Human Influence on Global Climate: A Comprehensive Synthesis of Evidence, Uncertainty, and Scientific Controversy

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Recommended citation: Moore, T. M. (2026). *Human influence on global climate: A comprehensive synthesis of evidence, uncertainty, and scientific controversy*. Manuscript retrieved from https://www.mooremetrics.com/climate-change. https://doi.org/10.5281/zenodo.24046991

Abstract

Human influence on climate is neither a binary proposition nor a single empirical question. The greenhouse effect is physically established, the modern rise in atmospheric carbon dioxide is overwhelmingly anthropogenic, the planet is retaining more energy than it emits, and the climate system has warmed. More difficult questions concern the magnitude of the human contribution, the equilibrium response to sustained forcing, the reliability of regional projections, the attribution of individual extremes, the balance of harms and benefits, and the cost-effectiveness of particular policies. This synthesis accepts the core evidence for anthropogenic warming while applying systematic skepticism to claims that depend heavily on model tuning, uncertain aerosol and cloud feedbacks, short observational records, selective scenario use, or poorly characterized natural variability. It applies the same standard to the contrarian literature: the strongest current versions of the "saturation," carbon-budget, causal-order, and energy-imbalance objections are examined directly, and each is shown to leave the foundational propositions intact—often on the objectors' own calculations. The synthesis also integrates evidence often underweighted in public debate: observationally constrained (energy-budget) estimates of climate sensitivity that fall below many model values, the persistence of carbon sinks, satellite-observed global greening, adaptation-driven declines in weather mortality alongside measurable attributable health losses, strong local controls on coastal and wildfire risk, and the distinction between hazard, exposure, and vulnerability. The result is neither a denial of human influence nor an endorsement of complacency. It is a case for calibrated confidence. Human activities have changed the climate, and continued emissions will add forcing; however, the precise sensitivity of the system, many regional consequences, and the net benefits of competing policy pathways remain materially uncertain. A scientifically defensible response should therefore combine emissions reduction where benefits plausibly exceed costs, adaptation to unavoidable change, investment in reliable low-carbon energy and resilience, transparent scenario labeling, and institutional humility about what models, attribution methods, and advocacy on every side can establish.

Keywords: climate attribution, climate sensitivity, Earth's energy imbalance, climate models, natural variability, extreme weather, sea-level rise, adaptation, risk communication

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1 The Challenge of Attribution

Whether, and to what extent, human activities influence the global climate system is among the most consequential scientific questions of the modern era. Public discussion often reduces it to a contest between "believers" and "deniers," but the underlying evidence does not fit that dichotomy. Several propositions that are routinely bundled together are analytically distinct: greenhouse gases alter radiative transfer; human activity has increased atmospheric greenhouse-gas concentrations; the planet is absorbing more energy than it emits; global temperature and ocean heat content have risen; human forcing caused most of those changes; the human contribution dominates on every relevant timescale and in every region; climate models accurately quantify future change; projected impacts are predominantly harmful; and a particular mitigation policy produces benefits greater than its economic and social costs. Evidence can be strong for an earlier proposition while remaining limited or assumption-dependent for a later one. The ladder is climbed one rung at a time, and confidence earned on one rung is not transferable to the next.

Among serious scientists the dividing line has rarely been the first rungs. Joseph Fourier identified the atmospheric trapping of infrared radiation in the 1820s, and Svante Arrhenius computed the warming expected from a doubling of carbon dioxide in 1896 (Arrhenius, 1896). Even the most prominent skeptic of the late twentieth century, the atmospheric physicist S. Fred Singer, wrote in 1988 that human activity was raising greenhouse-gas concentrations, that these gases "enhance the normal greenhouse effect of the atmosphere," and that the enhanced effect "should increase the Earth's average temperature—provided that all other factors remain the same" (reprinted in Singer et al., 2021). The crucial issue, he wrote, "then as now," was whether other factors—water vapor, clouds, ocean circulation—do remain the same. That is the question of feedbacks and magnitude. It was the scientifically serious locus of dispute in 1988 and it remains so.

The Intergovernmental Panel on Climate Change (IPCC) concludes that human influence has unequivocally warmed the atmosphere, ocean, and land. For 2010–2019 relative to 1850–1900, it assesses observed surface warming at 0.9–1.2°C and the likely human-induced contribution at 0.8–1.3°C, with a best estimate of 1.07°C (IPCC, 2021); the annually updated indicators that extend the IPCC methods put human-induced warming near 1.3°C by 2023 (Carlson et al., 2025). That conclusion is an important evidentiary anchor. A skeptical analysis should not evade it. At the same time, the confidence attached to global mean temperature attribution does not automatically transfer to regional rainfall, hurricane frequency, wildfire acreage, crop yields, economic damages, or the efficacy of a specific national policy.

Scientific skepticism is therefore not a third ideological position between acceptance and denial. It is a method of matching confidence to the quality, independence, and scope of the evidence—and it is a method only if it is applied symmetrically. In this manuscript, skepticism is directed principally toward four areas: the separation of forced change from natural variability; the use of tuned models as both generators and validators of attribution claims; the translation of global mean changes into regional or event-specific impacts; and the conversion of uncertain physical projections into claims of social emergency or policy inevitability. The same scrutiny is applied to the contrarian literature. Several recent and prominent examples are examined here at their strongest: a comment letter to a federal regulator by two eminent physicists arguing that carbon dioxide "has had virtually no warming power since 1750" (Lindzen & Happer, 2026); a sixty-page audit by a Nobel laureate in physics alleging that the planetary energy imbalance has been fabricated (Clauser, 2026); a paper that lists a large language model as its lead author and concludes that the anthropogenic hypothesis "collapses under scrutiny" (Grok 3 beta et al., 2025); and the posthumous third edition of Singer's *Hot Talk, Cold Science* (Singer et al., 2021). An assessment that engages only the weak forms of dissent has not earned its confidence. The greenhouse mechanism, the anthropogenic origin of the modern carbon-dioxide rise, the planetary energy imbalance, and a material human contribution to warming are accepted here. The contested questions concern magnitude, feedbacks, timing, impact, and response.

This distinction also clarifies the role of risk. Uncertainty does not imply safety, and low-probability high-consequence outcomes merit attention. Yet uncertainty cuts both ways: it applies to catastrophic tails, central estimates, policy effectiveness, technological substitution, behavioral adaptation, and the harms of costly or unreliable interventions. Rational climate governance must compare risks rather than treating only climate risk as morally relevant. It should be possible to recognize anthropogenic warming while questioning exaggerated timelines, implausible scenarios, false precision, or policies that transfer disproportionate costs to low-income households and developing societies (Koonin, 2021; Lomborg, 2020; Shellenberger, 2020).

2 Physical Foundations: Energy Balance, Greenhouse Forcing, and the Carbon Cycle

The physical basis of greenhouse warming is well established. Earth absorbs roughly 70% of incoming solar radiation because planetary albedo is approximately 0.30. A simple radiative-equilibrium calculation without an atmosphere yields an effective temperature near −18°C,

about 33°C below the observed global mean near 15°C. The difference is produced by an atmosphere that absorbs and re-emits outgoing infrared radiation. Nitrogen and oxygen are largely transparent at the relevant wavelengths, whereas water vapor, carbon dioxide, methane, nitrous oxide, and ozone absorb in specific spectral bands (Koonin, 2021).

Carbon dioxide is not the dominant greenhouse gas by total absorption, but it has disproportionate leverage because it absorbs in spectral regions that are not already completely opaque from water vapor, and because, unlike water vapor, it does not condense out of the atmosphere and so sets the baseline around which water vapor adjusts. Its radiative effect is approximately logarithmic in concentration: the forcing is well approximated by $\Delta F \approx 5.35 \ln(C/C_0)$ W m^{-2} (Myhre et al., 1998), so that each doubling produces a similar perturbation, conventionally estimated near 3.7–4 W m^{-2}. The effect of each additional molecule declines as concentration rises, but the effect of each additional doubling does not. The increase from about 278 ppm in 1750 to roughly 425 ppm today is 0.6 of a doubling and corresponds, by this approximation, to about 2.3 W m^{-2}, the largest single term in the anthropogenic forcing budget (IPCC, 2021). In the absence of feedbacks, restoring radiative balance after a doubling would require roughly 1–1.2°C of surface warming. The larger equilibrium response assessed by climate models arises from feedbacks involving water vapor, lapse rate, clouds, snow and ice, vegetation, and ocean heat uptake (Lindzen, 1997; Stephens, 2005).

The smallness of anthropogenic forcing relative to the planet's total energy throughput is often misunderstood. Absorbed solar energy is about 239 W m^{-2}, while net human forcing is of order 2–3 W m^{-2}, with greenhouse warming partly offset by aerosol and land-use cooling. A perturbation of about 1% can still be climatically significant because the climate system must balance incoming and outgoing energy to high precision. But the same comparison illustrates the measurement challenge: a confident estimate of a small net perturbation requires accurate characterization of much larger natural fluxes and of compensating forcings, especially aerosols and clouds (Koonin, 2021).

The anthropogenic origin of the modern carbon-dioxide increase is supported by several independent lines of evidence. Atmospheric concentration was comparatively stable through much of the Holocene before rising rapidly with industrialization; cumulative fossil-fuel emissions are more than sufficient to account for the increase; the Northern Hemisphere leads the Southern Hemisphere in concentration changes; the atmospheric carbon-isotope ratio has shifted toward the lighter signature of fossil carbon; atmospheric oxygen has declined in a manner consistent with combustion; and the ocean, which would have to be the

source if the increase were natural, is instead measurably gaining carbon, with a corresponding decline in its pH (IPCC, 2021; Koonin, 2021). These observations make a primarily natural origin for the postindustrial rise implausible. The objections that have nevertheless been raised against this conclusion are addressed in the next section.

The carbon cycle nevertheless moderates the atmospheric response. Fossil-fuel emissions are small relative to the gross annual exchange among atmosphere, ocean, and land, but they are an uncompensated addition to that cycling. Roughly half of annual anthropogenic emissions has historically remained in the atmosphere, while the rest has been absorbed by terrestrial and oceanic sinks. Ballantyne et al. (2012) estimated that combined land and ocean uptake rose from about 2.4 to 5.0 PgC per year between 1959 and 2010, sequestering approximately 55% of cumulative emissions over that interval. This does not make emissions harmless: the airborne fraction still raises concentration, and a substantial share of added carbon persists for centuries. It does show that the climate-carbon system contains important negative feedbacks whose future strength is a major projection uncertainty.

A useful distinction follows. In glacial-interglacial transitions, carbon dioxide operated initially as a feedback to orbitally initiated warming and then as an amplifier. In the industrial era, fossil emissions raise carbon dioxide directly, making it an external forcing on the contemporary system. The paleoclimatic lag between temperature and carbon dioxide therefore does not refute anthropogenic forcing. It does, however, caution against presenting the climate-carbon relationship as simple, instantaneous, or unidirectional (Caillon et al., 2003; Petit et al., 1999).

3 Objections to the Foundations: Saturation, the Carbon Budget, and Causal Order

Three objections to the propositions above recur in the contrarian literature, and each is advanced by credentialed scientists in recent publications. Each deserves a direct answer rather than dismissal, because each, if correct, would remove the first two rungs of the ladder. None is correct, and the reasons are instructive about how confidence should be assigned.

3.1 “Carbon dioxide is already saturated”

In a 2026 comment to the Securities and Exchange Commission, Richard Lindzen and William Happer argue that because the warming effect of each added molecule of carbon

dioxide declines as concentration rises, carbon dioxide had “lost virtually all its warming power” by the time concentration reached 280 ppm, so that the increase to 420 ppm produced only about 0.3°C and a further rise to 600 ppm would add a similar amount (Lindzen & Happer, 2026). Singer made the same claim more briefly: carbon dioxide “is already saturated—hence additional CO_2 is not very effective” (Singer et al., 2021).

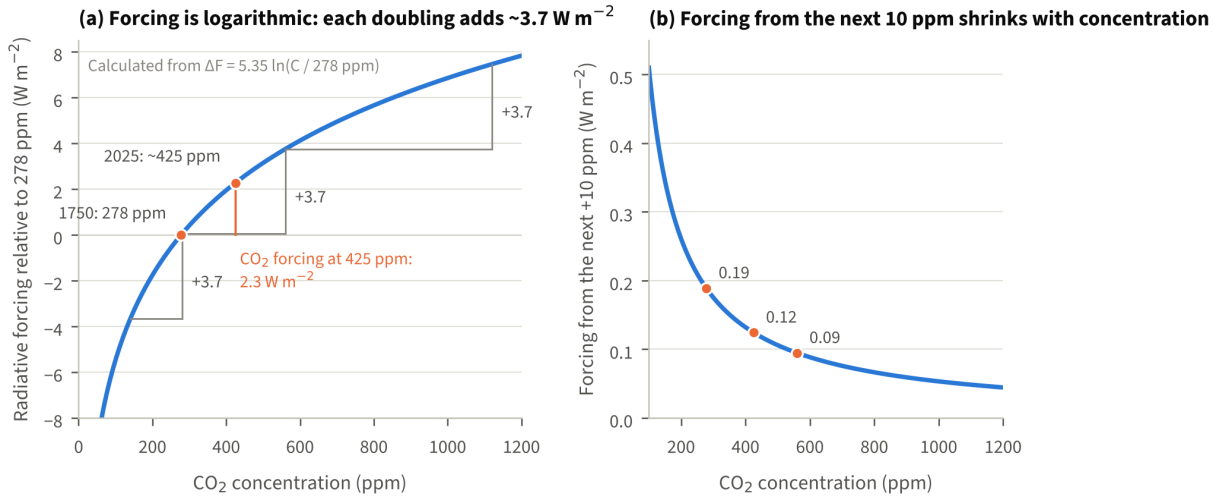


Figure 1. Why a logarithmic forcing is not a saturated one. Both panels are calculated from the standard approximation $\Delta F = 5.35 \ln(C/C_0)$ with $C_0 = 278$ ppm (Myhre et al., 1998); they illustrate the arithmetic of the forcing, not a measurement and not a climate sensitivity. (a) Each doubling—140 to 280, 280 to 560, 560 to 1,120 ppm—adds the same 3.7 W m^{-2}; the rise to about 425 ppm has supplied 2.3 W m^{-2} of the current doubling. (b) The forcing contributed by the next 10 ppm falls steadily with concentration. This is the fact on which the saturation argument rests; it is already built into panel (a), and it leaves the forcing per doubling unchanged.

The premise is correct and the conclusion does not follow from it. A logarithmic dependence is not saturation; it is the statement that each doubling contributes the same forcing, so that the step from 280 to 560 ppm matters exactly as much as the step from 140 to 280 ppm did (Figure 1). The physical reasons are two. First, although the center of the 15-micrometer absorption band is opaque near the surface, absorption in the wings of the band continues to grow with concentration. Second, and more fundamentally, saturation at the surface is not the relevant quantity. The planet sheds energy to space from the altitude at which the atmosphere becomes transparent at each wavelength; adding carbon dioxide raises that emission altitude into colder air, which radiates less, and the deficit persists until the entire column has warmed enough to restore the outgoing flux. This is standard radiative transfer, and it is what the critics’ own calculations show. In a high-resolution line-by-line computation, van Wijngaarden and Happer (2020) found that doubling carbon dioxide from 400 to 800 ppm reduces top-of-atmosphere flux by 3 W m^{-2} in a clear midlatitude atmosphere,

and that restoring balance requires 1.4 K of surface warming at fixed absolute humidity and 2.2–2.3 K at fixed relative humidity. Those values are not “virtually no warming power.” For a cloud-free column, they bracket the values that the energy-budget studies discussed later find most probable, and they reach the lower bound of the IPCC’s likely range. The much smaller temperature increments in the 2026 letter are obtained by an accounting the letter does not derive, and they are inconsistent with the published computation by one of its authors. What legitimately survives is a dispute about clouds—whether cloud changes offset part of the clear-sky response—which is precisely the feedback uncertainty treated later in this synthesis. The saturation argument, in other words, is a magnitude argument wearing the costume of an existence argument.

The letter supplements its physics with a chart spanning 600 million years, drawn from a 2007 web essay, purporting to show that temperature and carbon dioxide were inversely related through much of geological time. The current state of the art points the other way. A 2024 reconstruction assimilating proxy data with model simulations across the past 485 million years finds global mean surface temperature ranging from 11 to 36°C, identifies carbon dioxide as “the dominant control” on that variation, and infers an apparent Earth-system sensitivity near 8°C per doubling once slow feedbacks are included (Judd et al., 2024). Earlier claims of decoupling arose partly from ignoring the faint young Sun—solar luminosity was several percent lower in the early Phanerozoic, so higher carbon dioxide was required to sustain a given temperature—and from the large uncertainties in early proxies (Royer et al., 2004). Earth-system sensitivity over millions of years is not the same quantity as the equilibrium sensitivity relevant to this century, and the comparison should not be pushed too far. But the deep-time record is not a refutation of the radiative effect of carbon dioxide; on current reconstructions it is among the strongest evidence for it.

