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

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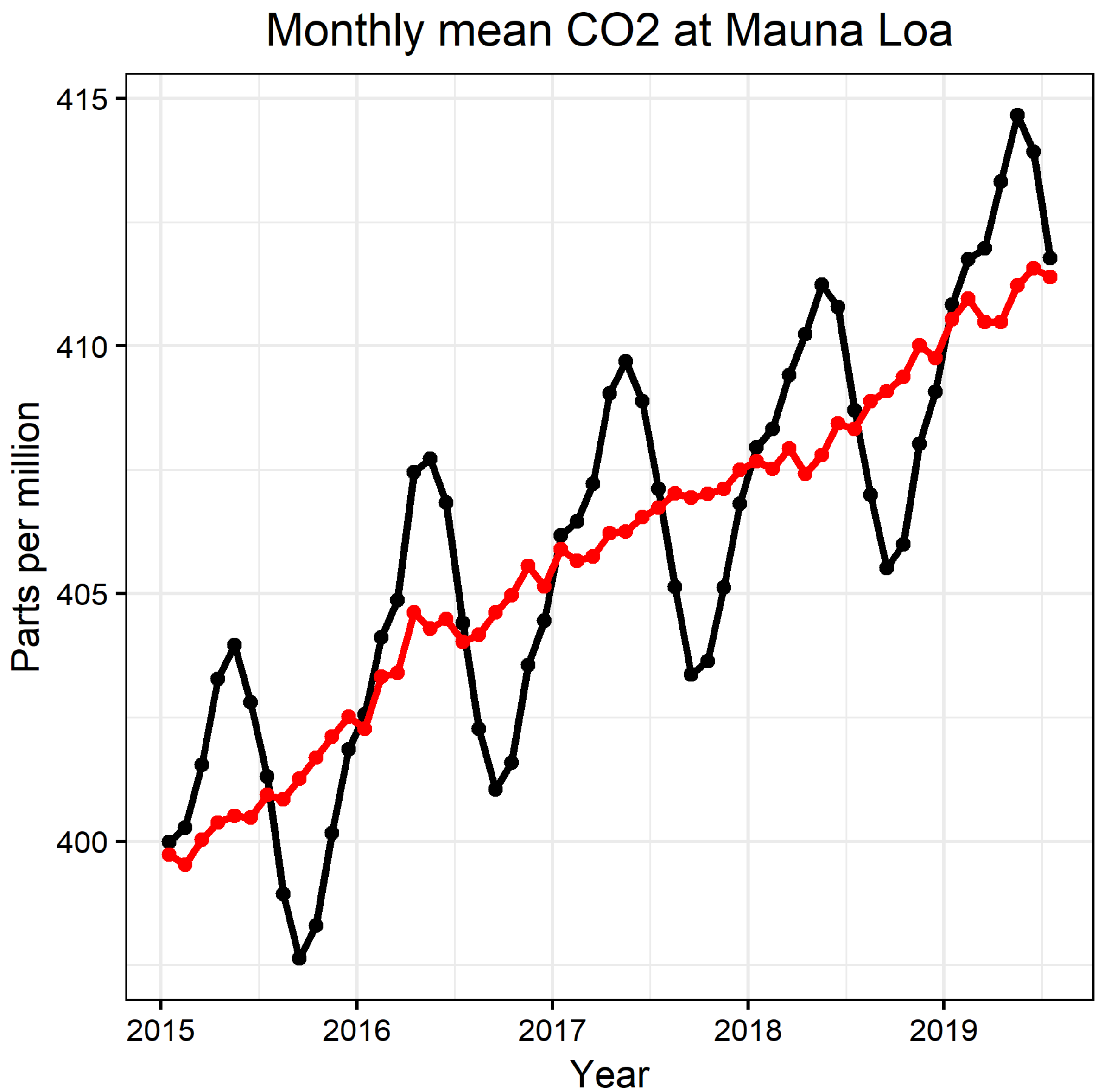

Figure S1. "Monthly mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. The carbon dioxide data ([black] curve), measured as the mole fraction in dry air, on Mauna Loa constitute the longest record of direct measurements of CO_2 in the atmosphere. […] The [**black line** represents] the monthly 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/

