Supplemental File S1

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

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Supplemental Tables

Table S1. Summary of variables shown in figures 2 and 3. Table columns show the variable name, update frequency, number of years with data, time of most recent data point, current value of the variable, change relative to the previous value, and rank (where rank 1 indicates the highest value to date). For variables with sub-annual frequency, the value, change, and rank are all based on year-to-date data. For example, they are based on the first 37.5% of each year for the variable "Carbon dioxide (CO_2 parts per million)" (since "Year" is equal to 2024.375). Note that variable time spans (# of years) differ significantly depending on the source. Variables that set all-time records (over their associated periods of record) are shown in blue and marked with asterisks. Sources for these variables are given in this supplement.

Variable	Type	Years	Year	Value	Change	Rank
Human population (billion individuals)*	Annual	75	2024	8.12	0.0735	1
Total fertility rate (births per woman)*	Annual	63	2022	2.26	-0.0123	63
Ruminant livestock (billion individuals)*	Annual	62	2022	4.22	0.0619	1
Per capita meat production (kg/yr)*	Annual	62	2022	45.2	0.393	1
World GDP (trillion current US $/yr)*	Annual	65	2024	96.1	2.99	1
Global tree cover loss (million hectares/yr)	Annual	23	2023	28.3	5.44	3
Brazilian Amazon forest loss (million hectares/yr)	Annual	36	2023	0.9	-0.257	26
Coal consumption (Exajoules/yr)*	Annual	59	2023	164	2.5	1
Oil consumption (Exajoules/yr)*	Annual	59	2023	196	4.81	1
Gas consumption (Exajoules/yr)	Annual	59	2023	144	0.0535	2
Solar/wind consumption (Exajoules/yr)*	Annual	59	2023	37.1	4.9	1
U.S. heat-related mortality (rate per 100,000 person-years)*	Annual	25	2023	0.62	0.15	1
Total institutional assets divested (trillion USD)*	Annual	12	2023	40.6	0.12	1
CO_2e emissions (gigatonnes CO_2 equivalent/yr)*	Annual	34	2023	40.4	0.83	1

Variable	Type	Years	Year	Value	Change	Rank
Per capita CO_2 emissions (tonnes CO_2 equivalent/yr)	Annual	34	2023	5.02	0.0598	11
GHG emissions covered by carbon pricing (%)*	Annual	35	2024	0.24	0.00805	1
Carbon price ($ per tonne CO_2 emissions)	Annual	33	2024	20.8	-2.18	7
Fossil fuel subsidies (billion USD/yr)*	Annual	13	2022	1100	566	1
Jurisdictions that have declared a climate emergency (#)*	Annual	8	2023	2360	25	1
Carbon dioxide (CO_2 parts per million)*	Subannual	46	2024.375	423	3.06	1
Methane (CH_4 parts per billion)*	Subannual	41	2024.292	1930	9.34	1
Nitrous oxide (N_2O parts per billion)*	Subannual	47	2023.956	337	1.08	1
Surface air temperature anomaly (change) (°C)*	Subannual	145	2024.538	1.28	0.243	1
Earth's energy imbalance (W/m^2; 12-mo. running mean)	Subannual	24	2024.369	1.4	-0.296	3
Ocean heat content change (10^{22} joules)*	Annual	19	2023	29.1	0.913	1
Ocean acidity (pH)*	Subannual	34	2022.666	8.05	-0.00549	34
Sea level change relative to 20-year mean (mm)*	Subannual	32	2024.504	63.8	9.8	1
Minimum Arctic sea ice (million km^2)	Annual	45	2023	4.37	-0.3	39
Greenland ice mass change (gigatonnes)*	Subannual	22	2024.29	-5470	-186	22
Antarctica ice mass change (gigatonnes)*	Subannual	22	2024.29	-2630	-302	22
Glacier thickness change (m of water equivalent)*	Annual	74	2023	-26	-1.23	74
Area burned in the United States (million hectares/yr)	Annual	41	2023	1.09	-1.98	33
Global tree cover loss due to fires (million hectares/yr)*	Annual	23	2023	11.9	5.2	1

Variable	Type	Years	Year	Value	Change	Rank
Billion-dollar floods in the United States (events/year)	Annual	44	2023	4	3	2
Extremely hot days relative to 1961-1990 (% of days/year)	Annual	73	2023	19.2	0.71	2

Table S2. Regional summaries for the 24 countries with greatest emissions and The European Union. Variables shown are "CO_2e" (total CO_2 equivalent emissions associated with fossil fuel consumption in mega tonnes), "Population" (human population size in millions), "CO_2e/capita" (CO_2e emissions per capita in tonnes per person), "Share" (percentage of all CO_2e emissions associated with fossil fuel consumption compared to the global total), and "GDP/capita" (per capita gross domestic product in US dollars per person). All data are for the year 2023. Population is based on FAOSTAT population projections (see supplementary methods for figure 2a for details). GDP/capita uses World Bank GDP (current US$) estimates (The World Bank 2024a). CO_2 emissions data are from The Energy Institute (2024) (see supplementary methods for figure 2k for details).

	CO_2e	**Population**	**CO_2e/capita**	**Share**	**GDP/capita**
China	12604	1458	8.6	31.2%	$12,207
United States	5130	340	15.1	12.7%	$80,474
India	3122	1429	2.2	7.7%	$2,485
The European Union	2526	449	5.6	6.2%	$40,874
Russia	2176	144	15.1	5.4%	$13,994
Japan	1039	123	8.4	2.6%	$34,170
Iran	937	89	10.5	2.3%	$4,503
Indonesia	862	278	3.1	2.1%	$4,941
Saudi Arabia	726	37	19.6	1.8%	$28,895
Canada	599	39	15.5	1.5%	$55,183
South Korea	594	52	11.5	1.5%	$33,076
Mexico	560	128	4.4	1.4%	$13,926
Brazil	525	216	2.4	1.3%	$10,044
South Africa	478	60	7.9	1.2%	$6,253
Turkey	457	86	5.3	1.1%	$12,912
Australia	440	26	16.7	1.1%	$65,200
Vietnam	372	99	3.8	0.9%	$4,347
United Arab Emirates	341	10	35.8	0.8%	$52,977
United Kingdom	339	68	5.0	0.8%	$49,309
Malaysia	322	34	9.4	0.8%	$11,649
Kazakhstan	309	20	15.7	0.8%	$13,333

	CO_2e	Population	CO_2e/capita	Share	GDP/capita
Thailand	302	72	4.2	0.7%	$7,172
Egypt	279	113	2.5	0.7%	$3,513
Iraq	278	46	6.1	0.7%	$5,512
Algeria	249	46	5.4	0.6%	$5,260
Top 25	**35564**	**5460**	**6.5**	**88.0%**	**$17,121**
World	**40418**	**8045**	**5.0**	**100.0%**	**$13,105**

Table S3. Climate-driven migration and displacement. Over the coming decades, climate change is expected to contribute to the displacement of many people globally. This table shows a selection of quotes from research on this subject. Note that estimates may be disputed and are dependent on modeling assumptions, timespans, climate impacts considered, and the treatment of non-climate factors (Gemenne 2011, Jakobeit and Methmann 2012, Kelman 2019, Durand-Delacre et al. 2021). See original papers for details and associated references.

