing agricultural yields, and by neutralising ocean alkalinity.

Anonymous.

This ignores other effects of rising CO_2 concentrations, i.e.: on climate. It is also failing to mention that increased CO_2 can reduce the nutrient density of some crops.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 5: Food, Fibre and Other Ecosystem Products | Climate Change 2022: Impacts, Adaptation and Vulnerability

2.1 CO2 as a contributor to global greening

Page 3

FALSE

While plant models predict increased photosynthesis in response to rising CO_2, Haverd et al. (2020) reported a CO_2 fertilisation rate much larger than model predictions. That is, CO_2 fertilisation had driven an increase in observed global photosynthesis by 30% since 1900, versus 17% predicted by plant models. If true it would indicate that global models of the socioeconomic impacts of rising CO_2 have understated the benefits to crops and agriculture.

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

The paper by Haverd et al. focuses on natural ecosystems, not crops. So whilst the findings that CO_2 fertilisation effects on global greening makes a larger share relative to other factors, the results are not directly transferable to the socio-economic impacts of rising CO_2 on agriculture. Rising CO_2 contributes to higher radiative forcing which increases global mean temperature and accelerates the global water cycle, causing increases in the severity and frequency of extreme weather events (e.g. droughts, heat-stress and wildfires), particularly threatening crop yields and production.

Quote given to Carbon Brief

Supporting evidence

1. Global Change Biology | Environmental Change Journal | Wiley Online Library

2.1 CO2 as a contributor to global greening

Page 3

MISLEADING

The growing CO_2 concentration in the atmosphere has the important positive effect of promoting plant growth by enhancing photosynthesis and improving water use efficiency.

Anonymous.

Promoting plant growth is not always positive, because some species benefit more than others, which creates risks to biodiversity. For example, in tropical forests, elevated CO_2 promotes the growth of lianas, which are parasites that threaten trees. Also increased CO_2 fertilisation is playing a role in disrupting grassland and savannah ecosystems by promoting tree and shrub growth ("woody encroachment").

Quote given to Carbon Brief

Supporting evidence

1. Increasing dominance of large lianas in Amazonian forests | Nature
2. Chapter 2: Terrestrial and Freshwater Ecosystems and Their Services | Climate Change 2022: Impacts, Adaptation and Vulnerability

2.1 CO2 as a contributor to global greening

Page 3

FALSE

Section 2.1.1

Anonymous.

The following section cites papers that are, in fact, showing evidence for other drivers of change, e.g. page 14 line 34 says "Piao et al. (2020) noted that greening was even observable in the Arctic", but Piao et al (2020) actually show that warming is the dominant driver of greening in the Arctic, not CO_2 fertilisation (see figure 4 and associated text). Also the authors of the DoE report contradict their own statement two paragraphs later by saying: "Chen et al. (2019) show that in China and India much of it is driven by land management changes."

Quote given to Carbon Brief

Supporting evidence

1. Characteristics, drivers and feedbacks of global greening | Nature Reviews Earth & Environment

2 Direct impacts of CO2 on the environment

Page 3

MISLEADING

Piao et al. (2020) and Chen et al. (2024) report that the greening trend continues with no evidence of slowdown.

Anonymous.

The DoE authors fail to mention another study which shows the opposite, that greening was reversed around the year 2000 over 90% of the global vegetated area.

Quote given to Carbon Brief

Supporting evidence

1. Inhibitive Effects of Recent Exceeding Air Temperature Optima of Vegetation Productivity and Increasing Water Limitation on Photosynthesis Reversed Global Greening - Chen - 2022 - Earth's Future - Wiley Online Library

2.1 CO2 as a contributor to global greening

Page 3

MISLEADING

Section 2.1

Dr David Crisp, retired atmospheric physicist.

Chapters 2 and 9 assert that CO_2 fertilisation will increase plant growth and crop yields. The proposed benefits of CO_2 fertilisation are not realised in this set of DGVMs because this is only one of several mechanisms that control plant growth. As any farmer knows, plant growth is rarely limited by the abundance of the most abundant nutrient. It is usually limited by the abundance of the least abundant nutrient. While increased CO_2 can accelerate plant growth in carefully controlled laboratory conditions, this rarely happens in nature or in large-scale agriculture. There, plant growth is usually limited by water, nitrogen, phosphorus, sunlight or temperature. These models include all of those effects. The range of outputs produced by the models reflects uncertainties in the relative roles of these processes and their potential evolution with climate change. This behaviour should foster serious concern (doubt) about the potential benefits of CO_2 fertilisation in a changing climate. There is no discussion of this here or in chapters 2.1 or 9.

Quote given to Carbon Brief

Supporting evidence

2.1 CO2 as a contributor to global greening

Page 4

MISLEADING

Had atmospheric CO_2 levels continued declining, plant growth would have declined and eventually ceased. Below 180ppm, the growth rates of many C3 species are reduced 40-60% relative to 350ppm (Gerhart and Ward (2010)) and growth has stopped altogether under experimental conditions of 60-140ppm CO_2. Some C4 plants are still able to grow at levels even as low as 10ppm, albeit very slowly (Gerhart and Ward (2010)).

Prof Joy Ward, provost and executive vice president, Case Western Reserve University.

“Ward, however, told WIRED in an emailed statement that her experiments were conducted under ‘highly controlled growth conditions’ to create a ‘mechanistic understanding’ of CO_2, and that climate change can cause a host of impacts on plants not accounted for in her study. ‘With rising CO_2 in natural ecosystems, plants may experience higher heat loads, extreme weather events such as droughts and floods and reduced pollinators – which can have severe net negative effects on plant growth and crop yields,’ she says. ‘Furthermore, our studies indicate that major disruptions in plant development such as flowering time can occur in direct response to rising CO_2, which were not mentioned in the report.’”

Quote from external source

Supporting evidence

2.1 CO2 as a contributor to global greening

Page 4

FALSE

Piao et al. (2020) and Chen et al. (2024) report that the greening trend continues with no evidence of slowdown, and CO_2 fertilisation remains the dominant driver.

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

Chen et al (2024) does not back up this statement. In the abstract, the author concluded that greening, whilst still increasing, has slowed down: "Our study highlighted that drought trend did not necessarily trigger vegetation browning, but slowed down the rate of greening." Piao et al. (2019) looked at the driver of global greening. They did not look at whether trends in global greening are rising or decreasing. In addition they analysis focused on historical observation (1980-2010) and did not assess future trends.

Quote given to Carbon Brief

Supporting evidence

1. The global greening continues despite increased drought stress since 2000 - ScienceDirect
2. Characteristics, drivers and feedbacks of global greening | Nature Reviews Earth & Environment

2.1 CO2 as a contributor to global greening

Page 4

MISLEADING

Had atmospheric CO_2 levels continued declining, plant growth would have declined and eventually ceased. Below 180ppm, the growth rates of many C3 species are reduced 40-60% relative to 350ppm (Gerhart and Ward (2010)) and growth has stopped altogether under experimental conditions of 60-140ppm CO_2. Some C4 plants are still able to grow at levels even as low as 10ppm, albeit very slowly (Gerhart and Ward (2010)).

Anonymous.

The decline in atmospheric CO_2 levels over the last few tens of millions of years stopped naturally, and for the last 800,000 years up until the Industrial Revolution did not show much of a trend, just fluctuating between about 170 and 280 parts per million. The hypothetical scenario of a further decline below these levels is not relevant – it is not the case that human-driven CO_2 emissions have somehow saved us from declining CO_2 levels and declining plant growth, as seems to be the implication behind this paragraph.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks | Climate Change 2021: The Physical Science Basis

2.1 CO2 as a contributor to global greening

Page 5

MISLEADING

The overwhelming theme is that plants, especially C3 plants, benefit from extra CO_2.

Anonymous.

While individual plants benefit in isolation, the overall effect on an ecosystem and biodiversity can be detrimental due to some species benefitting more than others and out-competing them – for example, lianas responding more than trees, which they damage, encroachment of trees and shrubs into grasslands and savannahs, and the promotion of invasive species and weeds.

Quote given to Carbon Brief

Supporting evidence

1. Increasing dominance of large lianas in Amazonian forests | Nature
2. Chapter 2: Terrestrial and Freshwater Ecosystems and Their Services | Climate Change 2022: Impacts, Adaptation and Vulnerability
3. Chapter 5: Food, Fibre and Other Ecosystem Products | Climate Change 2022: Impacts, Adaptation and Vulnerability

2.1 CO2 as a contributor to global greening

Page 5

MISLEADING

There are two mechanisms by which CO_2 confers a growth benefit

Anonymous.

A "growth benefit" to the plant is not necessarily beneficial in other ways – for example, from IPCC AR6: "Perennial crops and root crops may have a greater capacity for enhanced biomass under elevated CO_2 concentrations, although this does not always result in higher yields. For some food crops, nutrient density declines due to elevated CO_2." And: "Elevated CO_2 reduces some important nutrients such as protein, iron, zinc and some grains, fruit or vegetables to varying degrees depending on crop species and cultivars."

Quote given to Carbon Brief

Supporting evidence

1. Chapter 5: Food, Fibre and Other Ecosystem Products | Climate Change 2022: Impacts, Adaptation and Vulnerability

2.1 CO2 as a contributor to global greening

Page 5

MISLEADING

The gains induced by increasing CO_2 from 150ppm to 350ppm continue under a further doubling to 700ppm.

Anonymous.

This very simplistic illustration from a small laboratory study ignores key effects such as nutrient availability, which in the real world can constrain the response to elevated CO_2.

Quote given to Carbon Brief

Supporting evidence

1. Global Change Biology | Environmental Change Journal | Wiley Online Library

2.2 The alkaline oceans

Page 6

MISLEADING

Section 2.2.1

Dr John Kennedy, climate scientist.

"The first subsection builds towards the conclusion in the summary that ‘ocean life is complex and much of it evolved when the oceans were acidic relative to the present’. Leaving aside the vacuity of this argument for the moment – life itself evolved when there was little oxygen in the atmosphere, the biochemical innovations that flooded the atmosphere with oxygen were catastrophic for life then, but see how we would do without it now – their citations are spare and strange particularly within the context of later arguments about the value of models and the contention that this is some sort of meaningful ‘critical review’. The first paper they cite regarding long-term change in ocean pH is Krissansen-Totton et al. (2018), which uses a model to constrain climate and ocean pH of the early Earth up to the present. They find that ocean pH evolves monotonically from 6.6 (see the abstract of the paper for the broad uncertainty ranges) at 4.0 Ga to 7.0 at the Archean-Proterozoic boundary, and to 7.9 at the Proterozoic-Phanerozoic boundary reaching a modern value of 8.2. While we might raise an eyebrow that the ‘critical review’ finds models are good enough for the herculean task of reproducing almost the whole of Earth’s climate history, but not for understanding the past 200 years, the eyebrow is likely to go shooting off your face when you reach the sentence in the ‘critical review’ that says: ‘Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 to 7.0.’ I derive little comfort from the fact that simple life forms evolved in such conditions. The gist of the ‘critical review’ isn’t that simple life forms will survive the current warming, but that human society supported by a flourishing biosphere will not just survive but thrive. Anyway, this is only part of an argument and the whole of the argument is never really spelled out. It seems to go something like this: pH of the ocean varied in the past and we exist today, therefore we will always exist and pH of the ocean is unimportant.

"The second, shorter, long-term perspective, which feeds into this argument, mixes up surface pH (as shown in Figure 2.3 from the CMEMS dataset) with deep ocean pH (from Rae et al. (2018)) who (according to their abstract) ‘present deep-sea coral boron isotope data that track the pH – and thus the CO_2 chemistry – of the deep Southern Ocean over the past forty thousand years’. ‘Deep’ and ‘track’ are the operative words here. The estimated changes are ‘deep’, from a depth of around 750 metres and not the surface. Regarding ‘track’, the numbers quoted in the ‘critical review’ – pH of 7.4 to 7.5 20,000 years ago – came presumably from Figure S1 in the Rae paper, which provides an approximate conversion of the boron isotopes to pH. How very very approximate they are is shown by an inset uncertainty range, which extends from well below 7.4 to well above 7.6 suggesting great care is needed in the interpretation of the absolute pH values."

Quote from external source

Supporting evidence

1. Constraining the climate and ocean pH of the early Earth with a geological carbon cycle model | PNAS

2.2 The alkaline oceans

Page 6

MISLEADING

Section 2.2.2

Dr John Kennedy, climate scientist.

“The first two paragraphs of the ‘critical review’ are on that famous American landmark the Great Barrier Reef. And why not? Well. One ‘why not’ can be found in the IPCC report (AR6 WG2). Chapter 11 has a box (‘Box 11.2 | The Great Barrier Reef in Crisis’). It doesn’t mention ocean acidification as a risk to the GBR at all (though OA is mentioned frequently elsewhere). The two big risks mentioned are bleaching in response to marine heatwaves and erosion caused by tropical cyclones. Neither of these factors is unconnected to climate change. Ocean acidification may not be a risk to the GBR, but climate change certainly is. The AIMS website which is referenced in the ‘critical review’ even notes ‘a high tolerance in massive Porites to ocean acidification’. The GBR is introduced here as a 2,300km long straw man.

"The rest of the section concerns itself with the more general impacts of ocean acidification. But only glancingly. They cite Browman (2016) on the lack of null results in the literature and offer, as an example, Clements et al. (2021) which is about the direct effects of OA on the behaviour of fish specifically (not the reefs themselves) though it does have a juicy metascientific quote that serves their purpose of suggesting that discussion of the topic is one-sided. If anything, Clements et al. shows that the literature is no longer one-sided so it rather weakens the point they are trying to make...The Browman article is also somewhat meta and points out that papers on ocean acidification were appearing at an average rate of 300 per year between 2006 and 2015, with around 600 articles per year in each of 2013, 2014 and 2015. How many are there now? I don’t know. The Browman and Clements articles are both old-as in the context of a fast-moving field. A simple Google Scholar search will show you that not only are there huge numbers of papers mentioning the topic in the past five years, but there are even lots of review papers and meta analyses on the topic which cover a much broader range of impacts. Summarising that literature with just 12 references (including links to the data used) is not adequate by any definition.”

Quote from external source

Supporting evidence

1. Chapter 11: Australasia | Climate Change 2022: Impacts, Adaptation and Vulnerability
2. Continued coral recovery leads to 36-year highs across two-thirds of the Great Barrier Reef | Australian Institute of Marine Science
3. Applying organized scepticism to ocean acidification research | ICES Journal of Marine Science | Oxford Academic
4. Meta-analysis reveals an extreme "decline effect" in the impacts of ocean acidification on fish behavior | PLOS Biology

---

2.1 CO2 as a contributor to global greening

Page 6

MISLEADING

Derying et al. (2016) surveyed evidence on crop water productivity (CWP), the yield per unit of water used, drawing attention to the potential for CO2 both to enhance photosynthesis and to reduce leaf-level transpiration (water loss during leaf respiration). They surveyed all available FACE data (Free Air CO2 Enrichment – see Chapter 9) on crop yield changes for maize (corn), wheat, rice, and soybean and combined it with crop model data simulating yield responses as of 2080 under the extreme RCP8.5 emissions scenario in four growing regions (tropics, arid, temperate and cold) each of which were split into rainfed and irrigated sub-regions. They reported that models without CO2 fertilisation predicted CWP losses in every region, but those were more than offset by CO2 fertilisation so that all regions showed a net CWP gain. Deryng et al. (2016) also reported that negative impacts of warming on wheat and soybean yields were fully offset by CWP gains and mitigated by up to 90% for rice and 60% for maize.

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

While those are general conclusions of the paper, they are misleading by not mentioning the considerable discrepancy among modelled results. In fact, this paper was the first of its kind to present findings from the first global modelling intercomparison initiative of global gridded crop models, focusing specifically on how state-of-the-art models represented CO2 effects on crop yield and evapotranspiration, highlighting these effects as a dominant source of uncertainty in the results, outpassing the uncertainty resulting from the use of different climate change projections. The supplementary information of the paper includes the detailed uncertainty analysis. A key message of the paper was also to highlight the needs for further research on the effects of CO2 on crops and their representation in crop models. Toreti et al. (2020) provides a comprehensive review of the uncertainties associated with the effects of elevated CO2 on crops,

Quote given to Carbon Brief

Supporting evidence

1. PDF
2. Narrowing uncertainties in the effects of elevated CO2 on crops | Nature Food

---

2.1 CO2 as a contributor to global greening

Page 6

FALSE

Deryng et al. (2016) assumed that climate change would "exacerbate water scarcity". Yet while models do predict that drylands will expand under climate warming, current data show the opposite: greening is happening even in arid areas.

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

Greening and water scarcity are processes related to different carbon and water cycles, respectively. They cannot be directly compared. Deryng et al. (2016) didn't assume but reported findings from peer-reviewed scientific studies on water scarcity trends. Deryng et al (2016) specifically stated: "Research indicates unabated climate change will exacerbate water scarcity around the world. This is thought to threaten agricultural productivity and food security, especially in arid regions, where agriculture relies heavily on irrigation and consumes the majority of diverted freshwater."

Quote given to Carbon Brief

Supporting evidence

1. Global threats to human water security and river biodiversity | Nature
2. Multimodel assessment of water scarcity under climate change | PNAS

2.1 CO2 as a contributor to global greening

Page 6

FALSE

The IPCC has only minimally discussed global greening and CO2 fertilisation of agricultural crops. The topic is briefly acknowledged in a few places in the body of the IPCC 6th and earlier assessment reports but is omitted in all summary documents. Section 2.3.4.3.3 of the AR6 WG1 report, entitled "global greening and browning," points out that the IPCC special report on climate change and land had concluded with high confidence that greening had increased globally over the past two-to-three decades. It then discusses that there are variations in the greening trend among data sets, concluding that while they have high confidence greening has occurred, they have low confidence in the magnitude of the trend. There are also brief mentions of CO2 fertilisation effects and improvements in water use efficiency in a few other chapters in the AR6 WG1 and 2 reports.

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

Chapter 5 of IPCC WG2 AR6 has reported the state of knowledge of CO2 fertilisation effects on crops, including photosynthesis stimulation, evapotranspiration reductions, as well as elevated CO2 effects on the quality of crops. These are widely discussed throughout the chapter, including in figures 5.6, 5.7, and 5.11, as well as in sections 5.2.1 (Detection and Attribution of Observed Impacts), 5.4.1 (Observed Impacts of crop-based systems), 5.4.3 (Projected Impacts of crop-based systems), 5.4.4 (Adaptation Options of crop-based systems), 5.5.3 (Projected Impacts of Livestock-Based Systems), 5.6.2 (Projected Impacts of forestry systems), 5.10.3 (Projected Impacts of mixed systems), 5.12.2 (Mechanisms for Climate Change Impacts on Food Security), 5.12.4 (Projected Impacts on Food Security). The effects of elevated CO2 on food systems are also included in the summary tables 5.9 (Observed and predicted impacts of climate change on selected medicinal plant species) and 5.14 (Impacts from climate change drivers on the four dimensions of food security).

Quote given to Carbon Brief

Supporting evidence

1. Chapter 5: Food, Fibre and Other Ecosystem Products | Climate Change 2022: Impacts, Adaptation and Vulnerability

---

2.1 CO2 as a contributor to global greening

Page 6

FALSE

Overall, however, the policymaker summaries, technical summaries and synthesis reports of AR5 and AR6 do not discuss the topic.

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

The technical summary does include a statement of CO2 fertilisation effects on vegetation and crops. Specifically in the observed and projected impacts sections (TS.B.1.5 and TS.C.1.4) as well as in Figure TS.6 FOOD-WATER. The summary for policymakers includes a summary of the findings. In the case of agriculture the overall key risks are reported, which are based on the overall assessment of observed and projected impacts of climate change, including effects of CO2 fertilisation, as well as potential contribution of adaptation measures on global and regional food production and food security.

Quote given to Carbon Brief

Supporting evidence

1. Technical Summary | Climate Change 2022: Impacts, Adaptation and Vulnerability
2. Summary for Policymakers | Climate Change 2022: Impacts, Adaptation and Vulnerability

---

2.1 CO2 as a contributor to global greening

Page 6

MISLEADING

The IPCC has only minimally discussed global greening and CO2 fertilisation of agricultural crops.

Anonymous.

The IPCC has extensively discussed the promotion of plant growth by rising atmospheric CO2 concentrations and consequent effects on global vegetation and land carbon sinks, including in summary documents – just not using the specific term "global greening" since other terms are used. The AR6 WG1 carbon cycle chapter prominently discusses the uptake of carbon in land ecosystems, e.g. in the executive summary page ("The ocean and land sinks of CO2 have continued to grow over the past six decades in response to increasing anthropogenic CO2 emissions (high confidence)") and in Frequently Asked Question 5.1. The WG1 summary for policymakers includes a figure showing the land carbon sink (Figure SPM.7). In WG2, chapter 2 on terrestrial ecosystems also discusses this, e.g. in the executive summary: "Biome shifts and structural changes within ecosystems have been detected at an increasing number of locations, consistent with climate change and increasing atmospheric CO2 (high confidence)" and "A combination of changes in grazing, browsing, fire, climate and atmospheric CO2 is leading to observed woody encroachment into grasslands and savannah."

The WG2 technical summary includes a figure showing woody encroachment (Figure TS12) and the WG2 summary for policymakers states that "at the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere than they emit", but also notes: "However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources." (page 20 footnote 39). The WG2 food chapter extensively discusses effects of elevated CO2 on crops, including both past and projected future changes. The summary documents focus on overall outcomes from the combined effects of climate change, elevated CO2 and other changes in atmospheric composition. The IPCC also specifically notes that elevated CO2 can reduce nutritional quality in crops.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks | Climate Change 2021: The Physical Science Basis
2. IPCC AR6 Working Group 1: Summary for Policymakers | Climate Change 2021: The Physical Science Basis
3. Chapter 2: Terrestrial and Freshwater Ecosystems and Their Services | Climate Change 2022: Impacts, Adaptation and Vulnerability
4. Technical Summary | Climate Change 2022: Impacts, Adaptation and Vulnerability
5. Summary for Policymakers | Climate Change 2022: Impacts, Adaptation and Vulnerability
6. Chapter 5: Food, Fibre and Other Ecosystem Products | Climate Change 2022: Impacts, Adaptation and Vulnerability

---

2.1 CO2 as a contributor to global greening

Page 6

FALSE

The topic is briefly acknowledged in a few places in the body of the IPCC 6th and earlier assessment reports.

Anonymous.

The topic of CO2 fertilisation effects, including their limitations and interactions with other drivers of change, are extensively discussed in AR6 WG2 chapter 5 (Food, Fibre and Other Ecosystem Products). The term "CO2" appears 136 times in that chapter. In the WG1 report, Chapter 5 is "Global Carbon and Other Biogeochemical Cycles and Feedbacks" and, again, extensively includes discussion of CO2 effects as part of the carbon cycle.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 5: Food, Fibre and Other Ecosystem Products | Climate Change 2022: Impacts, Adaptation and Vulnerability

---

2.1 CO2 as a contributor to global greening

Page 6

FALSE

Overall, however, the policymaker summaries, technical summaries and synthesis reports of AR5 and AR6 do not discuss the topic.

Anonymous.

The WG1 summary for policymakers includes a figure showing the land carbon sink (Figure SPM.7) and the caption includes: "Land and ocean carbon sinks respond to past, current and future emissions...During the historical period (1850-2019) the observed land and ocean sink took up 1430 GtCO2 (59% of the emissions)." The WG2 technical summary includes a figure showing woody encroachment (Figure TS12) and the WG2 summary for policymakers states: "At the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere than they emit." It also notes: "However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources." In AR5, the WG1 SPM says: "Of these cumulative anthropogenic CO2 emissions...160 [70 to 250] GtC have accumulated in natural terrestrial ecosystems (i.e., the cumulative residual land sink)."

Quote given to Carbon Brief

Supporting evidence

1. IPCC AR6 Working Group 1: Summary for Policymakers | Climate Change 2021: The Physical Science Basis
2. Technical Summary | Climate Change 2022: Impacts, Adaptation and Vulnerability
3. Summary for Policymakers | Climate Change 2022: Impacts, Adaptation and Vulnerability
4. PDF

2.2 The alkaline oceans

Page 7

MISLEADING

Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 to 7.0 (Krissansen-Totton et al. (2018)).

Dr Josh Krissansen-Totton, assistant professor, Earth and space sciences , University of Washington.