3.2 “Humans emit only four percent of the carbon”

A second objection holds that human emissions, at roughly 10 PgC per year, are only about 4% of the 200–230 PgC that cycles annually between the atmosphere and the ocean and biosphere; that radiocarbon from nuclear testing left the atmosphere with a time constant of a few years, implying a residence time of 3–5 years rather than the centuries assumed by the IPCC; that the carbon-isotope record is consistent with natural sources; and that the 7% drop in emissions during the 2020 pandemic lockdowns left no visible mark on the Mauna Loa record. From these premises the conclusion is drawn that human carbon dioxide is “negligible” and that the atmospheric increase is natural (Grok 3 beta et al., 2025; Harde,

2017). Singer offered the same figure in a smaller form, describing the human contribution as “just 0.53 percent of the carbon entering the atmosphere each year” (Singer et al., 2021).

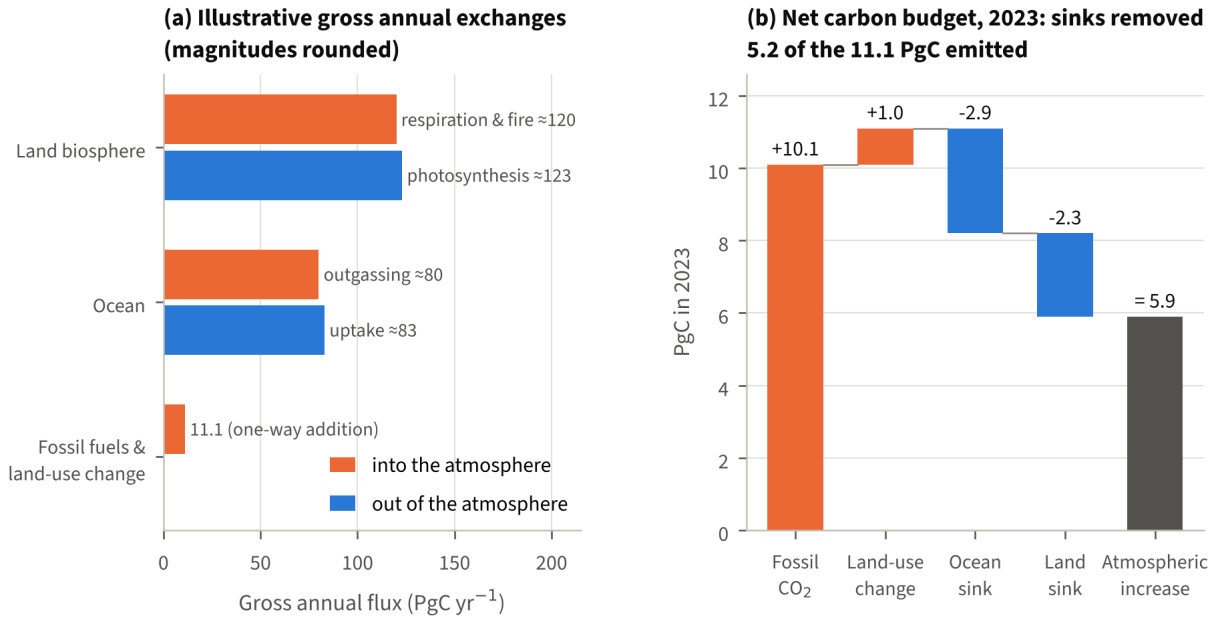


Figure 2. The carbon budget: gross exchange versus net addition. (a) Illustrative magnitudes of the two-way natural exchange: the atmosphere exchanges roughly 120 PgC per year with the land biosphere and roughly 80 PgC per year with the ocean in each direction, fluxes that are nearly balanced and are shown here as rounded representative values without uncertainties (IPCC, 2021). Human emissions of about 11 PgC per year are small by comparison but flow one way. Because the gross values are rounded, panel (a) implies slightly more net removal than the precise budget in (b). (b) The 2023 budget of the Global Carbon Project (Friedlingstein et al., 2025): fossil fuels and land-use change added 11.1 PgC; the ocean and land removed 5.2 PgC on net; the atmosphere retained the remaining 5.9 PgC, matching the measured global atmospheric increase of about 2.8 ppm. A system that removes carbon on net cannot be the source of the increase.

The argument fails on arithmetic that does not depend on any model. The gross natural fluxes are large but nearly balanced in both directions, like a bank account with large deposits and large withdrawals; a modest but persistent net deposit grows such an account without limit. The decisive test is the mass balance, and it can be run with the objectors’ own numbers. Human activity adds about 10 PgC per year. Atmospheric carbon dioxide rises by about 2.4 ppm per year, which is about 5 PgC. The rest of the system—ocean and land together—must therefore be removing roughly 5 PgC per year on net. A reservoir that is a net sink cannot simultaneously be the net source of the increase (Figure 2). The ocean, which the natural-origin hypothesis requires to be outgassing, is instead directly observed to be accumulating dissolved inorganic carbon and acidifying as a result (IPCC, 2021). The isotopic evidence points the same way: atmospheric carbon has become lighter in ^{13}C in the manner

expected from fossil input, and atmospheric oxygen has declined in proportion to combustion. Three independent tracers agree with the bookkeeping.

The residence-time argument rests on a conflation that has been explicitly diagnosed in the literature. The 3–5 year figure is the average time an individual molecule spends in the atmosphere before being exchanged for another; it measures the vigor of the gross exchange, not the fate of an excess. The time required for an added quantity of carbon to be removed is governed by the net uptake capacity of the ocean and biosphere, which is limited by carbonate chemistry and ocean mixing and is measured in centuries to millennia. The decay of bomb radiocarbon tracks the first quantity, not the second, because an atom of ^{14}C that enters the ocean is replaced by an atom of ^{12}C from the ocean with no change in total carbon. Köhler et al. (2018), commenting on Harde (2017), concluded that "to conflate residence time and adjustment time is a fundamental misunderstanding of the carbon cycle," and noted that a 4% anthropogenic share would imply an airborne fraction of about 7% rather than the observed 45%, leaving several hundred petagrams of emitted carbon with no identifiable destination.

The pandemic observation is not a refutation but a confirmed prediction. Global emissions fell by about 17% at the April 2020 peak and by roughly 4–7% for the year (Le Quéré et al., 2020). Seven percent of 10 PgC is 0.7 PgC, equivalent to about 0.3 ppm of atmospheric concentration before the sinks respond and perhaps 0.2 ppm after. The year-to-year variability of the growth rate, driven largely by the response of tropical ecosystems to El Niño, is of order ±1 ppm (Figure 3). Carbon-cycle arithmetic therefore implied, and researchers stated at the time, that the lockdown signal would be undetectable in the concentration record and that the climate effect would be negligible, about 0.01°C by 2030 (Forster et al., 2020). A test that cannot discriminate between hypotheses supports neither, and a forecast that comes true is not evidence against the theory that produced it. The anthropogenic origin of the modern rise is as secure as any claim in climate science. It is bookkeeping constrained by three tracers, and no amount of modeling uncertainty elsewhere alters it.

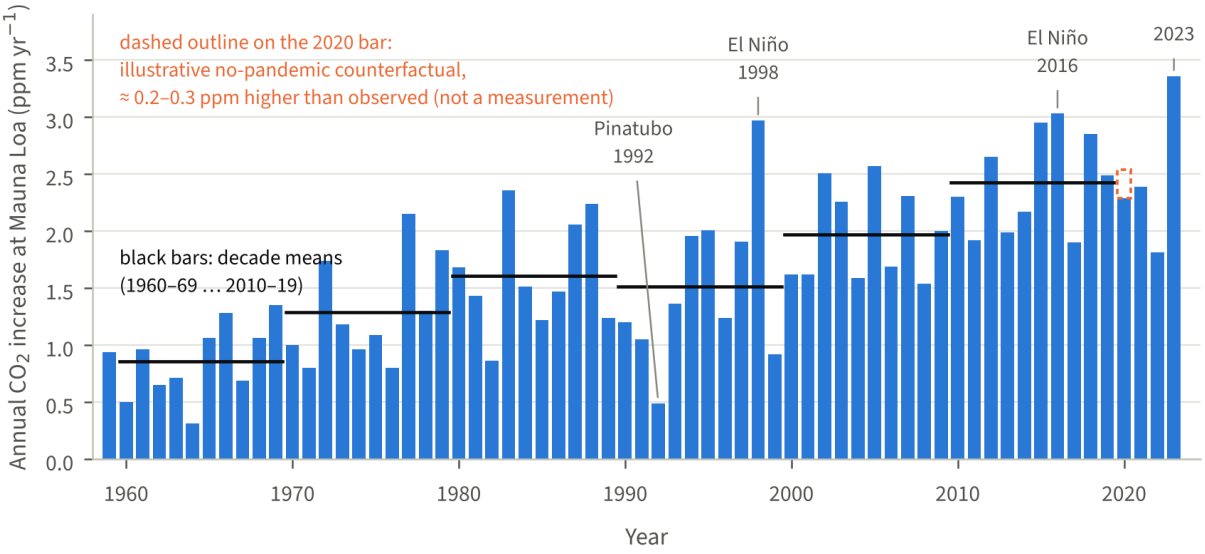


Figure 3. Year-to-year variability in the growth of atmospheric carbon dioxide at Mauna Loa, 1959–2023 (NOAA Global Monitoring Laboratory, 2024; data downloaded November 7, 2026). Annual growth swings by roughly ±1 ppm around the decadal means (black bars, 1960–1969 through 2010–2019), faster in El Niño years and slower after volcanic cooling. The dashed outline on the 2020 bar is an illustrative counterfactual, not an observation: it marks where the bar would stand had the 0.2–0.3 ppm reduction expected from the pandemic emission cut not occurred (Le Quéré et al., 2020). An effect of that size is small relative to ordinary annual variability, which is what the arithmetic predicted; its absence from the record is not evidence against it.

3.3 "Temperature leads carbon dioxide"

A third objection observes that changes in temperature precede changes in carbon dioxide—by 6–12 months in modern monthly data and by several centuries in the glacial record—and infers that carbon dioxide is an effect of warming rather than a cause (Humlum et al., 2013; Koutsoyiannis et al., 2023). Two timescales are involved, and the inference fails on both.

At interannual scales the observation is correct and has been understood for decades. In warm El Niño years, tropical drought and fire reduce land uptake and the growth rate of carbon dioxide rises; in cool years it falls. This modulates the growth rate by about a part per million around a trend of roughly 2.5 ppm per year. The lagged correlations that purport to show temperature "driving" carbon dioxide are computed on differenced or detrended series, a procedure that removes the trend by construction and therefore cannot speak to its cause (Richardson, 2013). The "hens and eggs" bidirectionality identified by Koutsoyiannis and colleagues is real at the scale of fluctuations and irrelevant to the trend, whose origin is fixed by the mass balance above. At glacial-interglacial scales, carbon dioxide did lag Antarctic temperature by centuries as a feedback on orbital forcing (Caillon et al., 2003). But a reconstruction of global temperature from 80 proxy records distributed around the world

shows that global temperature generally lagged carbon dioxide during the last deglaciation: Antarctica warmed first, carbon dioxide rose, and the rest of the planet followed (Shakun et al., 2012). The lag demonstrates that carbon dioxide participates in a feedback loop. It does not demonstrate that carbon dioxide cannot force, any more than the fact that fires are usually started by heat shows that fires cannot produce it. In the industrial era, emissions make carbon dioxide the external input, and the loop runs the other way.

None of these three objections touches the physics of infrared absorption, the arithmetic of the carbon budget, or the direction of the industrial-era causal chain. They are argued, in effect, as if the carbon budget had never been measured. Where they contain a legitimate residue—the magnitude of cloud feedback, the future strength of carbon-cycle feedbacks, the role of ocean variability in year-to-year fluctuations—that residue belongs in the ledger of uncertainties, not in the foundations.

4 Paleoclimate and the Natural-Variability Baseline

Any attribution claim requires a baseline for the magnitude, frequency, and spatial structure of natural climate variability. Paleoclimatic records demonstrate that the climate system changes substantially without industrial forcing. The Vostok ice core spans approximately 420,000 years and records four major glacial-interglacial cycles, with large Antarctic temperature changes and carbon-dioxide concentrations varying roughly between 180 and 280 ppm. Orbital forcing initiated the cycles, while greenhouse gases, ice-albedo effects, and ocean circulation amplified them (Petit et al., 1999). Caillon et al. (2003) estimated a lag of approximately 800 years between Antarctic warming and the carbon-dioxide rise at Termination III, consistent with initial ocean and circulation responses followed by carbon-cycle amplification. The correct inference is neither that carbon dioxide is climatically inert nor that it independently initiated those transitions. Causation operated through a coupled system in which the role of a variable changed over time, and correlation between temperature and carbon dioxide must be interpreted within a physical chronology.

Centennial and millennial records also show large regional departures from long-term means. Historical and proxy evidence documents a Medieval Climate Anomaly, a Little Ice Age, and other regional warm and cool intervals. Lamb (1965) described pronounced warmth and altered rainfall in parts of Europe during the early medieval period, while Ljungqvist (2010) reconstructed substantial extra-tropical Northern Hemisphere variability over the last two millennia. Soon and Baliunas (2003) and Soon et al. (2003) argued for broad expression of

medieval warmth, although the degree of global synchrony and whether medieval global mean temperature matched recent decades remain disputed.

That dispute is partly methodological. Proxy reconstructions combine heterogeneous indicators, each with dating uncertainty, local environmental influences, limited seasonal sensitivity, and nonclimatic trends. McIntyre and McKitrick (2005) showed that the principal-component procedure used in an influential reconstruction could preferentially extract hockey-stick-shaped series when tree-ring data were centered over a late calibration interval rather than the full period, and their Monte Carlo tests argued that the reported validation statistic did not exceed an appropriately constructed significance threshold. A National Research Council review convened in response concluded that late-twentieth-century warmth was very likely unprecedented in the preceding four centuries, with confidence declining for earlier periods—a more modest statement than either the original graphic or its harshest critics implied (National Research Council, 2006). The critique does not establish that all multiproxy reconstructions are invalid, nor does it overturn the instrumental warming record. It demonstrates that apparently technical preprocessing and validation choices can materially affect inferred historical shape and confidence.

The most defensible paleoclimatic conclusion is consequently more modest than either side of the public debate often suggests. Recent global warming occurs on top of a climate system with substantial natural variability, and regional climates have repeatedly experienced changes comparable to or larger than the global mean warming of the instrumental era. At the same time, evidence for past regional warmth is not by itself evidence that current global warming is natural: a past change requires a past cause, and the existence of natural causes in one century does not supply one for another. Paleoclimate strengthens the case for careful attribution, wider uncertainty bands, and explicit sensitivity analysis; it does not supply a complete alternative explanation for the modern trend.

5 The Instrumental Record: Robust Warming, Difficult Measurement

Multiple surface datasets show that global mean temperature has increased since the late nineteenth century, and the rise is corroborated by ocean heat content, glacier retreat, sea-level rise, and changes in many cryospheric indicators. The IPCC assesses 2010–2019 warming relative to 1850–1900 at 0.9–1.2°C and concludes that human influence is extremely

likely to be the main driver of ocean heat-content increase since the 1970s (IPCC, 2021). A skeptical account should begin from this convergence rather than from isolated records.

Nevertheless, “global mean surface temperature” is not directly measured by a single instrument. It is constructed from changing networks of land stations, marine observations, satellite-era data, homogenization procedures, spatial interpolation, and estimates for data-sparse regions. Station relocation, instrument changes, time-of-observation shifts, urbanization, land-use change, ship-to-buoy transitions, and uneven geographic coverage can create nonclimatic discontinuities. Homogenization is necessary, but it introduces analytical choices that deserve auditing. The relevant question is not whether adjustments occur, but whether their net effects and uncertainties are adequately represented.

Fall et al. (2011) found widespread noncompliance with siting standards in the U.S. Historical Climatology Network and showed that station exposure affected maximum and minimum temperature trends differently. Poorly sited stations tended to exaggerate minimum-temperature warming while muting maximum-temperature trends. This result does not demonstrate that the entire global trend is an artifact, because network-wide adjustments and comparisons with independent datasets can reduce local biases. It does show that trend estimates are sensitive to the physical environment of measurement and that claims of hundredths-of-a-degree precision should be interpreted cautiously.

The distinction between daily maximum and minimum temperature is especially informative. Christy et al. (2009) reported little trend in East African daytime maximum temperatures since the mid-twentieth century but stronger warming in nighttime minima. Daytime maxima occur in a deeply mixed boundary layer and are more tightly coupled to the lower atmosphere. Nighttime minima occur in a shallow, often decoupled layer that is highly sensitive to surface roughness, irrigation, land cover, aerosols, and urbanization. A strong minimum-temperature trend can therefore reflect a mixture of greenhouse forcing and local boundary-layer change rather than a simple increase in the heat content of the deep atmosphere.

5.1 Do the adjustments manufacture the trend?

The strongest version of the contrarian claim is that homogenization does not merely refine the record but creates it: that raw rural stations show little change, that the late-twentieth-century warming “is almost entirely fake, an instrumental artifact found only in the HadCRUT database” (Singer et al., 2021), and that adjusted datasets have been “tuned to

match CMIP model outputs" (Grok 3 beta et al., 2025). The claim can be tested, and it fails on four independent grounds.

