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Intergovernmental Panel on Climate Change's Sixth Assessment Report

April 29, 2022

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SUMMARY

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In 2021, the Intergovernmental Panel on Climate Change (IPCC) released *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I*, as part of its Sixth Assessment (AR6 WGI). The role of the IPCC as endorsed by the United Nations in plenary session in 1988 is "to provide internationally coordinated scientific assessments of the magnitude, timing and potential environmental and socio-economic impact of climate change and realistic response strategies." This CRS report serves as a primer for the AR6 WGI assessment. It is not comprehensive, instead presenting key findings pertinent to congressional consideration of risks related to natural and human-induced climate change and possible legislative responses.

The AR6 WGI presents current evidence of changes in the climate, including, but not limited to, the following: Global average surface temperature in 2011-2020 increased by approximately 1.0°C above the preindustrial period of 1850-1900; heatwaves have occurred more often and with greater intensity since the 1950s, while cold extremes have occurred less often in the same time period; scientists have high confidence that there has been a global increase in co-occurring droughts and heatwaves since 1950; terrestrial global average precipitation has increased, as has the frequency of heavy precipitation events; Arctic sea ice has decreased, while Antarctic sea ice has remained largely unchanged.

The AR6 report reinforces earlier IPCC scientific assessments that human activities are the primary driver of many of these observed changes. The new report concludes, "It is unequivocal that human influence has warmed the atmosphere, ocean, and land." While climate change is the result of human and natural climate drivers, greenhouse gases (GHGs) emitted by human activity have had the greatest effect, including the observed increase in global average surface temperature.

Since the release of the 2014 IPCC Fifth Assessment Report (AR5), information on climatic change has continued to accumulate, supporting greater scientific certainty regarding some aspects of this change. As the AR6 WGI *Summary for Policy Makers* states, "Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since AR5."

The AR6 WGI provides five emissions scenarios based on a wide range of assumptions about the future, covering socioeconomic behavior, technologies and resources, and possible efforts to mitigate GHG emissions, deforestation, air pollution, and other contributors to climate change. The two highest GHG emissions scenarios are associated with mean projected temperature increases of greater than 3.5°C (all increases are for the period 2081-2100 relative to 1850-1900). Mean projected temperature increases for the two lowest GHG emissions scenarios are below 2°C. A middle scenario, which some associate as closest to current policy trajectories, has a best-estimate increase of 2.7°C. The two lowest emissions scenarios are both based on net-zero carbon dioxide (CO_2) emissions (CO_2 emissions entirely offset by CO_2 removals) after 2050, and thereafter negative emissions, in which CO_2 removals are greater than CO_2 emissions and the concentration of CO_2 in the atmosphere decreases. Net-zero CO_2 emissions and negative CO_2 emissions do not occur in the other, higher emissions scenarios. Only the two lowest GHG emissions scenarios, with substantial GHG mitigation assumed, result in stabilizing the increase in global mean temperature, while the other emissions scenarios are still on an ascending temperature trajectory at 2100.

The AR6 WGI states the physical science basis of limiting climate change: "From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions." Congress may wish to exercise its oversight authorities in examining national progress toward fulfilling the updated U.S. Nationally Determined Contributions (NDCs) to mitigating climate change and consider options for shaping and funding the U.S. approach to the Paris Agreement commitments.

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Introduction

Scientific interest, investigation, and understanding of the effect of carbon dioxide (CO_2) and other greenhouse gases (GHGs) on the climate have been ongoing for over 100 years.[1] Since at least the 1980s, there has been an international focus on potential changes to the earth's climate system resulting from increases in the concentrations of CO_2 and other GHGs in the atmosphere due to human activity, as well as on discerning the roles of human and natural drivers of change.

To address this issue, the Intergovernmental Panel on Climate Change (IPCC) was formed by the United Nations Environment Program and the World Meteorological Organization in 1988.[2] In that year, the United Nations endorsed a role for the IPCC "to provide internationally coordinated scientific assessments of the magnitude, timing and potential environmental and socio-economic impact of climate change and realistic response strategies"[3] to government policymakers internationally.[4] There are 195 members of the IPCC, including the United States. Since 1990, the IPCC has provided scientific information to the international effort to address climate change, including to negotiators of the 1992 United Nations Framework Convention on Climate Change (UNFCCC); its subsidiary agreements, the Kyoto Protocol (KP) and the Paris Agreement (PA); and the annual negotiation sessions for these agreements that occur at their respective Conferences of the Parties (COPs).

The IPCC has three working groups. Working Group I (WGI) is mandated to address the physical science basis of climate change. Working Group II (WGII) focuses on the impacts of climate change, vulnerability to these impacts, and the potential for climate change adaptation. Working Group III (WGIII) has the mitigation of climate change as its topic area. Original research is not part of the IPCC mandate, but the IPCC, through the various working groups, provides "regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation."[5]

Since the early 1990s, the IPCC has published a series of climate-related reports and assessments. Assessments by the IPCC are compiled by volunteer experts, organized in working groups who review a range of materials including peer reviewed, published, scientific studies in an effort to provide a comprehensive understanding of the current state of knowledge of climate change. The review process for IPCC assessment reports is extensive and starts with the selection of experts as authors and reviewers from lists provided by the IPCC member governments and participant organizations. The assessment reports go through first- and second-order drafts, with expert review at each stage and with the second-order draft distributed to all IPCC member governments for review and comment. A final draft is subsequently distributed to all IPCC member governments. The final report is then subject to the IPCC endorsement process: "all IPCC reports must be formally endorsed by the responsible Working Group or Working Groups or Task Force and by the Panel at an IPCC Plenary Session."[6] *Climate Change 2021—The Physical Science*

[1] CRS Report R45086, *Evolving Assessments of Human and Natural Contributions to Climate Change*, by Jane A. Leggett.

[2] IPCC, About the IPCC, https://www.ipcc.ch/about/.

[3] United Nations General Assembly, Resolutions and Decisions Adopted by the General Assembly During Its Forty-Third Session Volume 1 20 September-22 December 1988, December 31, 1989, pp. 133-134, at https://documents-dds-ny.un.org/doc/UNDOC/GEN/NR0/761/73/img/NR076173.pdf?OpenElement.

[4] IPCC, About the IPCC, https://www.ipcc.ch/about/.

[5] IPCC, The Intergovernmental Panel on Climate Change, https://www.ipcc.ch/.

[6] IPCC, Preparing Reports, https://www.ipcc.ch/about/preparingreports/.

Basis is the sixth and most recent physical science assessment (AR6 WGI) of the IPCC on the physical science basis of climate change.[7] The WGII and WGIII reports are scheduled for publication in 2022.