"Krissansen-Totton told WIRED in an email that his work on ocean acidity billions of years ago has 'no relevance' to the impacts of human-driven ocean acidification today and that today calcium carbonate saturation is quickly diminishing in the ocean alongside rising acidity. Dissolved calcium carbonate is essential for many marine species, particularly those that rely on it to build their shells.'The much more gradual changes in ocean pH we observe on geologic timescales were typically not accompanied by the rapid changes in carbonate saturation that human CO2 emissions are causing, and so the former are not useful analogs for assessing the impact of ocean acidification on the modern marine biosphere,' he says."

Quote from external source

Supporting evidence

2.2 The alkaline oceans

Page 7

MISLEADING

Even if the water were to turn acidic, it is believed that life in the oceans evolved when the oceans were mildly acidic with pH 6.5 to 7.0 (Krissansen-Totton et al. (2018).

Dr James Rae, reader, geochemistry and climate, University of St Andrews.

Modern marine life and ecosystems (e.g. coral reefs and open ocean fisheries) are very different from the initial lifeforms that evolved in the earliest oceans (e.g. bacteria, single-celled organisms) and so have different adaptive ranges and vulnerabilities. In the same way that the environmental conditions which were suitable for dinosaurs have little relevance for optimal conditions for humans, there is little relevance in comparing early ocean bacterial habitats to the conditions to which modern marine life has adapted.

Quote given to Carbon Brief

Supporting evidence

2.2 The alkaline oceans

Page 7

MISLEADING

On the time scale of thousands of years, boron isotope proxy measurements show that ocean pH was around 7.4 or 7.5 during the last glaciation (up to about 20,000 years ago) increasing to present-day values as the world warmed during deglaciation (Rae et al. (2018)).

Dr James Rae, reader, geochemistry and climate, University of St Andrews.

The use of "ocean pH" in this statement is misleading, as it seems to imply whole ocean pH or (following from the text above) the pH of the surface ocean, whereas the boron isotope study referenced here (of which I was the first author) apply only to the deep Southern Ocean. These are completely different habitats occupied by completely different species. The habitats of most concern with respect to ocean acidification are in the surface (e.g. coral reefs, key fisheries), where pH was higher than today during the last ice age (e.g. Shao et al., 2019), not lower as suggested in figure 5 of Shao et al. (2019).

Quote given to Carbon Brief

Supporting evidence

1. Atmosphere-Ocean CO2 Exchange Across the Last Deglaciation From the Boron Isotope Proxy - Shao - 2019 - Paleoceanography and Paleoclimatology - Wiley Online Library
2. CO2 storage and release in the deep Southern Ocean on millennial to centennial timescales | Nature

---

2.2 The alkaline oceans

Page 7

MISLEADING

Thus, ocean biota appear to be resilient to natural long-term changes in ocean pH since marine organisms were exposed to wide ranges in pH.

Dr James Rae, reader, geochemistry and climate, University of St Andrews.

Natural long-term changes in ocean pH have a fundamentally different impact on ocean chemistry than rapid input of carbon from fossil fuels (see Honisch et al. (2011)). When ocean pH is lowered rapidly (e.g. on decadal to centennial timescales), the abundance of carbonate ions decreases rapidly. As these carbonate ions are the most critical ingredient for marine shell formation, shells become harder to grow. Technically, this is known as a drop in calcium carbonate saturation state and it makes calcium carbonate shell formation more energetically costly (e.g. Gagnon et al., (2021)). In contrast, when ocean pH is lowered slowly (e.g. on timescales of a thousand years or more), the dissolution of seafloor calcium carbonate, alongside weathering of rocks on land, has a buffering effect on ocean saturation state, allowing shell formation to continue unimpeded despite the lower pH. Today, anthropogenic CO2 emission is lowering ocean pH on decadal to centennial timescales, which are too rapid for these buffering processes to keep up with, resulting in lower calcium carbonate saturation states, and making shell formation more energetically costly and enhancing environmental stress on these organisms.

Quote given to Carbon Brief

Supporting evidence

1. The Geological Record of Ocean Acidification | Science
2. Controls on boron isotopes in a cold-water coral and the cost of resilience to ocean acidification - ScienceDirect

---

2.2 The alkaline oceans

Page 8

MISLEADING

Similarly, a meta-analysis (Clements et al. (2021)) of the negative effects of ocean acidification on reef fifish behavior found what they called a "decline effect": initially dramatic conclusions published in prominent journals showing apparently large impacts of acidification tended to be followed up by subsequent studies on larger sample sizes yielding much smaller and typically non-existent effects. They call for their colleagues to improve research practices to counter the "decline effect": [The] vast majority of studies with large effect sizes in this field tend to be characterised by low sample sizes, yet are published in high-impact journals and have a disproportionate influence on the field in terms of citations. We contend that ocean acidification has a negligible direct impact on fish behaviour, and we advocate for improved approaches to minimise the potential for a decline effect in future avenues of research (Clements et al. (2021)).

Dr Jeff Clements, marine ecologist, Fisheries and Oceans Canada (Gulf Region).

"Clements…says that the way the DoE report cites his research on ocean acidification and fish behavior is accurate 'from an explicit textual perspective'…Clements says in an email to WIRED that just because his review of the literature found fish behavior to be relatively unaffected by ocean acidification does not mean that a myriad of other ocean ecosystems, biological processes and species will fare similarly. Other work from his lab, meanwhile, has underscored the vulnerability of mussels to ocean warming and looked at how heat waves negatively alter clam behavior…'I want to make it clear that our results should not be interpreted to mean ocean acidification (or climate change more generally) is not a problem,' he tells WIRED. 'While effects on fish behavior may not be as severe as initially thought, other species and biological processes are certainly vulnerable to the impacts of acidification and the compendium of other climate change stressors that our oceans are experiencing.'"

Quote from external source

Supporting evidence

2.2 The alkaline oceans

Page 8

MISLEADING

Similarly, a meta-analysis (Clements et al. (2021)) of the negative effects of ocean acidification on reef fish behaviour found what they called a "decline effect": initially dramatic conclusions published in prominent journals showing apparently large impacts of acidification tended to be followed up by subsequent studies on larger sample sizes

yielding much smaller and typically non-existent effects.

Prof Fredrik Jutfelt, professor of fish ecophysiology, Norwegian University of Science and Technology.

The way the DoE report cites our own work is flawed, as they use a specific finding in a small subsection of the field to represent the state of the entire field. This is intellectually dishonest and unscientific, and suggests either gross incompetence or an underlying bias.

Quote given to Carbon Brief

Supporting evidence

1. Meta-analysis reveals an extreme "decline effect" in the impacts of ocean acidification on fish behavior | PLOS Biology

2.2 The alkaline oceans

Page 8

MISLEADING

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. The ancestors of modern coral first appeared about 245m years ago. CO2 levels for more than 200m years afterward were many times higher than they are today. Much of the public discussion of the effects of ocean "acidification" on marine biota has been one-sided and exaggerated.

Dr John Kennedy, climate scientist.

The factoid about coral appearing 245m years ago is unreferenced and not previously mentioned in the section. The contention regarding 'much of the public discussion' is likewise unreferenced and not mentioned elsewhere in the section. Public discussion and scientific discussion are two different things. Public discussion isn't discussed at all and, anyway, the 'critical review' is supposedly reviewing the science. I think it's safe to say it has failed there too.

Quote from external source

Supporting evidence

2.2 The alkaline oceans

Page 8

MISLEADING

In summary, ocean life is complex and much of it evolved when the oceans were acidic relative to the present. The ancestors of modern coral first appeared about 245m years ago. CO2 levels for more than 200m years afterward were many times higher than they are today. Much of the public discussion of the effects of ocean "acidification" on marine biota has been one-sided and exaggerated.

Dr James Rae, reader, geochemistry and climate, University of St Andrews.

As discussed above, long-term geological pH changes are not a good analogue for a rapid drop in pH of the type happening today, for the key reason that a rapid pH drop results in lowered calcium carbonate saturation state, which makes shell formation harder (e.g. Honisch et al., (2011)). To find better analogues for modern pH decline in the geological record, we need to look at times when ocean pH dropped more quickly. Data of this type are compiled in a recent study by Trudgill et al. (2025). These show that all of the major mass extinction events in the ocean for which we have pH reconstructions are associated with a rapid drop in ocean pH. The geological record thus suggests that rapid pH decline is a matter for serious concern for marine ecosystems and the communities and economies which they support.

Quote given to Carbon Brief

Supporting evidence

1. The Geological Record of Ocean Acidification | Science
2. Pulses of ocean acidification at the Triassic–Jurassic boundary | Nature Communications

---

References

Page 9

FALSE

Chen, X., Wang, Y., Liu, Y., and Piao, S. (2024). The global greening continues despite increased drought stress since 2000. Global Ecology and Conservation, 49, e02791.

Anonymous.

The author list is incorrect on this citation. It should be Xin Chen, Tiexi Chen, Bin He,

Shuci Liu, Shengjie Zhou and Tingting Shi. It falsely associates the paper with well-known authors and demonstrates lack of attention to detail.

Quote given to Carbon Brief

Supporting evidence

1. The global greening continues despite increased drought stress since 2000 - ScienceDirect

---

3 Human influences on the climate

Page 11

MISLEADING

The IPCC has downplayed the role of the sun in climate change, but there are plausible solar irradiance reconstructions that imply it contributed to recent warming.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

This is a vague and potentially misleading statement. The IPCC AR6 adopted the solar radiative forcing values recommended by CMIP6, while AR5 used those from CMIP5. In both cases, the TSI [total solar irradiance] reconstructions selected were the most advanced and extensively scrutinised available at the time (Matthes et al. (2017)). The notion that there exist "plausible" solar irradiance reconstructions implying a solar contribution to recent warming is misleading, since it leaves it vague as to how much it contributed. The most scientifically robust irradiance reconstructions indicate that this contribution has been relatively small in recent decades. The wording of this statement appears to implicitly reference the work of Connolly et al. (2021) and (2023), although only the former is cited in the DoE report. Connolly et al. (2021) argued that a significant portion, or even most, of recent global warming could be attributed to solar variability. However, their approach involved cherry-picking and balancing 16 TSI reconstructions: eight with low long-term variability and eight with high variability. To create this balance, they included outdated or superseded models while omitting many low-variability reconstructions.

The high-variability series used by Connolly et al. (2021):
- Hoyt and Schatten (1993) has been thoroughly discredited (see Chatzistergos (2024)). It includes arbitrary manual adjustments and even fabricated data, with some values seemingly copied from another solar index.

- Lean et al. (1995) is an early version of the NRL [Naval Research Laboratory] model that has since been superseded by multiple updated versions, most recently NRLTSI2/NNL (Coddington et al. (2016) and (2019)).
- Bard et al. (2000) used a simplified linear conversion from cosmogenic isotope production (e.g., 10Be) to TSI, without accounting for nonlinear effects such as geomagnetic modulation, atmospheric transport processes, or climate-driven deposition variations. These omissions have been addressed in more physically realistic models like SATIRE-M [Spectral And Total Irradiance REconstructions] (Wu et al. (2018)), which show significantly lower long-term variability. Furthermore, Delaygue and Bard (2011) revised the original Bard et al. (2000) reconstruction which was exhibiting low long-term variability, yet this update was ignored by Connolly et al. (2021).
- Shapiro et al. (2011), an older high-variability model, was effectively replaced by Egorova et al. (2018), which itself has been criticised by Yeo et al. (2020) for exaggerating long-term TSI changes. - Egorova et al. (2018) was included four times in the Connolly et al. (2021) analysis. Including Shapiro et al. (2011), a predecessor of Egorova's model, the same model family was effectively used five times, artificially inflating the weight of high-variability reconstructions.

Crucially, in all these high-variability models, the long-term TSI trends were not derived from observational constraints but were imposed as assumptions. Modern revisions of the NRL model (Lean (2018) and Coddington et al. (2019)) and the Hoyt and Schatten model (Chatzistergos (2024)) have significantly reduced these assumed trends to align with observational evidence. Therefore, treating these outdated, superseded, or methodologically flawed reconstructions as equally probable alternatives to modern, validated TSI models is scientifically unjustified. It creates a false equivalence that misrepresents the current state of solar irradiance research. Connolly et al. (2023), although not cited in the DoE report, extended the analysis to 27 TSI series. However, the same methodological issues persist. Many of the added reconstructions are either outdated or redundant versions of older models. Notably, the highest solar attribution results again stem from Hoyt and Schatten (1993) and Bard et al. (2000), both of which have been superseded and shown to be unreliable. Finally, the attribution method used by Connolly et al. (2021) was directly critiqued by Richardson and Benestad (2022), who identified substantial flaws in their regression methodology and treatment of uncertainty. Even with the analysis presented in Connolly et al. (2021) and (2023) when the outdated, superseded and implausible TSI series are removed, the result is that the solar contribution to global warming is significantly smaller than the anthropogenic one.

Quote given to Carbon Brief

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect
2. A Discussion of Implausible Total Solar-Irradiance Variations Since 1700 | Solar Physics
3. The Dimmest State of the Sun - Yeo - 2020 - Geophysical Research Letters - Wiley Online Library
4. GMD - Peer review - Solar forcing for CMIP6 (v3.2)
5. @damagedonegr.bsky.social on Bluesky

3.1 Components of radiative forcing and their history

Page 12

MISLEADING

The IPCC assesses the change in the radiative forcing by the sun to be negligible, based on their preference for data reconstructions that imply minimal solar change since pre-industrial times.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

The selection of TSI reconstructions for use in CMIP6 and IPCC AR6 was based on the scientific robustness and performance of the models, rather than the magnitude of TSI variability they imply (Matthes et al. (2017)). The two reconstructions adopted were SATIRE and NRLTSI (now referred to as NNLTSI). These models were chosen because they represent the most advanced TSI reconstructions currently available. SATIRE is a semi-empirical, physics-based model, while NNLTSI is a proxy-based regression model. Both have been extensively validated and demonstrate excellent agreement with direct satellite measurements of TSI, making them the most reliable choices for climate modeling to date.

Quote given to Carbon Brief

Supporting evidence

1. GMD - Peer review - Solar forcing for CMIP6 (v3.2)

3.1 Components of radiative forcing and their history

Page 12

MISLEADING

But Connolly et al. (2021) reviewed 16 different Total Solar Irradiance (TSI) reconstructions in the literature covering the years 1600-2000; the reconstructions vary from almost no change in TSI to a relatively large upward trend. Those authors note that the variation in TSI reconstructions combined with variations in surface temperature reconstructions allows for inferences consistent with either no or most 20th century warming being attributable to the sun.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

The approach by Connolly et al. (2021) involved cherry-picking and balancing 16 TSI reconstructions: eight with low long-term variability and eight with high variability. To create this balance, they included outdated or superseded models while omitting many low-variability reconstructions.

The high-variability series used by Connolly et al. (2021):
- Hoyt and Schatten (1993) has been thoroughly discredited (see Chatzistergos (2024)). It includes arbitrary manual adjustments and even fabricated data, with some values seemingly copied from another solar index.
- Lean et al. (1995) is an early version of the NRL [Naval Research Laboratory] model that has since been superseded by multiple updated versions, most recently NRLTSI2/NNL (Coddington et al. (2016) and (2019)).
- Bard et al. (2000) used a simplified linear conversion from cosmogenic isotope production (e.g., 10Be) to TSI, without accounting for nonlinear effects such as geomagnetic modulation, atmospheric transport processes, or climate-driven deposition variations. These omissions have been addressed in more physically realistic models like SATIRE-M [Spectral And Total Irradiance REconstructions] (Wu et al. (2018)), which show significantly lower long-term variability. Furthermore, Delaygue and Bard (2011) revised the original Bard et al. (2000) reconstruction which was exhibiting low long-term variability, yet this update was ignored by Connolly et al. (2021).
- Shapiro et al. (2011), an older high-variability model, was effectively replaced by Egorova et al. (2018), which itself has been criticised by Yeo et al. (2020) for exaggerating long-term TSI changes. - Egorova et al. (2018) was included four times in the Connolly et al. (2021) analysis. Including Shapiro et al. (2011), a predecessor of Egorova's model, the same model family was effectively used five times, artificially inflating the weight of high-variability reconstructions.

Crucially, in all these high-variability models, the long-term TSI trends were not derived from observational constraints but were imposed as assumptions. Modern revisions of the NRL model (Lean (2018) and Coddington et al. (2019)) and the Hoyt and Schatten model (Chatzistergos (2024)) have significantly reduced these assumed trends to align with observational evidence. Therefore, treating these outdated, superseded, or methodologically flawed reconstructions as equally probable alternatives to modern, validated TSI models is scientifically unjustified. It creates a false equivalence that misrepresents the current state of solar irradiance research.

Quote given to Carbon Brief

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect
2. A Discussion of Implausible Total Solar-Irradiance Variations Since 1700 | Solar Physics
3. The Dimmest State of the Sun - Yeo - 2020 - Geophysical Research Letters - Wiley Online Library
4. @damagedonegr.bsky.social on Bluesky
5. Solar Irradiance Variability: Comparisons of Models and Measurements - ADS

3.1 Components of radiative forcing and their history

Page 13

MISLEADING

A particularly thorny issue is the gap in TSI data between 1989 and 1991 due to a delay in the launch of a monitor following the Space Shuttle Challenger disaster on 28 January 1986.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

It is an overstatement to characterise the “ACRIM-gap” [A gap in TSI measurements between the ACRIM-1 and ACRIM-2 satellite monitoring experiments] as a "particularly thorny" issue. While it does contribute to uncertainty in the long-term trend of direct TSI measurements, a growing body of evidence challenges the notion of a TSI increase during the ACRIM-gap, evidence which the DoE report entirely overlooks. Notable examples include Amdur & Huybers (2023), Chatzistergos et al. (2025) and Krivova et al. (2009).

Quote given to Carbon Brief

Supporting evidence

1. A Bayesian Model for Inferring Total Solar Irradiance From Proxies and Direct Observations: Application to the ACRIM Gap - Amdur - 2023 - Journal of Geophysical Research: Atmospheres - Wiley Online Library
2. Revisiting the SATIRE-S irradiance reconstruction: Heritage of Mt Wilson magnetograms and Ca II K observations | Astronomy & Astrophysics (A&A)
3. ACRIM-gap and total solar irradiance revisited: Is there a secular trend between 1986 and 1996? - ADS

3.1 Components of radiative forcing and their history

Page 13

FALSE

Connolly et al. (2021) found that the IPCC's consensus statements on solar forcing were formulated prematurely through the suppression of dissenting scientific opinions.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

This is yet another statement in the DoE report that is vague. It is not clear what they refer to with consensus, is this about the long-term reconstructions, is it just about the ACRIM-gap that this paragraph discusses? In any case, it appears as a general statement which as such has to be labelled as false. The claim that dissenting scientific opinions are being suppressed is unfounded. Scientific consensus evolves through rigorous evaluation, not censorship. When significant methodological issues are identified, such as the arbitrary adjustments and fabricated data in the Hoyt and Schatten (1993) TSI reconstruction (Chatzistergos (2024)), it is scientifically appropriate to disregard such models as implausible. This is not suppression of dissenting voices, but the enforcement of standards for methodological soundness.

Another example is the Bard et al. (2000) TSI reconstruction, which has since been superseded by more advanced models. Bard et al. (2000) relied on a simplistic linear scaling of cosmogenic isotope production to estimate TSI variability, without accounting for the non-linear influence of geomagnetic field modulation on isotope production. This omission leads to inaccurate estimates of solar variability. Later reconstructions, such as those based on the SATIRE-M framework (e.g., Wu et al. (2018)), incorporate these critical non-linearities and have been shown to produce more consistent results with observational constraints. Albeit, uncertainties remain and more work is being invested in improving these reconstructions too. Furthermore, we have advanced physics-based irradiance reconstruction models, e.g. SATIRE-3D (Yeo et al. (2017) and (2020), which have been used to set robust constraints on the magnitude of plausible TSI variations. As a result, irradiance reconstructions that exceed this constraint are considered less plausible than those that remain within it. Disregarding outdated or methodologically flawed reconstructions is a hallmark of scientific integrity, not suppression. The continued use of discredited models undermines robust scientific discourse and misrepresents the state of knowledge. A reminder here that the study by Connolly et al. (2021) cherry-picked 16 TSI reconstructions, deliberately balancing the sample by including eight with small long-term trends and eight with pronounced trends. The high-variation models they used are Hoyt and Schatten (1993), Lean (1995), Bard et al. (2000), Shapiro et al. (2011) and Egorova et al. (2018; used 4 different versions). Besides the issues with Hoyt and Schatten (1993) and Bard et al. (2000) discussed above, Lean (1995) is an outdated precursor to the NRL (now NNL) model and is no longer considered plausible. Shapiro et al. (2011) and Egorova et al. (2018) are different versions of the same model both exceeding the Yeo et al. 2020 constraint.

Quote given to Carbon Brief

Supporting evidence

1. A Discussion of Implausible Total Solar-Irradiance Variations Since 1700 | Solar Physics
2. The Dimmest State of the Sun - Yeo - 2020 - Geophysical Research Letters - Wiley Online Library
3. Solar total and spectral irradiance reconstruction over the last 9000 years | Astronomy & Astrophysics (A&A)
4. Solar Irradiance Variability is Caused by the Magnetic Activity on the Solar Surface - ADS

3.1 Components of radiative forcing and their history

Page 13

MISLEADING

Section 3.1.1

Dr Mark Schoeberl, chief scientist, Science and Technology Corp.

The paper by Jenkins et al. (2023) did not include volcanic aerosol effects and thus estimated the wrong sign of the Hunga volcano radiative forcing. Subsequent papers (including my own) agree that Hunga would produce slight cooling. The inclusion of the Jenkins paper here suggests more uncertainty in the calculation than exists. All models and data analyses agree that Jenkins was incorrect (e.g. Stenchikov et al. (2025) and Zhuo et al. (2025)).

Quote given to Carbon Brief

Supporting evidence

1. Modeling the Radiative Forcing and Atmospheric Temperature Perturbations Caused by the 2022 Hunga Volcano Explosion - Stenchikov - 2025 - Journal of Geophysical Research: Atmospheres - Wiley Online Library
2. EGUsphere - Comparing Multi-Model Ensemble Simulations with Observations and Decadal Projections of Upper Atmospheric Variations Following the Hunga Eruption

---

3.2 Future emission scenarios and the carbon cycle

Page 15

FALSE

Comparisons of past scenario groups against observations show that IPCC emission projections have tended to overstate actual subsequent emissions. For the IPCC third and fourth Assessment Reports a set of emission projections from the special report on emission scenarios was used; these were referred to as the SRES scenarios. McKitrick et al. (2012) showed that, when converted to per capita values, the SRES scenario emissions distribution was skewed upwards compared with observed trends.

Dr Zeke Hausfather, research scientist, Berkeley Earth.

While some past IPCC emissions scenarios have overstated future total CO2 emissions (IS92B, A1F1, RCP8.5), others have understated them (IS92D, B2, RCP6). In general total CO2 emissions were on the high end of the range of both the 1992 IS92 scenarios and the 2000 SRES scenarios through 2015, before falling closer to the middle of the range in recent years. Notably both IS92 and SRES scenarios were all variations of baseline scenarios that did not explicitly include aggressive emissions mitigation.

Quote given to Carbon Brief

Supporting evidence

1. Emissions are no longer following the worst case scenario
2. ESSD - Global Carbon Budget 2024

3.2 Future emission scenarios and the carbon cycle

Page 15

FALSE

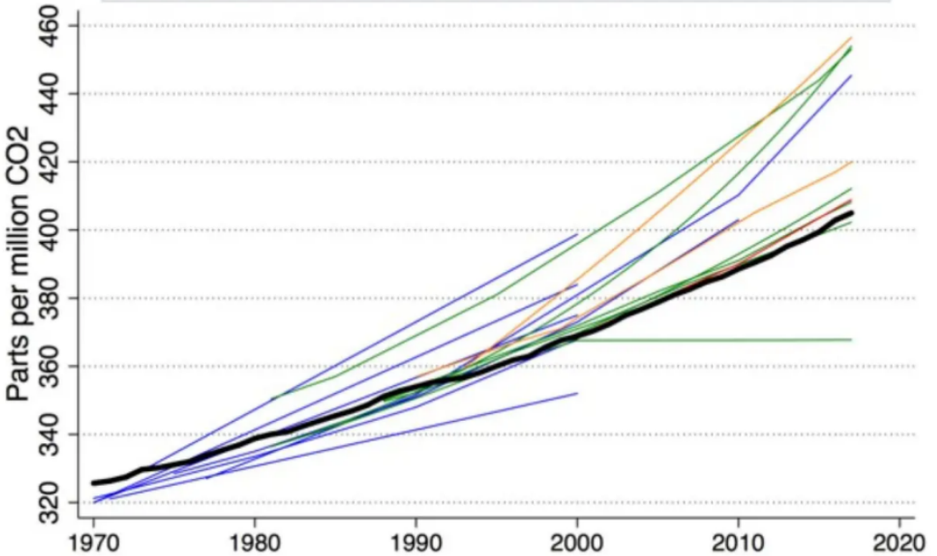


Figure 3.2.1 Since the 1970s successive families of emission and concentration projections (colored lines) have consistently overestimated observations (black line). Source: Hausfather *et al.* (2019) Figure S4.

