September 2, 2025

Mr. Joshua Loucks
U.S. Department of Energy
1000 Independence Avenue SW
Washington, D.C. 20585
DOEGeneralCounsel@HQ.DOE.Gov

Re: Docket No. DOE–HQ–2025–0207

Submitted via WWW.Regulations.Gov

Dear Mr. Loucks,

On behalf of the Competitive Enterprise Institute (CEI), we respectfully submit these comments on the Department of Energy's (DOE's) July 29, 2025, report, *A Critical Review of Impacts of Greenhouse Gas Emissions on the U.S. Climate*.

Our comments address each section of the report. We begin by reproducing the report's table of contents so that readers can easily see the complete list and sequence of the topics covered. Although we reviewed and approved each other's contributions, readers may find it useful to know that Dr. Legates is lead commenter on Chapters 1-10 of the DOE report and Dr. Lewis is lead commenter on Chapters 11-12 and section 1 of Chapter 9.

Sincerely,

David R. Legates, Ph.D.
Adjunct Fellow
Competitive Enterprise Institute

Marlo Lewis, Jr., Ph.D.
Senior Fellow
Competitive Enterprise Institute

Table of Contents

1. CARBON DIOXIDE AS A POLLUTANT

Chapter summary (from the Report): Carbon dioxide (CO_2) differs in many ways from the so-called Criteria Air Pollutants. It does not affect local air quality and has no human toxicological implications at ambient levels. It is an issue of concern because of its effects on the global climate.

Section summary: The Clean Air Act of 1970 regulates six Criteria Air Contaminants (particulate matter, ground-level ozone, sulfur dioxide, nitrogen dioxide, lead, and carbon monoxide) due to their local environmental and health impacts, such as odor, visibility issues, plant damage, and toxicity in humans. In 2007, the Supreme Court (*Massachusetts v. EPA*) classified greenhouse gases, including CO_2, as pollutants under the Act, despite scientific differences. Unlike the Criteria Contaminants, CO_2 does not affect visibility and is odorless, non-toxic at ambient levels, and essential for plant photosynthesis, with current atmospheric levels at about 430 ppm, rising 2 ppm annually. High indoor CO_2 levels (e.g., 1,000-1,500 ppm) may impair cognitive performance, but these are far above outdoor levels. CO_2 promotes global greening and agricultural yields but is primarily regulated due to its role as a greenhouse gas, contributing to global warming, a complex issue requiring further study.

The chapter acknowledges that the definition of "pollutant" for regulatory purposes is "ultimately a legal matter." It properly observes that "there are "important scientific distinctions" between CO_2 and criteria air pollutants, but one correction is in order. Carbon monoxide (CO) is a criteria pollutant, but like CO_2, it is odorless and does not affect visibility. What is decisively different about CO_2 is that it is non-toxic at ambient levels and essential to plant photosynthesis, making it a basic building block of the planetary biosphere.

The report's argument regarding "neutralizing ocean alkalinity" is important as the oceans are still alkaline and have not become acidic, a distinction that is usually lost on the general public who do not grasp this important concept. This section, in my view, is very well written.

It might be prudent to include a mention that this report is based on peer-reviewed research, not on speculation. I am sure one of the main criticisms will be that the report deviates from the consensus view but if it does, it does so with studies in the published and refereed literature. I have long noted that the Intergovernmental Panel on Climate Change (IPCC) and the National Climate Assessments (NCAs) write from a prescribed playbook and much of the literature is ignored because it departs from the consensus narrative. The scientific literature is much more hesitant to make the extreme statements present in media narratives and so-called "consensus" documents and includes the caveats, biases, uncertainties, and qualified statements that are extremely important to note.

2. DIRECT IMPACTS OF CO_2 ON THE ENVIRONMENT

Chapter summary (from the Report): CO_2 enhances photosynthesis and improves plant water use efficiency, thereby promoting plant growth. Global greening due in part to increased CO_2 levels in the atmosphere is well-established on all continents.

CO_2 absorption in sea water makes the oceans less alkaline. The recent decline in pH is within the range of natural variability on millennial time scales. Most ocean life evolved when the oceans were mildly acidic. Decreasing pH might adversely affect corals, although the Australian Great Barrier Reef has shown considerable growth in recent years.

2.1 CO_2 as a Contributor to Global Greening

2.1.1 Measurement of global greening

Subsection summary: Global greening, an increase in plant coverage measured by the Leaf Area Index (LAI) via satellite, has been observed over recent decades, driven significantly by rising CO_2 levels. Zhu et al. (2016) found greening across 25-50% of Earth's surface from 1982-2011, with CO_2 contributing 70% to this trend, particularly in the tropics, while land-use changes, warming, and nitrogen also played roles. Zeng et al. (2017) reported an 8% increase in global leaf area over 30 years, noting greening's role in mitigating warming. Studies like Chen et al. (2019) highlight land management in China and India as key drivers, with China accounting for 25% of the global LAI increase despite only 6.6% of vegetated area. Piao et al. (2020) observed greening even in the Arctic. Haverd *et al.* (2020) reported a 30% increase in global photosynthesis since 1900 due to CO_2 fertilization, exceeding model predictions of 17%, suggesting underestimated agricultural benefits. However, Keenan *et al.* (2023) estimated a lower rate closer to models. The greening trend continues without slowing, with CO_2 fertilization as the primary driver.

The argument made for greening and its enhancement by CO_2 fertilization is well-taken in this context. With respect to Zhu *et al.* (2016), the time-period of record was 1982 to 2009, not 2011 and their focus was on vegetated areas only, not the whole Earth. This latter issue is important as they did not consider phytoplankton in the oceans.

The discussion of Zeng *et al.* (2017) is accurate and useful; however, it would be prudent to cite Chen *et al.* (2024) more than just in passing, because it updates the record through 2020 and, more importantly, examines the *causes* for the greening (*i.e.*, air temperature, precipitation, solar radiation, soil moisture, and CO_2) and concludes that more than 75% (75.63%) of the land area has greened due to increased CO_2 concentrations.

With respect to model predictions and specific studies (*i.e.*, Haverd *et al.* (2020) and Keenan *et al.* (2023)), the discussion is correct and very useful. Some alarmists have suggested that greening may reverse in drought-prone areas, thereby offsetting the benefits of CO_2. I would suggest including statements that specifically address the so-called "drawbacks of greening," which include soil moisture depletion and amplified warming.

2.1.2 Photosynthesis and CO_2 levels

> **Subsection summary:** Plants build biomass through photosynthesis, where the enzyme Rubisco converts CO_2, water, and light into sugar via the C3 process. Rubisco evolved about 3 billion years ago when atmospheric CO_2 levels were significantly higher (2,000-4,000 ppm 400 million years ago, 1,000 ppm 200-50 million years ago), declining to 170 ppm during recent glaciations. Current CO_2 levels are ~430 ppm, up from 280 ppm in the early 1800s. Some plants adapted to low CO_2 by developing the C4 pathway, which enhances efficiency by concentrating CO_2 near Rubisco. C3 plants (*e.g.*, rice, wheat, soybeans) dominate agriculture, while C4 plants (*e.g.*, maize, sugarcane) can grow at lower CO_2 levels, down to 10 ppm. Below 180 ppm, C3 plant growth drops significantly, ceasing at 60-140 ppm. Rising CO_2 enhances plant growth, particularly for C3 plants, through two mechanisms: increased photosynthesis and improved water use efficiency, as higher CO_2 allows plants to keep stomata closed longer, reducing water loss. Studies, including Gerhart and Ward (2010), show significant growth benefits in plants like Velvetleaf when CO_2 increases from 150 ppm to 700 ppm.

This section is accurate and well-structured. The discussion that plants and animals thrived under higher CO_2 levels in earlier times is well-taken, as the usual narrative is that CO_2 concentrations in the atmosphere have never been this high (but they have, as the report correctly notes). With respect to increased water use efficiency due to reduced stomatal opening under higher CO_2 concentrations, I would elaborate on this more as it counters the usual narrative that CO_2 greening will lead to depleted soil moisture reserves, thereby stopping plant growth, creating more dead vegetation, and exacerbating wildfires. References to add that would enhance the argument include Allen *et al.* (2011), where they show that more CO_2 indicates plants will use less water and that higher CO_2 concentrations also dramatically raise the optimum growth temperature, and Cheng *et al.* (2017), where the authors demonstrate that "global change is causing the world's plants to grow in a more water-efficient way."

2.1.3 Rising CO_2 and crop water use efficiency

> **Subsection summary:** Deryng et al. (2016) analyzed crop water productivity (CWP), the yield per unit of water, using Free Air CO_2 Enrichment (FACE) data and crop models under the RCP8.5 (SSP5-8.5) emissions scenario for 2080. They found that rising CO_2 enhances photosynthesis and reduces transpiration, leading to net CWP gains across maize, wheat, rice, and soybean in all regions (Tropics, Arid, Temperate, Cold), despite models without CO_2 fertilization predicting losses. Warming's negative impacts on wheat and soybean yields were fully offset by CWP gains and mitigated by 90% for rice and 60% for maize. Cheng *et al.* (2017) reported that increased CO_2 from 1982-2011 boosted Gross Primary Production without increasing global plant water use due to CWP gains. Contrary to predictions of expanding drylands, Zhang *et al.* (2024) found that CO_2-driven greening prevents vegetation loss in arid areas, with only 4% of drylands at risk of desertification.

This section is accurate, and I also would use Allen *et al.* (2011) and Cheng *et al.* (2017) to strengthen the arguments. Further, I would suggest elaborating that crop water productivity

(CWP) gains vary across regions (from Deryng *et al.*, 2016) and that gross primary production (GPP) increases are not uniform globally with variation affected by both climate type and vegetation (from Cheng *et al.*, 2017). The section could also be strengthened by adding that satellite observations showing increased LAI in many arid regions are driven by CO_2 fertilization, contrary to model predictions of expanding drylands (from Zhang *et al.*, 2024). Moreover, I would highlight that land-use change and/or overgrazing can exacerbate desertification in some areas, which is a process that is outside of climate change causation and may mask some of the greening that could be attributed to CO_2 (see Huang *et al.*, 2016).

2.1.4 CO2 fertilization benefits in IPCC Reports

> **Subsection summary:** The IPCC minimally addresses global greening and CO_2 fertilization of crops in its reports. The AR6 Working Group I report (Section 2.3.4.3.3) acknowledges, with high confidence, that global greening has increased over the past 2-3 decades, as noted in the IPCC Special Report on Climate Change and Land. It highlights variations in greening trends across datasets, expressing low confidence in the trend's magnitude. Brief mentions of CO_2 fertilization and improved water use efficiency appear in AR6 Working Groups I and II, but the topic is absent from the Policymaker Summaries, Technical Summaries, and Synthesis Reports of both AR5 and AR6.

This section provides a concise summary of how the IPCC addresses global greening and CO_2 fertilization. However, an explanation could be proposed as to *why* the IPCC minimally discusses CO_2 fertilization and greening. I realize that may be speculative as the authors are probably not privy to why it was minimized but it may be useful to note. However, I do think it necessary to comment as to why this omission matters.

2.2 The Alkaline Oceans

2.2.1 Changing pH

> **Subsection summary:** The global average pH of surface seawater is currently about 8.04, down from 8.2 in pre-industrial times, due to increased atmospheric CO_2 absorption by oceans, which reduces their alkalinity. While often called "ocean acidification," this term is misleading as oceans remain alkaline (pH > 7.0) and are not expected to become acidic. A more accurate term is "ocean neutralization." Historical data suggest oceans were mildly acidic (pH 6.5–7.0) when marine life evolved, and during the last glaciation (up to 20,000 years ago), ocean pH was around 7.4–7.5, rising to current levels during deglaciation. Marine organisms have historically adapted to significant pH variations, indicating resilience to long-term pH changes.

This section is largely accurate and well-supported by scientific references, but there are a couple of areas where completeness could be improved. I appreciate the use of the terms "ocean neutralization" and "alkaline oceans" as it better reflects the nuance of an alkaline ocean that is tending toward neutral pH conditions. I would suggest, however, that the claim of a mildly acidic ocean during early periods in Earth's history is speculative, as making the determination of a specific range depends on geochemical models. Nevertheless, it does appear reasonable to assume that pH has increased over Earth's lifespan.

I would appreciate a statement that addresses geographical differences. For example, coastal areas, regions of upwelling, and the Arctic often experience lower pH which would underscore the issue that pH is not a single number that can be applied to the entire world's oceans.

It also would be useful to include a discussion of Clark *et al.* (2020) where a multi-year, international study found that reported adverse effects of acidification on coral reef fishes were not reproducible. The study found problems with methodology and small sample sizes (see also Nagelkerken and Connell, 2022) and alleged fraud in selected studies that were later verified (Enserink, 2021; 2022).

(A period is required at the end of the last sentence of the last paragraph.)

2.2.2 Coral reef changes

> **Subsection summary:** Concerns about decreasing ocean pH potentially reducing coral reef calcification rates are tempered by evidence of coral resilience and research biases. Coral reefs, like the Great Barrier Reef (GBR), experience natural pH swings (9.4 day to 7.5 night) due to photosynthesis. De'ath et al. (2009) reported a 14% decline in GBR calcification from 1990–2009, attributing it to warming and pH decline, but Ridd *et al.* (2013) corrected this, showing no change, though the original study garnered 541 citations compared to 11 for the correction. Recent data from the Australian Institute of Marine Science (2023) show a strong rebound in GBR coral cover, despite earlier declines linked to cyclones, heatwaves, runoff, and invasive species. Publication bias favoring alarming results exaggerates ocean acidification impacts, as noted by Browman (2016). A meta-analysis by Clements *et al.* (2021) found initial dramatic claims of acidification affecting reef fish behavior were overstated, with larger studies showing negligible effects, calling for improved research practices. Marine life, including corals that evolved 245 million years ago under higher CO_2 levels, appears resilient to pH changes, and public discourse on ocean acidification has often been one-sided.

It is important to underscore the daily variability in pH changes within coral reefs due to photosynthetic activity, as the media often claim that small changes to pH can be deadly to coral reefs. I am not swayed, and the reader should not be either, by the number of citations for De'ath *et al.* (2009) relative to Ridd *et al.* (2013); after all, the high number of citations for De'ath *et al.* (2009) provide evidence of groupthink. The tie-in to tropical cyclones, marine heatwaves, agricultural runoff, and invasive species is very useful, showing that marine ecosystems can be affected by much more than climate change.

A sentence addressing the concern that daily changes in pH are short-term and localized but small changes in pH that persist over long time-periods are important would be very helpful.

Moreover, I would suggest citing and discussing Manzello *et al.* (2021), Price *et al.* (2012), and Rivest *et al.* (2017), in addition to the dated, but useful, Revelle and Fairbridge (1957).

References

Allen, L.H. J., V.G. Kakani, J. C.V. Vu, and K.J. Boote, 2011: Elevated CO_2 increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. *Journal of Plant Physiology*, **168,** 1909-1918.

Clark, T.D., G.D. Raby, D.G. Roche, S.A. Binning, B. Speers-Roesch, F. Jutfelt, and J. Sundlin, 2020: Ocean acidification does not impair the behaviour of coral reef fishes. *Nature*, **577,** 370-375.

Enserink, M., 2021: Sea of doubts. *Science*, **372,** 560-565.

Enserink, M., 2022: Star marine ecologist guilty of misconduct, university says. *Science*, **377,** 699-700.

Huang, J., H. Yu, X. Guan, G. Wang, and R. Guo, 2016: Global semi-arid climate change over the last 60 years. *Climate Dynamics*, **46**(3), 1131–1150.

Manzello, D.P., I.C. Enochs, G. Kolodziej, R. Carlton, A. Bruckner, A. Dempsey, and P. Renaud, 2021: Pacific-wide pH snapshots reveal that high coral cover correlates with low, but variable pH. *Bulletin of Marine Science*, **97**(1), 1–26.

Nagelkerken, I., and S.D. Connell, 2022: Meta-analysis reveals an extreme “decline effect” in the impacts of ocean acidification on fish behavior. *PLOS Biology*, **20**(2): e3001511.

Price, N.N., T.R. Martz, R.E. Brainard, and J.E. Smith, 2012: Diel variability in seawater pH relates to calcification and benthic community structure on coral reefs. *PLoS ONE*, **7**(8), e43835.

Rivest, E.B., S. Comeau, and C.E. Cornwall, 2017: The role of natural variability in shaping the response of coral reef organisms to climate change. *Current Climate Change Reports*, **3**, 271–281.

3 HUMAN INFLUENCES ON THE CLIMATE

Chapter summary (from the Report): The global climate is naturally variable on all time scales. Anthropogenic CO_2 emissions add to that variability by changing the total radiative energy balance in the atmosphere.

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.

Climate projections are based on IPCC emission scenarios that have tended to exceed observed trends. Most academic climate impact studies in recent years are based upon the extreme RCP 8.5 scenario that is now considered implausible; its use as a business-as-usual scenario has been misleading.

Carbon cycle models connect annual emissions to growth in the atmospheric CO_2 stock. While models disagree over the rate of land and ocean CO_2 uptake, all agree that it has been increasing since 1959.

There is evidence that urbanization biases in the land warming record have not been completely removed from climate data sets.

3.1 Components of Radiative Forcing and Their History

3.1.1 Historical radiative forcing

Subsection summary: Earth's climate has naturally varied over its 4.6-billion-year history due to internal fluctuations (*e.g.*, atmosphere-ocean exchanges) and external influences (*e.g*., solar energy, volcanic eruptions). Human activities, such as CO_2 emissions, other greenhouse gases, and land-use changes, also alter the climate by affecting the Earth's energy balance, where absorbed sunlight (~240 W/m^2) is balanced by radiated heat. Radiative forcing quantifies disruptions to this balance, with positive forcing (*e.g.*, CO_2, other greenhouse gases) causing warming and negative forcing (*e.g.*, aerosols) causing cooling. The IPCC AR6 estimates CO_2 as the largest human-induced warming factor, with other greenhouse gases adding ~75% to its effect, while aerosols have a cooling effect with high uncertainty. Solar forcing is deemed negligible by the IPCC, but Connolly et al. (2021) highlight variability in Total Solar Irradiance (TSI) reconstructions, suggesting solar influence on 20th-century warming is uncertain due to issues like the Active Cavity Radiometer Irradiance Monitor (ACRIM data gap. Volcanic aerosols, like the 1815 Tambora eruption, cause episodic cooling, with recent eruptions like Hunga Tonga (2022) having uncertain impacts. Anthropogenic forcing has risen to ~3 W/m^2 since 1900, but its effect is small (~1%) compared to natural radiation flows, and other natural forcing sources remain poorly understood.

The discussion on climate variability, radiative forcing, and natural versus anthropogenic influences on Earth's climate is accurate and largely complete. With respect to solar forcing and Connolly *et al.* (2021), who found that the IPCC suppressed dissenting scientific opinions, it may be useful to note why the results of Lean (2017) should be disregarded. That study found small changes in total solar irradiance between the Medieval Maximum (1100 to 1250AD) and the Maunder Minimum (1645 to 1715AD).

Despite the data gap in the ACRIM satellite record of total solar irradiance, it might also be useful to note that IPCC uses PMOD reconstructions to fill in the record and suggest reasons why that might lead to problems (see Kopp, 2016). Moreover, the discussion lacks any contribution from water vapor and cloud feedback uncertainties which, again, undermines the attempt to label small changes in total solar irradiance as significant. This should be included to accentuate the important points made in the report.

The summary sentence "The IPCC AR6 estimates CO_2 as the largest human-induced warming factor, with other greenhouse gases adding ~75% to its effect, while aerosols have a cooling effect with high uncertainty" is likely a typo. The report presumably means the reverse—that CO_2 contributes ~75% of the *anthropogenic* greenhouse effect. Yes, water vapor contributes more than CO_2, but the sentence limits the discussion to just anthropogenic effects.

3.1.2 Change in atmospheric CO_2 since 1958

> **Subsection summary:** Carbon dioxide's warming effect is driven by its atmospheric concentration above the preindustrial level of 280 ppm. Data from the Mauna Loa observatory show CO_2 levels rising from 316 ppm in 1959 to ~430 ppm today, a 36% increase. At the end of the last glaciation, levels were ~180 ppm, close to critical thresholds where C3 plants (below 140 ppm) and C4 plants (below 100 ppm) begin to die, risking plant life if levels had continued to fall. Currently, only about half of human CO_2 emissions remain in the atmosphere, as land and ocean processes absorb ~50% of excess CO_2. Future CO_2 concentrations, and their climate impact, depend on (1) future global human CO_2 emissions and (2) the rate at which land and oceans remove excess CO_2.

Discussion on changes in atmospheric CO_2 since 1958 is well-written and complete. The only suggestions I have are to explain why Mauna Loa is supposedly representative of the globe as a whole and discuss what issues that may cause (and allude to data from the South Pole which corroborate the general trend). Moreover, the discussion also omits some uncertainties, such as the variability in ocean and land sinks. Again, this helps to argue that small trends are below measurement error.

3.2 Future Emission Scenarios and the Carbon Cycle

3.2.1 Emission scenarios

> **Subsection Summary:** Assessing future greenhouse gas (GHG) emissions involves uncertainties tied to demographics, economic activity, regulations, and energy/agricultural technologies, which drive projections of emissions, aerosol concentrations, and land-use changes, collectively influencing anthropogenic radiative forcing. The IPCC uses scenarios to estimate future radiative forcing, labeled by expected forcing in 2100, with current forcing at ~2.7 W/m^2. These scenarios, like the Special Report on Emission Scenarios (SRES) used in IPCC's Third and Fourth Assessments, often overestimated emissions compared to observed trends, as shown by McKitrick *et al.* (2012) and Hausfather *et al.* (2019), with CO_2 concentrations tracking the low end of projections.

For AR5, the IPCC introduced Representative Concentration Pathways (RCPs), ranging from RCP2.6 (~2.6 W/m², limiting warming below 2°C) to RCP8.5 (~8.5 W/m², implying ~5°C warming by 2100). RCP8.5, often mislabeled as the "business-as-usual" scenario, was designed as an extreme, low-probability case but has been criticized as implausible due to unrealistic energy and land-use assumptions (Burgess *et al.*, 2021; Pielke Jr. *et al.,* 2022). Hausfather and Peters (2020a) noted its misuse has led to misleading studies and media reports. Schwalm *et al.* (2020) defended RCP8.5, citing its alignment with 2005-2020 emissions, but Hausfather and Peters (2020b) argued this was due to offsetting errors in fuel and land-use emissions.

Pielke Jr. and Ritchie (2020) found ~16,800 papers from 2010-2020 used RCP8.5, with ~4,500 labeling it "business-as-usual," inflating alarmist narratives in scientific literature and media, including by the IPCC and U.S. National Climate Assessment. For AR6, the IPCC introduced Shared Socioeconomic Pathways (SSPs), which continue this upward bias. As of 2023, global CO_2 emissions, per the International Energy Agency, track below SSP7.0 and even SSP2-4.5, highlighting a persistent overestimation in IPCC scenarios and a skew toward apocalyptic projections in climate research.

The discussion on future greenhouse gas (GHG) emissions scenarios, their uncertainties, and the criticisms of IPCC scenarios (SRES, RCPs, SSPs) is accurate and well-taken. I am pleased to see the misuse of RCP8.5 as a "business-as-usual" baseline cited well and the tendency of some scenarios to overestimate emissions.

3.2.2 The carbon cycle relating emissions and concentrations

Subsection summary: Carbon dioxide emissions, primarily from fossil fuel burning, with minor contributions from deforestation and cement production, have increased atmospheric CO_2 concentrations, as tracked by the global carbon cycle. The atmosphere contains ~850 Gt of carbon (GtC), mostly as CO_2, with ~200 GtC exchanged annually between the atmosphere, land (~80 GtC), and oceans (~120 GtC). Human activities added 10.3 GtC in 2023, ~5% of the annual exchange. Natural processes, including plant growth and ocean uptake, sequester ~50% of human emissions, leaving the rest to accumulate in the atmosphere, causing CO_2 levels to rise at about half the rate of emissions. This 50% sequestration rate has remained relatively stable, though it varies slightly due to natural factors like El Niño, La Niña, and events like the 1991 Mt. Pinatubo eruption, which reduced atmospheric CO_2. Land vegetation, particularly at high latitudes, and soil carbon sequestration have increased CO_2 uptake, consistent with global greening observed since 1982. Ocean uptake is driven by increasing atmospheric CO_2 pressure, but biological ocean processes remain uncertain. All 20 land carbon cycle models tracked by the Global Carbon Project show increasing CO_2 removal since 1959, though future carbon cycle changes remain a key uncertainty for projecting CO_2 concentrations and climate impacts.

