

World Scientists' Warning of a Climate Emergency

WILLIAM J. RIPPLE, CHRISTOPHER WOLF, THOMAS M. NEWSOME, PHOEBE BARNARD, WILLIAM R. MOOMAW, AND 11,258 SCIENTIST SIGNATORIES FROM 153 COUNTRIES (LIST IN SUPPLEMENTAL FILE S1)

Scientists have a moral obligation to clearly warn humanity of any catastrophic threat and to “tell it like it is.” On the basis of this obligation and the graphical indicators presented below, we declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency.

Exactly 40 years ago, scientists from 50 nations met at the First World Climate Conference (in Geneva 1979) and agreed that alarming trends for climate change made it urgently necessary to act. Since then, similar alarms have been made through the 1992 Rio Summit, the 1997 Kyoto Protocol, and the 2015 Paris Agreement, as well as scores of other global assemblies and scientists' explicit warnings of insufficient progress (Ripple et al. 2017). Yet greenhouse gas (GHG) emissions are still rapidly rising, with increasingly damaging effects on the Earth's climate. An immense increase of scale in endeavors to conserve our biosphere is needed to avoid untold suffering due to the climate crisis (IPCC 2018).

Most public discussions on climate change are based on global surface temperature only, an inadequate measure to capture the breadth of human activities and the real dangers stemming from a warming planet (Briggs et al. 2015). Policymakers and the public now urgently need access to a set of indicators that convey the effects of human activities on GHG emissions and the consequent impacts on climate, our environment, and society. Building on prior work (see supplemental file S2), we present a suite of graphical vital signs of climate change over the last 40 years for human activities that can affect GHG emissions and change the climate (figure 1), as well

as actual climatic impacts (figure 2). We use only relevant data sets that are clear, understandable, systematically collected for at least the last 5 years, and updated at least annually.

The climate crisis is closely linked to excessive consumption of the wealthy lifestyle. The most affluent countries are mainly responsible for the historical GHG emissions and generally have the greatest per capita emissions (table S1). In the present article, we show general patterns, mostly at the global scale, because there are many climate efforts that involve individual regions and countries. Our vital signs are designed to be useful to the public, policymakers, the business community, and those working to implement the Paris climate agreement, the United Nations' Sustainable Development Goals, and the Aichi Biodiversity Targets.

Profoundly troubling signs from human activities include sustained increases in both human and ruminant livestock populations, per capita meat production, world gross domestic product, global tree cover loss, fossil fuel consumption, the number of air passengers carried, carbon dioxide (CO₂) emissions, and per capita CO₂ emissions since 2000 (figure 1, supplemental file S2). Encouraging signs include decreases in global fertility (birth) rates (figure 1b), decelerated forest loss in the Brazilian Amazon (figure 1g), increases in the consumption of solar and wind power (figure 1h), institutional fossil fuel divestment of more than US\$7 trillion (figure 1j), and the proportion of GHG emissions covered by carbon pricing (figure 1m). However, the decline in human fertility rates has substantially slowed during the last 20 years (figure 1b), and the pace of

forest loss in Brazil's Amazon has now started to increase again (figure 1g). Consumption of solar and wind energy has increased 373% per decade, but in 2018, it was still 28 times smaller than fossil fuel consumption (combined gas, coal, oil; figure 1h). As of 2018, approximately 14.0% of global GHG emissions were covered by carbon pricing (figure 1m), but the global emissions-weighted average price per tonne of carbon dioxide was only around US\$15.25 (figure 1n). A much higher carbon fee price is needed (IPCC 2018, section 2.5.2.1). Annual fossil fuel subsidies to energy companies have been fluctuating, and because of a recent spike, they were greater than US\$400 billion in 2018 (figure 1o).

Especially disturbing are concurrent trends in the vital signs of climatic impacts (figure 2, supplemental file S2). Three abundant atmospheric GHGs (CO₂, methane, and nitrous oxide) continue to increase (see figure S1 for ominous 2019 spike in CO₂), as does global surface temperature (figure 2a–2d). Globally, ice has been rapidly disappearing, evidenced by declining trends in minimum summer Arctic sea ice, Greenland and Antarctic ice sheets, and glacier thickness worldwide (figure 2e–2h). Ocean heat content, ocean acidity, sea level, area burned in the United States, and extreme weather and associated damage costs have all been trending upward (figure 2i–2n). Climate change is predicted to greatly affect marine, freshwater, and terrestrial life, from plankton and corals to fishes and forests (IPCC 2018, 2019). These issues highlight the urgent need for action.

Despite 40 years of global climate negotiations, with few exceptions, we have generally conducted business

