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Special Report

The 2024 state of the climate report: Perilous times on planet Earth

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We are on the brink of an irreversible climate disaster. This is a global emergency beyond any doubt. Much of the very fabric of life on Earth is imperiled. We are stepping into a critical and unpredictable new phase of the climate crisis. For many years, scientists, including a group of more than 15,000, have sounded the alarm about the impending dangers of climate change driven by increasing greenhouse gas emissions and ecosystem change (Ripple et al. 2020). For half a century, global warming has been correctly predicted even before it was observed—and not only by independent academic scientists but also by fossil fuel companies (Supran et al. 2023). Despite these warnings, we are still moving in the wrong direction; fossil fuel emissions have increased to an all-time high, the 3 hottest days ever occurred in July of 2024 (Guterres 2024), and current policies have us on track for approximately 2.7 degrees Celsius (°C) peak warming by 2100 (UNEP 2023). Tragically, we are failing to avoid serious impacts, and we can now only hope to limit the extent of the damage. We are witnessing the grim reality of the forecasts as climate impacts escalate, bringing forth scenes of unprecedented disasters around the world and human and nonhuman suffering. We find ourselves amid an abrupt climate upheaval, a dire situation never before encountered in the annals of human existence. We have now brought the planet into climatic conditions never witnessed by us or our prehistoric relatives within our genus, *Homo* (supplemental figure S1; CenCO2PIP Consortium et al. 2023).

Last year, we witnessed record-breaking sea surface temperatures (Cheng et al. 2024), the hottest Northern Hemisphere extratropical summer in 2000 years (Esper et al. 2024), and the breaking of many other climate records (Ripple et al. 2023a). Moreover, we will see much more extreme weather in the coming years (Masson-Delmotte et al. 2021). Human-caused carbon dioxide emissions and other greenhouse gases are the primary drivers of climate change. As of 2022, global fossil fuel combustion and industrial processes account for approximately 90% of these emissions, whereas land-use change, primarily deforestation, accounts for approximately 10% (supplemental figure S2).

Our aim in the present article is to communicate directly to researchers, policymakers, and the public. As scientists and academics, we feel it is our moral duty and that of our institutions to alert humanity to the growing threats that we face as clearly as possible and to show leadership in addressing them. In this report, we analyze the latest trends in a wide array of planetary vital signs. We also review notable recent climate-related disasters, spotlight important climate-related topics, and discuss needed policy interventions. This report is part of our series of concise annual updates on the state of the climate.

Recent trends in planetary vital signs

In 2023, various historical temperature and ice extent records were broken by enormous margins (figure 1; Ripple et al. 2023a). Both global and North Atlantic sea surface temperatures were far above their 1991–2024 averages for much of the year—a pattern that has continued well into 2024 (figure 1a, 1b). Although Antarctic and global sea ice extent have now come into range of previous years, they remain well below their 1993–2024 averages (figure 1c, 1d). Global daily mean temperatures were at record levels for nearly half of 2023 and much of 2024 (figure 1e). On our current emissions trajectory, we may regularly surpass current temperature records in future years (Matthews and Wynes 2022).

Of the 35 planetary vital signs we track annually (figures 2 and 3), 25 are at record levels (supplemental table S1). The global failure to support a rapid and socially just fossil fuel phasedown has led to rapidly escalating climate-related impacts (table 1). Below, we focus on variables that have either changed greatly or are at record extremes.

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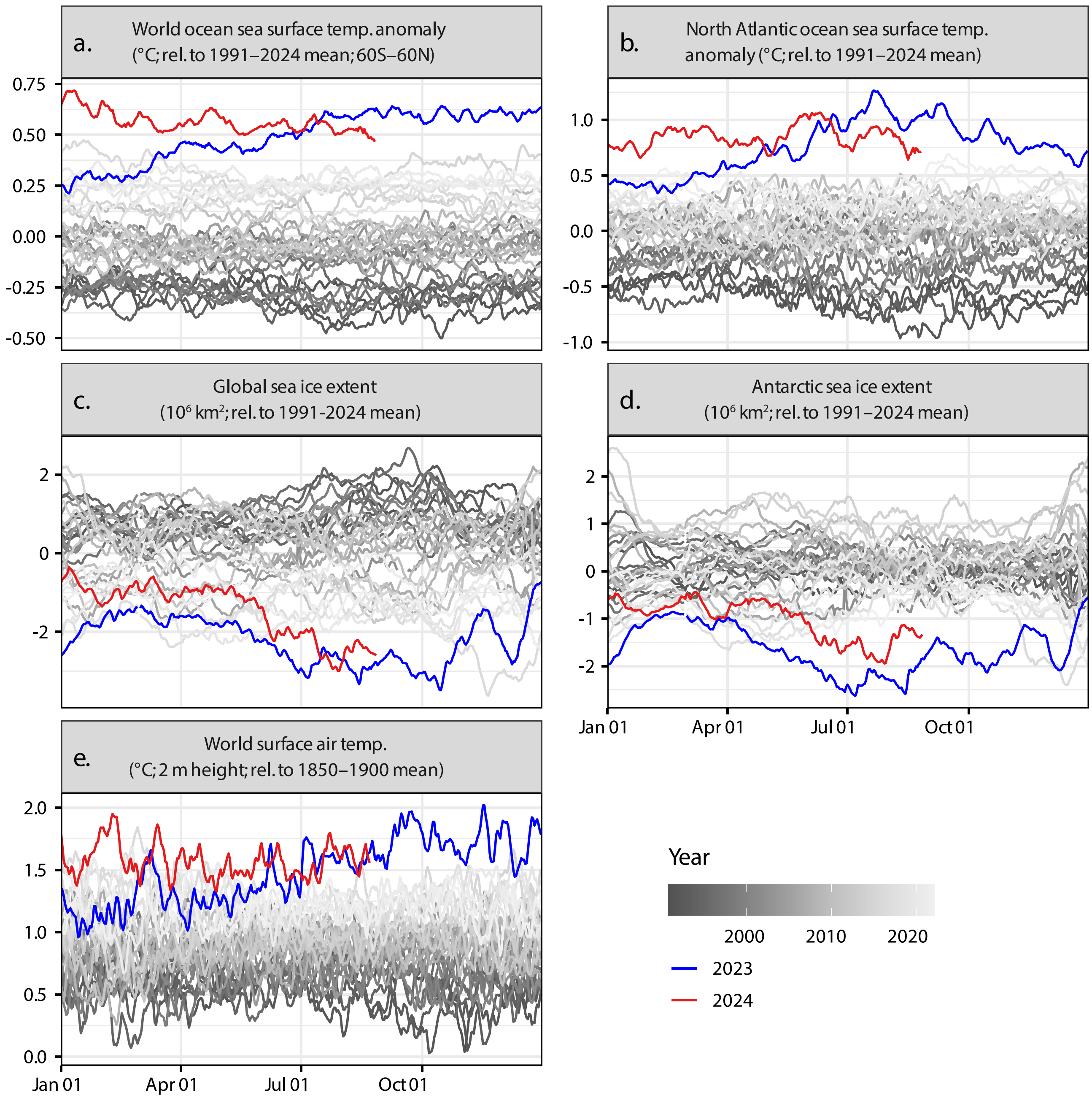

