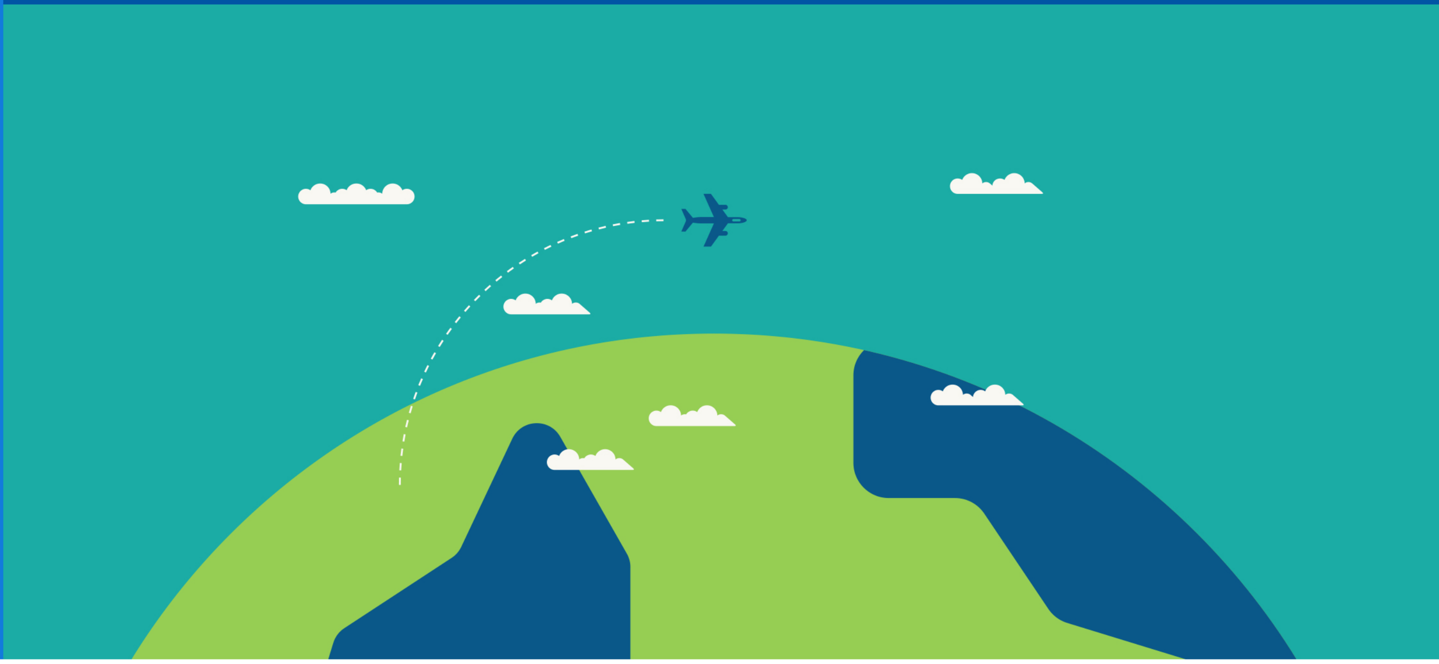
ICAO

INTERNATIONAL CIVIL AVIATION ORGANIZATION

REPORT ON THE FEASIBILITY OF A LONG-TERM ASPIRATIONAL GOAL (LTAG) FOR INTERNATIONAL CIVIL AVIATION CO_2 EMISSION REDUCTIONS

Appendix S1 Climate Science Context



ICAO COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION
MARCH/2022

Report on the Feasibility of a
Long-Term Aspirational Goal
Appendix S1

International Civil Aviation
Organization

Allowed Emission of Carbon Dioxide for Limiting Global Mean Temperature Increases to 1.5 or 2°C

Prepared for LTAG-TG by the following ISG Members:

S.D. Jacob, Federal Aviation Administration, Washington, DC, United States
D.S. Lee, Manchester Metropolitan University, Manchester, United Kingdom
D.J. Wuebbles, University of Illinois, Urbana, IL, United States
J.S. Fuglestvedt, CICERO, Oslo, Norway
D. Johansson, Chalmers University of Technology, Göteborg, Sweden
D.W. Fahey, NOAA Earth System Research Laboratory, Boulder, Colorado, United States
D. Hauglustaine, Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Saclay, France
R. Sausen, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany
P.F.J. van Velthoven, Royal Netherlands Meteorological Institute (KNMI), De Bilt, The Netherlands
S.R.H. Barrett, Massachusetts Institute of Technology, Cambridge, MA, United States

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Abstract

The amount of remaining carbon emissions – the ‘remaining carbon budget’ – allowed to limit global warming to 1.5 or 2°C over pre-industrial levels from all anthropogenic sources is provided in this report based on IPCC (2021). The remaining amounts of carbon emissions from 1st January 2020 are estimated to be 500 and 1350 gigatonne of CO_2 for 1.5 and 2°C limits respectively, for a 50% probability, and 400 and 1150 gigatonne of CO_2 limits respectively, for a 67% probability of limiting temperature increases to 1.5 and 2°C. Assumptions behind these estimates are described along with updates on the current level of global warming. Non-CO_2 effects (e.g., largely from methane, nitrous oxide, and fluorinated gases) are included in the above estimates and introduce in an uncertainty in the allowed CO_2 emissions for a given temperature limit and probability for staying at or below this limit. The total aviation forcing effect was approximately 3.5% of the total anthropogenic climate forcing in 2011. Aviation non-CO_2 climate effects are currently estimated to be about 2/3 of the total aviation forcing based on historical data although future projections are uncertain.

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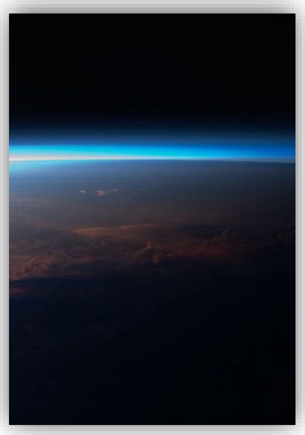
Key Messages



- Estimated cumulative net global anthropogenic CO_2 emissions from the start of 2020 to limit global warming to 1.5°C is 400 and 500 Gt CO_2 at 67% and 50% probability, respectively.
- For a warming limit of 2°C, the remaining allowed carbon emissions are estimated to be 1150 Gt CO_2 at 67% probability and 1350 Gt CO_2 at 50% probability.
- The uncertainty in these estimates remain large due to non-CO_2 effects, including unrepresented climate feedbacks, historical warming, and the variations in reductions in non-CO_2 emissions.
- Under the five illustrative scenarios considered by IPCC (2021), in the near term (2021-2040), the 1.5°C global warming level is very likely or likely to be exceeded during the 21st century under the very high and high GHG emissions scenarios. For the very low GHG emissions scenario, it is more likely than not that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming.
- Global warming of 2°C, relative to 1850–1900, would be exceeded during the 21st century under the high and very high GHG emissions scenarios. Global warming of 2°C would extremely likely be exceeded in the intermediate scenario. Under the very low and low GHG emissions scenarios, global warming of 2°C is extremely unlikely to be exceeded or unlikely to be exceeded.