Quote	**Source**
If global temperature rise is limited to 1.5°C by the end of the century [...] 30 to 60 million people are projected to live in hot areas where the average heat in the hottest month is likely to be too high for a human body to function well.	(Chazalnoel et al. 2017)
With global coastal populations totalling more than 600 million (projected to surpass one billion people this century[...]), any level of SLR is expected to impact and potentially displace a large population[...]	(Hauer et al. 2020)
[B]y 2050, 2.8 billion people will reside in countries facing severe ecological threats, compared to 1.8 billion in 2023	(Institute for Economics & Peace 2023)
[C]limate change has already put ~9% of people (>600 million) outside this niche. By end-of-century (2080–2100), current policies leading to around 2.7 °C global warming could leave one-third (22–39%) of people outside the niche.	(Lenton et al. 2023)
When global warming takes hold, there could be as many as 200 million people overtaken by disruptions of monsoon systems and other rainfall regimes, by droughts of unprecedented severity and duration, and by sea-level rise and coastal flooding.	(Myers 2005)
By 2050—in just three regions—climate change could force more than 143 million people to move within their countries.	(Rigaud et al. 2018)
[D]epending on scenarios of population growth and warming, over the coming 50 y, 1 to 3 billion people are projected to be left outside the climate conditions that have served humanity well over the past 6,000 y.	(Xu et al. 2020)

Table S4. Six steps to address climate change. The list below shows quotes from Ripple et al. (2020). Although these steps are important, they are not a comprehensive list of all needed actions. Note that references to figures have been updated to reflect similar figures in the present paper, which show more recent data.

Step	**Description**
Energy	The world must quickly implement massive energy efficiency and conservation practices and must replace fossil fuels with low-carbon renewables [figure 2h] and other cleaner sources of energy if safe for people and the environment [figure S3]. We should leave remaining stocks of fossil fuels in the ground (see the timelines in IPCC 2018) and should carefully pursue effective negative emissions using technology such as carbon extraction from the source and capture from the air and especially by enhancing natural systems (see “Nature” [step]). Wealthier countries need to support poorer nations in transitioning away from fossil fuels. We must swiftly eliminate subsidies for fossil fuels [figure 2o] and use effective and fair policies for steadily escalating carbon prices to restrain their use.
Short-lived pollutants	We need to promptly reduce the emissions of short-lived climate pollutants, including methane [figure 3b], black carbon (soot), and hydrofluorocarbons (HFCs). Doing this could slow climate feedback loops and potentially reduce the short-term warming trend by more than 50% over the next few decades while saving millions of lives and increasing crop yields due to reduced air pollution (Shindell et al. 2017). The 2016 Kigali amendment to phase down HFCs is welcomed.
Nature	We must protect and restore Earth's ecosystems. Phytoplankton, coral reefs, forests, savannas, grasslands, wetlands, peatlands, soils, mangroves, and sea grasses contribute greatly to sequestration of atmospheric CO_2. Marine and terrestrial plants, animals, and microorganisms play significant roles in carbon and nutrient cycling and storage. We need to quickly curtail habitat and biodiversity loss [figure 2f–2g], protecting the remaining primary and intact forests, especially those with high carbon stores and other forests with the capacity to rapidly sequester carbon (proforestation), while increasing reforestation and afforestation where appropriate at enormous scales. Although available land may be limiting in places, up to a third of emissions reductions needed by 2030 for the Paris agreement (less than 2°C) could be obtained with these natural climate solutions (Griscom et al. 2017).

Step	Description
Food	Eating mostly plant-based foods while reducing the global consumption of animal products [figure 2c–d], especially ruminant livestock (Ripple et al. 2014), can improve human health and significantly lower GHG emissions (including methane in the “Short-lived pollutants” step). Moreover, this will free up croplands for growing much-needed human plant food instead of livestock feed, while releasing some grazing land to support natural climate solutions (see “Nature” [step]). Cropping practices such as minimum tillage that increase soil carbon are vitally important. We need to drastically reduce the enormous amount of food waste around the world.
Economy	Excessive extraction of materials and overexploitation of ecosystems, driven by economic growth, must be quickly curtailed to maintain long-term sustainability of the biosphere. We need a carbon-free economy that explicitly addresses human dependence on the biosphere and policies that guide economic decisions accordingly. Our goals need to shift from GDP growth and the pursuit of affluence toward sustaining ecosystems and improving human well-being by prioritizing basic needs and reducing inequality.
Population	Still increasing by roughly 80 million people per year, or more than 200,000 per day [figure 2a–b], the world population must be stabilized—and, ideally, gradually reduced—within a framework that ensures social integrity. There are proven and effective policies that strengthen human rights while lowering fertility rates and lessening the impacts of population growth on GHG emissions and biodiversity loss. These policies make family-planning services available to all people, remove barriers to their access and achieve full gender equity, including primary and secondary education as a global norm for all, especially girls and young women (Bongaarts and O’Neill 2018).

Supplemental Figures

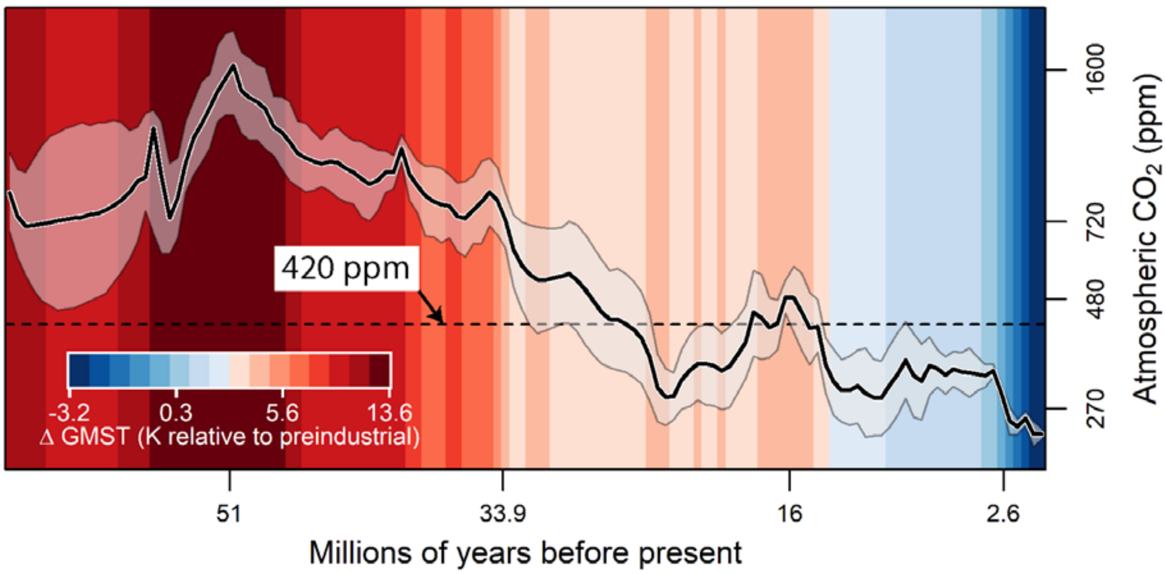

Figure S1. Estimated paleo-CO_2 concentration (black line) with 95% credible (gray band). The colors show global mean surface temperature relative to the preindustrial period. During the Pleistocene epoch (~2.58 million to ~11,700 years ago), CO_2 levels never reached anywhere near the present-day concentration of ~420 ppm in 2022 (dashed horizontal line). Data shown are from CenCO2PIP Consortium et al. (2023). The figure is adapted from an associated press figure (CenoCO2 2024), which is itself adapted from CenCO2PIP Consortium et al. (2023).