This section provides an accurate and concise overview of the global carbon cycle. It is highly accurate and reasonably complete.

CO_2 uptake by land processes

> **Subsection summary:** The uptake of excess atmospheric CO_2 by land processes, linked to global greening, is modeled by 20 dynamic global vegetation models tracked by the Global Carbon Project (Friedlingstein, 2024). All models confirm that vegetation and soils have been sequestering carbon from 1959 to 2023, but their long-term trends vary widely, differing by nearly a factor of seven. This significant variation highlights uncertainty in the rate of CO_2 removal by land processes, which contributes to uncertainty in future atmospheric CO_2 concentrations and, consequently, in climate model projections of future climate change.

This is a concise summary of the role of terrestrial ecosystems in sequestering atmospheric CO_2. To me, this discussion could be expanded a bit, but what is given is accurate and useful. For example, geographic differences could be included, and it could be noted that models differ in how much additional CO_2 is required to boost photosynthesis (see Peñuelas *et al.*, 2017), their sensitivity to air temperature, and the impact of land-use changes.

CO_2 uptake by ocean processes

> **Subsection summary:** The Global Carbon Project (Friedlingstein, 2024) uses 10 ocean biogeochemistry models to assess CO_2 uptake by oceans, showing that global oceans have been sequestering carbon at an increasing rate from 1959 to 2023. Unlike land models, which vary widely, ocean models show better agreement, with the fastest CO_2 uptake model only 65% faster than the slowest. However, Friedlingstein *et al.* (2022) note discrepancies in the strength of the ocean carbon sink, especially in the Southern Ocean, over the last decade. The average CO_2 uptake trend across land models is 25% larger than that of ocean models, indicating land processes are increasing CO_2 sequestration faster than ocean processes.

The text is a good and accurate overview of oceanic CO_2 uptake. However, I am left questioning *why* ocean CO_2 uptake is increasing. Is it the gradient in CO_2 in the atmosphere relative to dissolved CO_2 in the ocean surface or is it due to changes in phytoplankton carbon fixation? Providing a short explanation would help clarify what might be causing these trends.

Geographically, various locations have disparate issues. Limited observations, model differences, different data approaches, unique oceanic circulations—are any of these helpful in explaining why ocean CO_2 uptake is increasing?

3.3 Urbanization Influence on Temperature Trends

Section summary: Historical land temperature data, primarily collected in populated areas, is affected by Urban Heat Island (UHI) effects and other land surface changes, potentially exaggerating warming attributed to greenhouse gases. The IPCC acknowledges UHI contamination but claims data cleaning removes it, though its sufficiency is debated. AR6 and AR5 estimate UHI bias at no more than 10% of global land warming, citing older studies (*e.g.*, Jones et al., 1990; Peterson et al., 1999) with loose "rural" definitions (up to 10,000-100,000 people). These studies found minimal UHI effects, but their methods may not detect bias. Contrarily, studies like de Laat and Maurellis (2006) and McKitrick and Michaels (2007) suggest UHI contributes 30-50% to observed warming, correlating with socioeconomic development. AR4 dismissed those findings without evidence, a point conceded in AR5, which still upheld the 10% cap despite acknowledging contamination. Recent work by Soon *et al.* (2023) estimates significant UHI bias in Northern Hemisphere data (1850-2018), raising the warming trend from 0.55°C to 0.89°C per century. Studies like Parker (2006) and Wickham *et al.* (2013) found no urban-rural trend differences, but McKitrick (2013) showed such methods may miss UHI bias. Spencer *et al.* (2025) used historical population data to confirm significant UHI bias in U.S. summertime temperatures. Overall, while land records show warming, UHI biases likely inflate trends, and current data processing may not fully address this issue.

The discussion coherently provides a strong argument as to how the UHI may impart an upward bias into global land surface air temperature data. The only suggestion I can make is that recent studies (*i.e.*, Katata *et al.*, 2023; Li *et al.*, 2023; Zhou *et al.*, 2024) suggest the UHI is real but localized to just cities. However, their argument can be refuted by noting that most observations are located where people live—in urban areas.

References

Katata, G., M. Mauder, and Y. Ma, 2023: Urban blending effects in homogenized temperature records. *Journal of Applied Meteorology and Climatology*, **62**(4), 511–525.

Kopp, G., 2016: Magnitudes and timescales of total solar irradiance variability. *Journal of Space Weather and Space Climate*, **6**, A30.

Lean, J.L., 2017: Estimating Solar Irradiance Since 850 CE. *Earth and Space Science*, **5**(4), 133–149.

Li, Y., M. Zhao, and X. Wang, 2023: Urban heat island amplification during heatwaves: A global perspective. *Environmental Research Letters*, **18**(8), 084015.

Peñuelas, J., P. Ciais, J.G. Canadell, I.A. Janssens, M. Fernández-Martínez, J. Carnicer, *et al.*, 2017: Shifting from a fertilization-dominated to a warming-dominated period. *Nature Ecology & Evolution*, **1**(10), 1438–1445.

Zhou, C., K. Wang, and Q. Ma, 2024: Urban heat island effects on global temperature trends: A review of recent advances. *Earth-Science Reviews*, **250**, 104678.

4 CLIMATE SENSITIVITY TO CO_2 FORCING

Chapter summary (from the Report): There is growing recognition that climate models are not fit for the purpose of determining the Equilibrium Climate Sensitivity (ECS) of the climate to increasing CO_2. The IPCC has turned to data-driven approaches including historical data and paleoclimate reconstructions, but their reliability is diminished by data inadequacies.

Data-driven ECS estimates tend to be lower than climate model-generated values. The IPCC AR6 upper bound for the likely range of ECS is 4.0°C, lower than the AR5 value of 4.5°C. This lowering of the upper bound seems well justified by paleoclimatic data. The AR6 lower bound for the likely range of ECS is 2.5°C, substantially higher than the AR5 value of 1.5°C. This raising of the lower bound is less justified; evidence since AR6 finds the lower bound of the *likely* range to be around 1.8°C.

4.1 Introduction

Subsection summary: The magnitude of global warming due to increasing CO_2 concentrations is central to debates on climate change and policy. Equilibrium Climate Sensitivity (ECS) measures the expected warming from a doubling of pre-industrial CO_2 levels (280 ppm) after all climate components adjust, with rapid adjustments in the troposphere and slower ones in the deep ocean and cryosphere. Transient Climate Response (TCR) measures warming over shorter timescales with CO_2 rising 1% annually for 70 years. The 1979 Charney Report estimated ECS at 3.0 ± 1.5°C, a range largely reaffirmed by the IPCC until AR6, which narrowed it to 2.5–4.0°C (likely) and 2.0–5.0°C (very likely), though the lower bound reduction is disputed. ECS uncertainty significantly impacts policy: ECS above 4.5°C justifies immediate aggressive emission controls, while below 2.0°C, no controls are economically warranted. CO_2 doubling alone causes ~1°C warming, amplified by positive feedbacks like water vapor and reduced snow/ice cover, potentially reaching ~2°C. Higher ECS values rely on positive cloud feedbacks. ECS estimates come from climate models, historical data, paleoclimatic reconstructions, and feedback process understanding, yet uncertainty persists, complicating policy decisions.

The introduction provides a good overview of climate sensitivity to CO_2 forcing by framing the concept of Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR). The text is highly accurate and concise. The discussions of water and cloud feedbacks are important to note.

With respect to the Sherwood *et al.* (2020) reference, I would remove the word “simple” as it may imply a lack of sophistication in their analysis. However, note that Sherwood *et al.* (2020)

suggest a broader range of between 2.3° and 4.7°C when other factors are included, which is larger than the ~2°C that the report cites.

It might be useful to cite Knutti *et al.* (2017) as they discuss the multi-method approach used in studies of climate sensitivity, which is consistent with the text. It also might be useful to discuss briefly potential negative feedbacks that might partially offset warming (*e.g.*, Fennel and Long, 2019; Woodard *et al.*, 2019; Colman and Soden, 2021; Mülmenstädt *et al.*, 2021; Hansen *et al.*, 2023).

4.2 Model-based Estimates of Climate Sensitivity

> **Subsection summary:** The IPCC's AR4 and AR5 relied heavily on General Circulation Models (GCMs) to estimate Equilibrium Climate Sensitivity (ECS), the warming expected from a doubling of pre-industrial CO_2 levels. ECS is typically assessed via long simulations or "effective climate sensitivity" from a 150-year simulation with quadrupled CO_2. While ECS is an emergent property of GCMs, some models have been tuned to align with expected warming rates, as seen in the Max Planck Institute model (MPI-ESM1.2), where cloud feedbacks were adjusted to target an ECS of ~3°C (Mauritsen and Roeckner, 2020). Direct CO_2 doubling causes ~1°C warming, with additional warming from uncertain feedbacks, particularly positive cloud feedbacks, which depend on complex, small-scale processes like cloud distribution, height, phase, and particle size. Those processes, which are difficult for GCMs to simulate accurately, also affect water vapor, lapse rate, and albedo feedbacks. The ECS range widened from 2.0–4.7°C in CMIP5 (AR5) to 1.8–5.7°C in CMIP6 (AR6), driven by stronger positive cloud feedbacks in newer models. Due to concerns over model tuning and cloud parameterization uncertainties, AR6 shifted to data-driven methods for ECS assessment, moving away from reliance on GCM simulations.

This section is generally well-constructed and provides a clear overview of how climate models are used to estimate ECS. It is my understanding, however, that AR6 did indeed include multiple lines of evidence as a departure from AR4 and AR5. However, climate models still contributed to the final analysis and again overstated the observed warming in the global troposphere. I also would stress that tuning is still a concern with climate models as parameter choices can either directly or indirectly influence ECS. In addition, this section focuses primarily on cloud feedbacks and their parameterization; it could be strengthened by mentioning other factors (*e.g.*, water vapor and surface albedo feedbacks as well as ocean heat uptake and circulation) that contribute to the uncertainty in ECS, which would underscore climate model limitations.

Scafetta (2022) found that models having ECS that exceed 3.0°C significantly overestimate the observed global surface warming. He concludes that models with high and even moderate ECS "are unfit for prediction purposes."

It should be noted that climate models overstate warming because of two very simple reasons—models are overly sensitive to increases in atmospheric carbon dioxide concentrations (*i.e.*, the

ECS is too large; see Christy and McNider, 2017 and Curry, 2017) and the emission scenarios that are often used (*i.e.*, SSP5-8.5) assume too much carbon dioxide will be emitted into the atmosphere by 2100. Simply put, this is why McKitrick and Christy (2018) found a tendency for virtually every model to overstate warming, with statistically significant differences between the model simulations and observations in most model cases. This underscores the argument that if models cannot reproduce the observed atmospheric warming, then their prognostications of future warming and its attribution cannot be relied upon.

4.3 Data-driven Estimates of Climate Sensitivity

> **Section summary:** Climate sensitivity, specifically Equilibrium Climate Sensitivity (ECS), can be estimated using historical instrumental records of surface temperatures and ocean heat content, combined with data on climate forcings (*e.g.*, greenhouse gases, solar, volcanic, aerosols). Energy Balance Models are used, but uncertainties in feedback parameters amplify ECS uncertainties. Data quality, particularly for ocean heat storage (only reliable recently) and aerosol effects (which cool the climate), is a major challenge. Observed 20th-century warming can align with either low ECS with low aerosol cooling or high ECS with high aerosol cooling, complicating CO_2 warming isolation. Paleoclimate proxies from periods like the last glacial maximum (3–7°C colder) and mid-Pliocene (1–3°C warmer) suggest high ECS values are unlikely but carry large uncertainties and may not apply to the current climate.

Historical data-based ECS estimates (2012–2024) typically range from 1.0–2.5°C, lower than model-based estimates. AR6 relied heavily on Sherwood et al. (2020), combining historical, paleoclimate, and process-based data, estimating ECS at 3.1°C (likely 2.6–3.9°C). Lewis (2022) criticized this for methodological errors and subjective assumptions, proposing a lower ECS of 2.2°C (likely 1.8–2.7°C, very likely 1.6–3.2°C). AR6 suggested data-driven ECS might underestimate future warming due to a “pattern effect,” where a weakening west-east tropical Pacific temperature gradient could reduce heat radiation efficiency, increasing ECS. However, Seager et al. (2019) and Lee et al. (2024) argue the gradient has strengthened, suggesting models mischaracterize oceanic dynamics, and future ECS may be lower than current estimates due to increased cooling efficiency.

The section provides a detailed and well-informed overview of the topic. However, it might be useful to note the time-series bias (*e.g.*, satellite data only since the 1980s) and the limits of observational data records. Aerosol forcing could be elaborated upon. Citing Gregory *et al.* (2020) might be useful.

4.4 Transient Climate Response

> **Section summary:** The Transient Climate Response (TCR) measures global temperature increase when CO_2 doubles over 70 years at a 1% annual increase, offering a more observationally constrained climate sensitivity metric than

Equilibrium Climate Sensitivity (ECS). TCR avoids uncertainties in ocean heat uptake and long-term feedback timescales (e.g., ice sheets), making it better tied to historical warming. The IPCC AR6 estimates TCR's very likely range as 1.2–2.4°C, with a tighter upper bound than ECS. Lewis (2023) estimates TCR at 1.25–2.0°C, aligning more closely with AR6 than his ECS estimates, indicating better agreement on TCR.

While this section is accurate and concise, I feel it needs more discussion. A brief discussion on how TCR is estimated (*e.g.*, model simulations or historical temperature records) would be useful. It would be helpful to cite Skeie *et al.* (2018). My concern is that the section's brevity will imply that TCR is less important than ECS or that it is more easily or more accurately measured. I do not think the authors wish to convey these concepts to the reader.

References

Christy, J.R., and R.T. McNider, 2017: Satellite bulk tropospheric temperatures as a metric for climate sensitivity. *Asia-Pac. J. Atmos. Sci.*, **53**(4), 1-8.

Colman, R., and B.J. Soden, 2021: Water vapor and lapse rate feedbacks in the climate system. *Reviews of Modern Physics*, **93**(4), 045002.

Curry, J., 2017: *Climate Models for the Layman*, The Global Warming Policy Foundation.

Fennel, K., and M.C. Long, 2019: Carbon-Cycle Feedbacks Operating in the Climate System. *Current Climate Change Reports*, **5**(4), 282–295.

Gregory, J.M., T. Andrews, P. Ceppi, T. Mauritsen, and M.J. Webb, 2020: How accurately can the climate sensitivity to CO_2 be estimated from historical climate change? *Climate Dynamics*, **54**(1-2), 129–157.

Hansen, J., M. Sato, L. Simons, L.S. Nazarenko, I. Sangha, P. Kharecha, *et al.*, 2023: Global warming in the pipeline. *Oxford Open Climate Change*, **3**(1), kgad008.

Knutti, R., M.A.A. Rugenstein, and G.C. Hegerl, 2017: Beyond equilibrium climate sensitivity. *Nature Geoscience*, **10**(10), 727–736.

McKitrick, R., and J. Christy, 2018: A test of the tropical 200- to 300- hPa warming rate in climate models. *Earth and Space Science*, **5**, 529-536.

Mülmenstädt, J., M. Salzmann, J.E. Kay, *et al.*, 2021: An underestimated negative cloud feedback from cloud lifetime changes. *Nature Climate Change*, **11**, 508–513.

Scafetta, N., 2022: Advanced testing of low, medium, and high ECS CMIP6 GCM simulations versus ERA5-T2m. *Geophysical Research Letters*, **49**, e2022GL097716.

Skeie, R.B., T.K. Berntsen, M. Aldrin, M. Holden, and G. Myhre, 2018: Climate sensitivity estimates – sensitivity to radiative forcing time series and observational data. *Earth System Dynamics*, **9**(4), 1293–1312.

Woodard, D.L., S.J. Davis, and J.T. Randerson, 2019: Economic carbon cycle feedbacks may offset additional warming from natural feedbacks. *Proceedings of the National Academy of Sciences of the United States of America*, **116**(3), 759–764.

5 DISCREPANCIES BETWEEN MODELS AND INSTRUMENTAL OBSERVATIONS

Chapter summary (from the Report): 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), too much warming in the lower-and mid-troposphere and too much amplification of warming aloft.

Climate models also produce too much recent stratospheric cooling, invalid hemispheric albedos, too much snow loss, and too much warming in the Corn Belt. The IPCC has acknowledged some of these issues but not all.

5.1 Introduction

Section summary: Climate models are key tools for projecting future climate changes due to rising anthropogenic greenhouse gas levels, but their reliability is questioned due to persistent issues. Despite decades of development across approximately three dozen models globally, the range of projected warming for a doubling of CO_2 spans a factor of three, showing no reduction in uncertainty. Additionally, models struggle to accurately replicate historical climate trends, including surface, tropospheric, and stratospheric temperature trends, the vertical warming profile, and other features like snowfall. A consistent issue is that models tend to overestimate warming in response to historical forcings, indicating limitations in their ability to represent both past and future climate accurately.

The introduction is a concise and accurate summary of key issues related to climate model performance. With respect to the last sentence of the introduction, though, I would include that some models do not “err on the side of too much warming” (*e.g.*, Russian models) but that is because they have been tuned to provide less warming, not necessarily because of better physics.

A brief note as to the primary reasons why models differ (*e.g.*, uncertainties in parameterizations or how forcings are treated) would be useful in indicating the complexity of the climate system and how difficult it is to model.

5.2 Surface Warming

Section summary: A key test of climate model validity is their ability to replicate historical warming based on known changes in climate drivers like greenhouse gases. Scaffeta (2023) groups CMIP6 climate models into low (1.5–3.0°C), medium (3.0–4.5°C), and high (4.5–6.0°C) Equilibrium Climate Sensitivity (ECS) categories, comparing their post-1980 global average temperature simulations to three surface temperature records and one satellite-based lower troposphere dataset. Low-ECS models align well with observed warming, while medium- and high-ECS models significantly over-predict it. Spencer (2024) further confirms this model-observation mismatch, showing that most climate models exhibit substantially more warming than observed since 1979.

This section offers a concise summary of the performance of the latest generation of climate models in describing the warming of the Earth's surface. Note that the lower and upper bound to the range attributed to Scafetta (2023) is different from what he wrote—1.5°C and 6.0°C (in the report) versus 1.8°C and 5.7°C (in Scafetta, 2023).

I would suggest providing a brief explanation as to why models with higher ECS tend to overestimate warming (*e.g.*, uncertainties in clouds and aerosols or natural variability). I also would suggest mentioning the three surface temperature records and the satellite-based product. The impact of the UHI and its influence on surface temperature records should at least be noted.

It also might be useful to discuss Martin-Mikle and Fagre (2019), who provide evidence that the Little Ice Age was a global cooling event which supports the narrative of natural climate variability and that warming predates the Industrial Revolution and the advent of anthropogenic CO_2 emissions into the atmosphere.

5.3 Tropospheric Warming

Section summary: Climate models consistently overestimate warming in the tropical troposphere, a critical region where anthropogenic greenhouse gas warming is expected to be most pronounced, indicating flaws in modeled heat transfer processes that also affect surface warming. This issue, noted as a serious inconsistency since the 2006 U.S. Climate Change Science Program report, has worsened and is now global. McKitrick and Christy (2020, 2025) found that all CMIP6 models overpredict tropospheric warming trends from 1979–2014 (extended to 2024) compared to satellite, weather balloon, and reanalysis data, with statistically significant biases in most models, especially high-ECS models. The bias is most pronounced in the upper troposphere (~0.1°C/decade), though even low-ECS models overpredict warming. The IPCC AR6 acknowledges this mismatch, citing studies (*e.g.*, Mitchell *et al.*, 2013; Santer *et al.*, 2017a, b; McKitrick and Christy, 2018) and suggesting high climate sensitivity, aerosol forcing uncertainties, and missing negative tropical cloud feedbacks as contributors. Despite strong evidence, AR6 assigns only medium confidence to the warming bias, which could imply that future models with realistic tropospheric warming would have lower sensitivity than even the low-ECS CMIP6 models.

The argument that tropical troposphere temperature data provide a critical test of climate model validity and the finding that climate models "on average overstate warming" in that region are key to this section. This suggests flaws in measured surface fluxes can create biases in surface warming trends although the report could elaborate on the mechanisms that most often lead to bias. An acknowledgement of observational biases would also help understand why discrepancies might exist.

5.4 Vertical Temperature Profile Mismatch

Section summary: Climate models exhibit a significant discrepancy by overestimating warming amplification with altitude in the tropical troposphere, where anthropogenic CO_2 warming should be most pronounced. IPCC AR5's online supplement (Figure 10.SM.1) shows 1979–2010 tropical lower troposphere warming is so minimal it aligns with models lacking CO_2 forcing and falls outside the range of models with CO_2 forcing, a point obscured in the report and omitted from summaries. Adapted in Figure 5.5, this shows observed tropical warming (20°S–20°N) from 1979–2024 lies within the "no CO_2" model range and outside the "with CO_2" range across the atmospheric column. Christy and McNider (2017), updated in Figure 5.6, confirm that modeled temperature trends exceed observations from the surface to the upper troposphere, with satellite data (NOAA, UAH, RSS) showing trends below the entire model range. Model uncertainties, driven by varied parameterizations of complex processes like turbulence and moist thermodynamics, result in a ±40% spread in mid-troposphere trends. Studies (*e.g.*, Klotzbach *et al.*, 2009; Vogelsang and Nawaz, 2016) confirm models exaggerate amplification rates, indicating a systematic warming bias and misrepresentation of fundamental feedback processes. The IPCC AR6 did not address this issue.

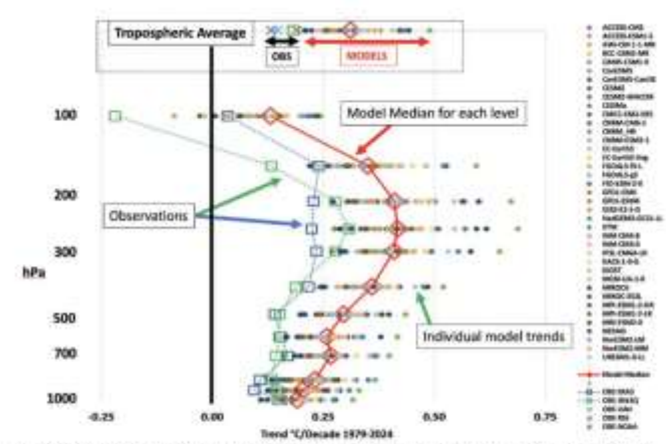


Figure 5.6: Modeled versus observed warming, tropical troposphere. Source: updated from Christy and McNider (2017) including data through 2024 and CMIP6 model outputs. Red line: model average. Green and blue lines: observational series (reanalysis).

This section is highly useful in that the mismatch between models and observations through the depth of the tropical troposphere was not included in AR6 or NCA5 but is important to understand model biases as the amplified warming aloft is largely missed by the models. As in Section 5.2, I would suggest identifying the three satellite data sets. In addition, I would use the phrase “models indicate” rather than “models say” in the first sentence of the second paragraph.

5.5 Stratospheric Cooling

> **Section summary:** The expected “fingerprint” of anthropogenic climate change includes tropospheric warming and stratospheric cooling, influenced partly by ozone depletion and recovery. IPCC AR6 (WG1, Ch. 2) reports that lower stratospheric temperatures (10–25 km) cooled from 1980–2019, with most cooling before 2000, partly amplified by volcanic eruptions (El Chichon 1982, Pinatubo 1991). However, since 2000, most datasets show no significant cooling, with some indicating weak warming in the lower stratosphere, as noted by Philipona *et al*. (2018), who observed a shift from late 20th-century cooling to early 21st-century warming at 15–30 km. Santer *et al.* (2023) confirm no cooling trend has re-emerged. This recent stratospheric warming, alongside ongoing tropospheric and surface warming, contradicts climate model predictions and the expected anthropogenic fingerprint, which anticipates continued stratospheric cooling.