Background

The ICAO CAEP Long Term Aspirational Goal Task Group (LTAG-TG) during the process of developing the scenarios for aviation CO_2 requested the following from the Impacts Science Group (ISG):

> *"ISG should examine the literature and summarize the amount of carbon dioxide (aka carbon budget) that can be released into the atmosphere while limiting the increase in global mean temperature to 1.5 and 2 degrees Celsius. These carbon budgets can then be compared against the aviation CO_2 scenarios being developed by LTAG-TG. The ISG should also capture the latest information on the impacts of non-CO_2 aviation emissions such that decision makers understand the relative impact of aviation CO_2 emissions and the non-CO_2 emissions on the climate."*

This report addresses the above request from the LTAG-TG.

Introduction

The aim of this report is to examine and summarize the understanding of the amount of carbon dioxide (CO_2), in terms of gigatons of CO_2 ($GtCO_2$), that could still be emitted into the atmosphere by human activities if the amount of climate change, in terms of global mean surface temperature increase, is to be limited to either 1.5 or 2 degrees Celsius (°C) over pre-industrial levels. The Paris Agreement sets a long-term temperature goal of: "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*" (Article 2.1 (a)) (as discussed later, this is often interpreted as starting with the period from 1850–1900 when adequate global temperature records became available). While CO_2 is the main driver of human induced long term climate change, about one-third of the current changes in climate relate to non-CO_2 emissions of other gases and particles emitted by human activities (Smith et al., 2020). We will start by considering these allowed emissions only in terms of CO_2, with assumptions of the contributions of non[1]-CO_2 effects included.

The concept of the cumulative carbon budget and the remaining allowed CO_2 emissions began to emerge clearly in 2009 (e.g., Allen et al 2009, Meinshausen et al 2009, Matthews et al 2009, Zickfeld et al 2009, WBGU 2009) and was subsequently featured in international climate assessments (IPCC 2014; 2018, 2021). The basis for this is an approximately linear relationship between cumulative CO_2 emissions and the resultant temperature response (e.g., IPCC, 2018). The concept is sometimes referred to in the literature as an allowed 'carbon budget', but more strictly refers to the remaining cumulative anthropogenic CO_2 emissions allowable from a chosen date for a given temperature level and probability. Based on the well-established relationship between cumulative CO_2 emissions and CO_2-induced temperature change, this concept implies that limiting the total amount of CO_2 emitted to the

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[1] Here, non-CO_2 effects on the carbon budget include methane, nitrous oxide, and fluorinated gases

atmosphere is a reliable means of not exceeding some specified temperature target for a given probability (Matthews et al., 2020). This is not to be confused with another concept, the historical carbon budget, which describes estimates of all major past and contemporary carbon fluxes in the Earth system (e.g., Friedlingstein et al., 2020).

The remaining carbon budget concept has now become mainstream in policy discourse (Lahn 2020) since it represents a relatively easy way of understanding how CO_2 emissions contribute to global mean surface temperature change and is a useful tool for communication. While there are several different definitions of carbon budgets in the literature, this report focuses on the cumulative carbon budgets, the integrated emissions over time that keep the warming below different warming levels.

It is recognized that non-CO_2 emissions of other greenhouse gases (GHGs) and particles play an important role in surface temperature change, and we briefly explain this role and the challenges associated with accounting for non-CO_2 emissions and non-CO_2 effects. This last point is of particular importance for aviation's current contribution to climate change, since nearly two thirds of aviation's current effective radiative forcing (ERF[2]) is attributable to non-CO_2 effects (Lee et al., 2021).

The general approach outlined in the literature is shown schematically in Figure 1. More details of the approach are provided in the following sections.

Factors affecting allowed emissions of CO_2

A variety of estimates exist in the scientific literature on the amount of carbon emissions allowed so that the global mean temperature stays below either 1.5 or 2°C. These are usually given with an associated range of probabilities, generally for 33%, 50% or 67%, of staying within the temperature limit. These ranges are largely based on the uncertainty in the Equilibrium Climate Sensitivity (ECS), the transient climate response (TCR), and the transient climate response relative to cumulative emissions of carbon (TCRE). The uncertainty of these depend on short-term feedbacks affecting climate change over the next few decades, as well as the longer-term equilibrium feedbacks (which includes feedbacks associated with long-term changes in land ice and the ocean), and for TCRE also on uncertainty in the carbon cycle.

There are several additional factors that require consideration in evaluating the remaining allowed CO_2 emissions. Those factors and associated uncertainties are described in the following sections. Since we are close to the 1.5° C limit, the remaining carbon budget is small and is quite sensitive to many different factors, including how much observed warming has occurred to date, the amount of non-CO_2 emissions and related climate effects in the future, and the assumed range of transient climate response in calculating the 17%, 33%, 50%, 67% or 83% chance of avoiding a 1.5 or 2°C world.

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[2] For some of the more technical concepts, please refer to the report's glossary of terms

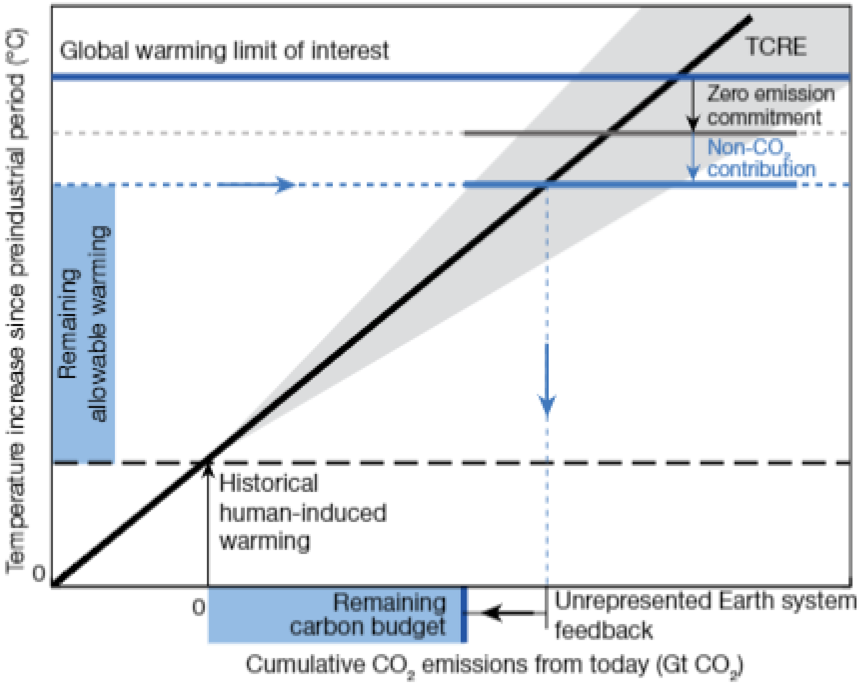


Figure 1. The schema shows how the remaining carbon budget can be estimated from various independently assessable quantities, including the historical human-induced warming, the Zero Emissions Commitment (ZEC) (temperature change that is still expected to occur after a complete cessation of CO_2 emissions), the contribution of future non-CO_2 warming (consistent with global net-zero CO_2 emissions or otherwise), the transient climate response relative to cumulative emissions of carbon (TCRE), and further adjustment for unrepresented Earth system feedback (such as methane released due to the melting of permafrost). The grey shading illustrates how uncertainty in TCRE propagates from the start point. Arrows and dashed lines are visual guides illustrating how the various factors combine to provide an estimate of the remaining carbon budget. The ZEC (Jones et al, 2019, MacDougall et al, 2020) is uncertain, and likely close to zero. The relative sizes of the various contributions shown in this schema are not to scale (From Rogelj et al. 2019).