First, the adjustments to the U.S. land record—which do increase the century-scale U.S. trend, chiefly through corrections for changes in time of observation and instrumentation—were checked against the U.S. Climate Reference Network, a set of 114 well-sited stations built specifically to need no adjustment. Over the 2004–2015 overlap, adjusted and raw USHCN mean and minimum temperatures and the reference network are "largely indistinguishable," the adjustments bring divergent station pairs closer to their reference neighbors, and for maximum temperature the homogenized network warms *less* than the pristine one, not more (Hausfather et al., 2016). A short record from 1.5% of Earth's surface has little power to detect a global trend, as the contrarian papers that cite its flatness do not acknowledge; but it has considerable power to test the adjustments, and they pass. Second, the largest single adjustment in the global record—the correction for the historical shift from uninsulated buckets to engine-intake and buoy measurements of sea-surface temperature—raises early-twentieth-century ocean temperatures and therefore reduces, rather than inflates, the century-scale global trend (Kennedy et al., 2011). The more recent buoy-era corrections, which do increase the post-2000 trend, were confirmed against instrumentally homogeneous records from buoys, Argo floats, and satellite radiometers that require no such corrections (Hausfather et al., 2017). Third, an independent reconstruction built by a group that began from a skeptical premise, using its own statistical framework and no reliance on the NOAA or Climatic Research Unit homogenization codes, reproduces the same warming (Rohde & Hausfather, 2020). Fourth, the satellite record on which Singer rested his case no longer says what it said when his book went to press. The lower-troposphere trend in the University of Alabama in Huntsville product is +0.16°C per decade since 1979, with 2024 the warmest and 2025 the second-warmest year in the satellite era (Spencer, 2026; Spencer et al., 2017), and the Remote Sensing Systems product gives roughly 0.2°C per decade, the difference arising from how each group corrects for orbital drift (Mears & Wentz, 2017). The "pause" that Singer predicted would continue to 2100 ended within a few years of the prediction. Surface warming is corroborated by two satellite groups, radiosondes, reanalyses, ocean heat content, sea level, glacier mass loss, and sea-ice decline, a convergence that would require each independent system to fail in the same direction by a similar amount.

The dispute is more often fought at the level of individual stations, and the Australian case that critics cite most—Rutherglen, an agricultural research station in Victoria—is instructive on both sides. Raw minimum temperatures recorded there since 1912 show a slight cooling;

after two step adjustments applied at 1966 and 1974, the official homogenized series warms. Marohasy (2017) argues that the station catalogue records no site move, that a control chart of the station's own minima shows no breakpoint, and that at least one neighboring station used to detect the breaks, Beechworth, has a discontinuity of its own—coinciding with a documented site move—that was never adjusted. These are legitimate questions, and the Bureau of Meteorology's answer to the first is partial but not empty: it has assembled a dozen documents from 1939 to 1978 indicating that the instrument enclosure moved at least once between 1958 and 1975—from sloping ground near a woolshed about 400 meters from the office to a flat site 700 meters from it—and the statistically detected breakpoints coincide with the probable move dates (Bureau of Meteorology, n.d.). An independent Technical Advisory Forum that reviewed the national dataset in 2015 found the adjustment methods consistent with good practice, noted that the raw and adjusted national series both show a clear warming trend and converge after 1960 as the network densifies, and recommended that uncertainties be quantified and the code and data published (Technical Advisory Forum, 2015). Two general points matter more than the particular station. A single-station comparison cannot identify a network-wide bias, because homogenization adjusts hundreds of stations in both directions and the question is whether the sum tilts the aggregate; that is the test the U.S. reference network and the independent reconstructions supply. And the critics' own peer-reviewed work shows why some adjustment is unavoidable. In a study that used rainfall-forecast skill to compare eight versions of the Cape Otway lighthouse record, Marohasy and Abbot (2015) concluded that the exceptional warmth in the raw maximum temperatures of the 1880s and 1890s was spurious—an artifact of the thermometer shed used before a Stevenson screen was installed in 1907–1908—and that a neighboring lighthouse series free of that problem warmed by about 0.8°C per century from 1887, "consistent with the global land surface temperature increase since 1880." That is a conventional homogenization finding reached by an unconventional route, and it is the reason national reference networks such as Australia's begin in 1910, after standard screens were in general use. The same study found that the official adjustments at Cape Otway did not measurably improve forecast skill, which is a fair observation about one station and no evidence about a continent.

Satellite microwave and radiosonde records nevertheless provide a partially independent perspective that should not be smoothed over, because they too require complex corrections for orbital drift, instrument replacement, diurnal sampling, and changing radiosonde practices, and because they disagree with models in a specific place. Christy et al. (2007, 2010) and Christy and McNider (2017) reported lower tropospheric warming and transient-

response estimates below many model simulations. Douglass et al. (2008) argued that modeled and observed trends in the tropical troposphere were inconsistent; Santer et al. (2008) replied that, once observational uncertainty and internal variability were properly treated, the inconsistency was not statistically established. The IPCC, while reaching a stronger attribution conclusion, notes that many CMIP6 models overestimated tropical mid- and upper-tropospheric warming during 1979–2014 by at least 0.1°C per decade (IPCC, 2021). This is a genuine model-observation discrepancy, even though updated satellite datasets show warming rather than the near-zero trends emphasized in earlier analyses, and even though the gap has narrowed rather than widened as the datasets have been revised.

Tropospheric amplification in the tropics is often described as a greenhouse "fingerprint," but that formulation is imprecise. Amplification primarily follows from moist-adiabatic adjustment and should occur under sustained tropical surface warming from many causes. Its muted observational expression may indicate model errors, observational errors, differences in the realized pattern of surface warming, or some combination. It does not by itself disprove greenhouse forcing. It does reduce confidence in claims that models accurately reproduce the vertical and regional structure of change.

5.2 The planetary energy budget

The most direct test of whether the planet is warming in a forced sense is not any temperature series but the energy budget itself. If more energy enters the climate system than leaves it, the surplus must appear somewhere, and about 89% of it appears in the ocean, with the remainder warming land and air and melting ice (von Schuckmann et al., 2023). The inventory of that heat, compiled from ocean profiles, borehole temperatures, ice-mass records, and atmospheric reanalyses, implies an average imbalance of about 0.48 W m^{-2} over 1971–2020 rising to about 0.76 W m^{-2} over 2006–2020 (von Schuckmann et al., 2023); the 2026 update of the inventory, built on a different ocean ensemble, gives larger values of about 0.6 and 0.9 W m^{-2} for the same intervals (Figure 4), so the estimates differ in magnitude but not in sign or direction. Independently, the satellite record of top-of-atmosphere radiation and the in situ record of ocean heat uptake each show the imbalance increasing at 0.50 ± 0.47 W m^{-2} per decade between mid-2005 and mid-2019, a doubling over the period, with the two trends statistically indistinguishable (Loeb et al., 2021). An energy imbalance of this size cannot be produced by station siting, urbanization, or homogenization, because the Argo float network that measures it has nothing to do with any of them. Nor can it be sustained for decades by internal variability, which redistributes heat but does not create it. A sustained positive imbalance requires a sustained forcing, and its growth during a period of declining

solar activity is the single observation that contrarian accounts most need to explain and most often omit (Figure 4).

Clauser (2026) is the exception; his audit confronts the energy imbalance directly and concludes that it has not been measured at all. His argument is that the satellite instruments cannot determine the absolute imbalance to the ±0.1 W m^{-2} that the question requires; that the raw CERES data in fact showed an implausible +6.5 W m^{-2}; that the published values were adjusted to match ocean heat content, which he terms "fudging"; that the ocean data are themselves flawed; and that the satellites were blind to sun glint from the ocean because of a scanning-geometry "design flaw." The first premise is correct and has never been hidden. The CERES team reported in 2009 that absolute calibration limits the satellite-derived net flux to about ±4 W m^{-2}, that the unadjusted five-year mean was 6.5 W m^{-2}, and that the product's absolute level was therefore anchored to the ocean heat-uptake estimate of 0.85 W m^{-2} (Loeb et al., 2009); the current product applies a one-time adjustment so that the global mean matches the in situ value of 0.71 W m^{-2} for 2005–2015 (Loeb et al., 2018). That is not a concealed manipulation but the stated design of the measurement system: the in situ ocean network supplies the absolute level, and the satellite supplies the variability and trend, which are stable to far better than the absolute calibration. The claim of glint blindness is contradicted by the instrument's documented operation. CERES radiometers were operated for extended periods in a rotating-azimuth-plane mode precisely to sample reflected radiance at all viewing azimuths, and the empirical angular-distribution models that convert radiance to flux are built from those measurements (Su et al., 2015). What the audit gets right is that pre-Argo ocean heat-content estimates, which depend on bias corrections to expendable bathythermograph data, differed among research groups by up to a factor of two, so that the imbalance before 2005 is considerably less certain than the imbalance since. What it gets wrong is the inference. The restored "unfudged" budget it proposes implies an imbalance near −2 W m^{-2}, which would require the ocean to be losing heat at a rate that the Argo network, with roughly four thousand autonomous floats profiling the upper two kilometers, directly contradicts. And the step from "no proven energy imbalance" to "no proven warming" fails regardless, because warming is measured by surface networks, satellites, radiosondes, boreholes, sea level, and ice mass, not by the energy budget alone. The honest summary is that the absolute imbalance before the Argo era is uncertain to within a factor approaching two; that since 2005 it has been measured by two independent systems that agree on magnitude and trend; and that it has grown as the Sun has quieted.

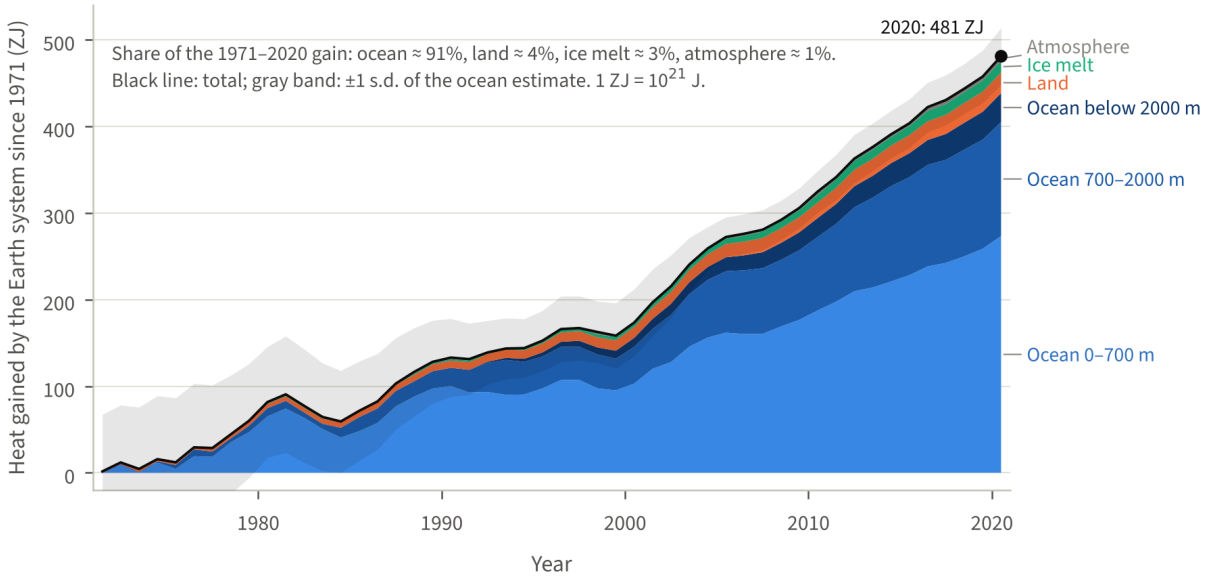


Figure 4. Where the energy has gone: heat accumulated by the Earth system since 1971, by reservoir, from the 2026 update of the Indicators of Global Climate Change inventory (Smith et al., 2026; method after von Schuckmann et al., 2023). One zettajoule (ZJ) is 10^{21} J. The plotted series ends in 2020 at about 481 ZJ, of which the ocean holds 91 percent, land 4 percent, melting ice 3 percent, and the atmosphere 1 percent; averaged over Earth's surface this is an imbalance of about 0.6 W m^{-2} over 1971–2020 and about 0.9 W m^{-2} over 2006–2020. The 2023 synthesis cited in the text reported a smaller total of 381 ± 61 ZJ (0.48 and 0.76 W m^{-2}) for the same intervals (von Schuckmann et al., 2023); the update's ocean ensemble is larger, and the two should not be read as one estimate. The gray band is ±1 standard deviation of the ocean estimate, dominated by sparse sampling before the Argo era. The ocean-only series continues to 2024 (about 509 ZJ; not plotted).

The appropriate synthesis is that warming is robust, while its exact magnitude, vertical structure, and regional distribution remain less certain than a single global index suggests. Measurement biases do not eliminate the observed trend, but neither should independent lines of evidence be treated as perfectly consistent when they are not. The scientific task is to explain discrepancies rather than to select whichever dataset best supports a preferred narrative.

6 Detection and Attribution: Evidence and Inferential Dependence

Detection asks whether an observed change exceeds what would be expected from internal variability. Attribution asks how much of that change is caused by specific forcings. The distinction is essential. A trend can be detected without its cause being uniquely identified,

and a physical mechanism can be real without explaining the full magnitude of an observed change.

The principal IPCC framework is optimal fingerprinting. Observed spatial and temporal changes are regressed on model-simulated response patterns for greenhouse gases, aerosols, natural forcings, and other influences. Control simulations estimate the covariance of internal variability; scaling factors above zero indicate detection, and intervals that include one indicate consistency between the modeled and observed response magnitude. The IPCC also considers likelihood-based, Bayesian, bootstrap, and counterfactual methods and looks for agreement across physically distinct variables (IPCC, 2021).

Using this framework, the IPCC estimates that well-mixed greenhouse gases produced 1.0–2.0°C of warming through 2010–2019, partly offset by 0.0–0.8°C of cooling from other anthropogenic forcings, primarily aerosols. It assigns only −0.1 to +0.1°C to natural external forcing and −0.2 to +0.2°C to internal variability over the period, yielding the best-estimate human contribution of 1.07°C (IPCC, 2021). The breadth and physical coherence of evidence across surface temperature, ocean heat, atmospheric moisture, cryosphere, and sea level make a substantial human contribution difficult to dismiss. The annually updated version of this decomposition (Figure 5) shows the structure of the estimate: greenhouse gases alone would have produced about 1.5°C of warming by 2025, aerosols and other human forcings have offset about 0.2°C, and natural forcing has generally contributed within about a tenth of a degree.

Two further considerations reinforce the sign of the conclusion even for a reader who distrusts fingerprinting. The first is the energy budget just described: the heat is accumulating, the accumulation is accelerating, and the measured natural forcings have been flat or declining while it does so. The second comes from the skeptical literature itself. The observationally constrained sensitivity estimates discussed below take the observed warming and ocean heat uptake as the system's response to the observed anthropogenic forcing; they are low-sensitivity estimates, not no-forcing estimates, and they imply that most of the modern warming is human-caused. A reader therefore cannot coherently hold both that climate sensitivity is low on energy-budget grounds and that the warming is natural. The two skeptical literatures are not cumulative; the stronger of them presupposes what the weaker denies.

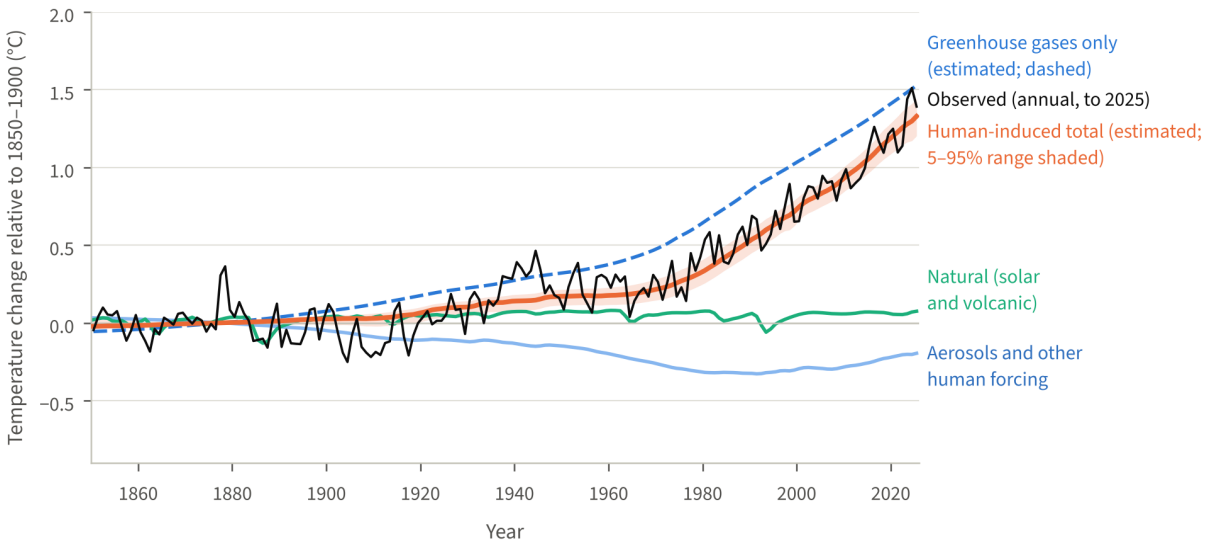


Figure 5. Observed warming and estimated contributions, 1850–2025 (Indicators of Global Climate Change data; Forster et al., 2025; Smith et al., 2026). The black line is the multi-dataset average of observed global mean surface temperature. The colored lines are estimated contributions from one attribution method, the global warming index of Walsh and colleagues; they are not separately observed records, and they are not the full multi-method synthesis in the Indicators. The 5–95 percent range is shaded for the human-induced total, which reaches 1.33°C (1.20–1.44) in 2025. Greenhouse gases alone would have produced about 1.5°C; aerosols and other human forcing offset about 0.2°C; the natural (solar and volcanic) contribution has generally stayed within about a tenth of a degree, reaching −0.13°C after the eruptions of the 1880s. Year-to-year departures of the observed series from the human-induced line reflect volcanic and solar forcing, internal variability such as El Niño, observational uncertainty, and the method's residual.

