Attribution of observed global warming to countries

Corinne Le Quéré CBE FRS
Royal Society Research Professor of Climate Change Science,
School of Environmental Sciences, University of East Anglia (UEA), UK.

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Summary

1. **It is now well established that climate change is overwhelmingly caused by the emissions of greenhouse gases (GHG) from human activities.** The main drivers of GHG emissions have been the use of fossil fuels, primarily for energy, and to a lesser extent the use of land, primarily from deforestation but also from agriculture. Future GHG emissions from human activities, regardless of their origin, will cause continued rise in global warming and associated climate change, with further impacts and risks.

2. **The level of global warming scales with cumulative emissions of carbon dioxide (CO_2) and with current emissions of methane (CH_4).** Hence CO_2 emissions need to decrease to "Net Zero" to stabilise the Earth's climate, alongside rapid decreases in methane and other GHG. According to the 6th Assessment report of the Intergovernmental Panel on Climate Change (IPCC), GHG reductions of -43% in 2030 compared to their 2019 levels are needed to limit climate change to 1.5°C above pre-industrial levels, and -21% to limit climate change to well below 2°C above pre-industrial levels in the same time horizon, with Net Zero CO_2 achieved around 2050 and 2070, respectively.

3. **Despite the urgent need to decrease global GHG emissions, emissions have continued to rise in the past decade.** CO_2 emissions, the dominant source of GHG emissions, have continued to rise in the past decade (2013-2022) by 0.2% per year on average. Methane emissions are rising steeply, by 0.9% per year on average over the past decade, but with large uncertainties. All gases combined, global GHG emissions have continued to rise over the past decade, by 0.6% per year on average. These trends are not aligned with limiting global warming well below 2°C or to 1.5°C above pre-industrial levels, which require rapid decreases in emissions of CO_2 and methane in the short term.

4. **Actions to tackle climate change can be effective, but so far, they have not been deep or widespread enough to reverse global GHG emissions.** Global GHG emissions have grown more slowly in the past decade compared to the decade before, although they are still rising. Notably, 26 countries have succeeded in significantly decreasing their CO_2 emissions from using fossil fuels in the past decade while growing their economies. These trends have been attributed to climate and energy policies that

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support reduced energy use and the substitution of fossil fuel by renewable energy sources. Despite this progress, the actions in place are insufficient and global GHG emissions continue to rise. As a result of continued GHG emissions, global warming has steadily grown each decade.

5. **Cumulative CO_2 emissions and annual methane emissions have clear origin in historical use of fossil fuels and land by countries.** The largest contributors to global cumulative emissions of CO_2 during 1851-2022 were the USA (20.5%), the EU27 (11.7%), China (11.7%), Russia (7.0%); and Brazil (4.6%). The largest contributors to annual methane emissions averaged over the past decade (2013-2022) were China (16.6%), India (8.7%), the USA (6.7%), Brazil (5.8%), and the EU27 (5.4%).

6. **Global warming can be attributed to countries based on their historical emissions of different GHG.** The top 10 contributors to global warming from their historical emissions of GHG during 1851-2022 are the USA (responsible for 17.0% of global warming due to GHG emissions; 0.28°C), China (12.5%; 0.21°C), the EU27 (10.3%; 0.17°C, including Germany 2.9% and France 1.3%), Russia (6.3%; 0.11°C), Brazil (4.9%; 0.081°C), India (4.7%; 0.078°C), Indonesia (3.7%; 0.061°C), the United Kingdom (2.4%; 0.040°C), Canada (2.1%; 0.035°C), and Japan (2.1%; 0.035°C). The 42 industrialised countries of the UNFCCC Annex I list in aggregate account for 45% (0.74°C) of global warming due to GHG emissions during 1851-2022, while the 47 Least Developed Countries (LDCs) in aggregate contributed 6% (0.10°C). The top seven emitters are also the largest contributors to global warming from emissions of GHG during the shorter 1990-2022, with China the largest contributor in that recent period.

7. **For most countries, GHG emissions from fossil fuels are the source of most of their contributions to global warming.** Globally, the use of fossil fuels was responsible for 65% of global warming caused by GHG emissions from human activities during 1851-2022, and 80% for the shorter 1990-2022 period. The use of land was responsible for the remainder, with 35% and 20% contributions to global warming caused by GHG from human activities during 1851-2022 and 1990-2022, respectively. Notable exceptions are Brazil and Indonesia in the top emitters mentioned above, for whom their GHG emissions from land use contribute more to global warming than their emissions from fossil fuel use.

8. **GHG emissions are based on self-reported data by each State with sufficient confidence level to establish the country's contributions to climate change.** Reporting of GHG emissions, and the underpinning energy and land use data, is overseen by the UN, which also verifies the respect of reporting procedures, and increasingly the country's plans and actions. GHG emissions are also produced by several established international institutions. Emissions of CO_2 from the use of fossil fuels, the largest contributor to global warming in most countries, benefit from the most reliable data. GHG emissions from the use of land involve biological processes that have larger uncertainties, but reporting methodologies are updated regularly with the latest data and understanding. Updates of GHG emissions take place regularly and are closely monitored by the scientific community.