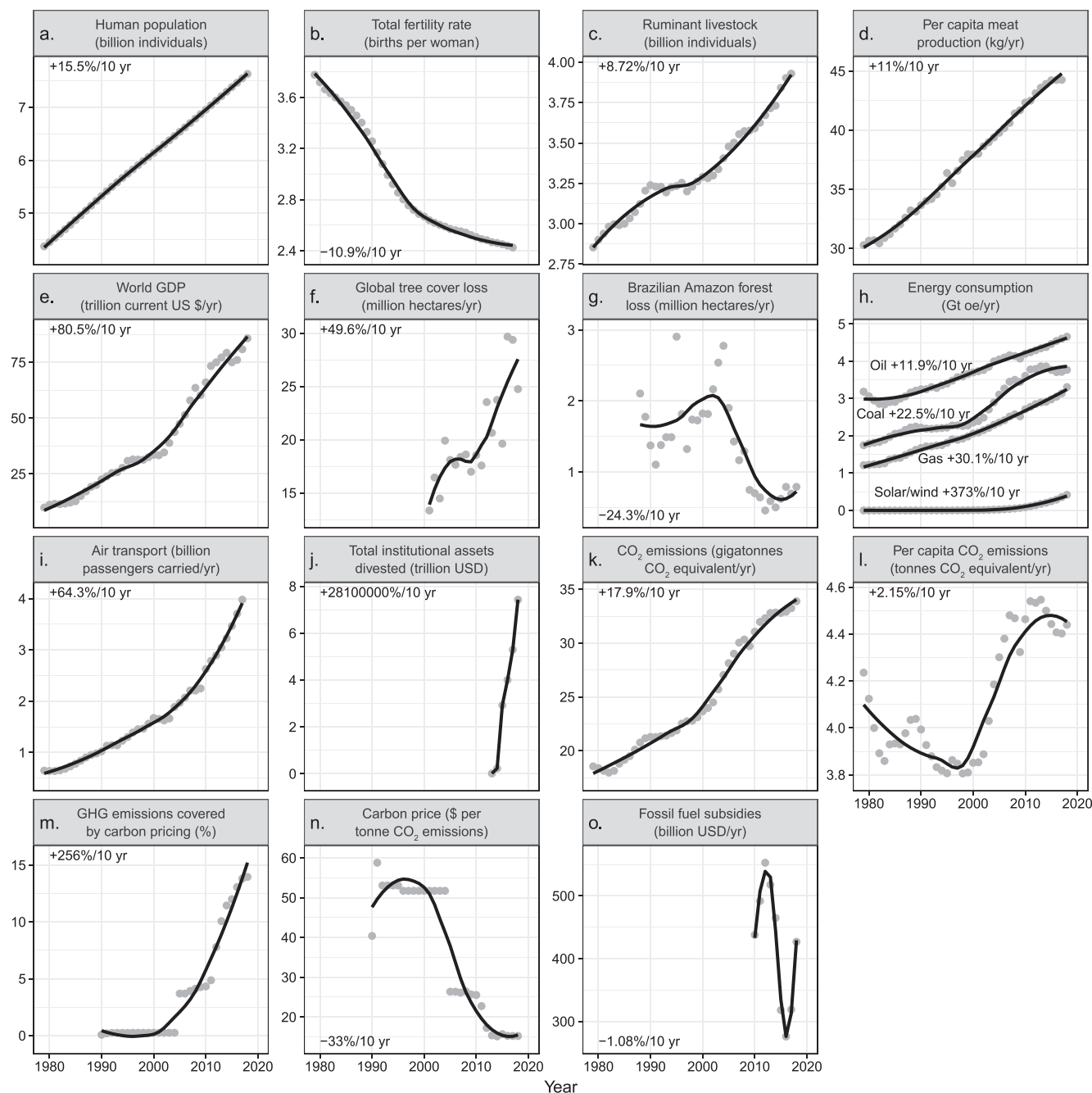


Figure 1. Change in global human activities from 1979 to the present. These indicators are linked at least in part to climate change. In panel (f), annual tree cover loss may be for any reason (e.g., wildfire, harvest within tree plantations, or conversion of forests to agricultural land). Forest gain is not involved in the calculation of tree cover loss. In panel (h), hydroelectricity and nuclear energy are shown in figure S2. The rates shown in panels are the percentage changes per decade across the entire range of the time series. The annual data are shown using gray points. The black lines are local regression smooth trend lines. Abbreviation: Gt oe per year, gigatonnes of oil equivalent per year. Sources and additional details about each variable are provided in supplemental file S2, including table S2.

as usual and have largely failed to address this predicament (figure 1). The climate crisis has arrived and is accelerating faster than most scientists expected (figure 2, IPCC 2018). It is

more severe than anticipated, threatening natural ecosystems and the fate of humanity (IPCC 2019). Especially worrisome are potential irreversible climate tipping points and nature's

reinforcing feedbacks (atmospheric, marine, and terrestrial) that could lead to a catastrophic "hothouse Earth," well beyond the control of humans (Steffen et al. 2018). These climate