Meaning of the 1.5 or 2°C target

The goal of the United Nations Framework Convention on Climate Change (UNFCCC) – officially adopted at the Cancun Convention of the Parties in 2010 (UNFCCC, 2010) – has been to aim to limit a global mean surface temperature increase to 2°C or less. The Paris Agreement then established a goal to "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels…*" (Article 2a). While this has been interpreted differently in the literature (e.g., Schleussner et al., 2016; Rajamani and Werksman 2018; Mace 2018), one goal is clearly to aim for limiting warming to 1.5 or 2°C with a given probability of staying below the given temperature. Some analyses, including most IAM studies, have provided a series of scenarios with different degrees of overshoot in temperature before the warming limit is reached by a given date (e.g., 2100 in Rogelj et al, 2018a, 2018b). The allowed carbon emissions can also be based on when various global warming levels such as 1.5 or 2°C is first reached. These choices can make a difference in the resulting emissions allowed.

Reference time period

Most of the existing analyses of temperature changes are based on the time period between the mid- to late-1800s and almost all of the major changes in globally averaged temperature have occurred since the 1850–1900 time period. However, if the aim is to account for carbon emissions since the industrial revolution began in the 1700s, then there should be additional CO_2 emissions and associated pre-1850 warming (Hawkins et al. 2017). Some human emissions and associated warming are likely to have occurred by the late-1800s, and if the aim is to really account for the carbon emissions since the beginning of the industrial revolution, then up to another 5-10 Gt CO_2 would have to be included in the past emissions. The remaining carbon emissions to limit warming to 1.5 or 2°C provided in this report are reproduced from the IPCC AR6 WG1 report (2021) that improved upon these previous studies by using a more consistent approach to estimate the remaining carbon budget.

Reference temperature record

Depending on the analysis, 2020 was either the first or the second warmest year on record, essentially tied with 2016, since nearly global observations of temperature became available in the late 1800s. The IPCC AR6 WG1 Report (IPCC, 2021) found that the global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900.

The absolute change depends on which dataset and analysis is used, with some such as NASA and Berkeley Earth being fully global (by accounting for the Polar Regions, especially by including satellite observations over the last 52 years) while others such as NOAA and the UK Hadley Centre use only available surface stations and ship data. Figure 2 shows that the different approaches result in very similar trends. These datasets also show that landmasses are generally warming at approximately twice the rate of the ocean and the Arctic is warming at twice the rate of the rest of the world. Nonetheless, the choice of record(s) will make a slight difference as to what temperature change has been reached.

In the coming decades, global temperatures are unlikely to go back to the much lower than 1990 values. This raises the question of what average surface temperature and length of the averaging period should be considered in determining how much change is left before a total change of 1.5^{o}C to 2^{o}C is reached. It is best to use a fully global analysis of the temperature record in these studies.

Transient Climate Response and Equilibrium Climate Sensitivity

The uncertainty in the Transient Climate Response (TCR) and the Equilibrium Climate Sensitivity (ECS) affect both the future projections of temperature change and hence the estimates of allowable carbon emissions. The TCR accounts for the rapid response after a forcing on climate – it is defined by the increase in global average temperature expected at a time when the atmospheric concentration of CO_2 has doubled. Correspondingly, ECS corresponds to the long-term increase in global average temperature expected to occur after the effects of a doubled CO_2 concentration have had time to reach a steady state. ECS is an important quantity used to estimate how the climate responds to radiative forcing. Based on multiple lines of evidence, the very likely range of equilibrium climate sensitivity is between 2°C (high confidence) and 5°C (medium confidence). The IPCC AR6 WG1 Report (2021) assessed best estimate is 3°C with a likely range of 2.5°C to 4°C (high confidence). The uncertainty in TCR and ECS are major factors in the probability ranges given in our estimated limits on remaining carbon emissions. Because of the slow response of land ice and the heat accumulation in the deep ocean, reaching an equilibrium temperature can take many centuries after CO_2 has doubled.

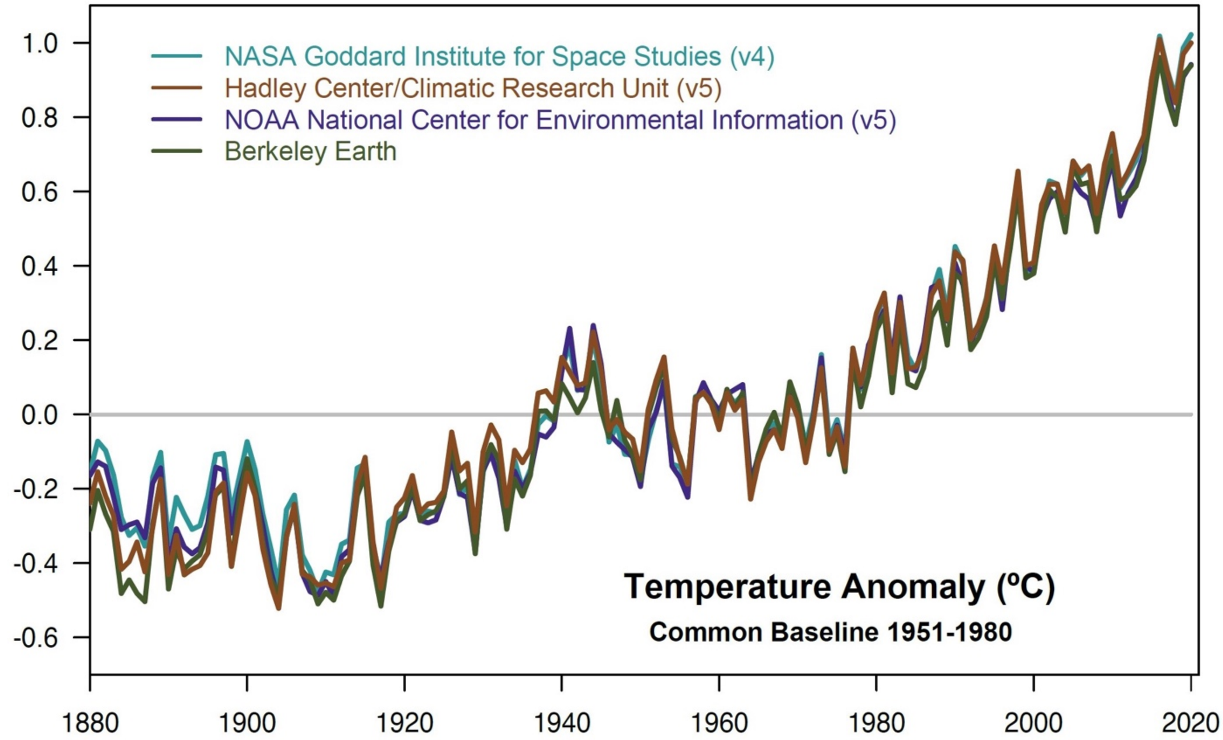


Figure 2. Yearly global temperature anomalies from 1880 to 2019, with respect to the 1951–1980 mean, as recorded by NASA, NOAA, the Berkeley Earth research group, and the Met Office Hadley Centre (UK). Though there are minor variations from year to year, all five temperature records show peaks and valleys in sync with each other. All show rapid warming in the past few decades, and all show that the past decade has been the warmest. From NASA (https://www.nasa.gov/press-release/2020-tied-for-warmest-year-on-record-nasa-analysis-shows).