The scientific basis for climate change

It is now well established that climate change is overwhelmingly caused by the emissions of greenhouse gases (GHG) from human activities. The science of the Earth's climate system is well understood. The greenhouse effect traps heat and warms the Earth's climate, a phenomenon known as global warming. Emissions of GHG from human activities increase the content of heat-trapping gases in the atmosphere, heating the climate system. Warming is observed consistently around the planet, on land and in the oceans, with widespread snow and ice melting, and coherent changes in rainfall patterns, vegetation, and ocean properties. The observed rate of global warming since 1970 has exceeded warming from natural climate variability for at least the past two thousand years where detailed observations exist. The contributions of natural causes to recent warming have been assessed thoroughly by many (30 in the latest IPCC) independent climate centres from around the globe. Natural causes, including the contributions from variations in the sun and from the effects of volcanic eruptions, have contributed practically nothing to the observed warming of the planet since the period 1850-1900 (commonly used to refer to the “pre-industrial” period). Evidence that the warming is caused overwhelmingly by the rise in GHG levels in the atmosphere from human activities has consistently strengthened in all six assessment reports published by the IPCC since 1990.

The increase of GHG in the atmosphere is primarily caused by fossil fuel uses, and by deforestation and other uses of land. Fossil fuel use is the main source of emissions of carbon dioxide (CO_2), which accounts for 70% of total GHG emissions from human activities today.[1] Activities that use fossil fuels include producing electricity and heat for power, industry and buildings, and transportation. CO_2 emissions are also produced by some industries through chemical processes (for example producing cement). Land use, and in particular deforestation, is another important source of CO_2 emissions. Fossil fuel and land use both contribute significantly to methane emissions (CH_4), which accounts for 18% of total GHG emissions from human activities today. Methane emissions in the land sector are predominantly from livestock rearing, and from landfills and waste. Emissions of nitrous oxide (N_2O) account for 6% of total GHG emissions and are primarily from nitrogen additions for fertilisation in agriculture. Emissions of F-gases account for 6% of total GHG emissions and are primarily due to products used in refrigeration.

Five sectors are responsible for global GHG emissions: energy supply, industry, land use (including agriculture and forestry), transport, and buildings. Their relative importance depends on whether one considers where emissions are produced or where they are used (Table 1). Levers for reducing emissions can tackle both the production and the end uses. For example, replacing coal or gas power stations by renewable energy generation is a lever that tackles production, while improving energy efficiency in industry and buildings is a lever that tackles end uses.

The level of global warming scales primarily with the cumulative emissions of CO_2 over the past, present, and future. Much of the emitted CO_2 remains in the atmosphere for a long time (a century for 30-50% of the CO_2 emissions, and longer than one thousand years for 15-40% of the CO_2 emissions)[2]. Thus, a large fraction of global warming from CO_2 emissions is irreversible on multi-century time scales unless CO_2 is actively removed from the atmosphere. Because of the long lifetime of CO_2, the level of global warming today is proportional to the cumulative emissions of CO_2 from past and present emissions, regardless of when or where they were emitted. Likewise, additional global warming this century and beyond will depend on the total amount of CO_2 emissions that will be emitted to the atmosphere by human activities between now and 2100 and beyond, regardless of when it will be emitted. Stopping further CO_2 emissions will stop further global warming, and therefore limit risks associated with climate change, but it will not reverse global warming to date. N_2O and F-gases have a long lifetime like CO_2 and therefore warming from these gases is also persistent over centuries and beyond, although their contribution to global warming is much smaller than that of CO_2.

The level of global warming is also influenced by annual methane emissions. In contrast to CO_2 emissions, methane emissions remain in the atmosphere only around 12 years. This means that if methane emissions were to decrease, the associated global warming would decrease within a few years.

Table 1: Sectors responsible for global GHG emissions.

Sector	Percent of global GHG emissions	
	By production	By use
Energy supply	34	12
Industry	24	34
Agriculture, forestry and other land use	22	22
Transport	15	16
Buildings	6	15

Source: IPCC WGIII Summary for policymakers (2022) based on 2019 values

Hence the level of global warming caused by methane emissions is related to annual emissions of this gas, rather than to the cumulative emissions as in the case of CO_2. Global warming from methane emissions is thus reversible if methane emissions cease. This property makes the reduction of methane emissions an attractive lever to reduce the level of global warming, although reductions in methane emissions do not lead by themselves to the stabilisation of world temperatures, which are dependent on cumulative emissions of CO_2 and other long-lived GHG.

Global CO_2 emissions need to reach "Net Zero" to limit further global warming, alongside decreases in total GHG emissions. Stabilising the climate requires that emissions from CO_2 become Net Zero. This means that CO_2 emissions need to decrease as much as possible, and any residual emissions that cannot be entirely stopped need to be compensated by actively removing CO_2 from the atmosphere (called carbon dioxide "removals"; CDRs). Removals can be done by carefully managing land, for example to achieve more reforestation or afforestation (planting new forests) than deforestation. Additional warming can also be limited by reducing the level of annual methane emissions. Emissions of N_2O and F-gases, which have a long lifetime, also need to be brought down to zero or compensated by removals.