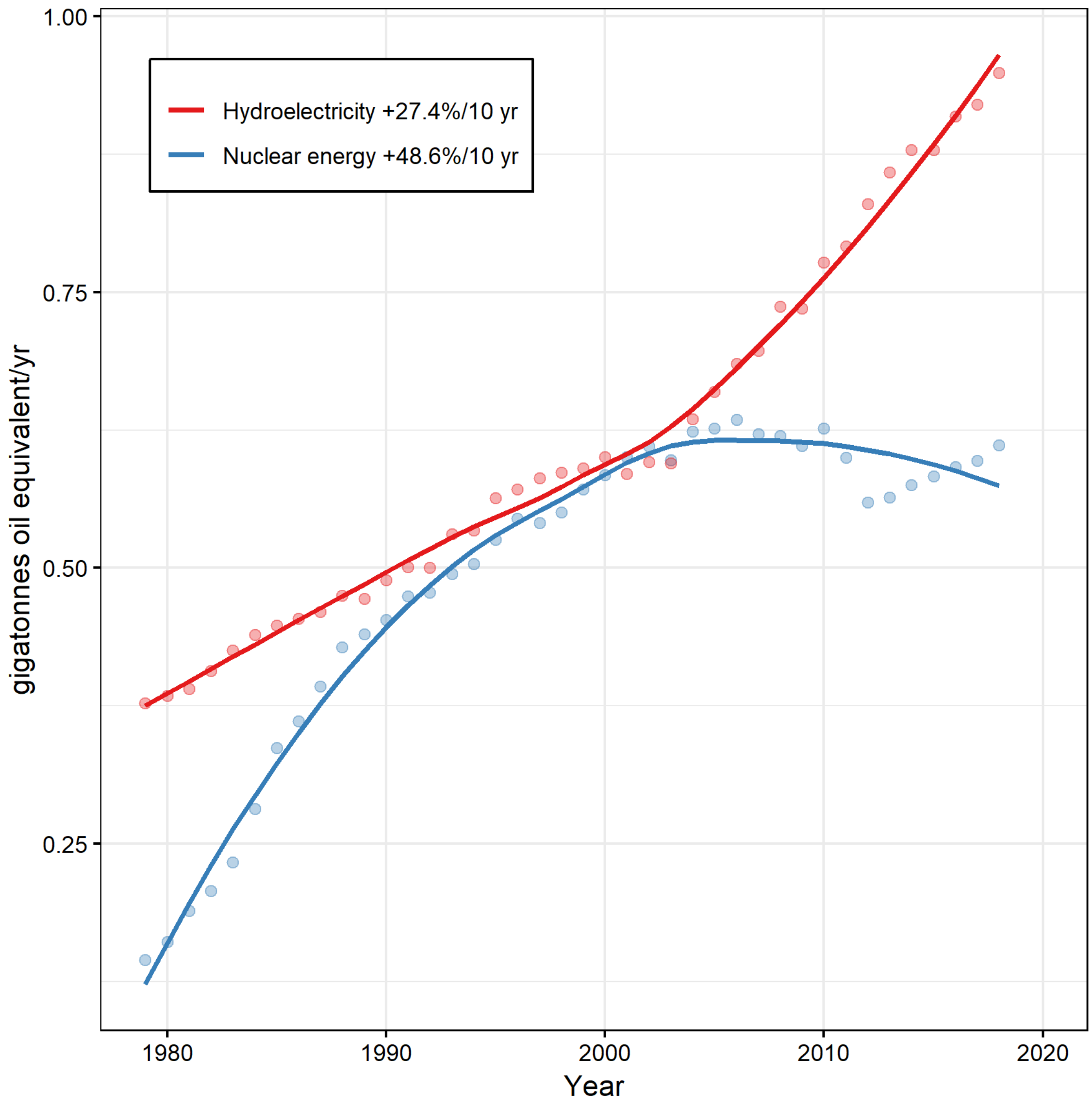

Figure S2. Annual consumption rates for nuclear energy and hydroelectricity (British Petroleum Company 2019). Rates shown in the legend are decadal change rates for the entire ranges of the time series (in percentage terms). See British Petroleum Company (2019) for other minor energy sources not shown 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 "CO_2" (total CO_2 emissions associated with fossil fuel consumption in mega tonnes CO_2), "Population" (human population size in millions), "CO_2/capita" (CO_2 emissions per capita in tonnes per person), "Share" (percentage of all CO_2 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_2O 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 CO_2, 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 CO_2. https://climate.nasa.gov/

2 Degrees Institute- uses six climate indicators including global temperature record, CO_2 levels, methane (CH_4) levels, nitrous oxide (N_2O) levels, oxygen (O_2) 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 CO_2 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).

CO_2 emissions (Figure 1k)

We used the British Petroleum Company's 2019 Statistical Review of World Energy as our source of data on CO_2 emissions (British Petroleum Company 2019). These CO_2 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 CO_2 emissions (Figure 1l)

We converted total CO_2 emissions (Figure 1k) to per capita CO_2 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 CO_2 (Figure 2a)

We obtained globally averaged estimates of atmospheric CO_2 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 CO_2 and latitude.

Atmospheric methane (Figure 2b)

We obtained globally-averaged annual estimates of atmospheric methane (CH_4) 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 (N_2O) 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 "pHmeas_insitu," 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 ≥ 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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