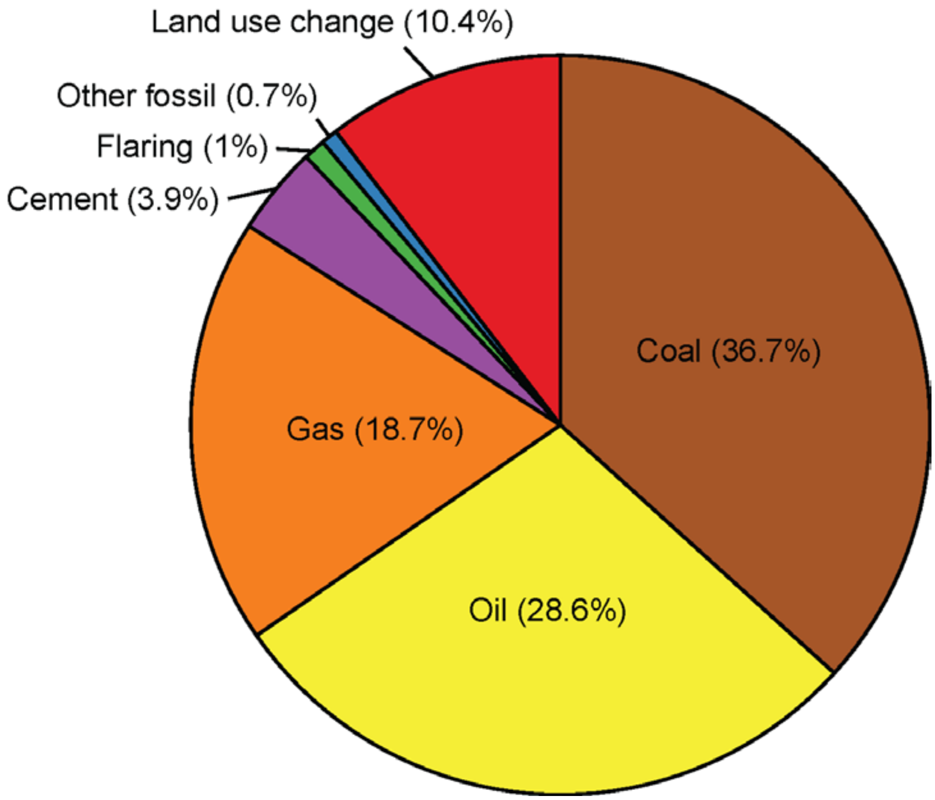

Figure S2. Global anthropogenic CO_2 emissions for 2022 by source. Total estimated emissions are 41.46 Gt CO_2 per year. All categories except land use change comprise fossil fuel and cement production emissions excluding carbonation. Land use change emissions include those associated with deforestation, forest regrowth (negative), other transitions, peat drainage & peat files, and wood harvest & other forest management. Data are from the "Global_Carbon_Budget_2023v1.1.xlsx" spreadsheet provided by the Global Carbon Budget (Friedlingstein et al. 2023). We acknowledge the Global Carbon Project, which is responsible for the Global Carbon Budget and we thank the modelling groups for producing and making available their model output.

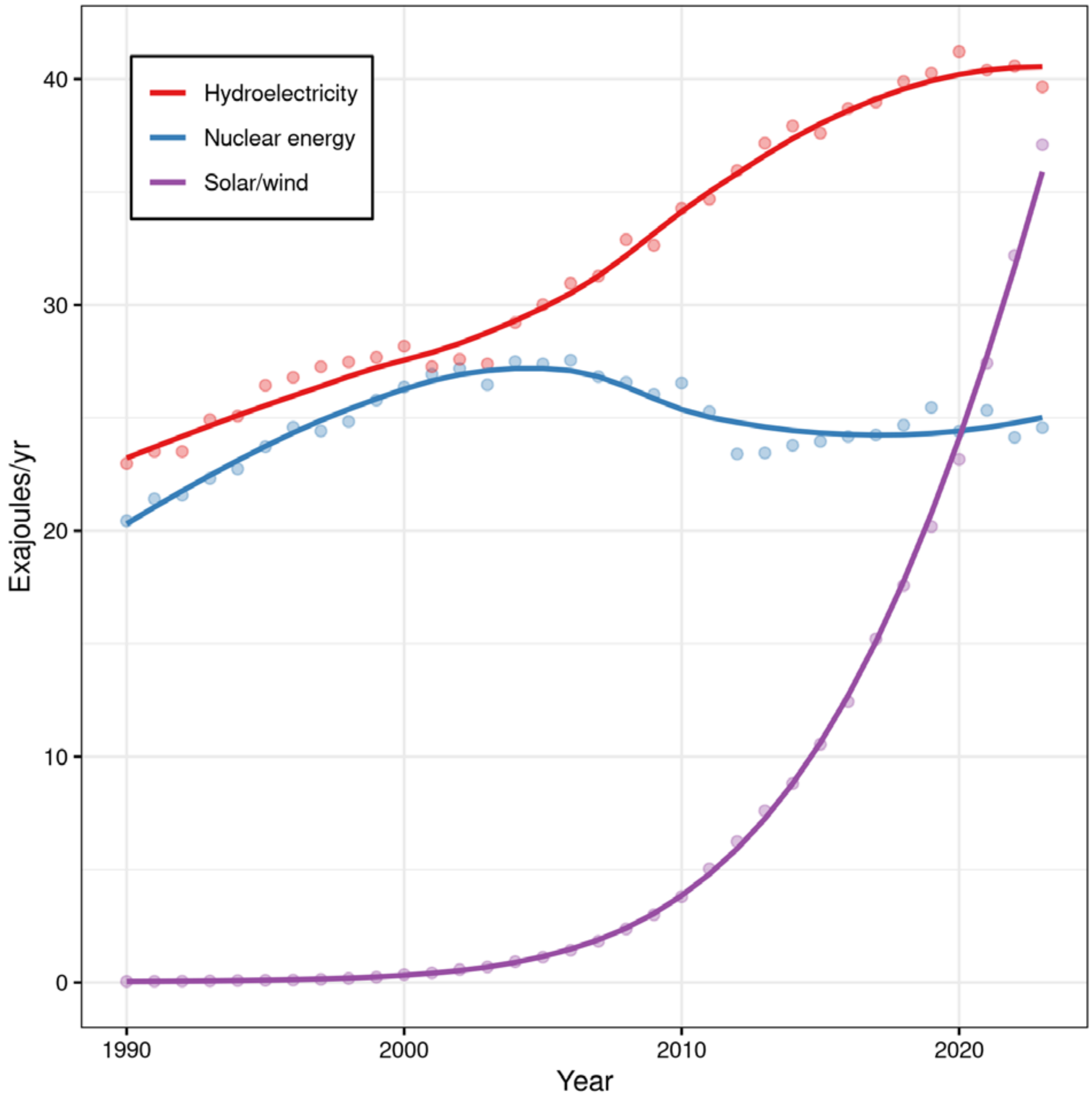

Figure S3. Annual consumption rates for nuclear energy, hydroelectricity, and solar/wind power (The Energy Institute 2024). Non-fossil fuel energy supply pathways in the future may include hydro and nuclear power in addition to solar and wind power (IPCC 2018). See The Energy Institute (2024) for other minor energy sources not shown in this figure. Figure 2h in the main text shows the consumption of fossil fuels as well as solar/wind energy. Note that hydroelectricity is associated with significant methane emissions (De Faria et al. 2015, Soued et al. 2022).