Achieving Net Zero CO_2 cannot rely mainly or even substantially on the deployment of removals based on technology, because of unproven scalability, energy penalties, and costs. In addition to land-based removals, removals can also, in small quantities, be achieved with technologies based on Carbon Capture and Storage (CCS), but the scalability of technology-based removals is unproven. There are mainly two types of removals using CCS: Bio-Energy with CCS (BECCS) and Direct Air capture with CCS (DACCS). BECCS competes with other uses of land, in particular food production, and therefore its expansion can only be limited. DACCS is particularly energy-intensive and practically inexistent today, and therefore cannot be a substantial solution by mid-century. The use of CCS by itself can help reduce the emissions from some economic sectors (industry and energy in particular), but CCS requires additional energy and does not capture all of the CO_2 emitted, and therefore it cannot, by itself, bring emissions down to zero. The potential for technology-based removals is further limited by the risks of failures or leakages, by the high costs associated with the development and use of these technologies, and by the lack of a monitoring framework and suitable governance. Therefore, achieving Net Zero cannot rely mainly or even substantially on the deployment of such technologies.

Rapid, deep, and widespread cuts in global GHG emissions are needed to limit global warming to well below 2°C above pre-industrial levels and as close as possible to 1.5°C, the aim of the Paris Agreement. According to the IPCC's 6th Assessment report, limiting climate change to 1.5°C above pre-industrial levels would require a reduction of total GHG by -43% in 2030 compared to their 2019 levels, while limiting climate change well below 2°C requires a reduction of -21% in the same time horizon (Table 2). Emissions scenarios that limit global warming "well below 2°C" have a peak global warming of 1.7°C (median value across scenarios) and a 67% probability of limiting global warming to 2°C. The emissions would need to continue to decrease afterwards, until CO_2 emissions reach Net Zero around 2050 (for 1.5°C) and around 2070 (for well below 2°C). Net Zero total GHG would also need to be achieved around 2085 if global

Table 2: Timelines for change in CO_2 and GHG emissions corresponding to current policies and needed for limiting global warming to well below 2°C and as close as possible to 1.5°C.

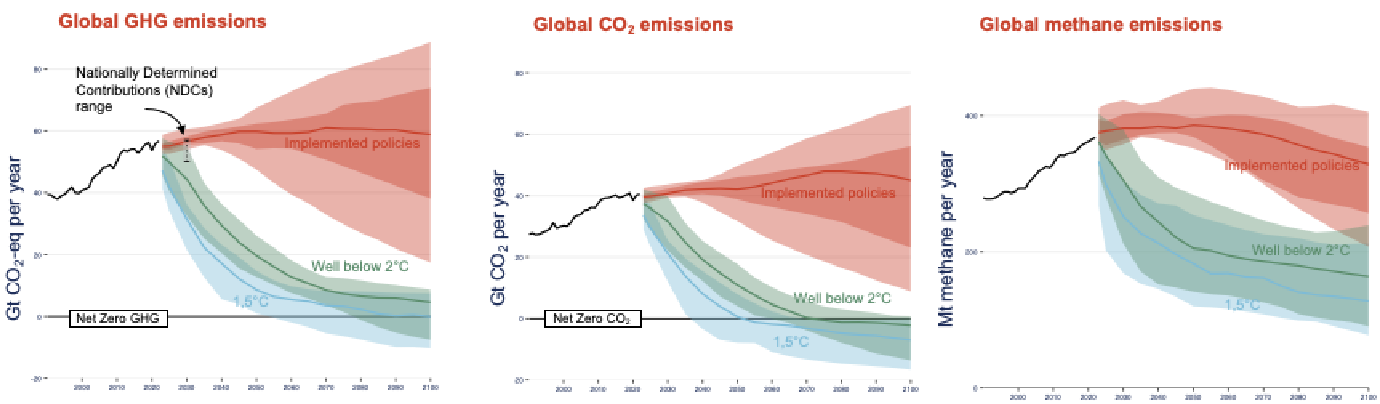
	Change in global GHG emissions in 2030 (from 2019)	**Year of Net Zero** CO_2	**Year of Net Zero** GHG
Implemented policies	no change projected		
2°C	–21%	2070	not essential
1.5°C	–43%	2050	2085

Source: IPCC Synthesis Report Summary for policymakers (2023) warming is to be kept to 1.5°C above pre-industrial levels. Note that additional removals, beyond those needed to limit further global warming, could work to reduce the level of warming slightly this century. Estimates of plausible reduced warming after an overshoot (i.e. temporary exceedance of a specified global warming level, followed by a decline to or below that level) are typically in the order of 0.1-0.2°C. They are highly uncertain, likely costly, and could incur additional risks.

Considering implemented climate policies only (not including implementation of Nationally-Determined Contributions (NDCs) under the Paris Agreement that are not yet in law) warming levels of around 3°C could be reached at the end of this century according to the extensive analysis of the IPCC 6th Assessment report[3]. Considering also current NDCs for 2030, including conditional contributions, would still lead to global warming exceeding the "well below 2°C" trajectory (Figure 1). The UNEP Emissions Gap Report of 2023[4] shows that even if NDCs were fully implemented, associated policies would lead to warming of 2.5°C to 2.9°C. The UNEP Production Gap Report of 2023[5] further shows that the assumption of full implementation is highly questionable, given the inconsistency between NDCs and government plans and projection pathways, which would lead to global production levels of 460%, 29% and 82% higher for coal, oil and gas, respectively, than production levels consistent with limiting warming to 1.5°C above pre-industrial levels. Thus, there is a need to strengthen both existing policies and actions, and existing commitments in the short and long term in order to limit the worst impacts of climate change.