Congress may find the IPCC assessment useful to understanding the degree to which the earth's climate has changed and may change in the future, the contributions of human and natural factors to observed changes, and some of the projected physical implications of climate change for human and natural systems. Congress may choose to consider the information in its deliberations on climate-relevant legislation, oversight of federal climate-related programs, and decisions on appropriations and oversight with respect to climate change science and federal activities.

For example, as a compendium of the strengths and uncertainties in climate science, AR6 WGI may provide insights that Congress could consider as part of its oversight and appropriations decisions for the scientific activities associated with the U.S. Global Change Research Program.[8] The AR6 WGI might be a useful resource for Congress in the evaluation of the program's level of funding, the allocation of resources among participating agencies, and the setting of research priorities.

As a concise introduction to the AR6 WGI, this CRS report, while not comprehensive, presents key findings from the Sixth Assessment Report that Congress may find relevant to the consideration of possible legislative responses to climate change. This CRS report has four sections. The first section presents the AR6 WGI findings regarding the current state of climate science, including the human influence on planetary warming, as well as currently observed climatic changes. The second section describes the scenario methodology used in AR6 WGI to provide an analysis of possible climate futures, using greenhouse gas emissions levels associated with a set of socioeconomic pathways. The third section describes the framework that AR6 WGI uses to present a scientific basis for limiting future climate change. The fourth section provides an analysis of the relationship between the scenarios used in AR6 WGI and the temperature benchmarks of the Paris Agreement, as well as the potential application of AR6 WGI in congressional evaluation of possible climate mitigation actions.

The Current State of Climate Science: Selected Findings of AR6 WGI

The IPCC AR6 WGI presents an examination of the current scientific understanding of climate change. It weighs evidence regarding whether and what changes may have occurred in the climate and climate-sensitive earth system components. The report's findings include

- a statement of human influence on warming,
- a detailed analysis of the human and natural drivers of that warming,
- a presentation of climate changes that have already been observed, and
- a section on the unprecedented nature of some of these changes.

[7] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021 (hereinafter IPCC WGI 2021).

[8] The U.S. Global Change Research program was mandated by Congress under the Global Change Research Act of 1990 "to provide for development and coordination of a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change" (P.L. 101-606).

An analysis of each of these findings is presented in the following sections.

Human Influence on Planetary Warming

The question of whether and how human activity, among other potential drivers, has contributed to climate change has been discussed and debated for many years. Scientists have considered many potential natural and human-induced drivers of climate change and have examined these influences for their effect on the current climate using evidence from both historical and geological records. Each version of the WGI report has included a precisely worded assessment of the human role in climate change, which has been monitored by many governments, news media, and civil society organizations around the world. Among the central findings of the AR6 WGI was the following: "It is unequivocal that human influence has warmed the atmosphere, ocean, and land."[9]

The statement is supported by a mechanism of human influence—the increases in well-mixed[10] greenhouse gases (GHGs),[11] including CO_2, methane (CH_4), nitrous oxide (N_2O), and halogenated gases (e.g., chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and hydrofluorocarbons [HFCs]) in the atmosphere: "Observed increases in well-mixed greenhouse gas (GHG) concentrations since around 1750 are unequivocally caused by human activities."[12] The heat-trapping character of GHGs in the atmosphere is one of their known physical properties.[13]

The AR6 WGI statement on human influence on warming differs from the earlier assessment of human influence included in the 2014 IPCC Fifth Assessment Report (AR5),[14] which states that

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[9] IPCC, "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 4 (hereinafter IPCC SPM WGI 2021).

[10] The glossary in IPCC WGI 2021 defines *well-mixed greenhouse gas* as follows:

> Well-mixed greenhouse gas.... A greenhouse gas that has an atmospheric lifetime long enough (> several years) to be homogeneously mixed in the troposphere, and as such the global average mixing ratio can be determined from a network of surface observations. For many well-mixed greenhouse gases, measurements made in remote regions differ from the global mean by < 15%.

[11] The glossary in IPCC, *Climate Change 2014: Mitigation of Climate Change—Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014, provides the following definition of *greenhouse gases*:

> Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect.

[12] IPCC SPM WGI 2021, p. 4.

[13] CRS Report R45086, *Evolving Assessments of Human and Natural Contributions to Climate Change*, by Jane A. Leggett.

[14] IPCC, *Climate Change 2014: Synthesis Report—Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014 (hereinafter IPCC AR5 WGI,II,III 2014).

anthropogenic GHGs (i.e., those emitted through human activity) "are *extremely likely*[15] to have been the dominant cause of the observed warming since the mid-20th century."[16]

Patterns and Drivers of Global Surface Temperature Changes

Among the topics the IPCC has addressed are the patterns of surface temperature changes and the drivers of those observed changes. The AR6 WGI report addresses the observed increase in global surface temperature of the earth since the industrial revolution in the following statement: "Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900."[17] AR6 WGI provides an analysis of the magnitude and causes of this increase, with statements of confidence and likelihood.[18] The observed increase in global mean temperature is stated as the result of both human and natural influences, known as *drivers* of variability and potential changes,[19] which have both heating and cooling effects. The AR6 WGI puts this increase into the context of changes in the earth's temperature that have occurred in the past. A presentation of these AR6 WGI findings appears later in this CRS report.

Well-mixed anthropogenic GHGs[20] have the largest reported effect of any driver analyzed, and this is a warming effect. Human emissions of sulfur dioxide aerosols and nitrogen oxides have a cooling effect. Halogenated gases have a warming effect, although those that destroy stratospheric ozone (CFCs, HCFCs, and others) had a cooling effect on the stratosphere from 1979 until their control in the mid-1990s[21] under the Montreal Protocol.[22] Other human drivers

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[15] IPCC notes the following in *Climate Change 2014: Mitigation of Climate Change—Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014:

> In the Synthesis Report, the certainty in key assessment findings is communicated as in the Working Group Reports and Special Reports. It is based on the author teams' evaluations of underlying scientific understanding and is expressed as a qualitative level of confidence (from very low to very high) and, when possible, probabilistically with a quantified likelihood (from exceptionally unlikely to virtually certain). Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

[16] IPCC AR5 WGI,II,III 2014, p. 17.

[17] IPCC SPM WGI 2021, p. 5.

[18] IPCC SPM WGI 2021, p. 4:

> Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed 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 a outcome or 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%; and exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%; more likely than not >50–100%; and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood is typeset in italics, for example, *very likely*. This is consistent with AR5. In this Report, unless stated otherwise, square brackets [x to y] are used to provide the assessed very likely range, or 90% interval.

[19] For explanation of climate, climate variability, and climate change, see CRS In Focus IF11446, *Weather and Climate Change: What's the Difference?*, by Jane A. Leggett.