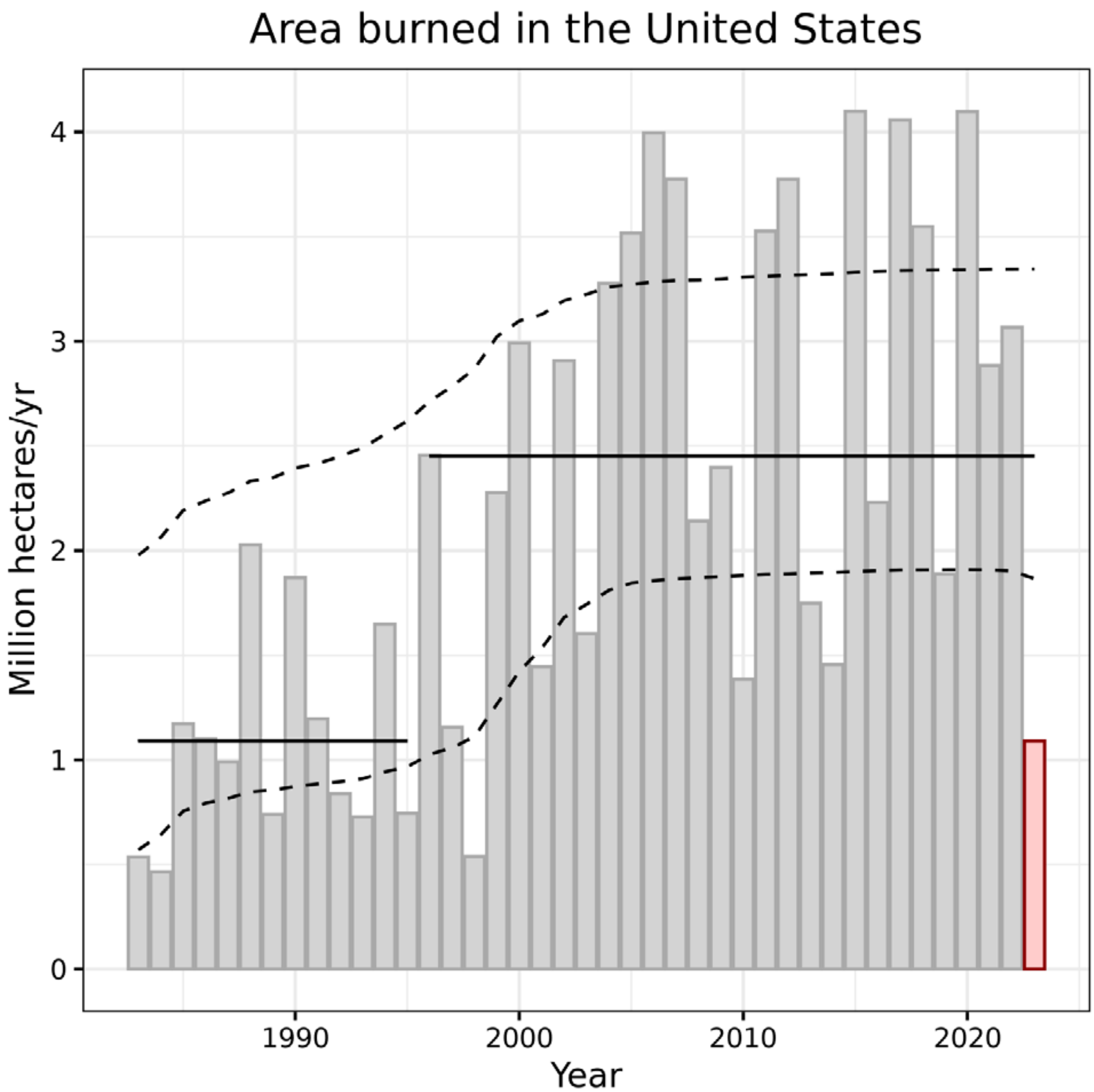

Figure S4. Approximate area burned in the U.S. through 2023 (see figure 3m). The solid black lines show the predicted mean area burned according to a Bayesian change-point regression model. The dashed black lines correspond to an 80% credible band. According to this model, a new fire regime began around 1996 [80% credible interval: (1985, 2005)], although more research is needed to support this finding. Weakly informative priors were used for the rate parameters and inference was based on 8,000 posterior samples (see Supplementary Methods).