Despite the urgent need to decrease global emissions of GHG, they have continued to rise in the past decade, albeit more slowly than in the previous decade. CO_2 emissions from fossil fuel use, the largest source of GHG emissions, have continued to rise in the past decade (2013-2022) by 0.5% per year on average. This growth is slower than the 2.5% per year growth observed in the decade before this (2003-2012), with the slowdown explained by climate and energy policies worldwide. CO_2 emissions from the use of land show a small but uncertain decline in the past two decades, with a slight decrease in emissions from deforestation and stable or slightly increasing removals from reforestation and afforestation (new forests). Growth in total CO_2 emissions from fossil and land use combined has substantially slowed in the past decade, but CO_2 emissions are still increasing by 0.2% per year on average (see Figure 1). Methane emissions are growing steeply, by 0.9% per year on average over the past decade, but with large uncertainties. With all three gases combined, global GHG emissions have continued to grow over the past decade, by 0.6% per year on average. These trends are not aligned with limiting warming well below 2°C or to 1.5°C above pre-industrial levels, which require emissions of CO_2 and methane to decrease rapidly.

Figure 1: Emissions trajectories consistent with limiting warming to well below 2°C and as close as possible to 1.5°C, compared to trajectories with implemented policies.



Source: Scenarios from the IPCC Synthesis Report Summary for policymakers (2023)3; data for 1990 to 2022 are from Jones et al. (2023)8 based on the Global Carbon Budget 20236 and PRIMAP-hist7.

Global warming from global GHG emissions

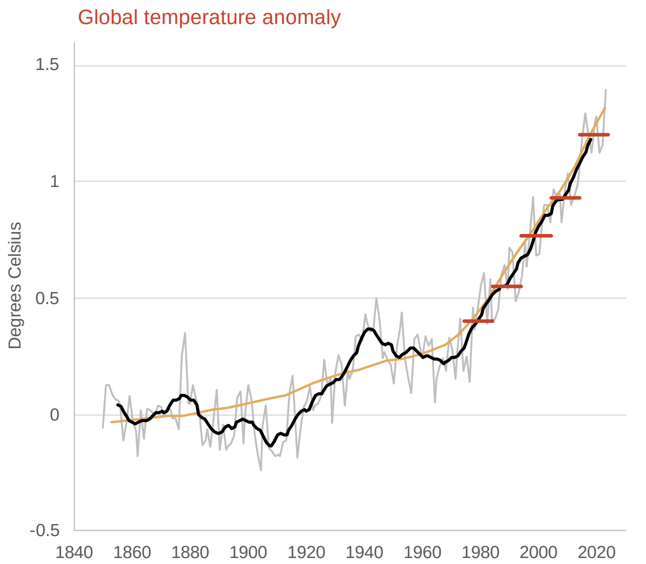
Global warming from human activities reached 1.15°C in the past decade (2013-2022) and can be attributed to historical emissions of specific GHGs. Emissions from CO_2, methane and N_2O generated global warming of 1.16°C, 0.42°C, and 0.08°C above pre-industrial levels, respectively, for a total warming contribution from GHG during 1851-2022 of 1.66°C. The warming from GHG was partly offset by cooling of 0.5°C mainly from pollution by aerosols.[8] Thus, for the contribution to global warming from GHG gases, CO_2, methane and N_2O accounted for 70%, 25% and 5%, respectively, whereas the contribution from F-gases remained negligible. Emissions from fossil fuel and land uses were responsible for 65% and 35% of global warming caused by human activities during 1851-2022, respectively. For the shorter 1990-2022 and 2013-2022 periods, GHG emissions from fossil fuel use accounted for a larger (and growing) proportion of the additional global warming induced by human activities, with 80% and 83%, respectively.

Global warming caused by human activities has steadily grown each decade in spite of growing knowledge on the impacts and risks of climate change. GHG emissions from human activities caused 0.1°C of global warming in the 1950s, rising to 0.24°C in the 2010s (Figure 2). Each decade has been substantially warmer than the previous one since 1960 as a result of human-induced global warming from GHG emissions. Individual years can be slightly warmer or cooler from the superposed natural variations that modulate annual temperatures.

Reporting of country and regional GHG emissions

GHG emissions are based on self-report by each State with sufficient confidence level to establish the country's contributions to climate change. Reporting of GHG emissions, and the underpinning energy and land use data, has taken place for decades. For energy-related emissions, reporting is generally a function of reported energy use, multiplied by emissions per unit of energy use at the level of the fuel type and activity. As for energy, process emissions (e.g. from cement production) are also a function of reported production multiplied by an emissions factor. For land-related emissions, reporting is generally a function of the activity level (e.g. for agriculture and forest management) or of the changes in land-uses (e.g. for deforestation), and can be integrated in time to

Figure 2: Observed global temperature change from the pre-industrial period (1850-1900), with the contribution of global warming due to human activities (in yellow).



Source: HadCRUT5 for the observations (grey for annual, black for 10-year running average, red for decadal averages); Forster et al (2023) for the human contribution (yellow; average of three estimates).

consider lags associated with decay or regrowth of vegetation and wood products. Emissions from energy-related uses are typically more reliable than emissions from land-related uses because the latter involve biological processes that are more difficult to monitor. Emissions related to products and services produced in another country, so-called "consumption-emissions", can also be estimated based on economic databases that follow the input and output within countries. Consumption-based methodologies have higher uncertainties than the standard "territorial-based" emissions, but they provide an approximate estimate of the country's reliance on others. International bunker fuels from international aviation and shipping are not included in countries emissions according to the UNFCCC methodologies, although there are country-based estimates (for example from the International Energy Agency). Bunker fuels represent 3% of global emissions.