Feedbacks in emissions and other uncertainties

The amount of global mean temperature change that is still expected to occur after a complete cessation of CO_2 emissions (due to the slow response of, for example, land ice and the heat accumulation in the deep ocean as well as climate carbon cycle feedbacks) is referred to as the 'The Zero Emissions Commitment' (ZEC) (Jones et al, 2019, MacDougall et al, 2020). The ZEC is uncertain and likely close to zero, meaning that the temperature impact of the historical cumulative CO_2 emissions is expected to stay roughly constant after CO_2 emissions have ceased (MacDougall et al, 2020).

Earth-system feedbacks like thawing permafrost or other factors like burning wildfires and tundra could also affect future levels of carbon. These feedbacks are normally not considered in the modeling studies of future temperature change (and therefore not included in the ZEC estimates), but IPCC (2021) taken into account these feedbacks in the estimate of the remaining Carbon budget through linear feedback analysis, with the assumption that these feedbacks reduce the budget with 26 ± 97 GtCO2 °C^{-1}. In addition, remaining uncertainties in the natural sources and sinks in the carbon cycle also could affect estimates of the budget of remaining allowed CO_2 emissions. These uncertainties are large but difficult to quantify and are not fully considered in evaluating the remaining allowed CO_2 emissions.

The analyses of allowed carbon also assume that potential impacts from natural changes in climate forcing, such as those from major changes in solar flux or from a series of large volcanic eruptions, will not occur during this time period, and that there will be no major changes from unforced natural variability.

Updated remaining carbon budgets

The remaining allowed CO_2 emissions estimated by IPCC is based on the geophysical basis of the approximate linear relationship between peak global mean temperature and cumulative emissions of carbon (that is, the transient climate response relative to cumulative emissions of carbon or TCRE). Note that the linearity of the TCRE relationship results from the compensation of individual non-linear processes that act to both increase and decrease the sensitivity of the temperature response to additional cumulative CO_2 emissions (Matthews et al. 2020).

Table 1 gives a summary of the remaining allowed CO_2 emissions to reach 1.5 or 2°C based on emission through the end of 2019 from the IPCC AR6 WG1 Report (2021). These limits are defined relative for the 17th, 33rd, 50th, 67th and, 83rd percentiles of TCRE, basically providing an estimate for the range of likelihoods for being able to stay within the given temperature change. For example, the 50th percentile means there is a 50% probability of globally averaged temperature staying within a 1.5°C increase since the 1850–1900 time period.

Based on the Global Carbon Project analyses (Friedlingstein et al. 2020), emissions of CO_2 from fossil fuel combustion, industrial processes, and land use change (summed) for 2020 are 39.9 Gt CO_2. The estimated emissions fell by about 7% in 2020, with this decrease largely thought to be a result of the COVID-19 pandemic (Le Quéré et al. 2020). Even accounting for the small reduction in 2020 emissions as a result of the COVID-19 pandemic, 2020 emissions would reduce the IPCC (2021) levels of remaining allowable CO_2 emissions by 40 Gt CO_2.

The latest estimates of the remaining carbon budget are small (e.g., 400 Gt CO_2 for a 67% probability of limiting the warming below 1.5°C and rapidly decreasing at the rate of about 40 Gt CO_2 a year). Matthews et al. (2020) note that “there is nevertheless a reasonable chance that the Paris Agreement goals remain within reach. However, this window of opportunity is closing with each passing year of tentative and insufficient action”.

Table 1. Estimates of remaining carbon budgets and their uncertainties. Assessed estimates are provided for additional human-induced warming, expressed as global surface temperature, since the recent past (2010-2019), which *likely* amounted to 0.8° to 1.3°C with a best estimate of 1.07°C relative to 1850–1900. Historical CO_2 emissions between 1850 and 2014 have been estimated at about 2180 ± 240 $GtCO_2$ (1-sigma range), while since 1 January 2015, an additional 210 $GtCO_2$ has been emitted until the end of 2019. GtCO2 values to the nearest 50. This table is reproduced from IPCC AR6 WG1 Report (Table TS.3 from the Technical Summary). Note that the remaining carbon budget is based on CO_2 emitted until December 31, 2019. Each year, approximately 40 GtCO2 is emitted reducing this remaining carbon budget.

Global surface temperature change since 2010–2019	**Global surface temperature change since 1850–1900 *(1)**	**Estimated remaining carbon budgets starting from 1 January 2020 and subject to variations and uncertainties quantified in the columns on the right**					**Scenario variation**	**Geophysical uncertainties*(4)**			
°C	*°C*	Percentiles of TCRE*(2) *$GtCO_2$*					Non-CO_2 scenario variation *(3)	Non-CO_2 forcing and response uncertainty	Historical temperature uncertainty*(1)	ZEC uncertainty	Recent emissions uncertainty *(5)
		17th	*33rd*	*50th*	*67th*	*83rd*	*$GtCO_2$*	*$GtCO_2$*	*$GtCO_2$*	*$GtCO_2$*	*$GtCO_2$*
0.43	***1.5***	*900*	*650*	*500*	*400*	*300*	Values can vary by at least ±220 due to choices related to non-CO_2 emissions mitigation	Values can vary by at least ±220 due to uncertainty in the warming response to future non-CO_2 emissions	±550	±420	±20
0.53	***1.6***	*1200*	*850*	*650*	*550*	*400*					
0.63	***1.7***	*1450*	*1050*	*850*	*700*	*550*					
0.73	***1.8***	*1750*	*1250*	*1000*	*850*	*650*					
0.83	***1.9***	*2000*	*1450*	*1200*	*1000*	*800*					
0.93	***2***	*2300*	*1700*	*1350*	*1150*	*900*					

*(1) Human-induced global surface temperature increase between 1850–1900 and 2010–2019 is assessed at 0.8–1.3°C (*likely* range; Cross-Section Box TS.1) with a best estimate of 1.07°C. Combined with a central estimate of TCRE (1.65 °C EgC^{-1}) this uncertainty in isolation results in a potential variation of remaining carbon budgets of ±550 $GtCO_2$, which, however, is not independent of the assessed uncertainty of TCRE and thus not fully additional.

*(2) TCRE: transient climate response to cumulative emissions of carbon dioxide, assessed to fall *likely* between 1.0–2.3°C EgC^{-1} with a normal distribution, from which the percentiles are taken. Additional Earth system feedbacks are included in the remaining carbon budget estimates as discussed in Section 5.5.2.2.5.

*(3) Estimates assume that non-CO_2 emissions are mitigated consistent with the median reductions found in scenarios in the literature as assessed in SR1.5. Non-CO_2 scenario variations indicate how much remaining carbon budget estimates vary due to different scenario assumptions related to the future evolution of non-CO_2 emissions in mitigation scenarios from SR1.5 that reach net zero CO_2 emissions. This variation is additional to the uncertainty in TCRE. The WGIII Contribution to AR6 will reassess the potential for non-CO_2 mitigation based on literature since the SR1.5.