Dr Zeke Hausfather, research scientist, Berkeley Earth.

Figure 3.2.1 focuses primarily on older climate models that predate the SRES scenarios. The only SRES scenarios included in the figure are A2 and A1B, and those actually track CO2 concentrations quite well. The disagreement is primarily with 1970s and 1980s era models; however, as Figure 1 in Hausfather et al. (2019) notes the trend in total forcing in these early models is actually a tad low due to their exclusion of non-CO2 GHGs.

Quote given to Carbon Brief

Supporting evidence

1. Evaluating the Performance of Past Climate Model Projections - Hausfather - 2020 - Geophysical Research Letters - Wiley Online Library

---

3.2 Future emission scenarios and the carbon cycle

Page 15

MISLEADING

The implausibility of the RCP8.5 scenario was examined by Burgess et al. (2021). The implausibility of RCP8.5 should not be interpreted as very unlikely (e.g. 95th 23 percentile) or a "worst case", but rather as genuinely implausible owing to the implausibility of the inputs required to reach a forcing of 8.5 W/m2. They noted that RCP8.5 has already diverged from observed trends in energy use and the near future trends diverge sharply from those of the International Energy Agency (IEA), which provides market-based projections of energy use for the coming decades. Pielke Jr. et al. (2022) further showed that the historic and projected IEA trends run near the bottom of the envelopes of both RCP projections and the more recent Shared Socioeconomic Pathway (SSP) scenario trends.

Dr Zeke Hausfather, research scientist, Berkeley Earth.

The authors do not clearly differentiate between the implausibility of a particular emissions scenario like that used to generate RCP8.5 and the forcing outcome of 8.5 watts per meter squared. The latter can come about not just through emissions, but also carbon cycle feedbacks (Hausfather and Betts (2020)). While it remains quite unlikely in my view that we end up at 8.5W/m2 by 2100 even with large carbon cycle feedbacks, it is not impossible under a RCP6.0 emissions pathway. Similarly, 8.5W/m2 radiative forcing becomes increasingly plausible post-2100 if emissions continue.

Quote given to Carbon Brief

Supporting evidence

1. Analysis: How 'carbon-cycle feedbacks' could make global warming worse - Carbon Brief
2. Narrowing the range of future climate projections using historical observations of atmospheric CO2 | Journal of Climate
3. Page Not Found

3.2 Future emission scenarios and the carbon cycle

Page 16

FALSE

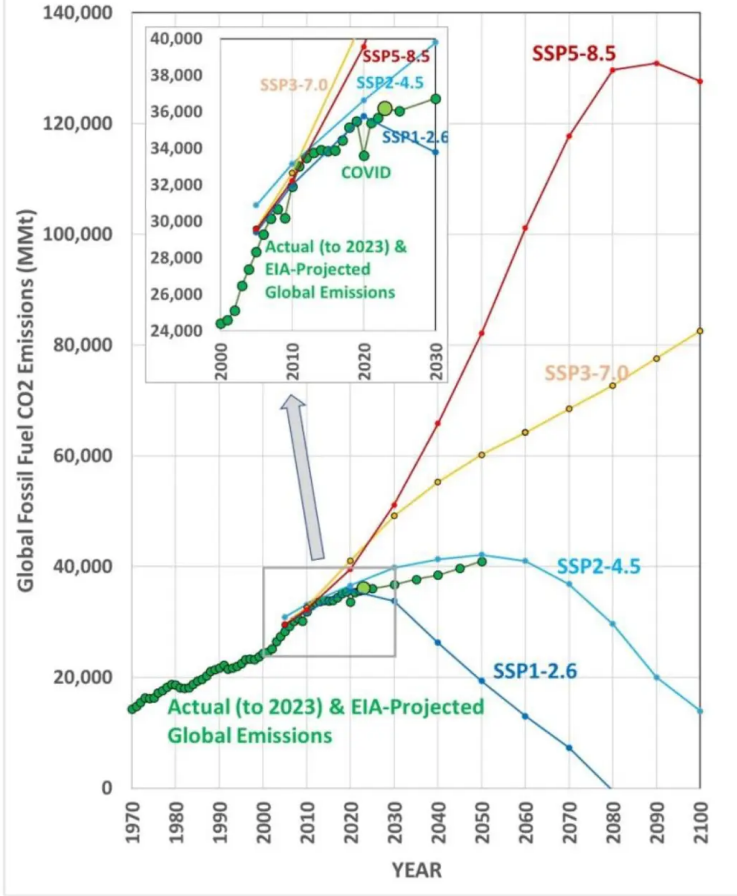


Figure 3.2.2. Observed and projected CO_2 emissions. Source: IPCC (SSP scenarios) and Energy Information Administration (EIA). Green: observed historical emissions and EIA projections. Other lines: SSP1-5. Data source: Friedlingstein *et al.* (2024).

Dr Zeke Hausfather, research scientist, Berkeley Earth.

The authors mistakenly conflate total global observed CO2 emissions in this text with CO2 emissions from fossil fuels alone (which are shown in Figure 3.2.2). If total CO2 emissions are used (including land-use emissions), then CO2 emissions fall right in the middle of the SSPs; in-line with SSP2-4.5 and SSP4-6.0, below SSP3-7.0 and SSP5-8.5, but above SSP1-1.9, SSP1-2.6 and SSP4-3.4.

Quote given to Carbon Brief

Supporting evidence

1. ESSD - Global Carbon Budget 2024
2. s19_2024_SSP_CO2.png (1852×1042)

3.2 Future emission scenarios and the carbon cycle

Page 17

MISLEADING

There are about 850Gt of carbon (GtC) in the Earth's atmosphere, almost all of it in the form of CO2. Each year, biological processes (plant growth and decay) and physical processes (ocean absorption and outgassing) exchange about 200GtC of that carbon with the Earth's surface (roughly 80GtC with the land and 120GtC with the oceans). Before human activities became significant, removals from the atmosphere were roughly in balance with additions. But burning fossil fuels (coal, oil, and gas) removes carbon from the ground and adds it to the annual exchange with the atmosphere.

Dr David Crisp, retired atmospheric physicist.

The total mass of carbon in the atmosphere is increasing over time as the carbon dioxide concentration increases. Crisp et al. (2022) quoted a mass of 877 Peta grams of Carbon (Pg C; one Pg C is equivalent to one billion tonnes of carbon (GtC) or 3.67 billion tonnes of CO2), which was a good estimate in 2020, when the atmospheric CO2 dry air mole fraction (a measurement of concentration) was around 412ppm. Here, their estimate of "about 850GtC", was relevant around a decade ago, when the average CO2 concentration was closer to 400ppm. The quoted gross annual exchange of carbon between land and the atmosphere and between the ocean and the atmosphere are erroneous and their relative values are reversed. Here, they state that land exchanges 80GtC with the atmosphere and the oceans exchange 120GtC with the atmosphere. They do not cite specific sources for these numbers. They do not come from Crisp et al. (2022). That paper cites gross ocean-atmosphere carbon flux of 90GtC per year and gross land-atmosphere carbon fluxes between 120 and 175GtC per year.

They end this paragraph by noting that the 10.3GtC emitted by fossil fuel use and cement manufacturing is only about 5% of annual emissions by the land biosphere and oceans. This is a half-truth that is clearly intended to be misleading. It fails to recognise that the atmosphere and climate respond to the net emissions and removals of carbon, not the gross fluxes. The land biosphere and ocean both add and remove carbon from the atmosphere, while fossil fuel use and other human activities only add carbon to the atmosphere. When averaged over the globe and over the year, the land biosphere and ocean remove as much carbon as they emit, along with over half of these anthropogenic emissions, yielding net emissions that are negative and only about half as large as the positive anthropogenic emissions. In this context, the net anthropogenic emissions are more than twice as large as the net natural CO2 fluxes.

Quote given to Carbon Brief

Supporting evidence

1. How Well Do We Understand the Land-Ocean-Atmosphere Carbon Cycle? - Crisp - 2022 - Reviews of Geophysics - Wiley Online Library

---

3.2 Future emission scenarios and the carbon cycle

Page 18

MISLEADING

The carbon cycle accommodates about 50% of humanity's small annual injection of carbon into the air by naturally sequestering it through plant growth and oceanic uptake, while the remainder accumulates in the atmosphere (Ciais et al. (2013)). For that reason, the annual increase in atmospheric CO2 concentration averages only about half of that naively expected from human emissions.

Dr David Crisp, retired atmospheric physicist.

Here, the report authors recognise that existing observations show that natural processes in the land biosphere and ocean consistently remove about 50% of the anthropogenic CO2 emissions. They also note that this ratio has been preserved as the fossil fuel emissions have increased. They attribute the increasing land uptake to the "global greening" phenomena described in chapter 2.1 of this work. However, that chapter fails to recognise that the increasing leaf area index (LAI) does not always indicate increased CO2 uptake. In particular, as noted in Crisp et al. (2022), many regions of the tropics, where the largest increases in LAI have been seen over the past 50 years, have started to transition from net CO2 sinks to net sources of CO2. These changes are due to the impacts of human activities (e.g. deforestation, forest degradation) and climate change (increasing temperature, drought, vapor pressure deficit).

The authors also fail to note that while tropical land is absorbing less CO2, these losses are being compensated mostly by increased carbon uptake by forests at mid and high latitudes. There, climate change is driving longer, warmer growing seasons and permafrost thaw is allowing trees to grow deeper, more massive root systems that sequester more carbon in the soil. The rapid growth, combined with higher temperatures and more frequent droughts at these latitudes, result in larger and more frequent wildfires, which release CO2. In summary, while the fraction of the anthropogenic CO2 that has been absorbed by the land biosphere has remained almost constant in response to increasing atmospheric CO2 abundances, different parts of the world are responding differently to climate change. The focus on “global greening” is a massive oversimplification of the system.

Quote given to Carbon Brief

Supporting evidence

1. How Well Do We Understand the Land-Ocean-Atmosphere Carbon Cycle? - Crisp - 2022 - Reviews of Geophysics - Wiley Online Library

---

3.2 Future emission scenarios and the carbon cycle

Page 18

MISLEADING

Section 3.2.2: subsections on "CO2 uptake by land processes" and "CO2 uptake by ocean processes"

Dr David Crisp, retired atmospheric physicist.

The last two subsections of this section focus on the carbon cycle models used by the Global Carbon Project. For both land and ocean, they note that this set of models predicts a range of estimates for the decadal uptake of CO2 by the land and ocean carbon sinks. They use these results to foster doubt in the utility of these methods for predicting future change in the carbon cycle as it responds to climate change. This is interesting because they fail to note that all of the Dynamic Global Vegetation Models (DGVMs) included in this set include CO2 fertilisation – a mechanism that the authors of this document advocate as a key benefit of increasing atmospheric CO2 amounts.

Quote given to Carbon Brief

Supporting evidence

3.3 Urbanisation influence on temperature trends

Page 20

MISLEADING

Peterson et al. had failed to find any difference in trends between rural and urban samples, although their definition of rural included local populations up to 10,000 persons while the relative influence of urbanisation begins well below that (Spencer et al. (2025)).

Dr Zeke Hausfather, research scientist, Berkeley Earth.

While Peterson et al. (1999) used a single proxy for urbanity, the follow-up Hausfather et al. (2013) study used four different proxies for urbanity in the conterminous US. It found little residual urban heat island (UHI) bias in the homogenised NOAA data, even when only rural stations are used for breakpoint detection and correction in the homogenisation process to avoid any risk of aliasing in a UHI signal.

Quote given to Carbon Brief

Supporting evidence

1. Quantifying the effect of urbanization on U.S. Historical Climatology Network temperature records - Hausfather - 2013 - Journal of Geophysical Research: Atmospheres - Wiley Online Library

---

3.3 Urbanisation influence on temperature trends

Page 21

MISLEADING

The influence of UHI warming is logarithmic in population, in other words it is strongest at low population density then levels off as local urbanisation expands (Oke (1973) and Spencer et al. (2025)). Hence failure to find a difference in warming rates between urban and rural stations does not prove the absence of UHI contamination.

Dr Zeke Hausfather, research scientist, Berkeley Earth.

This is both overly simplified – the actual environment immediately around the station matters a lot more than regional population density – and not particularly reflective of the literature. Some studies using pretty strict cutoffs for urbanity (e.g. Hausfather et al. (2013)) still find minimal differences in urban and rural stations.

Quote given to Carbon Brief

Supporting evidence

1. Quantifying the effect of urbanization on U.S. Historical Climatology Network temperature records - Hausfather - 2013 - Journal of Geophysical Research: Atmospheres - Wiley Online Library

---

3.3 Urbanisation influence on temperature trends

Page 21

FALSE

In summary, while there is clearly warming in the land record, there is also evidence that it is biased upward by patterns of urbanisation and that these biases have not been completely removed by the data processing algorithms used to produce climate data sets.

Dr Zeke Hausfather, research scientist, Berkeley Earth.

The authors of the DoE report make a strong claim based on papers by some of their team (McKitrick and Spencer) while ignoring other studies that point otherwise. There is by no means agreement that there is a meaningful unremoved UHI bias in land temperatures in the surface record. Indeed, Spencer et al. (2025) only examines raw temperature records and gets a result comparable to that found by Hausfather et al. (2013), but does not do the follow up analysis of homogenised temperature records to see if the UHI bias has been effectively detected and removed (as Hausfather et al. (2013) find that it was). The analysis in this section also ignores independent assessments by AIRS satellites (global; Susskind et al. (2019)) and the US Climate Reference Network (US; Hausfather et al. (2016)) that show the same rate of warming as the full land station network during the period of overlap, suggesting minimal UHI biases in recent decades. Finally, this section on UHI never bothers to point out that the world is mostly oceans, so even a significant (>10%) bias in land temperatures, if it existed, would have a much smaller effect on resulting global surface temperatures.

Quote given to Carbon Brief

Supporting evidence

1. Quantifying the effect of urbanization on U.S. Historical Climatology Network temperature records - Hausfather - 2013 - Journal of Geophysical Research: Atmospheres - Wiley Online Library
2. Recent global warming as confirmed by AIRS - IOPscience
3. Evaluating the impact of U.S. Historical Climatology Network homogenization using the U.S. Climate Reference Network - Hausfather - 2016 - Geophysical Research Letters - Wiley Online Library

---

Part I: Direct impacts of CO2 on the environment

3.1 Componnents of radiative forcing and their history

Page 13

MISLEADING

Box 4.1 in the IPCC AR6 Report addresses the climate impact of volcanic eruptions, noting three explosive volcanic eruptions that occurred in the first half of the 19th century. This included the 1815 Tambora eruption that resulted in the 'year without summer', with multiple harvest failures across the Northern Hemisphere. There is uncertainty about the sign of the relatively small forcing due to the submarine volcano Hunga Tonga which erupted in 2022 (Jenkins et al. (2023) and Schoeberl et al. (2024)).

Prof June-Yi Lee, professor of climate science, Pusan National University.

This paragraph is misleading and does not accurately reflect assessment on the volcanic forcings in AR6. First, the reference to "BOX 4.1" should be corrected to "Cross-Chapter Box 4.1". Second, it should be made clear that this Cross-Chapter Box in AR6 WGI Chapter 4 synthesizes assessments of volcanic aerosol forcings and their impacts on Earth system components across AR6 WGI Chapters 2, 3, 4, 7, 8, 9, and 11. The contested text implies that the AR6 assessment is not comprehensive and overlooks uncertainties related to relatively small forcings. However, AR6—particularly Section 2.2.2—provides a detailed assessment of volcanic aerosol forcing. Specifically, AR6 Chapter 2.2.2 notes: "A series of small-to-moderate eruptions since 2000 resulted in perturbations in stratospheric aerosol optical depth (SAOD) of 0.004–0.006 (Andersson et al., 2015; Schmidt et al., 2018). To conclude, strong individual volcanic eruptions cause multi-annual variations in radiative forcing. However, the average magnitude and variability of SAOD and its associated volcanic aerosol forcing since 1900 are not unusual in the context of at least the past 2.5 kyr (medium confidence).

Quote given to Carbon Brief

Supporting evidence

1. Chapter 4 | Climate Change 2021: The Physical Science Basis

---

3.2 Future emission scenarios and the carbon cycle

Page 15

MISLEADING

Although the IPCC does not claim its emission scenarios are forecasts, they are often treated as such.

Prof June-Yi Lee, professor of climate science, Pusan National University.

The text seems to indicate that the IPCC is unclear about the meaning of emission scenarios, which is not the case. Each Working Group report in AR6 explicitly states how emission scenarios are to be interpreted and used. For example, here is the statement of the emissions scenarios in Box SPM .1 of AR6 synthesis report: "Modelled scenarios and pathways are used to explore future emissions, climate change, related impacts and risks, and possible mitigation and adaptation strategies and are based on a range of assumptions, including socio-economic variables and mitigation options. These are quantitative projections and are neither predictions nor forecasts. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures."

Quote given to Carbon Brief

Supporting evidence

1. PDF

3.2 Future emission scenarios and the carbon cycle

Page 16

FALSE

The IPCC developed a new set of scenarios for AR6, the "Shared Socioeconomic Pathway" (SSP) scenarios, which have continued the bias shown in the RCP and SRES scenarios.

Prof June-Yi Lee, professor of climate science, Pusan National University.

This text is false because the SSP scenarios were developed not by the IPCC, but by international science communities. It is important to recognised that the AR6 WG3 assessed a large number of global modelled emissions pathways (about 1,202), which were categorised based on their assessed global warming over the 21st century; categories range from pathways that limit warming to 1.5C with more than 50% likelihood (noted >50% in this report) with no or limited overshoot (C1) to pathways that exceed 4C (C8). IPCC AR6 WG1 assessed the climate response to selected five illustrative scenarios based on Shared Socio-economic Pathways (SSPs) that cover the range of possible future development of anthropogenic drivers of climate change found in the literature. It is also very important to note that AR6 WG3 Chapter 3.3 comprehensively assessed feasibility of emissions scenarios including SSP5-8.5 and SSP1-1.9.

Quote given to Carbon Brief

Supporting evidence

1. PDF
2. Chapter 3: Mitigation pathways compatible with long-term goals

---

Part II: Climate response to CO2 emissions

4.2 Model-based estimates of climate sensitivity

Page 27

FALSE

AR6 (2021) did not rely on climate model simulations in their assessment of climate sensitivity, relying instead on data-driven methods.

Anonymous.

AR6 used multiple lines of evidence in the assessment of climate sensitivity: Understanding of climate processes, the instrumental record, palaeoclimates and model-based emergent constraints. Indeed, the authors of the DoE report contradict their own claim four paragraphs later by saying: "For AR6, the IPCC placed primary weight on the results of Sherwood et al. (2020) that combined historical data and palaeoclimate proxies with the process-based approach." Sherwood et al (2020) used climate models as one of their lines of evidence.

Quote given to Carbon Brief

Supporting evidence

1. IPCC AR6 Working Group 1: Summary for Policymakers | Climate Change 2021: The Physical Science Basis

---

4.3 Data-driven estimates of climate sensitivity

Page 28

MISLEADING

Most climate models simulate that rising GHGs will weaken the west-east temperature gradient, which led the IPCC in AR6 to conclude that data-driven ECS estimates understated the future ECS value. However, Seager et al. (2019) pointed out that, contrary to models, the west-east temperature gradient has been strengthening over time. They further argued that the mechanism predicting otherwise in climate models was based on a faulty characterisation of oceanic dynamics and there is no reason to expect the gradient to weaken. A similar argument was recently made by Lee et al. (2024), who concluded that "the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere"; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate might be lower than current estimates.

Dr Richard Seager, Ewing Lamont research professor, Columbia University.

The report is right to point out that we have drawn attention to the fact that the observed gradient has been strengthening while models robustly predict a weakening in response to rising GHGs. The report is also right that we suggested models get the response wrong due to biases in how they simulate the tropical Pacific Ocean…But inferences on the relation between SST, radiation and climate sensitivity for the short time period (strongly influenced by natural internal variability) are not readily transferable to understand these relations for the forced response in the gradient. I don't think we know what the implications for climate sensitivity are of the problem models have in reproducing the observed pattern of tropical Pacific SST change.

Quote given to Carbon Brief

Supporting evidence

4.3 Data-driven estimates of climate sensitivity

Page 28

MISLEADING

An argument emphasised in AR6 is that data-driven ECS estimates might understate the future warmingresponse to GHGs because of a so-called "pattern effect" (Forster et al. (2021)). The tropical Pacific is believed to strongly influence the overall efficiency with which the Earth radiates heat to space, but someregions remove heat more efficiently than others. If the west-to-east temperature gradient in the tropical Pacific is weakened in a warming climate, warming would concentrate where heat is less efficiently removed, raising ECS.

Prof Piers Forster, professor of climate physics, University of Leeds.

The citation is ok, but rather offhand and dismissive, given the large amount of evidence assessed on the pattern effect in the IPCC report – it's my chapter 7 which is cited. I also find that the literature on the pattern effect which the section…goes on to discuss is skewed and biased towards suggesting a small GHG cooling. It is especially missing a lot of other literature with conflicting evidence. Lots of literature that we cite in the IPCC report and evidence published since – including my own work – suggests a real pattern effect and high climate sensitivity. If you are going to present conflicting arguments to my IPCC chapter produced by many international authors and three rounds of peer review, including multiple government reviews, I think you would need to explain where these other studies we referenced in IPCC go wrong. I therefore find their argument weak.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity | Climate Change 2021: The Physical Science Basis

---

4.3 Data-driven estimates of climate sensitivity

Page 28

MISLEADING

A similar argument was recently made by Lee et al. (2024), who concluded that "the trajectory of the observed trend reflects the response to increasing GHG loading in the atmosphere"; in other words, GHG warming should lead to a future strengthening rather than a weakening of the temperature gradient. Increased efficiency of atmospheric cooling implies, if anything, that the future ECS in a warming climate might be lower than current estimates.

Prof Sukyoung Lee, distinguished professor of meteorology.

The report cited my article out of context. Current climate models predict tropical Pacific sea surface temperature (SST) gradients that do not align with observational trends, whereas the simple model used in my study does. This does not mean that the climate models have no value for predicting the effects of human activities on future climates. My study simply identified one specific aspect where models may need to be improved to make the predictions more accurate.

Quote given to Carbon Brief

Supporting evidence

1. Quantifying the processes of accelerated wintertime Tibetan Plateau warming: outside forcing versus local feedbacks | Climate Dynamics

---

5 Chapter summary

Page 31

FALSE

Climate models show warming biases in many aspects of their reproduction of the past several decades. In response to estimated changes in forcing they produce too much warming at the surface (except in the models with lowest ECS).

Prof Veronika Eyring, professor of climate modelling, German Aerospace Center & University of Bremen.

The CMIP6 historical simulations assessed in IPCC AR6 have an ensemble mean global surface temperature change within 0.2C of the observations over most of the historical period and observed warming is within the 5–95% range of the CMIP6 ensemble. Model biases are assessed to be small enough to support detection and attribution of human-induced warming (very high confidence).