The UNFCCC oversees and verifies the application of reporting procedures of GHG emissions by countries, and increasingly their plans and actions. Until 2023, only reporting for States listed in Annex I of the UNFCCC was required, with verification done at a technical level by the UNFCCC. Annex I countries are industrialised countries and economies in transition (including countries from the Former Soviet Union). Annex I countries submit a GHG inventory every year, and an evaluation of progress every two years. UNFCCC teams visit countries to verify their reporting and governance practices. From 2024, the UNFCCC reporting process will be reinforced to apply to all countries, and to verify that actions are taken place to meet the set objectives. The UNFCCC also details methodological updates based on IPCC reports, including for the relative effects of different GHGs on global warming. The UNFCCC processes are reinforced in countries where independent climate councils exist. Because of the processes and the scrutiny in place, GHG emissions reported by countries are generally the most reliable source of data on GHG emissions and their evolution through time.

GHG emissions by countries are also reported by international institutions, with regular updates. Several international institutions have developed the capacity to keep track of global, regional, and national emissions inventory. The International Energy Agency reports CO_2 emissions from fossil energy use by all top emitters. Research organisations have developed the capacity to report emissions by country (beyond those that report to the UNFCCC), building on methodologies developed by the IPCC and country reports for energy and land uses. These include the Global Carbon Budget[6], the Global Methane Budget[9], and the Global N_2O Budget[10] by the Global Carbon Project, the Indicators of Global Climate Change[1] published for the first time in 2023, and PRIMAP-hist[7]. The report here uses the latest available emissions and their contribution to warming estimated consistently with the latest IPCC findings as described in Jones et al (2023)[8], and updated to include emissions data for year 2022[6,7]. CO_2 emissions from the uses of land are based on IPCC methodologies and differ from the country reports to UNFCCC[11] (see methods).

Independent monitoring of countries' GHG emissions with earth observations provides complementary information. Earth observations of GHG levels or associated indicators, either from surface data (e.g. Mauna Loa station) or from satellite data (e.g. the OCO-2 sensor), provide additional information that help attribute regionally the growth in global GHG levels. Earth observations provide complementary information that indicate more precisely where emissions come from, for example around cities or large industries. Earth observations measure the concentration of GHG in the atmosphere, which result from the combination of emissions from human activities and natural processes. The emissions from human activities can then be inferred, but the uncertainties are higher than emissions estimated using energy and land use data reported by States.

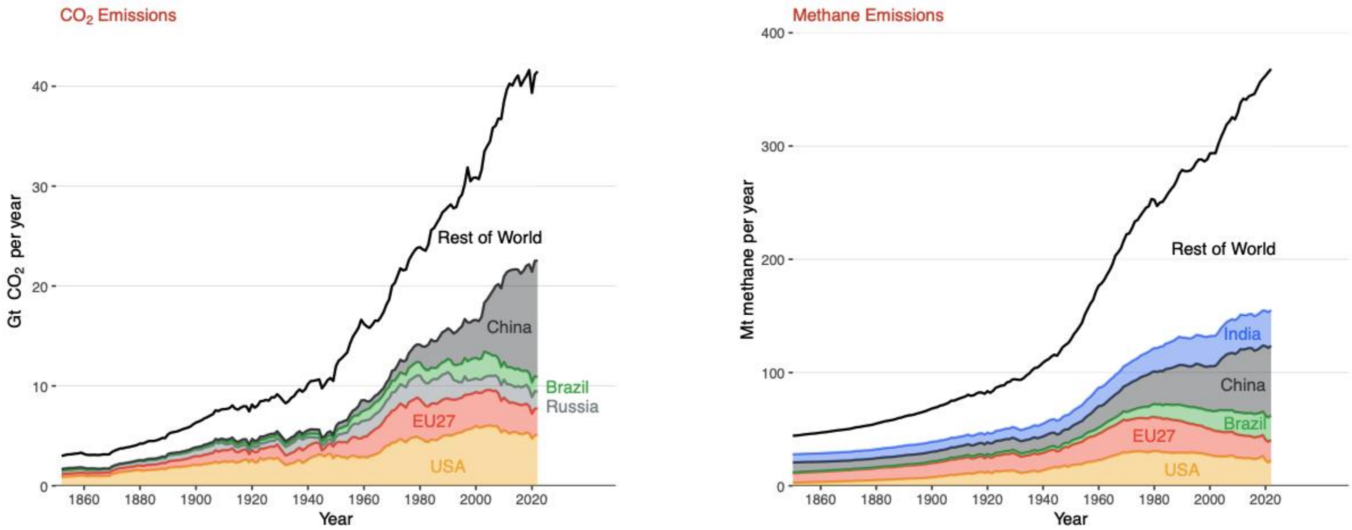
Country and regional GHG emissions and trends