The section is accurate in describing the expected anthropogenic fingerprint, the observed stratospheric cooling until 2000, and the subsequent response. Ozone recovery has been postulated as a mechanism for stratospheric warming by Solomon *et al.* (2016) or Randel *et al.* (2017), among others. Addressing this issue, albeit briefly, would be prudent.

Some CMIP6 models with interactive ozone chemistry or updated forcings simulate reduced cooling or stabilization in the lower stratosphere (*e.g*., Dhomse *et al.*, 2018). It also would be useful to address the uncertainties in satellite data sets (see Seidel *et al.*, 2016). Randel *et al.* (2017) also discuss the natural variability impacts that should be included.

5.6 Snow Cover Mismatch

> **Section summary:** Northern Hemisphere winter snow cover extent (SCE), as compiled by Rutgers University Snow Lab, shows no decrease and may even be increasing, contrary to climate model predictions of a decline due to warming (Connolly *et al.*, 2019). While models predict consistent SCE reduction across all seasons, observations indicate decreases only in spring and summer, with patterns differing from model projections, and autumn and winter show non-significant increases. IPCC AR6 notes agreement on spring SCE decline but highlights uncertainty in winter (October–February) trends, with the NOAA Climate Data Record showing an increase, while satellite-based and multi-observation datasets suggest declines. AR6 acknowledges challenges in winter SCE measurement due

> to cloud cover and low solar illumination. No significant trends are found in Pacific Coast (CA, OR, WA) mountain snowfall since the late 19th century (Christy, 2022). The discrepancy between models and observations, along with conflicting observational datasets, indicates a need for further research to resolve these inconsistencies.

While this section is largely accurate, much is made about increasing and decreasing trends. I would caution about interpreting slopes of data with weak correlations as anything other than "no significant trend" as I think that is the correct interpretation of Figure 5.7 and possibly the other datasets cited by p. 344 of AR6 WG1. A mention of the uncertainties in each of these observations would make it clear that the trend is not statistically significant and would underscore the problem associated with determining hemispheric snow cover totals.

5.7 Hemispheric Symmetry of the Planetary Albedo

> **Section summary:** Planetary albedo, the fraction of solar radiation reflected to space (~0.30), is critical to Earth's radiative energy balance, with small changes (0.01) equating to significant forcing (~3 W/m²), exceeding current anthropogenic forcing (~2.7 W/m²). Climate models struggle to match observed albedo values and show discrepancies among themselves (Stephens *et al*., 2015). Surprisingly, the Northern and Southern Hemispheres have nearly identical albedo over the 50-year satellite record, despite the Southern Hemisphere's greater ocean coverage, which is less reflective than land. This symmetry is due to cloudier Southern Hemisphere extra-tropical storm tracks compensating for surface albedo differences (Datseris and Stephens, 2021). CMIP6 models, however, fail to replicate this small observed albedo asymmetry (~0.1 W/m²), with some showing asymmetries up to 5 W/m² and disagreement on which hemisphere is more reflective (Rugenstein and Hakuba, 2023). These unphysical asymmetries may affect estimates of heat fluxes, temperature gradients, storminess, and ocean heat storage, undermining confidence in model projections due to issues with cloud feedback processes.

This section is generally accurate in its description of the challenges climate models face in reproducing observed patterns. Models project asymmetry in hemispheric albedo, but observations indicate symmetry or much smaller asymmetry. It should be stressed more that the model asymmetry is much greater than that of the anthropogenic forcing, which highlights the magnitude of model errors relative to the climate change signal we seek.

While I note the section admits that hemispheric symmetry "likely operates on large temporal and spatial scales," it would be useful to briefly mention some of the hypothesized drivers that may operate at these scales. A brief discussion of the observational and modeling challenges would also put into context the difficulty in estimating these parameters.

5.8 U.S. Corn Belt

Section summary: Climate models exhibit significant discrepancies with observations, particularly in the U.S. Corn Belt, a critical region for global food production. All thirty-six CMIP6 climate models overpredict summertime warming (June–August) in the twelve-state Corn Belt (IN, IA, IL, ND, SD, MO, MN, WI, MI, OH, KS, NE) from 1973–2022 compared to observed data. Contrary to model-based predictions (*e.g.*, Seager *et al.*, 2018), anticipated negative impacts on U.S. corn yields have not occurred. The IPCC recognizes limitations in regional climate model accuracy, suggesting users evaluate model outputs cautiously, as local biases may render models unfit for purpose, a view echoed by Palmer and Stevens (2019), who argue current models are inadequate for many regional applications.

More broadly, climate models show multiple biases: they overpredict surface warming (except in low-ECS models), lower- and mid-tropospheric warming, and warming amplification with altitude; they also overestimate stratospheric cooling, snow cover loss, and U.S. Corn Belt warming. Additionally, models fail to accurately replicate the small observed hemispheric albedo asymmetry, with discrepancies up to three times larger than CO_2's direct anthropogenic forcing. The IPCC acknowledges some of these issues but not all, highlighting ongoing challenges in model reliability.

This concluding section makes several claims about climate model performance in the U.S. Corn Belt, corn yield impacts, and the limitations of regional climate models. A brief mention could be made of the impact of improved irrigation techniques, heat- and drought-tolerant hybrids, and CO_2 fertilization (see, for example, Lobell *et al.,* 2014 and Lesk *et al.*, 2016). More should also be made of Figure 5.9 where thirty-six models all overestimated corn belt temperatures between 1973 and 2022 with about half projecting almost five to nine time more warming than observed.

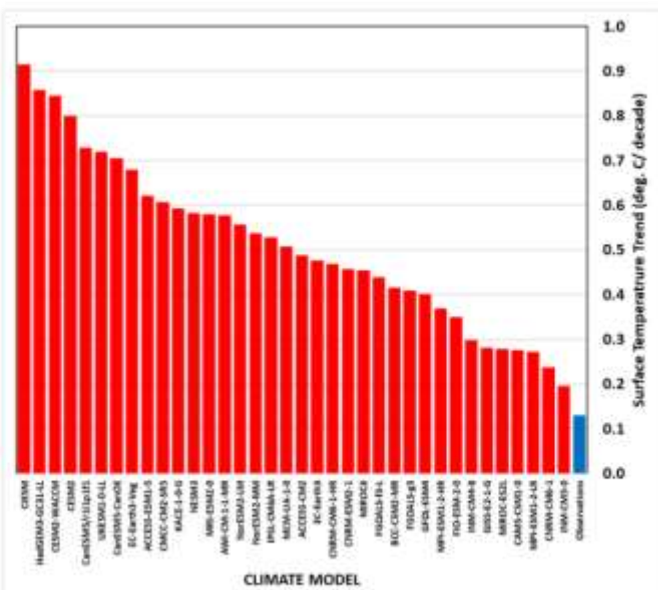


Figure 5.9: Modeled versus observed warming trends in the U.S. Corn Belt, 1973-2022.

References

Dhomse, S.S., D. Kinnison, M.P. Chipperfield, R.J. Salawitch, I. Cionni, M.I. Hegglin *et al.*, 2018: Estimates of ozone return dates from Chemistry-Climate Model Initiative simulations. *Atmospheric Chemistry and Physics*, **18**(11), 8409–8438.

Lesk, C., P. Rowhani, and N. Ramankutty, 2016: Influence of extreme weather disasters on global crop production. *Nature*, **529**(7584), 84–87.

Lobell, D.B., M.J. Roberts, W. Schlenker, N. Braun, B.B. Little, R.M. Rejesus, and G.L. Hammer, 2014: Greater sensitivity to drought accompanies maize yield increase in the U.S. Midwest. *Science*, **344**(6183), 516–519.

Martin-Mikle, C.J., and D.B. Fagre, 2019: Glacier recession since the Little Ice Age. *Arctic, Antarctic, and Alpine Research*, **51**(1), 280-289.

Randel, W.J., L. Polvani, F. Wu, D.E. Kinnison, C.-Z. Zou, and C. Mears, 2017: Troposphere-stratosphere temperature trends derived from satellite data compared with ensemble simulations from WACCM. *Journal of Geophysical Research: Atmospheres*, **122**(18), 9651–9667.

Seidel, D.J., J. Li, C. Mears, I. Moradi, J. Nash, W.J. Randel, *et al.*, 2016: Stratospheric temperature changes during the satellite era. *Journal of Geophysical Research: Atmospheres*, **121**(2), 664–681.

Solomon, S., D.J. Ivy, D. Kinnison, M.J. Mills, R.R. Neely III, and A. Schmidt, 2016: Emergence of healing in the Antarctic ozone layer. *Science*, **353**(6296), 269–274.

6 EXTREME WEATHER

Chapter summary (from the Report): Most types of extreme weather exhibit no statistically significant long-term trends over the available historical record. While there has been an increase in hot days in the U.S. since the 1950s, a point emphasized by AR6, numbers are still low relative to the 1920s and 1930s. Extreme convective storms, hurricanes, tornadoes, floods and droughts exhibit considerable natural variability, but long-term increases are not detected. Some increases in extreme precipitation events can be detected in some regions over short intervals but the trends do not persist over long periods and at the regional scale. Wildfires are not more common in the U.S. than they were in the 1980s. Burned area increased from the 1960s to the early 2000's, however it is low compared to the estimated natural baseline level. U.S. wildfire activity is strongly affected by forest management practices.

6.1 Introduction

Section summary: High-impact weather extremes, such as those involving temperature, precipitation, or high winds, can disrupt infrastructure and threaten human health. The key questions are whether these extremes are increasing in frequency or intensity over decades ("detection") and whether such changes are driven by anthropogenic greenhouse gas emissions ("attribution"). While warming is often assumed to worsen extremes based on thermodynamic arguments, attributing specific events to human influence is problematic, as climate reflects long-term statistical patterns, not individual events. With only ~130 years of reliable data, the observational record is too short to capture the full range of natural climate variability, complicating trend detection and attribution. Long-term natural oscillations, like those seen in the eight-century Nile River record, show that apparent trends in short records can be misleading, often exaggerating the significance of extremes.

The chapter focuses on detecting trends in extreme weather, noting that without a detected trend, attribution to human causes is baseless. Even when trends are observed, linking them to anthropogenic warming is not automatic, particularly for precipitation, which exhibits slow, irregular natural oscillations requiring long records for accurate analysis. Public and media narratives often claim worsening extremes due to climate change, but expert assessments (*e.g.*, IPCC SREX 2012, AR6 2021, U.S. NCA4 2017, NCA5 2023) are more cautious, highlighting difficulties in identifying trends and establishing causal links to greenhouse gases. The discussion draws on these reports and standard government data through 2024 to evaluate evidence, emphasizing a gap between public perception and scientific evidence.

This section accurately frames the complexity surrounding future patterns of extreme weather events. It appropriately highlights the distinction between weather and climate, the limitations of short observational records, and the challenges of attributing trends to anthropogenic causes. The report avoids overstating claims and emphasizes the need for caution when interpreting extreme weather trends, which aligns with the current scientific consensus.

High-impact weather extremes will indeed disrupt infrastructure and endanger human health and well-being and are well-documented for their societal impacts. The discussion about long-term changes in both detection and attribution (*i.e.*, the link to anthropogenic greenhouse gas emissions) is precise and reflects current understanding of climate science. Moreover, the thermodynamic arguments suggest that climate analysis focuses on statistical properties over long-time periods, not on single events.

That we have only about 130 years of reliable observational records is also a valid point, and paleoclimate records suggest that extreme events have occurred naturally over millennia and often exceed the severity of modern events. This caution is consistent with statistical analyses.

With respect to hydroclimatology, the issues cited regarding rainfall data and hydrological data are well-taken. It also is unfortunately true that media and public discourse oversimplify or exaggerate the connection between weather and climate change, which is underscored by assessments of the public's understanding of climate science.

I would suggest that "simple thermodynamic arguments" could be elaborated upon to enhance the understanding for laypersons. An acknowledgement of regional variability would also be useful to strengthen the introduction and, although I agree with it, the statement about public perceptions could be softened a bit since the average person is strongly swayed by extreme events they have witnessed or experienced first-hand.

I also think the ordering of the subsections could be made more logical if the sections were discussed in this order: temperature extremes, extreme precipitation, flooding, droughts, hurricanes and tropical cyclones, tornadoes, and wildfires.

6.2 Hurricanes and Tropical Cyclones

> **Section summary:** IPCC AR6 reports low confidence in long-term trends in tropical cyclone (TC) frequency or intensity due to changes in data collection technology, though it notes a likely increase in the global proportion of major (Category 3–5) TCs over the last four decades, with no clear trend in overall TC frequency. U.S. landfalling hurricanes since 1900 show no trend in frequency. Globally, since 1980, satellite data indicate ~50 hurricanes annually, with ~25 being major, showing a slight, non-significant increase in major hurricanes and a weak decrease in total hurricanes. Atlantic hurricanes, making up ~15% of global TCs, show significant increases since 1970, but this follows a low-activity period (1971–1994) due to the Atlantic Multidecadal Oscillation (AMO), with high activity in the 1950s–60s and 1930s comparable to recent decades. The AMO's warm phases (1926–1970, 1995–present) correlate with more major hurricanes due to higher sea surface temperatures (SSTs) and reduced vertical shear.
>
> Klotzbach *et al.* (2018) found no significant trend in U.S. landfalling hurricanes since 1920, with high variability driven by ENSO and AMO phases. The highest U.S. landfall year was 1886 (7 hurricanes), despite minimal human climate influence then. Among the strongest U.S. landfalling hurricanes (>150 mph), only one occurred in the 21st century. Warmer SSTs are hypothesized to increase hurricane intensity, storm surges, and rainfall, but short records and natural variability obscure trend detection. The complex dynamics of individual storms further complicate identifying changes in storm surges or rainfall.

Claims regarding the number of hurricanes and major hurricanes are correct as well as the statement about a weak decrease in total hurricanes and a slight, insignificant increase in major hurricanes, which is consistent with more recent studies like Knutson *et al.* (2020). Regional contributions of hurricane numbers are accurate, as is the note that pre-satellite era data likely undercount tropical cyclones, particularly for non-landfalling storms.

With respect to claims of a significant increase in Atlantic hurricane activity since 1970, it should be stressed that satellite technology and the change to the AMO warm phase have enhanced both the detectability and the occurrence of tropical cyclones, respectively. Moreover, claims by Mann *et al.* (2021) should be addressed as they suggest that the AMO may be an artifact of increases in greenhouse gases. Challenges raised by the report (*e.g.*, small sample size of landfalling storms and data limitations) are well-taken.

The report lacks discussion of storm size, tropical storm duration, and precipitation totals which are relevant to the climate change discussion. Kossin *et al.* (2020), for example, suggest that storms are slowing with a concomitant increase in precipitation totals. Moreover, changes in hurricane tracks and areas of formation also are not discussed (see Kossin *et al.*, 2014).

As AR6 reports medium confidence in an increase in major tropical storms, this should be addressed. In addition, the effect of rising SSTs on tropical storm formation should be fleshed out better. Given the importance of economic and societal impacts arising from landfalling hurricanes and the discussion of the impacts later in the report, it would be prudent to include a brief discussion of them here (noting, for example, that growth along the shoreline exacerbates the damage from landfalling storms).

6.3 Temperature Extremes

Section summary: IPCC AR6 reports that since the 1950s, hot extremes, including heatwaves, have become more frequent and intense across most land regions, while cold extremes have decreased in frequency and severity. In North America, AR6 notes a very likely increase in hot extreme intensity and frequency, with consistent warming in minimum temperatures but varied trends in maximum daily temperatures, particularly in the US. However, NCA4 highlights that US heatwave activity peaked in the 1930s, with the warmest daily temperatures decreasing in most eastern U.S. regions (*e.g.*, Midwest by ~2.2°F, Southeast by ~1.5°F) over the past century. Since the mid-1960s, the warmest daily temperatures have shown only a slight increase amidst high variability, and heatwave frequency, while increasing since the 1960s, remains below the 1930s peak. This indicates a complex pattern with significant historical and regional variations not fully captured by AR6's post-1950 focus.

Only NCA4 is cited but NCA5 is used later in the discussion. It would be prudent to include conclusions from NCA5 in this beginning section.

6.3.1 Temperatures in the US are becoming less extreme

Subsection summary: The United States Historical Climate Network (USHCN) dataset, covering 1,211 stations since December 1898, provides 126 years of daily maximum (Tmax, May–Sep) and minimum (Tmin, Dec–Mar) temperature records, with a median data availability of 98%. Despite potential urban heat island (UHI) biases, particularly affecting Tmin, the dataset is reliable for assessing trends in temperature extremes. Analysis shows that 60% of Tmax and 59% of Tmin records occurred before 1961, with the 1920s and 1930s (peaking in 1936) being exceptionally warm, and the 1899 Valentine's Day Arctic outbreak marking the most extreme cold event. Cold extreme frequency has declined significantly, with only 13% of Tmin records in the last quarter (1993–2024),

> while 25% of Tmax records occurred then, aligning with statistical expectations. The range between the hottest summer Tmax and coldest winter Tmin has decreased by ~5°F over 126 years, driven mainly by warmer winter Tmin (partly due to UHI) and a slight decline in summer Tmax. This indicates a U.S. climate less prone to extremes, contrary to media emphasis on extreme events, consistent with IPCC AR6 and NCA4 findings.

The discussion of the occurrence of maximum and minimum temperatures as well as cold outbreaks is appropriate. It accurately reports that "long term records show the U.S. climate has become less extreme over time (*i.e.*, milder) when measured by the range between warm season maxima and cold season minima." The conclusion that 25% of maximum air temperature records since the early 1990s aligns with "statistical expectations" needs clarification. Note too that this conclusion coincides with the adoption of the Automated Surface Observing System (ASOS) through the National Weather Service (NWS) modernization program, which could affect the results. This and other instrumentation and observational changes should be discussed as caveats against attempting to glean climate signals from changes in air temperature.

The claim made in the title of this section may be interpreted as a greater increase in winter temperatures than the rise in summer temperatures. This needs more clarification. Furthermore, NCA5 and NOAA both argue for an increase in heatwave frequency and, although that is addressed in Section 6.3.3, the impact and veracity of their conclusions need to be considered here as well. It would be helpful if data biases and inconsistencies were highlighted to underscore the problems associated with simply assuming that small trends might be statistically significant when they are not of practical significance.

It also would be useful to discuss *Lee et al.* (2014), which found that monthly maximum air temperatures are not increasing in the US. While a pattern of cooling exists in some areas with the maximum air temperature records, warming is more evident in minimum air temperatures. This is consistent with the urban heat island effect on warming.

6.3.2 Exceedances of a heat threshold

> **Subsection summary:** NCA5 reports an increase in days with temperatures at or above 95°F, particularly in the western US since the 1980s, driven by greater warming in that region, and highlights major heatwaves, including a record-breaking 2021 Pacific Northwest event. However, threshold metrics like days above 95°F can be misleading due to regional climate variability. Stations near the 95°F threshold may show large changes with small temperature shifts, while those consistently above or below show little change. Over 126 years, the average CONUS station recorded 129 days above 95°F per 6-year period, with regional variations (278 in the Southern Plains, 9 in the Northeast). Only three western regions show upward trends in 95°F days, while the CONUS overall and six other regions show declines. The 2021 Pacific Northwest heatwave, with a 5-day tropospheric temperature anomaly of +10.8°C, was an unprecedented event, not indicative of a broader trend, as global temperatures remained near normal (+0.03°C).

The report effectively uses a 126-year record (Figure 6.3.5) to rebut NCA5's claim that occurrences of 95°F and hotter days are increasing in CONUS overall. The report also accurately argues that using 95°F as a threshold metric for detecting climate change can be misleading, which is consistent with statistical analyses of temperature extremes (Perkins and Alexander, 2013).

However, the report focuses narrowly on just days exceeding 95°F. The final report should broaden discussion to consider other thresholds.

6.3.3 Heatwaves

> **Subsection summary:** Heatwaves, defined as six or more consecutive days exceeding the 90th percentile of daily temperatures (May–Sep), have greater societal impact than single-day temperature records. Analysis using the full 1899–2024 record from the U.S. Historical Climate Network (USHCN) shows no overall increase in heatwave frequency across the contiguous US (CONUS) compared to a century ago, consistent with NCA4 findings. Regional variations exist: The eastern two-thirds of the US saw more heatwaves in the early 20th century, while the West has seen increases recently (NCA5). Northern regions average 15–27 heatwave days per 15-year period, while southern regions see 37–54, reflecting differences in summer circulation patterns.
>
> NCA5 cites a USGCRP (2023) figure showing urban heatwaves (defined as ≥2 days with minimum apparent temperature above the 85th percentile) increasing from two per year in the 1960s to six in the 2020s across 50 major U.S. cities. However, this metric is misleading due to its start in the cold 1960s, urban heat island (UHI) effects inflating minimum temperatures, and the use of an unconventional heatwave definition. Summer maximum temperatures (Tmax), especially in rural areas, are a better metric for detecting greenhouse gas (GHG)-driven heatwave changes. Evidence suggests GHG emissions have minimal impact on CONUS heatwave trends, which are heavily influenced by urbanization and natural variability.

As the report's authors know, the definition of a "heatwave" is varied in the literature. The report defines heatwave as six or more consecutive days exceeding the 90th percentile of daily temperatures during May-September. NCA5's definition focuses on urban areas and shorter-duration events (*i.e.*, more than two days with minimum apparent temperature above the 85^{th} percentile) with an extended one-hundred-year baseline. A discussion of the impact of these disparate definitions should be included, as the report's use of a six-day threshold is more stringent, but aligns better with other studies (*e.g.*, Perkins and Alexander, 2013).

The report uses the entire record from 1899 to 2024 as a base period whereas NCA4 uses the 30-year period from 1961 to 1990—a cool interval compared to the 1930s, thereby creating a potential bias. The advantages of using the entire record for comparison should be noted.

The geographic discussion of heatwaves aligns with the findings of the NCA5. The report's attribution to "background warm season circulation" is consistent with studies like those by

Meehl et al. (2016), which link regional heatwave patterns to atmospheric dynamics. While the report argues correctly that summer maximum temperature is a better metric for detecting changes in background climate due, for example, to increasing greenhouse gas concentrations, NCA5's claim that minimum temperature trends are critical for health impacts due to reduced nighttime cooling should be included.

The report's statement that "GHG emissions have had little-to-no effect on heatwaves against the background of urbanization and natural climate variability," is in direct opposition to NCA5 and studies such as Knutson *et al.* (2017) and Diffenbaugh *et al.* (2017), which link greenhouse gas warming to trends in heatwaves. These differences should be addressed. The report correctly notes the role of natural variability in heatwave occurrences, such as the exceptional heat of the 1930s, and should be further emphasized to counter the claims of AR6 and NCA5.

6.4 Extreme Precipitation

> **Section summary:** IPCC AR6 reports high confidence in increased frequency and intensity of heavy precipitation events since the 1950s globally and in North America (1950–2018), with U.S. National Climate Assessments (NCA4, NCA5) noting increases primarily in the Northeast, less so in the West. However, McKitrick and Christy (2019, updated 2025) analyzed long-term station data (Pacific Coast since 1893, Southeast since 1872, Northeast since 1888) and found no significant trends in extreme precipitation when extending records back to the 19^{th} century or starting later than the 1950s (*e.g.*, 1978). On the Pacific Coast, associated with atmospheric rivers, only a few stations showed significant trends (*e.g.,* downward in Astoria, OR; positive in Big Sur, CA). In the Southeast, significant trends were limited to a few stations (*e.g.*, Mobile, AL; Vicksburg, MS). In the Northeast, average precipitation trends were significant in 12 of 27 stations, but regional averages showed no significant trends in variance or maxima.
>
> Analysis of 5-day deluges (1-in-5-year events) on the Pacific Coast and Southeast, and 3-day deluges in the Northeast, showed no clear increase in frequency over time, with clusters (*e.g.*, 1995–2019 in the Southeast, 1995–2014 in the Northeast) linked to natural variability, such as tropical storms. The Northeast's increase in extreme events (1997–2014) was driven by tropical cyclone-related precipitation, but this did not persist post-2014, and the amount per event has remained stable (Jong *et al.*, 2024). Urban infrastructure may influence local precipitation, but its effect on these stations is unclear. Overall, long-term U.S. data, accounting for precipitation's autocorrelation, do not support claims of increasing frequency or intensity of extreme rainfall events, suggesting natural variability dominates observed patterns.