Figure 1. Unusual climate anomalies in 2023 and 2024. Ocean temperatures (a, b) are presently far outside their historical ranges. These anomalies reflect the combined effect of long-term climate change and short-term variability. Sources and additional details about each variable are provided in supplemental file S1. Each line corresponds to a different year, with darker gray representing later years. All of the variables shown are daily estimates.

The human enterprise

Our graphical account illustrates how humanity's collective size and consumption patterns continued to accelerate on multiple fronts. Although fertility rates were down slightly to a record low in 2023, other variables set all-time record highs, including human population, ruminant livestock population, per capita meat production, and gross domestic product (GDP; figure 2a–2e). Human population and ruminant livestock population have been increasing at approximately 200,000 and 170,000 per day respectively. Decoupling the growth in all of these variables with greenhouse gas emissions may be difficult (Ripple et al. 2024).

Energy

Fossil fuel consumption rose by 1.5% in 2023 relative to 2022 (figure 2h), mostly because of substantial increases in coal consumption (1.6%) and oil consumption (2.5%; figure 2h). Renewable energy use also grew in 2023, with solar and wind consumption together rising 15% relative to 2022 (figure 2h). Much of this growth can be attributed to the fact that renewable energy is often cheaper than comparable new fossil fuel alternatives (Roser 2020). However, fossil fuel consumption remains roughly 14 times greater than solar and wind energy consumption (figure 2h) and recent growth in the renewable share of electricity generation

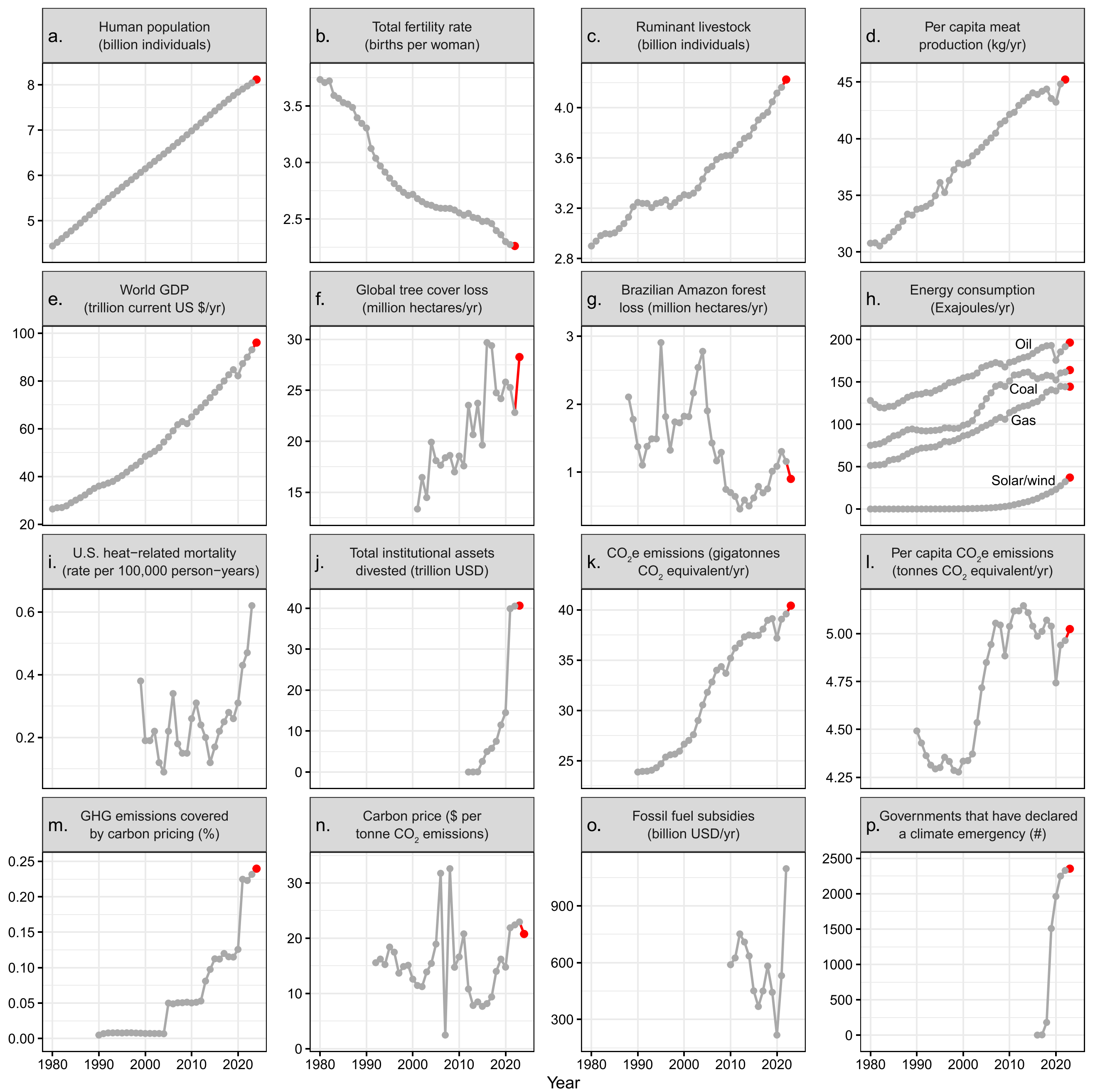

Figure 2. Timeseries of climate-related human activities. The data obtained since the publication of Ripple and colleagues (2023a) are shown in red (dark gray in black and white). In panel (f), tree cover loss does not account for forest gain and includes loss due to any cause. For panel (h), hydroelectricity and nuclear energy are shown in supplemental figure S3. Sources and additional details about each variable are provided in supplemental file S1.

mostly covered increased demand, instead of replacing fossil fuels (REN21 2024).