Cumulative CO_2 emissions, the main cause of human-induced climate change, has clear origin in historical use of fossil fuels and land by countries. The largest contributors to cumulative emissions of CO_2 during 1851-2022 were the USA (20.5%), whose emissions peaked around 2005; the EU27 (11.7%), with emissions decreasing since the early 1980s; China (11.7%), with most of its emissions occurring since 2000; Russia (7.0%); and Brazil (4.6%) (see Figure 3). All 42 industrial countries of the Annex I in aggregate account for 52% of cumulative CO_2 emissions, while all 47 Least Developed Countries (LDCs) in aggregate contributed 4.5%. As a result of the long-term trends in emissions by countries, the patterns have shifted in recent decades. The largest contributors to cumulative emissions of CO_2 during 1990-2022 were the China (19.4%), the USA (15.5%), the EU27 (9.3%), Brazil (5.1%), and Russia (4.8%). Globally, land use contributed 31% and fossil fuel use 69% to cumulative CO_2 emissions during 1851-2022. Land use emissions were the dominant source of global CO_2 emissions globally until the 1950s.

Annual methane emissions, the second largest cause of human-induced climate change after cumulative emissions of CO_2, is from current use of fossil fuels and land by countries. The largest contributors to annual methane emissions averaged over the past decade (2013-2022) were China (16.6%), India (8.7%), the USA (6.7%), Brazil (5.8%), and the EU27 (5.4%). All 42 industrial countries of the Annex I in aggregate account for 22.4% of annual methane emissions, while all 47 Least Developed Countries (LDCs) in aggregate contributed 10.6%.

Annual CO_2 emissions from fossil fuel use have peaked and decreased in 26 countries over the past decade (2013-2022), while their economies grew. These are: Belgium, Brazil, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong SAR, Israel, Italy, Jamaica, Japan, Luxembourg, the Netherlands, Norway, Portugal, Romania, Slovenia, South Africa, Sweden, Switzerland, United Kingdom,

Figure 3: Annual emissions for CO_2 and methane for the top five emitters for the period 1851-2022.



Source: Jones et al. (2023)[8] based on the Global Carbon Budget 2023[6] and PRIMAP-hist[7]

USA, and Zimbabwe, as well as the EU27 in aggregate.[6] The decreasing trends in fossil fuel CO_2 emissions have been attributed to climate and energy policies in many of those countries, associated with decreases in energy use and with renewable energy progressively replacing fossil energy.[3] The annual rate of decrease in fossil fuel CO_2 emissions has consistently reached 3-4% per year in the United Kingdom, Denmark, and Finland. In contrast, most countries where emissions did not decrease saw renewable energy use increasing alongside fossil energy use, not replacing it.[12]

Annual CO_2 emissions from fossil fuel use continue to rise or decrease only slowly in many industrialised countries of UNFCCC Annex I. These include Australia, Slovakia, Austria, New Zealand and Canada, whose fossil fuel CO_2 emissions decrease in the past decade but not significantly, and Poland, Russia and Hungary, whose emissions continue to rise. Fossil fuel CO_2 emissions also grow strongly in many emerging economies, including in Southeast Asia, including Indonesia, the Philippines, and Viet Nam, the most populous countries.

Growth in annual CO_2 emissions from fossil fuel use has slowed in many emerging economies, but emissions continue to grow. This includes China, whose emissions grew by 1.8% per year during the past decade compared to 7.9% per year during the decade before this. Likewise for India, emissions grew 3.3% per year in the past decade compared to 6.7% per year during the decade before this.

Annual CO_2 emissions from land use remain high, pushed up by deforestation. The biggest emitters of CO_2 from land use are Brazil, Indonesia, and the Democratic Republic of the Congo, which together account for 56% of land use CO_2 emissions of the past decade. The trends in country's CO_2 emissions from deforestation are difficult to quantify on an annual basis because of lags in decay and regrowth associated with biological processes. Several countries see a small net sink of CO_2 from land use. This means that their management actions in the land sector lead to more absorption of CO_2 than emissions, which generally occurs in regions where there has been historical abandonment of agriculture followed by reforestation and afforestation. Some of these trends have flattened in the past decade. Those sinks are fragile as they depend on the health of the ecosystems, which are affected by climate change.

The growth patterns in annual methane emissions tend to follow the growth patterns observed for annual CO_2 emissions in the past decade mentioned above.