*(4) Geophysical uncertainties reported in these columns and TCRE uncertainty are not statistically independent, as uncertainty in TCRE depends on uncertainty in the assessment of historical temperature, non-CO_2 versus CO_2 forcing and uncertainty in emissions estimates. These estimates cannot be formally combined and these uncertainty variations are not directly additional to the spread of remaining carbon budgets due to TCRE uncertainty reported in columns 3 to 7.

*(5) Recent emissions uncertainty reflects the ±10% uncertainty in the historical CO_2 emissions estimate since 1 January 2015.

Impacts on carbon emissions from the COVID-19 pandemic

The global pandemic related to COVID-19 and the subsequent forced lockdown led to large reductions in human activities, specifically during the first quarter of 2020. Le Quéré et al (2020) showed that daily CO_2 emissions dropped by 17% (11 – 25%) in early April compared with mean 2019 levels, with the aviation sector alone seeing a 60% (44 – 76%) drop. Similarly, Liu et al. (2020) found an abrupt 8.8% decrease in global CO_2 emissions (−1551 Mt CO_2) in the first half of 2020 compared with the same period in 2019. The magnitude of this decrease is found to be larger than during previous economic downturns or World War II. Liu et al. (2020) estimated that emissions from global aviation decreased by −44% (−200.8 Mt CO_2) during the first half of 2020, of which roughly 70% of the drop was related to international flights. The total number of flights and global aviation emissions show two large decreases, one in Asia near the end of January and another coincident with travel bans and lockdown measures in the rest of the world that began in the middle of March 2020. By the end of March 2020, there were 85% fewer flights than during the same period in 2019. Global aviation emissions began to rebound in late April and gradually increased throughout the end of July. However, international flight emissions in July 2020 were still 72.0% lower than the emissions in July 2019. According to an updated emission dataset from carbonmonitor.org (Liu et al., 2020b), all-sector CO_2 worldwide emissions in 2020 decreased by 4% compared with 2019, due to the COVID-19 pandemic (Figure 3). In contrast, the total worldwide emissions from aviation fell by nearly 50 percent in 2020.

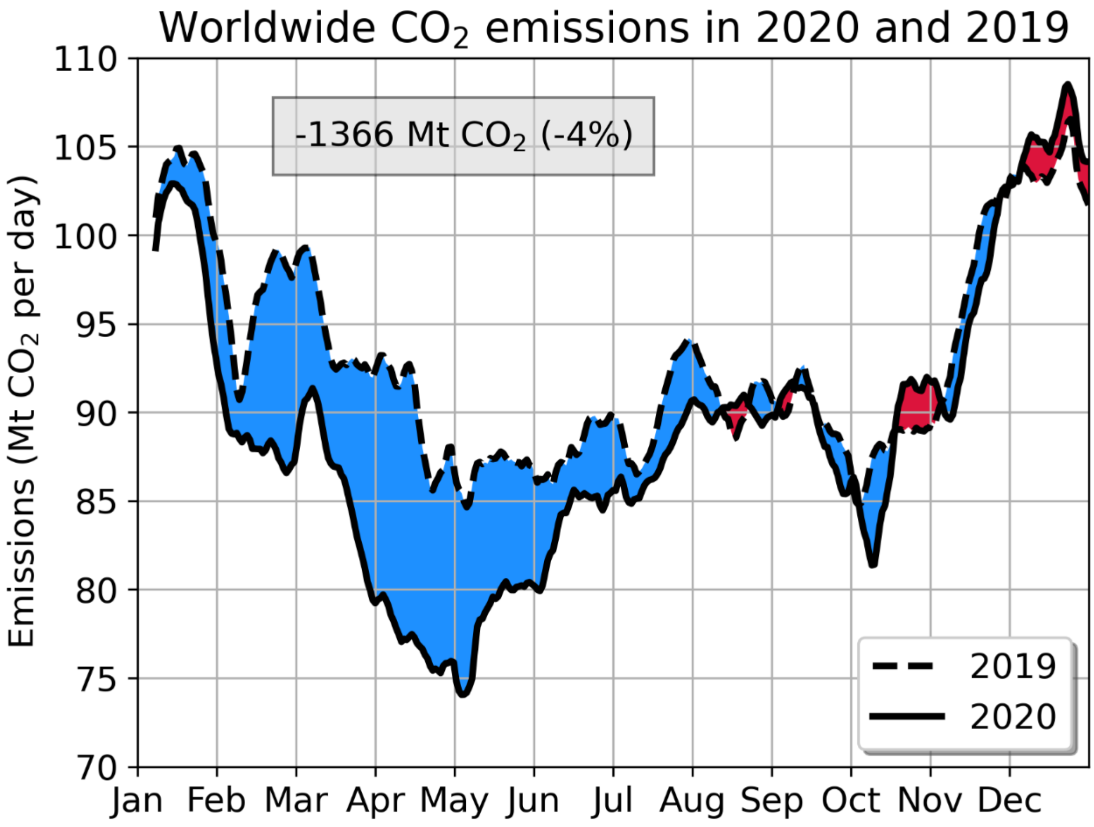


Figure 3. Worldwide all-sector CO_2 daily emissions from 1st January 2020 to 31st December 2020 compared to 2019 emissions. The shaded blue (red) area represents the decrease (increase) in CO_2 daily emissions due to the COVID-19 pandemic. Source: figure prepared based on carbonmonitor.org data (Liu et al., 2020b).

The role of non-CO_2 factors

Emissions of non-CO_2 greenhouse gases are also important in the calculation of overall response of climate under mitigation scenarios (e.g., 1.5°C) as calculated and presented by IPCC (2018). The long-lived greenhouse gases most often considered include nitrous oxide (N_2O) and some fluorinated gases. IPCC (2018) also refers to short-lived climate forcers (SLCFs) such as methane (CH_4), some fluorinated gases, ozone (O_3), and aerosols, all contributing to radiative forcing. These non-CO_2 forcing agents contribute differently to net non-CO_2 uncertainties; for example, in IPCC AR5 the present-day level of forcing from N_2O is assigned a 'very high' level of confidence; CH_4, fluorinated gases, aerosols and aerosol precursors are assigned a 'high' level of confidence; and ozone and precursors are given a 'medium' level of confidence (IPCC, 2014). 'Levels of confidence' in present-day forcings do not translate to uncertainties in forward emission scenarios but are indicative of the state of scientific understanding of these non-CO_2 forcing agents.

In summary of the overall role of non-CO_2 forcers on temperature goals, not reducing non-CO_2 forcing levels results in a significantly lower chance of limiting warming to 1.5°C for a given level of cumulative CO_2 emissions (see Figure 1 in this report and the conceptual Figure SPM1 in the IPCC 2018 report). In terms of emission reductions of some of the non-CO_2 forcing agents in scenarios limiting warming to 1.5°C with no, or limited overshoot, required reductions in emissions of black carbon and methane are 35% or more by 2050 relative to 2010 (IPCC, 2018; Figure 4).