Forests

Global tree cover loss rose from 22.8 megahectares (Mha) per year in 2022 to 28.3 Mha per year in 2023, reaching its third-highest level (figure 2f); this was at least partly because of wildfires, which caused tree cover loss to reach a record high of 11.9 Mha (figure 3n). High rates of tree cover loss can drive a set of related feedback loops, wherein the loss of forest carbon sequestration leads to additional warming, which can drive further losses in carbon sequestration and so on (Ripple et al. 2023b, Goldman and Carter 2024). This type of climate carbon feedback process could limit the success of some natural climate solutions. In 2023, there was also a dramatic decline in the land carbon sink according to Ke and colleagues (https://doi.org/10.48550/arXiv.2407.12447 [preprint: not peer reviewed]). On a more positive note, the deforestation rate in the Brazilian Amazon continued to decline, dropping from 1.16 Mha in 2022 to 0.90 Mha in 2023 (figure 2g). This decrease may be partly because of the shifting policies of Brazil's government (Vilani et al. 2023) and comes at a critical time given that the Amazon may be nearing a tipping point where a loss of resilience and positive feedback loops contribute to large-scale forest dieback (Boulton et al. 2022, Flores et al. 2024).

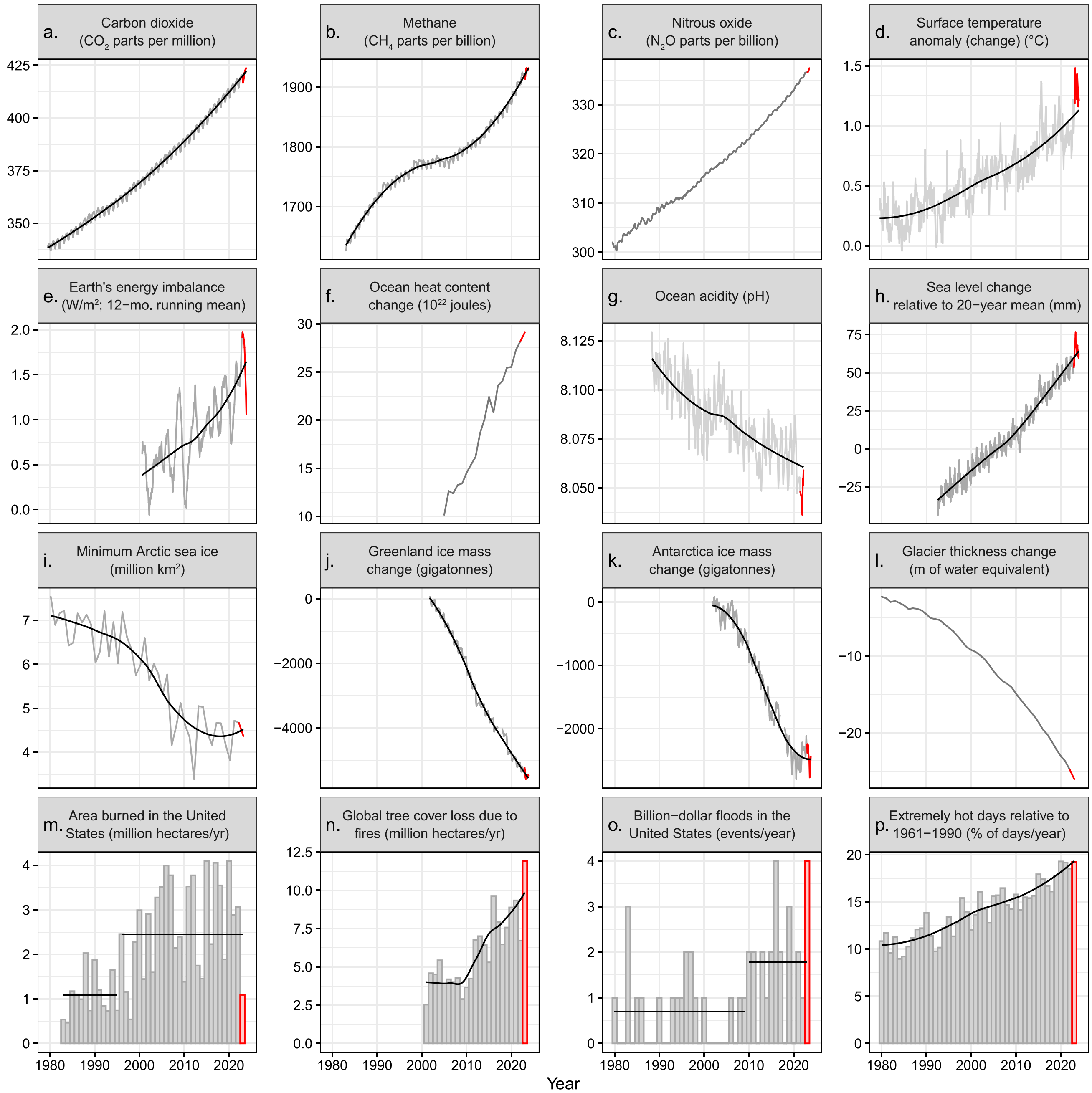

Figure 3. Timeseries of climate-related responses. The data obtained before and after the publication of Ripple and colleagues (2023a) are shown in gray and red (dark gray in black and white), respectively. For area burned (m) and billion-dollar flood frequency (o) in the United States, the black horizontal lines show changepoint model estimates, which allow for abrupt shifts (see the supplement). For other variables with relatively high variability, local regression trendlines are shown in black. The variables were measured at various frequencies (e.g., annual, monthly, weekly). The labels on the x-axis correspond to midpoints of years. Billion-dollar flood frequency (o) is influenced by exposure and vulnerability in addition to climate change. Sources and additional details about each variable are provided in supplemental file S1.