[20] The U.S. Geological Survey defines *anthropogenic* as "referring to environmental change caused or influenced by people, either directly or indirectly." See U.S. Geological Survey, Earthword: Anthropogenic, https://www.usgs.gov/news/science-snippet/earthword-anthropogenic.

[21] IPCC SPM WGI 2021, p. 5.

[22] The Montreal Protocol is an international treaty for the control of substances that deplete the stratospheric ozone layer. See U.S. Department of State, The Montreal Protocol on Substances That Deplete the Ozone Layer, https://www.state.gov/key-topics-office-of-environmental-quality-and-transboundary-issues/the-montreal-protocol-on-substances-that-deplete-the-ozone-layer/.

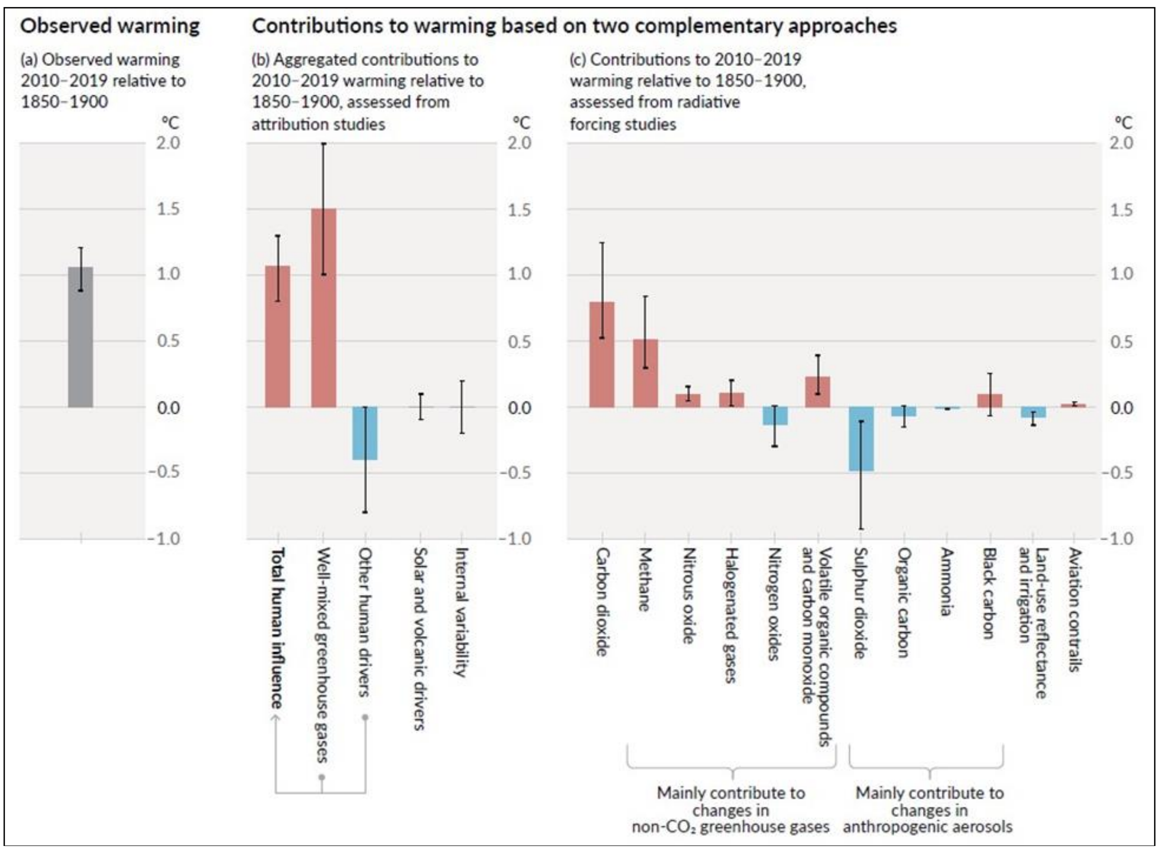
include the cooling effect of irrigation and some land-use changes, as well as the warming effect of aviation contrails and the inefficient combustion of biomass and fossil fuels that release soot, also known as black carbon. The natural drivers of global surface temperature change include changes in solar activity and volcanic eruptions, as well as the natural net internal variability of the climate system itself (see **Figure 1**).

Regarding the contribution to warming, the AR6 WGI concludes the following:

> It is likely that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. It is very likely that well-mixed GHGs were the main driver of tropospheric warming since 1979 and extremely likely that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s.[23]

The observed global temperature increase is the net result of all drivers, both human and natural, with both warming and cooling effects, acting simultaneously (**Figure 1**, panel (a)). Human-caused drivers of both warming and cooling are the largest of these drivers, with the warming effect of human-emitted well-mixed GHGs being the largest of all (**Figure 1,** panels (b) and (c)).

Figure 1. Global Surface Warming: Human and Natural Drivers



Source: Adapted from Figure SPM.2, panels (a), (b), and (c), in IPCC, "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 7.

[23] IPCC SPM WGI 2021, p. 5.

Notes: Panel (a) presents observed warming, the net result of the influences of all drivers pictured in panels (b) and (c). Panel (b) disaggregates the contributions to the warming between human drivers (e.g., well-mixed GHGs [warming = red] and stratospheric ozone depletion [cooling = blue]) and natural drivers (i.e., solar and volcanic activity) and internal climate variability, derived from attribution studies. Panel (c) presents values of individual drivers based on the calculations of their radiative forcing, or net warming (red bars) or cooling effect (blue bars).

The global surface temperature response to the combination of human and natural drivers and to natural drivers alone has been modeled and compared with observed values. This comparison is presented and discussed below.

Currently Observed Climate Changes

AR6 WGI states that from about 1750 to the present,[24] "Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred."[25] AR6 WGI presents numerous changes observable in data obtained from monitoring of the climate and climate-sensitive aspects of the earth system. The report identifies where climate-related changes are detectable, and with some detectable changes, the report assesses the likelihoods that a particular change is attributable to human influence. AR6 WGI states varying levels of confidence in being able to attribute observed changes to human influence. Further, there are varying levels of certainty about whether particular changes are influenced by human activity, and these are also reported explicitly.[26] The changes that are observed are not uniform with respect to their extent, the direction of the change, or the regional character of the change. As illustrated in the following quotation, the AR6 WGI concludes that changes in extremes of hot and cold are virtually certain to have occurred:

> It is virtually certain that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with high confidence that human-induced climate change is the main driver of these changes. Some recent hot extremes observed over the past decade would have been extremely unlikely to occur without human influence on the climate system.[27]

One manifestation of large-scale regional differences in the results of climate change is the observed quantity and extent of polar sea ice. Seasonal Arctic sea ice has decreased since 1979, a trend that is very likely to have been human induced, while seasonal Antarctic sea ice has remained unchanged in the same period.[28]

Retreat of glaciers is a consistent global phenomenon across many regions and assessed as very likely to have been influenced by human activity. The warming of the upper ocean since the 1970s is a globally consistent trend that is virtually certain and for which AR6 WGI states human influence to be extremely likely:[29] "ocean warming is largest near the surface, and the upper 75 m warmed by 0.11 [0.09 to 0.13] °C per decade over the period 1971 to 2010."[30]

[24] IPCC SPM WGI 2021, pp. 4-6.