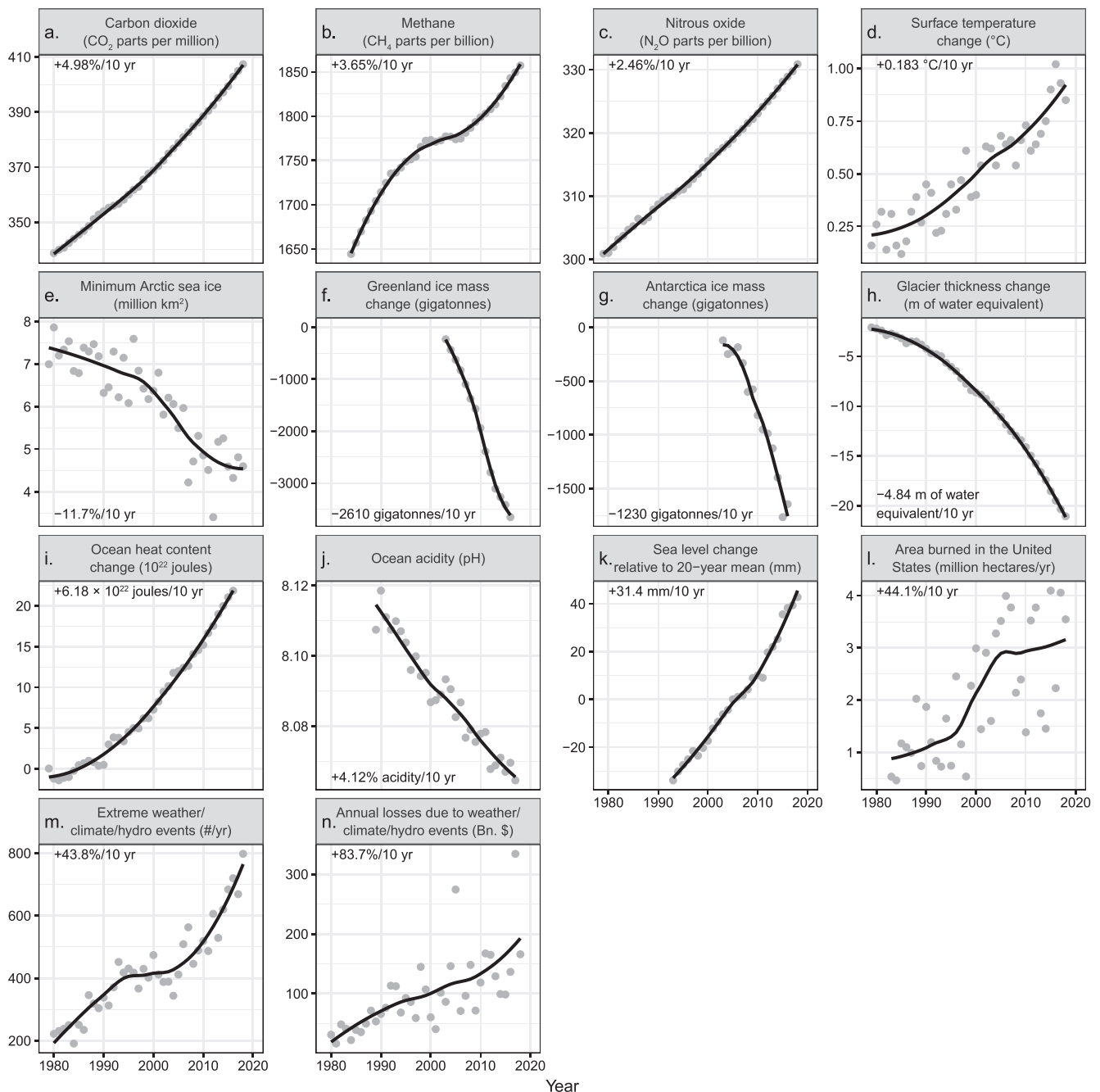


Figure 2. Climatic response time series from 1979 to the present. The rates shown in the panels are the decadal change rates for the entire ranges of the time series. These rates are in percentage terms, except for the interval variables (d, f, g, h, i, k), where additive changes are reported instead. For ocean acidity (pH), the percentage rate is based on the change in hydrogen ion activity, a_{H^+} (where lower pH values represent greater acidity). The annual data are shown using gray points. The black lines are local regression smooth trend lines. Sources and additional details about each variable are provided in supplemental file S2, including table S3.

chain reactions could cause significant disruptions to ecosystems, society, and economies, potentially making large areas of Earth uninhabitable.

To secure a sustainable future, we must change how we live, in ways that

improve the vital signs summarized by our graphs. Economic and population growth are among the most important drivers of increases in CO_2 emissions from fossil fuel combustion (Pachauri et al. 2014, Bongaarts and

O'Neill 2018); therefore, we need bold and drastic transformations regarding economic and population policies. We suggest six critical and interrelated steps (in no particular order) that governments, businesses, and the rest of

humanity can take to lessen the worst effects of climate change. These are important steps but are not the only actions needed or possible (Pachauri et al. 2014, IPCC 2018, 2019).

Energy

The world must quickly implement massive energy efficiency and conservation practices and must replace fossil fuels with low-carbon renewables (figure 1h) and other cleaner sources of energy if safe for people and the environment (figure S2). 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” section). Wealthier countries need to support poorer nations in transitioning away from fossil fuels. We must swiftly eliminate subsidies for fossil fuels (figure 1o) 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 2b), 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 CO₂. 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 1f–1g), 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).

Food

Eating mostly plant-based foods while reducing the global consumption of animal products (figure 1c–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” section). 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 1a–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).

Conclusions

Mitigating and adapting to climate change while honoring the diversity of humans entails major transformations in the ways our global society functions and interacts with natural ecosystems. We are encouraged by a recent surge of concern. Governmental bodies are making climate emergency declarations. Schoolchildren are striking. Ecocide lawsuits are proceeding in the courts. Grassroots citizen movements are demanding change, and many countries, states and provinces, cities, and businesses are responding.

As the Alliance of World Scientists, we stand ready to assist decision-makers in a just transition to a sustainable and equitable future. We urge widespread use of vital signs, which will better allow policymakers, the private sector, and the public to understand the magnitude of this crisis, track progress, and realign priorities for alleviating climate change. The good news is that such transformative change, with social and economic justice for all, promises far greater human well-being than does business as usual. We believe that the prospects will be greatest if decision-makers and all of humanity promptly respond to this warning and declaration of a climate emergency and act to sustain life on planet Earth, our only home.

Contributing reviewers

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Project website

To view the Alliance of World Scientists website or to sign this article, go to <https://scientistswarning.forestry.oregonstate.edu>.

Supplemental material

Supplemental data are available at *BIOSCI* online. A list of the signatories appears in supplemental file S1.

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Supplemental File S1 for the article “**World Scientists’ Warning of a Climate Emergency**” published in *BioScience* by William J. Ripple, Christopher Wolf, Thomas M. Newsome, Phoebe Barnard, and William R. Moomaw.

Contents: List of countries with scientist signatories (page 1); List of scientist signatories (pages 1-319).

List of 153 countries with scientist signatories: Albania; Algeria; American Samoa; Andorra; Argentina; Australia; Austria; Bahamas (the); Bangladesh; Barbados; Belarus; Belgium; Belize; Benin; Bolivia (Plurinational State of); Botswana; Brazil; Brunei Darussalam; Bulgaria; Burkina Faso; Cambodia; Cameroon; Canada; Cayman Islands (the); Chad; Chile; China; **Colombia**; Congo (the Democratic Republic of the); Congo (the); Costa Rica; Côte d’Ivoire; Croatia; Cuba; Curaçao; Cyprus; Czech Republic (the); Denmark; Dominican Republic (the); Ecuador; Egypt; El Salvador; Estonia; Ethiopia; Faroe Islands (the); Fiji; Finland; France; French Guiana; French Polynesia; Georgia; Germany; Ghana; Greece; Guam; Guatemala; Guyana; Honduras; Hong Kong; Hungary; Iceland; India; Indonesia; Iran (Islamic Republic of); Iraq; Ireland; Israel; Italy; Jamaica; Japan; Jersey; Kazakhstan; Kenya; Kiribati; Korea (the Republic of); Lao People’s Democratic Republic (the); Latvia; Lebanon; Lesotho; Liberia; Liechtenstein; Lithuania; Luxembourg; Macedonia, Republic of (the former Yugoslavia); Madagascar; Malawi; Malaysia; Mali; Malta; Martinique; Mauritius; Mexico; Micronesia (Federated States of); Moldova (the Republic of); Morocco; Mozambique; Namibia; Nepal; Netherlands (the); New Caledonia; New Zealand; Nigeria; Northern Mariana Islands (the); Norway; Pakistan; Panama; Papua New Guinea; Paraguay; Peru; Philippines (the); Poland; Portugal; Puerto Rico; Qatar; Réunion; Romania; Russian Federation (the); Rwanda; São Tomé and Príncipe; Saudi Arabia; Senegal; Serbia; Seychelles; Sierra Leone; Singapore; Slovakia; Slovenia; South Africa; Spain; Sri Lanka; Sudan (the); Suriname; Sweden; Switzerland; Taiwan; Tanzania, United Republic of; Thailand; Togo; Tunisia; Turkey; Turks and Caicos Islands (the); Uganda; Ukraine; United Arab Emirates (the); United Kingdom of Great Britain and Northern Ireland (the); United States of America (the); Uruguay; Venezuela (Bolivarian Republic of); Viet Nam; Virgin Islands (U.S.); Wallis and Futuna; Zambia; Zimbabwe.