Global greenhouse gases and temperature

Annual energy-related emissions increased 2.1% in 2023, and are now above 40 gigatons of carbon-dioxide-equivalent for the first time (figure 2k). The top three emitting countries are China, the United States, and India, which, together, account for over half of global emissions (supplemental table S2). Anthropogenic emissions of aerosol pollutants are declining; because these aerosols have a net cooling effect, this reduction may be causing the rate of global warming to accelerate (Hansen et al. 2023). On the basis of global year-to-date averages, the concentrations of carbon dioxide and methane are at record highs (figure 3a, 3b). Carbon dioxide levels were recently observed to be surging (NOAA 2024). Furthermore, the growth rate of methane emissions has been accelerating, which is very troubling (Shindell et al. 2024). Nitrous oxide is also at a record high (figure 3c); annual anthropogenic emissions of this potent long-lived greenhouse gas have increased by roughly 40% from 1980 to 2020 (Tian et al. 2024).

Surface temperature is at a record high, and 2024 is expected to be one of the hottest years ever recorded (figure 3d). Each 0.1°C of global warming places an extra 100 million people (or more)

Table 1. Recent climate disasters in November 2023 or later.

Timeframe	Climate disaster
November 2023	Storm Bettina over Black Sea brought heavy snowfall and rainfall to several countries along the Black Sea, affecting more than 2.5 million people and causing 23 fatalities. The burning of fossil fuels was responsible for an approximately twofold increase in the likelihood of this level of precipitation (Zachariah et al. 2024a).
February 2024	Wildfires in Chile killed at least 131 people and destroyed more than 14,000 homes. Climate change may have contributed to these fires by increasing the frequency and intensity of droughts and heatwaves, although other factors may have been involved, including El Niño and the loss of natural forests.
March–April 2024	Extreme heat affected a large portion of North Africa and the Sahel, potentially killing hundreds or thousands of people. Heat waves of this magnitude likely could not have occurred in the absence of climate change (Barnes et al. 2024a).
April 2024	Heavy rain led to flash floods in the Persian Gulf region, killing at least 33 people. Climate change probably exacerbated this rainfall.
March–May 2024	Heavy rainfall in East Africa caused severe flooding that killed hundreds and affected more than 700,000 people. This region has seen an increase in observed rainfall over the past 15 years that is at least partly attributable to climate change (Kimutai et al. 2024).
April–May 2024	Many regions of Asia experienced devastating heatwaves, with approximately 1,500 heat stroke fatalities in Myanmar alone (Pearce and Ware 2024). As part of the longest heat wave ever recorded in India, temperatures reached 50°C in some areas and heat-related illnesses resulted in at least 60 deaths. Climate change is making such heat waves more frequent and extreme in some parts of Asia (Zachariah et al. 2024b).
April–May 2024	Extensive flooding in southern Brazil devastated 478 cities, killed 173 people, and left 38 people missing, 806 injured, and 423,486 displaced. The estimated cost of the cleanup is US$3.7 billion (Malabarba et al. 2024). It was estimated that climate change roughly doubled the likelihood of the extreme rainfall that caused these floods (Clarke et al. 2024).
May 2024	A wind storm in Texas, United States killed 5 people and left more than 600,000 people without power. Climate change may be making straight-line wind storms such as this one more frequent and intense.
May 2024	Severe Cyclonic Storm Remal killed at least 84 people in India and Bangladesh. Climate change has led to an increase in the frequency and intensity of such severe storms.
May–June 2024	Mexico and nearby areas faced extreme heat; at least 125 people have died in Mexico because of heat-related illnesses this year. Climate change is increasing the frequency of such extreme heat waves (Pinto et al. 2024).
June 2024	At least 1,170 pilgrims died in Saudi Arabia during an intense heat wave with temperatures reaching over 50 C. Climate change is contributing to heat waves such as this one.
June 2024	Heavy rainfall in Bangladesh caused landslides that killed at least nine people and floods that left nearly 2 million people stranded. Climate change has increased the intensity of floods in this region.
June 2024	Devastating wildfires burned roughly 440,000 hectares in the Brazilian Pantanal wetlands, threatening economic activities and killing many wild animals. Climate change is estimated to have caused a 40% increase in the intensity of the weather conditions that drove these wildfires (Barnes et al. 2024b).
July 2024	Hurricane Beryl was an exceptionally strong Atlantic hurricane that affected parts of the Caribbean, United States, and Yucatán Peninsula; it killed 64 people and caused more than US$5 billion in damages. Climate change may have contributed to Beryl rapidly intensifying and reaching Category 5 status despite occurring relatively early in the hurricane season.
July 2024	A deadly heatwave in the Mediterranean resulted in at least 23 fatalities. It is highly likely that climate change contributed to the extreme temperatures that were observed.
August 2024	Hurricane Debby was a slow-moving hurricane that caused extensive flooding in the Southeastern United States and killed at least 10 people. Climate change has been linked to increasing hurricane rainfall and intensification rates and may be involved in the slowing of U.S. hurricanes.

Note: We list numerous recent disasters that may be at least partly related to climate change. This list is not intended to be exhaustive. Because of the recent nature of these events, our sources often include news media articles. For each event, we generally provide references indicating that the likelihood or strength of such an event may have increased because of anthropogenic climate change. References to scientific articles are given directly in the table, and links to news articles are provided in supplemental file S1. Some of these climate disasters may be at least partly related to changes in jet streams (Stendel et al. 2021, Rousi et al. 2022).

into unprecedented hot average temperatures (Lenton et al. 2023). On our current trajectory, future years will almost certainly be even hotter, because our climate continues to shift away from conditions associated with human thriving for much of Earth's population (Vecellio et al. 2023). Even in the most optimistic scenarios, large-scale climate adaptation efforts will be needed, particularly for the most vulnerable populations (Ripple et al. 2022).

Oceans and ice

Ocean acidity and ocean heat content are both at record extremes (figure 3f, 3g), which has led to various ocean-related climate impacts. For example, heat waves in 2021 and 2023 caused marine animal mass mortality events (White et al. 2023, Goreau and Hayes 2024). In addition, the average global sea level is presently at a record high, mostly because of both overall warming and a strong El Niño in 2023 and part of 2024 (figure 3h; Lee 2024).