The method is not assumption-free. Fingerprints are generated by models that share parameterizations, forcing datasets, and tuning targets. The covariance of internal variability is estimated from control runs whose multidecadal modes may differ from the real system. Averaging ensemble members with different phases can suppress internally generated variability, making the forced signal appear comparatively clean. Curry and Webster (2011) warned that twentieth-century tuning can create circularity when aerosol forcing or uncertain parameters are adjusted to reproduce the same record later used to validate the model. The 2025 report of the U.S. Department of Energy's Climate Working Group, written by five prominent critics of mainstream assessments, further argues that some optimal-fingerprinting implementations may violate standard regression assumptions, bias forcing coefficients upward, or underrepresent persistent time-series behavior (Climate Working Group, 2025). A National Academies review published the same year reached the opposite framing of the same literature, concluding that the evidence behind the 2009 endangerment finding "has stood the test of time, and is now reinforced by even stronger evidence" (National Academies of Sciences, Engineering, and Medicine, 2025). Both are cited

in this synthesis. Their disagreement is largely about weighting, emphasis, and impacts rather than about the propositions listed as high-confidence below, and the existence of two government-commissioned reviews with opposite tones within a single year is itself a datum about how much judgment the assessment process involves.

These critiques are serious but not automatically dispositive. Model dependence does not mean the fingerprints contain no information, and multiple independent variables can constrain attribution even when any one model is imperfect. Conversely, agreement among related models is not equivalent to independent replication. Confidence should increase most when attribution is robust to alternative covariance assumptions, forcing reconstructions, model subsets, observational products, time windows, and statistical methods. Econometric approaches such as cointegration, vector autoregression, and Granger-causality tests may provide useful checks, though they also depend on assumptions about stationarity, lag structure, and causal identification (Climate Working Group, 2025).

The strongest attribution claims concern global or large-scale variables with long records and clear physical mechanisms: global mean temperature, ocean heat content, stratospheric cooling during the ozone-depletion era, Arctic sea-ice decline, and global sea-level rise. Confidence generally weakens as the question becomes more local, more event-specific, or more dependent on simulated circulation. The conclusion that human forcing materially warmed the globe is therefore compatible with skepticism about the anthropogenic fraction of a regional drought, the change in the return period of a rare heatwave, or the projected rainfall response of a particular watershed.

7 Climate Models: Essential Tools, Imperfect Experiments

General circulation and Earth-system models solve discretized equations for momentum, mass, energy, and moisture on three-dimensional grids. Typical atmospheric grid cells are of order 100 km horizontally, with tens of vertical layers; ocean grids are finer but still cannot resolve many eddies and boundary processes. Century-scale simulations advance millions of time steps across roughly millions of atmospheric cells and tens or hundreds of millions of ocean cells (Koonin, 2021).

Many climatically important processes occur far below grid scale. Cloud microphysics, moist convection, turbulence, surface exchange, aerosol nucleation, and the effects of complex terrain must therefore be represented by parameterizations: semi-empirical relationships between resolved variables and unresolved fluxes. Parameterizations are not arbitrary, but

they incorporate judgment and calibration. Different plausible choices generate different cloud feedbacks, rainfall patterns, circulation responses, and climate sensitivities (Koonin, 2021; Stephens, 2005).

Models are also tuned. Parameters are adjusted so that top-of-atmosphere energy balance, global mean temperature, sea ice, cloud fields, or other climatological targets approximately match observations. Tuning is unavoidable because unresolved processes cannot be derived uniquely from first principles at model resolution. The problem is underdetermination: compensating errors can allow different model structures to reproduce selected historical metrics. If a high-sensitivity model is paired with strong aerosol cooling, it can match twentieth-century temperature about as well as a lower-sensitivity model paired with weaker aerosol cooling (Curry & Webster, 2011; Koonin, 2021).

This is why a multimodel ensemble should not be interpreted as a random sample from a known probability distribution. CMIP collections are “ensembles of opportunity”: models share code, parameterizations, institutional lineages, and forcing assumptions, while some centers contribute more simulations than others. Their spread is informative about model disagreement but is not a calibrated probability interval. Koonin (2021) notes that absolute global mean surface temperatures across CMIP5 models span roughly 3°C even when anomaly plots appear similar. Later generations have increased resolution and complexity without clear convergence in equilibrium climate sensitivity or some regional responses.

Historical performance is mixed. Models reproduce the broad late-twentieth-century global warming pattern, especially when anthropogenic forcings are included, and the IPCC reports that CMIP6 generally simulates global surface temperature within about 0.2°C over much of the historical record (IPCC, 2021). Yet models have difficulty with the rapid 1910–1940 warming, the phasing and amplitude of Atlantic and Pacific multidecadal variability, ENSO details, regional precipitation, and tropical tropospheric trends (Koonin, 2021). The weakness in regional rainfall extends to seasonal prediction, where statistical methods trained on long local records have in some regions outperformed the dynamical forecasts issued by national agencies (Abbot & Marohasy, 2017b); that is a limitation of a different kind from the forced centennial response, but it is a reminder of how much regional hydrology remains beyond the models’ reach. These limitations matter because the same processes influence near-term projections and event attribution.

Two contrarian tests of model performance deserve comment because they are widely repeated. The first computes the squared correlation between individual model runs and monthly observed anomalies and finds values near zero (Grok 3 beta et al., 2025). The test is

uninformative. No model is expected to reproduce the timing of unforced El Niño events or volcanic-free decades, so a monthly correlation mostly measures whether a model's random internal variability happens to align in phase with the real one. The appropriate comparisons are of forced trends and of warming per unit of realized forcing. By that standard most past projections have been consistent with observations once differences between projected and realized forcings are taken into account (Hausfather et al., 2020), while the tropical-troposphere discrepancy and the hot CMIP6 models remain genuine failures that the same standard exposes. The second test argues that because dozens of CMIP5 models disagree about parameters and produce different results, there is "no consensus" and the enterprise should be discarded (Clauser, 2026). Disagreement about the magnitude of feedbacks is exactly what the sensitivity range expresses; it is not disagreement about the sign of the response, which every model, every energy-budget estimate, and every paleoclimate constraint shares. The spread is an argument for weighting models by observations—a position this synthesis endorses—not for discarding the forced response.

Climate sensitivity remains the central uncertainty. Equilibrium climate sensitivity (ECS) is the eventual global mean warming after a sustained doubling of carbon dioxide; transient climate response (TCR) measures warming near the time of doubling under a gradual concentration increase. The long-standing Charney range of 1.5–4.5°C persisted for decades. CMIP6 models span approximately 1.8–5.7°C, with many high-sensitivity members driven by revised cloud feedbacks and warming faster than observations over the historical period (Climate Working Group, 2025). The width of this range, and the failure of successive model generations to narrow it, is itself an informative signal: sensitivity is governed largely by the same feedbacks—clouds above all—that models must parameterize rather than resolve, so models alone cannot be expected to pin it down.

A partially independent estimate comes from the historical energy budget. If the planet's effective radiative forcing, surface warming, and heat uptake are characterized between two well-separated periods, global energy conservation constrains sensitivity directly, with far less dependence on the internal structure of a general circulation model, through the relation ECS = $F_{2\times} \cdot \Delta T / (\Delta F - \Delta N)$, where $F_{2\times}$ is the forcing from doubled carbon dioxide and ΔN is the change in top-of-atmosphere radiative imbalance. Lewis and Curry (2015) applied this approach using the forcing and ocean-heat-uptake estimates compiled for the IPCC Fifth Assessment Report, selecting base and final periods to minimize and match volcanic and multidecadal influences. They obtained a median ECS of 1.64°C (17th–83rd percentile 1.25–2.45°C) and a median TCR of 1.33°C—values at the low end of the assessed likely range and well below the CMIP5 multimodel means of roughly 3.2°C for ECS and 1.8°C for TCR. Aerosol

forcing uncertainty dominated the width of their distributions, and the long upper tail arose because inversion from temperature alone cannot cleanly separate greenhouse from aerosol forcing.

Updating this analysis, Lewis and Curry (2018) extended the records to 2016 and incorporated revised greenhouse-gas forcing relationships (which raised methane forcing), post-1990 aerosol and ozone changes (which made aerosol forcing less negative), and newer ocean-heat-content datasets. Their best-constrained estimate gave a median ECS near 1.50°C (5th–95th percentile 1.05–2.45°C) with one temperature product, rising to roughly 1.66–1.76°C when spatially complete (infilled) temperatures and time-varying feedbacks were used, with TCR near 1.20–1.33°C. They interpreted these constraints as implying that most CMIP5 models overestimate the historical temperature response to forcing, most plausibly through excessive positive cloud feedback.

Energy-budget estimates carry well-known caveats. They assume an approximately constant feedback parameter over the historical period, whereas the effective sensitivity inferred from recent decades may be lower than the true equilibrium value because the spatial pattern of historical warming differs from the eventual equilibrium pattern—the so-called pattern effect. They are also sensitive to the aerosol forcing estimate and to the choice of periods. For these reasons the results are best read as a constraint that leans toward the lower part of the range rather than as a single definitive value. They are, however, a genuinely observational constraint, and their persistent divergence from high-sensitivity models is not dissolved by assuming that the models must be right.

The most direct engagement with the evidence underlying recent IPCC sensitivity ranges is Lewis's (2023) reanalysis of a major multiple-lines-of-evidence assessment (Sherwood et al., 2020) that strongly influenced the Sixth Assessment Report. That assessment combined process, historical, and paleoclimate evidence within a Bayesian framework to produce a relatively high and comparatively tight sensitivity range. Lewis argued that its procedure relied on a subjectively chosen prior and sequential updating whose intervals need not possess frequentist coverage, and he identified errors in the likelihood calculations for inputs with skewed distributions or nonlinear effects—including a coding error that reduced the assumed uncertainty in one paleoclimate carbon-dioxide value to a tenth of its intended magnitude. Substituting a mathematically derived, noninformative (Jeffreys) prior and corrected likelihoods, while retaining the original scientific inputs, actually raised the combined median sensitivity slightly, to about 3.2°C. The large downward change came instead from revising the physical inputs: weaker positive low-cloud feedback, a more

negative Planck feedback, updated historical forcing with a smaller pattern-effect adjustment, and revised paleoclimate treatments. With all revisions, Lewis obtained a median effective sensitivity of 2.16°C, a 17th–83rd percentile range of 1.75–2.70°C, and a 5th–95th percentile range of 1.55–3.20°C, assigning roughly a 36% probability to sensitivity below 2°C and characterizing values below 1.5°C or above 3.2°C as extremely unlikely.

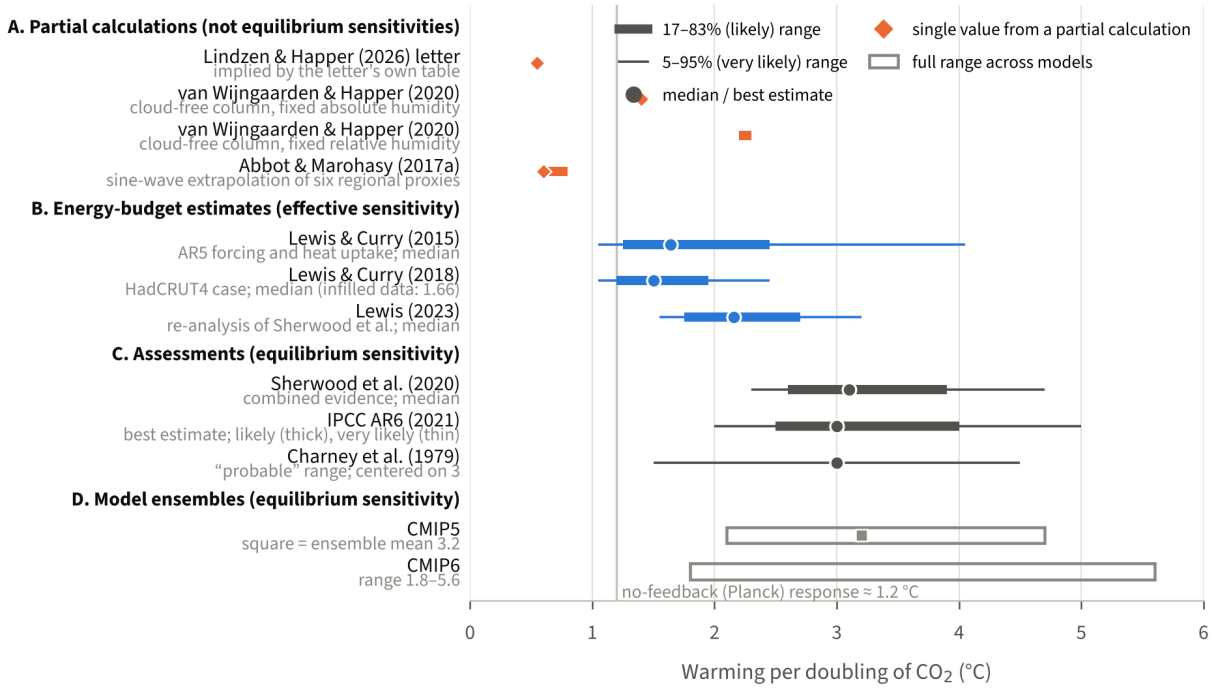


Figure 6. Estimates of warming per doubling of carbon dioxide discussed in the text, grouped by the kind of quantity each one is. Group A collects figures from the contrarian sources that are not equilibrium sensitivities: the Lindzen–Happer letter's value is implied by its own table of temperature increments; the van Wijngaarden–Happer values are for a cloud-free column with only the water-vapor feedback; the Abbot–Marohasy value is the divergence between six regional proxy records and a sine-wave extrapolation of their pre-1830 behavior. Group B shows observationally constrained energy-budget estimates, which measure effective rather than equilibrium sensitivity (Lewis & Curry, 2015, 2018; Lewis, 2023); the 2015 estimate has a wide upper tail (5–95 percent range 1.05–4.05°C) that is often omitted. Group C shows assessments (Charney et al., 1979; Sherwood et al., 2020; IPCC, 2021), and Group D the full ranges across the CMIP5 and CMIP6 model ensembles (Climate Working Group, 2025; IPCC, 2021), which are not probability intervals. The vertical line marks the no-feedback response of about 1.2°C.

Two lessons follow. First, the choice of statistical framework matters, but in this case it was not the driver of the disagreement: valid priors and corrected likelihoods alone did not lower the estimate, and the decisive factor was the specification of the physical inputs—the same feedbacks, forcings, and pattern effects that make sensitivity uncertain in the first place. Second, the existence of a range does not imply that every value within it is equally likely. Very low sensitivities must still account for the observed energy imbalance and the realized

warming; very high sensitivities must account for the absence of comparably rapid warming under historical forcing and for paleoclimatic constraints; and the observational and reanalyzed-Bayesian estimates cluster noticeably below the upper half of the CMIP6 range. None of this proves that low sensitivity is correct, because paleoclimate and process reasoning can support higher values and the pattern effect could raise the true equilibrium response above the historical estimate. But it does imply that a responsible assessment should weight models against observations rather than averaging an ensemble of opportunity, and should treat the upper-tail sensitivities that dominate worst-case impact projections as possibilities to be tested rather than as established central expectations (Lewis, 2023; Lewis & Curry, 2015, 2018).

The lowest figure in the contrarian literature comes from a different method altogether. Abbot and Marohasy (2017a) decomposed six regional proxy temperature records—tree rings from New Zealand, Tasmania, and the Canadian Rockies, Swiss lake sediments, a southern South American multiproxy series, and a Northern Hemisphere composite—into sums of sine waves fitted to the period before 1830, used those components to train a neural network, extrapolated the result through the twentieth century as the "natural" trajectory, and read the mean absolute difference between extrapolation and proxy (0.06–0.20°C) as the anthropogenic contribution, from which they inferred an equilibrium sensitivity of about 0.6°C. The paper was widely circulated as evidence that most recent warming is natural, and it is worth being precise about why it cannot bear that weight. The extrapolation assumes that preindustrial climate was a sum of stationary cycles, so that the Little Ice Age and the medieval warmth were periodic rather than forced by volcanic and solar activity; no forcing enters the model, and the "natural" curve is curve-fitting with no physical content. The six records are local, with year-to-year swings of about ±1°C that are an order of magnitude larger than those of the global mean, and half of them end between 1950 and 1980, before most of the anthropogenic warming occurred; reviewers also noted that the digitized Northern Hemisphere composite appears to be misdated by roughly 35 years, which would remove the most recent decades from the comparison entirely (Science Feedback, 2017). The deviations are tabulated as absolute values regardless of sign, and in the New Zealand record the projected natural series runs *warmer* than the proxy after 1960, which on the paper's own logic would imply anthropogenic cooling. And the final step converts a transient divergence, measured while the ocean was still absorbing heat, into an equilibrium quantity; a response that is still accumulating heat in the ocean is by definition not at equilibrium. The spectroscopic "sensitivities" with which the authors compare their figure are, like the van Wijngaarden–Happer column calculations, no-feedback or partial-feedback responses rather

than estimates of ECS. The paper is a useful marker of the floor of the published range, and the reasons it fails are the same reasons the energy-budget estimates, which incorporate forcing and heat uptake explicitly, deserve more weight than it does.