Quote given to Carbon Brief

Supporting evidence

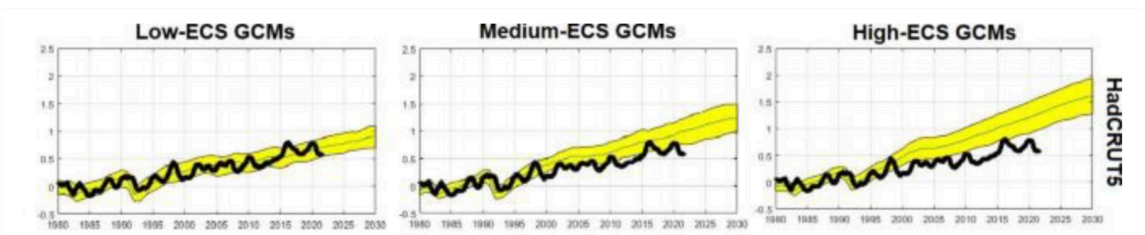
1. Chapter 3: Human Influence on the Climate System | Climate Change 2021: The Physical Science Basis

---

5.2 Surface warming

Page 33

MISLEADING



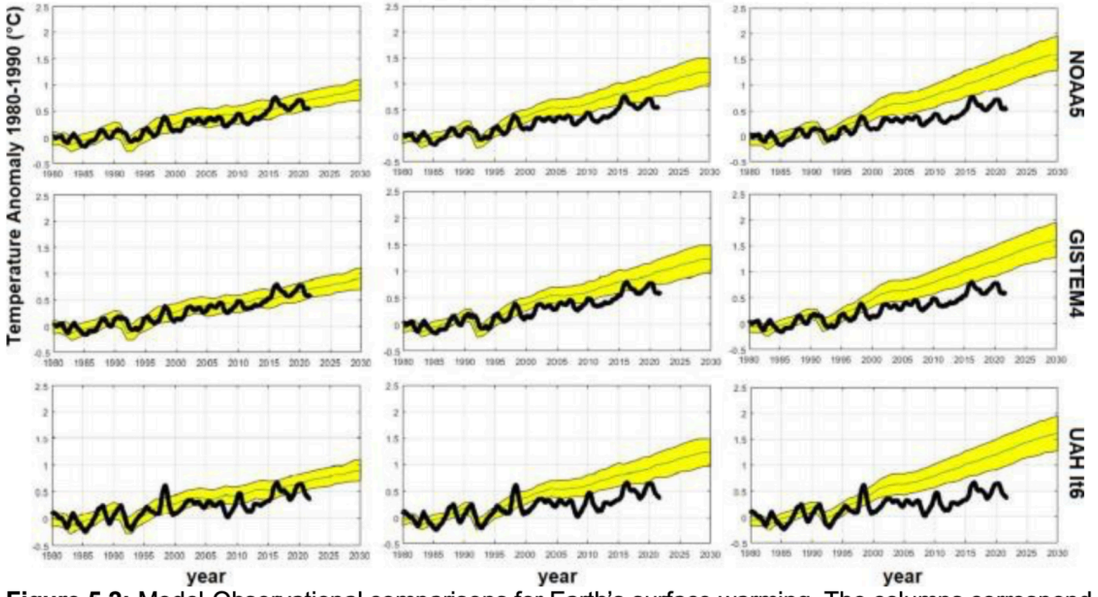


Figure 5.2: Model-Observational comparisons for Earth's surface warming. The columns correspond to model groups showing low-ECS (13 models) medium-ECS (11 models) and high-ECS (14 models), while the rows correspond to widely-used observed temperature records, the first three showing surface averages and the fourth showing the lower troposphere average. In each panel the yellow area denotes the mean and range (± one standard deviation) of climate model simulations for that group. The thick black line shows the observed annual average temperature in the indicated record. Source: Scafetta (2023) Fig.2.

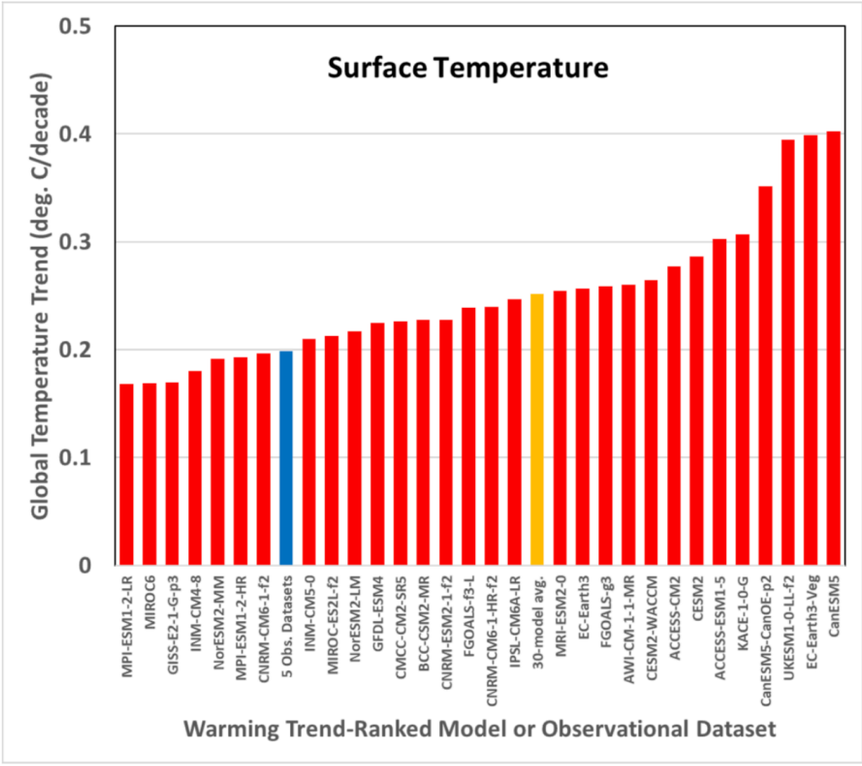


Figure 5.3 Global surface air temperature trends (°C/decade), 1979-2024, from various CMIP6 climate models (red, 30-model average in orange); and the average of three thermometer datasets (HadCRUT5, NOAA Global Temp, and Berkeley 1 deg.) and two reanalysis datasets (ERA5 and NCEP/NCAR R1) in blue. Data source: https://climexp.knmi.nl/start.cgi.

Prof Veronika Eyring, professor of climate modelling, German Aerospace Center & University of Bremen.

Figures 5.2 and 5.3 and related conclusions in the report need to be revised to (a) use a longer reference period for the anomalies to ensure the influence of internal variability is minimised in model-observational comparisons (e.g. reference period 1850–1900 as in IPCC AR6); (b) show the full historical record so that model performance can be evaluated beyond the satellite era; and (c) account for observational uncertainty.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 3: Human Influence on the Climate System | Climate Change 2021: The Physical Science Basis

---

5.4 Vertical temperature profile mismatch

Page 37

MISLEADING

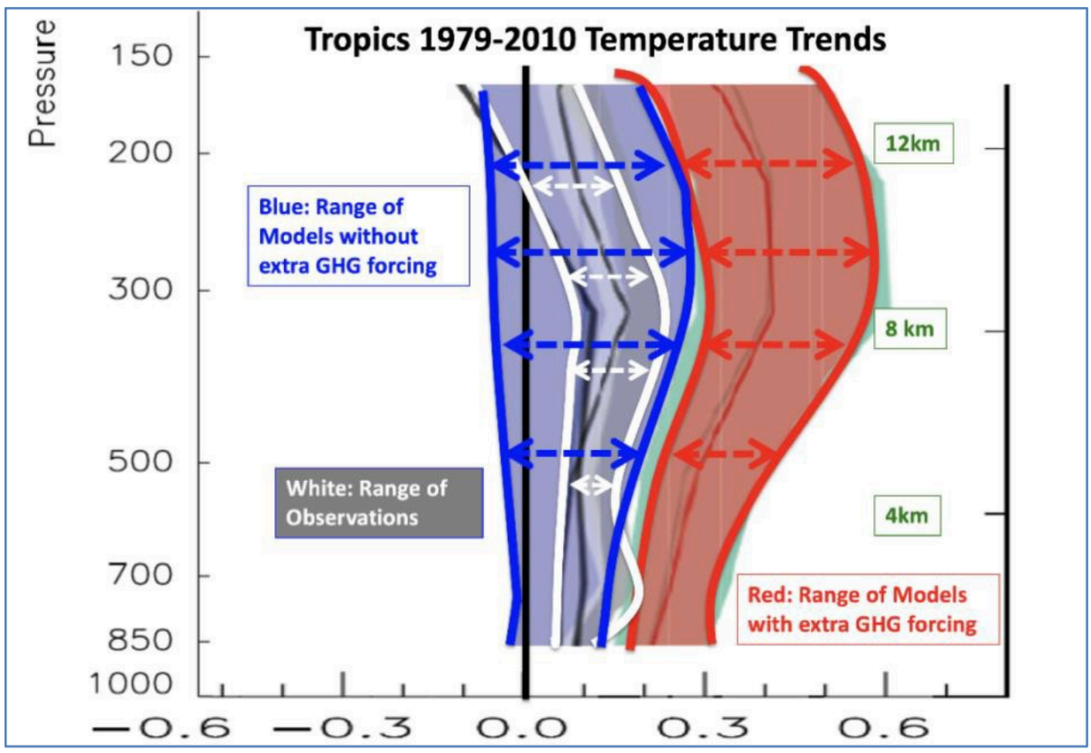


Figure 5.5: Vertical warming pattern for tropics (20S to 20N). Horizontal axis: °C/decade. Source: Annotated version of IPCC AR5 Figure 10.SM.1

Dr Katja Weigel, research scientist, department of climate modelling, University of Bremen & German Aerospace Center.

The warming bias in the atmosphere's temperature profile is not "common", but can be found in certain periods and regions. Different regions are, for example, shown in the original figure in IPCC AR5 SM.10.1. Models and observations were compared in Chapter 3.3.1.2.1 of the IPCC AR6 Report (Eyring et al. (2021). Here, different periods are included, showing that the tropical atmospheric temperature trends from radiosonde observations and models are in agreement over 1979 to 1997, but diverge over 1998 to 2014, with observations showing weaker tropospheric warming compared to climate models.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 3: Human Influence on the Climate System | Climate Change 2021: The Physical Science Basis
2. Chapter 10SM – Detection and Attribution of Climate Change: from Global to Regional – Supplementary Material — IPCC

5.5 Stratospheric cooling

Page 38

MISLEADING

An important element of the expected general "fingerprint" of anthropogenic climate change is simultaneous warming of the troposphere and cooling of the stratosphere. The latter feature is also influenced by ozone depletion and recovery. AR6 acknowledged that cooling had been observed but only until the year 2000. The stratosphere has shown some warming since, contrary to model projections.

Dr John Kennedy, climate scientist.

"The poverty of their viewpoint is exemplified in the section on 'stratospheric cooling' about one-third of which consists of a long quote from the IPCC AR6 WG1 chapter 2, enough to cite a description of how stratospheric temperatures have changed, but completely ignoring the section on the causes which can be found in section 3.3.1.2.2 of the IPCC WG1 report…They can't even be bothered to finish the one additional quote that takes up much of the rest of the section, the one from Philipona et al. (2018). The quote, which is from the abstract is cut short with a full stop, where the abstract goes on, after a comma, to say: 'which is consistent with a reversal from ozone depletion to recovery from the effects of ozone-depleting substances.' In other words, it's not that simple and the report relies for its effect on you not digging any further, not even the tiniest little bit."

Quote from external source

Supporting evidence

1. Chapter 2: Changing State of the Climate System | Climate Change 2021: The Physical Science Basis
2. Chapter 3: Human Influence on the Climate System | Climate Change 2021: The Physical Science Basis
3. Radiosondes Show That After Decades of Cooling, the Lower Stratosphere Is Now Warming - Philipona - 2018 - Journal of Geophysical Research: Atmospheres - Wiley Online Library

---

5.4 Vertical temperature profile mismatch

Page 38

FALSE

The IPCC AR6 did not assess this issue.

Dr Katja Weigel, research scientist, department of climate modelling, University of Bremen & German Aerospace Center.

The warming bias in the atmosphere's temperature profile discussed in IPCC AR6 WG1 Chapter 3.3.1.2.1 (Eyring et al. 2021).

Quote given to Carbon Brief

Supporting evidence

1. Chapter 3: Human Influence on the Climate System | Climate Change 2021: The Physical Science Basis

---

5.5 Stratospheric cooling

Page 39

MISLEADING

A combination of tropospheric warming and stratospheric cooling is a commonly cited "fingerprint" of anthropogenic climate change. Stratospheric warming since 2000 coincides with continued surface and tropospheric warming, a pattern that is not found in climate model simulations and is not apparently consistent with the anthropogenic fingerprint.

Dr Benjamin Santer, atmospheric scientist, Lawrence Livermore National Laboratory.

The DoE claim is not true. Climate models can and do show recovery of lower stratospheric temperature after 2000 in response to ozone recovery (and in accord with satellite observations). Over the full satellite era (1986 to 2024), models show very large cooling of the mid- to upper stratosphere in response to human-caused changes in CO2 and ozone (see Fig. 1 in the appended paper). The observed vertical structure of atmospheric temperature change IS consistent with model predictions and with basic theory. The DoE report cites the appended 2023 Santer et al. PNAS paper as"evidence of absence" of a human fingerprint on the vertical structure of atmospheric temperature. Our 2023 paper actually provides strong evidence FOR the positive identification of this human fingerprint in satellite data.

Quote given to Carbon Brief

Supporting evidence

1. Exceptional stratospheric contribution to human fingerprints on atmospheric temperature | PNAS

5.8 US corn belt

Page 42

FALSE

One of the largest discrepancies between models and observations is in the US corn belt, a region of particular importance to global food production. Figure 5.9 shows the warming trends for summertime (June, July, August) for the 12-state corn belt (IN, IA, IL, ND, SD, MO, MN, WI, MI, OH, KS, NE) during 1973-2022. All 36 climate models (red) warm far too rapidly compared to observations (blue).

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

There is no source for this and no methodological description. I don't believe the comparison between models and observation is correct.

Quote given to Carbon Brief

Supporting evidence

5.8 US corn belt

Page 43

MISLEADING

As discussed in Chapter 9, the anticipated negative effects of increasing temperatures on US corn yields have not materialised, in contrast to widely publicised studies proclaiming that theoretical future impacts are already being experienced (e.g., Seager et al. (2018))

Dr Richard Seager, Ewing Lamont research professor, Columbia University.

Our 2018 paper referred to changes in aridity and implications for what crops are grown and farm size and was not about corn yields. We suggest that changes patterns and values of precipitation and potential evapotranspiration would increase aridity over most of the US, which would, in the absence of adaptation, restrict corn cultivation to regions further east. But neither part of the two-part paper claims yields are reducing already due to climate change.

Quote given to Carbon Brief

Supporting evidence

1. Whither the 100th meridian? The once and future physical and human geography of America's arid-humid divide. Part II: The meridian moves east | Earth Interactions

---

6 Extreme weather

Page 46

MISLEADING

Section 6

Prof Kerry Emanuel, professor emeritus of atmospheric science, Massachusetts Institute of Technology.

The authors begin sensibly, in the introduction, stating that: 'Climate is about the statistical properties of weather over decades, not single events. Further, there are only about 130 years of reliable observational records that can be analysed statistically. That brief interval does not begin to contain all the extreme events that the climate system can create on its own.' It is odd, then, that they proceed to present timeseries of even shorter length and claim not to find trends of extreme events in them, thereby leading the reader to conclude that there are no underlying trends. They should have just stuck with their original statement and made the correct conclusion that observations usually do not suffice to detect extreme event trends of the predicted magnitude, and then turned to an exposition of what theory and models have to say.

It is very odd that there is almost no mention of theory and models [for] extreme events...Global climate data clearly and unequivocally show this bound increasing in virtually all of the tropical cyclone genesis regions. And, contrary to the statement in the DoE report, an upward trend in the proportion of very strong hurricanes HAS been detected and published. But instead of citing any of this, these authors violate their own introductory statement by citing short and generally unreliable records. For example, they state correctly that there is no detectable trend in continental US hurricane landfalls. But at an average of three landfalling storms per year, there are not nearly enough data to detect a trend of the predicted magnitude. Given that the Caribbean region had a high population density (and associated newspaper accounts) going back to the early 19th century, they could have looked at ALL Atlantic landfalls, not just the US. Had they done so, they would have discovered a clear upward trend.

Quote from external source

Supporting evidence

6 Extreme weather

Page 46

MISLEADING

Section 6

Prof Sonia Seneviratne, head of Institute for Atmospheric and Climate Science, ETH Zurich.

The text of chapter 6 often cites chapter 11 of the IPCC AR6, but is a clear example of cherry-picking. The authors repeatedly highlight low-confidence statements from the IPCC AR6 chapter 11 on changes in climate extremes which are mostly on side topics of little relevance, but they rarely cite any high confidence statements from that chapter.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 11: Weather and Climate Extreme Events in a Changing Climate | Climate Change 2021: The Physical Science Basis

6 Extreme weather

Page 46

MISLEADING

Most types of extreme weather exhibit no statistically significant long-term trends over the available historical record.

Prof Sonia Seneviratne, head of Institute for Atmospheric and Climate Science, ETH Zurich.

Importantly, there is no evidence substantiating the claim of the authors of this DOE "critical review" that "most types of extreme weather exhibit no statistically significant long-term trends over the available historical record”. It is not clear which types of "extreme weather" the authors refer to, which region(s) they are referring to, and what is the demonstration underlying the claim that "most" of these types exhibit no statistically significant long-term trends. I would ask the authors to provide the arguments substantiating this claim, as there is no rationale provided for this statement in the chapter.

I would also highlight the following conclusions from the IPCC AR6 chapter 11 which provide a very different collective assessment:
- "It is an established fact that human-induced greenhouse gas emissions have led to an increased frequency and/or intensity of some weather and climate extremes since pre-industrial time, in particular for temperature extremes."
- “Human-induced greenhouse gas forcing is the main driver of the observed changes in hot and cold extremes on the global scale (virtually certain)."
- "The frequency and intensity of heavy precipitation events have likely increased at the global scale over a majority of land regions with good observational coverage. Heavy precipitation has likely increased on the continental scale over three continents: North America, Europe, and Asia."
- "More regions are affected by increases in agricultural and ecological droughts with increasing global warming (high confidence)."
- "It is likely that the global proportion of Category 3–5 tropical cyclone instances has increased over the past four decades."

Quote given to Carbon Brief

Supporting evidence

1. Chapter 11: Weather and Climate Extreme Events in a Changing Climate | Climate Change 2021: The Physical Science Basis

---

6.2 Temperature extremes

Page 52

MISLEADING

Section 6.3

Prof Erich Fischer, lecturer at the department of environmental systems science, ETH Zurich.

The section on hot extremes is an extreme example of cherry-picking results. The report fails to acknowledge that the highlighted regions are some of the very few regions globally where the annual maximum temperatures have not increased (see e.g. IPCC AR6 WG1 Fig. SPM3). The report further highlights that in some regions the number of hottest days have not increased, yet omits that the hottest nights have increased over the same regions and periods (see figure 2.7 in the fifth US National Climate Assessment). Furthermore, the temperature of the warmest nights shows a positive trend over recent decades (Singh et al. 2023). The report further fails to refer to the extensive literature discussing the role of land-use changes and irrigation (Mueller et al. (2016)), aerosol forcing (Mascioli et al. (2017)) and unforced internal variability (Singh et al. (2023)) to the regions with little trends.

Quote given to Carbon Brief

Supporting evidence

1. Figure AR6 WG1 | Climate Change 2021: The Physical Science Basis
2. PDF
3. Circulation dampened heat extremes intensification over the Midwest USA and amplified over Western Europe | Communications Earth & Environment
4. Cooling of US Midwest summer temperature extremes from cropland intensification | Nature Climate Change
5. Timing and seasonality of the United States 'warming hole' - IOPscience

---

6.8 Wildfires

Page 70

MISLEADING

Nonetheless just focusing on the post-1985 interval the number of fires [in the US] is not increasing. The area burned did increase but only until about 2007.

Prof A Park Williams, hydroclimatologist, University of California.

The report's section on wildfire lumps the entire US together, smearing out what's going on in the western contiguous US despite the fact that it's the rapidly increasing western US wildfire activity that necessitates this report's wildfire section in the first place. On whether the area burnt in US forest fires has not increased: This is absolutely not the case in the western US, which is again the region that motivates most concerns about wildfire trends in the US. In the western US, the annual area burned has tripled over the past 40 years, driven by a 10-fold increase in annual forest-fire area and a

doubling of area burned in non-forest. The western US forest-fire area in 2020 nearly doubled the previous modern record (from 2012) and then 2021 nearly matched 2020. The increase in area burned did not come even close to ending in 2007 in the western US.

On whether fire management practices are responsible for US wildfire trends: Beginning roughly a century ago, the widespread implementation of fire-suppression policies allowed people to effectively take control of wildfire in the western US, but over the past several decades the annual area burned has quickly escalated despite ever intensifying and efforts toward fire suppression. That is, today's concern over wildfire shouldn't depend on how fires of today compare to those of the pre-suppression era, but should instead be related to how the rapidly increasing wildfire sizes in the western US today are occurring despite society's best efforts to avoid such a trend. Further, it's not simply the growing sizes of fires that are of concern. Fire size is simply easy to measure reliably. But as fires have grown larger, they have increasingly put people and property in the paths of flames, had such a negative impact on air quality that trends toward cleaner air since the 1980s have reversed even across much of the eastern US, and rapid increases in the extents of forest area burning at high severities have endangered many forest ecosystems despite fire being a natural ecosystem process."

Quote from external source

Supporting evidence

---

7 Changes in sea level

Page 75

FALSE

In evaluating AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the interval has elapsed by 2025, with sea level rising at a lower rate than predicted.

Prof Stefan Rahmstorf, professor of physics of the oceans, University of Potsdam.

Possibly they ignored acceleration, an observed fact, thus assuming that in the first half of the period half of the projected rise should have occurred. But, of course, the IPCC projections account for acceleration, so less than half of the rise should have occurred until now. In fact, projecting sea level rise until 2050 just by extrapolating the observed rise, including the observed acceleration, matches almost exactly the IPCC projections even though these are made in a completely different way.

Looking at the data, for the intermediate point 2030, the AR6 predicts a best estimate 9-10cm, relative to the same base period 1995-2014 (Table 9.9 of AR6 WG1). The satellite data show a rise of 74mm from that base period until 2025. At the same rate, that will be 93mm by 2030, well within in the best-estimate prediction.

Quote given to Carbon Brief

Supporting evidence

1. Near-Term Future Sea-Level Projections Supported by Extrapolation of Tide-Gauge Observations - Wang - 2025 - Geophysical Research Letters - Wiley Online Library
2. PDF
3. welcome | Sea Level Research Group

---

7 Changes in sea level

Page 75

FALSE

US tide gauge measurements reveal no obvious acceleration beyond the historical average rate of sea level rise.

Prof Stefan Rahmstorf, professor of physics of the oceans, University of Potsdam.

Most US tide gauges show acceleration, on the east coast that is statistically significant and larger than the global average acceleration, on the west coast less so.

Quote given to Carbon Brief

Supporting evidence

1. Sea Level Rise in the U.S.A. | Open Mind

7.1 Global sea level rise

Page 75

MISLEADING

Following the end of the Little Ice Age in the mid-19th century, tide gauges show that the global mean sea level began rising during the period 1820-1860, well before most anthropogenic greenhouse gas emissions.

Prof Stefan Rahmstorf, professor of physics of the oceans, University of Potsdam.

While it is true that that's before "most of" greenhouse gas emissions, it is unfair to compare the "start of" the rise with "most of" emissions. The industrial era is usually assumed to start in 1700 and CO2 concentration also starts to rise noticeably around 1820-1860, around the same time as sea level (see the Keeling curve).

Quote given to Carbon Brief

Supporting evidence

1. Timing of emergence of modern rates of sea-level rise by 1863 | Nature Communications
2. @rahmstorf.bsky.social on Bluesky

8.3 Attribution of global warming

Page 84

MISLEADING

AR6 states that natural external drivers since 1850-1900 have changed global surface temperature by -0.1C to +0.1C, and internal variability has changed it by -0.2C to +0.2C – on average having essentially no net impact on the warming since 1850-1900.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

The AR6 report presents this in Fig. SPM.2 as "Aggregated contributions to 2010-2019 warming relative to 1850-1900". This refers to the net effect of various climate drivers on global surface temperature between these two periods, not the maximum changes observed. The accompanying range represents the uncertainty in these estimates. It is therefore misleading to claim that AR6 asserts natural drivers have changed global temperature by ±0.1C since 1850-1900. In reality, Fig. SPM.1 shows that natural variability has led to temperature fluctuations of up to ±0.5C at different times, but the net contribution of natural drivers to long-term warming is estimated at around ±0.1C.

Quote given to Carbon Brief

Supporting evidence

1. IPCC AR6 Working Group 1: Summary for Policymakers | Climate Change 2021: The Physical Science Basis

---

8.3 Attribution of global warming

Page 84

MISLEADING

As discussed below, this minimal contribution of natural variability has been disputed by several publications that question the magnitudes of solar variability and internal variability from large-scale ocean circulations.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

This claim is supported by only a small number of studies that rely on cherry-picked, outdated, or scientifically implausible TSI reconstructions (e.g., Connolly et al. (2021) and (2023); Scafetta (2023); Soon et al. (2023); Grok et al. (2025); and Green and Soon (2025)). All of these studies rely heavily on the Hoyt and Schatten (1993) TSI series, which has been extensively criticised and discredited by Chatzistergos (2024) for its arbitrary adjustments, methodological flaws and use of fabricated data. As such, these claims do not reflect a broadly accepted scientific view. The review by Chatzistergos et al. (2023) provides a comprehensive and up-to-date overview of our current understanding of long-term solar irradiance variations and also explains why the practices underlying such claims are scientifically flawed. I note that although the Chatzistergos et al. (2023) review is cited in the DoE report, it is referenced for an unrelated and irrelevant reason and its core content is disregarded.