AR6 claims that heavy precipitation events for both the globe and North America have likely increased since the 1950s where data are sufficient. Likewise, both NCA4 and NCA5 suggest an increase in heavy precipitation events (with various definitions of "heavy" events, as noted) over

CONUS, especially in the Northeastern US. The Box "Perils of Short Data Records" clearly illustrates the limitations of using relatively short climate periods (~130 years) to assess the range of natural variability in general and of extreme precipitation events in particular.

One of the issues that is often overlooked has been the change in instrumentation resulting from the modernization program of the National Weather Service (NWS) in the early 1990s. Prior to modernization, the NWS used the standard raingage (SRG) with an 8-inch orifice diameter (opening of 324 cm^2) and without an attached wind shield (see Golubev *et al.,* 1992). The SRG is a can-type, manually read raingage that funnels rainfall into an internal collector of 32.4 cm^2 where a measuring stick is used to determine the water depth (magnified by a factor of ten to enhance accuracy). For snowfall measurement, the internal collector and the funnel are removed and the snowfall caught by the gauge is melted to provide an estimate of liquid water equivalent.

After the NWS modernization, the SRG was replaced by the Automated Surface Observing System (ASOS) which includes a heated tipping-bucket gauge which provides automatic, real-time measurements of both rainfall and snowfall thereby supplanting the need for human observers. Most of these systems were installed between late 1992 and mid-1994 (McKee *et al.*, 1994; ASOS, 1998). After installation, the heated tipping-bucket gauge was noted to greatly underestimate snowfall measurements, owing to evaporation from the surface of the funnel due to its artificial heating and the delay in the tipping bucket mechanism to position the next tipping bucket under the funnel (La Barbara *et al.,* 2022). Consequently, a new All-Weather Precipitation Accumulation Gauge (AWPAG) replaced the heated tipping bucket gauge to record precipitation during snowfall events in regions where snowfall was significant (Bartholf, 1994; White *et al.,* 2004; Dover and Fiore, 2007) between March 2003 and October 2006 (mostly replaced in 2004 and 2005).

This change in instrumentation could likely create or exacerbate an increase in raingage catch during the period from 1950 to 2024 (as evaluated by McKitrick and Christy, 2019; 2025). Two important differences should be noted—the height of the gage orifice was lowered from between 79 to 122 cm to approximately 46 cm and the new ASOS gages were equipped with an Alter wind shield. It has long been established that gage catch decreases with increasing wind speed which, due to surface roughness within the boundary layer, increases with the height of the gage orifice (see Neff, 1977; Legates, 1987; Groisman and Legates, 1994). As for wind shields, Groisman and Legates (1994) note that gage design and the presence and type of wind shield can introduce substantial discontinuities into a precipitation time series. Much additional evidence exists for the increase in precipitation catch efficacy as the gage height is lowered and/or a wind shield is employed (see Groisman *et al.*, 1999; Landolt *et al.*, 2004, and Devine and Mekis, 2008). Legates and DeLiberty (1993) estimated that the undercatch bias due to the wind lies between 5% and 8% for the continental U.S., while Golubev *et al.* (1992), Groisman *et al.* (1999), and Duchon and Essenberg (2001) corroborate that the use of a gage shield reduces most (*i.e.*, about 5% to 6%) of this undercatch bias.

Thus, it must be noted that the modernization of the NWS in the early 1990s created a jump discontinuity in the precipitation record. Given that the effect of the instrumentation change is to increase the gage-catch efficiency some, or possibly all, of the observed increase in heavy precipitation events may be artificially induced.

However, regional differences were marked, with higher trends observed in the Northeast US, and to a lesser extent in the Southeast and Midwest regions. In these areas, a high density of First Order NWS stations exist which contain this jump discontinuity. Another national network, the NWS Cooperative Station Network, is more prevalent in rural areas and is not subject to the instrumentation change associated with the NWS modernization program (NSTC, 2008). It is expected that the NWS modernization process would affect a higher proportion of stations in the more urbanized eastern and north-central US. This is particularly true in that Karl *et al.* (1996) noted that the NWS Cooperative Station Network was used to supplement data in the western US to provide more complete spatial coverage for the creation of the original version of the Climate Extremes Index (CEI). Note that the NWS Cooperative Station Network is not affected by the NWS modernization and its records do not exhibit a dramatic increase in precipitation.

6.5 Tornadoes

Section summary: The AR6 report indicates that observational trends in US tornadoes, hail, and lightning are not reliably detected due to inconsistent long-term data. It suggests with medium confidence that the annual number of tornadoes has remained relatively stable. Improved monitoring, driven by population growth and video recording, has increased reports of weak tornadoes, while strong to violent tornadoes are more consistently observed due to significant damage. Since 1950, strong to violent tornadoes have decreased by about 50%, while weak tornado counts have stabilized post-1990 due to better monitoring, with earlier data being incomplete.

It is true that tornado statistics are affected by visual observations of tornadoes and particularly by their damage patterns and extent. As the report notes, “Since statistics began in 1950, there has been a substantial decrease (by about 50%) in the number of strong to violent tornadoes…After 1990 the number of weak tornadoes in the US has remained roughly constant; data before that are incomplete due to limited monitoring.” Moreover, tornado records are affected by population and intensity since weak tornadoes in the past may have been under-observed due to a lack of visual identification. Strong-to-violent tornadoes are more likely observed, even in the early part of the record (Grazulis, 1993), but their limited numbers affect the pattern of damage that they may create. For example, a violent tornado that moves through a Kansas wheat field may not yield the damage of a strong tornado that strikes a small town nearby. Nevertheless, the trend for strong-to-violent tornadoes is indeed downward (Kunkel *et al.,* 2013) although one must be careful not to put much faith in trends associated with small numbers (Brooks *et al.*, 2014; Tippett *et al.*, 2016). AR6 and NCA5 both admit low confidence associated with trends in tornado frequencies.

Two specific issues that are missing in this discussion are the advent of Doppler weather radar (*e.g.*, the WSR-88D weather radars) and the change to the enhanced Fujita scale. In the early 1990s, the National Weather Service (NWS) replaced the WSR-57 and WSR-74 C- and S-band radars with the S-band WSR-88D since none of the existing cadre of weather radars had employed Doppler capabilities, which provides information on both wind speed and direction (although limited to only towards or away from the radar). This latter technological development has enhanced both tornado detection and warning and greatly increased the number of weak tornadoes that have been detected (Verbout *et al.*, 2006; Tippett *et al.*, 2016).

The Enhanced Fujita Scale is an improvement over the original Fujita Scale for categorizing tornadoes in that it includes construction quality and standardizes for different structure types (Murphy, 2021). The original Fujita Scale was based on observed damage to structures and vegetation. It was introduced in 1971 and updated in 1973 to consider path length and width (McDonald, 2001). It then was applied retroactively to tornadoes since 1950. Wind speeds on the Fujita Scale were determined to be too high for the damage that they created. For example, an F5 tornado on the Fujita Scale has wind speeds greater than 420 km/h (261 mph) while an EF5 tornado on the Enhanced Fujita Scale has wind speeds greater than 322 km/h (200 mph). These differences create difficulty in comparing storms rated on the old scale relative to the new scale. A minor caveat is that the report uses the phrase *severe tornadoes* when meaning strong-to-violent storms as the NWS uses the word *severe* in this context to include any significant damage or injury.

While the report highlights how monitoring changes have increased weak tornado reports and explains the consistent detection of strong tornadoes due to damage-based assessments, it does not discuss potential drivers and relationships due to natural variability (*e.g.*, ENSO) or improvements in damage assessment accuracy. Moreover, the report does not discuss changes in the spatial distribution of tornadic activity (Biddle *et al*., 2020) and could be enhanced to discuss briefly the effect of societal impact due to population and economic growth in vulnerable areas (Gensini and Brooks, 2018). In addition, a discussion of tornado outbreaks, rather than mere numbers, would be beneficial and add to the determination of trends in tornadoes.

6.6 Flooding

Section summary: The AR6 report, consistent with SREX and AR5, finds low confidence in global-scale changes in flood magnitude or frequency due to heterogeneous regional data. SR15 notes increased flood frequency and extreme streamflow in some regions and decreases in others. AR6 highlights high confidence in changed flood seasonality in cold, snowmelt-driven regions due to warming, but low confidence in global peak flow trends. The NCA4 reports mixed trends in U.S. streamflow extremes, with no robust evidence linking these to human influences, aligning with the lack of consistent changes in extreme precipitation.

The report agrees with AR6 that low confidence was observed for changes in both the magnitude and frequency of global-scale flooding. It also is true that the hydrological literature is divided on regional-scale flooding which makes assessments at the global scale difficult. Within the U.S., trends also are mixed, as evidenced by the NCA4, which is cited in the report.

However, the report is scant with respect to a discussion on flooding. NCA5 states that heavier rainfall events across the United States, combined with changes in land use, soil moisture, and snow, are increasing flood damage. The report notes that “heavier rainfall events are expected to increase across the Nation (very likely, very high confidence)." These claims need to be clarified even beyond the argument regarding heavier rainfall events that were addressed in Section 6.4.

The main argument that flood frequencies and intensities will increase is that increasing air temperatures, due to rising CO_2 concentration in the atmosphere, will increase saturation vapor pressure, which in turn will increase evaporation and evapotranspiration rates, thereby providing more moisture to the atmosphere. When it rains, more precipitation will occur, resulting in more flooding events and deeper floods when they occur.

It is no doubt that flood (or pluvials) frequencies and intensities have increased. However, the primary reason has been widespread urbanization. In just 30 years between 1985 and 2015, the amount of urban land area has increased by about 310,800 km^2 (120,000 mi^2) with approximately 70,000 km^2 (27,000 mi^2) in North America (Liu *et al.*, 2020). Liu and colleagues (2020) note, "we find that global urban extent has expanded by 9,687 km^2 per year … this rate is four times greater than previous reputable estimates from worldwide individual cities, suggesting an unprecedented rate of global urbanization …. the rate of urban expansion is notably faster than that of population growth …"

In the US, suburbanization and urbanization of rural areas and the growth of urban areas has led to substantial changes in land area that is now covered by impervious surfaces (*e.g.*, asphalt, concrete, buildings) where before, the landscape was largely undeveloped with grasslands and forests. For example, the City of Houston (TX) has undergone rapid and extensive urbanization between 1997 and 2016 (Rice University, 2025). In such areas, the impervious surfaces serve to facilitate water movement overland to the nearby streams and rivers, exacerbating the flood peak downstream.

Even the Palmer Drought Severity Index (PDSI) shows that the proportion of the CONUS that is classified as very wet exhibits much temporal variability but no long-term trend, which indicates a changing climate has little impact on the flood climatology of the US (NOAA, 2025—see Section 6.7 for further discussion).

6.7 Droughts

Section summary: IPCC AR6 indicates limited evidence of increased meteorological drought in most regions, with medium confidence in rising agricultural and ecological droughts across all continents but decreases in one region. Hydrological droughts show increases in only a few regions. NCA4 notes a decline in U.S. drought statistics due to increased precipitation, though recent droughts have reached record intensity in some areas, with the 1930s Dust Bowl remaining the benchmark. SREX highlights that recent droughts are not unprecedented, with severe "megadroughts" in historical records. Long-term US data show a slight, non-significant decline in extreme dryness. Kogan *et al.* (2020) find no global drought intensification or climate change connection since the 1980s. Overall, there is no evidence of increasing meteorological drought frequency or intensity in the US or globally in recent decades.

It is true AR6 suggests that several regions exhibit increases in meteorological drought and that agricultural and ecological droughts have occurred on all continents. Moreover, hydrological droughts have been observed to increase in several areas. On the other hand, NCA4 finds that increases in precipitation have caused droughts to decrease and that recent droughts are not unprecedented in either CONUS over the last century or more as well as in the paleoclimate record.

The report, however, focuses only on meteorological drought frequency and intensity, arguing that no evidence exists of its increase over either the U.S. or the globe. Only one citation is used to defend this assessment as well as NOAA NCEI's characterization of the U.S. classified as "very dry" from 1895 to 2025.

Urbanization clearly has increased the demand for water. More people and more water intensive activities put a strain on depleted or depleting resources, thereby exacerbating dry conditions when they arise. The question at hand, however, is whether droughts are becoming more frequent or intense due to increasing concentrations of greenhouse gases. One approach to removing the effect of urban water demand and simply focusing on water supply versus the climatological demand is the Palmer Drought Severity Index (PDSI). The report includes this useful tool and notes that the long-term trend is downward, albeit insignificantly so. However, more citations are needed to make this claim more robust.

In a detailed analysis of hydroclimatic droughts (and pluvials) in the conterminous US, McCabe and Wolock (2023) demonstrate the variability of the PDSI for eight subregions in the country. Their analysis examines the period from 1900 to 2014 using observational data from 1475 to 2005 obtained from gridded tree-ring reconstructions. Their conclusion stated that "the duration and severity of droughts and pluvials identified using runoff for the 1900 through 2014 period generally were not significantly different from the drought and pluvial characteristics identified using the PDSI for the 1475 through 2005 period." They also note that some droughts and pluvials before 1900 were longer and more severe than those that were identified using runoff after 1900.

Mo and Lettenmaier (2018) examined drought variability and trends from 1916 to 2013 and concluded, "we also found a predominance of decreasing trends in [droughts]; droughts occurred less often and events were less severe as time progressed … in particular, only 2 of the 16 great droughts (2012 and 1988) occurred in the second half of the record." Cook *et al.* (2014) identified 1934 as the worst North American drought year of the last millennium with over 70% of the western U.S. experiencing extreme drought. A lack of precipitation is the main driver of drought formation with increased evaporation and evapotranspiration driven by higher air temperatures as a secondary effect (McCabe *et al.*, 2023).

With respect to paleoclimatic time scales, Pederson *et al.* (2012) examined drought variability in the American Southeast from 1665 to 2010 using a dense and diverse tree-ring network. They concluded, "recent droughts are not unprecedented over the last 346 years … indeed, droughts of extended duration occurred more frequently between 1696 and 1820." This is consistent with the finding of Woodhouse and Overpeck (1998) which concluded that "droughts of the twentieth century, including those of the 1930s and 1950s, were eclipsed several times by droughts earlier in the last 2000 years, and as recently as the late sixteenth century … In general, some droughts prior to 1600 appear to be characterized by longer duration (*i.e.*, multidecadal) and greater spatial extent than those of the twentieth century."

6.8 Wildfires

> **Section summary:** The IPCC has not assessed wildfire attribution. Global wildfire activity, according to European Space Agency data, shows a declining trend in the 21st century, with constant or decreasing coverage across all continents (Samborska and Ritchie, 2024). However, fire intensity is increasing in some regions (Cunningham *et al.*, 2024), and wildfires contributed to a net global forest cover loss from 2001–2019 (Tyukavina *et al.*, 2022). In the US, active fire suppression since 1900 obscures natural baselines, but paleoclimatic data suggest higher historical wildfire activity (Marlon *et al.*, 2012). Despite recent increases in burned area, wildfire deficit persists compared to historical norms (Parks *et al.,* 2025). US data for 1926–2023 show no increase in fire frequency since 1985, with burned area peaking around 2007. Historically, the 1910 Big Blowup fire, which burned over three million acres, led to aggressive fire suppression policies, including the 1935 "10 a.m. rule." Recent science supports controlled burns and smaller, frequent fires for healthier forests, prompting a shift in US Forest Service strategies (Stephens *et al.*, 2021; Sommer, 2016).

As the DOE report notes, AR6 does not provide an attribution assessment of trends in wildfire frequencies and intensity, particularly in the western US, Canada, and Australia. While the report accurately states that wildfire coverage (burned area) has been constant or declining on every continent since 2001 (see also Williams *et al.,* 2019), it does not address fire frequency or intensity. AR6 notes, for example, that fire weather severity increased in some regions despite global declines in area burned. However, increases in fire weather do not automatically produce increases in fire activity. Increases in fire activity are likely influenced, or even caused by, local changes in addressing wildfire events or changes unrelated to global climate change (*e.g.*, removal of underbrush or actions related to fire prevention), which would undermine the regional aspect suggested by AR6.

The report notes that wildfires contributed to a net loss of forest cover from 2001-2019 but a caveat should be added to show that deforestation and logging also contribute significantly to forest loss (Hansen *et al.*, 2013). Moreover, the report does not account for regional differences (*e.g.*, the western US vs. the Southeastern US) or note the extreme fire years of 2020 and 2021, which could affect trend analysis.

The final DOE report should include a brief discussion of the AR6 finding that GHG-induced increases in air temperature and aridity worsen fire conditions in the western US. Temperature and moisture are not the only factors that lead to wildfire events. Discussing other important factors would help shed the notion that wildfires are directly tied to issues of global warming. In particular, the report should note that 80%-90% of US wildfires are started by people, and that the much of the public opposes prescribed burns—a critical wildfire management tool. A reference to Parks (2015), in addition to Parks (2025), would strengthen the argument as the latter article is not peer-reviewed.

References

ASOS, 1998: *Automated Surface Observing System (ASOS) User's Guide*. National Oceanic and Atmospheric Administration, Department of Defense, Federal Aviation Administration, and United States Navy, 61pp.

Bartholf, D.P., 1994: An evaluation of the ASOS temperature sensors and heated tipping bucket rain gauge at Syracuse, New York. *Eastern Region Technical Attachment No. 94-11A*, National Weather Service, 9 pp.

Biddle, M.D., R.P. Brown, C.A. Doswell III, and D.R. Legates, 2020: Regional differences in the human toll from tornadoes: A new look at an old idea. *Weather, Climate and Society,* **12**(4) 815–825.

Cook, B.I., R. Seager, and J.E. Smerdon, 2014: The worst North American drought year of the last millennium: 1934. *Geoph. Res. Let.*, **41**, 7298-7730.

Devine, K.A., and E. Mekis, 2008: Field accuracy of Canadian rain measurements. *Atmos.-Ocean*, **46**(2), 213–227.

Diffenbaugh, N.S., D. Singh, J.S. Mankin, D.E. Horton, D.L. Swain, D. Touma, *et al.,* 2017: Quantifying the influence of global warming on unprecedented extreme climate events. *Proceedings of the National Academy of Sciences*, **114**(19), 4881–4886.

Dover, J.M., and J.V. Fiore Jr., 2007: Development of the All-Weather Precipitation Accumulation Gauge transfer function for ASOS. *14th Symposium on Meteorological Observation and Instrumentation,* American Meteorological Society, San Antonio, TX.

Duchon, C.E., and G.R. Essenberg, 2001: Comparative rainfall observations from pit and above-ground rain gauges with and without wind shields. *Water Res. Res.*, **37**(12), 3253–3263.

Gensini, V.A., and H.E. Brooks, 2018: Spatial trends in United States tornado frequency. *npj Climate and Atmospheric Science*, **1**(1), 38.

Golubev, V.S., P.Ya. Groisman, and R.G. Quayle, 1992: An evaluation of the United States standard 8-in. nonrecording raingage at the Valdai Polygon, Russia. *J. Atmos. Oceanic Technol.*, **9**, 624–629.

Groisman, P.Ya., and D.R. Legates, 1994: The accuracy of United States precipitation data. *Bull. Amer. Meteor. Soc.*, **75**, 215–227.

Groisman, P.Ya., T.R. Karl, D.R. Easterling, R.W. Knight, *et al.*, 1999: Changes in the probability of heavy precipitation: Important indicators of climatic change. *Clim. Change*, **42**, 243–283.

Hansen, M.C., P.V. Potapov, R. Moore, M. Hancher, S.A. Turubanova, A. Tyukavina, *et al.,* 2013: High-resolution global maps of 21st-century forest cover change. *Science*, **342**(6160), 850–853.

Karl, T.R., R.W. Knight, D.R. Easterling, and R.G. Quayle, 1996: Indices of climate change for the United States. *Bull. Amer. Meteor. Soc.*, **77**, 279–292.

Knutson, T.R., J.J. Sirutis, M. Zhao, S.T. Garner, M.A. Bender, and R.E. Tuleya, 2017: Tropical cyclones and climate change. *Nature Climate Change*, **7**(2), 65–70.

Knutson, T.R., J.L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, *et al.,* 2020: Tropical cyclones and climate change. *Nature Geoscience*, **3**(3), 157–163.

Kossin, J.P., K.A. Emanuel, and G.A. Vecchi, 2014: The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509**(7500), 349–352.

Kossin, J.P., K.R. Knapp, T.L. Olander, and C.S. Velden, 2020: Global increase in major tropical cyclone exceedance probability over the past four decades. *Proceedings of the National Academy of Sciences*, **117**(22), 11975–11980.

Kunkel, K.E., T.R. Karl, H. Brooks, J. Kossin, J.H. Lawrimore, D. Arndt, *et al.,* 2013: Monitoring and understanding trends in extreme storms: State of knowledge. *Bull. Amer. Meteor. Soc.*, **94**(4), 499–514.

La Barbera, P., L.G. Lanza, and L. Stagl, 2002: Tipping bucket mechanical errors and their influence on rainfall statistics and extremes. *Water Sci. Technol.*, **45**(2), 1–9.

Landolt, S., M.L. Tryhane, R.M. Rasmussen, and J. Cole, 2004: A characterization of wind flow in and around an Alter shielded snowgauge. *11th Conf. on Aviation, Range, and Aerospace*, American Meteorological Society, Hyannis MA, paper 7.3.

Lee, J., S. Li, and R. Lund, 2014: Trends in extreme US temperatures. *Journal of Climate*, **27**(11), 4209-4225.

Legates, D.R., 1987: *A Climatology of Global Precipitation*. *Publ. Climatol.,* **40**(1), 85pp.

Legates, D.R., and T.L. DeLiberty, 1993: Precipitation measurement biases in the United States. *Water Resour. Bull.*, **29**(5), 855–861.

Liu, X., Y. Huang, X. Xu, X. Li, P. Ciais, P. Lin, K. Gong, A.D. Ziegler, *et al.*, 2020: High-spatiotemporal-resolution mapping of global urban change from 1985 to 2015. *Nature Sustainability*, **3**(7), 564-570.

Mann, M.E., B.A. Steinman, D.J. Brouwer, and S.K. Miller, 2021: Multidecadal climate oscillations during the past millennium driven by volcanic forcing. *Science*, **371**(6533), 1014–1019.

McCabe, G.J., and D.M. Wolock, 2021: Multi-year hydroclimatic droughts and pluvials across the conterminous United States. *Int. J. of Climatol.*, **41**, 1731-1746.

McCabe, G.J., D.M. Wolock, M. Lombard, R.W. Dudley, J.C. Hammond, J.S. Hecht, *et al.*, 2023: A hydrologic perspective of major U.S. droughts. *Int. J. of Climatol.*, **43**, 1234-1250.

McDonald, J.R., 2001: T. Theodore Fujita: His Contribution to Tornado Knowledge through Damage Documentation and the Fujita Scale. *Bull. Amer. Meteor. Soc.*, **82**(1), 63-72.

McKee, T.B., N.J. Doesken, and J. Kleist, 1994: *Climate Data Continuity with ASOS – 1994 Annual Report*. Climatology Report #94-3, Colorado State University, Fort Collins, CO, 62 pp.

McKitrick, R., and J.R. Christy, 2019: Assessing changes in US regional precipitation on multiple time scales. *Journal of Hydrology, 578*, 124074.

McKitrick, R. and J.R. Christy, 2025: Data and Code for CWG2025 Report, Mendeley Data, V1.

Meehl, G.A., C. Tebaldi, S. Tilmes, J.F. Lamarque, S. Bates, A. Pendergrass, and D. Lombardozzi, 2016: Amplified summertime warming in the Northern Hemisphere. *Nature Climate Change*, **6**(6), 634–639.

Mo, K.C., and D.P. Lettenmaier, 2018: Drought variability and trends over the Central United States in the instrumental record. *J. Hydrometeorol.*, **19**, 1149-1166.

Murphy, J.D., 2021: National Weather Service Instruction 10-1605, *National Weather Service*, A-77-78.

Neff, E.L., 1977: How much rain does a rain gage gage? *J. Hydrol.*, **35**, 213–220.