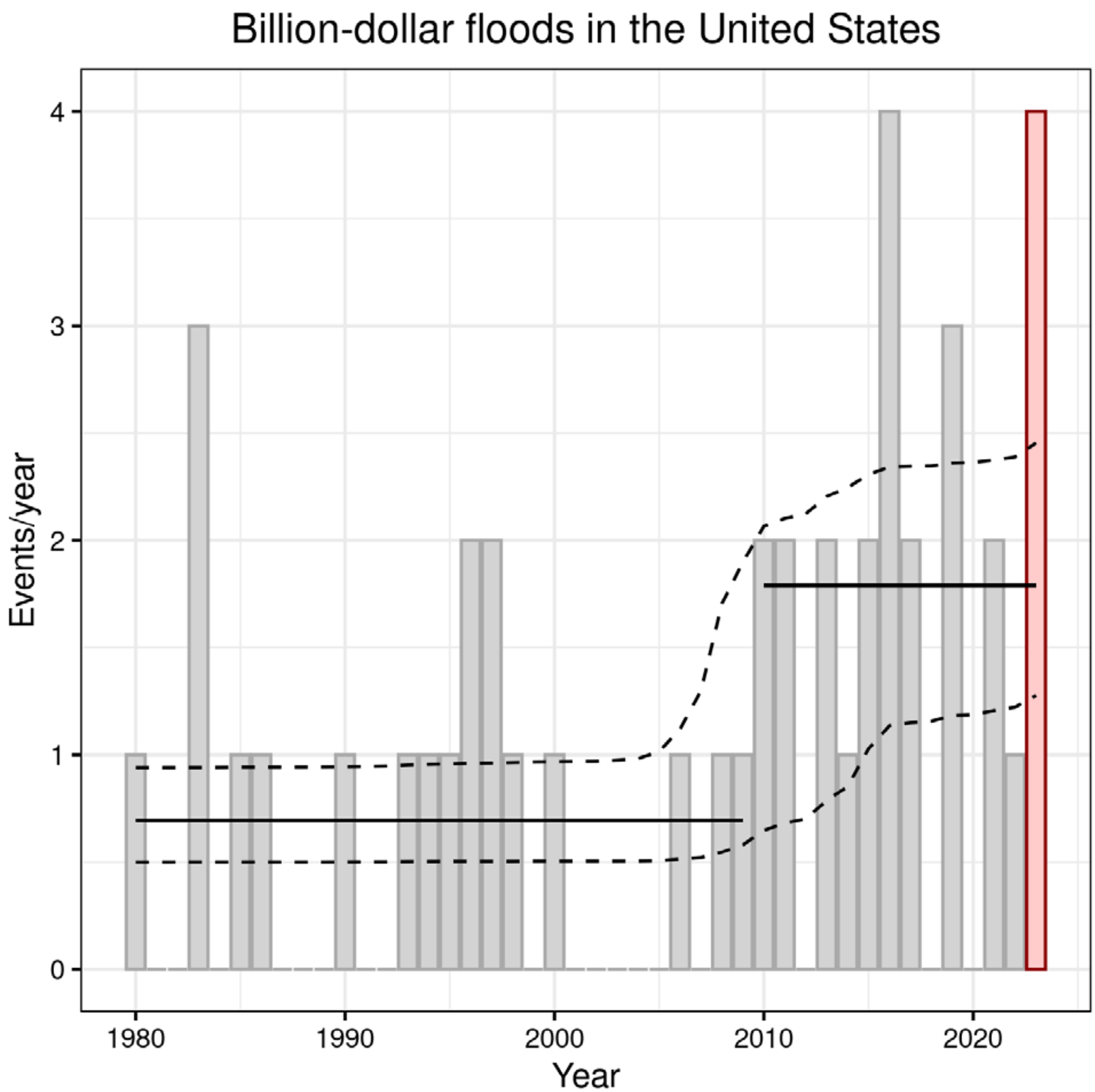

Figure S5. Number of inflation-adjusted billion-dollar floods in the U.S. through 2023 (see figure 3o). The solid black lines show the predicted mean number of floods according to a Bayesian change-point regression model. The dashed black lines correspond to an 80% credible band. According to this model, a new flood regime began around 2010 [80% credible interval: (2006, 2015)], although more research is needed to support this finding. Weakly informative priors were used for the rate parameters and inference was based on 8,000 posterior samples (see Supplementary Methods).

Climate Impacts: Untold Human Suffering in Pictures

Here, we present a compilation of photographs intended as a visual demonstration of the recent impacts of climate change. Photos generally show human suffering due to natural disasters that may be at least partly attributable to climate change.

All photos are Creative Commons licensed, Public Domain, or obtained with permission from journalists, and many were obtained through the Climate Visuals project (https://climatevisuals.org/), which compiles images from many sources. Specific credits are given with each image along with a brief description of the event. All quotations describing images are from the Climate Visuals project.

Brazil, 2024. Rescue of people stranded by floods in the city of Canoas, Rio Grande do Sul. Credit: Duda Fortes, Agência RBS.

Ethiopia, 2011. “Drought in Ethiopia due to rains unrealised.” Credit: Oxfam East Africa, CC BY 2.0.

Australia, 2013. Firefighters contain a bushfire burning around the town of Aberdare. Credit: Quarrie Photography | Jeff Walsh | Cass Hodge, CC BY-NC-ND 2.0.

Haiti, 2016. The aftermath of Hurricane Matthew. Credit: UN Photo/Logan Abassi, CC BY-NC-ND 2.0.

United States, 2023. Inspection of a storm-damaged roadway in California. Credit: Andrew Avitt / USDA Forest Service, Public Domain.

The Philippines, 2013. Remnants of a house on Leyte island that was destroyed by Typhoon Haiyan. Credit: Trocaire / Wikimedia, CC BY 2.0.

Recent climate-related disasters (Table 1)

Below, we list numerous recent disasters that may be at least partly related to climate change. This list is not intended to be exhaustive. Due to the recent nature of these events, our sources often include news media articles. We have considered only disasters that occurred after the most recent disaster listed in our previous year's report (i.e., after October, 2023).

Because of the natural variability and stochasticity of the Earth system, attributing specific extreme events (or parts of their impacts) to climate change is an exceptionally challenging(Stott et al. 2013, Trenberth et al. 2015)task (Stott et al. 2013, Trenberth et al. 2015). However, it may be possible in some cases (e.g., Strauss et al. 2021). For simplicity, we have generally adopted the framework of Stott et al. (2013), which is described by Trenberth et al. (2015 p. 725) as follows:

"[T]he approach is to characterize the event and ask (i) whether the likelihood or strength of such events has changed in the observational record, and (ii) whether this change is consistent with the anthropogenic influence as found in one or more climate models, and thereby assess the 'fraction of attributable risk'."

Thus, for each event, we provide references indicating that the likelihood or strength of such an event may have become more common due to anthropogenic climate change. For certain types of events (e.g., rainfall), this can be difficult to establish conclusively. Because of this potential issue, we have indicated cases where attribution (in the general sense described above) has a high degree of uncertainty. Since our intention is to provide a brief overview of potentially climate-related disasters, we have opted not to assess the "fraction of attributable risk" for each event.

Note that some of these climate disasters may be at least partly related to changes in jet streams (Stendel et al. 2021, Rousi et al. 2022).

1. (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 two-fold increase in the likelihood of this level of precipitation (Zachariah et al. 2024a).
2. (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.

3. (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).

4. (April 2024) Heavy rain led to flash floods in the Persian Gulf region, killing at least 33 people. Climate change probably exacerbated this rainfall.

5. (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).

6. (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).

7. (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).

8. (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 like this one more frequent and intense.

9. (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.

10. (May–June 2024) Mexico and nearby areas faced extreme heat; at least 125 people have died in Mexico due to heat-related illnesses this year. Climate change is increasing the frequency of such extreme heat waves (Pinto et al. 2024).

11. (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.

12. (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.

13. (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).

14. (July 2024) Hurricane Beryl was an exceptionally strong Atlantic hurricane that impacted 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.

15. (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.

16. (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.

Anomalies in 2024 (Figure 1)

Ocean temperatures (Figure 1 a,b)

Ocean surface temperature anomaly data come from the Climate Reanalyzer website (Climate Reanalyzer 2024a) and are derived from the “NOAA OISST V2.1” dataset (Huang et al. 2021).

Sea ice extent (Figure 1 c,d)

Antarctic and global sea ice extent data come from the “VIsualization Service of Horizontal scale Observations at Polar region” website (VISHOP 2024a). See the “Method for calculating sea-ice extent” section for details (VISHOP 2024b).

Surface temperature (Figure 1 e)

Global temperature data also come from the Climate Reanalyzer website (Climate Reanalyzer 2024b) and are derived from the “ECMWF Reanalysis v5 (ERA5)” dataset (Hersbach et al. 2018, Copernicus Climate Change Service (C3S) 2023). We adjusted these data to the 1850–1900 reference level by first subtracting the 1991–2020 mean (separately for each day) and then adding 0.88 °C (Copernicus 2023).