On the next page you will find my name with the institutional affiliation

List of 11,258 original scientist signatories (minus 166 invalid names, now totaling 11,092 signatories):

Name	Professional Position and/or Discipline	Institution	Country
Aarbakke, Dr. Ole Nicolai Staurland	Marine biology		Norway
Aarnoudse, Eefje		Center for International Development and Environmental Research, Giessen University	Germany
Aarssen, Lonnie	Professor of Biology	Queen’s University	Canada
Aas, Wenche	Senior Scientist	NILU - Norwegian Institute for Air Research	Norway
Aavik, Tsipe	Senior Research Fellow of Macroecology	University of Tartu	Estonia
Abad, Manuel	Researcher / Geology	Universidad de Atacama	Chile
Abadie, Juliet	PhD in ecology		France
Abalos, Javier	Animal behaviour	University of Valencia	Spain
Abarca, Mariana	Insect ecologist	Georgetown University	United States of America (the)
Abate, Maria	Assistant Professor of Biology	Simmons University	United States of America (the)
Abazajian, Kevork	Professor of Physics & Astronomy	University of California, Irvine	United States of America (the)
Abbate, Jessica	Postdoctoral Researcher in Infectious Disease Biology	Institut de Recherche pour le Developpement	France
Abbott, Brett	Landscape Ecologist		Australia
Abbott, Benjamin W.	Assistant Professor of Ecosystem Ecology	Brigham Young University	United States of America (the)
Abbott, Katherine	Aquatic Ecology		United States of America (the)

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Gutierrez, Marco	PhD Candidate	RMIT University	Australia
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Gutierrez Robledo, Luis Miguel	Director General	Instituto Nacional de Geriatria	Mexico
Gutleb, Arno	Group Leader	Environmental Scientist / Toxicologist	Luxembourg
Gutsche-Jones, Fanny	Community Manager	Citizen Science Center Zurich	Switzerland
Guuroh, Reginald Tang	Research Scientist	Council for Scientific and Industrial Research - Forestry Research Institute of Ghana	Ghana
Guy-Haim, Tamar	Marine Biology researcher	Israel Oceanography and Limnology Research	Israel
Guzmán-Jacob, Valeria	PhD. student. Biodiversity and Ecology	University of Göttingen	Germany
Guzy, Anna	Phd	University of Silesia	Poland
Gwedla, Nanamhla	PhD Candidate- Urban Ecology	Rhodes University	South Africa
Gwynne-Jones, Richard	Master of Biology (Marine and Freshwater)	Blue Domain	United Kingdom of Great Britain and Northern Ireland (the)
Haanappel, Evert	Biophysicist	CNRS	France
Haapakoski, Marko	Post doc researcher / Ecology	University of Jyväskylä / Konnevesi Research Station	Finland
Haber, Istvan	assistant professor	University of Pecs	Hungary
Haber, Ariela	Post doc		United States of America (the)
Haberstroh, Simon	PhD student		Germany
Habibzadeh, Nader	Assistant professor/Environmental science	Islamic Azad University	Iran (Islamic Republic of)
Habit, Evelyn	Professor	Facultad de Ciencias Ambientales. Universidad de Concepción.	Chile
Hacquin, Anne-Sophie	Research Engineer in Cognitive Science	ENS	France
Haddad, Stephanie	Research assistant	Queens	Canada
Haddock, Joanna	PhD in Ecology	The University of Sydney	Australia
Hadfield, Michael G.	Biology	University of Hawaii at Manoa	Uruguay
Hadjeras, Lydia	Postdoctoral researcher		Germany
Hadjioannou, Louis	Research Director	Enalia Physis Environmental Research Centre	Cyprus
haegele, anna	medical doctor		Germany
Haegeli, Pascal	Assistant Professor, Resource and Environmental Management	Simon Fraser University	Canada
Hagan, Emily		Hagan	United States of America (the)
Hage, Joseph	Biology Professor/Researcher	Algonquin college Ottawa	Canada
Hagedorn, Gregor	Senior Scientist	Museum für Naturkunde	Germany
Haggard, Judy	Wildlife biologist	Retired	United States of America (the)
Hagge, Jonas	Forest ecology	Technical University of Munich	Germany
Hagolle, Olivier		CESBIO	France
Haguet, Vincent	Engineering	CEA	France
Hahn, Thomas	Associate Professor in Ecological Economics	Stockholm University	Sweden

Supplemental File S2: World Scientists' Warning of a Climate Emergency

by William J. Ripple, Christopher Wolf, Thomas M. Newsome, Phoebe Barnard, William R. Moomaw, 11,258 scientist signatories from 153 countries (list in supplemental file S1)