Figure 6 places all of these estimates on a single axis, grouped by the kind of quantity each one is. The spread within the first group—between the Lindzen–Happer letter's stated increments, the same authors' published clear-sky calculation, and the proxy extrapolation—is the saturation argument's problem in one picture, and the distance between that group and the rest is the difference between a partial calculation and a sensitivity.

Clouds remain the largest structural challenge. Low clouds strongly reflect sunlight, while high clouds also impede outgoing longwave radiation. Small changes in cloud altitude, phase, coverage, or optical depth can produce radiative effects comparable to the forcing from greenhouse-gas changes. Stephens (2005) emphasized that models and observations must be evaluated together because cloud parameterizations are empirical and feedback estimates are difficult to infer from short satellite records. Lindzen and Choi (2011) interpreted tropical radiation-temperature covariation as evidence for stronger negative feedback and lower sensitivity, but the extrapolation from regional, short-term variability to global equilibrium response remains contested.

Aerosols create a parallel problem. Their direct scattering and indirect effects on cloud droplets offset an uncertain fraction of greenhouse warming. The CLOUD experiment showed that ammonia can enhance sulfuric-acid nucleation by orders of magnitude, yet the measured compounds were still insufficient to explain much observed boundary-layer nucleation, indicating missing processes (Kirkby et al., 2011). When a poorly constrained forcing is used to balance a poorly constrained sensitivity during model calibration, historical agreement cannot uniquely identify either quantity. This is precisely the degeneracy that energy-budget analyses attempt to sidestep by constraining forcing and heat uptake observationally rather than diagnosing them from the model itself (Lewis & Curry, 2015, 2018).

Models are therefore indispensable but conditional tools. They organize physical knowledge, test mechanisms, produce internally consistent scenarios, and reveal consequences that cannot be inferred from simple extrapolation. Their strongest uses concern large-scale response and qualitative direction. Their weakest uses involve precise regional forecasts, probability statements derived from ensemble frequency, and marginal temperature effects of small policy changes. Communicating this hierarchy of skill would strengthen, rather than weaken, public confidence in climate science.

8 Natural Forcing, Internal Variability, and the Residual Problem

Natural variability operates from days to millennia. ENSO redistributes ocean heat and alters global mean temperature over several years; the Pacific Decadal Oscillation and Atlantic multidecadal variability shape regional climate over decades; volcanic aerosols cool the surface episodically; solar variability changes incoming energy and may influence atmospheric chemistry; and cloud or circulation shifts can alter planetary albedo. No credible attribution analysis can treat these processes as an unstructured residual.

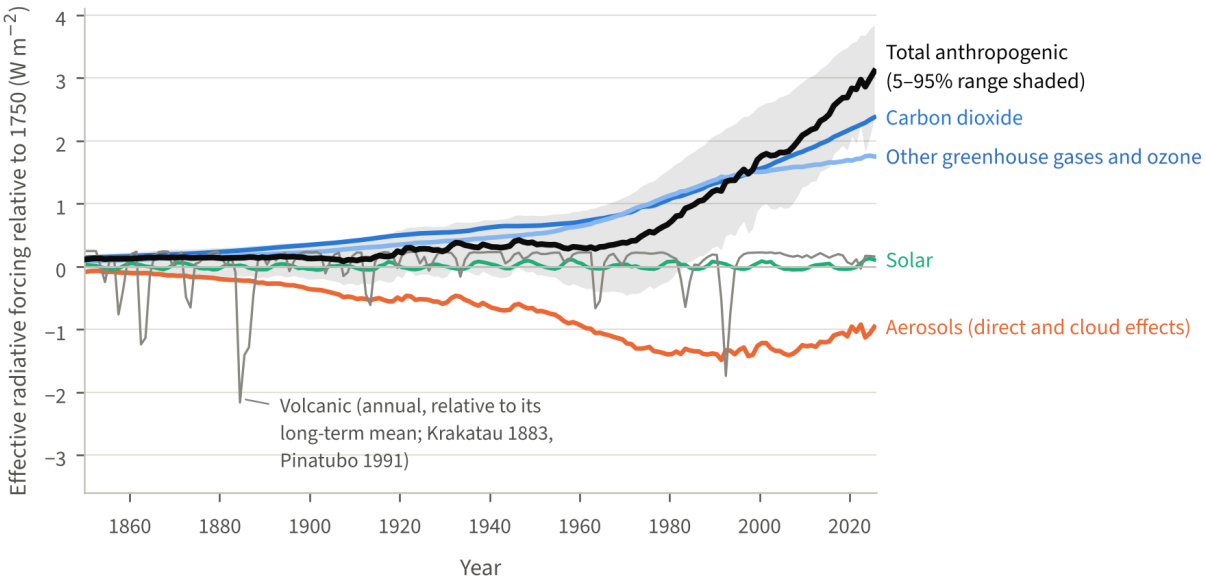


Figure 7. Effective radiative forcing by agent, 1850–2025, relative to 1750 (data from the Indicators of Global Climate Change update; Forster et al., 2025; Smith et al., 2026). In 2025 carbon dioxide contributes 2.4 W m^{-2}, other greenhouse gases and ozone 1.7, and aerosols −1.0 (5–95 percent range −1.6 to −0.4), for a total anthropogenic forcing of 3.1 W m^{-2} (2.3–3.8, shaded). Land-use albedo, contrails, and black carbon on snow are included in the total but not drawn separately; together they contribute about −0.05 W m^{-2}. Solar forcing has varied within about ±0.1 W m^{-2} and shows no sustained increase: the 2025 value (+0.10 W m^{-2}) is essentially equal to the 1957 peak, and the 1940–1960 mean was +0.03. Volcanic forcing is expressed relative to its long-term mean, so quiet periods appear slightly positive.

The IPCC estimates that natural external forcing contributed little to the net 1850–1900 to 2010–2019 warming, while internal variability contributed at most a few tenths of a degree over that interval (IPCC, 2021). This assessment is supported by the relatively small measured variation in total solar irradiance over recent satellite-era cycles and by the absence of a sustained twentieth-century volcanic trend. It is also consistent with ocean heat accumulation and the spatial pattern of many observed changes. Placed on a common axis,

the forcings differ by more than an order of magnitude: carbon dioxide alone now contributes about 2.4 W m^{-2}, other greenhouse gases and ozone about 1.7, aerosols roughly −1.0, and solar variation about 0.1 (Figure 7).

Alternative solar reconstructions and empirical studies have argued for a larger role. Soon (2005) reported a strong association between reconstructed solar irradiance and Arctic temperatures; Scafetta and West (2006) estimated that solar variability could account for a substantial fraction of twentieth-century warming; Neff et al. (2001) found coherence between cosmogenic solar proxies and Holocene monsoon variability; and Svensmark and Friis-Christensen (1997) proposed cosmic-ray modulation of clouds as an amplification mechanism. The Climate Working Group (2025) similarly argues that unresolved differences among irradiance composites and indirect mechanisms leave room for greater solar attribution. The most developed recent version of the case holds that the IPCC's choice among more than two dozen irradiance reconstructions is arbitrary, and that pairing a high-variability reconstruction with a rural-only Northern Hemisphere temperature series can attribute half or more of the warming since 1850 to the Sun (Connolly et al., 2021; Grok 3 beta et al., 2025).

These studies establish that solar-climate coupling is physically and historically plausible, but they do not provide a generally accepted quantitative alternative to greenhouse attribution, and the most developed version fails for two reasons. First, its attribution procedure fits the solar term before the anthropogenic term and assigns to the Sun all variance the two predictors share; fitting the anthropogenic term first assigns the Sun nearly nothing, so the result is a property of the ordering rather than of the data (Richardson & Benestad, 2022). Second, and decisively, irradiance has been measured directly from space since 1978. The standard composite shows no upward trend across four solar cycles; the disputed alternative composite shows a small rise between 1980 and 2000 followed by decline; and solar cycle 24, from 2008 to 2019, was the weakest in roughly a century. During that weak cycle the planet's energy imbalance doubled (Loeb et al., 2021). A solar explanation of recent warming requires an energy source that the measured Sun has not supplied. Proposed cosmic-ray-cloud relationships have not yielded a stable global effect large enough to fill the gap, and model studies that attribute most warming to solar-driven cloud changes depend on a cloud response that is assumed rather than measured. The prudent conclusion is that solar effects may be underrepresented in some regional or multidecadal analyses, not that they explain the modern global trend in full.

Internal modes create a more immediate attribution problem because their phase can accelerate or mask forced warming over policy-relevant intervals. The 1998–2012 slowdown, for example, is interpreted by the IPCC as a combination of Pacific variability and solar-volcanic influences superimposed on continuing ocean heat uptake (IPCC, 2021). Models need not predict the exact phase of unforced variability in a century-scale projection, but failure to reproduce realistic amplitude, persistence, and spatial structure broadens uncertainty in decadal and regional forecasts.

Recent changes in planetary albedo illustrate the remaining ambiguity. The Climate Working Group (2025) highlights a decline in albedo after 2015 equivalent to roughly 1.7 W m^{-2} of additional absorbed solar energy, associated with reduced low- and mid-level cloudiness. That change could represent internal variability, an externally forced cloud feedback, aerosol changes—including the sharp reduction in sulfur emissions from shipping after 2020—or a mixture. The observation is important; its causal interpretation is not yet settled, and it bears directly on the cloud-feedback question that governs sensitivity. Similar caution applies whenever a residual is assigned to anthropogenic forcing simply because known natural drivers appear insufficient.

Natural variability is thus neither a universal explanation nor a negligible nuisance. It cannot plausibly account for all modern warming, because it has no energy source of its own and the planet's energy content is rising; but it can materially affect rates, regional patterns, extremes, and short-window attribution. The residual problem should motivate better observations and model diagnostics, not rhetorical certainty.

9 Carbon Sinks, Global Greening, and Direct Effects of Carbon Dioxide

Climate discussions often treat carbon dioxide only as a radiative forcing, but the gas is also the substrate for photosynthesis. Rising concentration affects plant growth, water-use efficiency, ecosystem carbon uptake, and crop response. These direct effects do not cancel warming-related risks, but they are part of the net impact and should be quantified rather than dismissed as irrelevant.

Satellite leaf-area records show widespread greening. Zhu et al. (2016) combined three satellite products with a ten-model ecosystem ensemble and found statistically significant greening over approximately 25–50% of vegetated land from 1982 to 2009, compared with browning over less than 4%. Their factorial attribution assigned about 70% of the trend to

carbon-dioxide fertilization, roughly 9% to nitrogen deposition, 8% to climate change, and 4% to land-cover change, with considerable uncertainty. Carbon dioxide also improved water-use efficiency in arid regions through partial stomatal closure.

This result is one of the clearest documented benefits associated with rising carbon dioxide, but it requires qualification. Models may overstate fertilization in tropical forests where field experiments are scarce; nitrogen and phosphorus constraints can limit response; greening can reflect shrub encroachment or invasive species rather than ecological improvement; and leaf area does not directly measure biodiversity, carbon permanence, or nutritional value. The IPCC assigns only low confidence to carbon-dioxide fertilization as the dominant cause of satellite-observed greening, illustrating that the same observational trend can support different attribution judgments (IPCC, 2021; Zhu et al., 2016).

The persistence of natural sinks is similarly consequential. Ballantyne et al. (2012) found that absolute land and ocean uptake increased over the second half of the twentieth century rather than collapsing under warming. That resilience suggests substantial negative feedback, though sink efficiency relative to emissions and future saturation remain uncertain. Carbon-cycle models still differ widely in projected land uptake, reflecting uncertainty in nutrient limitation, soil respiration, disturbance, and ecosystem adaptation (Climate Working Group, 2025).

Agriculture provides a more direct policy-relevant example. Free-air carbon-dioxide enrichment experiments generally increase yields for C3 crops such as wheat, rice, and soybeans, while C4 crops such as maize benefit most under water stress. The Climate Working Group (2025) reports an average yield increase near 18% for C3 crops under a 200-ppm enrichment and argues that some crop-model studies understate adaptation and fertilization. Koonin (2021) notes that global calorie availability and major-crop yields have risen dramatically despite warming, with technology, irrigation, fertilizer, improved varieties, and management dominating the historical signal.

Benefits are not unlimited. Extreme heat around flowering can sharply reduce yields; pests and diseases may shift; water availability and soil degradation remain important; and elevated carbon dioxide can reduce protein, iron, and zinc concentrations in some crops. These effects can be addressed partly through breeding, biofortification, supplementation, and changes in cultivation, but they should not be ignored. The correct assessment is not that carbon dioxide is simply “plant food” or simply “pollution.” It is a radiatively active gas with both beneficial and harmful biological effects whose net consequences vary by ecosystem, climate, and management.

10 Extreme Weather and the Limits of Event Attribution

A warmer climate changes the statistical environment in which weather occurs, but different hazards respond differently. Thermodynamic variables such as temperature and atmospheric moisture are more directly linked to greenhouse forcing than dynamically complex phenomena such as tornadoes, tropical-cyclone tracks, blocking patterns, or regional drought. The confidence of an attribution claim should reflect that hierarchy.

The IPCC's own assessment of extremes displays exactly this gradient of confidence. Its dedicated chapter treats it as an established fact that human-induced greenhouse-gas emissions have increased the frequency or intensity of some extremes, but the strength of that conclusion varies enormously by hazard (IPCC, 2021). For hot extremes the assessed language is "virtually certain"; for the intensification of heavy precipitation it is "likely"; and for many drought, river-flood, tropical-cyclone, and severe-convective-storm metrics it falls to "medium" or "low confidence," with the direction of past change explicitly uncertain in several cases. The chapter also notes that changes generally scale with global warming, so that even half-degree increments produce statistically significant shifts at global and large-regional scales, with proportionally larger changes for rarer events. Read directly, the assessment is far more differentiated than the headline that "extremes are increasing," and the differentiation runs toward greater caution for the dynamically complex hazards, not less.

Heat extremes provide the strongest case. The IPCC concludes that greenhouse-gas forcing is the principal cause of more frequent or intense hot extremes and fewer or weaker cold extremes globally, with hot extremes having increased since 1950 in more than four-fifths of the assessed land regions (IPCC, 2021). A shift in the mean temperature distribution makes threshold exceedances more common even if circulation statistics are unchanged, and the chapter projects that the intensity of extreme heat at 2°C of global warming will be at least double, and at 3°C roughly quadruple, that at 1.5°C, with the largest regional amplification—up to about two to three times the global rate—over mid-latitude and semi-arid land and in the Arctic for cold extremes (IPCC, 2021). Even here, though, the assessment records important local modulation: soil-moisture feedbacks, irrigation, and crop expansion have attenuated summer hot extremes in some regions, while urbanization has exacerbated nighttime warmth. The contiguous United States is the most prominent regional exception to the global pattern. Its heat-wave index remains dominated by the Dust Bowl summers of the 1930s, and Singer was correct that the index shows no increase in the area affected by heat waves between 1895 and the 2010s (Singer et al., 2021). That is a real feature of one well-

measured region, attributable in part to agricultural intensification and soil-moisture changes, and it does not generalize: the global land record, drawn from dozens of regions, shows the opposite. And the magnitude of a particular event can still depend mainly on an unusual synoptic pattern. In its discussion of the 2021 Pacific Northwest heatwave, the Climate Working Group (2025) accepts an anthropogenic contribution of roughly 1.4–2°F to the temperature while questioning whether human forcing made the rare circulation pattern itself more probable. This distinction between thermodynamic amplification and dynamical causation is often lost in rapid attribution headlines.

Heavy precipitation also has a clear physical basis because warmer air can hold more water vapor. The IPCC finds that human influence likely contributed to large-scale precipitation changes and to the intensification of heavy precipitation over global land, while acknowledging substantial uncertainty in tropical patterns, streamflow, and circulation (IPCC, 2021). It ties this intensification to the Clausius-Clapeyron scaling of about 7% more atmospheric moisture per degree of warming, with frequency increases that are nonlinear and largest for the rarest events; at 4°C of warming it projects, for example, a likely doubling of what are currently ten-year events and a tripling of fifty-year events (IPCC, 2021). Crucially, the same chapter warns that this thermodynamic signal does not translate directly into river flooding: projections of peak streamflow are more uncertain than those for surface-water (pluvial) flooding because runoff depends on soil moisture, snowmelt, land cover, and human water management, and the assessed confidence in the direction of river-flood change is correspondingly lower. Observed total precipitation trends are also spatially heterogeneous. Koonin (2021) reports a small long-term increase over global land and a larger U.S. increase, but with different signs across regions and seasons, and a rise in short-duration heavy rainfall does not translate automatically into a uniform increase in river flooding because soil moisture, snowmelt, reservoirs, land cover, channel engineering, and basin geometry also matter.