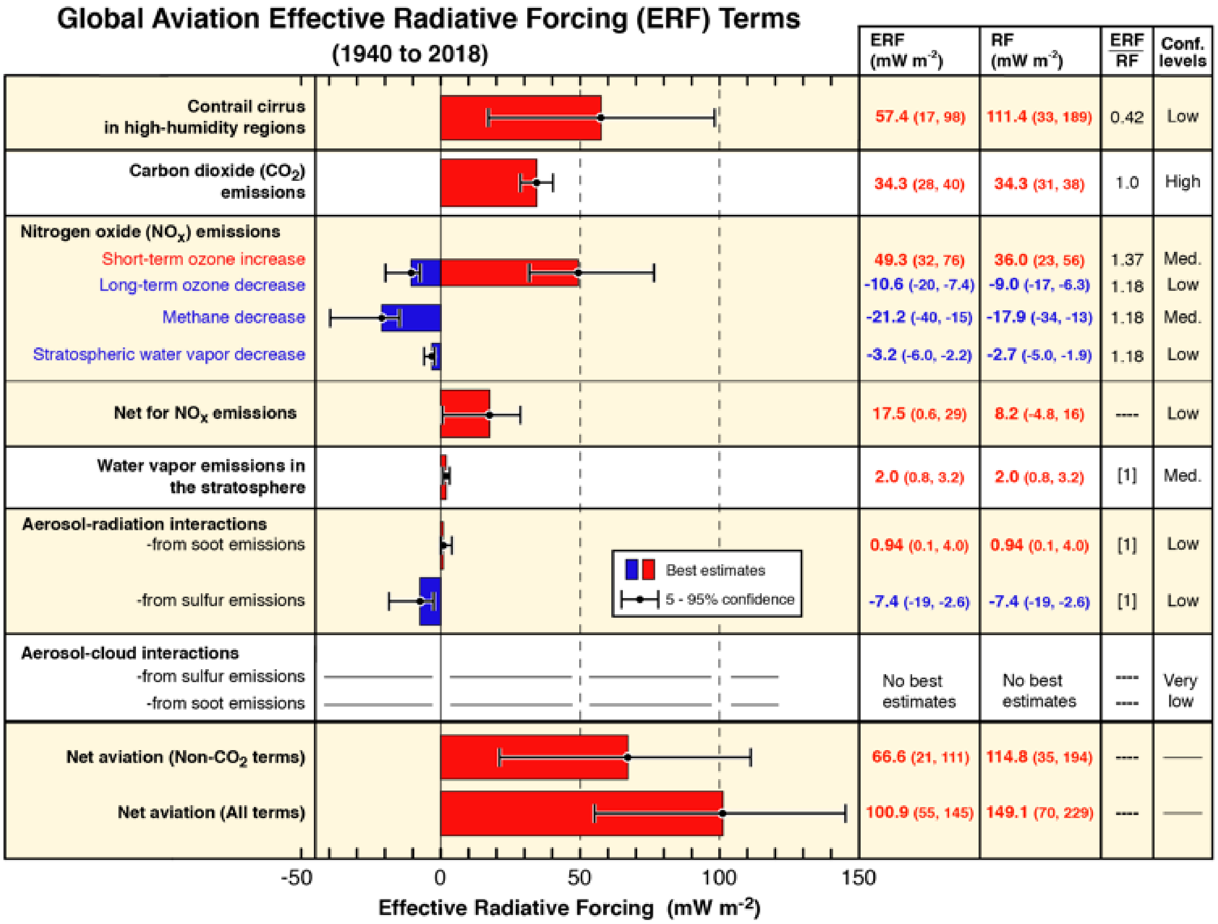
Future emissions of methane, nitrous oxide, aerosols, and other climate forcings are highly uncertain. As the use of fossil fuels is reduced, the relative influence of these components on the remaining carbon budget increases. According to IPCC (2018), the overall impacts of non-CO_2 forcers on remaining carbon budgets are significant and the non-CO_2 scenario variation is estimated to contribute ±220 Gt CO_2 (IPCC, 2021; Table 1).

The long-term effect of SLCFs would be underestimated when only considering the short atmospheric lifetimes. Emissions of SLCFs induce heating of the oceans that causes the temperature impact of the SLCFs to last for far longer than the time these forcers remain in the atmosphere. In addition, this increase in the temperature will likely have impacts on the carbon cycle, causing atmospheric CO_2 to increase through carbon-cycle climate feedbacks, further enhancing and extending the climate impact of SLCFs. Hence, SCLFs induce a temperature increase that will not disappear in a short time after the emissions of SLCFs are stopped.

Aviation non-CO_2 climate forcing and the cumulative carbon budget approach

Non-CO_2 forcing agents play an important role in the total anthropogenic forcing as noted above. Here we focus on the role of these non-CO_2 forcing agents as they relate to aviation emissions and aviation-induced cloudiness. It should be noted that aircraft do not emit long-lived N_2O or fluorinated gases and all of the non-CO_2 effects from aviation are short lived. The most recent assessment of aviation climate forcing separately evaluated the CO_2 and non-CO_2 forcing terms from global aviation operations for the period 2000 to 2018 (Lee et al., 2021). All non-CO_2 effects from aviation are due to SLCFs, some having lifetimes of a few hours only (e.g., contrail cirrus). The non-CO_2 effects of aviation are currently relatively large in comparison to relative non-CO_2 effects of many other industrial sectors. The aviation non-CO_2 terms arise from the emissions of nitrogen oxides (NO_x), water vapor (H_2O), and sulfate and soot aerosols, and from the formation of contrail cirrus induced by the emissions of water vapor and modified by the emission of soot. The quantitative contributions are shown as effective radiative forcing (ERF) terms in Figure 5 for global aviation operations over the period 1940 to 2018. The ERF metric is preferred over the traditional radiative forcing (RF) metric because it is a more consistent indicator of the eventual global mean temperature response (IPCC, 2013). The contribution of global aviation in 2011 was calculated by Lee et al. (2021) to be 3.5% of the net anthropogenic ERF.

Contrail cirrus formation is the largest positive (warming) ERF term. NO_x emissions give rise to four component terms associated with changes in methane, ozone and water vapor with the short-term ozone increase being the only warming term. The net NO_x effect is a warming. The direct effect of water vapor emissions results in a small warming term. The direct effects of soot and sulfate aerosol emissions create small warming and cooling terms, respectively. The forcing terms from aerosol-cloud interactions involving sulfate and soot are associated with large uncertainties and no quantitative best estimates are available. The sum of non-CO_2 terms in 2018 yields a positive (warming) ERF that is equivalent to approximately 2/3 of the aviation net ERF.



	ERF (mW m^{-2})	RF (mW m^{-2})	$\frac{ERF}{RF}$	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions: Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions: -from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions: -from sulfur emissions	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

Figure 4. Best-estimates for climate forcing terms from global aviation from 1940 to 2018 (Lee et al., 2021). The bars and whiskers show ERF best estimates and the 5–95% confidence intervals, respectively. Red bars indicate warming terms and blue bars indicate cooling terms. Numerical ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios and confidence levels.