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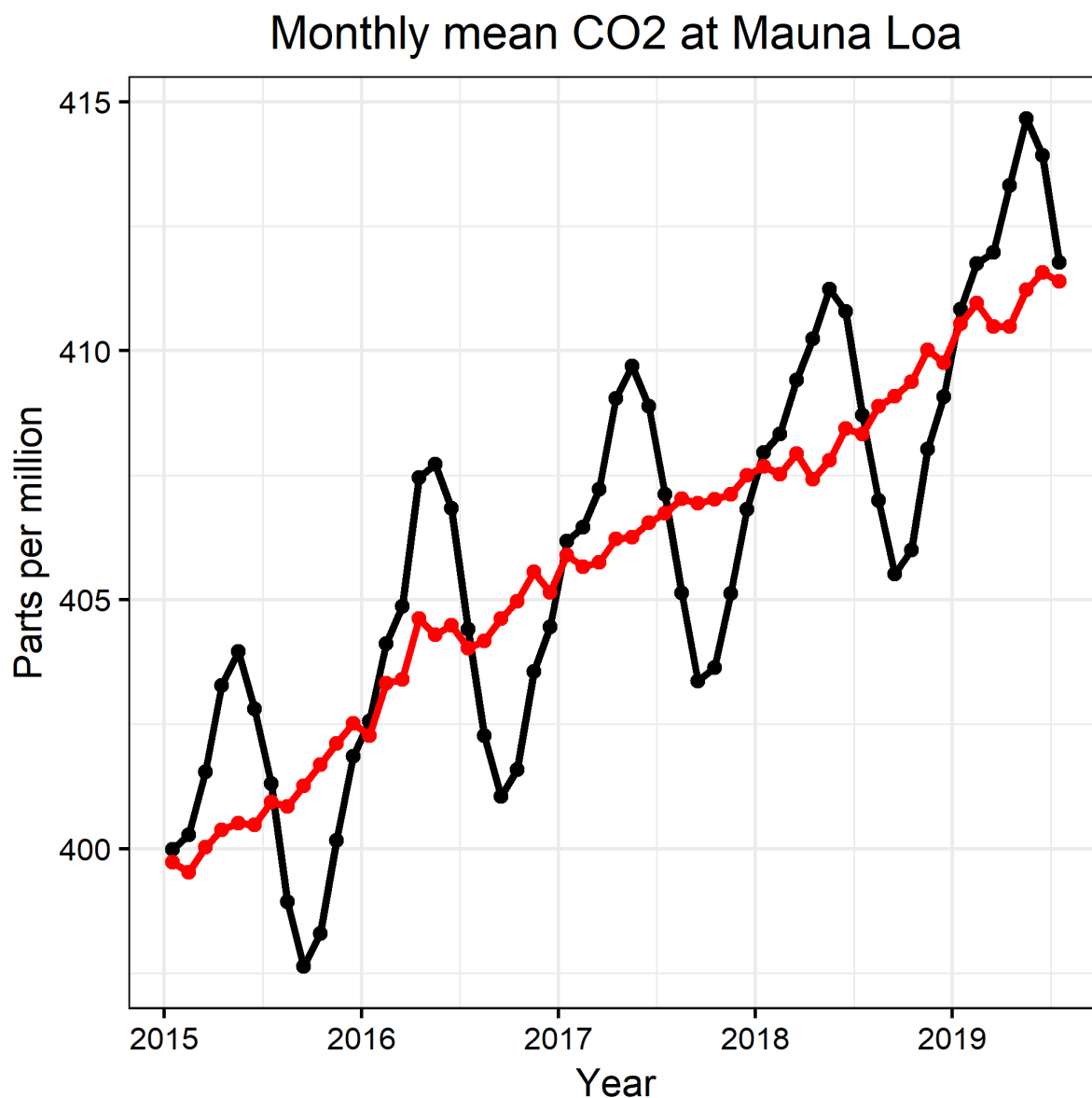


Figure S1. “Monthly mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. The carbon dioxide data ([black] curve), measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO₂ in the atmosphere. [...] The [black line represents] the monthly mean values, centered on the middle of each month. The [red line represents] the same, after correction for the average seasonal cycle. The latter is determined as a moving average of SEVEN adjacent seasonal cycles centered on the month to be corrected, except for the first and last THREE and one-half years of the record, where the seasonal cycle has been averaged over the first and last SEVEN years, respectively.” Source <https://www.esrl.noaa.gov/gmd/ccgg/trends/>