Methods for planetary vital signs

Ripple et al. (2020) compiled a set of global time series related to human actions that affect the environment and climate (e.g. fossil fuel consumption) and the associated environmental and climatic responses (e.g. temperature change). We have made a number of updates to this set of variables, which are described below. For completeness, we also describe all relevant methods, variables, and sources in full here, but note that there may be some overlap with Ripple et al. (2020) given the nature of this update.

Although the data used are from sources believed to be reliable, no formal accuracy assessment for these datasets has been made by us and users should proceed with caution. All the "human actions" time series are annual. However, many of the "environmental and climatic responses" time series are sub-annual (e.g., monthly). In contrast to Ripple et al. (2020), we opted to keep these time series at their original (source) frequency, rather than resampling to annual frequency.

For each variable, we calculated the following statistics:

1. The number of years with data (e.g., a variable with data from 2000 to 2023 would have 24 years of data)
2. The most recent year with data (can be fractional for sub-annual frequency variables – for example, 2021.35)
3. The most recent value of the variable (year-to-date average for sub-annual variables)
4. The most recent change in the variable (between current and preceding year-to-date averages for sub-annual variables)
5. The rank associated with the most recent value (#3) based on the entire time series. For example, a rank of 2 means the variable is at its second highest level ever (second highest year-to-date average for sub-annual variables).

While we only plotted data between 1980 and the present, we included data from before 1980 (if available) when calculating the above statistics.

Models for vital signs

For area burned in the United States and billion-dollar floods in the United States, we fit Bayesian changepoint models to explore the possibility of abrupt shifts in these time series. Following Fonnesbeck et al. (2017), we treated the number of billion-dollar floods in each year as Poisson distributed, with two rate parameters—one before the breakpoint and another after the breakpoint. We treated the breakpoint location itself as a latent discrete parameter, with a discrete uniform prior. For the rate parameter priors, we used weakly informative exponential distributions with mean 10 (and variance 100). We used the same approach to model area burned, except we treated the data as following exponential distributions, rather than Poisson distributions.

We marginalized out the latent discrete breakpoint parameters and fit the models using the Stan probabilistic programming language (Carpenter et al. 2017). We based inference on 8,000 MCMC posterior samples (from 4 chains with 2,000 burnin samples discarded per chain). It is important to note that this analysis is intended as a simple and preliminary assessment of possible abrupt shifts in certain climate-related disaster variables. To make rigorous conclusions, further research is needed. For example, followup work could consider more flexible probability distributions, account for possible temporal autocorrelation, or incorporate climate-related predictor variables.

For the plots of the other “environmental and climatic responses” variables with high variance, we included smooth trend lines calculated using locally estimated scatterplot smoothing. We fit the trend lines in R using the ‘loess’ function with default settings (degree 2, span 0.75) (R Core Team 2024).

Indicators of climate-related human activities (Figure 2)

Below, we list sources and provide brief descriptions of indicators used in our analysis. Full methods for each indicator are available at the provided sources.

Human population (Figure 2a)

We used the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) as our source of human population data (FAOSTAT 2024). For human population estimates, the source data used by FAOSTAT are derived from national population censuses. For 2022 through 2024, these estimates are classified as "year projections."

Total fertility rate (Figure 2b)

We obtained this variable from the World Bank (The World Bank 2024b). The full variable name is "Fertility rate, total (births per woman)" and the World Bank variables ID is SP.DYN.TFRT.IN. This variable was derived using data from multiple sources, including the United Nations Population Division. The full list of original sources is available at The World Bank (2024b). Total fertility rate is defined as "the number of children that would be born to a woman if she were to live to the end of her childbearing years and bear children in accordance with age-specific fertility rates of the specified year" (The World Bank 2024b).

Ruminant livestock population (Figure 2c)

We used the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) as our source of ruminant livestock population data (FAOSTAT 2024). We considered ruminants to be members of the following groups: cattle, buffaloes, sheep, and goats. For livestock estimates, the primary data sources are national statistics obtained using questionnaires or collected from countries' websites or reports. When national livestock statistics were unavailable, they were estimated by FAOSTAT using imputation (FAOSTAT 2024).

Per capita meat production (Figure 2d)

We used total meat production data from FAOSTAT along with FAOSTAT human population size estimates (figure 2a) to estimate per capita meat production (FAOSTAT 2024). The meat production estimates are for the "Meat, Total" item under the "Crops and livestock products" domain (FAOSTAT 2024).

World gross domestic product (Figure 2e)

We obtained this variable from the World Bank (2024c) for the years 1960 to 2023. The full variable name is "GDP (constant 2015 US$)" and the World Bank variable ID is NY.GDP.MKTP.KD. This variable was derived from multiple sources such as World Bank national accounts. For details, including limitations and exceptions, see The World Bank (2024c). Gross domestic product (at purchaser's prices) is defined as "the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products" (The World Bank 2024c).

We calculated a projection for 2024 gross domestic product (GDP) using the April 2024 edition of the International Monetary Fund's World Economic Outlook Database (IMF 2024). We first obtained the year 2024 percentage change estimate based on the variable "Gross domestic product, constant prices" in units "Percent change" (IMF 2024). We then used this percentage change estimate to predict total GDP (as measured by the World Bank in constant 2015 US dollars) in 2024. Because IMF projections and World Bank and World Economic Outlook GDP estimates likely differ in methodology, this 2024 estimate should only be considered an approximation.

Global tree cover loss (Figure 2f)

We obtained data on annual global tree cover loss from the updated version of Hansen et al. (Hansen et al. 2013). These data express loss globally in million hectares (Mha) and were derived from remotely-sensed forest change maps. It should be noted that loss is general and not linked to a specific type of deforestation. So, it includes wildlife, conversion to agriculture, disease, etc. Additionally, tree cover loss does not take tree cover gain into account. Thus, net forest loss may be lower than the reported numbers.

Some of the apparent variation in loss rates may be due to non-forest factors such as changes in the modeling algorithm, satellite data quality, and satellite data variability (Global Forest Watch 2022). Thus, trends in tree cover loss rates should be interpreted with this limitation in mind.

Brazilian Amazon forest loss (Figure 2g)

We obtained annual Brazilian Amazon forest loss estimates through 2022 from Butler (2023a) and for 2023 from Butler (2023b). Note that the 2023 estimate is preliminary.

Brazil contains about 60% of the Amazon rainforest. We used annual deforestation estimates rather than monthly ones because of high month-to-month variability. Due to cloud cover issues, each annual estimate is for the period from August 1 of the previous year to July 31. For example, the 2021 estimate is for deforestation occurring between August 1, 2020 and July 31, 2021.

The original source of these data is PRODES — the annual deforestation monitoring system of Brazil's National Institute for Space Research (INPE). PRODES deforestation estimates are based on remotely sensed Landsat-type data.