[25] IPCC SPM WGI 2021, p. 4.

[26] Where statements of levels of certainty appear in this CRS report, they are sourced from AR6 WGI unless stated otherwise.

[27] IPCC SPM WGI 2021, p. 8.

[28] IPCC SPM WGI 2021, p. 5.

[29] IPCC SPM WGI 2021, p. 5.

[30] IPCC WGI 2021, p. 1-168.

AR6 WGI states that there have likely been changes in the occurrence of major tropical cyclones, but the findings regarding trends and attribution are less certain:

> It is likely that the global proportion of major (Category 3–5) tropical cyclone occurrence has increased over the last four decades ... these changes cannot be explained by internal variability alone (medium confidence). There is low confidence in long-term (multi-decadal to centennial) trends in the frequency of all-category tropical cyclones.[31]

Unprecedented Changes in the Climate System

AR6 WGI states that some of the changes in the climate, or their observable effects, are unprecedented on a scale of centuries to millennia. This assessment is based on groups of studies estimating past CO_2, CH_4, and N_2O atmospheric concentrations, using a variety of analytic techniques, to cover periods going back 800,000 years for CH_4 and N_2O, and longer periods for CO_2.

> In 2019, atmospheric CO_2 concentrations were higher than at any time in at least 2 million years (high confidence), and concentrations of CH_4 and N_2O were higher than at any time in at least 800,000 years (very high confidence). Since 1750, increases in CO_2 (47%) and CH4 (156%) concentrations far exceed—and increases in N_2O (23%) are similar to—the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years (very high confidence).[32]

In AR6 WGI there is medium confidence that global surface temperatures are now higher than they have been for thousands of years (see **Figure 2**, panel (a)).

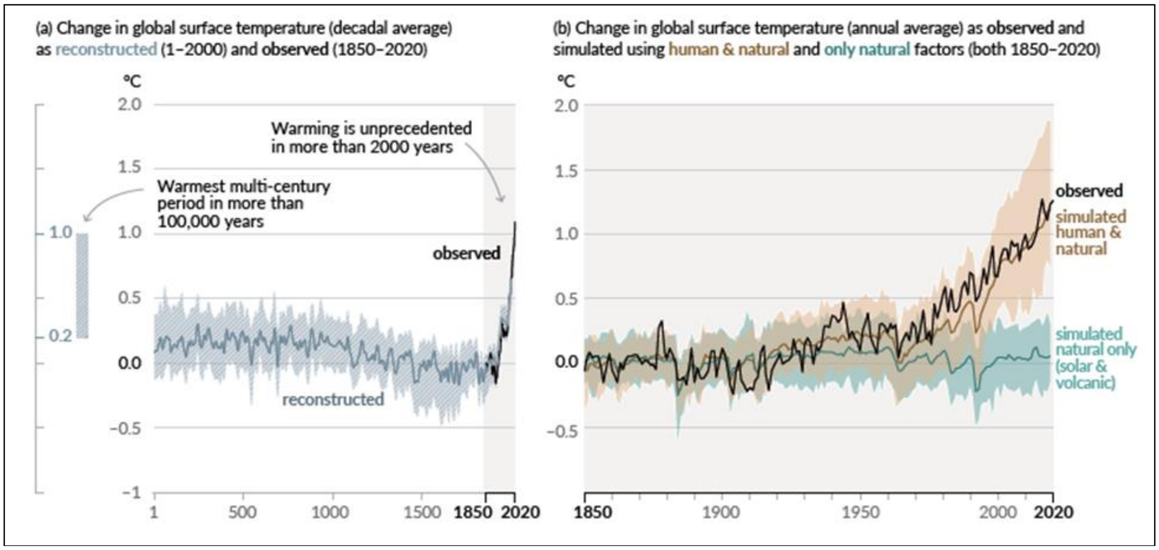
> Temperatures during the most recent decade (2011–2020) exceed those of the most recent multi-century warm period, around 6500 years ago [0.2°C to 1°C relative to 1850–1900] (medium confidence). Prior to that, the next most recent warm period was about 125,000 years ago, when the multi-century temperature [0.5°C to 1.5°C relative to 1850–1900] overlaps the observations of the most recent decade (medium confidence).[33]

[31] IPCC SPM WGI 2021, p. 9.

[32] IPCC SPM WGI 2021, p. 8.

[33] IPCC SPM WGI 2021, p. 8.

Figure 2. Changes in Global Surface Temperature



Source: Adapted from Figure SPM.1, in IPCC, "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 6.

Notes: In panel (a), the solid gray line is reconstructed from paleoclimate archives (years 1-2000), while the black line is from direct observations (years 1850-2020). The gray bar on the left side of the figure is the very likely temperature range for the warmest multicentury period from 100,000 years ago to the present. The very likely range of temperature reconstructions is indicated by gray shading. In panel (b), the black line is the observed global surface temperature over 1850-2020. The brown line is the Coupled Model Intercomparison Project 6 (CMIP6) climate model simulation for the same period, showing the modeled temperature response to human and natural climate drivers. The green line is the temperature response simulation of the same model with only natural drivers. The shaded areas are the very likely ranges of the simulations with corresponding colors.

In **Figure 2**, panel (b), the values for simulations using only natural drivers diverge from observed values after 1950, with observed values increasing to values above 1.0ºC by 2020, while values for natural drivers alone remain below 0.5ºC. The values for simulations of the combination of human and natural drivers are also above 1.0ºC by 2020. In some instances, it is not only the magnitude of the change but the speed with which the change has occurred that is unprecedented: "Global surface temperature has increased faster since 1970 than in any other 50-year period over the last 2000 years."[34] Additionally: "Global mean sea level has risen faster since 1900 than over any preceding century in at least the last 3000 years (high confidence)."[35]

Possible Climate Futures: Climate Pathways in AR6 WGI

Emissions Scenarios in AR6 WGI

In AR6 WGI, a set of five illustrative emissions scenarios are used as the primary way of examining and presenting possible climate futures. As AR6 WGI explains, "A set of five new

[34] IPCC SPM WGI 2021, p. 8.