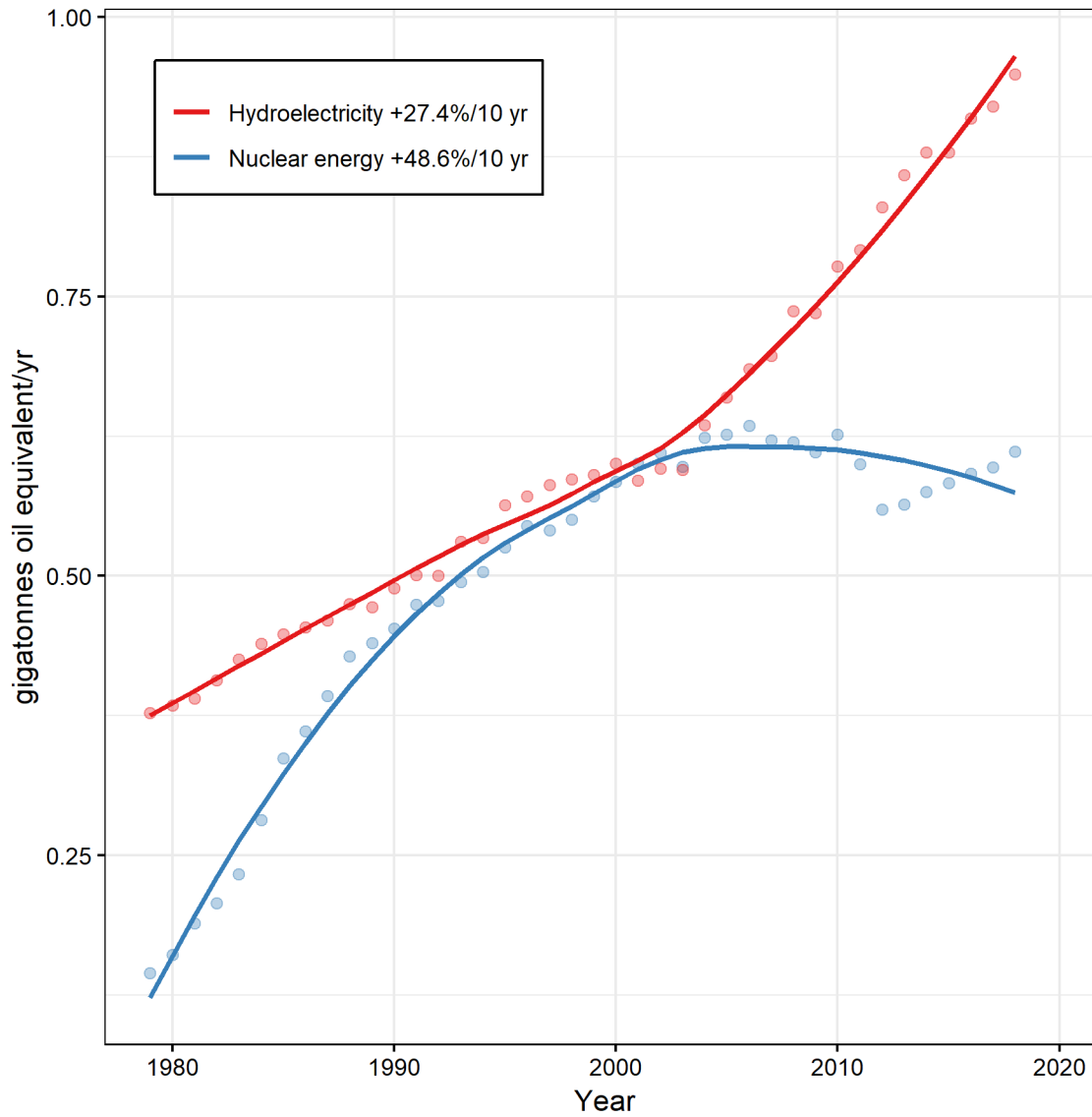


Figure S2. Annual consumption rates for nuclear energy and hydroelectricity (British Petroleum Company 2019). Rates shown in the legend are decadal change rates for the entire ranges of the time series (in percentage terms). See British Petroleum Company (2019) for other minor energy sources not shown in this figure. Figure 1h in the main text shows consumption of fossil fuels as well as solar/wind energy.

Supplemental Tables

Table S1. Regional summaries for 24 countries and The European Union. Variables shown are “CO₂” (total CO₂ emissions associated with fossil fuel consumption in mega tonnes CO₂), “Population” (human population size in millions), “CO₂/capita” (CO₂ emissions per capita in tonnes per person), “Share” (percentage of all CO₂ 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 2018, except GDP for Iran, which is from 2017 (2018 estimate was not yet available). Additional details on the variables are provided in the supplementary information below.

	CO ₂	Population	CO ₂ /capita	Share	GDP/capita
China	9429	1447	6.5	28.4%	\$9,400
United States	5145	327	15.7	15.5%	\$62,736
The European Union	3470	510	6.8	10.4%	\$36,806
India	2479	1354	1.8	7.5%	\$2,016
Russia	1551	144	10.8	4.7%	\$11,531
Japan	1148	127	9.0	3.5%	\$39,077
South Korea	698	51	13.6	2.1%	\$31,663
Iran	656	82	8.0	2.0%	\$5,536
Saudi Arabia	571	34	17.0	1.7%	\$23,305
Canada	550	37	14.9	1.7%	\$46,274
Indonesia	543	267	2.0	1.6%	\$3,898
Mexico	463	131	3.5	1.4%	\$9,330
Brazil	442	211	2.1	1.3%	\$8,868
South Africa	421	57	7.3	1.3%	\$6,376
Australia	417	25	16.8	1.3%	\$57,726
Turkey	390	82	4.8	1.2%	\$9,363
Thailand	302	69	4.4	0.9%	\$7,299
United Arab Emirates	277	10	29.0	0.8%	\$43,389
Malaysia	250	32	7.8	0.8%	\$11,048
Kazakhstan	248	18	13.5	0.7%	\$9,292
Singapore	230	6	39.7	0.7%	\$62,846
Vietnam	225	96	2.3	0.7%	\$2,539
Egypt	224	99	2.3	0.7%	\$2,526
Pakistan	196	201	1.0	0.6%	\$1,559
Ukraine	187	44	4.2	0.6%	\$2,977
Top 25	30511	5460	5.6	91.8%	\$13,960
World	33243	7550	4.4	100.0%	\$11,363

Table S2. Summary of human activity indicators. Table columns show the variable name, the most recent year with data, the value of the variable in that year, the rank for that year (rank #1 is the highest possible value), and the total number of years with data (since 1979). For example, human population was most recently estimated in 2018 to have a value of 7.63 billion individuals, which ranked as the greatest value among the 40 years of data available since 1979.

Variable	Year	Value	Rank	Total years
Human population (billion individuals)	2018	7.63	1	40
Total fertility rate (births per woman)	2017	2.43	39	39
Ruminant livestock (billion individuals)	2017	3.93	1	39
Per capita meat production (kg/yr)	2017	44.3	1	39
World GDP (trillion current US \$/yr)	2018	85.8	1	40
Global tree cover loss (million hectares/yr)	2018	24.8	3	18
Brazilian Amazon forest loss (million hectares/yr)	2018	0.79	22	31
Coal consumption (gigatonnes oil equivalent/yr)	2018	3.77	5	40
Oil consumption (gigatonnes oil equivalent/yr)	2018	4.66	1	40
Natural gas consumption (gigatonnes oil equivalent/yr)	2018	3.31	1	40
Solar/wind (gigatonnes oil equivalent/yr)	2018	0.42	1	40
Air transport (billion passengers carried/yr)	2017	3.98	1	39
Total assets divested (trillion USD)	2018	6.17	1	6
CO ₂ emissions (gigatonnes CO ₂ equivalent/yr)	2018	33.9	1	40
Per capita CO ₂ emissions (tonnes CO ₂ equivalent/yr)	2018	4.44	9	40
GHG emissions covered by carbon pricing (%)	2018	14	1	29
Carbon price (\$ per tonne CO ₂ emissions)	2018	15.2	28	29
Fossil fuel subsidies (billion USD/yr)	2018	427	6	9

Table S3. Summary of climatic response indicators. Table columns show the variable name, the most recent year with data, the value of the variable in that year, the rank for that year (rank #1 is the highest possible value), and the total number of years with data (since 1979). For example, atmospheric carbon dioxide concentration was most recently estimated in 2018 to have a value of 407 parts per million, which ranked as the greatest value among the 39 years of data available since 1979.