Continued sea level rise has the potential to displace hundreds of millions of people over the course of the century (Kulp and Strauss 2019). Melting continental ice contributes about half to sea level rise (Horwath et al. 2021), and the latest data indicate that Greenland's ice mass, Antarctica's ice mass, and the average glacier thickness are all at record lows (figure 3j–3l).

Climate impacts and extreme weather

Climate-related extreme weather and disasters are contributing greatly to human suffering (figure 4). Increasing heat and rainfall extremes are now far outside the historical climate (Robinson et al. 2021). The rapid increase in average global temperatures (figure 1e) has led to a massive rise in the incidence of heat extremes (figure 3p). This is linked to many adverse human outcomes, including direct mortality, increased healthcare costs, mental health issues, and deaths from cardiorespiratory diseases (Ebi et al. 2021). Climate change has already contributed to billions of people facing extreme heat (Arrighi et al. 2024). Heat-related mortality is rising rapidly in the United States (Figure 2i); the number of heat-related deaths increased by 117% from 1999 to 2023 (Howard et al. 2024). Last year, there were four billion-dollar floods in the United States (a tie for the record; figures 3o and S4). Since the publication of our last report (Ripple et al. 2023a), numerous other major climate-related disasters have occurred, including a series of heat waves across Asia that killed more than a thousand people and led to temperatures reaching 50°C in some parts of India (table 1). Because the Earth system is strongly nonlinear, extreme weather and disaster rates can increase dramatically in response to global warming, including impacts on plant and animal life (figure 3m, 3o and supplemental figures S4 and S5; Calvin 2019, Robinson et al. 2021).

Climate spotlight

In the present section, we spotlight recent developments in various different climate-related areas: coral bleaching, toxic orange rivers, solar radiation modification (SRM) research, climate scientists' opinion on global temperatures, climate change as a social justice issue, climate feedback loops and tipping points, and the risk of societal collapse.

Coral bleaching

Coral reefs benefit millions of people by providing a wide range of ecosystem services, including coastal protection, improved water quality, fisheries, and tourism opportunities; they also provide habitat for many species (Woodhead et al. 2019). Climate change is a particularly serious threat to coral reefs (Hoegh-Guldberg et al. 2017). Warm-water coral death is sometimes preceded by bleaching—the loss of a symbiotic relationship with microalgae (figure 5a; Hoegh-Guldberg et al. 2017). When a sharp spike in sea temperature unfolds well above the long-term average summer maximum, many corals die quickly within a week or two without having time to bleach. Others bleach and either die more slowly over a period of a few months or regain their color and survive (Hughes et al. 2018). As of 2024, extraordinarily warm ocean temperatures (figure 1a) are driving the fourth global-scale coral bleaching event ever recorded (previous events: 1998, 2010, 2014–2017; Thiem 2024).

Toxic orange rivers

Climate change in the Arctic is altering watershed hydrology and water biogeochemistry. Recently, researchers have observed an emergent threat in Arctic streams that turned orange because of increased iron and toxic metals (figure 5b). This discoloration began in the last decade, coinciding with rapid global warming and permafrost thaw (O'Donnell et al. 2024). Compared with clear streams, orange streams are more acidic, have higher turbidity, and have elevated sulfate, iron, and trace metals. This discoloration correlates with declines in macroinvertebrate diversity and fish abundance, affecting drinking water and subsistence fisheries in rural Alaska (O'Donnell et al. 2024).

Solar radiation modification research

SRM research, also known as *solar geoengineering research*, has been dramatically increasing in recent years (figure 5c). It involves potentially risky techniques to reflect sunlight away from Earth to mitigate climate change effects. General categories of SRM include atmospheric, terrestrial, and space-based applications (Keith 2020). Specific methods, for example, include injecting aerosols into the stratosphere or brightening marine clouds. The Intergovernmental Panel on Climate Change (IPCC) has concluded that stratospheric aerosol injection is the most-researched SRM method, but there are a number of environmental concerns (IPCC 2018, Visioni et al. 2020). SRMs are also controversial because of potential unintended consequences and ethical concerns. Critics argue that it is misguided and may disrupt weather patterns and deter emissions reduction efforts (Whyte 2018). However, research continues to explore its feasibility and risks. SRM is often seen as a temporary, potentially important solution to both reduce warming and corresponding damages including for the highly important and fast-warming subpolar regions (Smith et al. 2022). Research into solar geoengineering needs to focus on understanding the potential environmental, social, and geopolitical impacts, as well as assessing effectiveness and safety on both regional and global scales (Sovacool et al. 2022). In addition, interdisciplinary research is required to explore ethical, legal, and governance frameworks, along with public perception and acceptance, while emphasizing the critical importance of drastically reducing greenhouse gas emissions. There is a consensus study available as a roadmap for solar geoengineering research and research governance (National Academies of Sciences, Engineering, and Medicine 2021).

Climate scientists' opinion on global temperatures

A 2024 opinion poll has unveiled the predictions of hundreds of prominent climate scientists of the IPCC, senior authors, and review editors (380 respondents). From a personal perspective, nearly 80% of these scientists anticipate global temperatures increasing by at least 2.5°C above preindustrial levels by the end of the century (Carrington 2024). Nearly half of them foresee a rise of at least 3°C. A mere 6% believe that the internationally agreed-on limit of 1.5°C will be achieved (figure 5d). This parallels an earlier survey of IPCC scientists, which showed that approximately 60% expected warming of at least 3°C (Tollefson 2021). These projections paint a bleak picture of the future, with many scientists envisioning widespread famines, conflicts, mass migration, and increasing extreme weather that will surpass anything witnessed thus far, posing catastrophic consequences for both humanity and the biosphere (Carrington 2024). It is important to keep in mind, however, that such characterizations can suffer from conflation of matters of science (i.e., how much warming are we committed to for a given emissions pathway) and matters of policy (what pathways are still possible and what the obstacles are).