NOAA, 2025: https://www.ncei.noaa.gov/access/monitoring/uspa/wet-dry/0.

NSTC, 2008: *Scientific Assessment of the Effects of Global Change on the United States.* Committee on Environment and Natural Resources, National Science and Technology Council, G. Gray *et al.* (eds.), U.S. Climate Change Science Program, Washington DC, 261pp.

Parks, S.A., C. Miller, J.T. Abatzoglou, L.M. Holsinger, M.-A. Parisien, and S.Z. Dobrowski, 2015: Wildland fire deficit and surplus in the western United States, 1984–2012. *Ecosphere*, **6**(12), 1–13.

Pederson, N., A.R. Bell, T.A. Knight, C. Leland, N. Malcomb, K.J. Anchukaitis, K. Tackett, *et al.*, 2012: A long-term perspective on a modern drought in the American Southeast. *Environmental Research Letters*, **7**, 8.

Perkins, S.E., and L.V. Alexander, 2013: On the measurement of heat waves. *Journal of Climate*, **26**(13), 4500–4517.

Rice University, 2025: https://kinder.rice.edu/urbanedge/rapid-urbanization-houston-how-it-happened-and-why-it-matters.

Tippett, M.K., C. Lepore, and J.E. Cohen, 2016: More tornadoes in the most extreme U.S. tornado outbreaks. *Science*, **354**(6318), 1419–1423.

Verbout, S.M., H.E. Brooks, L.M. Leslie, and D.M. Schultz, 2006: Evolution of the U.S. tornado database: 1954–2003. *Weather and Forecasting*, **21**(1), 86–93.

White, S.G., L.J. Winans, and J.V. Fiore, Jr., 2004: Development of the All-Weather Precipitation Accumulation Gauge for ASOS, *8th Symposium on Integrated Observing and Assimilation Systems for Atmosphere, Oceans, and Land Surface*, American Meteorological Society, Seattle, WA.

Williams, A.P., J.T. Abatzoglou, A. Gershunov, J. Guzman-Morales, D.A. Bishop, J.K. Balch, and D.P. Lettenmaier, 2019: Observed impacts of anthropogenic climate change on wildfire in California. *Earth's Future*, **7**(8), 892–910.

Woodhouse, C.A., and J.T. Overpeck, 1998: 2000 years of drought variability in the Central United States. *Bull. Amer. Meteorol. Soc.*, **79**, 2693-2714.

7 CHANGES IN SEA LEVEL

Chapter summary (from the Report): Since 1900, global average sea level has risen by about 8 inches. Sea level change along US coasts is highly variable, associated with local variations in processes that contribute to sinking and also with ocean circulation patterns. The largest sea level increases along U.S. coasts are in the Galveston, New Orleans, and the Chesapeake Bay regions—locations associated with substantial local land sinking (subsidence) unrelated to climate change.

Extreme projections of global sea level rise are associated with an implausible extreme emissions scenario and inclusion of poorly understood processes associated with hypothetical ice sheet instabilities. In evaluating AR6 projections to 2050 (with reference to the baseline period 1995-2014), almost half of the interval elapsed by 2025, with sea level rising at a lower rate than predicted. U.S. tide gauge measurements reveal no obvious acceleration beyond the historical average rate of sea level rise.

7.1 Global Sea Level Rise

Section summary: Global sea level rise, a key climate impact linked to rising temperatures, results from thermal expansion of seawater, melting glaciers and ice sheets, and changes in land water storage. Regionally, ocean circulation patterns and geologic processes, including vertical land motion from groundwater withdrawal and fossil fuel extraction, influence sea level changes. AR6 reports a global mean sea level rise of 7.9 inches (5.9–9.8 inches) from 1901 to 2018, with an accelerating rate, currently at 0.12 inches/year. Sea levels rose fastest in the Western Pacific and slowest in the Eastern Pacific from 1993–2018. Satellite altimeters have been measuring sea level rise since 1993. Tide gauges, some dating back centuries, show sea level rise began in the 1820–1860 period, post-Little Ice Age, predating significant human-related greenhouse gas emissions.

This section on global sea level rise is accurate and provides a solid overview of the concept. I would suggest a brief discussion of uncertainties in estimating sea level rise and assumptions (*e.g.*, ice sheet collapse) that often are made.

The citation of NASA (2020) of ~3 mm yr^{-1} (0.12 in yr^{-1}) is superseded by AR6 and NASA (2023), which suggest values of between 3.7-4.2 mm yr^{-1} (0.15-0.17 in yr^{-1}) for 2006 to 2018. The earlier reference of NASA (2020) reflects an earlier period (1993 to 2018) and suggests acceleration, which should be addressed by the report. Addressing global sea level rise acceleration is important since AR6 argues for nearly a three-fold increase in the rate of sea level rise between 1901-1990 and 2006-2018.

Regional and local variability are mentioned but it could be stressed that the rate of sea level rise varies significantly around the globe with some areas (*e.g.*, Norway and Sweden) experiencing a sea level fall relative to the land owing to coastal uplift while others may see enhanced sea level rise due to land subsidence, neither of which are connected to changing greenhouse gas concentrations.

Research by Wöppelmann and Marcos (2016) demonstrate that sea level changes are often overwhelmed by vertical land motions (see also Legates, 2024), which are not properly considered. Hay *et al.* (2019) provide further confirmation that limitations in the methodology may have led to systematic overestimates in the 20th century global sea level rise.

7.2 US Sea Level Rise

Section summary: Global mean sea level rise, estimated at 0.12 inches/year, varies locally due to processes like vertical land motion (VLM), which can amplify or mitigate risks. In Canada, Alaska, and northern Washington, sea levels are decreasing due to glacial rebound uplift, while US Pacific coast tide gauges show low rise rates, and the Gulf Coast (Louisiana, Texas) and mid-Atlantic (Chesapeake Bay) experience the highest. Relative sea level rise (RSLR) from tide gauges combines climate-driven seawater volume increases with VLM, measured by GPS, which is influenced by subsidence (from groundwater/hydrocarbon extraction, soil drainage) or uplift. At San Francisco, Galveston, and Grand Isle, over half of RSLR is due to subsidence, with absolute sea level rise (ASLR) significantly lower:

- **San Francisco Bay**: RSLR is 7.8 inches over 100 years (0.08 inches/year), but VLM is -0.06 inches/year, yielding ASLR of 0.02 inches/year. Subsidence, especially in landfill areas like Treasure Island (up to 0.4 inches/year), drives local issues.

- **Galveston-Houston**: RSLR is 2.18 feet over 100 years (0.26 inches/year), with VLM of -0.19 inches/year, giving ASLR of 0.07 inches/year. Groundwater withdrawal causes significant subsidence (up to 10 feet by 1979).

- **New Orleans (Grand Isle)**: RSLR is over 3 feet in 100 years (0.36 inches/year), with VLM of -0.28 inches/year, resulting in ASLR of 0.08 inches/year. Geological subsidence and reduced Mississippi River sediment (down ~50% since the 1950s) are dominant drivers.

- **New York City (The Battery)**: RSLR is 11 inches over 100 years (0.11 inches/year), with VLM of -0.05 inches/year, yielding ASLR of 0.06 inches/year, about 55% of RSLR.

Local subsidence, often human-induced, significantly contributes to observed sea level rise, overshadowing global climate-driven effects in these areas.

In general, I am pleased with this section. A brief mention of the drivers of the absolute sea level rise (ASLR) rate would be helpful.

San Francisco Bay – include a brief mention of the relative sea level rise (RSLR) as well as the effect of tectonic activity and groundwater extraction for some areas of the basin.

Galveston—Houston – mention the small contribution of oil and gas extraction and sediment compaction.

New Orleans and the Mississippi River Delta – mention the impacts of the Mississippi River levees on sea levels.

New York City – mention briefly the effect on low-lying boroughs and the tunnel/subway systems.

7.3 Projected Sea Level Rise

Section summary: The primary concern regarding sea level rise is not the ~8 inches of global rise since 1900, but projections of accelerated rise due to climate warming. AR6 projects global mean sea level rise by 2050 to be 3.94–15.75 inches (5th–95th percentile) relative to 1995–2014, with high agreement across

> models and little sensitivity to emissions scenarios. For 2100, projections under the medium emissions scenario (SSP2–4.5) range from 7.9–39.4 inches, but there is low agreement due to uncertainties in ice sheet instabilities, especially for higher emissions scenarios. NOAA's 2022 projections estimate a 1-foot rise by 2050 at The Battery in Manhattan, a rate over twice the current and three times the historical average, described as "locked in" regardless of future emissions. This projection implies a significant acceleration, with its validity likely to be testable within a decade.

I also am pleased with this section but a bit more detail on the drivers of historical rise in sea level for New York City would be useful. A brief discussion of NOAA's (2022) sea level rise report would also be useful. NOAA's report implies that the trajectory of sea-level rise over the next 25 years is reasonably fixed regardless of which shared socio-economic pathway (SSP) becomes the global emissions scenario. NOAA's mid-range sea-level rise estimates for three SSPs are as follows: In 2050, sea levels are projected to increase by 25 centimeters under SSP5-8.5, 21 centimeters under SSP2-4.5, and 18 centimeters under SSP1-2.6. Sea levels are only 7 centimeters (2.8 inches) higher in the warmest scenario compared to the coolest.

References

Hay, C.C., E. Morrow, R.E. Kopp, and J.X. Mitrovica, 2015: Probabilistic reanalysis of twentieth-century sea-level rise. *Nature*, **517**(7535), 481-484

Legates, D.R., 2024: *Coastal Inundation: Rising Sea Levels Explained*. Center for Energy, Climate, and Environment, The Heritage Foundation, Special Report No. 278, 24pp.

NASA Analysis Sees Spike in 2023 Global Sea Level Due to El Niño. NASA Sea Level Change Portal, March 27, 2024. https://sealevel.nasa.gov/news/251/nasa-analysis-sees-spike-in-2023-global-sea-level-due-to-el-nino.

NOAA, 2002: Global and Regional Sea Level Rise for the United States, February 2022, Table 2.4.

Wöppelmann, G., and M. Marcos, 2016: Vertical land motion as a key to understanding sea level change and variability. *Reviews of Geophysics*, **54**(1), 64-92.

8 UNCERTAINTIES IN CLIMATE CHANGE ATTRIBUTION

> **Chapter Summary (from the Report):** "Attribution" refers to identifying the cause of some aspect of climate change, specifically with reference to anthropogenic activity. There is an ongoing scientific debate around attribution methods, particularly regarding extreme weather events. Attribution is made difficult by high natural variability, the relatively small expected anthropogenic signal, lack of high-quality data, and reliance on deficient climate models. The

IPCC has long cautioned that methods to establish causality in climate science are inherently uncertain and ultimately depend on expert judgement.

Substantive criticism of the main IPCC assessments of the role of CO_2 in recent warming focus on inadequate assessment of natural climate variability, uncertainties in measurement of solar variability and in aerosol forcing, and problems in the statistical methods used for attribution.

The IPCC does not make attribution claims for most climate impact drivers related to extreme events. Statements related to statistics of global extremes (*e.g.* event probability or return times, magnitude and frequency) are not generally considered accurate owing to data limitations and are made with low confidence. Attribution of individual extreme weather events is challenging due to their rarity. Conflicting claims about the causes of the 2021 Western North America Heatwave illustrate the perils of hasty attribution claims about individual extreme events.

8.1 Introduction

Section summary: The IPCC distinguishes **detection**—identifying statistically significant climate changes without explaining their cause—from **attribution**, which evaluates the relative contributions of causal factors, such as human greenhouse gas emissions versus natural factors like volcanic activity, with a formal confidence assessment. Detection uses statistical analysis to confirm changes beyond random variability (e.g., <10% chance due to internal variability). Attribution relies on comparing observations to model-based counterfactuals, as direct climate experimentation is impossible, requiring statistical inference and assumptions that all drivers are known. AR4 notes that unequivocal attribution is unattainable without controlled experiments, so attribution involves showing consistency with expected responses to forcings and ruling out alternative explanations, relying on expert judgment to account for uncertainties. AR5 highlights challenges in attribution due to limited high-quality, long-term data and incomplete understanding of processes linking climate change to impacts. Attributing extreme weather events to climate change remains debated due to inherent uncertainties and the complexity of causal chains in the climate system.

This introduction on climate change attribution is well-structured, clear, and grounded in authoritative sources. However, it is quite technical and although it is appropriate for an expert audience, readers who lack expertise in the field of climate change attribution will struggle to follow the arguments. For example, the sentence "Attribution involves comparison of observed events to model-generated counterfactuals" is difficult to parse. Please simplify the text. The phrase "all external and internal drivers of the system are known and represented" could be clarified by briefly explaining what these drivers are.

There is a bit of disconnect regarding the Assessment Reports. The definitions of detection and attribution are taken from AR6, but the subsequent discussion regarding attribution comes from AR4 and then the challenges are cited from AR5. Does AR6 provide similar statements regarding the challenges of detection and attribution?

8.2 Attribution Methods

Section summary: The IPCC uses several methods to attribute climate changes to natural or human-induced factors:

1. **Optimal Fingerprinting**: Employs linear regression to analyze observed climate data as a combination of climate model simulations with and without anthropogenic forcings, weighting data to reduce noise and account for model errors.

2. **Time Series Analysis**: Examines statistical differences between anthropogenic and natural variability to identify dominant drivers of observed temperature changes and infer causal relationships based on timing.

3. **Process-Based Attribution**: Combines observations, climate models, and theoretical insights to attribute changes in specific physical processes (e.g., monsoons, polar amplification) to forcings, focusing on regional phenomena.

4. **Extreme Event Attribution**:

    - **Probabilistic Event Attribution**: Uses large ensembles of climate model simulations to compare observed extreme events (e.g., heat waves, droughts) to counterfactuals, assessing human influence on likelihood or intensity.

    - **Storyline Approach**: Analyzes physical processes driving an extreme event and evaluates how anthropogenic forcings may have altered those processes.

These methods aim to distinguish human and natural contributions to climate change, though they face challenges due to data limitations and complex causal chains.

This section is well-organized and is much more readable than the introduction. However, terms such as “optimal fingerprinting” and “model-generated counterfactuals” should be defined since those not familiar with attribution methodology will not understand what you are trying to convey. An introductory sentence, such as “IPCC attribution methods use statistics and climate models to identify whether human or natural factors drive observed changes,” would help non-experts understand on what the methods focus.

Method limitations are not discussed. Please include a brief discussion of methodological problems, such as data limitations and model uncertainties. In addition, a brief note as to how these methods are used to affect policy decisions would help.

8.3 Attribution of Global Warming

Section summary: The IPCC’s attribution statements for global warming have evolved across its recent assessment reports:

- **AR4 (2007)**: States that *most* of the global temperature increase since the mid-20th century is *very likely* due to anthropogenic greenhouse gas (GHG) concentrations.

- **AR5 (2013)**: Asserts it is *extremely likely* that *more than half* of the global surface temperature increase during 1951–2010 was caused by anthropogenic GHGs and other forcings, with the human-induced contribution estimated to match the observed warming.

- **AR6 (2021)**: Estimates human-caused warming from 1850–1900 to 2010–2019 at 0.8°C–1.3°C (best estimate 1.07°C), with well-mixed GHGs contributing 1.0°C–2.0°C, aerosols cooling 0.0°C–0.8°C, natural drivers shifting -0.1°C to +0.1°C, and internal variability -0.2°C to +0.2°C. It is *very likely* that GHGs were the main driver of tropospheric warming since 1979.

> AR4 and AR5 focus on warming since the mid-20th century, using vague terms like "most" or "more than half" (51–99%) to account for uncertainties like natural variability, with confidence rising from *very likely* to *extremely likely*. AR6 shifts to a longer baseline (1850–1900), provides precise numerical ranges, but lowers confidence to *likely* for overall warming, attributing nearly all to GHGs, with highest confidence (*very likely*) for tropospheric warming since 1979.
>
> Criticisms of IPCC attribution analyses include inadequate consideration of natural climate variability, inappropriate statistical methods, and discrepancies between models and observations, which challenge the reliability of both general warming and extreme event attributions.

This section is clear and well-referenced. A brief sentence defining the AR6 baseline period of 1850 to 1900 as a pre-industrial reference would add clarity. In addition, please elaborate on what is meant by "inadequate assessment of natural climate variability" and "inappropriate statistical methods."

8.3.1 Natural Climate Variability

> **Subsection summary:** AR6 estimates that natural external drivers (*e.g.*, solar and volcanic activity) altered global surface temperature by -0.1°C to +0.1°C, and internal variability (*e.g.*, ocean circulations) by -0.2°C to +0.2°C since 1850–1900, suggesting negligible net impact on warming. However, several studies challenge this, arguing that AR6 underestimates the contributions of solar variability and internal variability from large-scale ocean circulations, indicating a potentially larger role for natural factors in recent warming.

Section 8.3 is comprehensive and well-researched. However, as in Section 8.1, the discussion is overly technical and will be difficult to parse for non-experts.

Solar variability

Subsection summary: The IPCC's AR5 report estimated a minimal radiative forcing from Total Solar Irradiance (TSI) changes (0.05 W/m²) from 1750 to 2011. In contrast, AR6 recognizes a higher TSI increase (0.7–2.7 W/m²) from the Maunder Minimum (1645-1715) to the late 20th century, though it relies on low-variability TSI datasets for climate model simulations, suggesting a small solar impact compared to anthropogenic forcing. Uncertainties in TSI measurements, particularly due to inconsistencies in satellite data since 1978 and disagreements over trends (*e.g.*, during the 1986–96 "ACRIM gap"), contribute to ongoing debates. Some studies indicate high solar activity during the 20th century's "Modern Maximum," with high-variability TSI datasets explaining significant preindustrial temperature changes, while others question multi-decadal TSI trends. Additionally, non-TSI effects (*e.g.*, UV changes, cosmic rays, magnetic fields) may amplify solar influence, potentially accounting for ~80% of solar-driven climate impacts, but these are not included in climate models and remain uncertain and debated.

Solar variability is thoroughly covered in this subsection. Discussion of non-TSI effects (*e.g.*, UV and cosmic rays) should be clarified, although their speculative impacts must be noted.

Natural variability of large-scale ocean circulations

Subsection summary: Variations in global mean surface temperature are influenced by large-scale ocean circulation patterns like the Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and El Niño-Southern Oscillation (ENSO), which affect ocean heat uptake, atmospheric circulation, and cloud distribution. Debate persists on whether these are purely internal climate variations or influenced by solar/astronomical factors or volcanic eruptions. Climate models (CMIP5, CMIP6) struggle to accurately simulate the amplitude and phasing of these multi-decadal oscillations, and averaging model ensembles cancels out internal variability, emphasizing external forcing (*e.g.*, CO_2) in attribution studies. The IPCC AR6 estimates internal variability impacts global temperatures by ±0.2°C (0.4°C trough-to-peak), but over centuries, these oscillations net out. However, their 60–80-year cycles can obscure attribution of recent 50-year warming trends, as models fail to capture correct timing.

Historical temperature records show a warming trend from 1905–1945, a slight cooling from 1945–1976 ("grand hiatus"), and accelerated warming post-1977, coinciding with the Great Pacific Climate Shift (1976–1977), when the PDO shifted from a cool to a warm phase. Early 20th-century warming, with low CO_2 increase (298–310 ppm, 1905–1941) and minimal volcanic activity, was likely driven by internal variability (*e.g.*, AMO, PDO) and possibly solar forcing, with 40–54% attributed to external forcing. Arctic warming in the 1930s and mid-century cooling were tied to synchronized Pacific-Atlantic variability and natural radiative forcing. The 1976 PDO shift amplified global warming, with studies suggesting 40% or more of late 20th-century warming may stem from natural internal variability rather than anthropogenic forcing.

The discussion of large-scale ocean circulation and their influence on global temperature trends is strong, but the critique of climate models could be more specific. Why do models tend to underestimate the observed variability (*e.g.*, the amplitude) and exhibit phase mismatches? How do these problems affect attribution and detection? The statement that ensemble averaging reduces the model simulated internal variability is critical but needs to be clarified. The discussion of the Great Pacific Climate Shift should be connected better to attribution by quantifying its impact more explicitly. Replace “secular trend” with “long-term trend” to clarify.

8.3.2 Optimal Fingerprinting

> **Subsection summary:** Optimal fingerprinting, introduced by Allen and Tett (1999), is a statistical method used to attribute climate change to human or natural forcings by comparing observed climate data to model-generated patterns (“fingerprints”) using Total Least Squares (TLS) regression. It decomposes observed changes into weighted signals from anthropogenic and natural forcings, with coefficients indicating detection and model consistency. Widely used by the IPCC since 2001, the method assumes accurate model representation of natural variability, but its statistical properties are understudied.
>
> McKitrick (2021–2025) critiques optimal fingerprinting, arguing it violates Gauss-Markov conditions, leading to biased coefficients. TLS, uniquely used in climate science, is unstable without stringent assumptions, often inflating anthropogenic signal estimates. McKitrick’s 2025 study compares conventional fingerprinting to robust econometric methods, finding an anthropogenic signal coefficient of ~0.4–0.65 (*vs.* IPCC’s ~1.0) for 1900–2010 and 1980–2010, suggesting models overstate greenhouse gas impacts by about half. Natural forcing signals require scaling up 2–4 times. These results align with a Transient Climate Sensitivity of 1.4°C, consistent with Lewis (2023). The critique suggests optimal fingerprinting’s reliability is questionable, necessitating re-evaluation of past attribution studies.

This is a critical examination of key climate attribution methods. However, my criticism of previous sections of this chapter holds here too—the text is too technically focused and assumes prior knowledge of the subject. Terms such as “Gauss-Markov conditions” or “fingerprinting coefficients” should be explained.

Transition from description of the various methods to McKitrick’s critique is rather sudden. A bridge sentence would help for readability.

I agree with McKitrick’s arguments, but the text should emphasize that while least squares methods lead to bias, many studies in science rely heavily on least squares. What is meant by least squares tend “to be unstable unless some strong assumptions hold?” I would disagree, however, that climate scientists are “virtually alone among scientific disciplines” in using total least squares (TLS) as it appears in other aspects of environmental science, even though it has been eschewed by econometricians. This section tends to focus only on critiques of TLS by McKitrick. Why do many climate scientists still use TLS despite its limitations?

The statement that "there is very little literature examining the statistical properties" of optimal fingerprinting is vague. Clarify what statistical properties should be more explicitly examined and what effect they have on optimal fingerprinting.

8.3.3 Time Series Methods

> **Subsection summary:** The IPCC AR5 (WGI 10.2.2) highlighted climate econometrics, an alternative to optimal fingerprinting, which uses time series analysis methods like unit root testing, Granger causality, and cointegration to assess climate change causality without relying on climate model accuracy. These methods, common in economics and finance, are gaining traction in climate science but depend on assumptions about data-generating processes that are hard to verify. Granger causality, a statistical tool, identifies directional influence between co-moving variables (*e.g.*, temperature and CO_2). For instance, Davidson *et al.* (2015) used Vostok ice core data to show temperature Granger causes CO_2 changes, not vice versa, contradicting claims in *An Inconvenient Truth*. While optimal fingerprinting, dominant in IPCC reports, relies on climate models and faces criticism for bias (*e.g.*, McKitrick 2021–2025), time series methods avoid model dependency but lack consensus due to varying results and assumptions.

With respect to optimal fingerprinting methods, this section is a welcome addition to the discussion of climate attribution. It expands the critique of optimal fingerprinting methods and including the Vostok ice core discussion is very useful.

While this section considers time series methods from econometrics, even climate scientists are not likely familiar with some of the terms, such as "Granger causality" or "cointegration analysis." Terminology needs to be better explained.

The text alludes to difficult assumptions regarding the data but does not make it clear what those assumptions are and their limitations. Please clarify these assumptions. In addition, briefly discuss the possible drawbacks associated with these methods.

8.4 Declining Planetary Albedo and Recent Record Warmth

> **Subsection summary:** Since 2015, a significant 0.5% reduction in planetary albedo, corresponding to an increase of 1.7 W/m² in absorbed solar radiation, has coincided with record global warmth, raising questions about its role in recent temperature increases. Planetary albedo, the fraction of solar radiation reflected into space (approximately 30%), is influenced by reflective surfaces like clouds, snow, and ice. While surface changes (*e.g.*, slight Arctic sea ice decline, stable Antarctic sea ice, slow snow cover reduction, and global greening) contribute minimally to albedo decline due to cloud masking, the primary driver is a 1–2% reduction in global cloud cover, particularly low- and mid-level clouds in the Northern Hemisphere and mid-level clouds in the Southern Hemisphere.