Quote given to Carbon Brief

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect
2. A Discussion of Implausible Total Solar-Irradiance Variations Since 1700 | Solar Physics

---

8.3 Attribution of global warming

Page 84

MISLEADING

AR5 concluded that the best estimate of radiative forcing due to Total Solar Irradiance (TSI) changes over the period 1750–2011 was very small (0.05 W/m2, Myrhe et al. (2014)).

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

This is an example of imprecise wording that could be misleading. In AR5, the solar radiative forcing difference between the 1745 and 2008 activity minima was estimated using TSI reconstructions from Wang et al. (2005), Steinhilber et al. (2009) and Krivova et al. (2010). These studies yielded a range of -0.02 to 0.071 Watts per metre squared (W/m2) for the difference (based on seven-year running means, with the caveat that the -0.02 W/m2 value comes from Steinhilber et al. (2009), which has a five-year resolution and uses 1965 as the minimum). Based on these estimates, AR5 adopted a range of 0-0.1 W/m2 with a central estimate of 0.05 W/m2, as explicitly stated in Table 8.SM.4 of the report. However, AR6 defined solar forcing in a different way to reflect the difference between full solar cycles rather than solar minima, as noted in chapter 7 of the WG1 report. This change in methodology is not acknowledged in the DoE report, which may lead to misunderstandings or incorrect comparisons between AR5 and AR6 values.

Quote given to Carbon Brief

Supporting evidence

1. PDF

8.3 Attribution of global warming

Page 84

MISLEADING

AR6 acknowledges substantially higher values and a much larger range of estimates of changes in TSI over the last several centuries, stating that the TSI between the Maunder Minimum (1645-1715) and the second half of the 20th century increased by 0.7–2.7 W/m2, a range that includes both low and high variability TSI data sets (Gulev (2021)).

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

The sentence is vague (in particular as to what they refer with "higher values") and potentially conflates two related but distinct concepts: radiative forcing and TSI differences, which were both mentioned but not clearly distinguished. Considering that the previous sentence discusses radiative forcing, one can assume that with "higher values" they refer to radiative forcing too, which would make the statement false. This is easily understood by comparing the statements in AR6 and AR5 about the range of solar radiative forcing.

The AR6 WG1 report (page 958) states:
"In contrast to AR5, the solar effective radiative forcing (ERF) in this assessment uses full solar cycles rather than solar minima. The pre-industrial TSI is defined as the mean from all complete solar cycles from the start of the 14C SATIRE-M proxy record in 6755 BCE to 1744 CE. The mean TSI from solar cycle 24 (2009–2019) is adopted as the assessment period for 2019. The best estimate solar ERF is assessed to be 0.01 W/m2, using the 14C reconstruction from SATIRE-M, with a likely range of -0.06 to +0.08 W/m2 (medium confidence). The uncertainty range is adopted from the evaluation of Lockwood and Ball (2020), who performed a Monte Carlo analysis of solar activity from the Maunder Minimum to 2019 using several datasets, resulting in an ERF range of -0.12 to +0.15 W/m2. The Lockwood and Ball (2020) full uncertainty range is halved since the period of reduced solar activity in the Maunder Minimum had ended by 1750 (medium confidence)." By comparison, the AR5 WGI report (page 689) states:
"The best estimate from our assessment of the most reliable TSI reconstruction gives a seven-year running mean radiative forcing (RF) between the minima of 1745 and 2008 of 0.05 W/m2. Our assessment of the range of RF from TSI changes is 0.0 to 0.10 W/m2."

Thus, the solar radiative forcing estimates in AR5 and AR6 are broadly consistent, with AR6's best estimate slightly lower. If the statement instead refers to TSI differences, this would also be misleading. The AR6 WGI (page 297) lists a TSI difference between the Maunder Minimum and the second half of the 20th century ranging from 0.7 to 2.7 W/m2. The lower bound likely corresponds to the SATIRE-T reconstruction, while the upper bound comes from the Yeo et al. (2020) constraint on the dimmest possible state of the sun. It is important to note that Yeo et al. (2020) does not reconstruct TSI during the Maunder Minimum but rather provides a theoretical constraint on the minimum plausible solar irradiance. This constraint effectively excludes TSI reconstructions with large amplitude variability, such as Egorova et al. (2018). Almost all current TSI reconstructions indicate significantly smaller long-term TSI trends (Chatzistergos et al.

(2023)). These include the SATIRE and NRL (now NNL) models recommended for CMIP6 and AR6.

Quote given to Carbon Brief

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect
2. The Dimmest State of the Sun - Yeo - 2020 - Geophysical Research Letters - Wiley Online Library
3. Placing limits on long-term variations in quiet-Sun irradiance and their contribution to total solar irradiance and solar radiative forcing of climate | Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences

---

8.3 Attribution of global warming

Page 84

FALSE

The IPCC has only minimally discussed solar influences on global and regional climate.

Prof Mike Lockwood, professor of space environmant physics and president of the Royal Astronomical Society, University of Reading.

Contrary to this statement, there is much discussion in the last three IPCC assessment reports.

Quote given to Carbon Brief

Supporting evidence

1. Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity | Climate Change 2021: The Physical Science Basis

---

8.3 Attribution of global warming

Page 84

MISLEADING

Section 8.3.1

Prof Andreas Schmittner, college of Earth, ocean and atmospheric science, Prof Veronika Eyring, professor of climate modelling and Prof June-Yi Lee, professor of climate science.

Overall, this section overemphasizes uncertainty and claims an inadequate assessment of natural climate variability in IPCC AR6, whereas we do know with high certainty that anthropogenic greenhouse gas emissions have caused the global warming over the last 50-100 years. There are no credible forcings other than greenhouse gases that could have caused that warming. Temperature measurements in the ocean show that the ocean is warming from the top down, which is inconsistent with a role of ocean circulation in causing atmospheric warming (Barnett et al., 2005; Cheng et al., 2020). Energy conservation requires that if ocean circulation had caused surface warming there must be cooling in the subsurface. However, this is not observed. The ocean has warmed at all depth, most at the surface, a pattern that is consistent with anthropogenic warming. This should be mentioned in the part entitled "Natural Variability of Large-Scale Ocean Circulation", otherwise this part is misleading. Since AR5, there has been increasing and robust evidence that external forcings—including anthropogenic greenhouse gases and aerosols, as well as natural volcanic aerosols—have modulated the Atlantic Multidecadal Oscillation over the historical period, as assessed in AR6 WGI Section 3.7.7. This important aspect is completely overlooked in Section 8.3.1. Although state-of-the-art climate and Earth system models tend to underestimate natural internal climate variability, single-model large initial-condition ensembles have provided a pathway to better quantify its range. Using several such ensembles, AR6 WGI Box 4.1 assessed that the 5–95% ensemble range of annual mean global surface air temperature is approximately ±0.25 °C (MIROC6, IPSL-CM6A), spanning from about ±0.2 °C (CanESM5) to ±0.3 °C (EC-Earth3). This model-based estimate is consistent with observation-based estimates. To correct this, the following changes must be made in the DOE CWG document: - Revise the statements that claim an inadequate assessment of natural climate variability by IPCC AR6. IPCC AR6 lists extensive peer-reviewed literature that led to the following assessment: "When estimated over the entire historical period (1850–2020), the contribution of natural variability to global surface warming of –0.23°C to +0.23°C is small compared to the warming of about 1.1°C observed during the same period, which has been almost entirely attributed to the human influence." - Include evidence from ocean warming pattern, which is inconsistent with changes in ocean circulation causing the observed global warming, but which is consistent with anthropogenic warming causing heat entering the ocean from above. - Include the growing body of robust evidence that external forcings have modulated the Atlantic Multidecadal Oscillation over the historical period, which has important implications for attributing recent trends to natural internal variability.

Quote given to Carbon Brief

Supporting evidence

1. Penetration of Human-Induced Warming into the World's Oceans | Science
2. Record-Setting Ocean Warmth Continued in 2019 | Advances in Atmospheric Sciences
3. Human Influence on the Climate System (Chapter 3) - Climate Change 2021 – The Physical Science Basis

---

8.3 Attribution of global warming

Page 85

MISLEADING

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990s, before a decline in the early 21st century; this period is often termed the "Modern Maximum" (Chatzistergos et al. (2023); Solanki et al. (2004); Usoskin et al. (2007)). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz (2021)).

Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

"Although the sentence in which they cite us is factually accurate in isolation, the surrounding text creates a misleading impression. More importantly, our review paper, which they cited, explains why their subsequent paragraph has misleading and wrong statements."

Quote from external source

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect

---

8.3 Attribution of global warming

Page 85

MISLEADING

However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes (2017)).

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

This sentence creates a misleading impression that, although AR6 acknowledged the possibility of high secular trends in total solar irradiance (TSI), it arbitrarily dismissed them in favor of two TSI reconstructions with relatively low variability. In fact, the 2.7 W/m2 figure cited in AR6 should not be interpreted as an actual historical TSI difference between the Maunder Minimum and the present, but rather as a physical upper bound on the maximum plausible difference between the sun's dimmest possible state and its current irradiance. Importantly, the Maunder Minimum is unlikely to represent this dimmest state and modern TSI reconstructions suggest a substantially smaller long-term trend than what a 2.7 W/m2 Maunder-to-present difference would imply. This upper limit, derived from Yeo et al. (2020), effectively excludes high-variability TSI reconstructions that exceed this threshold. For this reason, the CMIP6 and IPCC AR6 selected two TSI reconstructions, SATIRE (Yeo et al. (2014) and Wu et al. (2018)) and NRLTSI (now referred to as NNLTSI, Coddington et al. (2016), not based on their implied variability magnitude, but because they represent the most advanced, scientifically robust, and rigorously validated models currently available (Matthes et al. (2017)). SATIRE is a semi-empirical, physics-based model, whereas NRLTSI is a proxy-based regression model. Both have undergone extensive scrutiny and show excellent agreement with direct satellite measurements of TSI.

Quote given to Carbon Brief

Supporting evidence

1. GMD - Peer review - Solar forcing for CMIP6 (v3.2)
2. The nature of solar brightness variations | Nature Astronomy

---

8.3 Attribution of global warming

Page 85

MISLEADING

While AR6 shows a substantially greater solar impact than does AR5, the overall impact of solar forcing on the climate was still assessed to be small compared to anthropogenic forcing.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

The statement is vague and unclear in what it means by “AR6 shows a substantially greater solar impact than AR5”, especially since the same sentence acknowledges that solar forcing was assessed to be small compared to anthropogenic forcing, implying a correspondingly small solar impact. This apparent contradiction likely stems from confusion on the part of the DoE authors regarding the distinction between radiative forcing and total solar irradiance (TSI) differences as presented in AR5 and AR6, as discussed in previous comments.

Quote given to Carbon Brief

Supporting evidence

8.3 Attribution of global warming

Page 85

MISLEADING

However, the impact of solar variations on the climate is uncertain and subject to substantial debate (Lockwood (2012); Connolly et al. (2021)) - something that is not evident in the IPCC assessment reports.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

AR6 acknowledges the high-variability reconstruction by Egorova et al. (2018) and references studies by Yeo et al. (2020) and Lockwood & Ball (2020), discussing the inherent uncertainty in estimating the secular trend in solar irradiance variations. The earlier study by Lockwood (2012) is not included because its findings are superseded by the more recent Lockwood & Ball (2020). Mike Lockwood was actually one of the contributors to AR6. Thus, IPCC AR6 did adequately discuss the existing uncertainty in irradiance modelling and, thus, its effects on Earth's climate. However, what the authors of the DoE report seem to mean with this sentence is that AR6 does not discuss the Connolly et al. (2021) study. It is worth repeating that the Connolly et al. (2021) paper gave a misleading presentation of the literature. In particular, Connolly et al. (2021) cherry-picked 16 TSI reconstructions, deliberately balancing the sample by including eight with small long-term trends and eight with pronounced trends.

However, their inclusion of several outdated or discredited models within the high-variability group is misleading, particularly given the DoE chapter summary's claim that all selected reconstructions are plausible (Chatzistergos et al. (2023) and Chatzistergos (2024)).

As noted in previous comments, the issues with Connolly et al. (2021) undermine the credibility of their results. While there is legitimate uncertainty about the exact magnitude of long-term solar irradiance trends, Connolly et al. (2021) exaggerated the solar impact by cherry-picking outdated and superseded series that display implausibly large TSI variations.

Quote given to Carbon Brief

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect
2. A Discussion of Implausible Total Solar-Irradiance Variations Since 1700 | Solar Physics
3. The Dimmest State of the Sun - Yeo - 2020 - Geophysical Research Letters - Wiley Online Library

---

8.3 Attribution of global warming

Page 85

MISLEADING

There are several rival composite TSI datasets that disagree as to whether TSI increased or decreased during the period 1986-96.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

It is also important to note that the effect of ACRIM-gap in the trends of the different TSI composites is generally small (Chatzistergos et al. (2023) and Kopp (2025)). While the issue with ACRIM does contribute to the uncertainty in the long-term trend of direct TSI measurements, a growing body of evidence challenges the notion of a TSI increase during the ACRIM-gap, evidence which the DoE report entirely overlooks. Notable examples include Amdur & Huybers (2023), Chatzistergos et al. (2025) and Krivova et al. (2009). By having given such emphasis on the ACRIM-gap the DoE report gives the misleading impression that there can be significant increase in TSI, which could account for the global warming over the same period. Thus, this statement can be misleading.

Quote given to Carbon Brief

Supporting evidence

1. A Bayesian Model for Inferring Total Solar Irradiance From Proxies and Direct Observations: Application to the ACRIM Gap - Amdur - 2023 - Journal of Geophysical Research: Atmospheres - Wiley Online Library
2. Revisiting the SATIRE-S irradiance reconstruction: Heritage of Mt Wilson magnetograms and Ca II K observations | Astronomy & Astrophysics (A&A)
3. ACRIM-gap and total solar irradiance revisited: Is there a secular trend between 1986 and 1996? - ADS
4. Solar irradiance measurements | Living Reviews in Solar Physics

---

8.3 Attribution of global warming

Page 85

MISLEADING

Further, the satellite record of TSI is used to calibrate proxy models that infer past solar variations from sunspots and cosmogenic isotope measurements (Velasco Herrera et al. (2015)).

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

There are several issues with this sentence, particularly concerning the choice of the sole reference, which may mislead readers into believing that existing total solar irradiance (TSI) reconstructions depend heavily on direct TSI measurements for determining long-term trends. This is generally incorrect. Moreover, the phrasing gives the impression that only proxy models exist, overlooking the important class of physics-based semi-empirical models.

1) Missing relevant literature: The statement omits key papers on irradiance reconstruction models (e.g., Coddington et al. (2016); Wu et al. (2018); and Chatzistergos et al. (2024)) and authoritative reviews (e.g., Chatzistergos et al. (2023) and (2024); and Solanki et al. (2013)) that provide a more accurate and comprehensive perspective.

2) Choice of reference: The DoE cites only Velasco Herrera et al. (2015) to support the claim, which is problematic. That work is not an irradiance reconstruction model but a machine learning extrapolation inherently dependent on the chosen TSI reference series. Given the chaotic nature of solar activity, such extrapolations from limited data lack scientific merit (see Petrovay (2020)). Moreover, the predictions from Velasco Herrera et al. (2015) for 2015–25 are already contradicted by actual direct TSI

measurements obtained since.

3) Proxy models: These reconstruct irradiance variations by scaling or regressing solar activity indices against reference TSI data. While the choice of reference series can influence results depending on the regression method, the effect is not always big. For example, Chatzistergos et al. (2020) demonstrated that the choice of TSI reference has negligible impact on minimum-to-minimum trends in their regression model. Similarly, Figure 7c in Chatzistergos et al. (2024) shows only a minor effect of different TSI references on their century-long TSI reconstruction.

4) We have not only proxy models but also physics-based semi-empirical models. Models such as SATIRE and SRPM do rely on tuning some free parameters by comparison to direct TSI measurements. However, this tuning does not significantly affect the long-term trends, as shown in multiple studies (e.g., Chatzistergos et al. (2021)). Notably, Chatzistergos et al. (2025) explicitly states about their irradiance reconstruction with SATIRE-S that "the trend in the updated SATIRE-S TSI composite is independent of measured TSI".

Quote given to Carbon Brief

Supporting evidence

1. Understanding the secular variability of solar irradiance: the potential of Ca II K observations | Journal of Space Weather and Space Climate
2. Revisiting the SATIRE-S irradiance reconstruction: Heritage of Mt Wilson magnetograms and Ca II K observations | Astronomy & Astrophysics (A&A)
3. Modelling solar irradiance from ground-based photometric observations | Journal of Space Weather and Space Climate
4. Reconstructing solar irradiance from historical Ca II K observations - I. Method and its validation | Astronomy & Astrophysics (A&A)

8.3 Attribution of global warming

Page 85

MISLEADING

There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990s, before a decline in the early 21st century; this period is often termed the "Modern Maximum." (Chatzistergos et al. (2023); Solanki et al. (2004); Usoskin et al. (2007))

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System

Research.

The citation of Chatzistergos et al. (2023) in support of the statement about the "Grand Modern Maximum" of solar activity is somewhat misleading. First, the cited paper is a review focused specifically on solar irradiance modeling and long-term trends in irradiance reconstructions. The Grand Modern Maximum is mentioned only briefly in the introduction and is not a subject of analysis in the paper. Moreover, the concept of the Grand Modern Maximum is primarily based on direct sunspot observations, as discussed in works such as Chatzistergos et al. (2017) and Usoskin et al. (2016), which is clearly stated in Chatzistergos et al. (2023), but omitted in the DoE report. The other two studies cited in the DoE, Solanki et al. (2004) and Usoskin et al. (2007), inferred this period in sunspot number series reconstructed from cosmogenic isotope data. However, these data do not cover the full extent of the modern maximum, and the connection between isotope-based and direct sunspot records remains uncertain. Recent reconstructions like Wu et al. (2018; where both Sami K. Solanki and Ilya G. Usoskin are co-authors) continue to support the existence of a Grand Modern Maximum, but suggest it was less pronounced than earlier assumed.

I presume the authors do not include this study because it was used to reconstruct irradiance variations and returned a rather small secular trend, which would conflict with the claim they want to make here. It is important to recognise that elevated sunspot activity during the second half of the 20th century does not, on its own, determine how much solar irradiance increased, as information on faculae is also essential. Irradiance variations are driven not only by sunspots but also by faculae and network magnetic features. Unfortunately, direct facular observations only extend back to 1892, and their use prior to the 1970s has been rather limited. Consequently, reconstructing past irradiance variations requires assumptions about the relationship between sunspots and faculae, which introduces uncertainty into estimates of the secular trend. However, recent efforts to extract facular information from Ca II K observations (e.g., Chatzistergos et al. (2024)) and to extend irradiance reconstructions back to 1892 indicate only a minimal long-term trend over the 20th century, consistent with state-of-the-art reconstructions such as SATIRE. As mentioned above also updated reconstructions with cosmogenic isotope data (Wu et al. (2018)) suggest a rather small long-term trend. None of this context is provided in the DoE report, resulting in a potentially oversimplified or overstated implication that a large secular trend is more likely, despite the balance of current evidence.

Quote given to Carbon Brief

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect
2. Recalibration of the Sunspot-Number: Status Report | Solar Physics
3. Solar activity over nine millennia: A consistent multi-proxy reconstruction | Astronomy & Astrophysics (A&A)
4. Understanding the secular variability of solar irradiance: the potential of Ca II K observations | Journal of Space Weather and Space Climate

---

8.3 Attribution of global warming

Page 85

MISLEADING

However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz, 2021).

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

This statement is misleading because it refers to section 3 of Schmutz (2021), which focuses on direct measurements of solar irradiance only since 1978, whereas the DoE report in the previous sentence was discussing the grand modern maximum and thus longer-term trends beyond the period covered by direct TSI measurements. Furthermore, the uncertainty in determining the long-term trend, both from direct measurements and modeled reconstructions, is widely acknowledged in the scientific literature and is not limited to a small group of scientists. Nevertheless, all current evidence and advances consistently indicate a relatively weak secular trend in total solar irradiance (TSI) variations.

Quote given to Carbon Brief

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect
2. Changes in the Total Solar Irradiance and climatic effects | Journal of Space Weather and Space Climate

---

8.3 Attribution of global warming

Page 85

MISLEADING

This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70% of the temperature variability since pre-industrial times (Scafetta (2013); Stefani (2021)).

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

Neither of the two papers cited for the claim that "datasets with high TSI variability can explain more than 70% of the temperature variability since pre-industrial times". Stefani (2021) did not even use any TSI series; instead, he performed a linear regression between the geomagnetic aa-index and sea surface temperature. Scafetta (2013, p27) states: "Figure 15B compares the Central England Temperature (CET) record and the TSI model by Hoyt and Schatten plus the ACRIM TSI record; an overall good correlation is observed since 1700, which suggests that the major observed climatic oscillations are solar induced and that the sun explains about 50-60% of the warming observed since 1900."

This raises two major concerns. First, the statement in the report is incorrect since neither Scafetta (2013) nor Stefani (2021) demonstrate that TSI can account for "more than 70% of the temperature variability since preindustrial times". Second, the conclusion by Scafetta (2013) relies on the Hoyt and Schatten (1993) TSI model after connecting it to the ACRIM TSI composite. The Hoyt and Schatten 1993 TSI model has been shown to be highly unrealistic and is now widely discredited (Chatzistergos (2024)). As detailed in Chatzistergos (2024), the Hoyt and Schatten model includes multiple arbitrary adjustments and fabricated data for one index spanning over a decade, which appear to have been copied from another index. Critically, the model's high variability was not a result of the model but was imposed by the authors. When updated underlying indices and direct TSI composites (e.g., PMOD, Montillet et al. (2022), ACRIM) are considered, it becomes clear that Hoyt and Schatten (1993) exaggerated TSI variation amplitudes by roughly a factor of five (Chatzistergos (2024)). The discrepancy is even greater when compared to the ACRIM TSI composite, which Hoyt and Schatten's model is incompatible with. This seriously undermines the reliability of conclusions drawn from the Hoyt and Schatten model for attributing recent climate change to solar variability.

Therefore, the two given references do not corroborate the claim of the DoE report.

This statement likely originates from Connolly et al. (2023), but the same criticisms previously discussed regarding Connolly et al. (2021) apply here as well. Connolly et al. (2021) and (2023) cherry-picked TSI reconstructions to amplify several outdated or discredited models with high secular trends. As noted in previous comments, these issues undermine the credibility of their results. While there is legitimate uncertainty about the exact magnitude of long-term solar irradiance trends, Connolly et al. (2021) and (2023) exaggerated the solar impact by cherry-picking outdated and superseded series that display implausibly large TSI variations.

Quote given to Carbon Brief

Supporting evidence

1. A Discussion of Implausible Total Solar-Irradiance Variations Since 1700 | Solar Physics
2. Long-term changes in solar activity and irradiance - ScienceDirect

---

8.3 Attribution of global warming

Page 85

MISLEADING

The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

This statement is misleading and confusing. First, the choice of TSI satellite record does not substantially influence the estimated solar contribution to climate change; rather, it is the choice of modelled TSI series, which was the topic of the previous sentence, that can have an impact. Second, as explained above, the high-variability TSI reconstructions used by Connolly et al. (2021) and (2023) to attribute most warming to the Sun are outdated, superseded, and scientifically implausible. While there is indeed uncertainty regarding the long-term trend in solar irradiance, which naturally affects the precise estimate of solar-driven global warming, all current evidence indicates this contribution is relatively small. The sentence in the DoE report, however, dramatically exaggerates this uncertainty and its implications.

However, it is also possible that the authors of the DoE report intended to suggest that the choice of TSI satellite records influences the reconstruction outcomes and thus the estimated solar contribution to global warming. This interpretation would also be misleading, as explained earlier, but reiterated here:

1) While the choice of reference TSI series can affect proxy model results depending on the regression approach, this effect is often small. For example, Chatzistergos et al. (2020) demonstrated that the choice of TSI reference has a negligible impact on minimum-to-minimum trends in their regression model. Similarly, Figure 7c in Chatzistergos et al. (2024) shows only minor differences when using various TSI references in their century-long reconstruction.

2) This effect is typically negligible in physics-based semi-empirical models. Various studies have confirmed the minimal impact on SATIRE reconstructions when changing the reference TSI series (e.g., Chatzistergos et al. 2021). Notably, for the latest version of SATIRE-S, Chatzistergos et al. (2025) explicitly state that "the trend in the updated SATIRE-S TSI composite is independent of measured TSI".