Untold Human Suffering in Pictures

Figure 4. Photograph series depicting the impacts of climate-related disasters. First row (left to right): Rescue of people stranded by floods in the city of Canoas, Rio Grande do Sul (Brazil, 2024; Duda Fortes, Agência RBS), “Drought in Ethiopia due to rains unrealised” (Ethiopia, 2011; Oxfam East Africa; CC BY 2.0). Second row: Firefighters contain a bushfire burning around the town of Aberdare (Australia, 2013; Quarrie Photography, Jeff Walsh, Cass Hodge; CC BY-NC-ND 2.0), The aftermath of Hurricane Matthew (Haiti, 2016; UN Photo/Logan Abassi; CC BY-NC-ND 2.0). Third row: Inspection of a storm-damaged roadway in California (United States, 2023; Andrew Avitt/USDA Forest Service), Remnants of a house on Leyte island that was destroyed by Typhoon Haiyan (The Philippines, 2013; Trocaire/Wikimedia; CC BY 2.0). All quotes are from the Climate Visuals project (https://climatevisuals.org). See supplemental file S1 for details and more pictures.

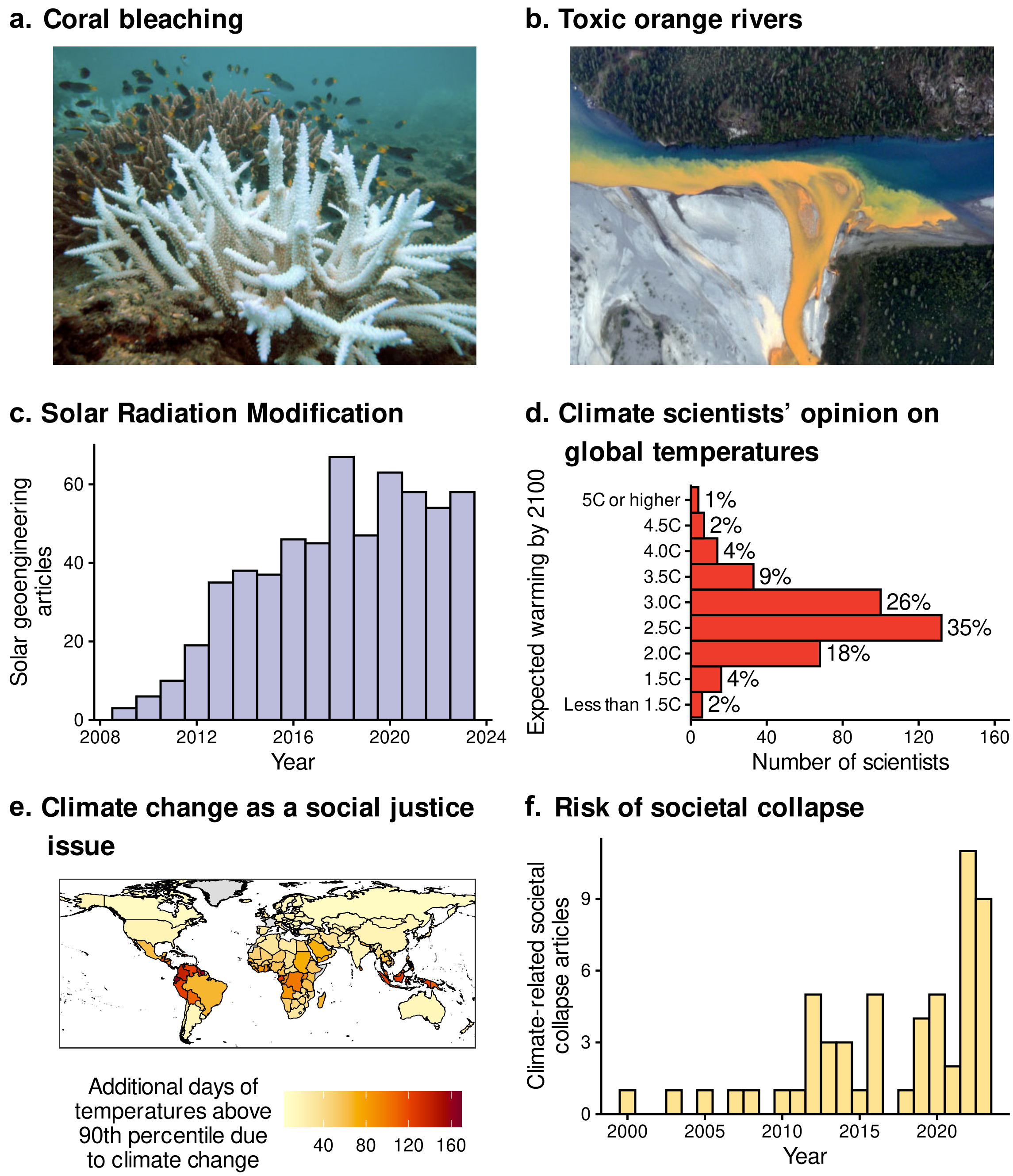

Figure 5. Climate change spotlight topics. Already, many serious climate impacts are occurring, including coral bleaching (a) and permafrost thaw contributing to orange rivers with reduced fish abundance and drinking water quality (b). Recent years have seen a dramatic increase in the number of scientific publications related to solar radiation modification (c). A survey of hundreds of IPCC senior authors and review editors indicates that the majority expect catastrophic warming of at least 2.5 degrees Celsius this century (d). Extreme heat is expected to disproportionately affect people in less wealthy countries that have lower emissions (e). Climate change could eventually contribute to societal collapse—a possibility that is increasingly being considered by researchers (f). See supplemental file S1 for data sources and details. Photographs: (a) Acropora/Wikimedia Commons, (b) Ken Hill/National Park Service.

There is no way to know, for example, whether the polled IPCC physical scientists based their assessments on the science or simply on their views of the political prospects for action (Mann and Hayhoe 2024).

One of the numerous challenges for scientists is how to communicate about climate change (Guenther 2024). Some have argued that attitudes of pessimism and resignation can be obstructive to climate action. Moreover, some say those who oppose action have resorted to alternative strategies including the propagation of pessimism, because embracing a sense of helplessness can undermine the motivation for action (Mann and Hayhoe 2024). Conversely, it has also been suggested that optimism gives rise to inaction, if people think things are fine and therefore action is not needed (Wilson 2021). In any case, the importance of tone may be overstated in this context, and more research is needed to better identify motivating factors for climate action (Bamberg et al. 2018).