> Possible causes include natural climate variability (e.g., the 2014–2016 El Niño, shifts in the Pacific Decadal Oscillation, and North Atlantic circulation changes) or positive cloud feedbacks to warming, though no clear feedback trigger emerged in 2015. The 2022 Hunga Tonga eruption, which injected water vapor and sulfate aerosols into the stratosphere, may have contributed to the record-low albedo in 2023 by altering cloud patterns via stratosphere-troposphere interactions, though its global impact remains uncertain and requires further research. Reduced sulfate aerosols from shipping regulations (2010–2020) likely have a limited global effect. The cloud cover decline has a radiative impact exceeding that of doubled CO_2, highlighting its significance for climate sensitivity and warming attribution. Whether this reflects a temporary natural fluctuation or persistent feedbacks will require more data to resolve.

This section is quite compelling and an important inclusion in the report. Although it is readable, some terms, such as planetary albedo and cloud masking, should be defined when first used.

I would prefer a more detailed discussion of clouds, particularly the impact of low- and mid-level clouds. Also, the discussion of the Hunga Tonga eruption needs to expand if it is to be included in the report.

(A period is required at the end of the last sentence of the last paragraph.)

8.5 Attribution of Climate Impact Drivers

> **Section summary:** The IPCC (AR6, Ranasinghe et al., 2021) defines "climate impact drivers" (CIDs) as physical climate conditions (*e.g.*, temperature, extreme weather) that affect society or ecosystems, noting they can be detrimental, neutral, or beneficial. AR6 Table 12.12, reproduced as Table 8.1 in the DOE report, assesses the anthropogenic influence on 33 CIDs, finding high confidence in an anthropogenic signal for only five (*e.g.*, mean air and ocean temperature) and medium confidence for four (*e.g.*, ocean chemistry changes). Most CIDs, including wind, precipitation, flooding, and drought, show no detectable human influence, with natural variability dominating. The IPCC does not expect anthropogenic signals to emerge for most weather-related CIDs by century's end, even under the extreme RCP8.5 scenario, which is criticized as implausible and misleading. That is additional evidence attribution methods may overstate human influence while underestimating natural variability, and climate models are inadequate for precise regional projections. Extreme weather patterns, like windstorms or droughts, remain largely unattributable to human activity due to regional variability and trend reversals.

This section on the attribution of climate impact drivers is a concise and critical addition to the report. It integrates well with the previous sections of the report. The IPCC appears to be of two minds. On the other hand, IPCC attribution methods "tend to overstate the anthropogenic influence and understate the role of natural variability." On the other hand, a "striking feature" of

AR6 Table 12.12 is “how few CIDs exhibit an anthropogenic signal sufficient to distinguish them from natural variability.” Here is the DOE report’s summary of Table 12.12:

> “Out of the 33 weather impact categories listed, an anthropogenic signal is asserted with high confidence in only five, and with medium confidence in a further four. (Note that one of the CIDs is an increase in CO_2 levels, and since it is a tautology to attribute this to increased CO_2 levels this CID can be ignored.) For the rest the IPCC does not claim to have detected anthropogenic drivers. Of the five high confidence assertions, two are for changes in average temperatures (air and ocean) hence are not measures of extreme weather. Further, two of the four medium confidence assertions are related to ocean chemistry and thus are likewise not related to extreme weather. The IPCC does not assert a human influence on many non-temperature weather features such as wind, precipitation, flooding, or drought.”

Even more striking is the information in columns four and five of Table 12.12—columns omitted in Table 8.1. Columns four and five reveal that even under RCP8.5 and SSP5-8.5, no climate signal is expected to emerge in either 2050 or 2100 for the following CIDs: frost, river flood, landslide, aridity, hydrological drought, agricultural and ecological drought, fire weather, mean wind speed, severe wind storm, tropical cyclone, sand and dust storm, heavy snowfall and ice storm, hail, snow avalanche, coastal flood, coastal erosion, marine heatwave, air pollution weather, and surface radiation (Pielke Jr., 2024). In the final DOE report, Table 8.1 should be enlarged to reproduce AR6 Table 12.12 in its entirety.

Table 12.12 | Emergence of CIDs in different time periods, as assessed in this section. The colour corresponds to the confidence of the region with the highest confidence: white cells indicate where evidence is lacking or the signal is not present, leading to overall low confidence of an emerging signal.

Climatic Impact-driver Type	Climatic Impact-driver Category	Already Emerged in Historical Period	Emerging by 2050 at Least for RCP8.5/SSP5-8.5	Emerging Between 2050 and 2100 for at Least RCP8.5/SSP5-8.5
Heat and Cold	Mean air temperature	1		
	Extreme heat	2	3	
	Cold spell	4	5	
	Frost			
Wet and Dry	Mean precipitation		6, 7	
	River flood			
	Heavy precipitation and pluvial flood			8
	Landslide			
	Aridity			
	Hydrological drought			
	Agricultural and ecological drought			
	Fire weather			
Wind	Mean wind speed			
	Severe wind storm			
	Tropical cyclone			
	Sand and dust storm			
Snow and Ice	Snow, glacier and ice sheet		9	10
	Permafrost			
	Lake, river and sea ice	11		
	Heavy snowfall and ice storm			
	Hail			
	Snow avalanche			
Coastal	Relative sea level		12	
	Coastal flood			
	Coastal erosion			
Open Ocean	Mean ocean temperature			
	Marine heatwave			
	Ocean acidity			
	Ocean salinity	13		
	Dissolved oxygen	14		
Other	Air pollution weather			
	Atmospheric CO_2 at surface			
	Radiation at surface			

White cells indicate CIDs where an anthropogenic signal is not present or not expected.

8.6 Extreme Event Attribution (EEA)

Section summary: IPCC AR6 presents a mixed assessment of anthropogenic influence on extreme weather and climate events. Chapter 11 of WG1 (Seneviratne *et al.*, 2021) claims strengthened evidence since AR5 for human influence on extreme precipitation, droughts, tropical cyclones, and compound extremes, asserting some recent hot extremes are unlikely without human impact. Conversely, Chapter 12 (Ranasinghe *et al.*, 2021, Table 12.12) reports high confidence in anthropogenic signals only for increased extreme heat in tropical and mid-latitude regions, medium confidence for reduced extreme cold in some regions, and no evidence of human influence on river floods, heavy precipitation, drought, fire weather, windstorms, or tropical cyclones.

The World Weather Attribution (WWA) initiative, a key player in extreme event attribution (EEA), uses large ensembles of regional climate models to compare events in current versus pre-industrial climates. Despite its public influence, WWA faces criticism for non-peer-reviewed findings, litigation-driven analyses, and methodological flaws, including assuming all post-industrial warming is anthropogenic and inadequately accounting for natural variability. EEA struggles with limited data, as extreme events are rare, and many analyses only use post-1950 or post-1970 data, ignoring earlier severe events. Paleoclimate data further complicates attributing events beyond natural variability.

Methodological challenges include defining events and handling outliers, which may reflect a changed climate or a different natural regime (e.g., heatwave vs. normal weather). Statistical issues, such as fitting multiple distributions to data or bias in estimating return periods for single extreme events, add uncertainty (Visser and Petersen, 2012; Sardeshmukh et al., 2015; Barlow et al., 2020; Miralles and Davison, 2023). These uncertainties suggest caution in linking individual extreme events to climate change, as attribution remains ambiguous and unresolved.

This section on extreme event attribution (EEA) is a critical and nuanced addition to the report and fits in well with the previous sections. The inclusion of statistical and conceptual challenges increases its relevance.

As before, terms such as “extreme event attribution” and “counterfactual pre-industrial climate” require clarification. The critique of World Weather Attribution (WWA) is well-made but a specific example of a controversial WWA analysis would make it clearer. What does “shaping analyses to serve litigation” mean?

Discussion of bias and other issues is excellent, but the text could be simplified to provide more clarity. The claim that the elimination of outlier bias has “not yet been established” should be explained in more detail. In the same vein, data limitations, particularly since 1950 or 1970, could relate better to the previous discussions on natural variability. Why do paleoclimate reconstructions complicate attribution?

8.6.1 Case Study – 2021 Western North America Heat Wave

Subsection summary: The 2021 Western North America heat wave, peaking in late June, set temperature records in Portland, OR (116°F) and Seattle, WA (108°F). The World Weather Attribution (WWA) team claimed it was "virtually impossible" without human-induced climate change, estimating it as a 1-in-1000-year event, 150 times rarer without climate change, and 2°C hotter than in pre-industrial times. However, counter-analyses challenge these claims. Bercos-Hickey (2022) and McKinnon and Simpson (2022) argued the event's extreme temperatures were statistically improbable with or without climate change, likely due to "bad luck" in meteorological conditions. The 2023 Oregon Climate Assessment found no evidence that climate change increased the likelihood of the heat dome's unique weather patterns, driven by a mid-tropospheric ridge, tropical disturbance, subsidence, downslope warming, and low soil moisture, with no regional trends in drought or heat waves amplifying the event.

Mass *et al.* (2024) estimated anthropogenic warming added ~2°F to the event's magnitude but found no evidence of greenhouse gases enhancing the meteorological setup. Bercos-Hickey *et al.* (2022) and Zeder *et al.* (2023) criticized WWA's methods, noting that extreme value distributions and return period estimates were unreliable for such an outlier, overestimating the event's rarity and climate change's role. They suggested human influence added only 1.4–1.8°F to temperatures. Overall, peer-reviewed studies indicate the heat wave was primarily driven by rare natural meteorological conditions, with limited anthropogenic contribution, contradicting WWA's high-profile claims.

This case study is a good addition to the chapter as it illustrates the difficulties in extreme event attribution and directly follows the earlier sections of the chapter. It reinforces the theme of overstated anthropogenic influence and the significant role of natural variability.

Terms such as "mid-tropospheric ridge" and "Generalized Extreme Value distributions" should be defined as the educated, non-expert may not be familiar with them. Explicitly linking WWA and its drawbacks to the earlier EEA section would be quite useful (see Pielke Jr., 2024).

Can the "rare meteorological conditions" be specified in more detail? Are they black swan events or are they linked to natural variability that was discussed earlier in this Chapter? It also would be useful to give a concrete reference to support the lack of trends in heatwaves in the Pacific Northwest.

Specifically, why does Generalized Extreme Value fail for this event? Moreover, the reference to Pearl (2009) seems to appear without prior context. Briefly explain its relevance.

(In keeping with the section with case studies for sea level rise, the "*8.6.1*" should be removed.)

References

Pielke, R. Jr., July 24, 2024: We don't need no stinking science, *The Honest Broker*, https://ctse.aei.org/we-dont-need-no-stinking-science/.

9 CLIMATE CHANGE AND U.S. AGRICULTURE

> **Chapter Summary (from the Report):** There has been abundant evidence going back decades that rising CO_2 levels benefit plants, including agricultural crops, and that CO_2-induced warming will be a net benefit to US agriculture. The increase in ambient CO_2 has also boosted productivity of all major US crop types. There is reason to conclude that on balance climate change has been and will continue to be neutral or beneficial for most US agriculture.

9.1 Econometric Analysis

> **Section summary:** The section reviews seven econometric studies of the impacts of future warming on agricultural yields. Mendelsohn et al. (1994) concluded that global warming would be slightly beneficial to US agriculture due to adaptive responses. Deschênes and Greenstone (2007) estimated that climate change would increase the annual profits of US agriculture by $1.3 billion in 2002 dollars (2002$) or 4 percent. Deschênes and Greenstone (2012) revised their conclusions and projected potentially large losses to US agriculture due to anthropogenic warming. Schlenker and Roberts (2009) argued that yield gains under past warming would not carry over to the future, with corn and soy yields decreasing sharply due to climate change. Burke and Emerick (2016) concluded that climate change would have large negative impacts on corn and soy yields. Ortiz-Bobea (2019) concluded that pessimistic results in previous studies were due to using an inaccurate measure of the returns to farming activity. Bareille and Chakir (2023) found that conventional econometric modeling implied negative effects of warming on French agricultural land, but that updated modeling implied climate change would be very beneficial to French agriculture.

In short, some studies expect rising temperatures to overwhelm farmers' adaptive responses, and some expect farmers to sustain or improve yields in a warming world. The DOE report finds a critical omission in all seven studies:

> "A major deficiency of all these studies, however, is that they omit the role of CO_2 fertilization. Climate change as it relates to this report is caused by GHG emissions, chiefly CO_2. 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 CO_2 that drives them. As explained in Chapter 2, CO_2 is a major driver of plant growth, so this omission biases the analysis towards underestimation of the benefits of climate change to agriculture."

NCA4 and NCA5 purport to take CO_2 fertilization into account, yet their climate change impact assessments for agriculture are quite pessimistic. If possible, the final DOE report should identify and briefly evaluate the CO_2 fertilization coefficients used in NCA4 and NCA5.

9.2 Field and Laboratory Studies of CO_2 Enrichment

Section summary: Free Air CO_2 Enrichment (FACE) experiments and laboratory studies have shown that elevated CO_2 levels significantly enhance crop growth. Ainsworth *et al.* (2020) summarized 250 FACE studies, finding an average 18% yield increase in C3 plants with a 200 ppm CO_2 increase, while C4 plants benefited mainly under drought. Laboratory experiments reported on *CO2Science.org* showed substantial growth benefits for key U.S. crops at +300 ppm CO_2: soybeans (+50.9%), maize (+23.7%), and wheat (+67.6%). Soybeans also exhibited improved photosynthesis and water use efficiency under drought (Li, 2013). Maize showed enhanced drought tolerance, with only a 13% growth loss under elevated CO_2 (720 ppm) compared to 41% at ambient levels (Allen Jr., 2011). Wheat yields increased by 16% at +166 ppm, though grain protein decreased by 7%, with varietal selection mitigating quality impacts (Blandino, 2020). A 2021 NBER report (Taylor and Schlenker, 2021) using satellite data estimated CO_2 emissions since 1940 boosted U.S. crop production by 50-80%, with per-ppm yield increases of 0.5% for corn, 0.6% for soybeans, and 0.8% for wheat, also noting enhanced drought resilience.

The section provides a comprehensive overview of how elevated CO_2 levels impact crop growth, drawing from both field-based free air CO_2 enrichment (FACE) experiments and controlled laboratory studies. The evidence presented suggests that elevated CO_2 significantly boosts both crop yields and drought resistance, which bode well for agricultural productivity with enhanced CO_2. That FACE, laboratory, and satellite data all agree is a strong indicator that crops, particularly C3 crops, will thrive in a world with higher CO_2 concentrations.

9.3 Crop Modeling Meta-Analyses

Section summary: Despite evidence of CO_2 and warming benefits on crop growth, the U.S. EPA in 2023 significantly increased its Social Cost of Carbon (SCC) estimate, heavily influenced by a 2017 meta-analysis by Moore *et al.* (2017), which projected global crop yield declines due to climate warming. Nearly half of the EPA's 2030 SCC estimate relied on these projected agricultural damages. McKitrick (2025) re-evaluated the Moore *et al.* (2017) database, finding that only 862 of the claimed 1,722 studies had complete records, with many missing critical CO_2 change data. By recovering this data, McKitrick expanded the usable sample by 40%. His analysis showed that, unlike the original findings suggesting yield decreases with warming (up to 5°C), the complete dataset indicated stable or increased global crop yields, challenging the pessimistic projections used by the EPA.

Estimates of the Social Cost of Carbon (SCC) by the U.S. EPA is evaluated by its reliance on a 2017 meta-analysis by Moore *et al.* (2017), and a subsequent re-examination by McKitrick (2025) who found that whereas Moore *et al.*'s (2017) partial data set implied warming would decrease yields of maize, soy, rice, and wheat, the complete data set implied constant or increasing global yields, even out to 5°C warming. Note, however, that the EPA used other models, including those by the Climate Impact Lab (Climate Impact Lab, 2023) and Howard and Sterner (2017).

A brief discussion of the Moore *et al.* (2017) methods is warranted as it would help put their findings in context. In addition, please discuss why the results of Moore *et al.* (2017) differed from Challinor *et al.* (2014) who emphasized the benefits of CO_2 fertilization. Moreover, how did McKitrick (2025) perform his data recovery exercise and are there any known limitations to his analysis?

Please also include in the discussion the research by Ainsworth *et al.* (2020) that suggests CO_2 will enhance crop yields. In addition, are there potential limitations such as reduced nutritional quality of crops? If so, these should be discussed. The report makes good use of the extensive database of laboratory studies by CO2Science.org reporting increased photosynthesis rates, water-use efficiency, and dry-weight biomass of food crops exposed to elevated CO_2 levels. The same source reviews more than two-dozen studies reporting CO_2-enhanced production of health promoting substances in common fruits and vegetables.

9.4 CO_2 Fertilization and Nutrient Loss

> **Section summary:** Elevated CO_2 levels can increase crop biomass but may reduce protein and micronutrient (*e.g.*, iron, zinc) concentrations, though evidence on nutrient dilution is mixed and not solely attributable to CO_2 (Ebi *et al.*, 2021; Ziska 2022). Rising temperatures may offset nutrient losses in some cases (Köhler *et al.*, 2019). Adaptive strategies to counter potential nutrient dilution include: 1) Selective breeding, both conventional and genetic (*e.g.*, Golden Rice for vitamin A), which is cost-effective and location-specific (Saltzman *et al.,* 2017; Ebi *et al.*, 2021); 2) Food fortification, such as adding folic acid to flour or iron to cereals; and 3) Affordable dietary supplements like multivitamins. In low-income countries, where micronutrient deficiencies are prevalent, supplements are a proven low-cost solution. IPCC scenarios (SSP3, SSP5) projecting high CO_2 emissions also predict significant global income growth by 2100, reducing poverty and enabling access to these strategies. Overall, rising CO_2 benefits U.S. agriculture, and nutrient dilution can be addressed through tailored, research-driven mitigation.

This section provides a good discussion of the potential nutrient dilution in crops due to elevated CO_2 levels. Reference to the results of Taylor and Schlenker (2021) and Ainsworth *et al.* (2020) would help strengthen the claim of a “net benefit to U.S. agriculture” and confirm the benefits of CO_2 enhancement.

This section also provides a useful overview of both decades-old and more recent widespread practices that increase the micronutrient content of cereals, flour, and many other foods, noting also the widespread availability of nutritional supplements. In addition, the chapter correctly observes that all shared socioeconomic pathway (SSP) emission scenarios project increases in global per capita income, which should make nutritional supplements and adaptive micronutrient strategies increasingly affordable. It should again be noted that SSP5-8.5 is an extreme scenario and, as such, overstates the possible negative effects of CO_2 on food quality. A reference to Terando *et al.* (2020) would be sufficient.

References

Ainsworth, E.A., L. Lemonnier, and J.M. McGrath, 2020: Free-air CO_2 enrichment (FACE) experiments: A review of effects on crop yield and quality. *Annual Review of Plant Biology*, **71**, 67–93.

Challinor, A.J., J. Watson, D.B. Lobell, S.M. Howden, D.R. Smith, and N. Chhetri, 2014: A Meta-analysis of Crop Yield under Climate Change and Adaptation. *Nature Climate Change* **4**(4): 287–291.

Climate Impact Lab, 2023: *Data-driven Spatial Climate Impact Model (DSCIM)*. Available at: https://github.com/ClimateImpactLab/DSCIM.

CO2Science.org Health Effects (CO_2-Plant Production of Health-Promoting Substances: Common Food Plants), https://www.co2science.org/subject/h/co2healthpromoting.php.

Howard, P.H., and T. Sterner, 2017: Few and Not So Far Between: A Meta-analysis of Climate Damage Estimates. *Environmental and Resource Economics*, **68**(1): 197–225.

Terando, A., D. Reidmiller, S.W. Hostetler, J.S. Littell, T.D. Beard Jr., *et al.* 2020: Using information from global climate models to inform policymaking—The role of the U.S. Geological Survey, 25p. pp.

10 MANAGING RISKS OF EXTREME WEATHER

Chapter Summary (from the Report): Trends in losses from extreme weather and climate events are dominated by population increases and economic growth. Technological advances such as improved weather forecasting and early warning systems have substantially reduced losses from extreme weather events. Better building codes, flood defenses, and disaster response mechanisms have lowered economic losses relative to GDP. The US economy's expansion has diluted the relative impact of disaster costs, as seen in the comparison of historical and modern GDP percentages. Heat-related mortality risk has dropped substantially due to adaptive measures including the adoption of air conditioning, which relies on the availability of affordable energy. US mortality risks even under extreme warming scenarios are not projected to increase if people are able to undertake adaptive responses.

10.1 Socioeconomic Context

Section summary: Climate change risks in the US are influenced more by societal factors, such as wealth exposure in disaster-prone areas and vulnerabilities of poorer populations, than by changes in weather hazards. Despite population growth from 76 million in 1900 to over 331 million in 2020, deaths from weather disasters have significantly declined, exemplified by the 1900 Galveston hurricane (8,000 deaths, 0.01% of population) versus Hurricane Katrina in 2005 (1,800 deaths, 0.0006% of population). Technological advances, including early warning systems, satellite monitoring, and improved forecasting, have reduced losses, with weather forecasting yielding an estimated $31.5 billion in annual benefits and hurricane forecast improvements saving $5 billion per hurricane. Infrastructure enhancements, such as post-1992 Florida building codes, the Galveston Seawall, and New Orleans' storm surge system, have minimized damage, as seen in Hurricanes Michael (2018) and Isaac (2012). Inland dams, like those managed by the Tennessee Valley Authority, prevent approximately $309 million in annual flood damage, with $406 million in damage avoided during Hurricane Helene (2024).

This section provides a compelling overview of the socioeconomic context of extreme weather by noting that it is societal factors and not changes in the extreme weather itself that leads climate risk in the US. Noting that developments in the National Weather Service's ability to warn the public, satellite monitoring, improved forecasting, and changes in building codes have been instrumental in mitigating climate risk is an important component of this section. I would also mention that the advent of doppler weather radar has been at the forefront of the technological advances that should be mentioned. I am impressed that this section of the report effectively demonstrates the importance of technological and societal advancements that mitigate the impacts of extreme weather events.

10.2 Data Challenges

Section summary: Since 1980, NOAA's Billion Dollar Disaster series reported a rise in U.S. weather-related disasters costing over $1 billion (inflation-adjusted), with a notable increase since 2008, often cited as evidence of worsening climate-driven extreme weather. However, Pielke Jr. (2024) argues this trend reflects increased population and wealth, not necessarily more frequent or intense weather events, as greater economic exposure amplifies damage. He shows that disaster losses as a proportion of GDP have decreased by about 80% since 1980. NOAA's data was criticized for lacking transparency and failing to normalize for population and wealth growth. In May 2025, NOAA withdrew the Billion Dollar Disaster product from publication (Pielke Jr., 2025). Technological advances, including better forecasting, early warning systems, building codes, and flood defenses, have significantly reduced economic losses relative to GDP, with the expanding U.S. economy further diluting disaster cost impacts.

This section on the socioeconomic context of weather-related disasters focuses on data challenges and raises critical points about the interpretation of trends and the complexities of attributing economic losses to climate change. The discussion of NOAA's Billion Dollar Disaster Series importantly points out the serious limitations in its methodology that led to its withdrawal as a regular NOAA product. This section also nicely couples with Section 10.1 by noting that disaster losses are driven more by societal factors than changes in extreme weather events. It might be useful to go further, however, and discuss how the withdrawal of NOAA's dataset affects public policy going forward.