[35] IPCC SPM WGI 2021, p. 8.

illustrative emissions scenarios ... explore the climate response to a broader range of greenhouse gas (GHG), land-use and air pollutant futures than assessed in AR5. This set of scenarios drives climate model projections of changes in the climate system."[36] The scenarios are designed to span a range of plausible futures. The following key aspects and issues pertaining to the scenarios, and their relationship to possible climate futures, are presented in this section of the report:

- descriptions of the scenarios,
- GHG emissions trajectories of the scenarios, and
- scenarios and temperature trends.

At the end of this report, an example is provided of an analysis using the AR6 WGI scenario information, with potential relevance to aspects of the Paris Agreement.

Scenario Descriptions

AR6 WGI includes five illustrative Shared Socioeconomic Pathway (SSP) scenarios, used to explore a set of possible climate futures. The SSP scenarios were developed using varying sets of assumptions about socioeconomic trajectories, resource and technological change, and alternative policy frameworks for environmental and other possible objectives.[37] A specific example of the kinds of variation in policy frameworks that form the basis of the SSP scenarios are the differences in the strength of air pollution controls included in the underlying socioeconomic narratives.[38] Each SSP scenario includes values for GHG emissions, land-use changes, and air pollution levels for the period from 2015 to 2100.[39] These are used to model the climate response, including changes in global surface temperature, arctic sea ice extent, and global sea-level rise, among others. The scenarios are used as reference points throughout AR6 WGI to identify these future climate pathways and to provide a common framework for discussion.

There are two low-emissions scenarios, SSP1-1.9 and SSP1-2.6; one that is mid-range, SSP2-4.5; and two that are high-emissions scenarios, SSP3-7.0 and SSP5-8.5. In the scenario designation, SSP refers to the Shared Socioeconomic Pathway assumptions underlying the scenario, while the second number is the scenarios' radiative forcing[40] at 2100, a measure of warming capacity. In order to reach specified endpoints of radiative forcing by 2100, the creators of the scenarios generated alternative storylines of population, economic, geopolitical, technological, and other assumptions that would be consistent with socioeconomic and emissions pathways reaching those specified endpoints.

Scenarios and Emissions Trajectories

The five emissions scenarios included for analysis in AR6 WGI provide a wide range of different emissions trajectories spanning the period 2015 to 2100. There are scenarios in which emissions continue to increase to 2100 and scenarios with sharp, rapid emissions reductions that eventually turn to net removals of CO_2 after mid-century. Across all of the scenarios, CO_2 is the largest

[36] IPCC SPM WGI 2021, p. 12.

[37] IPCC WGI 2021, p. 1-98.

[38] IPCC WGI 2021, p. TS-22.

[39] IPCC WGI 2021, p. TS-21.

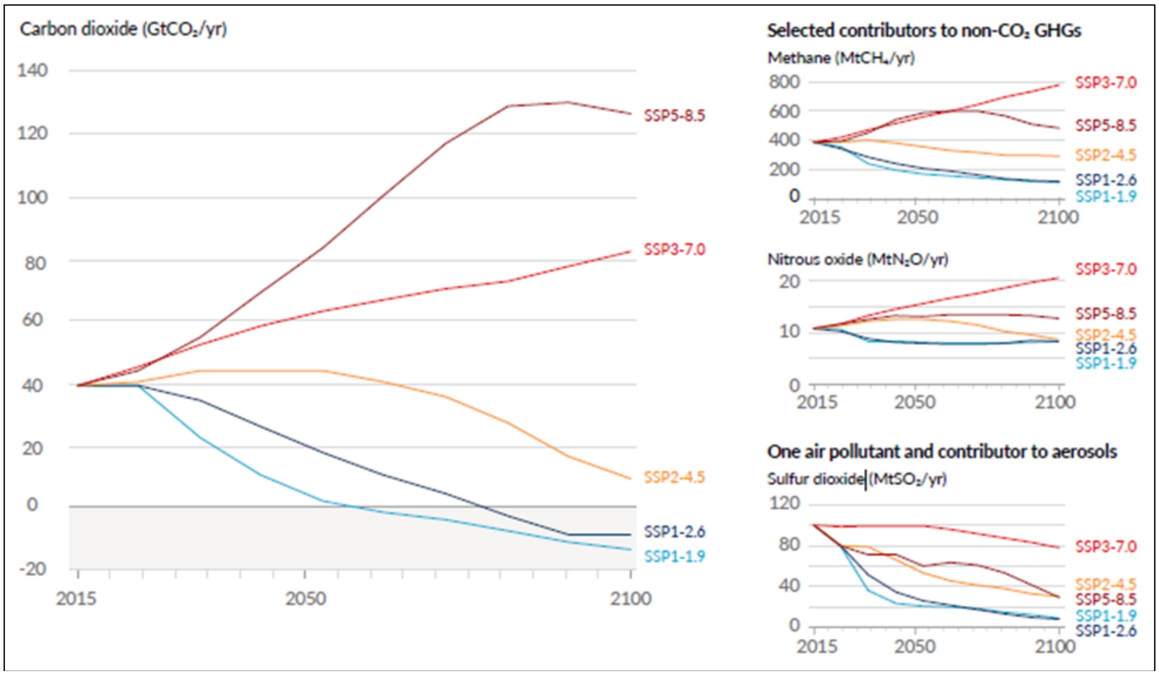
[40] Atmospheric GHGs trap heat, creating an energy imbalance with more energy coming in to the earth system than going out, resulting in warming. The difference between the energy coming in from the sun and the energy emitted back into space by the earth is referred to as *radiative forcing*. See National Oceanic and Atmospheric Administration, Climate Forcing, https://www.climate.gov/maps-data/climate-data-primer/predicting-climate/climate-forcing.

contributor to global surface temperature increases that the climate models project at the end of the period of analysis.

By 2100, CO_2 emissions under the SSP3-7.0 are slightly more than double CO_2 emissions levels of 2015, while CO_2 emissions under SSP5-8.5 are more than triple those of 2015. The CO_2 emissions trajectories of these two high-emissions scenarios differ over the period 2015-2100. Scenario SSP3-7.0 increases continuously over the time period, while SSP5-8.5 begins to decline after 2085. SSP2-4.5, the mid-range emissions scenario, increases above 2015 levels at a lower rate than either SSP3-7.0 or SSP5-8.5 and then begins to decline after 2050 (**Figure 3**).

Global CO_2 emissions under the two lowest emissions scenarios, SSP1-1.9 and SSP1-2.6, never increase above 2015 emissions levels and decline after 2020 (**Figure 3**). After 2050, both of these scenarios reach a point of "net zero" CO_2 emissions, where emissions of CO_2 are balanced by permanent removals of CO_2.[41] After reaching net zero emissions, the lowest scenarios assume "negative emissions"[42] in which, as a result of human activities, removals of CO_2 from the atmosphere exceed emissions, such that CO_2 concentrations in the atmosphere decline (**Figure 3**).