For a given global mean surface temperature limit that should be met at a given probability, the larger the warming contribution from non-CO_2 forcers, the lower must the cumulative CO_2 emissions be (see the previous section and Figure 1). A potential way to determine the contribution of aviation non-CO_2 effects on temperature change would be by applying climate models for an ensemble of emission scenarios. However, due to the relatively small forcing and the high natural variability of the climate system, it would be difficult to separate the aviation effect from total climate change. However, simplified climate models (e.g., Skeie et al., 2009) can be used for calculations of sectoral contributions to global temperature change. Furthermore, comparing the contribution of the aviation non-CO_2 effects to CO_2 emissions can also be done by the use of 'CO_2-emission equivalence' metrics (Table 2). Note that the underlying application and policy context determine the choice of metric (Fuglestvedt et al., 2010) used for equivalence of emissions. Such approaches are not ideal or exact, and should only be seen as indicative of the relative contribution of non-CO_2 forcing agents to a global temperature limit (due to the difficulty of placing forcings with different atmospheric lifetimes on a common scale).

Table 2. CO_2-equivalent emissions for the ERF components of 2018 aviation emissions and cloudiness (Lee et al., 2021).

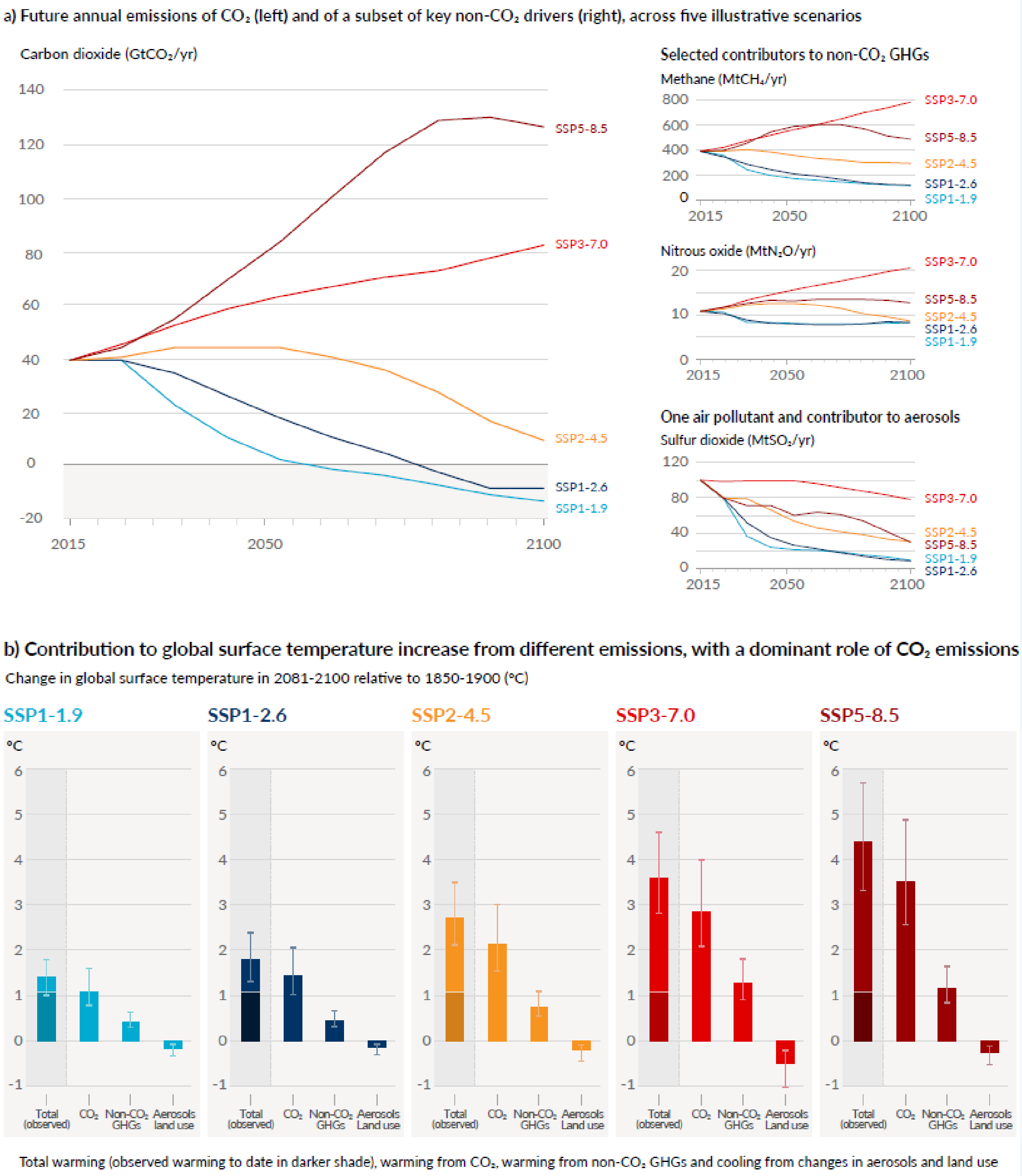
CO_2-eq emissions (Tg CO_2 yr^{-1}) for 2018

ERF term	GWP_{20}	GWP_{50}	GWP_{100}	GTP_{20}	GTP_{50}	GTP_{100}	$GWP*_{100}$ (E^*_{CO2e})
CO_2	1034	1034	1034	1034	1034	1034	1034
Contrail cirrus (Tg CO_2 basis)	2399	1129	652	695	109	90	1834
Contrail cirrus (km basis)	2395	1127	651	694	109	90	1834
Net NO_x	887	293	163	-318	-99	19	339
Aerosol-radiation							
Soot emissions	40	19	11	12	2	2	20
SO_2 emissions	-310	-146	-84	-90	-14	-12	-158
Water vapor emissions	83	39	23	27	4	3	42
Total CO_2-eq (using km basis)	4128	2366	1797	1358	1035	1135	3111
Total CO_2-eq / CO_2	4.0	2.3	1.7	1.3	1.0	1.1	3.0

ERF, as used in Figure 4, would not be suitable in defining the remaining carbon budget as it is a backward-looking metric (i.e., it accounts for all past emissions up to a given time). Instead, a forward-looking perspective has to be used; see Table 2 for a comparison of how different metric approaches affect the relative importance of non-CO_2 terms to that of aviation CO_2 emissions. IPCC (2018) used scenarios for non-CO_2 components to estimate their impact on the remaining carbon budget.

Lee et al., (2021) estimate, based on GWP*, that the aviation induced total CO_2-emission equivalence would be 3 times as large as the CO_2 effect (see Table 2, right-most column). It should be noted that this estimate is highly uncertain as are other metric estimates (see below for further details) and that no agreement on the choice of the most suitable metric has been obtained so far.