10.3 Mortality from Temperature Extremes

10.3.1 Heat and Cold Risks

> **Subsection summary:** In a warming world, extreme heat events are expected to become more frequent, while extreme cold events decrease, a trend observed globally but less clearly in the continental US. Cold-related mortality significantly outweighs heat-related deaths, with global studies showing cold causes 18.5 times more deaths than heat (Gasparini *et al.*, 2015). In the US, cold accounts for about twice as many deaths as heat (EPA, 2025), with 5.5% of deaths linked to cold versus 0.4% to heat (Gasparini *et al.,* 2015). Cold risks begin at moderate temperatures, unlike heat, which primarily causes deaths via heat stroke. US heat-related mortality has declined sharply—by 75% from the 1960s to 1990s (Davis *et al.,* 2003), 60% from 1987 to 2005 (Bobb *et al.*, 2014), and over 90% from 1962 to 2006 (Nordio *et al.*, 2015)—due to adaptations like improved healthcare, air conditioning, and behavioral changes. Adaptation also reduces cold-related mortality risks, especially later in seasons (Allen and Sheridan, 2018; Lee and Dessler, 2023). Rising temperatures are linked to net lives saved by reducing cold-related deaths. The IPCC AR6 Synthesis report highlights increased heat-related mortality but omits the larger decline in cold-related deaths. Wang *et al.* (2018) project no significant increase in US heat-related mortality by 2050, assuming continued adaptation, emphasizing that ignoring adaptation overestimates future risks.

Mortality risks associated with heat waves and cold spells are presented in a comprehensive analysis. It is important to note that cold events significantly cause more deaths than excessive heat, both globally and in the US, and how heat-related mortality has steadily declined in recent decades. The report correctly notes that adaptation is a key factor in mortality reduction.

Would it be possible to add a discussion that ties the additional cost of non-dispatchable sources of energy (*e.g.*, wind and solar) to rising energy costs and the strain on the grid by foregoing coal and natural gas?

In addition, this section focuses only on mortality which is the focus of Section 10.3.2. Some discussion of non-mortality impacts, such as the economic cost of electricity and morbidity issues would strengthen this section.

10.3.2 Mortality Risks and Energy Costs

> **Subsection summary:** A 2016 study (Barreca *et al.*, 2016) found that U.S. mortality risks from temperature extremes, both hot and cold, have significantly decreased due to the adoption of central heating and air conditioning (AC) since 1960. Before 1960, days above 90°F (32°C) increased mortality risk by 2.2%, but post-1960, this dropped to 0.3%, an 85% reduction, entirely attributed to widespread AC use enabled by affordable electricity. Cold days below 39°F (4°C) saw mortality risk halved from 1% to 0.5% post-1960. However, energy affordability remains critical. Doremus *et al.* (2022) showed that while wealthy and poor households adjust energy use similarly for moderate temperature swings, low-income households increase energy spending less during extreme cold (<5°C, 0.5% *vs.* 1.2% for high-income) and not at all during extreme heat (>30°C), even with AC access. Cong *et al.* (2022) confirmed similar trends in Arizona, highlighting that energy costs leave low-income households vulnerable to weather extremes despite widespread heating and cooling adoption.

This section provides a clear analysis of how technological adaptations, especially access to electricity and home heating and cooling, have offset the health effects of extreme weather. It also correctly notes that reductions in energy affordability might undermine the advances that have been made in this area. I would briefly discuss policy-induced increases in the costs of energy and air conditioning as barriers to adaptation, much like the discussion I suggested should be added in Section 10.3.1.

References

Lieberman, B., May 6, 2024: "Biden Is Coming for Your Air Conditioner: New regulations will drive up the cost of units and refrigerants," *The Wall Street Journal*, https://www.wsj.com/opinion/biden-is-coming-for-your-air-conditioner-regulations-add-cost-c0212a80.

Lieberman, B. August 24, 2025: "How to Beat the High Cost of Cooling: Biden climate rules made air-conditioning more expensive. Trump and Congress can reverse them." *The Wall Street Journal*, https://www.wsj.com/opinion/how-to-beat-the-high-cost-of-cooling-6604bebd.

11 CLIMATE CHANGE, THE ECONOMY, AND THE SOCIAL COST OF CARBON

> **Chapter Summary (from the Report):** Economists have long considered climate a relatively unimportant factor in economic growth, a view echoed by the IPCC itself in AR5. Mainstream climate economics has recognized that CO_2-induced warming might have some negative economic effects, but they are too small to justify aggressive abatement policy and that trying to "stop" or cap global warming even at levels well above the Paris target would be worse than doing nothing. 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 modeling uncertainties either find no evidence of a negative effect on global growth from CO_2 emissions or find poor countries as likely to benefit as rich countries.
>
> Social Cost of Carbon (SCC) estimates are highly uncertain due to unknowns in future economic growth, socioeconomic pathways, discount rates, climate damages, and system responses. The SCC is not intrinsically informative as to the economic or societal impacts of climate change. It provides an index connecting large networks of assumptions about the climate and the economy to a dollar value. Some assumptions yield a high SCC and others yield a low or negative SCC (*i.e.* a social benefit of emissions). The evidence for or against the underlying assumptions needs to be established independently; the resulting SCC adds no additional information about the validity of those assumptions. Consideration of potential tipping points does not justify major revisions to SCC estimates.

Those introductory paragraphs accurately distill the detailed literature reviews that follow. Climate change costs are unlikely to significantly hinder US and global economic growth. Coercive "solutions" are likely to do more harm than good. Assigning dollar values to projected climate change effects does not validate the assumptions on which impact assessments derive. As Pindyck (2013) observed, social cost modeling that purports to monetize the effects of climate change "suggests a level of knowledge and precision that is simply illusory and can be highly misleading."

11.1 Climate Change and Economic Growth

11.1.1 Overview

> **Subsection summary:** This subsection summarizes a variety of evidence supporting the IPCC AR5's assessment that "Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change," and economist Thomas Schelling's earlier conclusion that "in the United States, and probably Japan, Western Europe, and other developed countries, the impact [of climate change] on economic output will be negligible and unlikely to be noticed."

The report notes that William Nordhaus's DICE model projects 4.1°C of warming by 2100, which is higher than many IPCC models estimate, yet Nordhaus's "optimal" climate policy "aims for +3.5°C warming, in other words we modestly scale back fossil fuel use and otherwise just live with almost all the warming." Nordhaus calculated that "capping warming at 2.5°C creates total costs of $177.8T, which is $43.2T worse than doing nothing at all."

Recent research by Pielke Jr. *et al.* (2022) further undermines the 'desperate times require desperate measures' rationale for aggressive mitigation policies. They find that the most realistic

21st century emission scenario is SSP2-3.4. Assuming 3.0°C climate sensitivity, SSP2-3.4 results in 2.0°C-2.4°C of warming by 2100. That means the current BAU emissions baseline is already on track to outperform Nordhaus's optimal mitigation policy by more than 1.0°C.

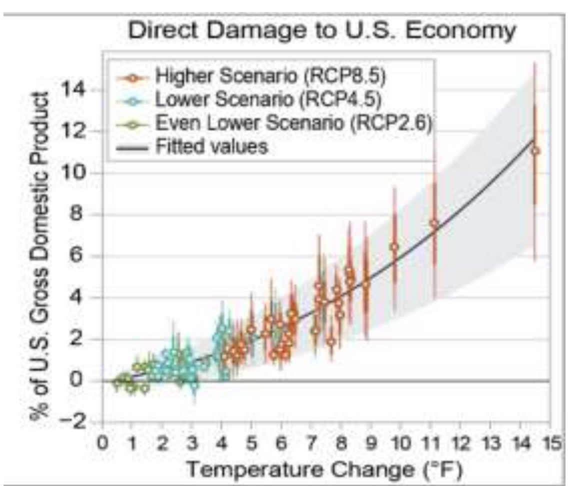
11.1.2 Empirical Analysis of Climate Change and Economic Growth

> **Subsection summary:** This subsection reviews several econometric studies and reasonably concludes the net impacts of warming on global growth and per capita income will likely be negligible. For example, the Biden administration's CEA/OMB report on climate change and macroeconomic forecasting examines a dozen peer reviewed studies. The studies on average project an end of century global GDP loss of less than 1% from a warming of 4.0°C.

The report also notes that even using the extreme RCP8.5 scenario, Berg *et al.* (2023) estimate a global GDP loss of 1.9% compared to a world with no warming. In other words, instead of global GDP increasing 400% by 2100 in a non-warming world, global GDP increases 392% percent in an RCP8.5 world. If warming is moderate—because the actual emission trajectory is SSP2-3.4 or something close to it, and climate sensitivity is near the low-end of the IPCC range, warming should make little difference to global economic growth and could potentially contribute to it due to longer growing seasons, fewer cold-related deaths, and the agricultural productivity gains from atmospheric CO_2-fertilization.

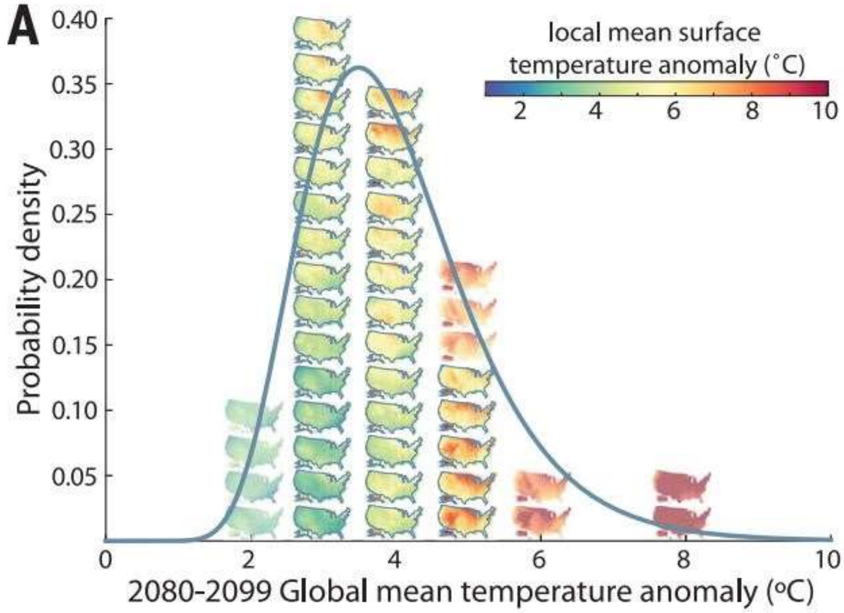
Here the DOE report might reiterate Nordhaus's caution. Spending trillions of dollars in the near-term to benefit our richer end-of-century descendants could backfire, holding back 21st GDP growth by more than 1.9%.

NCA4 (USGCRP, 2018) warned that unchecked warming could raise end-of-century global temperatures by 8.0°C and reduce US GDP by 10 percent (Davenport and Pierre-Louis, 2018). That estimate came from a single study, Hsiang *et al.* (2017). Although NCA4 reproduced Hsiang *et al.*'s chart projecting GDP loss as a function of global-mean temperature, it did not reproduce their chart showing the probabilities of specific temperature increases.



Source: ***NCA4, Vol. II, Ch. 29, p. 1360, adapted from Hsiang et al. (2017).***

Hsiang *et al.* (2017) found that even when the warm-biased CMIP5 model ensemble is run with the warm-biased RCP8.5 scenario, global warming hits 8.0°C in only 1% of model runs.



Source: ***Hsiang et al. (2017). An 8°C warming has a probability of 0.01 when CMIP5 is run with RCP8.5.***

NCA4 concealed from readers the extreme unlikelihood of its worst-case scenario, allowing *The New York Times* and other media to present an implausible disaster as a probable future absent new stronger commitments to 'global action' (Lewis, 2025).

If, per Pielke Jr. (2022), the world is now on an SSP2-3.4 emission trajectory, which implies a 21st century warming of 2.0°C-2.4°C (assuming 3.0°C climate sensitivity), then, according to the Hsiang et al. chart reproduced on p. 1360 of NCA4, global warming will reduce US GDP by about 1% in the 2090s.

The DOE report's comment on the Biden CEA/OMB report applies here: "Given that the economy's annual growth rate is expected to be 1-2 percent, the impact of a warming globe on the U.S. GDP is indeed negligible."

11.2 Models of the Social Cost of Carbon

Section summary (from the Report): The Social Cost of Carbon (SCC) is a tool for quantifying the economic impact of carbon dioxide emissions, helping policymakers weigh the costs and benefits of climate policies. It estimates the damage caused by emitting one additional ton of CO_2, expressed in dollars. More formally, the SCC is the discounted present value of the current and future marginal loss of economic welfare due to an additional ton of CO_2 entering the atmosphere.

11.2.1 Estimating the SCC

> **Subsection summary:** This subsection compares SCC values to more familiar economic statistics. For example, data on prices and quantities can be used to estimate the current inflation rate or the per capita GDP growth rate, and uncertainties associated with those metrics are "well-understood." In contrast, "there are no market data available to measure many, if not most, of the marginal damages or benefits believed to be associated with CO_2 emissions."

For example, there is "no market in which people can directly attach a price" to the risk of dying from extreme weather. Economists can try to infer such values from transactions in real estate or insurance markets, "but isolating the component of price changes attributable to atmospheric CO_2 levels is very difficult." Moreover, as the DOE report authors surely know, key SCC components can controversial (climate sensitivity, CO_2 fertilization, discount rates) or highly speculative (300-year socioeconomic development projections, tipping point risks).

Consequently, SCC values must be "imputed using economic models," and those models are critically dependent on assumptions. In the report's words:

> "No amount of data collection can change the fact that many components of the SCC are unknown and rely on judgment and opinion based on knowledge of the underlying literature on the physical effects of climate change. SCC calculations are thus best thought of as 'if-then' statements: if the following assumptions hold, then the SCC is $X per tonne."

The foregoing assessment raises a question that the report briefly addresses at the end of the chapter: Is the SCC too speculative and prone to user manipulation to inform regulatory decisions, climate mitigation benefit estimates, and carbon tax legislation?

11.2.2 Variations in the SCC

> **Subsection summary:** This section describes four key inputs into SCC determinations that vary depending on modelers' assumptions: discount rates, equilibrium climate sensitivity, damage function coefficients, and emission scenarios.

My comments address each of those topics in turn.

<u>Discount Rates</u>

The report clarifies that the discount rate "represents the opportunity cost of spending money today rather than investing it and then having more to spend tomorrow." The report might usefully add a brief discussion of whether SCC-based decision-making likely leads to obtuseness about the fundamental economic principle of opportunity cost.

To the extent policy decisions are based on SCC calculations, they do not consider the opportunity costs of alternative investments precluded by requiring capital expenditures on climate change mitigation. Bang-for-buck comparisons may reveal there are many better options than compulsory CO_2 emission reductions for building capital stock of future generations (Kreutzer, 2016), promoting health and saving lives (Lomborg, 2023), and mitigating climate-related damages (Lewis, 2025).

Thus, even assuming scientists could determine the social cost of carbon with the same objectivity as they can the boiling point of water at sea level, they would not know, absent extensive economic analysis, whether a carbon tax or emission standard based on the 'real' SCC produces a net social benefit or does more harm than good by diverting capital from higher-value investments.

Equilibrium Climate Sensitivity

The report correctly observes that "most recent data-driven ECS values tend to be lower" than the 3.0°C or 3.1°C default values in official SCC estimates, and that "use of lower empirically derived ECS values dramatically lower the resulting SCC estimate, even when low discount rates are used." As the report later points out, when some SCC calculation models are run with empirically based ECS values and robust CO_2 fertilization estimates, there are significant probabilities of negative SCC values (*i.e.*, net benefits).

Damage Function Coefficients

The report correctly observes that US government's SCC Interagency Working Group (IWG) gave short shrift to the agricultural benefits of CO_2 atmospheric enrichment. Specifically, DICE and PAGE, two of the three integrated assessment models (IAMs) informing the IWG's SCC estimates in 2010, 2013, 2016, and 2021, do not explicitly estimate CO_2 fertilization effects. The FUND model provides such estimates, but it relies on studies conducted "prior to the publication of the current evidence of global greening and the magnitude of benefits to crops from elevated CO_2." Ignoring or depreciating CO_2 fertilization inflates the perceived net cost of CO_2 emissions.

Emission Scenarios

The report correctly observes that IAMs run with higher emission scenarios tend to generate higher SCC estimates, and as noted, Chapter 3 discusses the "implausibility" of extreme scenarios, such as RCP8.5. The report should add a brief discussion of the emission scenarios underpinning US government SCC estimates.

The IWG estimated SCC values using an average of five emissions trajectories (EPRI, 2014). Four are no-policy emission scenarios from a 2009 Stanford Energy Modeling Forum study known as EMF-22. Each scenario plots socioeconomic development and emissions from 2000 to 2100. The fifth is a policy future, added by the IWG, in which CO_2 concentrations stabilize at 550 parts per million (ppm) in 2100. The IWG then extended the five trajectories out to the year 2300, albeit in a manner that might be described as techno-pessimism.

Lacking socioeconomic development scenarios for the 22nd and 23rd centuries, the IWG assumed that industrial carbon intensity would decline at the same rate during 2100-2300 as the five baselines projected for 2090-2100. In other words, the extensions assumed no technological breakthroughs would occur such as might dramatically accelerate rates of carbon intensity decline over the next 200 years.

The IWG did not report the total quantity of emissions in each of the five trajectories over the 300-year analysis period, nor did it provide any context to assess their realism. Fortunately, the Electric Power Research Institute (EPRI) did just that in a 2014 technical review of the IWG's 2010 and 2013 technical support documents (TSDs). EPRI (2014) toted up the emissions and compared those quantities to total potential CO_2 emissions in the world's estimated fossil fuel reserves.

Cumulative emissions in the five trajectories average out to 17,195 $GtCO_2$ — roughly 2.4 to 4.6 times estimated fossil fuel reserves. That should have raised eyebrows even in 2010. To produce emission totals that high, the same governments that negotiated the Kyoto Protocol in 1997 and Copenhagen Agreement in 2009 would have to abandon "climate action" for almost three centuries and do so despite the IWG's expectation of increasingly damaging climate change impacts. The combined USG1-5 emission baseline made little sense (Pielke Jr., 2021). Neither the IWG's 2016 TSD nor its 2021 TSD addressed EPRI's critical assessment of the IWG emission baselines (Lewis, 2025).

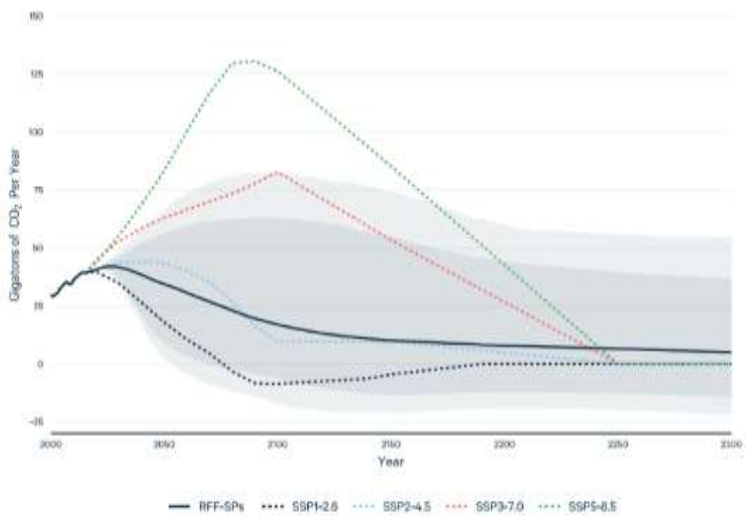
Table 4-6
Cumulative fossil and industrial CO_2 emissions in the USG assumptions and estimated fossil fuel reserves

Cumulative CO_2 emissions ($GtCO_2$)		
	By 2200	By 2300
USG1	11,207	16,741
USG2	20,024	33,023
USG3	8,113	10,864
USG4	14,092	20,504
USG5	3,691	4,843
Estimated reserves ($GtCO_2$)	3,674 - 7,113	

Source: *EPRI (2014). The IWG's five baseline emission trajectories (USG1-USG5) compared to estimated fossil fuel reserves.*

For perspective, in 2022, Resources for the Future (RFF) published updated emission baselines for both the 21st century and the 300-year SCC analysis period (RFF, 2022). BAU in the RFF's 21st century baseline closely matches SSP2-4.5, the mid-range scenario in IPCC AR6. In the RFF's baseline projection, global CO_2 emissions are about half those projected in SSP5-8.5 (and RCP8.5) in 2050 and about one-fifth those projected in 2100.

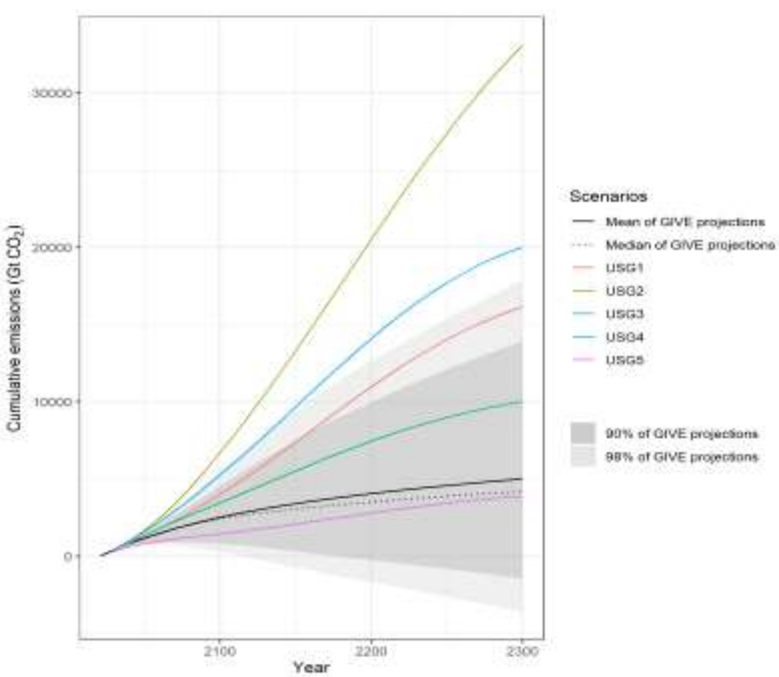
Figure 8. Net Annual Emissions of CO_2 from RFF-SPs and SSPs



Notes. Lines represent median values, and dark and light shading represent the 5th to 95th (darker) and 1st to 99th (lighter) percentile ranges of the RFF-SPs.

Source: *Kevin Rennert et al. (2022). The solid black line is the RFF's baseline projection. The dotted blue line is SSP2-4.5. The dotted green line is SSP5-8.5.*

Upon request, RFF lead author Kevin Rennert created a chart comparing the updated baselines to the IWG baselines. The EPA adopted the RFF baselines in its November 2023 SC-GHG report (EPA, 2023).



Source: *Kevin Rennert. The mean projection of GIVE in 2300 is 5,000 $GtCO_2$—less than one-third of the USG1-5 mean of 17,195 $GtCO_2$.*

Let that sink in for a moment. The first step in SCC analysis is selecting the socioeconomic scenarios responsible for generating the emissions that drive the physical impacts of climate change and, ultimately, the social damage. Through four iterations over an 11-year period, the IWG relied on emission baselines that on average project more than three times the quantity of CO_2 emissions in the updated, Biden EPA-approved, RFF baseline.

The White House Council of Economic Advisors hailed the IWG's 2021 SCC analysis as "a return to science" and "evidence-based" climate policy benefit estimates (Boushey, 2021). Pielke Jr. (2021) disagreed: "The Biden administration just flunked its first scientific integrity test."

Emission Scenarios: Less Is More?

The DOE report states that "in 2023 the U.S. Environmental Protection Agency raised its preferred SCC value about 5-fold over the estimates it had issued ten years earlier." I would rephrase that description as follows: In 2023, the EPA raised its *central SCC values* about *3-fold* over the estimates it had issued *only three years earlier.*

In the IWG's 2021 TSD, the central SCC estimate for 2050 is \$85/ton. In the EPA's 2023 report's central estimate, the central SCC in 2050 is \$310/ton—more than three times larger.