Figure 3. Future Emissions and Temperature Increases for the AR6 WGI Scenarios



Source: Adapted from Figure SPM.4, in IPCC, "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 13.

Note: The figure illustrates the human-caused annual emissions of CO_2, non-CO_2 GHGs, and SO_2 for the scenarios presented in AR6 WGI during the 2015-2100 time frame.

Negative emissions rely on carbon dioxide removals (CDRs), technologies and methods to remove carbon dioxide from the atmosphere and permanently sequester it. CDR technologies

[41] IPCC SPM WGI 2021, p. 30.

[42] The glossary in IPCC AR5 WGI,II,III 2014 provides the following definition of *net negative emissions*: "A situation of net negative emissions is achieved when, as result of human activities, more greenhouse gases (GHGs) are sequestered or stored than are released into the atmosphere."

include afforestation, reforestation, soil carbon sequestration,[43] bioenergy with carbon capture and storage[44] (BECCS), ocean fertilization, enhanced weathering, and direct air carbon capture and storage[45] (DACCS).[46] Of these, BECCS and afforestation/reforestation (AR) are the CDR methods that are more typically assumed in scenarios that hold global temperature increases below 2°C, although both of these CDRs face land-use constraints.[47] The effects of most CDR technologies and methods are speculative, as their utility has not been demonstrated at the scales required to achieve the levels of CO_2 removal assumed in the lowest emissions scenarios.

The pattern of non-CO_2 GHG emissions for the scenarios differs from those of CO_2. Under the SSP1-2.6, SSP1-1.9, and SSP2-4.5 scenarios, CH_4 emissions decline below 2015 levels by 2100, but never achieve net zero. This projection is also the case for N_2O. Emissions of CH_4 and N_2O are highest at 2100 for SSP3-7.0 and higher than SSP5-8.5, which has the highest CO_2 emissions at this point in the analysis. Emissions of the air pollutant SO_2 decline for all scenarios, but do not reach net zero. (See **Figure 3.**)

All the SSPs result in global average temperature increases that exceed 1.5ºC around mid-century or earlier. Of the five emissions scenarios included in AR6 WGI, SSP1-2.6 and SSP1-1.9 are very likely to keep the global surface temperature increase below 2.0ºC by 2100, while SSP1-1.9 returns the increase, following a peak, to 1.4ºC relative to preindustrial levels, by 2100. The other, higher emissions scenarios—SSP2-4.5, SSP3-7.0 and SSP5-8.5—have temperature increases at 2100 that have best estimates ranging from 2.7ºC to 4.4ºC. (See **Table 1.**)

[43] For more information, see CRS Report R46956, *Agriculture and Forestry Offsets in Carbon Markets: Background and Selected Issues*, by Genevieve K. Croft et al.

[44] For more information, see CRS Report R44902, *Carbon Capture and Sequestration (CCS) in the United States*, by Angela C. Jones and Ashley J. Lawson.

[45] For more information, see CRS In Focus IF11501, *Carbon Capture Versus Direct Air Capture*, by Ashley J. Lawson.

[46] The following definitions are contained in the IPCC, "Annex I: Glossary" in *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 2018:

> *Afforestation*: Planting of new forests on lands that historically have not contained forests. *Reforestation*: Planting of forests on lands that have previously contained forests but that have been converted to some other use. *Soil carbon sequestration (SCS)*: Land management changes which increase the soil organic carbon content, resulting in a net removal of CO_2 from the atmosphere. *Bioenergy with carbon dioxide capture and storage (BECCS)*: Carbon dioxide capture and storage (CCS) technology applied to a bioenergy facility. *Ocean fertilization*: Deliberate increase of nutrient supply to the near-surface ocean in order to enhance biological production through which additional carbon dioxide (CO_2) from the atmosphere is sequestered. *Enhanced weathering*: Enhancing the removal of carbon dioxide (CO_2) from the atmosphere through dissolution of silicate and carbonate rocks by grinding these minerals to small particles and actively applying them to soils, coasts or oceans. *Direct air carbon dioxide capture and storage (DACCS)*: Chemical process by which CO_2 is captured directly from the ambient air, with subsequent storage.

[47] IPCC, *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 2018, p. 316.

Table 1. Changes in Global Surface Temperature During the 21st Century for Emissions Scenarios Included in AR6 WGI

	Near term, 2021-2040		Mid-term, 2041-2060		Long term, 2081-2100	
Scenario	**Best estimate (°C)**	***Very likely* range (°C)**	**Best estimate (°C)**	***Very likely* range (°C)**	**Best estimate (°C)**	***Very likely* range (°C)**
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

Source: Adapted from Table SPM.1 in IPCC, "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 14.

Notes: The table presents global surface temperature changes reported for three time periods during the 21st century, for the five emissions scenarios presented in AR6 WGI. Temperature changes are in relation to average global surface temperature during the time period 1850-1900.

Not all modelers accept that the SSP1-1.9 scenario could be achieved.[48] Even should SSP1-1.9 prove feasible, achieving this temperature is not assured; even with the lowest emissions scenario considered in AR6 WGI, there is uncertainty about achieving this outcome.

For the high-emission SSP5-8.5 scenario, the best estimate for the temperature increase by 2100 is 4.4°C. Experts have questioned whether SSP5-8.5 is a plausible scenario.[49] In AR6 WGI no likelihood is assigned to any of the scenarios, and all are considered possible.[50] One objection to SSP5-8.5 is that it requires "an unprecedented five-fold increase in coal use by the end of the century"[51] to achieve its designated radiative forcing endpoint. An argument supporting SSP5-8.5 is that the levels of emissions need not come from fossil fuels alone, but that emissions from land-use changes, such as deforestation, could be large enough to make the scenario's emissions levels plausible.[52] The scenarios included in AR6 WGI are "one of many possible scenarios that could be consistent with the concentration pathway [resulting in the range of radiative forcing levels including that of 8.5 Wm^{-2}]."[53] Other scenarios, more closely resembling recent GHG levels, investment patterns, and policies, suggest that current GHG trajectories more closely resemble SSP2-4.5, and could fall in a range of the middle scenarios. In an article published in *Global*

[48] A key analysis on the scenarios used by the IPCC states, "1.9 W m−2 scenarios could not be achieved in several models under SSPs with strong inequalities, high baseline fossil-fuel use, or scattered short-term climate policy." Joeri Rogelj et al., "Scenarios towards Limiting Global Mean Temperature Increase below 1.5 °C," *Nature Climate Change* vol. 8, no. 4 (April 2018).

[49] References to multiple critiques are in Zeke Hausfather, "Explainer: The High-Emissions 'RCP8.5' Global Warming Scenario," *Carbon Brief,* August 21, 2019.

[50] IPCC WGI 2021, p. TS-22.