There are no precise future projections of the aviation non-CO_2 forcing terms due to the uncertainty in global aviation operations and in estimating contrail and NO_x forcing in a changing climate. For example, increases in stringency to lower aviation NOx emissions coupled with anticipated reductions in surface NO_x emissions due to lower fossil fuel use, will decrease the NO_x ERF from global aviation and may change its sign to even become a cooling term (Skowron et al., 2021). On the other hand, the calculation of the NO_x effects may be strongly underestimated by the perturbation method that has been widely applied and summarized in the results of Lee et al. (2021). For instance, Grewe et al. (2019) show that the RF from NO_x might be a factor of 6 larger, by employing a 'tagging' method. However, the tagging method currently only applies to the short-term ozone increase of the net NO_x response. The evaluation of the aviation non-CO_2 ERF contribution is incomplete due to the absence of ERF best estimates for the aerosol-cloud interactions of aviation aerosols (Lee et al., 2021). Existing ERF estimates span a large range of magnitude and include both large warming and cooling values. New results are expected from ongoing research activities.



a) Future annual emissions of CO_2 (left) and of a subset of key non-CO_2 drivers (right), across five illustrative scenarios

b) Contribution to global surface temperature increase from different emissions, with a dominant role of CO_2 emissions

Change in global surface temperature in 2081-2100 relative to 1850-1900 (°C)

Total warming (observed warming to date in darker shade), warming from CO_2, warming from non-CO_2 GHGs and cooling from changes in aerosols and land use

Figure 5. Future anthropogenic emissions of key drivers of climate change and warming contributions by groups of drivers for the five illustrative scenarios used by IPCC. (2021). The five scenarios are SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. Panel a) Annual anthropogenic (human-caused) emissions over the 2015–2100 period. Shown are emissions trajectories for carbon dioxide (CO_2) from all sectors ($GtCO_2$/yr) (left graph) and for a subset of three key non-CO_2 drivers considered in the scenarios: methane (CH_4, $MtCH_4$/yr, top-right graph), nitrous oxide (N_2O, MtN_2O/yr, middle-right graph) and sulfur dioxide (SO_2, $MtSO_2$/yr, bottom-right graph, contributing to anthropogenic aerosols in panel b). Panel b) Warming contributions by groups of anthropogenic drivers and by scenario are shown as change in global surface temperature (°C) in 2081–2100 relative to 1850–1900, with indication of the observed warming to date. Bars and whiskers represent median values and the *very likely* range, respectively. Within each scenario bar plot, the bars represent total global warming (°C; total bar) (see Table SPM.1) and warming contributions (°C) from changes in CO_2 (CO_2 bar), from non-CO_2 greenhouse gases (non-CO_2 GHGs bar; comprising well-mixed greenhouse gases and ozone) and net cooling from other anthropogenic drivers (aerosols and land-use bar; anthropogenic aerosols, changes in reflectance due to land-use and irrigation changes, and contrails from aviation; see Figure SPM.2, panel c, for the warming contributions to date for individual drivers). The best estimate for observed warming in 2010–2019 relative to 1850–1900. Contribution by groups of drivers are calculated with a physical climate emulator of global surface temperature which relies on climate sensitivity and radiative forcing assessments. (Reproduced from IPCC AR6 WG1 Report, Figure SPM.4).

Future scenarios

The emission scenarios considered by IPCC (2021) presented in Figure. 5, Global warming of 1.5°C relative to 1850-1900 would be exceeded during the 21st century under the intermediate, high and very high scenarios considered (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021-2040), the 1.5°C global warming level is very likely[3] to be exceeded under the very high GHG emissions scenario (SSP5-8.5), likely to be exceeded under the intermediate and high GHG emissions scenarios (SSP2-4.5 and SSP3-7.0), more likely than not to be exceeded under the low GHG emissions scenario (SSP1-2.6) and more likely than not to be reached under the very low GHG emissions scenario (SSP1-1.9). Furthermore, for the very low GHG emissions scenario (SSP1-1.9), it is more likely than not that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming (IPCC AR6 WG1 Report 2021 SPM B1.3).

Based on the assessment of multiple lines of evidence by IPCC (2021), global warming of 2°C, relative to 1850–1900, would be exceeded during the 21st century under the high and very high GHG emissions scenarios considered (SSP3-7.0 and SSP5-8.5, respectively). Global warming of 2°C would extremely likely be exceeded in the intermediate scenario (SSP2-4.5). Under the very low and low GHG emissions scenarios, global warming of 2°C is extremely unlikely to be exceeded (SSP1-1.9), or unlikely to be exceeded (SSP1-2.6). Crossing the 2°C global warming level in the mid-term period (2041–2060) is very likely to occur under the very high GHG emissions scenario (SSP5-8.5), likely to occur under the high GHG

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[3] IPCC (2021) expresses the level of confidence using five qualifiers: very low, low, medium, high and very high, and typeset in italics, for example, medium confidence. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%.

emissions scenario (SSP3-7.0), and more likely than not to occur in the intermediate GHG emissions scenario (SSP2-4.5) (IPCC AR6 WG1 Report 2021 SPM B1.2).

Glossary of Terms

Carbon Budget: As noted in IPCC (2021), this term refers to two concepts in the literature: (1) an assessment of carbon cycle sources and sinks on a global level, through the synthesis of evidence for fossil-fuel and cement emissions, emissions and removals associated with land use and land use change, ocean and natural land sources and sinks of carbon dioxide (CO_2), and the resulting change in atmospheric CO_2 concentration. This is referred to as the Global Carbon Budget; (2) the maximum amount of cumulative net global anthropogenic CO_2 emissions that would result in limiting global warming to a given level with a given probability, taking into account the effect of other anthropogenic climate forcers. This is referred to as the Total Carbon Budget when expressed starting from the pre-industrial period, and as the Remaining Carbon Budget when expressed from a recent specified date.

Note 1: Net anthropogenic CO_2 *emissions are anthropogenic* CO_2 *emissions minus anthropogenic* CO_2 *removals.*

Note 2: The maximum amount of cumulative net global anthropogenic CO_2 *emissions is reached at the time that annual net anthropogenic* CO_2 *emissions reach zero.*

Note 3: The degree to which anthropogenic climate forcers other than CO_2 *affect the Total Carbon Budget and Remaining Carbon Budget depends on human choices about the extent to which these forcers are mitigated and their resulting climate effects.*

Note 4: The notions of a Total Carbon Budget and Remaining Carbon Budget are also being applied in parts of the scientific literature and by some entities at regional, national, or sub-national level. The distribution of global budgets across individual different entities and emitters depends strongly on considerations of equity and other value judgements.

ERF: Effective Radiative Forcing – a more accurate radiative forcing indicator of global mean temperature response than RF.

GTP: Global Temperature change Potential

GWP_{xx}: Global Warming Potential for ‘xx’ time horizon (years)

GWP^*_{100}: A modified usage of the GWP metric.

IAM: Integrated Assessment Model – a simplified and fast scientific model to quantify climate impacts generally used to inform decision making.

Remaining Carbon Budget: Estimated cumulative net global anthropogenic CO_2 emissions in this report from the start of 2021 to the time that anthropogenic CO_2 emissions reach net zero that would result, at some probability, in limiting global warming to a given level, accounting for the impact of other anthropogenic emissions.

RF: Radiative Forcing – is a measure of the influence a forcing term has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system relative to the preindustrial period and is an index of the importance of the forcing term as a potential climate change mechanism.

SLCF: Short lived climate forcers – climate forcers such as methane, ozone and aerosols that have a short atmospheric lifetime and therefore have a short-term climate effect.

TCR: Transient Climate Response – increase in global average temperature expected at a time when the atmospheric concentration of CO_2 has doubled from preindustrial levels.

TCRE: Transient Climate Response (TCR) relative to cumulative Emissions of carbon.

ZEC: Zero Emissions Commitment – The amount of subsequent temperature change following a complete cessation of CO_2 emissions.

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