With the increasingly undeniable effects of climate change, a dire assessment is an honest assessment. Denying the existential threat posed by climate change is becoming increasingly less

Table 2a. Summary of amplifying physical feedback loops.

Feedback	Effect of climate change	Effect on climate change
Water vapor†	↑ Increasing water vapor content	↑ Greenhouse effect
Sea ice albedo*†	↑ Sea ice melting or not forming	↓ Albedo
Ice sheets*†‡	↑ Glacier and ice sheet melting/instability	↓ Albedo
Sea level rise‡	↑ Sea levels	↓ Albedo (↑ coastal submergence)
Snow cover†	↓ Snow cover	↓ Albedo
Clouds†	Δ Cloud distribution and optical properties	Δ Cloud albedo and greenhouse effect
Ocean stratification	↑ Ocean stratification	↓ Carbon uptake by ocean
Solubility pump†	↑ Atmos. CO_2 levels	↓ CO_2 absorption by ocean
CH_4 hydrates*‡	↑ CH_4 hydrate dissociation rates	↑ Release of CH_4 into atmos.
Ice–elevation‡	↓ Ice sheet or glacier elevation	↑ Glacier and ice sheet melting, ↓ albedo
Antarctic rainfall‡	↓ Ice sheet extent, ↑ precipitation	↓ Albedo, ↑ deep ocean warming

Note: Feedback loops that may involve tipping elements are flagged with asterisks (*). As an approximate indicator of feedback loops that are most likely to be partly included in certain climate models, feedback loops that are referenced in figure TS.17 (feedback loops overview) or figure 5.29 (biogeochemical feedback loops) of IPCC (2021) are flagged with daggers (†). Many of these feedback loops will likely have major effects on Earth's climate, but others may be more speculative. Feedback impacts operate on a range of time scales; feedback loops we believe to be particularly slow are flagged with double daggers (‡). Symbols indicate decreasing (↓), increasing (↑), and changing (Δ). Abbreviations: atmospheric, atmos.; CH_4, methane; CO_2, carbon dioxide. See Ripple and colleagues (2023b) for full loop descriptions, grouping information, limitations, and selected references. The table and caption are adapted from Ripple and colleagues (2023b).

plausible. The fact is that avoiding every tenth of a degree of warming is critically important. Rather than presenting a climate change prognosis pessimistically or optimistically, we just want to act truthfully and tell it like it is. We must emphasize both urgency and agency when it comes to our characterizations of the needed action on climate (Mann 2023).

Climate change as a social justice issue

Climate change is a matter of diversity, equity, and inclusion (DEI), because the wealthy people that emit the most greenhouse gases are generally less vulnerable to climate impacts (figure 5e). Although the ramifications of emissions are global, they are particularly severe in the Global South (Ngcamu 2023). Vulnerability to climate change is shaped by a complex interplay of social, economic, and political factors, leaving historically diverse, underserved, and marginalized communities disproportionately affected (Levy and Patz 2015). DEI principles underscore the urgency to address these disparities. Embedding climate change within the framework of organizational DEI activities may help to foster comprehensive and meaningful progress toward equity and sustainability. By recognizing the disproportionate impacts of climate change on marginalized communities, organizations can work toward rectifying historical injustices by funding countries in the Global South to maintain decarbonization while addressing urgent climate change concerns. In addition, DEI considerations are relevant to international climate policy; for example, they can help guide efforts to rapidly and equitably phase out fossil fuel extractions (Muttitt and Kartha 2020).

The ethical dimensions of climate change have led many faith leaders to speak out on the issue (e.g., Nhat Hanh 2015, Pope Francis 2023). This represents an opportunity for diverse communities to build alliances around the issue.

Climate feedback loops and tipping points

Awareness and research need to increase on climate feedback loops. Feedback loops are processes that can either amplify or reduce the effects of greenhouse gas emissions. Many significant feedback loops enhance warming. At least 28 amplifying feedback loops have been identified (tables 2a, 2b). A particularly concerning feedback loop is the permafrost feedback loop, which involves rising temperatures causing permafrost thawing. This process releases more carbon dioxide and methane, leading to further warming. Areas of active climate feedback loop research include permafrost–cloud interactions (de Vrese et al. 2024), glacier meltwater (Pelle et al. 2023), and biodiversity (Weiskopf et al. 2024). Because feedback loops are not yet fully integrated into climate models, current emissions reduction plans might fall short in adequately limiting future warming.

Some climate feedback loops are linked to tipping points, potentially triggering major and irreversible changes in the Earth system without further pushing by human activities. Tipping elements are biophysical systems on Earth with tipping point behavior that contribute to regulating the climate system (Lenton et al. 2008). They have recently been assessed for their tipping sensitivity. Five of sixteen climate tipping elements are likely to cross their tipping points at 1.5°C: the Greenland ice sheet, the West Antarctic ice sheet, boreal permafrost, low-latitude coral reefs, and the Barents Sea Ice (Armstrong McKay et al. 2022). Several climate tipping elements are connected, and if one tips, others may tip, triggering a tipping point cascade (Wunderling et al. 2024). Overall, this points to a complex situation where climate controlling feedback loops and tipping point systems are interconnected in a way that could trigger self-perpetuating processes that amplify warming beyond human control. Therefore, we recommend the IPCC publish a special report on feedback loops and tipping points.

Risk of societal collapse

The climate emergency is not an isolated issue. Global heating, although it is catastrophic, is merely one aspect of a profound polycrisis that includes environmental degradation, rising economic inequality, and biodiversity loss (Hoyer et al. 2023). Climate change is a glaring symptom of a deeper systemic issue: ecological overshoot, where human consumption outpaces the Earth's ability to regenerate (Rees 2023, Ripple et al. 2024). Overshoot is an inherently unstable state that cannot persist indefinitely. As pressures increase and the risk of Earth's climate system switching to a catastrophic state rises (Steffen et al. 2018), more and more scientists have begun to research the possibility of societal collapse (Brozović 2023). Even in the absence of global collapse, climate change could cause many millions of additional deaths by 2050 (WHO 2023).

Along with the broader danger of overshoot, climate change could contribute to a collapse by increasing the likelihood of

Table 2b. Summary of amplifying biological feedback loops.