[51] Zeke Hausfather and Glen P. Peters, "Emissions—The 'Business as Usual' Story Is Misleading," *Nature,* vol. 577, no. 7792 (2020), p. 618.

[52] Christopher R. Schwalm, Spencer Glendon, and Philip B. Duffy, "Reply to Hausfather and Peters: RCP8.5 Is Neither Problematic nor Misleading," *Proceedings of the National Academy of Sciences,* vol. 117, no. 45 (2020), p. 27793.

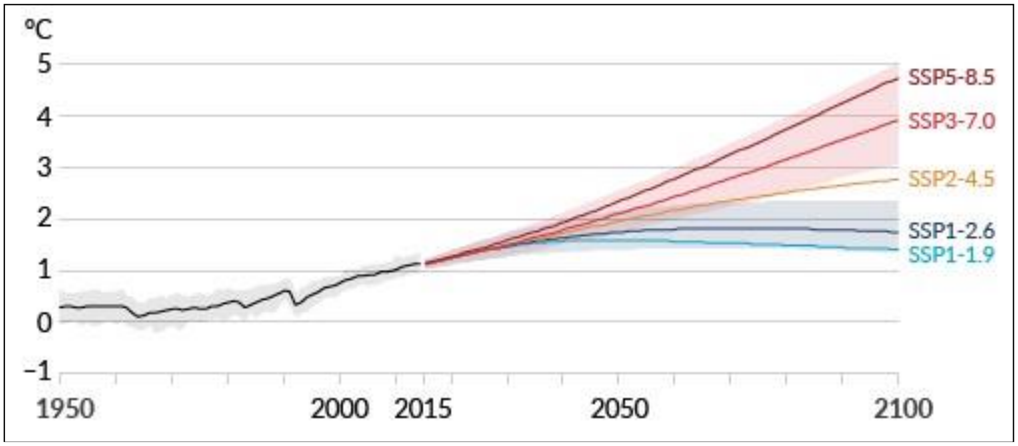
[53] Detlef van Vuuren et al., "The Representative Concentration Pathways: An Overview," *Climatic Change,* vol. 109, no. 1 (2011), p. 5.

Environmental Change, researchers stated, "For many dimensions the SSP2 marker implementation also reflects an extension of the historical experience, particularly in terms of carbon and energy intensity improvements in its baseline."[54]

Scenarios and Temperature Trends

The difference in temperature trend distinguishes the low-emissions scenarios from the other scenarios. For the low-emissions scenarios SSP1-1.9 and SSP1-2.6, temperature increases halt, whereas for emissions scenarios SSP2-4.5, SSP3-7.0, and SSP5-8.5, temperatures continue to increase during the time period analyzed (**Figure 4**).

Figure 4. Changes in Global Surface Temperatures for Scenarios Included in AR6 WGI



Source: Adapted from Figure SPM.8, panel (a), in IPCC, "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 22.

Notes: The figure depicts temperature changes under scenarios included in AR6 WGI in relation to 1850-1900. The shaded areas indicate uncertainty—the very likely global surface temperature change ranges for SSP3-7.0 (red shading) and for SSP1-2.6 (blue shading).

Limiting Future Climate Changes: The Scientific Framework

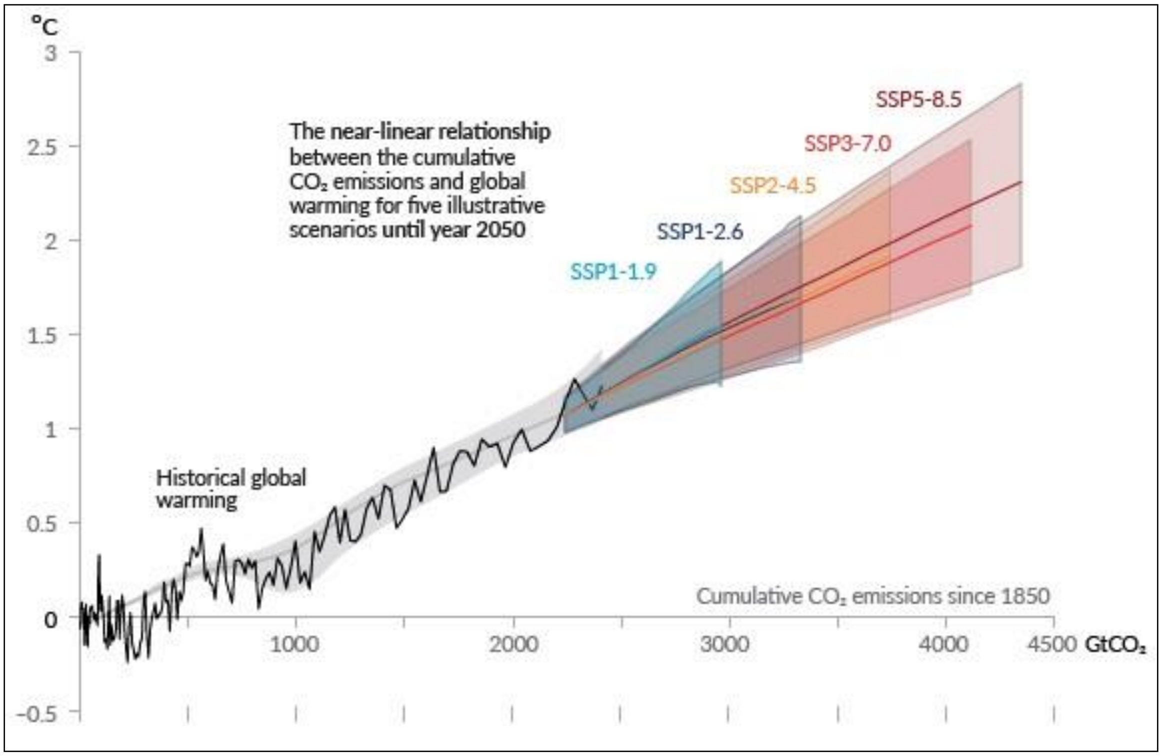
A noteworthy finding of AR6 WGI is the observed and modeled, almost linear, relationship between cumulative anthropogenic emissions of CO_2 and global temperature increases (**Figure 5**). This finding is the stated scientific basis in AR6 WGI for the ability to limit future climate changes.

> This Report reaffirms with high confidence the AR5 finding that there is a near-linear relationship between cumulative anthropogenic CO_2 emissions and the global warming they cause. Each 1000 $GtCO_2$ of cumulative CO_2 emissions is assessed to likely cause a 0.27°C to 0.63°C increase in global surface temperature with a best estimate of 0.45°C.[55]

[54] Oliver Fricko et al., "The Marker Quantification of the Shared Socioeconomic Pathway 2: A Middle-of-the-Road Scenario for the 21st Century," *Global Environmental Change*, vol. 42 (2017), p. 251.