Variable	Year	Value	Rank	Total years
Carbon dioxide (CO ₂ parts per million)	2018	407	1	39
Methane (CH ₄ parts per billion)	2018	1860	1	35
Nitrous oxide (N ₂ O parts per billion)	2018	331	1	40
Surface temperature change (°C)	2018	0.85	4	40
Minimum Arctic sea ice (million km ²)	2018	4.6	35	40
Greenland ice mass change (gigatonnes)	2016	-3660	14	14
Antarctica ice mass change (gigatonnes)	2016	-1640	13	14
Glacier thickness change (m of water equivalent)	2018	-21.1	40	40
Ocean heat content change (10 ²² joules)	2016	21.9	1	38
Ocean acidity (pH)	2017	8.06	29	29
Sea level change (cm)	2018	42.8	1	26
Area burned in the United States (million hectares/yr)	2018	3.55	6	36
Extreme weather/climate/hydro events (#/yr)	2018	798	1	39
Annual losses due to weather/climate/hydro events (Bn. \$)	2018	166	4	39

Other graphical indicators

Global Climate Observing System (GCOS)- uses seven climate indicators including surface temperature, ocean heat, atmospheric CO₂, ocean acidification, sea level, glaciers, and arctic and Antarctic sea ice extent. <https://gcos.wmo.int/en/home>

NASA vital signs of the planet- uses five climate indicators including global temperature, arctic ice minimum, ice sheets, sea level, and CO₂. <https://climate.nasa.gov/>

2 Degrees Institute- uses six climate indicators including global temperature record, CO₂ levels, methane (CH₄) levels, nitrous oxide (N₂O) levels, oxygen (O₂) levels, and global sea levels. <https://www.2degreesinstitute.org/>

IPCC 1.5C Report- uses the global warming index. https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

Methods

We compiled a set of global time series related to human actions that affect the environment (e.g. fossil fuel consumption) and environmental and climatic responses (e.g. temperature change). Descriptions and sources for each variable are given in the next section. 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. We only considered indicator variables that are updated at least every year. We converted each variable to annual format by averaging together observations within each calendar year if necessary, excluding data from the first and last years when incomplete (first year incomplete: ocean acidity, Greenland and Antarctica ice mass; last year incomplete: nitrous oxide, Greenland and Antarctica ice mass). For each variable, we removed years prior to 1979. We then computed smooth trend lines 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 2018).

We used the trend lines to calculate the rate of change of each variable. For ratio variables (i.e. those with a ‘true’ zero, like atmospheric CO₂ concentration), we computed percentage change, and for interval variables (which can be shifted up or down arbitrarily, like sea level) we computed additive change. For ratio variables, we used the following formula for 10-year percentage change:

$$r_{ratio} = 100\% \times \left[\left(\frac{y_{end}}{y_{start}} \right)^{\frac{10}{t_{end}-t_{start}}} - 1 \right]$$

Where y_{start} and y_{end} are the start and end values of the trend line and t_{start} and t_{end} are the start and end years. This is the 10-year percentage change with a decadal compounding interval. For example, a variable that increased at a rate of 15% per decade over its entire time span would have a value of 15% according to this formula. For ocean acidity (pH), we calculated percentage change in terms of hydrogen ion activity (a_{H^+}) (lower pH values represent greater acidity). For interval variables, we used the formula

$$r_{interval} = 10 \times \frac{y_{end} - y_{start}}{t_{end} - t_{start}}$$

Indicators of human activities that can affect GHG emissions or climate change (Figure 1)

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

Human population (Figure 1a)

We used the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) as our source of human population data (FAOSTAT 2019). For human population estimates, the source data used by FAOSTAT are from national population censuses.

Total fertility rate (Figure 1b)

We obtained this variable from the World Bank (The World Bank 2019a). 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 (2019a). 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 2019a).

Ruminant livestock population (Figure 1c)

We used the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) as our source of ruminant livestock population data (FAOSTAT 2019). 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 2019).

Per capita meat production (Figure 1d)

We used total meat production data from FAOSTAT along with FAOSTAT human population size estimates (Figure 1a) to estimate per capita meat production (FAOSTAT 2019). These data “are given in terms of dressed carcass weight, excluding offal and slaughter fats” (FAOSTAT 2019).

Gross domestic product (Figure 1e)

We obtained this variable from the World Bank (The World Bank 2019b). The full variable name is “GDP (current US\$)” and the World Bank variable ID is NY.GDP.MKTP.CD. This variable was derived from multiple sources, including World Bank national accounts. The full list of sources is available at The World Bank (2019b). Gross domestic product is “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” (2019b).

Global tree cover loss (Figure 1f)

We obtained data on annual global tree cover loss from Global Forest Watch (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.

Brazilian Amazon forest loss (Figure 1g)

We obtained annual Brazilian Amazon forest loss estimates from Butler (2017). Brazil contains about 60% of the Amazon rainforest. The sources used by Butler (2017) were the Brazilian National Institute of Space Research (INPE) and the United Nations Food and Agriculture Organization (FAO). Although the INPE has not provided a deforestation estimate for 2019, their wildfire activity data show a major spike associated with widespread deforestation (Amigo 2019).

Energy consumption (Figure 1h)

We used the British Petroleum Company's 2019 Statistical Review of World Energy as our source of data on energy consumption (British Petroleum Company 2019). 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 gigatonnes oil equivalent (Gt oe). Other sources of low carbon energy such as hydropower and nuclear power are shown in Figure S2. Although not used in this report, global energy consumption data are also available from the International Energy Agency (IEA 2018).

Air transport (Figure 1i)

We obtained this variable from the World Bank (The World Bank 2019c). The full variable name is "Air transport, passengers carried." The corresponding World Bank variable ID is IS.AIR.PSGR. This variable was derived from multiple sources, including the International Civil Aviation Organization. The full lists of sources is available at The World Bank (2019c). Air transport includes both domestic and international travelers.

Divestment (Figure 1j)

Divestment data were obtained from 350.org (350.org 2019; Fossil Free 2019). They cover institutional divestment by 1,117 organizations. The most commonly represented institutions were faith-based organizations, philanthropic foundations, educational institutions, governments, and pension funds (Fossil Free 2019). Using 350.org's divestment database, we calculated cumulative total institutional divestment by year (since 2013) based on the "date of record" variable, which "generally represents the organization's divestment commitment announcement date" (350.org 2019).

CO₂ emissions (Figure 1k)

We used the British Petroleum Company's 2019 Statistical Review of World Energy as our source of data on CO₂ emissions (British Petroleum Company 2019). These CO₂ emissions data "reflect only [...] consumption of oil, gas and coal for combustion related activities" (British Petroleum Company 2019). They do not account for carbon sequestration, other CO₂ emissions, or other greenhouse gas emissions.