3) As mentioned earlier, the DoE authors cited Velasco Herrera et al. (2015) instead of irradiance reconstruction models, which may have caused the confusion. Velasco Herrera et al. (2015) presented a machine learning extrapolation that inherently depends on the chosen TSI reference series. Given the chaotic nature of solar activity, such limited-data extrapolations lack scientific robustness (see Petrovay (2020)). Moreover, Velasco Herrera et al. 2015 predictions for 2015-25 have already been contradicted by direct TSI measurements collected since.

Quote given to Carbon Brief

Supporting evidence

1. Long-term changes in solar activity and irradiance - ScienceDirect

---

8.3 Attribution of global warming

Page 85

FALSE

Scafetta et al. (2023) suggests that ~80% of solar influence on climate might stem from non-TSI mechanisms.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

The reference is incorrect, there is no Scafetta et al. (2023); this should be Scafetta (2023). Although Scafetta (2023) indeed makes this claim, it is yet another such claim of attributing most global warming to the sun mainly based on the use of the discredited Hoyt and Schatten (1993) TSI series (Chatzistergos (2024)). Scafetta (2023) bases his analysis on a combination of three TSI series: Hoyt and Schatten (1993), Egorova et al. (2018) and the one recommended by CMIP6. Since the Hoyt and Schatten (1993) TSI series was not updated prior to Chatzistergos (2024), Scafetta extended it by linking it to the ACRIM TSI composite. Chatzistergos (2024) demonstrated that the high variability imposed by Hoyt and Schatten (1993) is inconsistent with direct TSI measurements and that a variability magnitude approximately five times smaller is required.

Additionally, Chatzistergos (2024) showed that the Hoyt and Schatten (1993) model conflicts particularly with the ACRIM composite by exhibiting opposite trends during the so-called ACRIM-gap, making Scafetta's extension of Hoyt and Schatten (1993) with ACRIM invalid. Thus, with Egorova et al. (2018) exceeding the Yeo et al. (2020) physical constraint, and considering the multiple methodological issues identified with the Hoyt and Schatten (1993) series (Chatzistergos (2024)), the resulting conclusions by Scafetta (2023) are unlikely. Furthermore, Scafetta himself acknowledged that even when allowing for solar effects beyond radiative forcing, the solar influence remains minimal with the CMIP6 TSI forcing. Therefore, the claim that solar influence accounts for more than 80% of warming is unsupported.

Quote given to Carbon Brief

Supporting evidence

1. A Discussion of Implausible Total Solar-Irradiance Variations Since 1700 | Solar Physics

---

8.3 Attribution of global warming

Page 85

MISLEADING

There are numerous candidate processes, including solar ultraviolet changes; energetic particle precipitation; atmospheric-electric-field effect on cloud cover; cloud changes produced by solar-modulated galactic cosmic rays; large relative changes in the magnetic field; and the strength of the solar wind. Such solar indirect effects are not included in climate models, although indirect methods of estimating their impacts suggest they are significant.

Dr Theodosios Chatzistergos, astrophysicist, Max Planck Institute for Solar System Research.

It is exaggerated and incorrect to claim that the impacts of such effects are significant. Many of these effects are described vaguely in the DoE report, making their implications unclear (for example, "large relative changes in the magnetic field") without specifying what that entails. Additionally, the influence of cosmic rays on cloud formation has been shown to be negligible, as demonstrated by the CLOUD experiment at CERN (Pierce (2017)). While some effects on Earth's atmosphere from other processes have been studied (e.g., Mironova et al. (2015) and Sinnhuber & Funke (2020)), their effects are generally considered to be small.

Quote given to Carbon Brief

Supporting evidence

1. Cosmic rays, aerosols, clouds, and climate: Recent findings from the CLOUD experiment - Pierce - 2017 - Journal of Geophysical Research: Atmospheres - Wiley Online Library
2. Energetic Particle Influence on the Earth's Atmosphere - ADS
3. Energetic electron precipitation into the atmosphere - ScienceDirect

---

8.3 Attribution of global warming

Page 85

MISLEADING

However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes, (2017)).

Prof Mike Lockwood, professor of space environmant physics and president of the Royal Astronomical Society, University of Reading.

The statement is true, but very misleading as it is made to sound that larger TSI-drift papers were ignored. There is only one very high TSI drift reconstruction and it is very much an outlier – other reconstructions show much smaller drift. There is also analysis of recent solar cycles that shows that the low TSI change reconstructions are correct.

Quote given to Carbon Brief

Supporting evidence

1. Placing limits on long-term variations in quiet-Sun irradiance and their contribution to total solar irradiance and solar radiative forcing of climate | Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences

---

8.3 Attribution of global warming

Page 85

MISLEADING

However, the impact of solar variations on the climate is uncertain and subject to substantial debate (Lockwood (2012); Connolly et al. (2021)) – something that is not evident in the IPCC assessment reports.

Prof Mike Lockwood, professor of space environmant physics and president of the Royal Astronomical Society, University of Reading.

This is highly misleading as it conflates regional and global climate. The cited references were discussing regional climates where there is more uncertainty and some (limited) solar influence through downward propagation of stratospheric responses, especially in winter. The global climate is not open to such uncertainty. The cooling (as opposed to warming) of the global stratosphere shows conclusively that the effect of solar change on the global climate is minimal compared to effects of changing solar irradiance.

Quote given to Carbon Brief

Supporting evidence

1. Human and natural influences on the changing thermal structure of the atmosphere | PNAS

8.3 Attribution of global warming

8.3 Attribution of global warming

Page 85

MISLEADING

However, the recommended forcing dataset for the CMIP6 climate model simulations used in AR6 for attribution studies averages two data sets with low solar variability (Matthes (2017).

Prof Katja Matthes, director, GEOMAR Helmholtz Centre for Ocean Research Kiel.

It is correct that the long-term trend in TSI is rather on the low variability side, but it is completely ignored that other more extreme trends (high variability datasets) are completely unrealistic. We only provide an extreme Maunder Minimum case as a sensitivity experiment.

Quote given to Carbon Brief

Supporting evidence

1. GMD - Solar forcing for CMIP6 (v3.2)

8.3 Attribution of global warming

Page 85

MISLEADING

While AR6 shows a substantially greater solar impact than does AR5, the overall impact of solar forcing on the climate was still assessed to be small compared to anthropogenic forcing. However, the impact ofsolar variations on the climate is uncertain and subject to substantial debate (Lockwood (2012); Connolly et al. (2021) – something that is not evident in the IPCC assessment reports. The variations of TSI over time remain a challenging problem. Since 1978, there have been directmeasurements of TSI from satellites. However, the data exhibits non-negligible inconsistencies, and interpreting any multi-decadal trends in TSI requires comparisons of observations from overlapping satellites. There are several rival composite TSI datasets that disagree as to whether TSI increased ordecreased during the period 1986-96 (the ACRIM gap; see Chapter 4). Further, the satellite record of TSI is used to calibrate proxy models that infer past solar variations from sunspots and cosmogenic isotope measurements (Velasco Herrera et al. (2015)).There is substantial evidence for high solar activity in the second half of the 20th century (starting in 1959) and extending into the 1990s, before a decline in the early 21st century; this period is often termedthe "Modern Maximum". (Chatzistergos et al. (2023); Solanki et al. (2004); Usoskin et al. (2007)). However, some scientists have concluded that it is not possible to be confident of any multi-decadal trend in TSI (Schmutz (2021)). This uncertainty causes some reconstructions of TSI from 1750 to have low variability (implying a very low impact of solar variations on global mean surface temperature) whereas datasets with high TSI variability can explain more than 70% of the temperature variability since pre-industrial times (Scafetta (2013); Stefani (2021)). The choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings.

Prof Katja Matthes, director, GEOMAR Helmholtz Centre for Ocean Research Kiel.

In Matthes et al. (2017), we conclude the following two points (just as an example of mis-citation):

1) A new and lower TSI value is recommended: the contemporary solar-cycle average is now 1,361.0 +/-0.5W/m^2 (Prša et al. (2016)).

2) Over the last three solar cycles in the satellite era, there is a slight negative TSI trend in the CMIP6 dataset. A recent reconstruction of the TSI, with a proper estimation of its uncertainties, suggests that this downward trend between the solar minima of 1986 and 2009 is not statistically significant (Dudok de Wit et al. (2017)). The TSI trend leads to an estimated radiative forcing on a global scale of -0.04 W/m^2, which is small in comparison with other forcings over this period.

Therefore the sentence in the DoE report stating that the "choice of TSI satellite record used in an analysis can therefore substantially influence how much climate change is attributed to human versus natural forcings" is completely wrong and ignores the thorough science. The radiative forcing to this natural forcing – even if we would have chosen a different TSI dataset – is small (-0.04 W/m^2).

The next completely wrong statement is that "such solar indirect effects are not included in climate models". In Matthes et al. (2017), we provide a comprehensive dataset including TSI and solar spectral irradiance data as well as solar particle forcing for the first time. We also provide an ozone dataset with the indirect effect included. Many of the CMIP6 models do include spectral solar irradiance as well as ozone changes, so the indirect effect and some even the particle effects. I am really shocked about these wrong statements. The IPCC is based on sound scientific evidence and this DoE report is kicking the evidence with feet. Misinterpreting and mis-citing or not at all citing important work (such as the important parts of Matthes et al. (2017) where we provide sound scientific evidence and discuss the details) – this is just horrible. By taking out only parts of the story and "simplifying it", it is becoming simply wrong. This is not sound science.

Quote given to Carbon Brief

Supporting evidence

1. GMD - Solar forcing for CMIP6 (v3.2)
2. NOMINAL VALUES FOR SELECTED SOLAR AND PLANETARY QUANTITIES: IAU 2015 RESOLUTION B3 - IOPscience
3. Methodology to create a new total solar irradiance record: Making a composite out of multiple data records - Dudok de Wit - 2017 - Geophysical Research Letters - Wiley Online Library

8.3 Attribution of global warming

Page 87

FALSE

The causes of the early 20th century warming are discussed by Hegerl et al. (2017 and 2019). The atmospheric CO_2 concentration increased from 298ppm in 1905 to 310ppm in 1941, implying that CO_2 had little impact. Volcanic activity during this period was very low and solar forcing is uncertain. Yet Hegerl et al. (2017) somehow inferred that 40-54% of this warming could be attributed to external forcing, with the rest associated with internal variability. Bronniman et al. (2024) focused on the causes of the cooling in the first decade of the 20th century in the southern hemisphere. They found that the cooling was related to a La-Niña-like pattern in the Pacific, a cold tropical and subtropical South Atlantic, a cold extratropical South Pacific, and cool southern midlatitude land areas. The Southern Annular Mode was positive, with a strengthened Amundsen–Bellingshausen seas low, although the spread of the data products is considerable. The warming in the 1930s and subsequent cooling during mid-century was particularly pronounced in the Arctic. Bokuchava and Semenov (2021) find that these variations were most likely caused by acombined effect of long-term natural climate variations in the North Atlantic and North Pacific with a contribution of the natural radiative forcing related to the reduced volcanic activity and variations of solar activity, as well as growing greenhouse gases concentrations. Tokinaga et al. (2017) showed that the combined effect of internally generated Pacific and Atlantic interdecadal variability intensified Arctic warming in the early 20th century. The synchronised Pacific-Atlantic warming drastically alters planetary-scale circulations over the Northern Hemisphere; these same circulation patterns have a global influence.

Dr Gabriele Hegerl, professor of climate system science, University of Edinburgh.

The authors discuss my papers on the early 20th century warming (Hegerl et al. (2017) and (2019)). For example, they argue that "the atmospheric CO_2 concentration increased from 298ppm in 1905 to 310ppm in 1941, implying that CO_2 had little impact". This is a faulty argument. First of, the analysis in the paper focuses on 1901-50, not the shorter period, and secondly, it cannot be argued that 12ppm has "little impact". It does have an impact, even though smaller than the total warming at the time (as shown in the paper). Indeed, it causes a noticeable warming of about 0.2C globally, based on our analysis (partly offset by aerosol cooling at the same time as shown in the paper). They also argue that volcanic activity was low – which is correct and exactly the reason for a small positive forcing as the climate moves towards a less volcanically forced background state (which we also found contributed roughly 0.1C). We really disagree with the characterisation of having "somehow" inferred that about half the warming was forced as this is shown and discussed in the paper as originating from a published Bayesian attribution analysis that accounts for model uncertainty - which is very different from an ad hoc "somehow" approach. The authors then discuss the important contribution unusual circulation made to this warming particularly in the Arctic, which we fully agree with. Regional short term variations are to a large extent driven by interesting variability, while a global mean trend over 50 years as in that case is driven to a substantial part by forcing. This is how climate works. Meanwhile, there are publications suggesting that some of the early 20th century cool start into the warming may be affected by data uncertainty – something an up to date DOE report maybe should have recognised and cited?

Quote given to Carbon Brief

Supporting evidence

1. The early 20th century warming: Anomalies, causes, and consequences - PubMed
2. Causes of climate change over the historical record - IOPscience
3. Early-twentieth-century cold bias in ocean surface temperature observations | Nature
4. Evaluating the Performance of Past Climate Model Projections - Hausfather - 2020 - Geophysical Research Letters - Wiley Online Library

8.3 Attribution of global warming

Page 88

MISLEADING

When the Great Pacific Climate Shift is accounted for in climate attribution analyses since 1950, 40% or more of the warming in the second half of the 20th century is attributed to natural internal variability (McLean et al. (2009); Tung and Zhou (2013); Chylek et al. (2016); and Scafetta (2021)).

Prof June-Yi Lee, professor of climate science, Pusan National University.

There are three problematic aspects in this contested text. First, the argument relies exclusively on Tung and Zhou (2013) and is not fully supported by the other three cited references. Specifically, McLean et al. (2009) and Scafetta (2021) provide no quantitative estimates of the contribution of internal variability to warming trend. Moreover, the estimate presented in Chylek et al. (2016) is substantially lower than that of Tung and Zhou (2013). According to Chylek et al. (2016), the contribution of the Atlantic Multidecadal Oscillation (AMO) to the 1970-2005 warming was between 0.13 and 0.20C (depending on the AMO index used), compared with a greenhouse gas contribution of 0.49-0.58C.

Second, while Figure 4 of Tung and Zhou (2013) suggests that internal variability may account for approximately 40% of the observed global warming over the past 50 years, it does not contribute significantly to the long-term warming trend over periods exceeding 75 years. This interpretation is consistent with the AR6 assessment (Section C.1, WGI SPM), which states: "Natural drivers and internal variability will modulate human-caused changes, especially at regional scales and in the near term, with little effect on centennial global warming. These modulations are important to consider in planning for the full range of possible changes."

Third, the statement does not acknowledge the ongoing debate regarding the role of external forcings in driving AMO variability. Recent studies have highlighted that what has traditionally been interpreted as an internally generated oscillation may, at least in part, reflect externally forced variability, thereby complicating to the estimation of the contribution of internal variability to global warming when relying solely on statistical analyses of observational data.

Quote given to Carbon Brief

Supporting evidence

1. Using data to attribute episodes of warming and cooling in instrumental records
2. The role of Atlantic Multi-decadal Oscillation in the global mean temperature variability | Climate Dynamics

8.3 Attribution of global warming

Page 89

MISLEADING

Section 8.3.3

Prof Andreas Schmittner and Prof Peter U. Clark, college of Earth, ocean and atmospheric science, Oregon State University.

In the second paragraph, the authors write: "An application to the well-known Vostok ice core data revealed an error in Al Gore's documentary An Inconvenient Truth. Gore showed the data and drew attention to the coherence of temperature and CO_2 changes over a 440,000 year span, which he asserted was due to CO_2 driving temperature changes. But temperature changes can also affect atmospheric CO_2 levels. Davidson et al. (2015) examined the series and found that temperature Granger causes CO_2 but not the reverse. In other words on the time scales represented in the Vostok data, the coherence in the series is primarily due to the influence of temperature on CO_2 levels, not the feedback of CO_2 levels on temperature." This section should clarify that the Vostok ice core data are oxygen isotopes, a proxy for regional temperature in Antarctica. They do not represent global temperature. Using a reconstruction of global temperature over the last deglaciation (last 20,000 years) Shakun et al. (2012) find that CO_2 leads temperature and thus likely causes much of the warming over that time period. This should be mentioned here.

This section is also contrary to the vast majority of palaeoclimate literature, which has established that atmospheric CO_2 has an important influence on global temperatures during past ice-age cycles. For example, radiative forcing of CO_2 and ice sheets similarly contribute to colder temperatures during the Last Glacial Maximum (Broccoli (2000); Broccoli & Manabe (1987); Hansen et al. (1984); Köhler et al. (2010); Schmittner et al. (2011)); and Weaver et al. (1998)) and simulations of glacial cycles with constant CO_2 underestimate ice volume changes (Abe-Ouchi et al. (2013) and Ganopolski & Calov (2011)). This should be mentioned here, since otherwise it will leave the reader with the false impression that CO_2 variations are unimportant for ice age climate changes.

In the first paragraph, there are several non-peer reviewed citations – e.g. Razzak (2021) and Dagsvik and Moen (2023). The Razzak (2021) paper is problematic because it removes the trends in both CO_2 and temperature data and then investigates the residuals, finding no correlations using only statistical methods. However, physical understanding of Earth's radiation budget clearly suggests that the trend in CO_2 causes the observed temperature trend (Pierrehumbert (2011)). Thus, removing the trends in both time series is not appropriate for attribution studies. Razzak (2021) also ignores other external forcings such as aerosols. I suggest to remove Razzak (2021) and other non-peer reviewed citations. Studies that include other forcings find convincing effects of CO_2 on global warming over the last 100 years (e.g. Lean and Rind (2009)).

Quote given to Carbon Brief

Supporting evidence

1. Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume | Nature
2. Tropical Cooling at the Last Glacial Maximum: An Atmosphere–Mixed Layer Ocean Model Simulation in: Journal of Climate Volume 13 Issue 5 (2000)
3. The influence of continental ice, atmospheric CO2, and land albedo on the climate of the last glacial maximum | Climate Dynamics
4. CP - The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles
5. Climate Sensitivity: Analysis of Feedback Mechanisms - Hansen - 1984 - Geophysical Monograph Series - Wiley Online Library
6. What caused Earth's temperature variations during the last 800,000 years? Data-based evidence on radiative forcing and constraints on climate sensitivity - ScienceDirect
7. How will Earth's surface temperature change in future decades? - Lean - 2009 - Geophysical Research Letters - Wiley Online Library
8. Infrared radiation and planetary temperature | Physics Today | AIP Publishing
9. Climate Sensitivity Estimated from Temperature Reconstructions of the Last Glacial Maximum | Science
10. Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation | Nature
11. Simulated influence of carbon dioxide, orbital forcing and ice sheets on the climate of the Last Glacial Maximum | Nature

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

Arguably the most striking change in the Earth's climate system during the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth. Figure 8.2 shows the planetary albedo variations since 2000, when there are good satellite observations. The 0.5% reduction in planetary albedo since 2015 corresponds to an increase of 1.7 W/m^2 in absorbed solar radiation averaged over the planet (Hansen and Karecha (2025)). For comparison, Forster et al. (2024) estimate the current forcing from the increase in atmospheric CO_2 compared to pre-industrial times to be 2.33 W/m^2.

Prof Piers Forster, professor of climate physics, University of Leeds.

[The citation] is correct, but it presents a somewhat incomplete comparison with the absorbed solar radiation. One's a very long-term forcing, the other is a mix of forcing and response over a shorter period, so the two numbers are not very comparable. All Earth's energy budget terms need to be considered and understood together. And when all components are analysed together, the cause of the Earth's energy balance can be traced to GHG warming and the Earth's system response with a good degree of certainty, as explained by the Hodnebrog et al. (2024) paper already referenced. This text as written is ok, but for me it plays up the uncertainties somewhat.

Quote given to Carbon Brief

Supporting evidence

1. ESSD - Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence
2. Recent reductions in aerosol emissions have increased Earth's energy imbalance | Communications Earth & Environment

8.4 Declining planetary albedo and recent record warmth

Page 90

FALSE

Arctic sea ice extent has declined by about 5% since 1980

Anonymous.

September sea ice (1979-88 average compared to 2015-24 average) is 34% lower today according to OSISAF [Ocean and Sea Ice Satellite Application Facility] observations and 35% lower according to NSIDC [National Snow and Ice Data Center]. For the annual mean sea ice extent, the percentage reduction is 14% according to NSIDC and OSISAF. The number is higher in summer because that is when there is the most sea ice loss and the seasonal minimum, so the least amount to start with. In addition, the evidence given to support this statement links to a figure showing sea ice decline in Antarctica in July.

Quote given to Carbon Brief

Supporting evidence

1. Sea-ice index | OSI SAF
2. Data Tools | National Snow and Ice Data Center

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

...although following 2007 there has been a pause in the Arctic sea ice decline (England et al. (2025)).

Anonymous.

What they say is true and is correctly cited, but lacking context. In the latest version published recently [the DoE report cites a preprint version], the authors note that they "find that the existence of this slowdown also predisposes the sea ice cover for a more rapid decline in the near future". They add that they "would like to underscore that pause or slowdown are used interchangeably to refer to an extended period with little or no decline in sea ice cover, due to the observed realisation of multi-decadal climate variability on top of the response to anthropogenic forcing, temporarily interrupting the ongoing long-term reduction in Arctic sea ice. This does not imply a cessation of human-induced climate change and, instead, it is likely that sea ice would have increased over this period without human influence."

Quote given to Carbon Brief

Supporting evidence

1. Minimal Arctic Sea Ice Loss in the Last 20 Years, Consistent With Internal Climate Variability - England - 2025 - Geophysical Research Letters - Wiley Online Library

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

Regarding Antarctic sea ice, the IPCC AR6 concludes that "There has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability." (Summary for Policymakers, A.1.5)

Anonymous.

While this is true, it is misleading because they neglect to mention that Antarctic sea ice cover has had a dramatic decline since 2015 and the last few years have seen record lows. Studies have found that these record lows were unlikely to have happened before over the last century. Missing out the last few years of Antarctic sea ice trajectory is a huge omission.

Quote given to Carbon Brief

Supporting evidence

1. A regime shift in seasonal total Antarctic sea ice extent in the twentieth century | Nature Climate Change
2. A twenty-first century structural change in Antarctica's sea ice system | Communications Earth & Environment

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

Section 8.4

Dr Helge F. Goessling, climate physicist and group leader, Alfred Wegener Institute.

The authors manage to avoid statements that are individually clearly wrong. It is even somewhat difficult to nail down individual sentences that would be clearly misleading taken alone, because that depends on the context they are placed in. However, considering the section as a whole, I think it's pretty clear that they are over-emphasising uncertainties and the possible relative role of natural variability while down-playing the two other main possible mechanisms behind the albedo decline of the last two and a half decades, namely a possibly emerging positive low-cloud feedback and (largely indirect) aerosol effects.

Quote given to Carbon Brief

Supporting evidence

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

Section 8.4

Prof Richard Allan, professor of climate science, University of Reading.

I did not spot major errors in the section on planetary albedo, although I consider that there is an emphasis on abruptness of temperature and albedo changes, which artificially emphasise the role of natural variability. which could be misleading.

Quote given to Carbon Brief

Supporting evidence

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

A sharp recent increase in global average temperatures has raised the question of short-term drivers of climate. One such candidate is the fraction of absorbed solar radiation which has also increased abruptly in recent years. The question is whether the change is an internal feedback to warming caused by greenhouse gases, or whether something else increased the fraction of absorbed radiation which then caused the recent warming.

Prof Richard Allan, professor of climate science, University of Reading.

A "sharp recent increase in global temperature" and "the fraction of absorbed solar radiation which has also increased abruptly" are potentially misleading since while both global surface temperature and absorbed solar radiation have varied with ENSO, they have also increased steadily over time (Loeb et al. (2024) and Forster et al. (2024)). This wording could artificially emphasise the role of natural variability.

Quote given to Carbon Brief

Supporting evidence

1. Observational Assessment of Changes in Earth's Energy Imbalance Since 2000 | Surveys in Geophysics

8.4 Declining planetary albedo and recent record warmth

Page 90

MISLEADING

Arguably the most striking change in the Earth's climate system during the 21st century is a significant reduction in planetary albedo since 2015, which has coincided with at least two years of record global warmth.

Prof Richard Allan, professor of climate science, University of Reading.

Planetary albedo has decreased before 2015 as well as after, though the decreases are larger around 2012-14 (increases in absorbed sunlight in Loeb et al. (2024), Fig. 5a). Decreases in reflected sunlight up to 2016 are captured by some climate models applying observed SST (Loeb et al. (2020)), suggesting that they are a response to global warming and its spatial pattern (Andrews et al. (2022)), though it is not clear how much of the pattern of global warming is explained by radiative forcing and how much internal variability.