[55] IPCC SPM WGI 2021, p. 28.

Figure 5. Global Surface Temperature Increases as Function of Cumulative CO_2 Emissions



Source: Adapted from Figure SPM.10, in IPCC, "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis—Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 2021, p. 28.

Notes: The black line depicts historical global surface temperature increases from 1850 to 2019 in relation to cumulative CO_2 emissions since 1850. The colored lines and areas show the *very likely* range of global surface temperature increases from 2020 to 2050, for the scenarios SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 in relation to their additional cumulative CO_2 emissions. The projected global warming includes all anthropogenic climate influences.

The AR6 WGI states that with incremental global temperature increases, there are also measurable changes in some sensitive components of the earth system that become larger.

> With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (very likely), and heavy precipitation (high confidence), as well as agricultural and ecological droughts in some regions (high confidence). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (medium confidence). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (medium confidence). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are larger for rarer events (high confidence).[56]

[56] IPCC SPM WGI 2021, p. 15.

Not all changes in components of the earth system are proportional to global temperature increases. Some, like Antarctic sea ice, show little sensitivity to the climate changes in the observational record, and AR6 WGI states, "There is low confidence in the projected decrease of Antarctic sea ice."[57]

The scientific basis for limiting future climate change, stated in AR6 WGI, is the relationship between cumulative CO_2 emissions, emissions of other GHGs, other climate drivers, and increasing temperatures. Limiting global temperature increases and associated changes in climate-sensitive earth system components requires limiting cumulative CO_2 emissions, limiting emissions of other GHGs, and limiting other climate drivers.

> From a physical science perspective, limiting human-induced global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality.[58]

The AR6 WGI Scenarios and the Paris Agreement Temperature Benchmarks

The emissions scenarios of AR6 WGI may be used as a framework for analyzing options for implementing policies related to the Paris Agreement (PA).[59] AR6 WGI frequently uses benchmarks of global temperature increases of 1.5°C and 2.0°C above preindustrial levels (global surface temperatures over 1850-1900) for comparing the estimated global temperature trajectories of the AR6 WGI emissions scenarios. These temperature increase values are stated in the PA as follows:

> Article 2
>
> 1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:
>
> (a) 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.[60]

Emissions and climate projections from the AR6 WGI scenarios can be used to analyze projections of global GHG emissions based on nonbinding pledges that each party submits as their "Nationally Determined Contributions (NDCs)" under the PA.[61] The NDCs are to be

[57] IPCC SPM WGI 2021, p. 16.

[58] IPCC SPM WGI 2021, p. 27.

[59] The 2015 Paris Agreement (PA) is the second subsidiary agreement to the UNFCCC; the Kyoto Protocol is the first. The United States became a party to the PA under the Obama Administration, withdrew from the agreement under the Trump Administration and, on January 20, 2021, rejoined it under the Biden Administration. The PA is a complex, multifaceted agreement that includes aspects that are specifically relevant to the scenario analysis presented in AR6 WGI, such as the temperature benchmarks stated in the quoted passage.

[60] United Nations Framework Convention on Climate Change, *Paris Agreement*, 2015 p. 3 (hereinafter UNFCCC PA 2015).

[61] UNFCCC PA 2015, p. 3.

submitted every five years and state how each party intends to abate its GHG emissions.[62] The AR6 WGI scenarios include emissions levels and the associated temperature changes that climate models project for those emissions levels. The estimated emissions levels of the NDCs can be compared with the AR6 WGI scenario emissions levels as part of an analysis of temperature changes that may be associated with the NDCs.

Considerations for Congress

In 2021, the Secretariat of the UNFCCC published a synthesis report on "Nationally determined contributions under the Paris Agreement."[63] The report includes a section on "Contribution towards achieving the objective of the Convention as set out in its Article 2, and towards Article 2, paragraph 1(a) ... of the Paris Agreement."[64] The information provided in the report suggests that the current emissions trajectory through 2030, based on the NDCs, is closely aligned with the IPCC emissions scenario SSP2-4.5. The projected very likely temperature increase for this scenario at 2100, included in AR6 WGI, exceeds 2.0ºC (**Table 1**) and does not achieve the objective of the convention set out in Article 2.

Under the terms of the PA, the timeline for communicating NDCs is every five years,[65] and as stated in Article 4, Section 3 of the PA, "Each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition."[66] The PA also sets a goal for "peaking of greenhouse gas emissions ... so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases."[67] *Net-zero emissions* is a similar term for achieving this balance. *Net-zero emissions*, or *net-zero*, refers to situations where human-caused GHG emissions are balanced by removal of GHG from the atmosphere.[68]

As part of a climate change mitigation strategy, some governments are developing GHG emissions reduction strategies that include domestic legislation to realize net-zero emissions and revising emissions reduction levels in the progression of NDCs. Some countries, including Japan and the United Kingdom, have updated their NDCs with increasingly ambitious emissions reduction goals and passed domestic net-zero emissions legislation. The United States has increased the ambition of the emissions reductions in an updated NDC, but has not, as of this writing, enacted domestic net-zero legislation.[69]

With respect to the United States' most recent NDCs, Congress may wish to exercise its oversight authorities in examining national progress toward fulfilling the updated U.S. NDCs. Congress

[62] UNFCCC, Nationally Determined Contributions (NDCs), https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs.

[63] UNFCC, *Nationally Determined Contributions Under the Paris Agreement (Synthesis Report by the Secretariat)*, 2021.

[64] UNFCC, *Nationally Determined Contributions Under the Paris Agreement (Synthesis Report by the Secretariat)*, 2021, p. 26.

[65] UNFCCC PA 2015, p. 5.

[66] UNFCCC PA 2015, p. 4.

[67] UNFCCC PA 2015, p. 3.

[68] CRS Report R46945, *Greenhouse Gas Emission Reduction Pledges by Selected Countries: Nationally Determined Contributions and Net-Zero Legislation*, by Kezee Procita.

[69] CRS Report R46945, *Greenhouse Gas Emission Reduction Pledges by Selected Countries: Nationally Determined Contributions and Net-Zero Legislation*, by Kezee Procita.

could also consider options for shaping and funding the U.S. approach to the PA commitments.[70] For example, there have been a number of legislative proposals introduced during the 117th Congress that seek to address a range of GHG emissions sources as part of an effort to move the United States toward net-zero emissions.[71] The information provided in AR6 WGI may help to inform Congress when considering the United States' participation in the PA and the most recent U.S. NDCs.

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[70] See CRS In Focus IF11746, *United States Rejoins the Paris Agreement on Climate Change: Options for Congress*, by Jane A. Leggett.

[71] For example, see H.R. 1512, which would create requirements to reduce GHG emissions with a goal of achieving net-zero emissions by 2050.