Per capita CO₂ emissions (Figure 1l)

We converted total CO₂ emissions (Figure 1k) to per capita CO₂ emissions using FAOSTAT human population size estimates (Figure 1a).

Greenhouse gas emissions covered by carbon pricing (Figure 1m)

The data on percentage of greenhouse gas emissions covered by carbon pricing schemes are taken directly from World Bank Group (2019). When multiple schemes covered the same emissions, the emissions were associated with the earliest of the schemes. The data were accessed using the Carbon Pricing Dashboard. They were last updated on April 1, 2019.

Carbon price and share of greenhouse gas emissions covered by carbon pricing (Figure 1n)

These data were derived from World Bank Group (2019). 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. The data were accessed using the Carbon Pricing Dashboard. They were last updated on April 1, 2019.

Fossil fuel subsidies (Figure 1o)

We obtained data on fossil fuel subsidies from the International Energy Agency (2019a). Fossil fuel consumption subsidies are global totals in 2018 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" (International Energy Agency 2019b). The subsidy amount is equal to the product of this price gap and the amount consumed (International Energy Agency 2019b).

Indicators of actual climatic impacts (Figure 2)

Atmospheric CO₂ (Figure 2a)

We obtained globally averaged estimates of atmospheric CO₂ concentration from NOAA's Global Greenhouse Gas Reference Network (NOAA 2019a). Specifically, we used the variable "Globally averaged marine surface annual mean data." It is based on data collected by The Global Monitoring Division of NOAA/Earth System Research Laboratory using a global network of sampling sites. Global means were estimated by first smoothing observations from each site across time and then estimating the relationship between atmospheric CO₂ and latitude.

Atmospheric methane (Figure 2b)

We obtained globally-averaged annual estimates of atmospheric methane (CH₄) concentration from NOAA (Ed Dlugokencky, NOAA/ESRL 2019). We used the "Globally averaged marine surface annual 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 & Tans 1995). The data are reported as a "dry air mole fraction" (Ed Dlugokencky, NOAA/ESRL 2019).

Atmospheric nitrous oxide (Figure 2c)

We obtained data on nitrous oxide (N₂O) concentration from the NOAA/ESRL Global Monitoring Division ("Combined Nitrous Oxide data from the NOAA/ESRL Global Monitoring Division") (NOAA/ESRL Global Monitoring Division 2019). We used the global monthly mean estimates (measured in parts per billion). As noted in their description, the dataset is a weighted average of estimates from NOAA/ESRL/GMD measurement programs.

Surface temperature change (Figure 2d)

We obtained global mean surface temperature anomaly data from NASA/GISS (2019). We used the unsmoothed annual Land-Ocean Temperature Index variable. The temperature anomaly/change estimates combine land and ocean surface temperatures. The baseline period used for setting zero is the 1951-1980 mean.

Minimum Arctic sea ice (Figures 2e)

We obtained minimum Arctic sea ice estimates from NASA (2019). They are derived from satellite observations. For each year, the data show the average Arctic sea ice extent for the month of September, which is when the annual minimum occurs. According to NASA (2019), "Arctic sea ice reaches its minimum each September. September Arctic sea ice is now declining at a rate of 12.8 percent per decade, relative to the 1981 to 2010 average. The graph above shows the average monthly Arctic sea ice extent each September since 1979, derived from satellite observations. The 2012 extent is the lowest in the satellite record."

Greenland ice mass (Figure 2f)

We obtained total land ice mass change measurements for Greenland from NASA (2019). These data show the changes in ice sheet mass (in Gt) since April 2002. They come from NASA's GRACE satellites. According to NASA (2019), the Greenland ice sheet has “seen an acceleration of ice mass loss since 2009.”

Antarctica ice mass (Figure 2g)

We obtained total land ice mass change measurements for Antarctica from NASA (2019). These data show the changes in ice sheet mass (in Gt) since April 2002. They come from NASA's GRACE satellites. According to NASA (2019), the Antarctica ice sheet has “seen an acceleration of ice mass loss since 2009.”

Cumulative glacier thickness change (Figure 2h)

We obtained cumulative glacier mass balance data from the World Glacier Monitoring Service (WGMS 2019). 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 2019).

Ocean heat content (Figure 2i)

We obtained pentadal ocean heat content time series data from NOAA's National Centers for Environmental Information (NCEI) (NOAA 2019b). 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).

Ocean acidity (Figure 2j)

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 2019). 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 “pH_{meas_in situ},” which is described as the “mean measured seawater pH, adjusted to in situ temperature, on the total scale” (HOT 2019). To report percentage change for this variable, we first converted pH to hydrogen ion activity (a_{H^+}) using the formula $a_{H^+}=10^{-pH}$.

Extreme weather events (number) (Figure 2k)

These data come from Munich Re's NatCatSERVICE (Munich Re 2019). Extreme weather events are meteorological, hydrological, or climatological events that “have caused at least one fatality and/or

produced normalized losses \geq US\$ 100k, 300k, 1m, or 3m (depending on the assigned World Bank income group of the affected country).” The entire database contained 18,169 events, but we excluded geophysical events, leaving a total of 16,585 events. These span three categories: meteorological events (tropical cyclones, extratropical storms, etc.), hydrological events (floods, mass movements), and climatological events (droughts, forest fires, etc.).

Extreme weather events (economic losses) (Figure 2l)

These data come from Munich Re’s NatCatSERVICE (Munich Re 2019) as described above. Economic losses (in 2018 USD) were “Inflation adjusted via country-specific consumer price index and consideration of exchange rate fluctuations between local currency and US\$” (Munich Re 2019).

Sea level change (Figure 2m)

We obtained data on global mean sea level from GSFC (2017) [linked to from NASA (2019)]. As noted in the dataset description, the graph available at <http://climate.nasa.gov> is based on plotting heights “with respect to the first cycle (January) of 1993.” 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.” It should be noted that temperature increase and the warming of the entire ocean is a major contributor to sea-level rise (WCRP Global Sea Level Budget Group 2018).

Total area burned by wildfires in the United States (Figure 2n)

These data come from the National Interagency Coordination Center at The National Interagency Fire Center (National Interagency Coordination Center 2018) and include Alaska and Hawaii. They are derived from information published in Situation Reports. Because sources of the figures are unknown prior to 1983, we omitted data before 1983. The total for 2004 does not include state lands within North Carolina.

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