Quote given to Carbon Brief

Supporting evidence

1. New Generation of Climate Models Track Recent Unprecedented Changes in Earth's Radiation Budget Observed by CERES - Loeb - 2020 - Geophysical Research Letters - Wiley Online Library

8.4 Declining planetary albedo and recent record warmth

Page 91

MISLEADING

The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade: • Natural climate variability • Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha (2025))

Dr Helge F. Goessling, climate physicist and group leader, Alfred Wegener Institute.

Maybe even more importantly, they omit the third major possible mechanism behind the cloud-cover decline altogether, namely indirect aerosol effects. They do mention aerosols and recent aerosol emission reductions, but only prior to the part where they state that the main reason for the albedo-decline seems to be related to clouds (which, by itself, is true). They write: "The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade." However, the indirect aerosol effect, although uncertain, is likely even stronger than the direct aerosol effect, and it is an important candidate for explaining a part of the recent cloud-cover decline. By omitting this completely, they further emphasise the relative importance of natural variability to a degree that can not be considered appropriate.

Quote given to Carbon Brief

Supporting evidence

8.4 Declining planetary albedo and recent record warmth

Page 91

MISLEADING

Surface albedo changes have thus contributed only weakly to the recent planetary albedo decline, particularly when averaged annually and globally.

Prof Richard Allan, professor of climate science, University of Reading.

Surface albedo has also contributed significantly to the decline in global albedo according to Loeb et al. (2024), which accounts for cloud masking: "...part of the positive –SW trend is impacted by decreases in surface albedo from declining sea-ice coverage during the CERES period". However, this applies to the period since 2000, rather than during 2015, which line 10 [of the DoE report] is referring to, while the decrease in planetary albedo has been observed over the full CERES period rather than just in 2015 (Loeb et al. (2024)).

Quote given to Carbon Brief

Supporting evidence

1. Observational Assessment of Changes in Earth's Energy Imbalance Since 2000 | Surveys in Geophysics

8.4 Declining planetary albedo and recent record warmth

Page 91

MISLEADING

Loeb et al. found that decreases in low- and mid-level clouds since 2015 are the primary reason for decreasing planetary albedo in the northern hemisphere, whereas in the southern hemisphere the decrease in planetary albedo is primarily due to decreases in mid-level clouds across all latitude zones.

Prof Richard Allan, professor of climate science, University of Reading.

The stated "decreases in low- and mid-level clouds" is misleading since Loeb et al. (2024) find decreases in cloud cover and also reflectance have contributed to the increase in absorbed sunlight along with surface albedo decreases (that can are related to ice melt elsewhere in the article): "[W]e find that decreases in low and middle cloud fraction and reflection and reduced reflection from cloud-free areas in mid-high latitudes are the primary reasons for increasing ASR [absorbed solar radiation] trends in the [northern hemisphere]...In the [southern hemisphere] the increase in ASR is primarily from decreases in middle cloud reflection and a weaker reduction in low-cloud reflection." The increase in reflection counters arguments presented that the decreases in aerosol are not influencing the decreases in albedo as their effect on making clouds brighter diminishes (e.g. Hodnebrog et al. (2024)), while the additional steady rise in ASR during the CERES period is also consistent with cloud and ice-albedo feedbacks to warming (Forster et al. (2021); Tselioudis et al. (2025); and Norris et al. (2016)) as well as declining global aerosol emissions (Quaas et al. (2022)).

Quote given to Carbon Brief

Supporting evidence

1. Observational Assessment of Changes in Earth's Energy Imbalance Since 2000 | Surveys in Geophysics

8.4 Declining planetary albedo and recent record warmth

Page 91

MISLEADING

The issue then becomes the cause of the change in cloud cover. Two explanations have been posited for the declining cloud cover over the past decade: • Natural climate variability • Changes in low cloud cover associated with warming sea surface temperatures, implying an emerging positive feedback to climate change (Hansen and Karecha (2025))

Prof Richard Allan, professor of climate science, University of Reading.

Two explanations for decreased global albedo are presented, but the decline in ocean aerosols is ignored and this has been identified as an important driver of decreased global albedo (e.g. Hodnebroeg et al. (2024)). Combined with overemphasis of the abruptness of changes, this is potentially misleading since it overemphasises the role of natural variability.

Quote given to Carbon Brief

Supporting evidence

1. Recent reductions in aerosol emissions have increased Earth's energy imbalance | Communications Earth & Environment

8.4 Declining planetary albedo and recent record warmth

Page 92

MISLEADING

It is not easy to justify a new positive low cloud feedback that began emerging in 2015 since there is no obvious feedback trigger starting at that time.

Dr Helge F. Goessling, climate physicist and group leader, Alfred Wegener Institute.

I think this is an example of a "straw man argument", because it's clear that there would not be a trigger starting exactly at some point. Rather, a forced signal (like a positive cloud feedback) would be superimposed by natural variations, and at some point, depending on signal-to-noise ratio (and possible other forcings) and how the associated forcing grows, the forced signal can emerge from the noise. An associated timeseries may just look like something kicked in at a specific time.

Quote given to Carbon Brief

Supporting evidence

8.4 Declining planetary albedo and recent record warmth

Page 92

MISLEADING

However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds: • The 2014-16 was one of the strongest El Niño events on record. • A cold anomaly beginning in 2015 in the subpolar gyre of the North Atlantic reflects a shift in the ocean circulation pattern associated with decadal variability in the Atlantic (Frajka-Williams et al. (2017); Arthur et al. (2021)). • The Pacific Decadal Oscillation positive index peaked in 2016, then declined and has been in negative territory since late 2019. • Eruption of the submarine Hunga-Tonga volcano in 2022.

Dr Helge F. Goessling, climate physicist and group leader, Alfred Wegener Institute.

When it comes to natural variability, they are listing quite comprehensively which aspects of natural variations could – in principle – have had an impact on planetary albedo, in part also overemphasising some aspects that rather clearly can not have had a major impact on the longer-term decline, such as ENSO (as we also investigated in our paper). Also their interpretation of results for the Hunga Tonga eruption and its possible contribution to the recent warming surge seems not to be a balanced representation of the recent literature about it, which does not suggest a major contribution. Also, they provide their list of natural variability aspects right after the down-playing statement about the possible low-cloud feedback mentioned above, saying: "However, there are numerous natural climate signals during this period that are associated with atmospheric circulation changes that can influence the distribution of clouds." This shows quite clearly that they want to emphasise the natural variability over the possible low-cloud feedback.

Quote given to Carbon Brief

Supporting evidence

8.4 Declining planetary albedo and recent record warmth

Page 92

MISLEADING

It is not easy to justify a new positive low cloud feedback that began emerging in 2015 since there is no obvious feedback trigger starting at that time.

Prof Richard Allan, professor of climate science, University of Reading.

A change in the SST pattern has been linked to a decline in low-altitude cloud over some stratocumulus regions (Andrews et al. (2022) and Loeb et al. (2020)) and it is misleading to paint these changes as requiring new feedbacks.

Quote given to Carbon Brief

Supporting evidence

1. New Generation of Climate Models Track Recent Unprecedented Changes in Earth's Radiation Budget Observed by CERES - Loeb - 2020 - Geophysical Research Letters - Wiley Online Library

8.4 Declining planetary albedo and recent record warmth

Page 92

MISLEADING

A change of 1-2% in global cloud cover has a greater radiative impact on the climate than the direct radiative effect of doubling CO2.

Prof Richard Allan, professor of climate science, University of Reading.

Short-term interannual fluctuations are unfairly compared with long-term radiative forcing. Also, a decrease in global albedo is an expected consequence of global warming as feedbacks cause ice to melt and some clouds to diminish (e.g. Forster et al. (2021)). This signal in shortwave radiation is seen to a greater extent than in the longwave since decreases in outgoing longwave due to rising greenhouse gases being offset by the increases in outgoing longwave from the resulting higher temperatures that are influenced by the greenhouse gases, but also declining aerosol and feedbacks that amplify the warming through ice melt and cloud responses to warming (e.g. Raghuraman et al. (2024)).

Quote given to Carbon Brief

Supporting evidence

1. Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity | Climate Change 2021: The Physical Science Basis

8.6 Extreme event attribution (EEA)

Page 96

FALSE

The existence of an outlier at the end of a data series poses the problem that estimates of the event probabilities will be biased whether the outlier is included or excluded (Barlow et al. (2020)). Methods to eliminate the bias have not yet been established.

Dr Ophélia Miralles, research scientist, ETH Zurich and Prof Anthony C. Davison, professor of mathematics, École Polytechnique Fédérale de Lausanne.

The text suggests that the presence of the trigger event at the end can't be dealt with, whereas the argument in Barlow and in our paper is that it can be dealt with (if the selection event is known) with appropriate statistical methods specifically detailed in both papers.

Quote given to Carbon Brief

Supporting evidence

1. Timing and spatial selection bias in rapid extreme event attribution - ScienceDirect
2. Inference for Extreme Values Under Threshold-Based Stopping Rules | Journal of the Royal Statistical Society Series C: Applied Statistics | Oxford Academic

8.6 Extreme event attribution (EEA)

Page 96

MISLEADING

Methods to eliminate the bias have not yet been established, leading some experts (e.g. Miralles and Davison (2023)) to argue that in settings in which a data series contains a single extreme event at the end, estimation of a return period for the extreme event will be so biased and uncertain that it should be avoided altogether.

Dr Ophélia Miralles, research scientist, ETH Zurich and Prof Anthony C. Davison, professor of mathematics, École Polytechnique Fédérale de Lausanne.

The cited paper does argue that the estimated return period is highly variable and so one should avoid using it, but also states that if it has to be used, one should clearly state its uncertainty. It does not imply that fast weather attribution should not be performed at all.

Quote given to Carbon Brief

Supporting evidence

1. Timing and spatial selection bias in rapid extreme event attribution - ScienceDirect

8.6 Extreme event attribution (EEA)

Page 97

MISLEADING

Zeder et al. (2023) also concluded that the methods employed by Philip et al. (2022, the WWA analysis) tend to overstate the rarity of extreme heat waves, leading to a biased perception of the effect of climate change on the heatwave event: "The tendency to overestimate the return period of observed extreme heatwave events may fuel the impression that seemingly impossible heatwave extremes are currently clustering at an unprecedented rate."

Prof Erich Fischer, lecturer at the department of environmental systems science, ETH Zurich.

The quote taken from the paper Zeder et al. (2023) led by my (former) PhD student, Joel Zeder, is in itself correct, yet taken completely out of context. Our paper shows indeed that when using relatively short observational timeseries, return level estimates may be systematically underestimated and return periods may be overestimated, which affects the calculation of the risk ratio in attribution studies. We further concluded that the risk of extreme heatwaves could be underestimated in both past and present-day climate and recommend following an approach like Miralles and Davison (2023). This paper applied the recommended approach specifically to the 2021 Pacific north-west heatwave. However, both Miralles and Davison (2023) and Zeder et al. (2023) show that while methodological choices affect the exact estimate of the risk ratio, all estimates show a strong role of long-term warming increasing the probability of the event.

Quote given to Carbon Brief

Supporting evidence

1. The Effect of a Short Observational Record on the Statistics of Temperature Extremes - Zeder - 2023 - Geophysical Research Letters - Wiley Online Library
2. Timing and spatial selection bias in rapid extreme event attribution - ScienceDirect

Part III: Impacts on ecosystems and society

9.1 Econometric analyses

Page 104

FALSE

Bareille and Chakir (2023) assembled a large data base on farm sale prices in France for properties that sold twice between 1996 and 2019. They could replicate pessimistic results showing negative effects of warming on agricultural land values using conventional econometric modelling.

Dr Francois Bareille, researcher in economics, INRAE & University Paris-Saclay.

Bareille and Chakir (2023) do reproduce the standard results obtained from "conventional econometric modelling" like the Ricardian approach proposed by Mendelsohn et al. (1994). However, these standard results in no way demonstrate "negative effects of warming on agricultural land values". Rather, as illustrated in Figure 5 of their study, Bareille and Chakir (2023) closely mimic the outcomes of the Ricardian approach in similar contexts, which points to slightly positive impacts of climate change on farmland values. Such findings are consistent with the broader literature when applied to contexts with moderate climate conditions. Nevertheless, as has been extensively discussed, these results are likely subject to bias arising from omitted variables.

Quote given to Carbon Brief

Supporting evidence

1. The impact of climate change on agriculture: A repeat-Ricardian analysis - ScienceDirect
2. The empirical analysis of climate change impacts and adaptation in agriculture - ScienceDirect
3. The Use of Cross-Sectional Analysis to Measure Climate Impacts on Agriculture: Theory and Evidence | Review of Environmental Economics and Policy: Vol 11, No 2

9.1 Econometric analyses

Page 104

FALSE

But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture.

Dr Francois Bareille, researcher in economics, INRAE & University Paris-Saclay.

Bareille and Chakir (2023) do not identify any negative impacts of climate change on land values; across all methodologies they employ, the evidence consistently points toward positive effects of recent climate trends.

Quote given to Carbon Brief

Supporting evidence

1. The impact of climate change on agriculture: A repeat-Ricardian analysis - ScienceDirect

9.1 Econometric analyses

Page 104

MISLEADING

But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture.

Dr Francois Bareille, researcher in economics, INRAE & University Paris-Saclay.

These results are derived from recent climate trends over the period 1990-2020 in the context of French agriculture. While such moderate warming may generate short-term benefits for agriculture, more substantial – and as yet unobserved – warming is likely to result in losses. It is well established that higher temperatures induced by climate change can produce non-linear effects, with moderate warming potentially yielding gains, but more pronounced warming leading to detrimental impacts.

Quote given to Carbon Brief

Supporting evidence

1. Global non-linear effect of temperature on economic production | Nature

9.1 Econometric analyses

Page 104

MISLEADING

But by taking advantage of the repeat sales data, which provides information on site-specific changes in land prices, they found the results reversed and implied that climate change will be very beneficial for French agriculture.

Dr Francois Bareille, researcher in economics, INRAE & University Paris-Saclay.

While such a result may arise in contexts like France (where northern regions remain, for the time being, too cold to cultivate high-value crops), these findings are highly context-specific and cannot be generalised to other settings. This is particularly true for a large and heterogeneous country like the US, where both climatic and agricultural conditions differ substantially from those in France. Bareille and Chakir (2023) provide indirect evidence that the positive impacts of recent climate change on French agriculture identified with their approach are likely driven by vineyard expansion, a phenomenon highly specific to France and not transferable to the US context.

Quote given to Carbon Brief

Supporting evidence

1. The Use of Cross-Sectional Analysis to Measure Climate Impacts on Agriculture: Theory and Evidence | Review of Environmental Economics and Policy: Vol 11, No 2

9.1 Econometric analyses

Page 104

MISLEADING

The authors concluded that, taking adaptation into account, a warming climate would yield positive benefits for French agriculture that were between two and 20 times larger than had previously been estimated. On average, with full adaptation, they concluded that climate change under the medium RCP4.5 scenario could double the value of French farmland by 2100

farmland by 2100.

Dr Francois Bareille, researcher in economics, INRAE & University Paris-Saclay.

These results are obtained using a novel method, the so-called repeat-Ricardian approach. In contrast to other studies cited in the report – such as Mendelsohn et al. (1994), Deschênes and Greenstone (2007), Schlenker and Roberts (2009) and Burke and Emerick (2016) – this approach has not yet been replicated in other contexts. Its findings should therefore be interpreted with caution. By comparison, dozens of replications and extensions of Deschênes and Greenstone (2007), Schlenker and Roberts (2009) and Burke and Emerick (2016) consistently document negative impacts of climate change on crop productivity in the US, but also worldwide.

Quote given to Carbon Brief

Supporting evidence

1. Impacts of climate change on global agriculture accounting for adaptation | Nature

---

9.1 Econometric analyses

Page 105

MISLEADING

A major deficiency of all these studies, however, is that they omit the role of CO2 fertilisation. Climate change as it relates to this report is caused by GHG emissions, chiefly CO2. The econometric analyses referenced above focus only on temperature and precipitation changes and do not take account of the beneficial growth effect of the additional CO2 that drives them.

Dr Francois Bareille, researcher in economics, INRAE & University Paris-Saclay.

All of these studies implicitly account for the effects of CO2 fertilisation on agriculture insofar as local CO2 concentrations are correlated with changes in temperature and precipitation. Moreover, Hultgren et al. (2025) show that the positive effects of CO2 fertilisation only partially offset the negative impacts of anthropogenic climate change on crop yields arising from changes in temperature and precipitation.

Quote given to Carbon Brief

Supporting evidence

1. Impacts of climate change on global agriculture accounting for adaptation | Nature

9.2 Field and laboratory studies of CO2 enrichment

Page 105

MISLEADING

One of the ways the effect of CO2 on crop growth has been studied is through "free air enrichment experiments" or FACE plots, in which small sources of CO2 are placed in fields surrounding plants and the growth response to elevated CO2 under varying weather conditions are recorded. Ainsworth et al. (2020) summarises results from about 250 such studies. They found that elevation of CO2 by 200ppm caused anaverage 18% increase in crop yield in C3 plants. C4 plants exhibited benefits mainly under drought conditions.

Prof Steve Long, Ikenberry Endowed University Chair, University of Illinois.

While this report is correct in saying that, in isolation, our research has shown that an increase in CO2 does (on average for C3 crops) results in increased yields and decreased quality, and that it can increase water use efficiency. But when account is taken of the accompanying changes in tropospheric ozone, temperature, atmospheric water vapor pressure deficit and extreme drought, heat and flooding events then the overall effect of GHG driven climate and atmospheric change is strongly negative.

Quote given to Carbon Brief

Supporting evidence

9.3 Crop modelling meta-analyses

Page 107

MISLEADING

McKitrick (2025) re-examined the Moore et al. database and found that, while it claimed to cover 1,722 studies, only half the entries (N=862) had complete records, so that the sample available for regression analysis was much smaller than both studies indicated. McKitrick noted that the records most commonly missing were the changes in ambient CO2 and found that in many cases these could be recovered from the underlying studies or the original climate scenario tables, thereby increasing the usable sample size by 40%. The crop yield projections incorporating the newly available data changed considerably. As shown in Figure 9.2, whereas the partial data set implied warming would decrease yield

(blue lines), the complete data set implied constant or increase global yields, even out to 5C warming (green lines).

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

Regression analysis of historical climate impacts on crop yield do not capture the impact of non-linear processes, such as effects of extreme heat stress occuring at crop anthesis. Hence the conclusion based on a single approach is misleading (Moore et al. (2017) and McKitrick (2025)). The IPCC assessed a range of peer-reviewed publications based on regression analysis and process-based models, also including the CO2 fertilisation effects (for example, see AR6 WG2, chapter 14, p1,956, for synthesis on US agriculture).

Quote given to Carbon Brief

Supporting evidence

1. Chapter 14: North America | Climate Change 2022: Impacts, Adaptation and Vulnerability

---

9.4 CO2 fertilisation and nutrient loss

Page 107

MISLEADING

Evidence has shown that CO2 -induced biomass gains are sometimes accompanied by reductions in the concentrations of protein and other key nutrients such as iron and zinc (Ebi et al. 2021)."

Prof Kristie Ebi, professor of global health and Dr Becca Neumann, associate professor of civil and envrionmental engineering.

All plants absorb carbon dioxide from the atmosphere, using photosynthetic pathways to break down that carbon dioxide into carbon and oxygen, and then using the carbon to grow. Eighty-five percent of plants use a photosynthetic pathway that, based on biochemical characteristics, is termed C3; these C3 plants include important crops such as wheat, rice, barley, oats, rye, soybean and potatoes. Field experiments with wheat and rice under a doubling of CO2 from pre-industrial concentrations demonstrate that protein declines by about 10%, B-vitamins by as much as 30% and micronutrients by about 5% (see Ebi et al. (2021) and associated references). Wheat and rice each provide about 20% of calories consumed worldwide, with wide regional variability (Awika

(2011) and Shiferaw et al. (2013)). Corn, sorghum and millet use a different photosynthetic pathway (C4) and are not expected to experience declines in nutrient density with higher CO2 concentrations. The DoE CWG report conflates these two photosynthetic pathways into "sometimes" without being clear that declines in nutrient density are consistently seen under elevated CO2 for C3 crops (Loladze (2002) and (2014); Loladze et al. (2019); Myers et al. (2014); Taub et al. (2008); J. Wang et al. (2019) and (2020); and Zhu et al. (2018)), which are widely consumed in the US.

The DoE CWG report also ignores a key fact raised in Ebi et al. (2021) that elevated CO2 and elevated temperature can increase toxins such as arsenic and cadmium in crops (Dhar et al. (2020); Farhat et al. (2021) and (2023); Guo et al. (2011); Muehe et al. (2019); J. Wang et al. (2019); Y. Wang et al. (2023); and Yuan et al. (2021)), not just dilute nutrients. Ingestion of toxins in food results in illness, shortened life span, reduced quality of life and death (Gibb et al. (2019)).

Quote given to Carbon Brief

Supporting evidence

1. Nutritional quality of crops in a high CO2 world: an agenda for research and technology development - IOPscience
2. Major Cereal Grains Production and Use around the World | ACS Symposium Series
3. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security | Food Security
4. Rising atmospheric CO2 and human nutrition: toward globally imbalanced plant stoichiometry?: Trends in Ecology & Evolution
5. Hidden shift of the ionome of plants exposed to elevated CO2 depletes minerals at the base of human nutrition | eLife
6. Rising Atmospheric CO2 Lowers Concentrations of Plant Carotenoids Essential to Human Health: A Meta-Analysis - Loladze - 2019 - Molecular Nutrition & Food Research - Wiley Online Library
7. Increasing CO2 threatens human nutrition | Nature
8. Global Change Biology | Environmental Change Journal | Wiley Online Library
9. Changes in grain protein and amino acids composition of wheat and rice under short-term increased [CO2] and temperature of canopy air in a paddy from East China - Wang - 2019 - New Phytologist - Wiley Online Library
10. Responses of wheat and rice grain mineral quality to elevated carbon dioxide and canopy warming - ScienceDirect
11. Carbon dioxide (CO2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries | Science Advances
12. The Increase in the Arsenic Concentration in Brown Rice Due to High Temperature during the Ripening Period and Its Reduction by Silicate Material Treatment
13. Altered arsenic availability, uptake, and allocation in rice under elevated temperature - ScienceDirect
14. When does temperature matter? Response of rice arsenic to heat exposure during different developmental stages | Plant and Soil
15. Elevated CO2 Levels Affects the Concentrations of Copper and Cadmium in Crops Grown in Soil Contaminated with Heavy Metals under Fully Open-Air Field Conditions | Environmental Science & Technology
16. Rice production threatened by coupled stresses of climate and soil arsenic | Nature Communications
17. Climatic CO2 level-driven changes in the bioavailability, accumulation, and health risks of Cd and Pb in

paddy soil–rice systems - ScienceDirect
18. Warming facilitates microbial reduction and release of arsenic in flooded paddy soil and arsenic accumulation in rice grains - ScienceDirect

---

9.4 CO2 fertilisation and nutrient loss

Page 107

MISLEADING

Some experiments have shown that the rising temperatures expected to accompany higher CO2 levels will offset this loss (Köhler et al. (2019)) although the evidence for this is mixed, as is the evidence that nutrient dilution observed to date is entirely attributable to higher CO2 (Ziska (2022)).

Prof Kristie Ebi, professor of global health and Dr Becca Neumann, associate professor of civil and envrionmental engineering.

Some experiments have shown that rising temperatures expected to accompany higher CO2 levels can offset nutritional losses (Köhler et al. (2019) and, while the DoE CWG report acknowledges that evidence for this temperature compensation is mixed, it fails to cite studies that found partial or no compensation in nutritional density when elevated CO2 was crossed with elevated temperature (e.g., Jayawardena et al. (2021); J. Wang et al. (2019); Wei et al. (2021); and Ziska et al. (1997)). On the flip side of crop nutritional quality, increased temperatures are expected to increase toxin levels in crops. Wang et al. (2020) found that while warmer temperatures moderately mitigated the loss of nutrients associated with elevated CO2, the warmer temperatures simultaneously increased manganese, molybdenum, chromium, nickel, cadmium and lead concentrations in rice and wheat. A study investigating arsenic contamination of rice found that grain arsenic concentrations were more elevated when elevated CO2 was combined with elevated temperature than when either elevated CO2 or elevated temperature operated alone (Muehe et al. (2019)).