Tropical cyclones illustrate the difficulty of short and changing records. Reliable global monitoring begins in the satellite era, while earlier records depend on ships, landfalls, aircraft reconnaissance, and corrections for missed storms. Klotzbach and Landsea (2015) found that apparent increases in the most intense hurricanes were sensitive to the analysis period and improvements in satellite observation. Koonin (2021) emphasizes that no robust long-term trend is evident in global cyclone numbers or U.S. landfalling hurricanes, although some projections indicate higher rainfall rates and a 10–20% increase in selected intensity metrics under approximately 2°C of warming. The IPCC's synthesis is consistent with this layered picture: it assesses that the global proportion of the most intense (Category 3–5)

tropical cyclones has likely increased over the past four decades, that the latitude of peak intensity has migrated poleward in the western North Pacific, and that the frequency of rapid-intensification events has likely increased, while projecting that the total global frequency of tropical cyclones will decrease or remain unchanged with warming (IPCC, 2021). Rising intensity among the strongest storms and higher rainfall rates are therefore compatible with stable or declining overall frequency—precisely the combination that headline claims of "more hurricanes" tend to blur. These statements can all be true simultaneously: frequency may show little trend, the strongest storms may intensify somewhat, and economic losses may rise mainly because more people and property occupy vulnerable coasts.

Tornado records are even more affected by detection changes. Raw U.S. counts rose as Doppler radar, public reporting, and damage surveys captured weak events that would previously have been missed. Restricting analysis to stronger tornadoes removes the apparent increase: Koonin (2021) reports no long-term trend in EF1+ events and a decline in EF3+ events since the mid-twentieth century. This caution is shared by the IPCC, which assigns low confidence to observed trends in the severe-convective-storm environment beyond the associated precipitation, while projecting a medium-confidence lengthening of the U.S. severe-storm season (IPCC, 2021). Climate models cannot resolve tornadoes directly, so projections depend on imperfect environmental proxies such as convective available potential energy and wind shear.

Floods and droughts resist simple global narratives. U.S. streamflow trends vary by region, and the IPCC has historically expressed low confidence in the sign of global flood changes. Instrumental drought indices show limited long-term U.S. change, while tree-ring records reveal medieval megadroughts in the American Southwest that exceeded many modern events (Koonin, 2021). The IPCC attributes increases in agricultural and ecological drought in some regions to human influence, operating primarily through greater evapotranspiration under higher temperatures and net radiation (medium confidence), while concluding that precipitation trends are not the main global driver of drought trends; increasing agricultural and ecological drought has been detected on all continents in multiple regions, with decreases in only a few, and the most severe and widespread changes emerge at higher warming levels (IPCC, 2021). This does not imply that warming cannot worsen drought through evapotranspiration or snowpack loss. It means that precipitation variability, land management, water demand, and internal circulation remain major controls, and short records can misrepresent the natural envelope.

Wildfire is similarly multicausal. Global satellite-observed burned area declined by roughly 25% from 1998 to 2015, largely because agricultural intensification reduced savanna burning, even as large forest-fire activity increased in parts of western North America (Koonin, 2021; Shellenberger, 2020). Climate-driven fuel aridity can increase fire potential, but ignition, suppression policy, prescribed burning, forest density, invasive grasses, utility infrastructure, and development in the wildland-urban interface strongly mediate realized losses. The Climate Working Group (2025) argues that management and historical fire deficits are central to U.S. trends. Assigning every large fire primarily to climate change can obscure interventions that would reduce risk more directly.

Rapid event-attribution studies compare the observed climate with a modeled counterfactual world without anthropogenic forcing. They can estimate how warming changed the probability or intensity of an event, but results depend on model fidelity, the event definition, the selected region and duration, the tail distribution, and the stability of the background climate. Rare outliers are especially sensitive to assumptions. Such studies are useful when framed as conditional analyses, not as direct measurements of causation.

Two contrarian treatments of extremes warrant brief comment because they travel widely. Clauser (2026) reproduces a NOAA climate-extremes index, plots it alongside its own mirror image, and argues that because a reader cannot tell at a glance which is which, no trend exists. A visual mirror test is not a statistical test, and the index in question is a composite for the contiguous United States, not a global record; the IPCC's statements about hot extremes rest on station data across dozens of land regions, most of which do not share the U.S. 1930s anomaly. Singer's chapters, conversely, assemble the real regional exceptions—U.S. heat waves, global accumulated cyclone energy, declining global burned area—and present them as if they were the global picture (Singer et al., 2021). Each of those exceptions is genuine, and each appears in this synthesis; the error is in the generalization, not the observation.

Compound events—concurrent or sequential extremes such as simultaneous heat and drought, or storm surge coinciding with extreme rainfall—are an area where the IPCC expresses growing but still qualified confidence, judging that their probability has likely increased and will continue to increase, with high confidence for concurrent heatwaves and droughts and medium-to-high confidence for fire weather and compound flooding (IPCC, 2021). Because such combinations can stress interdependent systems—power grids, water supply, or global food production—more than any single hazard, they are an appropriate focus for research and resilience planning even where confidence in individual component trends remains modest.

The broad conclusion is asymmetric. Confidence is high that warming increases hot extremes and can intensify heavy rainfall. Confidence is lower for global changes in hurricanes, tornadoes, floods, droughts, and wildfire, especially at regional scales. Climate change should neither be excluded from these hazards nor invoked as a universal first cause.

11 Sea-Level Rise: Global Signal, Local Consequence

Global mean sea level has risen since the nineteenth century as the ocean has warmed and land ice has melted. The IPCC concludes that human influence is very likely the main driver of global mean sea-level rise since at least 1971 (IPCC, 2021). Koonin (2021) summarizes an increase of roughly 250 mm since 1880, with an average rate near 1.8 mm per year over the full interval and about 3 mm per year in recent satellite-era estimates (Figure 8).

The recent rate is higher than the century average, but the history is not monotonic. Tide-gauge reconstructions show substantial multidecadal variability, including rates during parts of the early twentieth century that approached the initial satellite-era rate. Koonin (2021) argues that presentations based only on cumulative level can obscure this variability and that rate-of-change series provide a more demanding test of acceleration. The existence of earlier rapid intervals does not disprove anthropogenic acceleration; it widens the uncertainty around when and how clearly it emerges from natural and measurement variability.

Whether acceleration has now emerged is a question the data can answer, and Singer's treatment provides a useful foil because it makes a falsifiable claim: that sea level has risen at a steady 1–2 mm per year for centuries with no acceleration, that the rate did not respond to the 1915–1945 warming, and that accumulating Antarctic ice must therefore be offsetting thermal expansion, so that the twenty-first century should expect about six inches (Singer et al., 2021). Three lines of evidence now weigh against each element. The satellite altimeter record, corrected for the Pinatubo eruption and ENSO, shows a climate-driven rate of 2.9 mm per year over 1993–2017 and a statistically significant acceleration of 0.084 ± 0.025 mm per year per year, which if sustained implies roughly 65 cm of rise by 2100 relative to 2005 (Nerem et al., 2018); the IPCC assesses the 2006–2018 rate at 3.7 mm per year (IPCC, 2021). A tide-gauge reconstruction for 1900–2015 using methods designed to capture both trend and variability finds a persistent acceleration beginning in the 1960s, three-quarters of it associated with the Indo-Pacific and South Atlantic (Dangendorf et al., 2019). And the Antarctic Ice Sheet, far from accumulating, lost about 2,720 billion tonnes between 1992 and 2017 according to the reconciled estimate of 24 satellite surveys, with the rate roughly tripling from about 76 to 219 billion tonnes per year after 2012, almost all of it through ocean-

driven melting of outlet glaciers (Shepherd et al., 2018). The absence of a visible acceleration during the modest early-twentieth-century warming is a real observation, but it is consistent with the small thermal and glacial response expected from a few tenths of a degree, and it provides no evidence about the response to three times as much warming sustained for decades. Singer's six inches is below the lowest IPCC scenario; it is not a reading of the current data. The full record, and the rate derived from it, are shown in Figure 8: the twentieth-century rate was variable and occasionally reached 2.5 mm per year, as Koonin notes, but the most recent 20-year windows are the first to approach 4 mm per year.

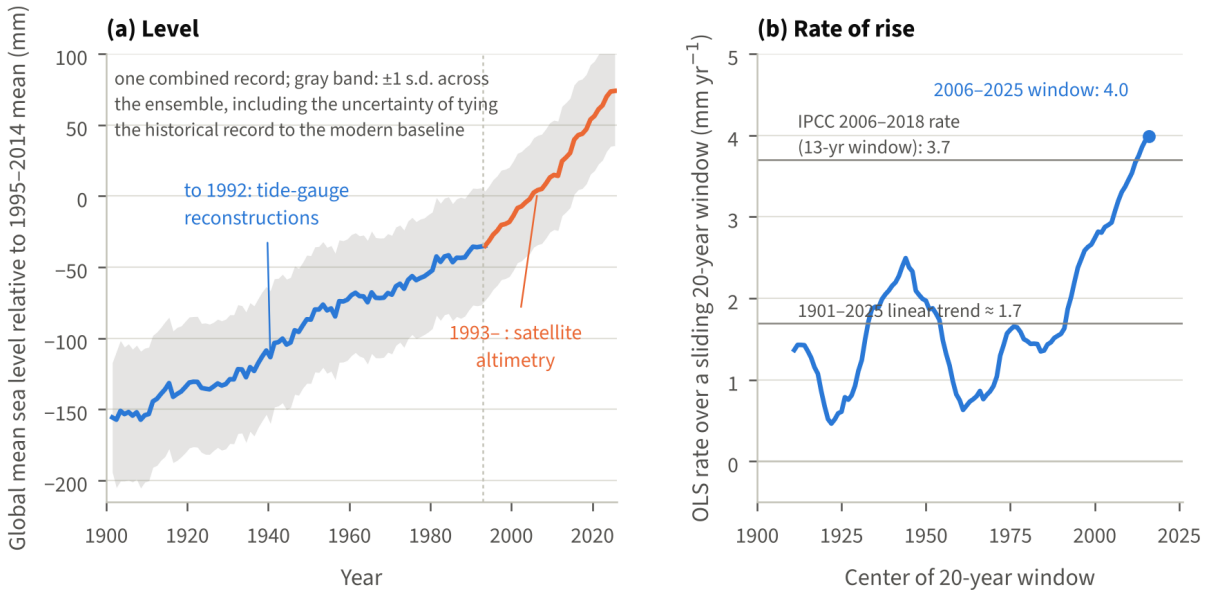


Figure 8. Global mean sea level, 1901–2025. (a) The Indicators of Global Climate Change combined record (Smith et al., 2026): an ensemble of tide-gauge reconstructions through 1992 spliced to satellite altimetry from 1993 onward (see Dangendorf et al., 2019, and IPCC, 2021, for the underlying reconstructions), expressed relative to the 1995–2014 mean. Because the series is one spliced record, the continuity of the two segments is not an independent comparison of methods. The gray band is ±1 standard deviation across the ensemble and carries the uncertainty of tying the historical reconstructions to the modern baseline (about 38 mm in 2025), which is far larger than the altimetry-only uncertainty of about 3 mm. (b) Ordinary least-squares rates over sliding 20-year windows, plotted at the window center. The rate varied between roughly 0.5 and 2.5 mm per year through the twentieth century, including the rapid interval of the 1930s–1940s that Koonin (2021) emphasizes; the final window (2006–2025) gives 4.0 mm per year, and the full-record linear trend is 1.7 mm per year. Overlapping windows are not independent, so the panel displays the record rather than tests it; the acceleration itself is established by the formal analyses cited in the text.

Global mean sea level is also not the quantity experienced by a coastal community. Relative sea level combines ocean height with vertical land motion, regional circulation, gravitational effects from changing ice mass, sediment compaction, groundwater withdrawal, and tectonics. The Climate Working Group (2025) reports that much of the high relative rise at

Galveston and Grand Isle is attributable to subsidence, leaving a smaller absolute ocean component. Conversely, glacial rebound causes relative sea level to fall in some high-latitude locations. Local planning should therefore use local tide gauges, geodesy, storm-surge history, and land-motion projections rather than a global mean alone.

Twenty-first-century projections depend on emissions, ocean heat uptake, glacier loss, and ice-sheet dynamics. High-end outcomes are dominated by uncertain mechanisms of rapid Antarctic or Greenland ice loss. Lower outcomes still imply meaningful increases in nuisance flooding, erosion, saltwater intrusion, and storm-surge exposure. The uncertainty is not a reason to ignore the risk; it is a reason to favor flexible adaptation pathways that can be scaled as observations clarify acceleration.

The Netherlands and other low-lying regions demonstrate that high exposure need not imply unmanageable vulnerability when societies invest in barriers, pumps, drainage, zoning, and emergency planning (Shellenberger, 2020). Poorer regions may lack that capacity, making development and reliable infrastructure central climate policies. Sea-level risk is best understood as the interaction of a real global signal with highly local geology, settlement, wealth, and governance.

12 Ecological, Human, and Economic Consequences

The severity of climate change cannot be inferred from temperature alone. Consequences depend on exposure, vulnerability, technology, institutions, and adaptation. A hazard can intensify while mortality falls, or remain stable while losses rise because more assets are placed in harm's way. Separating these components is essential to avoid attributing socioeconomic trends mechanically to climate.

Weather-related mortality has declined dramatically over the last century despite population growth and warming. Shellenberger (2020) reports that decadal natural-disaster deaths fell by about 92% from the 1920s to the 2010s. Koonin (2021) similarly cites an approximately 80-fold decline in weather-related death rates, attributing much of the improvement to forecasting, flood control, medical care, stronger buildings, and economic development. These trends do not prove that future climate damages will be small, but they demonstrate that vulnerability is not fixed and that adaptation can dominate the human outcome.

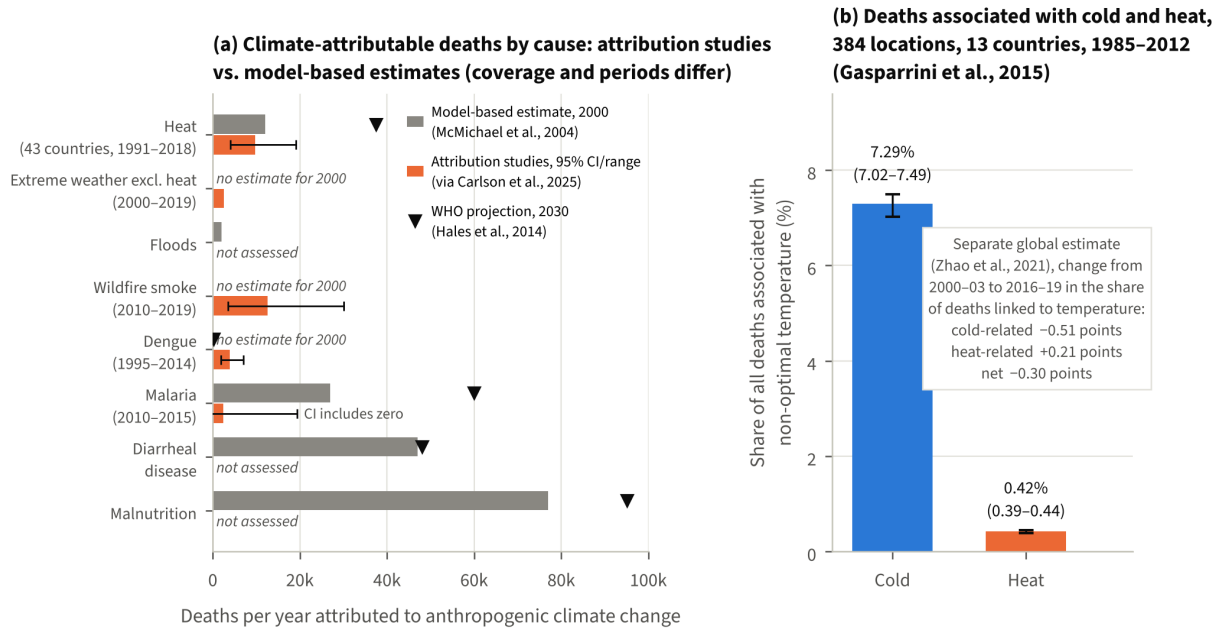


Figure 9. Climate-attributable mortality estimates and mortality associated with non-optimal temperature. (a) Deaths per year attributed to anthropogenic climate change by end-to-end attribution studies (orange, with 95 percent confidence intervals or ranges where reported), set against the model-based estimates for the year 2000 published by the World Health Organization (gray; McMichael et al., 2004) and its later projections for 2030 (triangles; Hales et al., 2014), all as compiled by Carlson et al. (2025). The comparison is indicative, not a measure of forecast error: the attribution studies cover different periods and populations (noted in the row labels), heat covers 43 countries, the malaria interval includes zero, and the largest modeled categories—malnutrition and diarrheal disease—have never been assessed by attribution methods. Dengue has no year-2000 estimate; the attributed 3,925 deaths exceed the 2030 projection of 258 by an order of magnitude, whereas attributed malaria deaths fall an order of magnitude below the year-2000 estimate. (b) In 384 locations across 13 countries during 1985–2012, temperatures below the local optimum were associated with 7.29 percent of deaths (95 percent empirical CI 7.02–7.49) and temperatures above it with 0.42 percent (0.39–0.44) (Gasparrini et al., 2015). These are associations with non-optimal temperature, not effects of anthropogenic warming. In a separate global analysis, the share of deaths associated with non-optimal temperature fell by 0.30 percentage points between 2000–2003 and 2016–2019, as a 0.51-point decline in the cold-related share outweighed a 0.21-point rise in the heat-related share (Zhao et al., 2021).