Feedback	Effect of climate change	Effect on climate change
Peatlands†	↑ Drying and fire, ↓ Soil carbon	↑ Release of CO_2 into atmos.
Wetlands†	↑ Wetlands area (↑ precipitation)	↑ CO_2 seq., ↑ CH_4 emissions
Freshwater	↑ Aquatic plant growth rates	↑ CH_4 emissions
Forest dieback*	↑ Amazon and other forest dieback	↓ CO_2 seq., Δ albedo
Northern greening	↑ Boreal forest area, Arctic vegetation	↑ CO_2 seq., ↓ albedo
Insects	Δ Insect ranges and abundances	↓ CO_2 seq., Δ albedo
Wildfire†	↑ Fire activity in some regions	↑ CO_2 emissions, Δ albedo
Soil carbon (other)	↑ Loss of soil carbon	↑ CO_2 emissions
Soil nitrous oxide†	Δ Soil microbial activity	↑ Nitrous oxide emissions
Permafrost emissions*†	↑ Permafrost thawing	↑ CO_2 and CH_4 emissions
Permafrost–cloud	↑ Permafrost thawing, landscape drying	↓ Summer cloudiness, ↓ albedo
Soil and plant ET	↑ ET from soils and plants	↓ Latent heat flux
Microbes (other)	↑ Microbial respiration rates	↑ CO_2 and CH_4 emissions
Plant stress	↑ Thermal stress, ↑ droughts	↑ Plant mortality, ↓ CO_2 seq.
Desertification	↑ Desert area	↓ CO_2 seq., Δ albedo
Coastal productivity	↑ Coastal ecosystem degradation	↓ Coastal ecosystem carbon seq.
Metabolic rates	↑ Phytoplankton respiration rates	↑ CO_2 released into atmos.

Note: Feedback loops that may involve tipping elements are flagged with asterisks (*). As an approximate indicator of feedback loops that are most likely to be partly included in certain climate models, feedback loops that are referenced in figure TS.17 (feedback loops overview) or figure 5.29 (biogeochemical feedback loops) of IPCC (2021) are flagged with daggers (†). Many of these feedback loops will likely have major effects on Earth's climate, but others may be more speculative. Feedback impacts operate on a range of time scales. Symbols indicate decreasing (↓), increasing (↑), and changing (Δ). Abbreviations: atmospheric, atmos.; CH_4, methane; CO_2, carbon dioxide; evapotranspiration, ET; sequestration, seq. See Ripple and colleagues (2023b) for full loop descriptions, grouping information, limitations, and selected references. The table and caption are adapted from Ripple and colleagues (2023b) with the addition of the permafrost–cloud feedback (de Vrese et al. 2024).

catastrophic risks such as international conflict or by causing multiple stresses, resulting in system-wide synchronous failures (Kemp et al. 2022). The number of published articles using *climate change* and *societal collapse* language has been dramatically increasing (figure 5f; supplemental methods). Climate change has already displaced millions of people, and has the potential to displace hundreds of millions or even billions more, leading to greater geopolitical instability (Table S3). By the end of the century, roughly one-third of people worldwide could be outside the human climate niche, facing increased risk of illness and early death, famine, and a host of other adverse outcomes (Lenton et al. 2023).

Conclusions

Despite six IPCC reports, 28 COP meetings, hundreds of other reports, and tens of thousands of scientific papers, the world has made only very minor headway on climate change, in part because of stiff resistance from those benefiting financially from the current fossil-fuel based system. We are currently going in the wrong direction, and our increasing fossil fuel consumption and rising greenhouse gas emissions are driving us toward a climate catastrophe. We fear the danger of climate breakdown. The evidence we observe is both alarming and undeniable, but it is this very shock that drives us to action. We recognize the profound urgency of addressing this global challenge, especially the horrific outlook for the world's poor. We feel the courage and determination to seek transformative science-based solutions across all aspects of society (table S4). Our goal is to provide clear, evidence-based insights that inspire informed and bold responses from citizens to researchers and world leaders.

Rapidly phasing down fossil fuel use should be a top priority. This might be accomplished partly through a sufficiently high global carbon price that could restrain emissions by the wealthy while potentially providing funding for much-needed climate mitigation and adaptation programs. In addition, pricing and reducing methane emissions is critical for effectively mitigating climate change. Methane is a potent greenhouse gas, and unlike carbon dioxide, which persists in the atmosphere for centuries, methane has a relatively short atmospheric lifetime, making reductions impactful in the short term (Shindell et al. 2024). Drastically cutting methane emissions can slow the near-term rate of global warming, helping to avoid tipping points and extreme climate impacts.

In a world with finite resources, unlimited growth is a perilous illusion. We need bold, transformative change: drastically reducing overconsumption and waste, especially by the affluent, stabilizing and gradually reducing the human population through empowering education and rights for girls and women, reforming food production systems to support more plant-based eating, and adopting an ecological and post-growth economics framework that ensures social justice (Table S4). Climate change instruction should be integrated into secondary and higher education core curriculums worldwide to raise awareness, improve climate literacy, and empower learners to take action. We also need more immediate efforts to protect, restore, or rewild ecosystems.

The surge in yearly climate disasters shows we are in a major crisis with worse to come if we continue with business as usual. Today, more than ever, our actions matter for the stable climate system that has supported us for thousands of years. Humanity's future depends on our creativity, moral fiber, and perseverance. We must urgently reduce ecological overshoot and pursue immediate large-scale climate change mitigation and adaptation to limit near-term damage. Only through decisive action can we safeguard the natural world, avert profound human suffering, and ensure that future generations inherit the livable world they deserve. The future of humanity hangs in the balance.

Supplemental material

Supplemental data are available at *BIOSCI* online.

The methods and details of planetary vital sign variables used in this report along with other discussion appear in supplemental file S1 of this article. A list of the scientist signatories for Ripple and colleagues (2020) as of 29 March 2023 appears in supplemental file S2 of this article. Note that these signatures are not for the current article.

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The World Scientists' Warning of a Climate Emergency paper (Ripple et al. 2020) now has more than 15,600 signatories from 165 countries, and we continue to collect signatures from scientists. To sign or learn more, visit the Alliance of World Scientists website at https://scientistswarning.forestry.oregonstate.edu. To view *A Scientist's Warning*, a recent documentary film on scientists speaking out, visit https://www.youtube.com/watch?v=byXGCPo-80w.

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