Table ES-1: Social Cost of CO_2, 2020 – 2050 (in 2020 dollars per metric ton of CO_2)[3]

	Discount Rate and Statistic			
Emissions Year	5% Average	3% Average	2.5% Average	3% 95th Percentile
2020	14	51	76	152
2025	17	56	83	169
2030	19	62	89	187
2035	22	67	96	206
2040	25	73	103	225
2045	28	79	110	242
2050	32	85	116	260

Source*:* *IWG (2021). Central estimate for 2050 is \$85/ton CO_2*

Table 3.1.1: Social Cost of Carbon ($SC\text{-}CO_2$) by Damage Module, 2020-2080 (in 2020 dollars per metric ton of CO_2)

	Near-Term Ramsey Discount Rate and Damage Module								
	2.5% Near-Term Rate			2.0% Near-Term Rate			1.5% Near-Term Rate		
Emission Year	DSCIM	GIVE	Meta-Analysis	DSCIM	GIVE	Meta-Analysis	DSCIM	GIVE	Meta-Analysis
2020	110	120	120	190	190	200	330	310	370
2030	140	150	150	230	220	240	390	350	420
2040	170	170	170	280	250	270	440	390	460
2050	210	200	200	330	290	310	500	430	520
2060	250	220	230	370	310	350	550	470	570
2070	280	240	250	410	340	380	600	490	610
2080	320	260	280	450	360	410	640	510	650

Source: *EPA (2023). Central estimate for 2050 is \$310/ton CO_2*

That is a strange result, and the DOE report should discuss it. As just mentioned, the EPA adopts RFF's updated emissions baseline, which projects 5,000 gigatons of CO_2 emissions during 2000-2300—less than one-third the quantity in the IWG baseline. The most basic idea in SCC analysis is that the damage from the next ton of emissions chiefly depends on the cumulative quantity of CO_2 emitted up to that point. To infer more than three times the per-ton social cost from fewer than one-third the previously projected emissions is deeply counter-intuitive.

How do dramatic reductions in projected CO_2 emissions produce dramatic increases in estimated social damage? Far from explicating this less-is-more paradox, the EPA's 170-page social cost report does not even acknowledge it.

One factor contributing to the higher SC-GHG values is the EPA's reduction of the central estimates discount rate from 3 percent to 2 percent. The lower the discount rate, the higher the calculated present value of future climate change costs and climate change mitigation benefits.

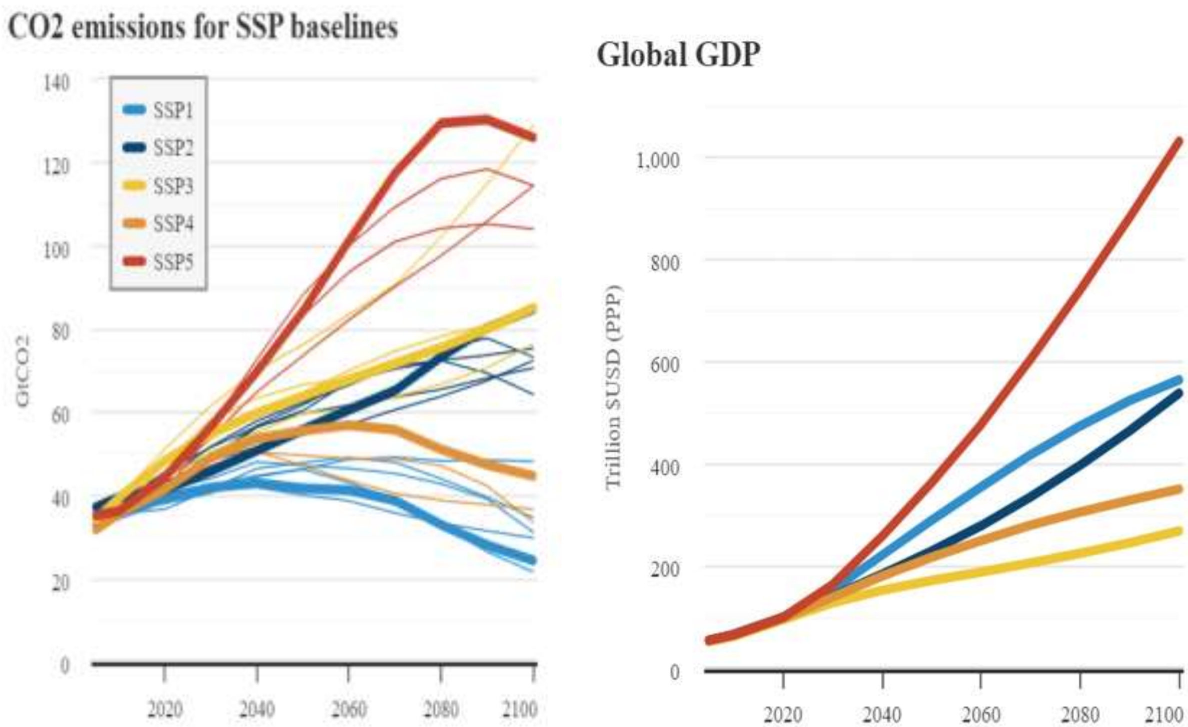
However, that is not the sole factor, as can be seen by comparing the two tables above. When discounted at 2.5 percent, the SCC in 2050 is \$116/ton in the IWG's calculation and \$200-210/ton in the EPA's calculation. The EPA SCC estimate is 73-84 percent higher, even when both are discounted at the same rate.

Roger Pielke, Jr. appears to have penetrated the mystery, which is twofold. The following is a simplified presentation. The final report should take a deeper dive than I can provide here.

First, although the EPA replaced the older "return to coal" baselines with RFF's updated baselines, the EPA's damage-calculation models and underlying studies are still based on RCP8.5 (or SSP5-8.5). That is to say, the damage calculators assume significant probabilities of temperature increases as high as any projected under RCP8.5, with the result that each ton of emissions is assigned a value comparable to that which it might have in an RCP8.5 world (Pielke Jr., 2023b).

Second, the EPA combines RCP8.5—or, more precisely, the heat from the associated fossil-intensive, high growth socioeconomic scenario, SSP5—with the social fragility of the poorest socioeconomic scenario, SSP3 (Pielke Jr., 2023a).

The two scenarios differ drastically in terms of wealth and adaptive capabilities. In 2100, global per capita income in SSP3 is $20,000; in SSP5, it is almost $140,000. Of the five shared socioeconomic pathways, SSP5 has the greatest adaptive capabilities; SSP3, the least (Riahi *et al.*, 2017; Hausfather *et al.*, 2018). However, only SSP5 has the capacity to match (or even exceed) RCP8.5 emission totals—precisely because of its rapid, fossil-fueled economic growth.



Source: *Hausfather (2018)*

In short, if I correctly understand Pielke, Jr. (2023a), EPA 2023's SCC estimates derive from a franken-scenario—an implausible amalgam of SSP3 social vulnerability and SSP5 economic growth, emissions, and warming. That is a no-no. As EPRI explained in its critique of the IWG process, a proper socioeconomic scenario provides "a complete and cohesive story with internal consistency between emissions drivers and emissions such that there are well defined relationships" (EPRI, 2014). Combining the emissions of SSP5 with the poverty of SSP3 is not science. It is science fiction with an incoherent storyline.

Length of Analysis Period

The report should mention a fifth basic SCC input that depends at least partly on modeler preference: the analysis period. As noted, US government SCC estimates are based on a 300-year analysis period extending from 2000 to 2300. That methodological choice allows projected climate damage to accumulate far beyond the horizon of informed speculation about population growth, economic development, and technological advancements.

CEI recommends that SCC analysis be removed from federal agency rulemaking and benefit-cost analysis, and Trump administration guidance directs agencies to discontinue monetizing the effects of GHG emissions unless such estimates are "plainly required" by the agencies' governing statutes (OIRA, May 2025). However, if agencies ever again publish official SCC estimates, and they revive the 300-year analysis period, they should also provide sensitivity cases with shorter baselines. Although still akin to crystal ball gazing, ending the analysis in 2150 would be less presumptuous. Heritage Foundation studies indicate that scaling back the analysis period to 150 years would reduce projected climate damage by about 25 percent (Dayaratna and Kreutzer, 2013).

11.2.3 Evidence for Low SCC

In this subsection, the report draws logical inferences from information presented earlier. CO_2 fertilization has a stronger beneficial effect on agriculture than was known when the IWG integrated assessment models were being parameterized. Recent research indicates ECS is lower than previously estimated. The final report should also note the long-term (and apparently ongoing) declines in climate-related morality and relative economic impact of weather-related damage. The report helpfully reminds readers that the SCC focuses on the social impacts of CO_2 emissions and does not measure the private marginal benefits to consumers or society from the availability of fossil fuels. In this connection, the report cites Tol (2017), who found that "the private benefit of carbon is large relative to the social cost."

Specifically, Tol (2017) estimated that the global average private benefit of fossil energy use is $411 per ton of CO_2. In contrast, the mean of published SCC estimates in studies using a 3% pure rate of time preference was $12 per ton of CO_2.

11.2.4 Tipping points

In this subsection, the report distinguishes between tipping points ("abrupt changes") produced by "external energy" sufficient to disrupt "inherently stable" systems and abrupt changes arising from the internal dynamics of inherently unstable systems, perhaps after a small external perturbation.

As to the first type, the report observes that AR6 "finds little evidence for impending collapse of the Atlantic Meridional Overturning Circulation or the West Antarctic ice sheet," "finds there is no tipping point associated with Arctic Sea ice," and "considers" catastrophic release of methane hydrates from thawing permafrost "very unlikely."

As to the second type, the report sensibly opines that "If such tipping points are possible the most appropriate stance for economic policy is to maximize resilience to any form of external catastrophe since it is unlikely we could predict it or prevent it from happening."

11.2.5 Are There Alternatives?

In this one-paragraph subsection, the report begins by citing researchers who regard SCC estimates as useless or worse: "It is increasingly being argued that the SCC is too variable to be useful for policymakers. Cambridge Econometrics (Thoung, 2017) stated it's 'time to kill it' due to uncertainties. The UK and EU no longer use SCC for policy appraisal, opting for 'target-consistent' carbon pricing (UK Department for Energy Security and Net Zero, 2022; Dunne, 2017)."

The report stops short of calling for the SCC's removal from policy determination: "However, the uncertainty of SCC estimates doesn't mean that other regulatory instruments are inherently better or more efficient. Many emissions regulations (such as electric vehicle mandates, renewable energy mandates, energy efficiency regulations and bans on certain types of home appliances) cost far more per tonne of abatement than any mainstream SCC estimate, which is sufficient to establish that they fail a cost-benefit test."

Apparently, the report favors some sort of official SCC determination to help policymakers spotlight the economic inefficiency of GHG regulations. However, the same limited utility can be achieved by citing academic estimates. Or better still, by comparing the high cost of climate regulations to the putative benefits, which typically are too small to be detected, verified, or experienced.

The report underestimates the mischief inherent in having the US government produce, or put its imprimatur on, specific SCC estimates. Official US government SCC estimates would perpetuate the "pretense of knowledge and precision"—the illusion that SCC analysis is an objective and reliable touchstone for regulatory decisions. And if for regulatory decisions, why not for all capital expenditures? The SCC is a force-multiplier for would-be central planners—a veritable "One Number to Rule Them All."

As Pindyck (2013) cautioned, by manipulating the knobs and dials, SCC models "can be used to obtain almost any result one desires." The 11-year track record of the IWG and the EPA's 2023 SCC reboot suggests that many SCC practitioners desire to make fossil fuels look unaffordable no matter how cheap, and regulatory climate policies look like a bargain at any price. Whatever its virtues as a blackboard exercise, SCC analysis in political practice is computer-aided hucksterism. The final DOE report should reassess its support for keeping SCC analysis in the federal regulatory arsenal.

References

Boushey, H., February 26, 2021: "A Return to Science: Evidence-based Estimates of the Benefits of Reducing Carbon Pollution," Council of Economic Advisors Blog, https://bidenwhitehouse.archives.gov/cea/written-materials/2021/02/26/a-return-to-science-evidence-based-estimates-of-the-benefits-of-reducing-climate-pollution/.

Davenport, C., and K. Pierre-Louis, November 23, 2018: "U.S. Climate Report Warns of Damaged Environment and Shrinking Economy." *The New York Times*, https://www.nytimes.com/2018/11/23/climate/us-climate-report.html.

Dayaratna, K.D., and D. Kreutzer, November 21, 2013: Loaded DICE: An EPA Model Not Ready for the Big Game, Backgrounder No. 2860. The Heritage Foundation, https://www.heritage.org/environment/report/loaded-dice-epa-model-not-ready-the-big-game.

Electric Power Research Institute (EPRI), 2014: *Understanding the Social Cost of Carbon: A Technical Assessment*, Section 4, 14-15, https://www.jstor.org/stable/90009413.

Hausfather, Z., April 19, 2018: Explainer: How 'Shared Socioeconomic Pathways' explore future climate change. *Carbon Brief*, https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change/.

Hsiang, S.M., R.E. Kopp, A. Jina, J. Rising, M. Delgado, S. Mohan, D.J. Rasmussen, *et al.*, 2017. Estimating Economic Damage from Climate Change in the United States. *Science*, **356** (6345), 1362-1369, https://www.science.org/doi/10.1126/science.aal4369.

Interagency Working Group on the Social Cost of Greenhouse Gases, February 2021: Technical Support Document: Social Cost of Carbon, Methane, and Nitrous Oxide, Interim Estimates under Executive Order 13990, https://bidenwhitehouse.archives.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf.

Kreutzer, D., June 16, 2016: "Discounting Climate Costs". Heritage Foundation, https://www.heritage.org/environment/report/discounting-climate-costs.

Lewis, M., 2025: "Chapter 1: Modernizing EPA Science Policies," Bakst and Lewis, eds., Modernizing the EPA: A Blueprint for Reform, Competitive Enterprise Institute, pp. 65-69, https://cei.org/studies/modernizing-the-epa-a-blueprint-for-congress/.

Lomborg, B., November 3, 2021: "We're Safer from Climate Disasters than Ever Before," *The Wall Street Journal*, https://www.wsj.com/opinion/climate-activists-disasters-fire-storms-deaths-change-cop26-glasgow-global-warming-11635973538.

Lomborg, B., January 1, 2023a: "The risk of dying from climate-related disasters has declined precipitously," X, https://twitter.com/BjornLomborg/status/1612790152539131904.

Lomborg, B., 2023b: *Best Things First.* Copenhagen: Copenhagen Consensus Center, https://lomborg.com/best-things-first.

Office of Information and Regulatory Affairs (OIRA), May 5 2025: Memorandum for Regulatory Policy Officers at Departments and Agencies and Executive Directors of Commissions and Boards: Guidance Implementing Section 6 of Executive Order 14154, Entitled "Unleashing American Energy," https://www.whitehouse.gov/wp-content/uploads/2025/02/M-25-27-Guidance-Implementing-Section-6-of-Executive-Order-14154-Entitled-Unleashing-American-Energy.pdf.

Pielke Jr., R., February 28, 2021: "The Biden administration just flunked its first scientific integrity test." *The Honest Broker*, https://rogerpielkejr.substack.com/p/the-biden-administration-just-failed.

Pielke Jr., R., *et al.*, 2022: Plausible 2005-2050 emissions scenarios project between 2°C and 3°C of warming by 2100. *Environ. Res. Lett.*, **17**, 02407, https://iopscience.iop.org/article/10.1088/1748-9326/ac4ebf.

Pielke Jr., R., April 24, 2023a: "Public Health and Climate Change: How to be an informed consumer in public discussions of climate change." *Substack*, https://rogerpielkejr.substack.com/p/public-health-and-climate-change.

Pielke Jr., R., December 4, 2023b: "Secret Sauce: You'll Never Guess What Drives the Biden Administration's Social Cost of Carbon." *Substack*, https://rogerpielkejr.substack.com/p/secret-sauce.

Pielke Jr, R., July 21, 2025: "Human Progress versus Climate Evangelism: Humanity marks an incredible achievement that some don't want you to know about," *Substack*, https://rogerpielkejr.substack.com/p/human-progress-versus-climate-evangelism.

Pindyck, R.S., 2013: Climate Change Policy: What Do the Models Tell Us? *Journal of Economic Literature* 2013, **51**(3), 860–872 https://web.mit.edu/rpindyck/www/Papers/PindyckClimateModelsJELSept2013.pdf.

Riahi, K., D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimari, *et al.*, 2017: The Shared Socio-Economic Pathways and their energy, land use, and greenhouse gas emissions implications: An Overview, *Global Environmental Change*, **42**, 153-168.

Tol, S.J.R., 2017: The Private Benefit of Carbon and its Social Cost, University of Sussex Economics, *Working Paper Series No. 07-2017, https://www.sussex.ac.uk/webteam/gateway/file.php?name=wps-07-2017.pdf&site=24*.

USGRCP, 2018: Fourth National Climate Assessment, Volume 2: Impacts, Risks, and Adaptation in the United States; Chapter 29. Reducing Risks Through Emissions Mitigation, p. 1360.

12 GLOBAL CLIMATE IMPACTS OF U.S. EMISSIONS POLICIES

Chapter Summary (from the Report): US policy actions are expected to have undetectably small direct impacts on the global climate and any effects will emerge only with long delays.

12.1 The Scale Problem

This section begins by noting a critical difference between criteria pollutants and carbon dioxide:

> "The emissions rates and atmospheric concentrations of criteria air contaminants are closely connected because their lifetimes are short and their concentrations are small; when local emissions are reduced the local pollution concentration drops rapidly, usually within a few days. But the global average CO_2 concentration behaves very differently, since emissions mix globally and the global carbon cycle is vast and slow. Any change in local CO_2 emissions today will have only a very small global effect, and only with a long delay."

That analysis is correct. As noted in our comments on Chapter 7.3, instantaneously replacing the warmest emission trajectory (RPC8.5) with the coolest (RCP2.6) would avert only 7 centimeters (2.8 inches) of sea level rise between now and 2050. In similar vein, the report cites Wigley (1998)'s estimate that full compliance with the Kyoto Protocol would mean the estimated business-as-usual level of global warming arrives by 2105 instead of 2100, and Lomborg (2016)'s estimate that full compliance with the Paris Accord's initial commitments would avert about 0.1°C of warming by 2100 and delay hitting the BAU temperature by about a decade.

The section correctly concludes:

> "Thus, in contrast with conventional air pollution control, even drastic local actions will have negligible local effects, and only with a long delay. The practice of referring to unilateral U.S. reductions as 'combatting climate change' or 'taking action on climate on the assumption we can stop climate change therefore reflects a profound misunderstanding of the scale of the issue."

12.2 Case Study: U.S. Motor Vehicle Emissions

In this section, the report uses the EPA's tailpipe CO_2 standards for model year 2027-2032 light duty vehicles to illustrate the scale problem.

The authors calculate that US cars and light trucks accounted for only 3 percent of global energy-related CO_2 emissions in 2022. They conclude: "To a first approximation, we can say that even eliminating all U.S. vehicle-based emissions would retard the accumulation of CO_2 in the atmosphere by a year or two over a century."

The reduction in the overall warming trend would be about 3 percent, which is "far below the limits of measurability." The authors conclude: "Given that global-average temperature is the most direct climate change metric, impacts on any secondary climate metrics (e.g. severe weather, floods, drought, etc.) from reducing U.S. vehicle CO_2 emissions would be even less measurable." Although an obvious inference from the foregoing, the report should add that the impact of the EPA's tailpipe CO_2 standards would be even further below detection levels, because the requirements target only "new" cars and light trucks produced during model years 2027-2032, not "all" US light-duty vehicles.

Similar analyses come to similar conclusions. For example, the EPA recently closed the comment period for its proposed repeal of the Biden administration's "carbon pollution standards" (CPS) for fossil-fuel power plants. The key statutory issue in that rulemaking is whether power plant emissions of CO_2 “contribute significantly” to dangerous air pollution. Bennett (2025) offers a reasonable estimate based on conservative inputs.

Bennet (2025) uses the US government’s standard climate-policy impacts calculator, a model called MAGICC, run with its default 3°C equilibrium climate sensitivity (ECS) estimate, even though empirically constrained ECS estimates tend to be lower. He uses the IPCC AR6 mid-range emission scenario—SSP2-4.5—even though recent research suggests the world is on a lower emissions trajectory. He assumes the current US global share of CO_2 emissions of 13% will hold steady for the next 75 years even though the US share has been declining for the past 25 years.

Under those assumptions, MAGICC estimates that eliminating all US power plant CO_2 emissions by 2030 would avert 0.015°C of warming by 2050. That is almost 10 times smaller than the uncertainty range in the UK Met Office’s global annual average surface temperature data during 1850-2024 and less than half the uncertainty range in the UK Met Office’s global annual average surface temperature data in recent decades (Met Office Hadley Centre observations datasets, 2025). Note, the “uncertainty” here is the uncertainty from the coverage and aggregation of various readings. It does not include the additional uncertainty in the temperature readings themselves.

In short, the global warming produced by US fossil-fuel power plants is too small to be detected or verified. The second and third order effects on weather patterns and public health would be even harder to identify. Thus, even if we assume the ongoing rise in atmospheric GHG concentration may reasonably be anticipated to endanger public health and welfare, CO_2 emissions from US power plants do not “contribute significantly” to such dangerous air pollution.

12.3 Concluding Thoughts

The report concludes as follows:

> “This report supports a more nuanced and evidence-based approach for informing climate policy that explicitly acknowledges uncertainties. The risks and benefits of a climate changing under both natural and human influences must be weighed against the costs, efficacy, and collateral impacts of any ‘climate action,’ considering the nation’s need for reliable and affordable energy with minimal local pollution. Beyond continuing precise, un-interrupted observations of the global climate system, it will be important to make realistic assumptions about future emissions, re-evaluate climate models to address biases and uncertainties, and clearly acknowledge the limitations of extreme event attribution studies. An approach that acknowledges both the potential risks and benefits of CO_2, rather than relying on flawed models and extreme scenarios, is essential for informed and effective decision-making.”

The authors’ concluding thoughts are essentially a plea for realism and rationality in climate science and policy. The report makes many valuable contributions to public understanding of where climate science and policy have gone awry and the nature of the much-needed improvements.

References

Bennett, B., 2025: *The Materiality of US CO_2 Emissions on Global Climate*. Texas Public Policy Foundation, June, https://www.texaspolicy.com/wp-content/uploads/2025/06/2025-06-LP-Materiality-of-US-CO2-Emissions.pdf.

About the Commenters

Dr. David R. Legates is currently the Director of Research and Education of the Cornwall Alliance for the Stewardship of Creation and an Adjunct Fellow at CEI. He is a retired professor of climatology from the University of Delaware, having also held tenured positions at the University of Oklahoma and Louisiana State University. He has served as the chief research scientist for the Center for Computational Geosciences at the University of Oklahoma, a research scientist at the Southern Regional Climate Center at the Louisiana State University, the Delaware State Climatologist, the Deputy Assistant Secretary of Commerce for Environmental Observation and Prediction within NOAA, and as the executive director of the United States Global Change Research Program in the Office of Science and Technology Policy. He was a member of the President's Committee on the National Medal of Science, a consultant to the Global Precipitation Climatology Project sponsored by the World Meteorological Organization at Deutscher Wetterdienst, a member of the American Meteorological Society's Board of Certified Consulting Meteorologists, the University of Delaware representative to the Universities Space Research Association (USRA), and a national expert for the International Organizing Committee for the World Meteorological Organizations' Solid Precipitation Measurement Intercomparison Project. He is recognized as a Certified Consulting Meteorologist with the American Meteorological Society and has been awarded the Frederick Seitz Memorial Award, the Petr Beckmann Award, and the Courage in Defense of Science Award.

Dr. Marlo Lewis, Jr. is a Senior Fellow at CEI's Center for Energy and Environment. A prolific commenter on EPA and other federal agency rulemakings, Marlo has been a leader in CEI's work on the Kyoto Protocol, *Massachusetts v. EPA*, climate science, the Paris Agreement, the Clean Power Plan, fuel economy regulation, air quality standards, the social cost of carbon, and carbon taxes. He has been published in *The Hill*, *The Federalist*, *CQ Researcher*, and other publications, and has appeared on various television and radio programs, including Oprah Winfrey, where he provided counterpoint to Al Gore on *An Inconvenient Truth*. He is the co-editor, with Daren Bakst, of CEI's 2025 book, *Modernizing the EPA: A Blueprint for Congress*, and author the chapter on modernizing EPA science policies. Marlo served as a policy analyst in two State Department Bureaus during the second Reagan administration and as Staff Director for the House Government Reform Subcommittee on National Economic Growth, Natural

Resources, and Regulatory Affairs in the 106th Congress. He holds a Ph.D. in Government from the Harvard University Graduate School of Arts and Sciences.