The same point can be made from the opposite direction, and an honest synthesis must make it. A new line of "end-to-end" attribution research estimates present-day health losses by comparing observed outcomes with a counterfactual climate lacking anthropogenic forcing. A 2025 review identified twenty such studies; all but one reported net harm, and the five with global scope sum to roughly 31,000 attributable deaths per year from heat, wildfire smoke, dengue, malaria, and extreme weather, valued at roughly US$100–360 billion annually depending on how the value of a statistical life is adjusted across countries (Carlson et al., 2025). The authors are candid about the limits of their evidence base: the studies concentrate on heat, on mortality, and on Europe; nearly all are led from institutions in high-

income countries; major expected pathways such as malnutrition and diarrheal disease have never been assessed by these methods; and the attribution-based total of about 31,000 is far below the model-based estimate of 166,000 deaths per year that the World Health Organization produced two decades ago—though the two cover different causes, periods, and populations and are not directly comparable—with dengue running an order of magnitude above the WHO's later projection and malaria an order of magnitude below its year-2000 estimate (Figure 9). Two further caveats matter for interpretation. These are gross rather than net figures: averted deaths are excluded by design, and the one study that examined cold found that warming has reduced cold-related mortality in London (Hajat et al., 2024, as cited in Carlson et al., 2025). And the monetized totals swing by a factor of three with a single analytic choice about how to value lives across income levels.

The net picture is clarified by the largest global analysis of temperature-related mortality. Across 384 locations in 13 countries during 1985–2012, temperatures below the local optimum were associated with 7.3% of deaths and temperatures above it with 0.4%, with most of the burden from moderate rather than extreme temperatures (Gasparrini et al., 2015). Over 2000–2019, about 9.4% of global deaths—more than five million per year—were associated with non-optimal temperatures, and the temperature-attributable share fell by 0.30 percentage points between 2000–2003 and 2016–2019, because the cold-related share declined (−0.51 points) by more than the heat-related share rose (+0.21 points) (Zhao et al., 2021). These findings are compatible with the attribution studies rather than contradictory to them: a warming climate is simultaneously adding heat deaths that can be counted and subtracting cold deaths that are harder to see, and adaptation has so far driven the total down. Singer's claim that "climate change is good for you" and the claim that it already constitutes "a public health emergency" are mirror-image overstatements of the same data (Carlson et al., 2025; Singer et al., 2021). The policy-relevant quantity is the marginal effect of additional warming on a population whose vulnerability is itself changing, and that quantity depends on income, air conditioning, housing, and public health as much as on the thermometer. Figure 9 sets the two accountings side by side; they answer different causal questions, and neither is a measurement of the other.

Economic loss statistics require the same care. Nominal disaster losses tend to rise with population, wealth, and coastal development. Normalized hurricane losses show much weaker trends, and expert assessments have generally attributed most historical increases in losses to exposure rather than changing hazard (Shellenberger, 2020). The Climate Working Group (2025) frames disaster risk as hazard multiplied by exposure and vulnerability and argues that losses per event relative to gross domestic product have declined. Policy that

reduces only emissions while ignoring zoning, construction standards, drainage, fuel management, and warning systems addresses only one part of the risk equation.

Agricultural impacts are mixed and adaptive. Warming can reduce yields in already hot regions, increase heat stress, and alter water demand. At the same time, higher carbon dioxide can enhance photosynthesis and water-use efficiency; longer growing seasons can benefit cooler regions; and technology has historically raised yields far faster than climate has reduced them. Koonin (2021) notes that wheat, rice, and maize yields more than doubled from 1961 to 2011, while per-capita calorie supply increased. Shellenberger (2020) emphasizes that many food-system projections continue to show rising production across warming scenarios because innovation, irrigation, improved cultivars, and farm management dominate.

Land use is the mechanism that links development to biodiversity outcomes, and here the evidence complicates simple narratives of an ever-expanding human footprint. Shellenberger (2020) argues that agricultural intensification—higher yields from fertilizer, irrigation, improved varieties, and mechanization—allows more food to be produced on less land, "sparing" habitat that extensive farming would otherwise consume, and that replacing draft animals with machinery frees cropland formerly devoted to animal feed. Consistent with this, global food production has risen far faster than agricultural land area, pasture area has contracted in many regions even as meat and dairy output increased, and global livestock land appears to have peaked around 2000 before declining by hundreds of millions of acres, aided by a shift from beef toward more feed-efficient poultry. Industrial livestock and crop systems achieve much of this efficiency through density and breeding that minimize land per unit of output; by one meta-review cited by Shellenberger, pasture-based beef required many times more land and generated several times more emissions per kilogram than feedlot beef, so scaling extensive "free-range" production to meet demand would tend to expand rather than spare habitat. These trends do not render land-use change benign—active deforestation frontiers remain a serious problem, and intensification carries its own nutrient and pollution burdens—but they indicate that environmental impact is better evaluated per unit of production and per unit of land than inferred from gross consumption, and that productivity gains can reduce pressure on ecosystems.

Ecological narratives also require causal discrimination. The 2019 claim that the Amazon supplies 20% of the world's oxygen confused gross photosynthesis with net ecosystem oxygen production, which is near zero after respiration and decomposition. Fire counts that year were elevated relative to 2018 but near the longer-term average, while deforestation

remained a serious land-use problem (Shellenberger, 2020). Correcting an exaggerated claim does not make forest loss benign. It helps target the real drivers: agricultural incentives, governance, roads, enforcement, land tenure, and productivity.

Biodiversity decline is likewise driven by multiple pressures, including habitat conversion, overharvesting, invasive species, pollution, and poverty-linked dependence on biomass fuels. Climate change can compound these stresses, but it is not always the dominant present cause. Coral reefs are the clearest case in which it already is: the 2016 marine heatwave on the Great Barrier Reef killed corals in proportion to accumulated heat exposure and transformed the assemblages of roughly 29% of its 3,863 reefs within months, a direct thermal effect that no amount of local management could have prevented (Hughes et al., 2018). Singer's verdict of "no link" between warming and coral health does not survive that record (Singer et al., 2021), although the longer-term capacity of reefs to adapt through symbiont shuffling and selection remains an open and important question. Shellenberger (2020) argues that development, secure energy, and effective waste and land management often protect ecosystems more directly than symbolic restrictions on consumption. That thesis can be overstated, yet it usefully resists the tendency to relabel every environmental problem as a climate problem.

Macroeconomic damage estimates are highly model-dependent. Koonin (2021) summarizes estimates in which warming up to about 3°C reduces global gross domestic product by no more than several percent relative to a much larger future economy. Such figures are not trivial, particularly when losses fall on vulnerable populations, but they differ sharply from claims of inevitable civilizational collapse. Integrated assessment models translate climate sensitivity, socioeconomic growth, damage functions, adaptation, discount rates, and policy costs into a social cost of carbon. The Climate Working Group (2025) correctly describes these values as conditional "if-then" outputs rather than direct measurements. Small changes in discounting, sensitivity, fertilization, or damage curvature can move the result substantially—and because health impacts dominate recent official estimates of the social cost of greenhouse gases (Carlson et al., 2025), the gross-versus-net accounting question raised above propagates directly into the policy number.

This does not establish that damages are modest with certainty. Economic models struggle with conflict, migration, ecosystem loss, correlated shocks, and low-probability tipping events. Conversely, they also struggle to represent innovation, substitution, autonomous adaptation, and the benefits of carbon dioxide. Honest analysis should present a range of

results and identify the assumptions doing the work rather than elevating a single dollar value to an empirical fact.

13 From Research to Rhetoric: The Distortion of Climate Communication

Understanding public climate discourse requires attention not only to the underlying science but to the several filters through which it reaches decision-makers. Koonin (2021) distinguishes ordinary science—provisional, quantitative, uncertainty-aware, and open to challenge—from what he calls "The Science": a simplified public narrative presented as settled and policy-determinative. He does not allege a coordinated conspiracy. Instead he describes a "telephone game" in which information degrades as it passes from primary research, to full assessment reports of thousands of pages, to their Summaries for Policymakers, to press releases, and finally to media and political rhetoric. Each stage can introduce omission, simplification, or emphasis that serves non-scientific goals, and few participants—including many scientists and officials—ever consult the primary layers.

The persistence of distortion is explained by incentives rather than dishonesty. Koonin (2021) argues that media organizations face click-driven economics, shrinking scientific expertise, and the intrinsic salience of disaster imagery, which is easier to package than null trends or attribution uncertainty. Political actors on both sides can exploit the issue: some minimize well-supported findings, while others suppress uncertainty and label methodological dissent as denial. Scientific institutions and individual researchers operate under funding, publication, and reputational pressures that can reward dramatic conclusions; Koonin describes the resulting suspension of normal critical standards as otherwise careful scientists becoming "climate simple." Advocacy organizations whose fundraising depends on a sense of emergency have a structural interest in maintaining urgency, and the public—time-constrained and reliant on trusted outlets—rarely audits the claims. Koonin invokes the "Gell-Mann amnesia" effect, whereby readers notice errors in coverage of subjects they know well yet continue to trust the same outlet on unfamiliar topics.

Concrete cases illustrate how framing can decouple from data. Shellenberger (2020) examines the 2017 viral image of an emaciated polar bear presented as emblematic of climate change and contrasts it with population data: of nineteen recognized subpopulations, roughly two had increased, four decreased, five were stable, and the remainder lacked reliable counts, yielding no discernible overall decline, while historical hunting had removed

more bears than the current estimated abundance. The prominent critic of the exaggeration —a zoologist—received no fossil-fuel funding and accepted anthropogenic warming. Correcting a false parable does not make habitat loss unimportant; it demonstrates that vivid imagery can substitute for demographic evidence.

Disputes about the assessment process itself are as old as the process. In 1996 Frederick Seitz, a former president of the National Academy of Sciences, charged in the *Wall Street Journal* that more than fifteen passages in the attribution chapter of the IPCC's Second Assessment Report had been altered or deleted after the scientists had approved the text, nearly all in the direction of removing expressions of doubt about a detectable human influence (Seitz, 1996, reprinted in Singer et al., 2021). The IPCC and the chapter's lead author replied that the changes were made in response to government review comments as the panel's procedures required, and a detailed scholarly account concluded that the revisions were permitted under the procedures as then written, while acknowledging that those procedures were ambiguous about changes made after plenary approval (Edwards & Schneider, 2001). The controversy matters less for who was right than for what it established: that the summarizing and negotiating layers of the assessment process are where authorship, wording, and uncertainty language are decided, and that those layers were contestable from the first.

Two more recent cases involve the same layers. Shellenberger (2020) recounts economist Richard Tol's account of serving as a convening lead author for the impacts chapter and Summary for Policymakers of the IPCC Fifth Assessment Report. Tol described a shift from earlier drafts—which emphasized that many severe impacts reflect poverty and mismanagement and can be reduced by development—toward more apocalyptic "Four Horsemen" framing, and he criticized the Summary for omitting context on adaptation, cold-stress reduction, and improved cultivars while foregrounding weakly supported claims about poverty traps, conflict, and migration. Tol ultimately dissented from the Summary and asked to have his name removed. A parallel episode was the campaign against political scientist Roger Pielke Jr. after congressional testimony on disaster losses: he was publicly labeled a "denier" and became the target of insinuations about undisclosed funding that a university investigation did not substantiate, prompting objections from scientific journals and societies about the chilling effect. These cases do not show that the mainstream assessment is wrong; they show that the summarizing and communicating layers are more contestable than the phrase "the science says" implies (Koonin, 2021; Shellenberger, 2020).

Shellenberger (2020) presses the interpretation further, reading the most apocalyptic strain of environmentalism as a quasi-religious narrative—complete with a fall from a natural Eden and an impending secular apocalypse—that supplies meaning, heroism, and moral urgency, and that would help explain the persistence of vivid but weakly supported claims. That interpretation is more speculative and should be held loosely; the documented gap between imagery and data in the polar-bear and assessment cases stands on its own regardless of any psychological account.

The psychological consequences of climate communication are now measurable, and the measurements cut in more than one direction. A meta-analysis of 94 studies and 170,747 adults in 27 countries found that exposure to climate-change information was the second-strongest correlate of climate anxiety ($\rho = 0.45$), behind only future orientation, and that anxiety was associated with greater psychological strain ($\rho = 0.33$) and lower subjective well-being ($\rho = -0.22$), as well as with belief in anthropogenic climate change, perceived risk, and perceived scientific consensus (Kühner et al., 2025). The same anxiety was associated with pro-environmental intentions and collective action ($\rho = 0.52$–0.62), and most of it was sub-clinical: scores on a scale that captures functional impairment averaged 1.8 on a five-point scale, against 3.5 for single-item worry. The authors conclude that climate anxiety is largely adaptive and should not be pathologized, and they advise communicators not to "try to alleviate legitimate worry"—a normative judgment that illustrates how readily values enter the interpretation of correlational data. The studies are cross-sectional, concentrated in Europe, and mostly of modest quality by the authors' own coding, so causal direction cannot be established. What the evidence does support is modest and important: the emotional costs of communication scale with exposure, they are real but mostly not disabling, and the case they make is for accuracy and proportion rather than for either alarm or reassurance.

Risk language should distinguish "alarming" evidence from "alarmist" rhetoric. Risbey (2008) notes that some findings are legitimately alarming, while rhetorical exaggeration can still undermine trust. Claims that climate change will cause near-term human extinction are not supported by the assessment literature, and prominent scientists have rejected them (Shellenberger, 2020). Repeated use of apocalyptic framing can produce fatalism, encourage poorly designed emergency measures, and crowd out practical adaptation. Conversely, minimizing all risk because some advocates exaggerate it is equally unsound.

For nonexperts, Koonin (2021) offers a diagnostic checklist for recognizing distorted communication. Warning signs include pejorative labels such as "denier" or "alarmist" in place of argument; failure to distinguish natural from anthropogenic drivers; appeals to an

undefined “97% consensus”; conflation of weather with multidecadal climate; the omission of magnitudes, baselines, denominators, or uncertainty intervals; alarming analogies presented without scale; and the presentation of conditional model projections as if they were observations or predictions. He particularly cautions against describing worst-case, high-emissions scenarios as “business as usual” without defending their socioeconomic assumptions—a point developed in the next section. None of these tests requires specialized training, and each shifts attention from rhetoric back to evidence.

The checklist is only useful if it is applied to every side, and the contrarian sources examined in this synthesis fail it as plainly as the alarmist ones. An audit that describes openly published calibration choices as “fraud” and “scientific misconduct” and closes with “if it ain’t been proved broke, don’t fix it” substitutes label for argument (Clauser, 2026). A book that calls the late-twentieth-century warming “fake” and the attribution of extremes “all fake news” does the same (Singer et al., 2021). A paper accepted twelve days after submission, with a language model as lead author and co-authors who describe themselves as having steered it toward their own prior publications, does not meet the replication and transparency standards this synthesis demands of the IPCC (Grok 3 beta et al., 2025). A regulatory comment that supports a claim about 600 million years of climate with a chart from a web essay would not pass peer review in any field (Lindzen & Happer, 2026). And a claim that there has been “no warming since 1998” has an expiration date that has now passed. The pathologies Koonin identifies—omitted baselines, conflated timescales, conditional claims presented as findings, pejorative framing—are not the property of one camp. They are what happens when any party stops treating confidence as something that has to be earned.

14 Scenarios, Policy, and Response Under Uncertainty

Climate communication fails when it confuses an emissions pathway with a prediction. Representative Concentration Pathways and Shared Socioeconomic Pathways are conditional scenarios, not assigned probabilities. High-emissions pathways such as RCP8.5 are useful for stress testing, but Koonin (2021) and the Climate Working Group (2025) argue that they have often been presented as “business as usual” despite assumptions about population, coal use, energy intensity, and technology that became increasingly implausible. Using a high-end scenario without labeling its assumptions inflates projected impacts and distorts cost-benefit comparisons.

The opposite error is to dismiss high-end scenarios because they are unlikely. Tail risks matter, especially where adaptation is difficult or irreversible thresholds are plausible. The proper practice is transparent scenario weighting: present central, low, and high pathways; separate scenario uncertainty from model uncertainty; and show how conclusions change when extreme assumptions are removed. A robust policy should perform reasonably across a range of plausible futures rather than depend on one favored trajectory.