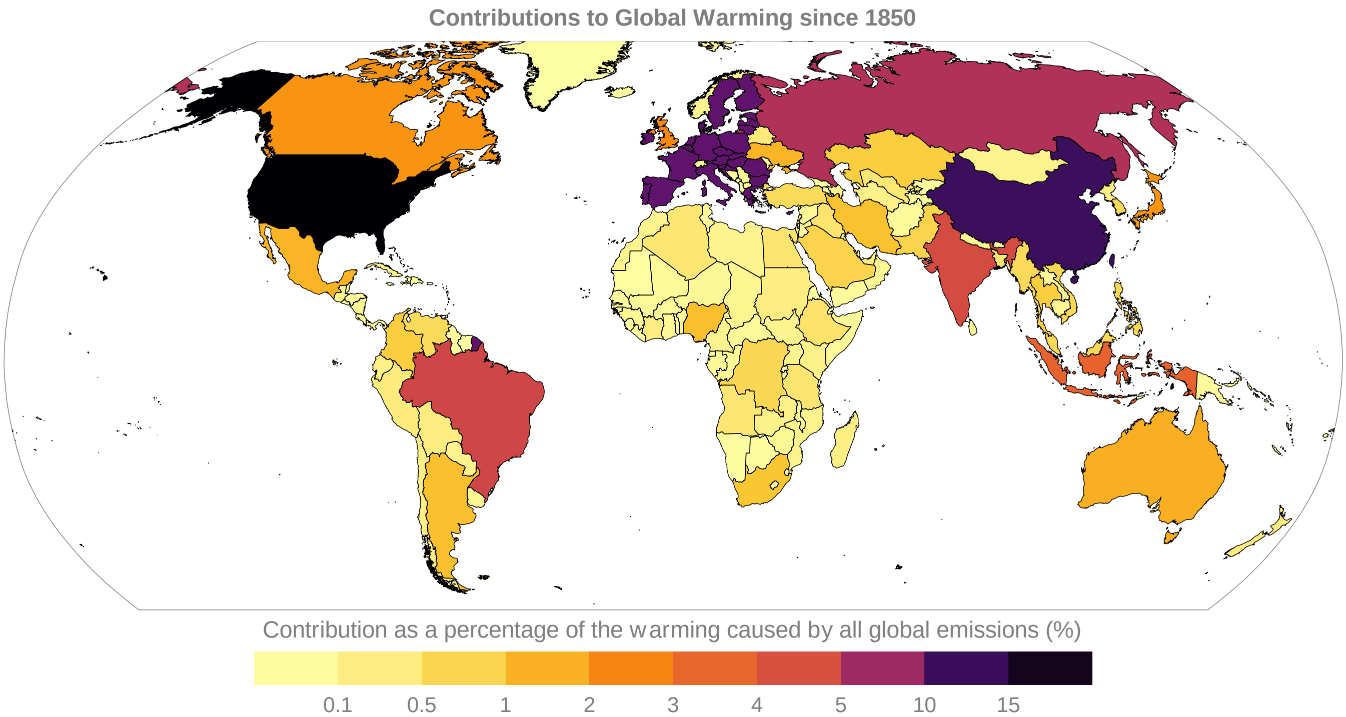
Country and regional contributions to global warming

The warming that occurred so far can be attributed to countries based on their historical emissions of GHG.

Using the emissions of different GHG by country that are available annually since 1850, it is possible to estimate the contribution of each country to observed global warming by considering the different lifetime of specific GHG (CO_2, methane and N_2O), and accounting for the influence of each of these GHG on global temperatures (Figure 4; see Methods). The warming attribution to countries can be done separately for different periods (for example 1851-2022 or 1990-2022) by considering only the country's emissions during these periods. The warming attribution can also be done for the total warming, for the warming due to fossil fuel and land use emissions separately, and for the warming due to different GHG.

The top 10 contributors to global warming from historical emissions of GHG during 1851-2022 are the USA (responsible for 17.0% of the global warming in 2022 due to their historical GHG emissions; 0.28°C), China (12.5%; 0.21°C), the EU27 (10.3%; 0.17°C, including Germany 2.9%, France 1.3%, Poland 1.0% and Italy 0.9%), Russia (6.3%; 0.11°C), Brazil (4.9%; 0.081°C), India (4.7%; 0.078°C), Indonesia (3.7%; 0.061°C), the United Kingdom (2.4%; 0.040°C), Canada (2.1%; 0.035°C), and Japan (2.1%; 0.035°C). The GHG emissions from these contributors, together with those from Australia (1.5%; 0.025°C), Mexico (1.4%; 0.023°C), Ukraine (1.4%; 0.022°C), Nigeria (1.2%; 0.019°C), Argentina (1.2%; 0.019°C), and Iran (1.1%; 0.019°C), amount to three quarters of the global warming due to GHG emissions during 1851-2022 (Table 3). Of those countries, most of their contributions to global warming originate from fossil fuel sources, except for Brazil, Indonesia, Australia, and Argentina where emissions from land uses, including agriculture and forestry, account for more than half of the attributed global warming. Emissions from bunkers (international shipping and aviation) are also important and are entirely from fossil fuels. All 42 industrial countries of the Annex I in aggregate account for 45% (0.74°C) of global warming due to historical GHG emissions (1.66°C), while all 47 Least Developed Countries (LDCs) in aggregate contributed 6% (0.10°C). Although the exact country contributions may vary a little based on the data sources, especially for emissions related to land use, the dominant patterns are robust.

Figure 4: Contributions to global warming caused by GHG emissions from human activities during 1851-2022 per country or region (for the EU27).



Source: Jones et al. (2023)[8]. Explore interactive data visualsiation of the map.

Table 3. Largest contributors to global warming from GHG emissions during 1851-2022, with the fraction due to emissions from fossil fuels and from land use.