The second half of the statement above (i.e., "… as is the evidence that nutrient dilution observed to date is entirely attributable to higher CO2") draws an incorrect conclusion from Ziska (2022). Ziska (2022) presents a figure (Figure 1) that shows newer breeding lines of spring wheat have less percent protein, but that all the breeding lines have experienced declines in percent protein over the 20th century. Thus, Ziska (2022) acknowledges that breeding can change nutritional density but ultimately concludes that "[CO2] is directly affecting protein concentration separate from breeding history".

Quote given to Carbon Brief

Supporting evidence

1. Increased temperatures may safeguard the nutritional quality of crops under future elevated CO2 concentrations - Köhler - 2019 - The Plant Journal - Wiley Online Library
2. meta-analysis of the combined effects of elevated carbon dioxide and chronic warming on plant %N, protein content and N-uptake rate | AoB PLANTS | Oxford Academic
3. Changes in grain protein and amino acids composition of wheat and rice under short-term increased [CO2] and temperature of canopy air in a paddy from East China - Wang - 2019 - New Phytologist - Wiley Online Library
4. Responses of rice qualitative characteristics to elevated carbon dioxide and higher temperature: implications for global nutrition - Wei - 2021 - Journal of the Science of Food and Agriculture - Wiley Online Library
5. Growth and Yield Response of Field-Grown Tropical Rice to Increasing Carbon Dioxide and Air Temperature | Agronomy Journal
6. Responses of wheat and rice grain mineral quality to elevated carbon dioxide and canopy warming - ScienceDirect
7. Rice production threatened by coupled stresses of climate and soil arsenic | Nature Communications
8. Rising Carbon Dioxide and Global Nutrition: Evidence and Action Needed

---

9.4 CO2 fertilisation and nutrient loss

Page 107

MISLEADING

If nutrient dilution does occur under rising CO2 levels, there are several adaptive strategies that could be pursued. First, selective breeding to raise micronutrient content is already established (Saltzman et al. (2017)) and has proven to be a cost-effective agronomic strategy (Ebi et al. (2021)).

Prof Kristie Ebi, professor of global health and Dr Becca Neumann, associate professor of civil and envrionmental engineering.

Biofortification via selective breeding has been used successfully to raise the zinc, iron and vitamin A content of crops, per Saltzman et al. (2017). However, this approach is not a "proven" agronomic strategy, cost-effective or otherwise, for addressing simultaneous nutrient dilution by elevated CO2. Ebi et al. (2021) specifically stated: "An additional challenge for biofortification is the tendency of rising CO2 concentrations to diminish the concentrations of multiple nutrients concomitantly (Loladze (2014a) and (2014b)) in contrast to biofortification that targets only one or a few selected nutrients." Further, biofortification cannot address the issue of increased toxin levels in crops associated with elevated CO2 and CO2-induced warming.

Quote given to Carbon Brief

Supporting evidence

1. Availability, production, and consumption of crops biofortified by plant breeding: current evidence and future potential - Saltzman - 2017 - Annals of the New York Academy of Sciences - Wiley Online Library
2. Nutritional quality of crops in a high CO2 world: an agenda for research and technology development - IOPscience
3. Hidden shift of the ionome of plants exposed to elevated CO2 depletes minerals at the base of human nutrition | eLife

---

References

Page 108

FALSE

Deryng, D., Elliott, J., Folberth, C. et al. (2021) Regional disparities in the beneficial effects of rising CO2 concentrations on crop water productivity. Nature Climate Change 6, 786–790 (2016). https://doi.org/10.1038/nclimate2995

Dr Delphine Deryng, lead author, IPCC AR6 WG2.

The date of the citation is incorrect, and I didn't find reference to this paper in the text of the chapter

Quote given to Carbon Brief

Supporting evidence

9.4 CO2 fertilisation and nutrient loss

Page 108

MISLEADING

Optimal strategies will be location-specific because they vary by crop, climate and soil type (Ebi et al. (2021)).

Prof Kristie Ebi, professor of global health and Dr Becca Neumann, associate professor of civil and envrionmental engineering.

Developing new cultivars requires significant investments and generally take years (see CGIAR programmes). Such programmes will not be developed locally, nor will the investment make sense if the developed cultivar only applies to a specific location.

Quote given to Carbon Brief

Supporting evidence

1. CGIAR: Science for humanity's greatest challenges

9.4 CO2 fertilisation and nutrient loss

Page 108

MISLEADING

Second, fortification of food products with micronutrients is already routine. Folic acid (a B vitamin) is added to flour and many other foods; iodine is added to table salt, most commercial breakfast cereals are fortified with iron and numerous vitamins, etc. Third, dietary supplements in the form of multivitamin tablets are inexpensive, widely-available and routinely consumed.

Prof Kristie Ebi, professor of global health and Dr Becca Neumann, associate professor of civil and envrionmental engineering.

Fortification and dietary supplements do not currently alleviate nutrient deficiencies; therefore, it is unlikely that such approaches will alleviate nutrient deficiencies in the future, particularly if they are exacerbated by lower crop nutrient density. For example, 30% of women and girls worldwide (15-49 years) currently have iron-deficiency anemia (World Health Organization, 2025), including nearly 40% of women and girls (12-21 years) in the US (Weyand et al. (2023)). These deficiencies exist despite decades of dietary supplement availability (Macdougall (2017)). The DoE CWG report ignores that high CO2 concentrations affect a wide range of macro and micronutrients beyond iron and zinc, such as lithium (for mental health), magnesium (for muscle and nerve function, blood pressure regulation, bone health and energy production) and others (Loladze (2014)). Dietary supplements do not address these critical contributions to hidden hunger (Wallace et al. (2014)). US government guidelines emphasise that supplements are not an adequate substitute for a nutrient dense diet (US Department of Agriculture and US Department of Health and Human Services (2010)). Further, fortification of food or use of supplements will not address the health risk posed by increased toxin concentrations in grain associated with elevated CO2 and CO2-induced warming.

Quote given to Carbon Brief

Supporting evidence

1. Anaemia in women and children
2. Prevalence of Iron Deficiency and Iron-Deficiency Anemia in US Females Aged 12-21 Years, 2003-2020 | Adolescent Medicine | JAMA | JAMA Network
3. Iron Supplementation: What's New? | Blood | American Society of Hematology
4. Hidden shift of the ionome of plants exposed to elevated CO2 depletes minerals at the base of human nutrition | eLife
5. Multivitamin/Mineral Supplement Contribution to Micronutrient Intakes in the United States, 2007–2010: Journal of the American College of Nutrition: Vol 33, No 2
6. PDF

9.4 CO2 fertilisation and nutrient loss

Page 108

MISLEADING

One concern about reliance on adaptive strategies is whether they are feasible in low-income countries. Micronutrient deficiency is already a problem in the developing world and dietary supplements have proven to be an effective low-cost response (Ebi et al. (2021)).

Prof Kristie Ebi, professor of global health and Dr Becca Neumann, associate professor of civil and envrionmental engineering.

As noted in the previous comment, micronutrient deficiency is a health problem in developing and developed countries; dietary supplements have not solved the problem. Micronutrient deficiency is expected to increase with elevated CO2 (Beach et al. (2019); Smith and Myers (2019); Weyant et al. (2018); and Zhu et al. (2018)). As supplements have been unable to fully address the current deficiencies in micronutrients, it is unlikely they will successfully ameliorate a future increased health burden caused by nutrient dilution in crops. In addition, as noted in the previous comment, supplements will not address the health issues posed by increased toxin concentrations in grain expected with elevated CO2 and CO2-induced warming.

Quote given to Carbon Brief

Supporting evidence

1. Combining the effects of increased atmospheric carbon dioxide on protein, iron, and zinc availability and projected climate change on global diets: a modelling study - The Lancet Planetary Health
2. Global Health Implications of Nutrient Changes in Rice Under High Atmospheric Carbon Dioxide - Smith - 2019 - GeoHealth - Wiley Online Library
3. Anticipated burden and mitigation of carbon-dioxide-induced nutritional deficiencies and related diseases: A simulation modeling study | PLOS Medicine
4. Carbon dioxide (CO2) levels this century will alter the protein, micronutrients, and vitamin content of rice

grains with potential health consequences for the poorest rice-dependent countries | Science Advances

9.4 CO2 fertilisation and nutrient loss

Page 108

MISLEADING

It should also be noted the IPCC emission scenarios that generate high levels of warming also involve strong income growth. The SSP scenarios assume that, compared to 2005 levels, global per capita income will double by 2100 in the lowest growth case (SSP3), and in the highest emission case (SSP5) global per-capita income will grow nearly 16-fold. In that scenario even the poorest regions (Africa and the Middle East) end up with a per capita income of about US$126,000, 70% higher than current US per capita income (about US$75,000). Consequently the same scenarios in which CO2 levels increase the most are also those in which global poverty is largely eliminated, in which case all countries would be able to afford dietary supplements as necessary to address micronutrient deficiencies, if they arise and cannot be addressed using on-farm agricultural strategies.

Prof Kristie Ebi, professor of global health and Dr Becca Neumann, associate professor of civil and envrionmental engineering.

The US is one of the wealthier countries in the world, yet many US citizens suffer from micronutrient deficiencies. Wallace et al. (2014) used data from the National Health and Nutrition Examination Survey (2007-10) to determine that despite the fact that 51% of Americans consume multivitamin/mineral supplements with greater than nine micronutrients, many fail to meet the estimated average requirement for vitamin A (35%), vitamin C (31%), vitamin D (74%), vitamin E (67%), vitamin K (77%), calcium (39%), magnesium (46%), potassium (100%) and choline (92%). Bird et al. (2017) concluded that "nearly one-third of the US population is at risk of deficiency in at least one vitamin, or has anemia".

Growth and development of children and lifespan health depends on adequate intake of micronutrients. Decreasing the nutrient density of diets through continued emissions of CO2 will exacerbate the situation, even with any associated income growth.Ingestion of toxins in food is a global problem that affects the health of millions of people, including those living in wealthy countries (Consumer Reports (2012) and (2014); and Gibb et al. (2019)). A growth in income will not offset the health risk posed by contaminated food. It is expected that this health risk will grow as elevated CO2 and

CO2-induced warming increase the toxin content of crops (Dhar et al. (2020); Farhat et al. (2021) and (2023); Guo et al. (2011); Muehe et al. (2019); J. Wang et al. (2019); Y. Wang et al. (2023); and Yuan et al. (2021).

Quote given to Carbon Brief

Supporting evidence

1. Multivitamin/Mineral Supplement Contribution to Micronutrient Intakes in the United States, 2007–2010: Journal of the American College of Nutrition: Vol 33, No 2
2. Arsenic In Your Food Investigated - Consumer Reports
3. Estimates of the 2015 global and regional disease burden from four foodborne metals – arsenic, cadmium, lead and methylmercury - ScienceDirect
4. The Increase in the Arsenic Concentration in Brown Rice Due to High Temperature during the Ripening Period and Its Reduction by Silicate Material Treatment
5. Altered arsenic availability, uptake, and allocation in rice under elevated temperature - ScienceDirect
6. Elevated CO2 Levels Affects the Concentrations of Copper and Cadmium in Crops Grown in Soil Contaminated with Heavy Metals under Fully Open-Air Field Conditions | Environmental Science & Technology
7. Rice production threatened by coupled stresses of climate and soil arsenic | Nature Communications
8. Changes in grain protein and amino acids composition of wheat and rice under short-term increased [CO2] and temperature of canopy air in a paddy from East China - Wang - 2019 - New Phytologist - Wiley Online Library
9. Climatic CO2 level-driven changes in the bioavailability, accumulation, and health risks of Cd and Pb in paddy soil–rice systems - ScienceDirect
10. Warming facilitates microbial reduction and release of arsenic in flooded paddy soil and arsenic accumulation in rice grains - ScienceDirect

---

9.4 CO2 fertilisation and nutrient loss

Page 108

MISLEADING

In summary, there is abundant evidence going back decades that rising CO2 levels benefit plants, including agricultural crops, and that CO2-induced warming will be a net benefit to US agriculture. To the extent nutrient dilution occurs there are mitigating strategies

available that will need to be researched and adapted to local conditions.

Prof Kristie Ebi, professor of global health and Dr Becca Neumann, associate professor of civil and envrionmental engineering.

There is abundant evidence that under ideal conditions (i.e., adequate nutrients and water and optimal temperatures), crop productivity increases with rising CO2 levels (e.g., Ainsworth & Long (2020)). These increases diminish or disappear when conditions are non-ideal (i.e., nutrients are limited, water and temperatures are sub-optimal). As CO2 concentrations increase, ambient temperatures will continue warming and weather patterns will shift, altering water and nutrient availability. It is not clear that boosts in productivity generated by elevated CO2 will compensate for the damage to plant productivity caused by these other stressors. In many parts of the world, even with adaptation, crop yields are expected to decline (Hultgren et al. (2025)). Further, discussed in the comments above, elevated CO2 is associated with declining nutrient density in crops. Therefore, it is disingenuous to state that there is "abundant evidence going back decades that rising CO2 levels benefit plants". This statement cherry-picks the productivity boost to plants associated with rising CO2 levels while ignoring the negative human health outcomes that will co-occur. The scientific consensus is that CO2-induced warming will be harmful to US agriculture, leading to yield declines (Hu et al. (2024); Hultgren et al. (2025); Lobell et al. (2011); Lobell and Field (2007); and Zhao et al. (2017)). Physiological studies of crops show there is an optimal temperature at which yields maximise. When temperatures are below or above this optimal point, yields decline.

Further, as outlined in the comments to Section 9.4 above, CO2-induced warming is associated with increased toxin levels in crops.It is factually inaccurate to state that "CO2-induced warming will be a net benefit to US agriculture". There are strategies, such as biofortification and supplementation, that can be employed to help mitigate nutrient dilution in crops, as discussed in Ebi et al. (2020). However, as outlined in the comments above, these approaches currently do not address nutrient deficiencies and therefore it is unrealistic to expect that they will be able to address future nutrient deficiencies exacerbated by rising CO2 levels and crop nutrient density. Further, these strategies will not solve the problem of increased concentrations of toxins in crops associated with increased CO2 and/or CO2-induced warming.

Quote given to Carbon Brief

Supporting evidence

1. Major Cereal Grains Production and Use around the World | ACS Symposium Series
2. Impacts of climate change on global agriculture accounting for adaptation | Nature
3. Climate change impacts on crop yields: A review of empirical findings, statistical crop models, and machine learning methods - ScienceDirect
4. Climate Trends and Global Crop Production Since 1980 | Science
5. Global scale climate–crop yield relationships and the impacts of recent warming - IOPscience
6. Temperature increase reduces global yields of major crops in four independent estimates | PNAS
7. Nutritional quality of crops in a high CO2 world: an agenda for research and technology development - IOPscience

---

10.3 Mortality from temperature extremes

Page 111

MISLEADING

Section 10.3.1

Dr Antonio Gasparrini, biostatistician and epidemiologist, London School of Hygiene & Tropical Medicine.

In relation to my area of research, the report cites two articles (Gasparrini (2015) and Zhao (2021)) in support of the statement that cold-related mortality far exceeds heat-related mortality in most of the regions. While true, this says little about the impact of climate change on temperature-related deaths. In fact, the focus should be on the respective (and opposite) change in the heat and cold contributions, not their absolute values. In this respect, there is some evidence that the expected reduction in cold-related mortality will not offset the increase in heat-related mortality, in particular under more extreme climate change scenarios (Gasparrini (2017) and Masselot (2025)). More importantly, the level of adaptation to heat required to offset such a positive net effect should be very high, in the order of 90% reduction (Masselot (2025)).

Quote given to Carbon Brief

Supporting evidence

1. Mortality risk attributable to high and low ambient temperature: a multicountry observational study - PubMed
2. PDF
3. Estimating future heat-related and cold-related mortality under climate change, demographic and adaptation scenarios in 854 European cities - PubMed

---

11 Climate change, the economy, and the social cost of carbon

Page 116

FALSE

An influential study in 2012 suggested that global warming would harm growth in poor countries, but the finding has subsequently been found not to be robust. Studies that take full account of modelling uncertainties either find no evidence of a negative effect on global growth from CO2 emissions or find poor countries as likely to benefit as rich countries.

Prof Richard Tol, professor at the department of economics, University of Sussex.

"The second sentence is wrong. The authors refer to "studies", but without references. Tol (2024) finds that the then-available studies jointly point to a negative impact of climate change on global economic growth. My less systematic reading of the literature since has not led me to change my mind. Their conclusion that 'poor countries' are 'likely to benefit' is again not backed up with references. Tol (2024), the only reference in the paragraph, concludes the opposite."

Quote from external source

Supporting evidence

1. A meta-analysis of the total economic impact of climate change - ScienceDirect

---

11.1 Climate change and economic growth

Page 117

MISLEADING

Nor have past extreme weather events had a significant effect on US banks' performance (Blickle et al. (2021)); warming has even been shown to be beneficial for the finance and insurance sector (Mohaddes et al. (2023)).

Dr Kamiar Mohaddes, deputy director of the Cambridge executive MBA programme, University of Cambridge.

"The way our findings have been presented is misleading...Investigating the long-term macroeconomic effects of climate change across 48 US states, we provide evidence for the damage that climate change causes in the US using various economic indicators at the state level: growth rates of Gross State Product (GSP), GSP per capita (income), labour productivity and employment as well as output growth in 10 economic sectors (e.g. agriculture, manufacturing, services, retail and wholesale trade). Just to be clear, (1) these are not 'small negative effects' and (2) we do indeed show that climate change has negative effects on income in the US. We show that while #weather shocks have level effects (or temporary growth impacts), climate change – by shifting the long-term average and variability of weather – impacts the US economy's ability to grow in the long term! We study economic activity in all sectors of the US economy –agriculture, forestry & fisheries; mining, construction, manufacturing, transport, communications and public utilities, wholesale trade, retail trade, financial services & property, services and government –and find that the impact of climate change on sectoral output growth is broad based – each of the 10 sectors considered is affected by at least one of the four climate variables."

Quote from external source

Supporting evidence

1. Climate change and economic activity: evidence from US states | Oxford Open Economics | Oxford Academic

---

11.1 Climate change and economic growth

Page 120

MISLEADING

Section 11.2 Models of the social cost of carbon

Dr Gernot Wagner, climate economist, Columbia Business School.

That section is based on a woefully outdated reading of the literature. In Moore et al (2024), we provide a synthesis of evidence of the latest such studies. We "perform a comprehensive synthesis of the evidence on the SCC, combining 1,823 estimates of the SCC from 147 studies with a survey of authors of these studies." In summary: "This synthetic distribution has a mean of $283 per tonne of CO2 for a 2020 pulse year (5% to 95% range: $32 to $874), higher than most official government estimates, including a 2023 update from the US EPA." So far from there being "evidence for low SCC" (DOE report p.123), sadly, there is ample evidence of the opposite.

Quote given to Carbon Brief

Supporting evidence

1. Synthesis of evidence yields high social cost of carbon due to structural model variation and uncertainties | PNAS

11.2 Models of the social cost of carbon

Page 121

MISLEADING

Economists use IAMs to compute the SCC. Two of the best-known are the Climate Framework for Uncertainty, Negotiation and Distribution ("FUND", Tol 1997) and Nordhaus' DICE. EPA (2023) introduced new ones for its recent work. IAMs embed a "damage function" or set of functions relating ambient temperature to local economic conditions. The assumptions embedded in the damage function will largely determine the resulting SCC. IAMs also assume a long-term discount rate or, as in DICE, compute the optimal internal discount rate as part of the solution.

Prof Richard Tol, professor at the department of economics, University of Sussex.

"The literature is vast. I counted 446 papers with estimates. There are numerous commentaries; and two handfuls of meta-analyses (e.g. Tol (2023) and Moore et al. (2024)). Instead, the authors wrote their own review, which omits the most influential papers and misses key insights. Cherry-picking may be a better term than review."

Quote from external source

Supporting evidence

1. Social cost of carbon estimates have increased over time | Nature Climate Change
2. Synthesis of evidence yields high social cost of carbon due to structural model variation and uncertainties | PNAS

11.2 Models of the social cost of carbon

Page 123

FALSE

Tol (2017) estimates that the private benefit of carbon is large relative to the social cost.

Prof Richard Tol, professor at the department of economics, University of Sussex.

"This paper was never published in a peer-reviewed journal and is therefore not admissible by the rules of the US government. The paper was peer-reviewed and rejected, because my private benefit [of carbon] is an average, whereas the social cost is a marginal. The two cannot be compared (unless you make a ridiculous assumption about linearity). I still hope to fix the paper one day. As it stands, however, the comparison is wrong."

Quote from external source

Supporting evidence

1. The Private Benefit of Carbon and its Social Cost

11.2 Models of the social cost of carbon

Page 125

MISLEADING

Dietz et al. incorporated several potential tipping points (abrupt changes) into an SCC model and found they added about 25% to the estimate, mainly associated with thawing permafrost and release of methane hydrates. However, the IPCC considers this scenario very unlikely (AR6 Technical Summary p. 107).

Dr Gernot Wagner, climate economist, Columbia Business School.

Dietz et al., in its main specification, finds a median increase in the SCC of "about 25%" (27%) and a mean increase of over 40% (42%). That comparison of median and mean points to a heavily right-skewed distribution. Indeed, Figure 2 shows as much. It also shows, for example, that we find a ~10% chance that these tipping points alone increase the SCC by at least 100% – that is, double it.

Quote given to Carbon Brief

Supporting evidence

1. Economic impacts of tipping points in the climate system | PNAS

Glossary

IPCC: The Intergovernmental Panel on Climate Change, the UN body for assessing the science related to climate change. IPCC works in five-to-eight year cycles and comprises three working groups of scientists, each focusing on different aspects of climate science and the response to climate change. Each assessment cycle, scientists appointed by the IPCC produce three reports summarising the latest climate science, as well as "special reports" and a synthesis report, which serve as key inputs to

international climate negotiations.

WG1/2/3: The three working groups of the IPCC. Working Group I (WG1) deals with the physical science basis of climate change, Working Group II (WG2) with climate change impacts, adaptation and vulnerability and Working Group III (WG3) with mitigation of climate change.

AR6: The sixth assessment report of the IPCC, which was published in 2013-14.

AR5: The fifth assessment report of the IPCC, which was published in 2021-23.

CMIP5/6: The Coupled Model Intercomparison Project (CMIP) is the international modelling effort that feeds into the IPCC's influential assessments. CMIP5 was developed for AR5, while CMIP6 was developed for AR6.

Methodology

The DoE report references around 350 sources. Of these, around 240 are peer-reviewed research papers. Other sources include books, commentary articles and letters published in journals, as well as "grey" literature, such as study preprints, blog posts, news articles and government websites.

For this factcheck, Carbon Brief emailed the corresponding authors of all 240 peer-reviewed studies. If the corresponding author did not respond or the email address bounced, Carbon Brief contacted another report author – typically the lead author, if separate to the corresponding author.

In 20 cases, the corresponding author was also an author on the DoE report itself. These authors were not invited to factcheck their own work.

Carbon Brief asked the corresponding authors to read the section of the report that cites their work and to identify if it uses their work to make "misleading" or "false" statements.

False was described as "statements/statistics that are factually incorrect or untrue".

Misleading was described as "statements/statistics that are presented in a way that distort the meaning, create a false impression or omit/cherry-pick crucial details".

(Carbon Brief also invited various topic experts to contribute their responses. Respondents were also invited to forward Carbon Brief's request to other experts.)

Carbon Brief's factcheck also includes comments from scientists who have already reacted to the DoE report in public, via media articles, social media or blog posts. Links to these sources are included with the relevant responses.

Carbon Brief ensured that any scientists contributing to the factcheck in an anonymous capacity have the appropriate expertise to comment on the sections of the report that they factchecked.

Any pages with "misleading" and "false" statements are shown in orange and red, respectively, in the main graphic. Pages that are not coloured are either accurate, or have not yet been factchecked.

There has been some speculation that artificial-intelligence tools might have been used to generate some parts of the report, particularly the citations, due to some "hallucinatory"-type mistakes. For example, a Carbon Brief article from 2017 is cited, but the credited author is mistakenly listed as another Carbon Brief journalist.

However, Carbon Brief ran samples of the report's main text through several AI text checker tools and found there is a "very low probability" they were generated using AI. It was not possible to do similar checks of the report's citations.

Carbon Brief invites any scientists who notice further errors in the report to email info@carbonbrief.org.

Update: This article was updated twice on 22/08/25 to include 14 new responses from scientists.

CarbonBrief
CLEAR ON CLIMATE

Published under a CC license. You are welcome to reproduce unadapted material in full for non-commercial use, credited 'Carbon Brief' with a link to the article. Please contact us for commercial use.

Published by Carbon Brief Ltd © 2025 - Company No. 07222041