Energy consumption (Figure 2h)

We used the Energy Institute's 2024 Statistical Review of World Energy as our primary source of data on energy consumption (The Energy Institute 2024). For energy consumption, we used the following time series: coal, oil, natural gas, solar, and wind. We grouped solar and wind together into a single category. Coal consumption data are only for commercial solid fuels. In each case, the units of energy consumption are exajoules (per year). Other sources of low carbon energy such as hydropower and nuclear power are shown in figure S3.

Heat-related deaths (Figure 2i)

We obtained data on heat-related mortality in the United States from Howard et al. (2024). The specific variable is the age-adjusted mortality rate per 100,000 person-years for heat-related deaths. This variable allows for comparisons across time since it accounts for changes in population age structure. See Howard et al. (2024) for more details, 95% confidence intervals, and original data source information.

Divestment (Figure 2j)

Divestment data were obtained from version 3.0 of the Global Fossil Fuel Divestment Commitments Database (Stand.earth 2024). The database covers institutional divestment by 1,615 organizations. The most commonly represented institutions were faith-based organizations, educational institutions, philanthropic foundations, pension funds, and governments. We focused on the "Total AuM committed to divest (trillions of $)" variable, which is provided in the AUMGraph section of the database.

Note that more sophisticated metrics are needed to determine which companies should be subject to divestment (Mormann 2020).

CO_2 emissions (Figure 2k)

We used the Energy Institute's 2024 Statistical Review of World Energy as our source of data on CO_2 emissions (The Energy Institute 2024). Specifically, we used the variable "Carbon Dioxide

Equivalent Emissions from Energy, Process Emissions, Methane, and Flaring," which is defined as "the sum of carbon dioxide emissions from energy, carbon dioxide emissions from flaring, methane emissions (in carbon dioxide equivalent) associated with the production, transportation and distribution of fossil fuels, and carbon dioxide emissions from industrial processes" (The Energy Institute 2024).

Per capita CO_2 emissions (Figure 2l)

We converted total CO_2 emissions (figure 2k) to per capita CO_2 emissions using FAOSTAT human population size estimates (figure 2a).

Greenhouse gas emissions covered by carbon pricing (Figure 2m)

The data on percentage of greenhouse gas emissions covered by carbon pricing schemes are taken from World Bank (2024), and were accessed using the Carbon Pricing Dashboard (World Bank Group 2024). They were last updated on April 1, 2024.

Carbon price and share of greenhouse gas emissions covered by carbon pricing (Figure 2n)

These data were derived from World Bank Group (2024). The data were accessed using the Carbon Pricing Dashboard (World Bank Group 2024). They were last updated on April 1, 2024.

To estimate the global carbon price, we used the average of the individual scheme prices weighted by the percentage of greenhouse gas emissions covered by each scheme. When multiple schemes covered the same emissions, the emissions were associated with the earliest of the schemes. We considered only schemes where the price rate label was listed as "Single price." Thus, prices associated with more specific schemes covering individual fuels, sectors, etc. were not included in the calculation.

Fossil fuel subsidies (Figure 2o)

We obtained data on fossil fuel subsidies between 2010 and 2022 using the International Energy Agency subsidies database (IEA 2022). Fossil fuel consumption subsidies are global totals in 2020 billion US dollars. They cover oil, electricity, natural gas, and coal.

Subsidy values are estimated using the price-gap approach, which involves comparing "average end-user prices paid by consumers with reference prices that correspond to the full cost of supply" (IEA 2022). The subsidy amount is equal to the product of this price gap and the amount consumed (IEA 2022).

Note that when implicit costs (e.g., undercharging for environmental impacts) are considered, the total effective amount of subsidies is much higher—on the order of $7 trillion USD as of 2022 (IMF 2023).

Climate emergency declarations (Figure 2p)

We obtained data on climate emergency declarations from the "Climate Emergency Declaration (CED) data sheet" (Climate Emergency Declaration 2024). These data track governments that have either declared or recognized a climate emergency. We converted these data to annual totals by considering only cumulative total declarations at the end of each year. For example, the total number of declarations by 2018 corresponds to the number of declarations made prior to December 31, 2018 (including those made in preceding years).

Indicators of climate-related responses (Figure 3)

Atmospheric CO_2 (Figure 3a)

We obtained globally averaged monthly estimates of atmospheric CO_2 concentration from NOAA's Global Monitoring Laboratory (Lan et al. 2024a). Specifically, we used the dataset "Globally averaged marine surface monthly mean data." Note that data for the most recent year are subject to change; potential changes are typically minor. Beginning on February 10, 2021, these CO_2 data are on the WMO X2019 scale. See Global Monitoring Laboratory (2021) for details on the difficulty in attributing a change in atmospheric CO_2 concentration to COVID-19.

Atmospheric methane (Figure 3b)

We obtained globally-averaged monthly estimates of atmospheric methane (CH_4) concentration from NOAA (Lan et al. 2024b). We used the "Globally averaged marine surface monthly mean data" dataset. These data are derived from measurements made at a global network of sampling sites that were smoothed across time and plotted versus latitude (Dlugokencky et al. 1994, Masarie and Tans 1995). The data are reported as a "dry air mole fraction" (Lan et al. 2024b).

Atmospheric nitrous oxide (Figure 3c)

We obtained data on nitrous oxide (N_2O) concentration from Dutton et al. (2024). These global monthly mean estimates are measured in parts per billion and are derived by smoothing data collected from a global network of air sampling sites (Dlugokencky et al. 1994, Masarie and Tans 1995).

Surface temperature anomaly (change) (Figure 3d)

We obtained global monthly mean surface temperature anomaly data from the NASA GISS Surface Temperature Analysis (GISTEMP v4) dataset (Lenssen et al. 2019, GISTEMP Team 2024). We used the "Combined Land-Surface Air and Sea-Surface Water Temperature Anomalies (Land-Ocean Temperature Index, L-OTI)" "Global-mean monthly, seasonal, and annual means" variable. These temperature anomaly/change estimates combine land and ocean surface temperatures. The baseline period used for setting zero is the 1951-1980 mean.

Earth's energy imbalance (Figure 3e)

As an indicator of Earth's energy imbalance, we used global monthly mean TOA All Sky Net Flux estimates from NASA's CERES_EBAF-TOA_Ed4.2 product (Loeb et al. 2018). Roughly, this variable reflects heat accumulation by the Earth; for more details, see Loeb et al. (2018) and

Kato et al. (2018). These data were obtained from the NASA Langley Research Center CERES ordering tool at https://ceres.larc.nasa.gov/data/.

Because this time series has exceptionally high variability, we applied a 12-month running mean smooth. For example, the value in June 2012 corresponds to the average monthly means between July 2011 and June 2012. This was done prior to calculating a loess trendline as described in the "Methods for planetary vital signs" section.

Ocean heat content (Figure 3f)

We obtained yearly (not pentadal) ocean heat content time series data from NOAA's National Centers for Environmental Information (NCEI) (NOAA 2024a). The specific dataset is h22-w0-2000m.dat, which is accessible under "Basin time series fields ASCII files" (NOAA 2024a)

These data are in units of 10^{22} joules and cover the depth range 0-2000 m. The reference period is 1955-2006 (Levitus et al. 2012). For plotting, we associated each value with the midpoint of the corresponding year (as in the dataset).