A related error, characteristic of the contrarian literature, is to demand proof before action. Singer, Revelle, and Starr argued in 1992 that "the scientific base for a greenhouse warming is too uncertain to justify drastic action at this time" and that "there is little risk in delaying policy responses," because understanding would improve within a decade (reprinted in Singer et al., 2021); Clauser (2026) ends his audit with the maxim that nothing should be fixed until it has been "proved broke." Proof is the wrong standard. Decisions under uncertainty are made on expected costs and benefits, and both the costs of action and the costs of inaction carry distributions rather than point values. The 1992 prediction has also been tested by three decades of data: the heat accumulated, the warming continued at roughly the rate the forcing framework implied, and the energy imbalance grew. What remains valuable in that essay is not its counsel of delay but its list of measures that "make sense even if the greenhouse effect did not exist"—pricing externalities, removing subsidies, nuclear power, efficiency where it pays—which overlaps substantially with the portfolio recommended below.

Beyond scenario labeling, Koonin (2021) frames the response problem by separating what society could do, what it should do, and what it will do. The first question is scientific and technological, the second turns on contested values and distributive judgments, and the third depends on political and economic feasibility. His central forecast is that deep global mitigation will prove far harder than policy rhetoric implies. Because atmospheric carbon-dioxide concentration reflects cumulative emissions and excess carbon dioxide persists for centuries, merely reducing annual emissions slows the growth of concentration; stabilization requires net emissions to approach zero, plausibly around the middle of the century for the Paris temperature targets. Yet world energy demand is projected to rise by roughly half by midcentury, concentrated in developing economies, while fossil fuels still supply about four-fifths of primary energy. The Paris Agreement, in this reading, is a mechanism of nonbinding, nationally determined, self-reported pledges without enforcement, and the gap between pledged emissions and pathways compatible with its temperature targets is large. Unilateral controls also invite carbon leakage as energy-intensive production relocates, and developing states rationally prioritize energy access,

sanitation, and growth unless low-emission technologies become cost-competitive or wealthier countries finance the transition at a far greater scale.

If rapid global decarbonization proves improbable, three contingency responses deserve analysis. Koonin (2021) surveys solar radiation management, carbon dioxide removal, and adaptation. Stratospheric aerosol injection could in principle cool the planet quickly and at modest direct cost, but it would require indefinite maintenance, risk a "termination shock" if halted, produce spatially uneven effects on temperature and precipitation, and raise acute governance problems, including unilateral deployment by a single state or wealthy actor. Carbon dioxide removal reverses atmospheric loading more directly but faces daunting scale: removing on the order of ten gigatonnes annually at costs above one hundred dollars per tonne implies expenditures around a trillion dollars per year, together with vast transport and sequestration infrastructure, while biological uptake through reforestation is slower and constrained by land, permanence, and ecology. Adaptation, by contrast, is cause-agnostic, incremental, local, politically tractable, and effective against both natural and anthropogenic change. Koonin proposes an "adaptation wedges" framework in which interventions are compared by hazard, geography, cost, efficacy, and interaction with mitigation, and recommends prioritizing resilience to hazards already observed while strengthening development and governance in poorer countries. Adaptation as the dominant practical response, with mitigation and exploratory geoengineering research as complements, is a recurring conclusion of the skeptical literature—including Singer's (Singer et al., 2021)—and it is one on which the skeptical and mainstream assessments are closer than their rhetoric suggests.

The relationship between energy and human welfare is central to any realistic policy. Shellenberger (2020) argues that affluence and per-capita energy use are tightly coupled, that apparent emissions reductions in wealthy countries partly reflect the offshoring of energy-intensive manufacturing and its embodied emissions, and that "energy leapfrogging"—the hope that poor countries can reach high incomes using substantially less energy than earlier industrializers—is not well supported by cross-national experience, in part because efficiency gains lower the effective price of energy services and stimulate additional consumption through rebound effects. He emphasizes energy density and power density as organizing variables: the historical progression from biomass to coal, then toward oil, natural gas, and nuclear power, reduces the mass and land required to deliver useful energy and can move combustion away from households, improving indoor air quality. The same substitution logic, associated with the work of Cesare Marchetti, describes how superior technologies displace inferior ones before the older resource is exhausted—kerosene and

later vegetable oils displaced whale oil, sparing whales well before the 1982 moratorium—implying that decarbonization is more likely to succeed by making low-carbon energy cheaper and denser than by mandating scarcity.

This perspective also bears on development policy. Shellenberger (2020) contends that reliable grids, industrial capacity, transportation, irrigation, and large-scale generation are prerequisites for escaping poverty, and criticizes a late-twentieth-century shift in development financing toward small-scale, decentralized interventions that can provide household lighting but not the firm power required for manufacturing, modern hospitals, water treatment, or mechanized agriculture. He situates contemporary alarmism within a long neo-Malthusian tradition—from Malthus through later writers who successively relocated the binding limit from food to minerals, energy, pollution sinks, and climatic stability—and argues that this tradition has repeatedly underestimated technological adaptation; Singer made the same argument in the same terms (Singer et al., 2021). Against it he sets the work of Ester Boserup, who treated population pressure as a spur to agricultural innovation, and Amartya Sen, who showed that famine typically results from entitlement failure and distributional collapse rather than absolute scarcity. The policy implication is that infrastructure, markets, and productive capacity—not fixed natural ceilings—are the principal determinants of human vulnerability, and that poverty reduction is itself an environmental strategy, because prosperous societies can better afford conservation, adaptation, and cleaner energy.

The importance of prioritizing large mitigation levers over symbolic ones is illustrated by agriculture. Shellenberger (2020) notes that although dietary-change campaigns are prominent, their mitigation potential is modest: agricultural emissions are a limited share of the total, and even large shifts toward vegetarian diets reduce personal or national emissions only slightly once economy-wide accounting and rebound effects are included, leaving energy-system decarbonization as the dominant lever. Combined with the land-use efficiency of intensive production discussed earlier, this suggests that the environmentally favorable path in food, as in energy, runs through productivity gains rather than de-intensification. The general methodological proposition is that policies and technologies should be compared as complete alternatives—by lifecycle emissions, land footprint, power density, reliability, cost, and scalability—rather than judged against an unattainable zero-impact baseline.

Policy should be evaluated as a portfolio. Emissions reduction can lower long-term forcing, especially when adopted broadly and sustained. Adaptation reduces near-term harm regardless of the precise attribution of a hazard. Research and development can lower the

future cost of clean energy, storage, industrial heat, carbon capture, advanced nuclear power, and low-carbon fuels. Resilient infrastructure, water systems, fire management, crop innovation, and disease control address impacts directly. Nature-based measures can provide carbon, watershed, and habitat benefits, though their permanence and land requirements must be assessed (Wang et al., 2023).

Energy reliability and affordability are not side issues. Air conditioning, heating, refrigeration, hospitals, water treatment, communications, and modern agriculture reduce climate vulnerability. The Climate Working Group (2025) reports that excess mortality associated with very hot U.S. days declined sharply after 1960, largely through air conditioning. Policies that raise energy prices or reduce reliability can therefore impose health costs, particularly on low-income households. This does not favor fossil energy indefinitely; it favors transitions that preserve or improve energy services.

National policies must also be judged by scale and leakage. Carbon dioxide is globally mixed, so unilateral reductions slow the accumulation rate rather than rapidly lowering concentration. The Climate Working Group (2025) estimates that eliminating emissions from U.S. cars and light trucks, about 3% of global energy-related carbon dioxide, would reduce the global warming trend by at most a similar percentage if not offset elsewhere. The precise calculation depends on the baseline and policy response, but the qualitative point is sound: climate benefits require international participation, and domestic policy should account for relocation of industry and emissions.

A skeptical policy framework is not a case for inaction. It is a case for proportionality, sequencing, and accountability. High-value actions include eliminating subsidies that encourage risky development; pricing externalities where administratively feasible; funding basic and applied energy research; expanding transmission and firm low-carbon generation; improving methane control where leakage is measurable; modernizing grids; protecting critical infrastructure; and strengthening adaptive capacity in poorer regions. Policies should be revised when costs exceed forecasts or benefits fail to appear.

The precautionary principle applies to both climate change and climate policy. Continued high emissions create long-lived risks, but rapid restructuring can create energy poverty, fiscal strain, land-use conflict, mineral dependence, and reliability failures. The rational response is not to choose one precaution and ignore the other. It is to compare them openly.

15 What Can Be Said with High Confidence

The propositions below are those that survive the strongest objections examined in this synthesis. Each is supported by multiple independent lines of evidence, and each is conceded, in substance, by the critics' own calculations or data once those are read in full.

1. **1. The greenhouse effect is real and quantitatively important.** Carbon dioxide absorbs infrared radiation; its forcing is logarithmic, not saturated; and a doubling produces a direct forcing near 3.7–4 W m^{-2}, of which the industrial-era rise has already supplied about 2.3 W m^{-2}. Feedbacks determine the larger temperature response. The critics' own line-by-line calculations reproduce the forcing and imply 1.4–2.3°C of clear-sky warming per doubling (Koonin, 2021; Lindzen, 1997; Myhre et al., 1998; van Wijngaarden & Happer, 2020).
2. **2. The modern carbon-dioxide rise is anthropogenic.** The atmosphere gains about half of what is emitted and the ocean and biosphere absorb the rest, so the natural system is a net sink and cannot be the source; isotopic change, oxygen decline, ocean carbon accumulation, and hemispheric gradients independently confirm fossil combustion and land-use change as the cause. The residence-time objection conflates molecular turnover with the removal of an excess (IPCC, 2021; Köhler et al., 2018; Koonin, 2021).
3. **3. The climate system has warmed, and it is retaining energy.** Surface networks, two satellite groups, radiosondes, ocean heat content, sea level, glacier mass, and sea ice provide independent evidence of warming, and the planet's energy imbalance—measured independently by satellite and by the Argo float network, which agree—roughly doubled between 2005 and 2019. Warming is unequivocal, and the energy accumulation cannot be an artifact of station siting or homogenization (IPCC, 2021; Loeb et al., 2021; Rohde & Hausfather, 2020; von Schuckmann et al., 2023).
4. **4. Human forcing is the principal cause of the warming since the mid-twentieth century.** The IPCC's best estimate assigns approximately 1.07°C of the 2010–2019 warming relative to 1850–1900 to human influence, with a likely range of 0.8–1.3°C; the measured Sun has supplied no additional energy over the period in which the imbalance grew; and the observational sensitivity estimates that constrain the response to be modest presuppose that the forcing is anthropogenic. The magnitude is uncertain to a few tenths of a degree; the sign and dominance are not (IPCC, 2021; Lewis & Curry, 2018; Loeb et al., 2021).

5. **5. Some consequences are already detectable.** Hot extremes have increased across most assessed land regions, cold extremes have decreased, the ocean has accumulated heat, glaciers and Arctic sea ice have declined, sea-level rise has accelerated since the 1960s, and ice sheets are losing mass. Attribution is strongest at large scales and weaker for many regional hazards (Dangendorf et al., 2019; IPCC, 2021; Shepherd et al., 2018).
6. **6. Human outcomes are mediated by exposure, vulnerability, and adaptation.** Development, infrastructure, warnings, energy access, and land management can substantially reduce mortality and losses even under changing hazards; net temperature-related mortality has fallen this century even as attributable heat deaths have risen (Climate Working Group, 2025; Koonin, 2021; Shellenberger, 2020; Zhao et al., 2021).

16 What Remains Materially Uncertain

1. **1. Climate sensitivity and feedback tails.** Clouds, aerosols, ocean heat uptake, and pattern effects leave a consequential range in ECS and TCR. Observationally constrained energy-budget estimates and reanalyzed Bayesian assessments cluster below the upper half of the model range, while some high-sensitivity models warm too rapidly and very low estimates face other observational constraints (Climate Working Group, 2025; Koonin, 2021; Lewis, 2023; Lewis & Curry, 2015, 2018; Stephens, 2005).
2. **2. The exact partition between forced change and multidecadal variability.** The long-term human contribution is strong, but internal ocean-atmosphere modes can materially alter regional and decadal trends, and the cause of the post-2015 albedo decline is unresolved (Climate Working Group, 2025; IPCC, 2021; Koonin, 2021).
3. **3. Regional precipitation, circulation, and many extremes.** Model skill is uneven for tropical rainfall, drought, floods, cyclones, tornadoes, blocking, and wildfire. The IPCC's own confidence for many of these hazards is medium or low, and event-attribution estimates are conditional on model and statistical choices (Climate Working Group, 2025; IPCC, 2021; Koonin, 2021).
4. **4. High-end ice-sheet and sea-level outcomes.** Continued and accelerating rise is expected, but the probability and timing of rapid dynamic ice loss remain deeply uncertain. Local relative sea level also depends strongly on vertical land motion (Climate Working Group, 2025; Koonin, 2021).
5. **5. Net ecological and agricultural effects.** Warming, fertilization, water stress, nutrient constraints, pests, adaptation, and land management interact. Global greening is real,

but its ecological quality and persistence are not captured by leaf area alone, and agricultural land use has in fact contracted in many regions through intensification (IPCC, 2021; Shellenberger, 2020; Zhu et al., 2016).

6. **6. The net human-health balance at the margin.** Attributable heat, smoke, and vector-borne deaths are measurable and rising, cold-related deaths are falling, and the attribution literature is geographically narrow and excludes averted deaths by design. The marginal effect of additional warming on a population whose vulnerability is changing is not yet well constrained (Carlson et al., 2025; Gasparrini et al., 2015; Zhao et al., 2021).
7. **7. Economic damages and optimal policy.** Discounting, growth, adaptation, technological change, damage functions, and international participation dominate many cost-benefit results. Social-cost estimates are conditional rather than directly observed, and the feasibility, cost, and distributional effects of rapid mitigation are themselves uncertain (Climate Working Group, 2025; Koonin, 2021; Lomborg, 2020).

17 Toward Epistemic Humility and Adaptive Governance

Climate science has achieved genuine successes. The radiative mechanism was identified long before modern warming, the anthropogenic carbon signal is measurable, the planet's energy imbalance is now tracked by two independent observing systems, and multiple components of the Earth system have changed in physically coherent ways. These achievements justify concern and continued mitigation. They do not justify treating every model output, impact estimate, or policy prescription as equally established.

A more reliable scientific culture would disclose tuning choices, evaluate models against out-of-sample observations, publish absolute as well as anomalous fields, distinguish ensemble spread from probability, and test attribution under alternative estimates of internal variability. It would report when models fail, reward replication, and resist selective time windows. Yang et al. (2021) found low statistical power and effect-size exaggeration in field studies of global-change biology, reinforcing the need for preregistration, data transparency, and publication of null results beyond climate modeling itself. The same culture would hold dissent to the same standard: a critique that would overturn the carbon budget needs to show where the carbon went, and a critique that would overturn the energy imbalance needs to explain the Argo record.

Koonin (2021) proposes a specific institutional reform to serve these ends: formal adversarial, or "Red Team," review of major climate assessments. A technically qualified team would be charged with identifying weak assumptions, omitted evidence, inferential gaps, and sensitivity to model or scenario choices, and the assessment's authors would respond, with the exchange made public. He grounds the proposal in a distinction between peer review of individual research papers—which evaluates a focused contribution and is followed, ideally, by replication or refutation—and review of assessment reports, which select, weight, and synthesize thousands of studies for nonexpert decision-makers, so that authorship, narrative structure, and uncertainty language become decisive. Because governments can select assessment authors, impose few conflict-of-interest constraints, and negotiate the final wording of Summaries for Policymakers, conventional peer review of the underlying literature does not, in his view, independently validate the high-level synthesis. The two opposed government-commissioned reviews of 2025 (Climate Working Group, 2025; National Academies of Sciences, Engineering, and Medicine, 2025) are an unplanned version of this experiment, and their principal lesson is that the exercise is most valuable when the two sides are required to engage each other's strongest evidence rather than to publish past one another. The aim of a Red Team is not to reject mainstream findings but to separate conclusions robust to challenge from those dependent on fragile assumptions or rhetorical compression—an objective consonant with, rather than opposed to, scientific norms.

Policy institutions should mirror that humility. Decisions can be robust without pretending uncertainty has disappeared. Coastal defenses can be designed in stages; building codes can incorporate safety margins; energy systems can diversify rather than bet on a single technology; and emissions policy can use periodic review clauses tied to observed costs, technology, and climate response. Adaptation is not surrender, and mitigation is not proof of catastrophe. They are complementary forms of risk management.

The central question is no longer whether humans influence climate. They do, through greenhouse gases, aerosols, and land-use change, and the strongest contrarian arguments, examined at full strength, leave that conclusion where it was. The more difficult questions are how large the response will be, how impacts will be distributed, which risks deserve priority, and which interventions will reduce total harm rather than merely signal concern. Those questions remain open enough to require skepticism and mature enough to require action.

The scientifically defensible position is therefore neither complacency nor panic. It is calibrated confidence: strong where multiple independent observations and physical

mechanisms converge; provisional where results depend on tuned models or short records; and explicitly conditional where policy outcomes depend on economic and technological assumptions. Such a framework can support emissions reduction, adaptation, prosperity, and environmental stewardship without demanding ideological conformity or false certainty.

Transparency and Openness

Generative artificial intelligence. Claude Opus 4.8, Claude Fable 5.1, GPT-5.6 Sol, GPT-6, and Grok 4.3 were used in preparing initial drafts of the manuscript, in revision, and for proofreading. The author reviewed and edited all output and takes responsibility for the content.

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