Rank	Country	Warming contribution (°C)	Percent of global warming	Cumulative percent	Fossil fraction	Land fraction
1	**USA**	0.282	17.0%	17.0%		
2	**China**	0.208	12.5%	29.5%		
3	**EU27**	0.170	10.3%	39.8%		
4	**Russia**	0.105	6.3%	46.1%		
5	**Brazil**	0.082	4.9%	51.0%		
6	**India**	0.078	4.7%	55.7%		
7	**Indonesia**	0.061	3.7%	59.4%		
	Germany	0.047	2.9%			
8	**United Kingdom**	0.040	2.4%	61.8%		
9	**Canada**	0.035	2.1%	63.9%		
10	**Japan**	0.035	2.1%	66.0%		
11	**Australia**	0.025	1.5%	67.5%		
12	**Mexico**	0.023	1.4%	68.9%		
13	**Ukraine**	0.023	1.4%	70.2%		
	France	0.022	1.3%			
	Bunkers	0.020	1.2%	71.4%		
14	**Nigeria**	0.019	1.2%	72.6%		
15	**Argentina**	0.019	1.2%	73.7%		
16	**Iran**	0.019	1.1%	74.9%		
	Poland	0.017	1.0%			
17	**South Africa**	0.017	1.0%	75.9%		
18	**Kazakhstan**	0.014	0.87%	76.8%		
19	**Thailand**	0.014	0.87%	77.6%		
	Italy	0.014	0.87%			
20	**Colombia**	0.014	0.87%	78.5%		

The same countries figure among the largest contributors to global warming from emissions of GHG during the shorter 1990-2022, with China the largest contributor in that period (see Annex A). The dominance of emissions from fossil fuels has further strengthened over the recent time period, while CO_2 sinks on managed land by a few countries make a small contribution to reducing the rate of global warming (see Annex A).

Principles and limits to country attribution

The attribution of GHG emissions and associated global warming can be done within set principles and limits. Available emissions data provide a strong and coherent basis for assessing country's contributions to global warming using known correspondence between emissions and observed warming. Attribution estimates can be done from 1851 or from any year chosen as start year. Emissions reported by the countries themselves are generally the most reliable source of information and will be increasingly scrutinised by the UNFCCC. Improvements in methodology for emissions accounting takes place continuously, and attention is particularly needed to improve the estimates of emissions from land uses which use different conventions from those of the IPCC[11].

The attribution of global warming at the countries level should be made on the basis of their GHG emissions, as is done here, excluding the cooling effect of aerosols and other pollutants which currently masks part of the warming due to GHG. Aerosols and other pollutants should be reduced to improve air and water quality, and to respect national and international laws on pollution, irrespective of climate objectives. Coordinated policies and actions would avoid pernicious incentives and ensure maximum synergies between climate and air quality policies. Methodologies to estimate country contributions to global warming based on GHG emissions are updated regularly to incorporate latest data and understanding.

Methods and Data

The method used here is described in Jones et al. (2023)[5] and is consistent with the latest finding of the IPCC. The warming from CO_2 emissions is calculated as a product of the transient response to cumulative emissions (TCRE) of CO_2 assessed by the IPCC at 1.65 °C per 1000 Pg C emitted, with a likely range 1.0–2.3 °C per 1000 Pg C. The warming from N_2O is calculated as for CO_2 but after converting N_2O emissions into equivalent-CO_2 emissions using a global warming potential (GWP) over a time horizon of 100 years reported in the IPCC AR6. The warming from methane is calculated based on the conversion of methane emissions to equivalent- CO_2 emissions using GWP* which takes into account the short lifetime of methane compared to CO_2, and then converting to warming using the TCRE. The contribution of F-gases to warming is neglected in this analysis.

Data sources: CO_2 emissions are from the Global Carbon Budget 2023[6]. Fossil CO_2 emissions are based on country reports to the UNFCCC when they exist, or derived largely from UN energy databases when not, extended to 2022 based on energy growth reported by the Energy Institute. Historical data prior to 1990 and UNFCCC reporting are predominantly derived from the Carbon Dioxide Information Analysis Center (CDIAC). Land CO_2 emissions are based on three bookkeeping method that keep track of reported land-use change and activities, mainly with data from the FAO extrapolated to 2022. These will differ from emissions reported by countries because of differences in scope and in data sources[11]. Methane and N_2O emissions are from the PRIMAP-hist database, which prioritises data reported by countries to the UNFCCC with a preliminary assessment for year 2022.

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Annex A

Largest contributors to global warming from GHG emissions during 1990-2022, with the fraction due to emissions from fossil fuels and from land use

Rank	Country	Warming contribution (℃)	Percent of global warming	Cumulative percent	Fossil fraction	Land fraction
1	China	0.140	20.5%	20.5%		
2	USA	0.080	11.7%	32.2%		
3	EU27	0.043	6.3%	38.5%		
4	Brazil	0.040	5.8%	44.3%		
5	India	0.039	5.7%	50.0%		
6	Indonesia	0.030	4.4%	54.3%		
7	Russia	0.026	3.8%	58.1%		
8	Japan	0.017	2.4%	60.6%		
	Bunkers	0.013	1.9%	62.5%		
9	Canada	0.012	1.8%	64.3%		
10	Iran	0.012	1.7%	66.0%		
11	Mexico	0.012	1.7%	67.7%		
12	Saudi Arabia	0.009	1.4%	69.1%		
	Germany	0.009	1.4%			
13	South Africa	0.008	1.2%	70.3%		
14	Australia	0.008	1.2%	71.4%		
15	South Korea	0.008	1.2%	72.6%		
16	Pakistan	0.008	1.1%	73.7%		
17	Nigeria	0.007	1.1%	74.8%		
18	Democratic Repub	0.007	1.0%	75.8%		
19	Türkiye	0.006	0.9%	76.7%		
20	Malaysia	0.006	0.91%	77.6%		