Ocean acidity (Figure 3g)

As a proxy for global ocean acidity, we used a time series of seawater pH from the Hawaii Ocean Time-series surface CO2 system data product (HOT 2024). This data product was adapted from Dore et al. (2009). The data were collected at Station ALOHA (22°45'N, 158°00'W). We used the variable "pHmeas_insitu," which is described as the "mean measured seawater pH, adjusted to in situ temperature, on the total scale" (HOT 2024).

Note that the pH scale is logarithmic. Since the Industrial Revolution, global average surface ocean pH has decreased by 0.11, corresponding to a roughly 30% increase in hydrogen ion concentration (NOAA PMEL Carbon Group 2024).

Sea level change (Figure 3h)

We obtained data on global mean sea level from GSFC (2021). The variable we used was "GMSL (Global Isostatic Adjustment (GIA) not applied) variation (mm) with respect to 20-year TOPEX/Jason collinear mean reference." According to the dataset description, the "TOPEX/Jason 20 year collinear mean reference is derived from cycles 121 to 858, years 1996-2016" (GSFC 2021). For details, see Beckley et al. (2010) and Beckley et al. (2017).

It should be noted that temperature increases and the warming of the entire ocean are the main contributors to sea-level rise (WCRP Global Sea Level Budget Group 2018).

Minimum Arctic sea ice (Figure 3i)

We obtained minimum Arctic sea ice estimates from Wiese (2024) and NSIDC/NASA (2024). They are derived from satellite observations. For each year, the data indicate the average Arctic sea ice extent for September, which is when the annual minimum occurs. According to NSIDC/NASA (2024), "Arctic sea ice reaches its minimum extent [...] each September. September Arctic sea ice is now declining at a rate of 12.2% per decade, compared to its average extent during the period from 1981 to 2010." For plotting purposes, we associated each observation with September 15 (the approximate midpoint of the month).

Greenland ice mass (Figure 3j)

We obtained total land ice mass change measurements for Greenland from Wiese (2024) and NSIDC/NASA (2024). These data show changes in ice sheet mass (in Gt) since April 2002. They come from NASA's GRACE satellites (GRACE and GRACE-FO JPL RL06Mv2 Mascon Solution). The data are in the form of anomalies relative to April 2002. The measurement frequency is roughly monthly. The gap in the data between June 10, 2017 and June 14, 2018 corresponds to the time between missions, and should be kept in mind when interpreting the year-to-date means that we present. For more details on these data, see Watkins et al. (2015).

Antarctica ice mass (Figure 3k)

We obtained total land ice mass change measurements for Antarctica from Wiese (2024). These data show the changes in ice sheet mass (in Gt) since April 2002. They come from NASA's GRACE satellites (GRACE and GRACE-FO JPL RL06Mv2 Mascon Solution). The measurement frequency is roughly monthly. The gap in the data between June 10, 2017 and June 14, 2018 corresponds to the time between missions, and should be kept in mind when interpreting the year-to-date means that we present. For more details on these data, see Watkins et al. (2015).

Cumulative glacier thickness change (Figure 3l)

We obtained cumulative glacier mass balance data from the World Glacier Monitoring Service (WGMS et al. 2023, WGMS 2024). These data were derived from a database with information about changes in mass, volume, etc. of individual glaciers over time. They are based on averaging over a global set of reference glaciers and are measured relative to 1970.

The units of these data are meters of water equivalent. According to the World Glacier Monitoring Service, "A value of -1.0 [meter of water equivalent] per year is representing a mass loss of 1,000 kg per square meter of ice cover or an annual glacier-wide ice thickness loss of about 1.1 m per year, as the density of ice is only 0.9 times the density of water" (WGMS 2024).

For plotting, we associated each value with the midpoint of the corresponding year.

Total area burned by wildfires in the United States (Figure 3m)

These data come from the National Interagency Coordination Center at The National Interagency Fire Center (National Interagency Coordination Center 2024) and include Alaska and Hawaii. The total for 2004 does not include state lands within North Carolina.

Although wildfire risk depends on many factors including forest management, climate change is likely a significant contributor in the United States (An et al. 2015, Dahl et al. 2023) and globally (Jolly et al. 2015).

As with global tree cover loss due to fires (figure 3m), this dataset does not distinguish between natural and human-ignited fires.

Global tree cover loss due to fires (Figure 3n)

We obtained global estimates of tree cover loss due to fires from Tyukavina et al. (2022). Tree cover refers to vegetation with a height of 5 m or greater. These estimates exclude the burning of felled trees, but include both natural and human-ignited fires (Tyukavina et al. 2022).

These data were downloaded using the Global Forest Watch platform (World Resources Institute 2024).

Billion-dollar floods in the United States (Figure 3o)

We obtained data on the frequency of billion-dollar floods in the United States from NOAA (2024b). This dataset covers the number of floods per year (since 1980) with at least 1 billion USD in damages. All damage estimates were CPI-adjusted to 2024 (NOAA 2024b). See Smith (2022) for details.

Climate change is likely associated with increasing flood risk in many parts of the world, although estimates may be highly uncertain (Hirabayashi et al. 2013, Alfieri et al. 2017). Because the data we present relate to economic damages, an increasing trend may be partly due to rising vulnerability, exposure, and GDP (Cardona et al. 2012, Lavell et al. 2012).

Extremely hot days relative to 1961-1990 (Figure 3p)

We used the “TX90p” temperature metric to assess the frequency of extremely hot days (Donat et al. 2013). This variable is derived from the GHCNDEX dataset and indicates the proportion of days where the maximum temperature exceeds the 90th percentile for the baseline period 1961-1990. Thus, it should remain around 10% in the absence of an overall temperature trend. To obtain a single global time series, the gridded spatio-temporal time series were averaged across Earth’s surface (from -84 to 84 latitude). For details, see Zhang et al. (2005) and Donat et al. (2013). These data were downloaded from climdex.org. We acknowledge the Climdex website www.climdex.org for making available observational climate indices used in this study.

Note that climate change has been linked to increases in both the frequency and intensity of extreme heat events (Luber and McGeehin 2008).

Climate Spotlight (Figure 5)

Solar Radiation Modification

To determine the number of scientific articles published on geoengineering each year, we searched the Clarivate Web of Science (WoS) as follows:

- Topic matching “solar geoengineering” OR “solar radiation modification” OR “solar radiation management”
- Document types “Article” or “Review Article”
- Search restricted to Core Collection database

Web of Science Topic searches cover titles, abstracted, and keywords (keyword plus and author keywords).

Climate change as a social justice issue

We mapped climate-related extreme heat using the dataset provided by Climate Central et al. (2024). The specific variable we mapped is the increase in the “average days of temperatures above 90th percentile.” It is associated with the period May 15, 2023 to May 15, 2024. As described in this dataset, the estimates of average days of temperatures above the 90th percentile are “based on residents’ exposure, averaged across entire population).” See Climate Central et al. (2024) for details.

Risk of societal collapse

To determine the number of climate-related scientific articles published on this topic each year, we searched WoS using the procedure described in the Solar Radiation Modification section above except with the following query:

(TS="societal collapse" OR TS="civilization collapse") AND (TS="climate change" OR TS="global warming")

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